A modelling study of eddy-splitting by an Island/Seamount

By Yang et al.

The response to the Referees' comments and other short comments

We are very grateful to the time and efforts of the editor and referees. Your comments greatly help us to improve our present manuscript and further work. We have considered your comments carefully and improved our manuscript following the comments. Please note our one by one responses to your comments in blue and also revised manuscript with track changes in red attached at the end.

Referee #1:

Received and published: 30 January 2017

General comments

This manuscript presents the results of a series idealized ocean modelling simulations that illustrate the different behavior of eddy-splitting when an island/seamount is included in model's bathymetry. While the simulation results appear to be interesting, I have the following concerns with respect to the generalization and dynamic interpretation of the results:

1. The "Introduction" section provides a review of previous studies regarding eddy behavior under the influence of topography; however, the remaining questions and challenges on "eddies under the influence of island/seamount" are not explicitly explained. P3L10 states "The special processes and characteristics of splitting have not been elucidated completely", and P3L15 says "to examine its kinematic characters and test eddy splitting process using numerical simulations". Indeed, the above statements are consistent with what being presented: the paper primarily focuses on describing kinematics of simulated eddies but offers little on understanding dynamics. One wonders whether this is sufficient for a primary publication.

Reply: The eddy-topography interaction is affected by many factors. This study focuses on the influences of island/seamount on eddy splitting. Your comments benefit our improvement and we have corrected the deficiencies in the introduction, and added the comments on mechanics of eddy-splitting in the revised version which is attached at the end in section 4.2. Our quantitative results, namely, the relationship between eddy-splitting and two dimensionless parameters, have wide implications and have not been reported in the literature previously.

2. A major conclusion of the study is the dependence of eddy behavior on two non-dimensional numbers: R the ratio of island radius to eddy radius, and S the ratio of eddy submergence depth to eddy vertical depth. The question to ask is: can eddy radius and vertical depth be all arbitrary? What role does background stratification – that defines the local Rossby radius of deformation – play in defining these length scales? I note that the background stratification is the same for all the model experiments. Can this limit the generalization of the dependence of splitting behavior on R and S? I feel that besides simply describing kinematics, providing dynamic explanation of the model results will make this study more valuable.

Reply: In section 4.3 of the paper, we compared interactions between different sized eddies and islands. When they have a similar scale ratio (R and S), they have similar eddy splitting patterns. Therefore we can say that the eddy radius and vertical depth can be arbitrary.

As to background stratification, we did not discuss how it affects the behavior of eddy splitting. We think that ocean stratification is important like the other factors mentioned in the short comments. We will expand our study to explore those aspects in our next phase of the work. In addition, we add the explanation of eddy-splitting in section 4.2.

3. English writing needs significant improvement.

Reply: Thank you for your suggestions, we have done our best in the revised version following your and other referee’s suggestions.

Technical corrections:

1. Model parameters: P5L13: 10ˆ(-4) mˆ2/s for diffusion of heat: it is bit large for vertical but is way too small for horizontal.

Reply: There was an error in the original manuscript. We used vertical eddy diffusivity of 10^(-4) m^2/s and zero horizontal diffusivity, which is now stated in the revised manuscript. The vertical diffusivity value of 10^(-4) m^2/s may be a bit large, but it compensates the zero horizontal diffusivity. The main purpose for the use of the diffusion terms is to avoid instabilities around islands without too much soomthing. We have done some tests to see the sensitivity of model results to diffusivity/viscosity parameters and found that the results are robust.

2. Reference citation: a format seems to be odd, e.g., P2L23, "Chang et al. (Chang et al., 2012)", etc.

3. P12L17: reference of Sheng and Tang (2003): this study is for the Caribbean Sea but not for SCS. 4. P13L22 "Guihua, W" should be "Wang, G.", and similar for other co-authors listed.

Reply: All technical corrections were made in the text, thanks for the detailed suggestions.

Referee #2:

Received and published: 12 December 2016

General comments

The manuscript is very interesting, and adds to the literature on interactions between eddies and topography. By introducing two non-dimensional parameters for island size and submergence depth, they identify no splitting, weak splitting, and splitting regimes. To my knowledge, this is new. Therefore, the paper should be published.

However, when reading this some questions/issues came up and the manuscript will benefit from a revision before being published, taking the comments, small and more major, into account.

