Three-Dimensional Thermohaline Characteristics of Luzon Cold Eddy with Double-Eddies Structure

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Abstract. A high-resolution three-dimensional thermo-salt-current numerical model was established to study the structure, and evolution of the Luzon cold eddies (LCEs) based on FVCOM. Study findings showed that, because of the double-eddies structure of LCEs, the isotherm and isohaline show the special characteristics of rising on both sides and falling down between them.

1. Introduction
Luzon Cold Eddy (LCE) is one of the important circulation features in the northern SCS in winter [1], and its existence has been well verified in many studies [2, 3, 4]. Since the discovery of mesoscale eddies, the three-dimensional structure of mesoscale eddies has attracted extensive attention. Due to the difficulty in obtaining the measured data, the researches on the three-dimensional structure of mesoscale eddies in the SCS are mostly focused on a single eddy [5, 6, 7]. Some scholars have also simulated and analyzed the vertical structure of mesoscale eddies in the South China Sea using oceanic numerical models [8, 9]. At present, the three-dimensional structure of the Luzon cold eddy and its evolution process remain unknown.

In this paper, a three-dimensional ocean dynamic model of the SCS was constructed based on the unstructured finite volume model, FVCOM [10]. The double-eddies structure of the Luzon Cold Eddy was reproduced, and as well as the three-dimensional thermohaline structure was analyzed and explored.

2. Model description
The range of the model is 99°E-146.5°E and 2.5°N-27°N, covering the SCS and the Philippine Sea, including 67,347 cells and 35,142 triangular nodes (Fig. 1). The grids of offshore, islands and the Northern SCS with complex dynamic characteristics were encrypted, and the highest horizontal resolution is 5000m. Gradually transitioning to the sea and the open boundary, the lowest horizontal resolution is 78000m. The coastline Data are taken from GSHHS Data released by the National Geophysical Data Center (NGDC). The bottom topography was extracted from the ETOPO1 global model with a resolution of 1′×1′. The mixed s coordinate is adopted in the vertical direction of the model, which is divided into 41 layers. For the grid points with water depth less than 80m, are uniformly layered; for those greater than 80m, the top 5 layers and bottom 5 layers are 2m-deep, and the middle layers are uniformly layered.
The model started with the initial tide level and flow velocity given as 0. The influence of wind field and heat flux was considered, but the influence of runoff was not considered. The open boundary of the model was driven by the predicted water level constants of 13 tidal components (M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4, and MN4) by TPXO7.2. Wind field data and heat flux data were from the NCEP Climate Forecast System Reanalysis (NCEP-CFSR) published by the National Center for Environmental Forecasting (NCEP) of the United States.

The initial temperature and salinity data were derived by an interpolation of HYCOM global daily snapshot 0Z 1/12 degree GOFS 3.1 reanalysis data based on the hydrodynamic model. In order to consider the influence of the external strong current, the model was nested to HYCOM global model [11], the open boundary control equation is as follows:

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\begin{aligned}
    U &= U_H + U_T \\
    V &= V_H + V_T \\
    \zeta &= SSH + \zeta_T \\
    S &= S_H \\
    T &= T_H
\end{aligned}
\]

\(U_H, V_H, SSH, S_H, T_H\) represent eastern-direction velocity, northern-direction velocity, sea surface height, salinity and temperature interpolated from HYCOM model. \(U_T, V_T, \zeta_T\) were the velocity and tide level predicted by TPXO model.

Fig. 1. (a). Range and topography of the model (unit: m); (b). Mesh of the model

3. Model validation

Fig. 2-3 show the comparison of the monthly average distribution between the satellite data and the model results. The SSHA data is from the northern part of the multi-satellites provided by AVISO, and the SST data is from MODIS Aqua satellite. There is a high consistency between the satellite data and the model results. The verification of sea surface height anomaly and sea surface temperature proves that the calculated results of this model are reliable and the model has high reliability, which can provide data support for subsequent studies.
4. Results and discussion

4.1. Double-eddies structure of LCE
The model simulation results showed that the structure of the Luzon cold eddy has a double-eddies structure in the winter of 2013 (Fig. 4). There are two distinct cyclonic eddies in the northwest of Luzon: The one being marked as LCE1 is on the western side of Luzon, centrally located at 118.1°E 18.1°N, whose range is about 117.1°E-119.4°E, 17.1°N-18.94°N; Another one being marked as LEC2 is on the northwestern side of Luzon, centrally located at 116.1°E 18.4°N, whose range is about 115.6°E-116.9°E, 17.9°N-19.19°N. The two cold eddies have independent eddy structures.

