Continental Shelf Research ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Interannual variability of the subtropical countercurrent eddies in the North Pacific associated with the Western-Pacific teleconnection pattern

Chun Hoe Chow [a,d], Yu-heng Tseng [b,*], Huang-Hsiung Hsu [a], Chih-Chieh Young [c]

[a] Research Center for Environmental Changes, Academia Sinica, Taiwan
[b] Climate and Global Dynamics Division, National Center for Atmospheric Research, United States
[c] Hydrotech Research Institute, National Taiwan University, Taiwan
[d] Department of Oceanography, National Sun Yat-sen University, Taiwan

ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form
14 July 2016
Accepted 10 August 2016

Keywords:
Oceanic eddies
Pycnocline shoaling
Western Pacific teleconnection
Air-sea interaction
Interannual variability

ABSTRACT

The connection and the relevant dynamical processes between oceanic eddies in the North Pacific Subtropical Countercurrent (STCC) region and the atmospheric Western-Pacific (WP) teleconnection is investigated on interannual timescales. North of the STCC region, the local northerly surface wind anomalies cool the ocean surface during negative phases of the WP teleconnection. The local surface cooling modifies the meridional gradient of sea surface temperature (SST), strengthening the SST front at its south. In the STCC region, we show the meridional gradient of surface-heat-flux forcing caused by the local surface cooling is the same order as the Ekman-convergence forcing. The strengthened SST front then leads to the pycnocline shoaling in the STCC region, which can also enhance the growth of baroclinic instability to produce more oceanic eddies, in addition to the enhanced STCC proposed previously. These dynamics are reversed during the positive phases of WP teleconnection.

1. Introduction

The variability of oceanic eddies in the North Pacific Subtropical Countercurrent (STCC) region has drawn much attention over the last decades (Qiu, 1999; Roemmich and Gilson, 2001; Hwang et al., 2004; Qiu and Chen, 2005; Qiu and Chen, 2010; Chow and Liu, 2012; Yang et al., 2013). Based on satellite observations, the eddy signature reflected by sea surface height (SSH) variation has a dominant time scale of about 100 days and a dominant eddy wavelength of about 800 km along the STCC band (Liu and Li, 2007; Qiu and Chen, 2010). The number of anticyclonic eddies is larger than that of cyclonic eddies by about 16.9% (Yang et al., 2013) climatologically. The eddies, which are most active in spring (Qiu, 1999), typically move westward at a speed of about 0.1 m/s due to the planetary beta effect (Cushman-Roisin et al., 1990; Hwang et al., 2004; Lin et al., 2006).

The westward moving eddies can interact with the Kuroshio when approaching Taiwan, modulating Kuroshio transport and path (Yang, 1999; Zhang et al., 2001; Yuan et al., 2006; Shen et al., 2014; Chow et al., 2015). They can affect the local circulation in the South China Sea after penetrating through the Luzon Strait when the Kuroshio becomes weak during fall and winter (Sheu et al., 2010). They also transport heat northward via meridional advection in the subtropical North Pacific (Roemmich and Gilson, 2001; Qiu and Chen, 2005). The warm and cold sea surface temperature (SST) tongues formed by the meridional advection could influence ocean wind variability (Small et al., 2005; Chow and Liu, 2012).

During its negative phases, the pattern of the atmospheric Western-Pacific (WP) teleconnection consists of a north-south dipole of 500-hPa geopotential height anomalies (H500 anomalies), with the northern lobe of positive anomalies located over the Kamchatka Peninsula and another broad southern lobe of opposite sign covering portions of southeastern Asia and the western subtropical North Pacific (Fig. 1) (Wallace and Gutzler, 1981). The eddies in the North Pacific STCC region are active in some years, corresponding to the negative phases of the WP pattern (referred to "WP teleconnection pattern" hereafter) on interannual timescales (Qiu and Chen, 2010; Shen et al., 2014). The eddy strength is mainly determined by the vertical shear between the eastward-flowing STCC and the subsurface westward-flowing North Equatorial Current (NEC). When the STCC flows faster, larger vertical shear increases the baroclinic instability of the STCC-NEC system, potentially forming more eddies (Qiu and Chen, 2010). The STCC resides below the southern boundary of the WP-pattern southern

* Correspondence to: CGD/NCAR, PO Box 3000, Boulder, CO 80307-3000, United States.
E-mail addresses: kilmerchow@gate.sinica.edu.tw (C.H. Chow), ytseng@ucar.edu (Y.-h. Tseng), hhhsu@gate.sinica.edu.tw (H.-H. Hsu), youngjay@ntu.edu.tw (C.-C. Young).

