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The formation and dynamics of the cold-dome off northeastern Taiwan

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ABSTRACT

The cold-dome off northeastern Taiwan is commonly observed by remote-sensing of Sea Surface Temperature (SST) and in-situ observation. The recent remote-sensing SST and subsurface Argo profiles were analyzed to investigate possible formation mechanisms and dynamics. The observed time series of SST anomaly suggested that the surface cold-dome occurred more frequently in summer, including an unusual contribution due to the cold water residual associated with typhoon events. Subsurface hydrographic features from Argo float data indicated that the near-shore thermocline can be lifted up about 85 m by Kuroshio dynamics, and the cold saline deep water (100 m deep off northeastern Taiwan) can only result from subsurface Kuroshio. We examined the possible formation mechanisms using a duo-grids North Pacific Ocean model (DUPOM) with a horizontal resolution of 1/8° for the East Asian Seas and 1/4° for the remaining North Pacific. The model reproduced several cold-dome formation events and displayed typical cold-dome features. Further analysis shows that the geostrophic component of Kuroshio transport is the main contributor to the cold-dome formation (57.4% of the total isotherm uplift) and dominates seasonal occurrence of the cold-dome. The contribution resulting from the associated cyclonic eddy is only 3.3% of the total isotherm uplift. Additional sensitivity tests suggested that the remaining contribution (39.6% of the total isotherm uplift) is mainly due to the topographically controlled upwelling in this region. Moreover, the local boundary Ekman transport may enhance the surface appearance of the cold-dome, but plays only a minor role.

1. Introduction

The circulation and air–sea exchange in the southern East China Sea (ECS) and their interaction with the regional current system due to complex bathymetry and continental shelves is not completely understood. A well-known complexity exists off northeastern Taiwan, where a cold-dome associated with a cyclonic eddy (Chuang et al., 1993; Hsueh, 2000) is commonly observed. The properties of the cold-dome have been documented extensively through field surveys (for example, Tang and Tang, 1994; Tang et al., 2000; Tang et al., 1999), satellite remote sensing (for example, Cheng et al., 2009; Gong et al., 1992; Lin et al., 1992), and numerical studies (Wu et al., 2008a). Importantly, the water in this area is nutrient-rich due to the upwelling in the cold-dome (Chen, 1996; Chen et al., 2003; Hsu, 2005), and is regarded as one of the primary fishing grounds around Taiwan. The complex circulation also contributes substantially to the exchange of water mass, heat, and salinity of the ECS, Taiwan Strait Water (TSW), and Kuroshio (Chen and Sheu, 2006; Hsueh, 2000; Isobe, 2008; Matsuno et al., 2009). Therefore, a better understanding of the cold-dome formation and its interaction with regional circulation is crucial and requires more knowledge of nutrient sources and the associated water exchange in this region.

Satellite remote sensing data show that the cold-dome normally occurs on the Mien-Hua Canyon (MHC), where the temperatures are lower than the surrounding waters by about 3–6 °C, and is observed more frequently in summer than in winter (Cheng et al., 2009). Because the Kuroshio axis east of Taiwan migrates seasonally, seaward in summer and shoreward in winter (Tang et al., 2000), the variation in cold-dome occurrence may be linked to the Kuroshio. However, the cold surface temperatures in winter may reduce the possible cold-dome recognition (Liu et al., 1992), and the surface buoyancy change due to the precipitation carried by frequent typhoon events can induce the upwelling of subsurface water (Chen et al., 2003) and thus enhance its seasonal appearance. Furthermore, hydrographic surveys northeast of Taiwan show that Kuroshio Tropical Water (KTW, or Kuroshio Subsurface Water), characterized by a salinity maximum, is commonly upwelled onto the continental shelf all year round (Chuang and Liang, 1994; Hsueh et al., 1992; Hsueh et al., 1993; Liu et al., 1995; Liu et al., 1992; Wong et al., 1991) and forms the basis of the surface cold-dome (see Table 1 for the abbreviations and the associated Nomenclatures of the water masses used hereafter). The upwelling of KTW shows similar seasonal

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Table 1
The abbreviations and associated nomenclatures of the water masses.

Abbreviation	Nomenclature
CCW	China Coast Water
CW	Continental Water
KSW	Kuroshio Surface Water
KTW	Kuroshio Tropical Water, or Kuroshio Subsurface Water
TSW	Taiwan Strait Water

variations with Kuroshio migration; KTW carries more water mass onto the continental shelf in summer than in winter (Chen et al., 1995).

The cold-dome is often accompanied with a cyclonic eddy off northeastern Taiwan. The eddy may be arose through the upwelling-induced buoyancy wave constrained by the associated Rossby radius of deformation and acts like a pseudo-wall, blocking the advection of warm water from TSW (Tang et al., 2000; Chuang et al., 1993; Tang and Tang, 1994; Tang et al., 2000; Tang et al., 1999). However, the surface eddy may also be introduced by the island wake instability, as the flow found on the lee side of the Izu Islands (Isoguchi et al., 2009). Specifically, the characteristics of the surface cyclonic eddy are probably impacted by the surrounding asymmetric flow strength, as contributed by the TSW and Kuroshio and its variations. This flow enhanced cyclonic motion can feed more cold water into the cold-dome and its contribution will be verified numerically.

