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Investigation of the island-induced ocean vortex train of the Kuroshio Current using satellite imagery

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ABSTRACT

In this study, we used satellite imagery to conduct a statistical study of the ocean vortex train induced by the Kuroshio Current on the leeward side of Green Island, Taiwan. The spatial scale and characteristics of the ocean vortex train were analyzed using image datasets from five different high-resolution satellites, including optical imagery from the Satellite Pour l'Observation de la Terre and the Formosat-2 satellites and synthetic aperture radar imagery from the European Remote Sensing Satellite, Advanced Land Observing Satellite, and Sentinel-1. Satellite altimetry data and a moored acoustic Doppler current profiler (ADCP) were used to calculate the velocity of the Kuroshio Current. The ADCP data suggest that the velocity increases on the western side of the vortex train when it is formed on the leeward side of Green Island. Data from the moderate-resolution imaging spectroradiometer (MODIS) showed that the sea surface temperature of the recirculation water was over 2 °C colder and the chlorophyll-*a* concentration was two times higher than that of the surrounding waters. These phenomena suggested upwelling, mixing processes, and an island-mass effect. Wind forcing had a pronounced effect on the characteristics of the vortex train. High-resolution satellite images indicate that the averaged aspect ratio of the vortex train is 2.09 and the dimensionless width is 2.02 under southerly winds, compared to 1.91 and 2.76, respectively, under northerly winds.

1. Introduction

The flow pattern in the vortex of an obstacle depends on the Reynolds number (Re) of the flow. Periodic oscillation of the vortex occurs when the Re value is between 40 and 70. Above a limiting value of $Re < 60–90$, shedding of standing eddies behind the object occurs. This flow pattern is referred to as a von Kármán vortex street (Pattiaratchi et al., 1987). Vortex streets occur frequently in the atmosphere (Li et al., 2000; Nunalee and Basu, 2014) and ocean (Barton et al., 2000; Young and Zawislak, 2006; Dong et al., 2007; Zheng et al., 2008, 2012; Teinturier et al., 2010; Topouzelis and Kitsiou, 2015). Ocean vortices and island-induced ocean vortex trains (IOVTs) are types of small-scale or mesoscale ocean phenomena, which often enhance biological productivity via upwelling and turbulent mixing and are closely associated with fishing activities (Caldeira et al., 2002, 2005; Hasegawa et al., 2004, 2009).

The Kuroshio Current, a western boundary current in the North Pacific, originates from the North Equatorial Current and flows northward from east of the Philippines to south of Japan. This current could provide a source of energy because it is rapid and steady as it passes the east coast of Taiwan. For a potential Kuroshio power test site near Green Island, located at 22°35′N 121°28′E, 40 km off the southeastern coast of Taiwan, several factors have to be considered, such as the Kuroshio Current velocity, island wakes, and the seabed topography. According to in-situ measurements and numerical model simulations, it has been clearly shown that a high potential power density distribution is located in the northwestern area of Green Island, which is close to the influence area of the island vortex street (Hsu et al., 2015b). Because the vortex street has an adverse effect on the stability and power efficiency of turbine generators and the related anchoring platform, an understanding of the origins of the Green Island vortex is therefore an important research topic for energy exploitation of the Kuroshio Current.

Ship surveys and satellite altimetry data have reported that the Kuroshio Current east of Taiwan has a mean maximum velocity of ~1.2 m/s (Yang et al., 2015) and an average velocity of ~0.76 m/s (Hsu et al., 2016). The incoming Kuroshio Current forms an ocean vortex and IOVT behind Green Island (Chang et al., 2013; Liang et al., 2013; Huang et al., 2014; Zheng and Zheng, 2014; Hsu et al., 2015a). When the Kuroshio Current strikes Green Island directly, a recirculation develops leeward of the island, followed by a wavy tail resembling a weak vortex street and a cold eddy that likely originates downstream of Green Island. The IOVT may be affected by the Kuroshio Current

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velocity; it has been simulated via numerical modeling (Huang et al., 2014) and measured by in situ data (Chang et al., 2013). Besides, the seasonal variation of Green Island IOVT affected by different wind directions has been mentioned by Hsu et al. (2015a) using a numerical model. They found that different wind directions may change the spatial scales of the vortex area. The seasonality and size of the IOVT have to be considered, because changes in the spatial scales of IOVT may affect the consideration on site selection of the Kuroshio power generators. However, numerical simulations and a one-time survey cannot provide a synoptic view of the IOVT. To have a synoptic understanding the seasonality and spatial scales of the IOVT and its relationship with the Kuroshio Current velocity, high-spatial resolution satellite images and geostrophic velocities derived from satellite altimeter data are applied to conduct a statistical study of the Green Island vortices. Satellite imagery from 2001 to 2015 and data from two ADCPs moored on the western side and in the lee of Green Island are used to investigate the spatial characteristics and seasonal variability of the vortex and IOVT. In this paper, we also discuss the atmospheric wind forcing which could affect the spatial configuration of an ocean vortex train on a short-time scale. The analysis of the spatial characteristic, variations of IOVT and wake extension distance by satellite imagery, and Kuroshio flow speed observed by ADCPs moored data will provide quite reference values for numerical simulation of the Green Island wake in the future.