4.2. Three-dimensional thermohaline characteristics
The thermohaline results of the model are interpolated linearly to 12 depths: 10, 50, 75, 100, 150, 200, 250, 300, 500, 750, 1000, 1500m (Fig. 5).

The surface water temperature is relatively uniform, and the center of the cold eddy is almost invisible, which indicates that the temperature signal of eddy is not that obvious in the surface layer, and the eddy signal is attenuated due to the influence of sea-air interaction and surface heat flux. In the
depth of 50m, the edge of the cold eddy surrounds the 22.5°C isotherm. Within the cold eddy area, there are two negative temperature anomaly regions, whose lowest temperature is 22°C, corresponding to the double eddy structure. The horizontal temperature gradient reaches its maximum at the depth of 75m. On the southwest side of the cold eddy, the maximum horizontal temperature gradient reaches 0.05°C/km. A similar eddy isotherm distribution can be found at the depth from 75m to 300m. The lowest temperature at the cryogenic center decreases with depth: it drops to 20°C at 75m, to 19°C at 100m, to 16°C at 150m, to 13°C at 200m, to 12°C at 250m, to 10°C at 300m. Meanwhile, the horizontal temperature gradient decreases with the increase of depth. The anomaly temperature signal of the cold eddy is relatively significant between the depth from 50m to 500m, and the eddy-like negative temperature anomaly region of the cold eddy basically disappears below 500m.

Similar to isotherm, the uprising salinity distribution in different horizontal depths also indicates the existence of eddies. It can be told that the salinity at the center of the cold eddy, especially below 200m, is slightly higher than the surrounding area, although the salinity signal is not that significant compared with the temperature signal.

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**Fig.5.** Thermohaline distribution of the Luzon cold eddies at different depths (temperature: black contour line, unit: °C, salinity: color filling diagram, unit: psu) (a).10m; (b).50m; (c).75m; (d).100m; (e).150m; (f).200m; (g).250m; (h).300m; (i).500m; (j).750m; (k).1000m; (l).1500m

**Fig.6-7** shows the thermohaline vertical profile along 118°E and 18°N, respectively. Since the 118°E longitude line does not pass through LCE2, in Fig.7, only the thermohaline structure of LCE1 is clearly shown. Within the LCE1 eddy range of 17.1°N to 19°N, it can be seen that the surface thermohaline change is not obvious. The thermohaline isoline below the depth of 50m has an obvious
uplift trend: the maximum vertical displacement of the thermohaline reached more than 20m and 50m, respectively.

The 18°N latitude line passes through LCE1 and LCE2, we can find from Fig.8: within the range of 115.5°E 116.9°E, latitude line passes through LCE2 and the thermohaline isoline has an obvious rising trend. At the LCE2 eddy center around 116.2°E, the vertical displacement of the isotherm and the vertical temperature gradient reaches their maximum value. The region’s isotherm fell slightly when it passes between two cold eddies, LCE2 and LCE1, then continued to rise when passes LCE1. It is also found that the isohaline at the edge of the eddy rises more obviously, while the isohaline in the eddy falls down slightly.

![Fig.6](image1.png)
**Fig.6.** (a). Temperature distribution; (b). Salinity distribution along 118°E section

![Fig.7](image2.png)
**Fig.7.** (a). Temperature distribution; (b). Salinity distribution along 18°N section

5. **Conclusions**

A three-dimensional ocean dynamic model of the SCS was validated and employed to study the thermohaline characteristic of the LCEs with its double-eddies structure in the northern SCS. This study provided a detailed description of the three-dimensional temperature and salinity structure of the LCEs.

(1) The Luzon cold eddies are distributed as one or two cyclonic eddies. The temperature signal of LCE was not obvious in the surface layer, and it was attenuated due to the influence of sea-air
interaction and surface heat flux. Below the surface, there were two negative temperature anomaly zones in LCE area, corresponding to the double-eddies structure. The salinity at the center of LCE, especially below 200m, was slightly higher than the surrounding area, although the salinity signal was not that significant compared with the temperature signal.

(2) Because of the double-eddies structure of LCEs, the isotherm and isohaline show the special characteristics of rising on both sides and falling down between them vertically.

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