http://dx.doi.org/10.1016/j.csr.2016.08.006
0278-4343/

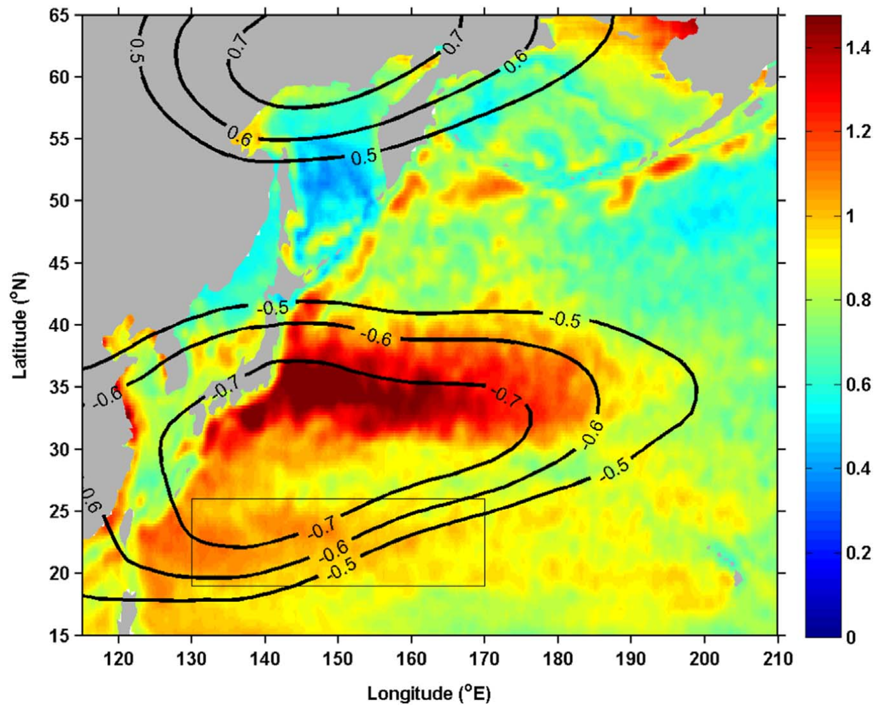

Fig. 1. The normalized standard deviation of SSH anomalies from altimetry observation (colors) from 1993 to 2010, superimposed with the negative phase of WP pattern (selected contours), during December to following April from 1993 to 2010. The standard deviation values shown are natural logarithm. The WP pattern is shown by the correlation between the WP index provided by the Climate Prediction Center (CPC) and the geopotential height at 500 hPa provided by the European Center for Medium-Range Weather Forecasts (ECMWF). The box centered at about 22°N shows the region of interest within 130° to 170°E and 19° to 26°N. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

lobe (Fig. 1; box centered at about 22°N approximately shows the region of STCC). Qiu and Chen (2010) show that the surface winds associated with the negative phases of WP pattern increase Ekman convergence at the surface in the subtropics and then strengthen the STCC, modulating the interannual variability of the STCC and eddies. On interannual to decadal timescales, the forcing of Ekman convergence and surface heat flux is important for eddy variability in the region (Qiu and Chen, 2013). The Kuroshio transport east of Taiwan can be altered significantly by the interannually varying eddies (Yang, 1999; Zhang et al., 2001) related to the WP pattern (Shen et al., 2014).

This paper aims to clarify the dynamical processes linking these eddies and the WP pattern on interannual timescales by answering the following scientific questions: (1) How are the anticyclonic and cyclonic eddies connected with the atmospheric variability; (2) What are the other key factors controlling the state and variability of eddies in addition to the increase of STCC flow speed suggested in Qiu and Chen (2010); and (3) How are these key factors influenced by the WP pattern? It is found that these eddies vary with the WP pattern under circumstances of steep thermocline tilt in the subtropics (Qiu and Chen, 2010; Shen et al., 2014). We hypothesize that, besides the STCC flow speed, the variability of pycnocline depth, which to date was not a focus for the eddy-activity issue, may play an important role to enhance the growth of baroclinic instability and eddies in the STCC region. Thus, the surface-wind variability modulated directly by the WP pattern alters the background SST gradient field via surface heat flux and Ekman convergence, resulting in changes of pycnocline depth leading to the observed interannual variability of eddy fields. Moreover, this paper also investigates the atmospheric variability from the surface up to the 500-hb height, corresponding to the eddy activity, thus completing the dynamical processes linking the WP pattern defined at the 500-hb height to eddies at the surface.

Section 2 describes the methodology and data used. Section 3 shows the STCC eddy bands, followed by the discussion of the oceanic interannual variability related to the WP pattern in Section 4. Section 5 details the heat-flux process linking the eddy interannual variability to that of WP pattern. Finally, results are discussed and summarized in Section 6.

2. Methodology

2.1. Observation and reanalysis

Monthly SSH-anomaly data is gridded at a 0.25° resolution from 1993 to 2010, distributed from the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) (Ducet et al., 2000). To study the ocean vertical structure, we used the temperature and salinity (TS) profiles of "EN3_v2a" monthly 1° objective analysis dataset from 1993 to 2010 (Guinehut et al., 2009), provided by the Met Office Hadley Center. The EN3_v2a reanalysis is mainly based on the data of Argo and Global Temperature and Salinity Profile Project (GTSPP).

The TS profiles of EN3_v2a are then used to estimate the buoyancy frequency (N^2) at approximately 0–540 m depth and 23.8-sigma depth to represent the shallow upper-layer variability. The buoyancy frequency was estimated from:

$$N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}, \tag{1}$$

where $\frac{\partial \rho}{\partial z}$ is the density vertical gradient, ρ_0 is the reference density and g is the gravity. The 23.8-sigma surface was chosen because it resides at the depth varying between 50 and 95 m, slightly below the mixed layer depth at about 50 m (Qu, 2003). This sigma surface reasonably estimates the shallow upper-layer thickness variability.

To analyze the corresponding atmospheric variability, we used the monthly 1° dataset of the Interim Reanalysis of the European

Please cite this article as: Chow, C.H., et al., Interannual variability of the subtropical countercurrent eddies in the North Pacific associated with the Western-Pacific teleconnection pattern. Continental Shelf Research (2016), http://dx.doi.org/10.1016/j.csr.2016.08.006