2. Data

2.1. High-resolution satellite imagery

Green Island is located at 22°35′N 121°28′E, 40 km off the southeastern coast of Taiwan. The water depth around the island varies from 50 m to 4000 m (Fig. 1). In this area, ocean vortices are formed on the leeward side of Green Island by the incoming bathymetry-deflected Kuroshio Current. The resulting vortex shedding, upwelling of colder water, and vortex trains are accompanied by higher bio-productivity. To examine the spatial scales of the ocean vortices and IOVT, image datasets from five different high-resolution satellites, including panchromatic images from Satellite Pour l'Observation de la Terre (SPOT) and the Formosat-2 satellite and SAR images from the European Remote Sensing Satellite (ERS-2), Advanced Land Observing Satellite (ALOS), and Sentinel-1 (Table 1) are used.

The SPOT and Formosat-2 satellite data are in the form of panchromatic images. The first SPOT satellite (SPOT-1) was launched in 1986, with a 10-m panchromatic and 20-m multispectral imagery resolution capability. The latest (SPOT-7) was launched in 2014, with a 1.5-m panchromatic and 6-m multispectral spatial resolution. The SPOT series of satellites were initiated by the Centre national d'études spatiales (CNES). Formosat-2 was launched on May 20, 2004, by the National Space Organization, Taiwan. It has a spatial resolution of 2 m for panchromatic and 8 m for multispectral imagery.

Table 1
Summary of high-resolution satellite images used in this study.

Satellite	Sensor
SPOT 1–4	HRV (High Resolution Visible)
SPOT-5	HRG (High Resolution Geometrical)
SPOT-6 & 7	NAOMI (New AstroSat Optical Modular Instrument)
Formosat-2	Panchromatic sensor and Multispectral sensor
ERS-2	C-SAR (C-band Synthetic Aperture Radar)
ALOS-1 & 2	PALSAR (Phased Array type L-band Synthetic Aperture Radar)
Sentinel-1	C-SAR (C-band Synthetic Aperture Radar)

The ERS-2 satellite was placed into orbit in 1995 and retired in 2011. This satellite was equipped with SAR with a spatial resolution of 20 m and a swath of 100 km at the C-band with VV polarization. Sentinel-1, which was launched in 2014, provided continuity following the retirement of ERS-2 at the end of the Envisat mission. Sentinel-1 is a two-satellite constellation with the prime objective of monitoring the land and ocean using a C-band SAR to provide continuous SAR images. The ALOS-1 satellite was launched in 2006 and retired in 2011 and was followed by the ALOS-2 satellite in 2014; both were initiated by the Japan Aerospace Exploration Agency (JAXA). The ALOS series satellite payload included Phased Array-type L-band Synthetic Aperture Radar (PALSAR) for day-and-night and all-weather land observations.

2.2. Satellite altimetry data

Daily Absolute Dynamic Topography (ADT) data with 1/4°× 1/4° grid spatial resolution provided by Archiving Validation and Interpretation of Satellite Data in Oceanography (AVISO) are employed in this study. ADT is deduced from the Sea Level Anomaly (SLA) using a Mean Dynamic Topography (MDT), i.e., ADT = SLA + MDT, where MDT is mean sea surface minus the geoid (SSALTO/DUACS User Handbook, 2016).

2.3. Moderate-resolution imaging spectroradiometer data

The moderate-resolution imaging spectroradiometer (MODIS) is an instrument carried by the Terra and the Aqua satellites. MODIS sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*) images with 250-m spatial resolutions were used to show the features of the ocean vortices and the vortex trains leeward of Green Island. The images were processed from MODIS Level 0 data for Level 2 data using the SeaDAS program version 7.3, which created a 250-m resolution image with replication for the 500-m and 1-km resolution bands and resampling using the nearest method from the swath to the Mercator projection grids. The Level 0 data were downloaded from NASA's OceanColor

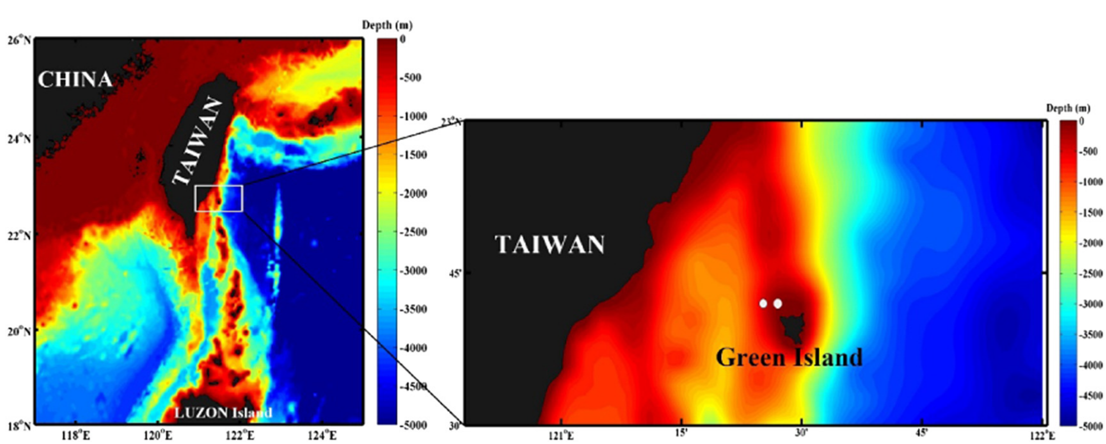

Fig. 1. Locations of Green Island and two ADCP stations, shown as white dots.