In addition to the cyclonic eddy, local wind effects could contribute to the formation of the cold-dome. Gong et al. (1992) reported that the disappearance of the cold-dome in summer was associated with the summer monsoon. Recently, Chang et al. (2009) showed that the upwelling introduced by Kuroshio is much larger than the effects of Ekman pumping based on an eddy-resolving numerical model. Furthermore, Chang et al. (2010) applied a simplified heat budget equation to investigate the temperature change due to Ekman transport and surface heat flux for the case of surface current against wind direction. This explained the variations in the wind stresses of Peng-Chia Yu and sea surface temperatures (SST) of Long-Tung buoy; however, the seasonal appearance of the cold-dome, particularly the major occurrence in summer, is still unanswered when this method is applied.

In addition to a local wind adjustment, the precipitation and surface wind carried by typhoons may also induce the cold-dome pattern. Chen et al. (2003) observed the nutrient enhancement after the passage of Typhoon Herb in July 1996 and demonstrated that the buoyancy flux increase due to typhoon precipitation would suggest an enhancement of upwelling. Typhoon-induced current velocities can further change the axis of Kuroshio (Chen et al., 2003; Morimoto et al., 2009) and may affect the cold-dome formation. Furthermore, the atmospheric cooling effects and the inertial current induced by a typhoon can last for several days after the passage of the typhoon (Wu et al., 2008b).

Based on these previous studies, a consensus has clearly not yet formed on the formation mechanisms of the cold dome. The main objective of this study was to investigate and evaluate different formation mechanisms of the cold-dome frequently observed off northeastern Taiwan. An enhanced understanding of the formation mechanisms could improve the regional prediction capability and reduce the model uncertainty. In this study, we adopted field data (Argo float data and satellite SST images) to examine properties of the cold-dome off northeastern Taiwan. The cold-dome formation was then studied numerically by a basin-scale, eddy-resolving dual-domain Pacific Ocean Model (DUPOM), which well resolved the Kuroshio, and provided a greater understanding of the regional ocean dynamics in the vicinity of northeastern Taiwan (Tseng et al., 2011; Jan et al., 2010). We evaluated the major and other secondary contributions to the cold-dome formation by analyzing several potential mechanisms in the model, such as geostrophic adjustment uplift, topographic upwelling, and turbulent mixing as well as Ekman boundary transport.

This paper is organized as follows. Section 2 provides the temporal characteristics of the surface cold-dome and subsurface variation of hydrographic properties to investigate the physical processes occurring in the cold-dome. Section 3 describes the numerical model, DUPOM. Section 4 contains a numerical analysis of the properties and possible mechanisms of cold-dome formation. Section 5 discusses the contributions of different formation mechanisms. The conclusions are addressed in Section 6.

2. Recent observations of cold-domes

Both remote-sensing data and Argo floats were used to quantify the surface and subsurface behaviors of the cold-dome. We mainly focused on the area off northeastern Taiwan from 120°E, 24°N to 124°E, 28°N, as shown in Fig. 1(a). The merged SST data from both microwave (MW) and infrared (IR) remote sensing were used to analyze the spatial and temporal variation of SST off northeastern Taiwan, and provide some surface evolution for the cold-dome formation. The MW and IR merged SST data were obtained from Remote Sensing Systems (available at www.remss.com). High resolution MW and IR merged SST data are available at a $0.09^\circ \times 0.09^\circ$ spatial resolution over the global region ($\pm 90^\circ$). Daily mean SST data were used.

For the subsurface data, we analyzed the temperature and salinity distribution from the Argo profiles, which are quality-controlled through USGODAE (Global Ocean Data Assimilation Experiment, www.usgodae.org). The Argo floats have been deployed over the world's oceans, and have provided reliable measurements of temperature and salinity profiles of the upper 2000 m of the ocean. The temperature measurement is reliable (accuracy: ~10^{-3} °C) and the surface temperature is usually used to calibrate the remote-sensing SST (Udaya Bhaskar et al., 2009). Note that no continuous daily Argo data are available, and therefore a time series analysis for Argo data at a specific location is difficult.

2.1. Spatial patterns of SST during the cold-dome events

Satellite SSTs for 2008 and 2009 were studied; 731 daily data were acquired and the cold-dome was found in 84 of them (11.5%). Normally, the temperature inside the cold-dome is more than 3 °C lower than that of the surroundings in summer. In winter, this difference is rarely observed because the surrounding water is also cold and the temperature difference is not so significant. Fig. 2 shows four typical spatial patterns of SST distribution when a cold-dome was observed (images are taken from May 16, 2008; July 30, 2008; May 2, 2009; and November 7, 2009). According to Cheng et al. (2009) (their Fig. 6), the center of the cold-dome off northeastern Taiwan is usually restricted to isobaths east of 100 m and west of 1000 m. The dark-red encircled region in Fig. 2 was chosen by this criterion and is termed the Cold-Dome Favorable Region (CDFR) hereafter. In these representative images, the fronts, resulting from the large temperature gradient, are clearly detected between warm Kuroshio water and cold Continental Water (CW). In particular, the edge of Kuroshio, similarly to those shown in the paper of Lin et al. (1992), can be identified clearly in all panels of Fig. 2, except panel (b). Fig. 2(b) presents a different frontal pattern, where the surface flow was strongly affected by the category 2 typhoon (on the Saffir-Simpson scale) Fung-Wong, whose center was located at 121°E, 24.1°N on July 28, 2008 and which had a radius of approximately 220 km. These patterns imply some different formation mechanisms for the cold-dome, suggesting a highly complicated circulation pattern in this region. More details are discussed later.