Firstly, they use the MITgcm with DX = 2.5 km and DX = 50 m near the surface in their study. They state correctly that MITgcm is non-hydrostatic. Have they used it in non-hydrostatic mode? They do not have the resolution to capture non-hydrostatic effects, and these effects may be important in the boundary layer towards the island/seamount as the eddy start to interact. There will be an upstream blocking effect and transfer of energy to smaller scales in this area. I noticed fairly large values of heat diffusion coefficients and vertical eddy viscosity. Are these necessary to avoid instabilities around the island. It would be interesting to see figures of the temperature, vorticity, and/or flow field in the near field around the island. Are the overall rules of thumb given robust to model choices, grid size, and parameterizations?

Reply: We are pleased to read that 'The manuscript is very interesting, and adds to the literature on interactions between eddies and topography', and 'it is new'.

We have not used the non-hydrostatic option although the model have the capability of non-hydrostatic dynamics. As you say, the model resolution cannot capture the non-hydrostatic effect. We agree with you that the non-hydrostatic effect is important in the interaction near the boundary and energy transfer to smaller scales, which are the future topics of research. However in this paper the main focus is on the eddy evolution and eddy-splitting which we think the non-hydrostatic dynamics plays a minor role.

As to the values of the heat diffusion and vertical eddy viscosity used in the model, the main purpose is to avoid instabilities around the island. Some limited model experiments show that the results of the eddy movement and eddy splitting are robust (also see our response to referee #1).

Secondly, for uniform flow against an obstruction, there will be eddies generated and oscillations. Non-hyd. pressure in the boundary layer plays a crucial role. With a sequence of eddies hitting an island, will the next eddy be shed in the same way as the first? I would think that the first eddy leaves a vorticity field behind around the island, and this will affect the next?

Reply: What you have mentioned is very interesting, and we guess that a sequence of eddies hitting an island will be different from an isolated eddy hitting an island. This is an aspect we should explore in our next phase of the work.

Thirdly, in the experiments, the island/seamount is placed in the middle of the trajectory of the eddy. Do they always hit spot on? Can it be splitting if they hit more to one side of the island?

Reply: A related matter was mentioned in the work of Simmons and Nof (2000) who idealized the seamount as a wall (see references in the manuscript). However, large differences have been found when an eddy colliding with an island compared with a wall. So more work is needed to test the influence of the hitting point in the eddy-island interaction.

It will be too much to address these issues in the present paper, but they may include some discussions of this.

Reply: Thanks for your suggestions. We have added the relevant discussion on these issues in the last section of the paper.

Specific Comments

Page 7: We believe that the secondary eddy comes from eddy-splitting rather than being formed independently. Remark: This can be checked by using a tracer, and will give added value, see second remark above.

Reply: Yes, you are right. Actually, the temperature used in the model can be seen as a kind of tracer. We have reformulated this sentence in the revision.

Page 8 line 10: which positive vorticity has increased Remark: Fig 6 is a snapshot after 50 days. How can we see that PV has increased?

Reply: Yes, in the revision we substitute it with a time series of snapshots of the eddy evolution to see the change of PV.

In the interaction with seamount studies, only warm eddies are used. Are the warm and cold eddy cases symmetric?

Reply: We have added one model experiment using a cold eddy to investigate this and found the results are similar.

Technical Corrections

Page 1 line 15: And the scale ... > The scale ...

Page 2 line 22: Chang et al. (Chang et al.,2012) > Chang et al.(2012) Similar remark on Kersale et al. below

Page 4 around Eq. 1: Remove . before the equation and change Where to where.

Page 4 around Eq. 2 and 3: Remove : and Where to where

Page 4 line 19: compoment > component

Page 6 line 7: warm eddy and cold eddy > the warm eddy and the cold eddy

Page 6 lines 20 and 21: But the cold eddy > However, the cold eddy

Page 7 line 7: mirror symmetry > mirror symmetric

Page 7 line 11: Diameter > The diameter

Page 8 line 3: generation > the generation

Page 8 line 4: to eddy generation > to the eddy generation

Page 8 line 4: shows the cyclone > shows that the cyclone

Page 9 line 1: Different > different

Page 9 line 3: "has the similar behavior" : Please, reformulate.

Page 9 line 6: Start the sentence: In the study, we define two ..

Page 9 line 12: shows when > shows that when

Page 11 line 10: eddy-splitting not > eddy-splitting is not

Page 11 line 18: This is reason > This is the reason

Page 11 line 21: main settings of experiments > the main settings of the experiments

Reply： All technical corrections were made in the text, many thanks.

Short comments by L. Sun:

Received and published: 12 December 2016

In general, the topic is interesting and the study is relevant for Ocean Science. There will be numbers of extension works following this study, given that it clearly figures out the frame of such works. However, the broad but imprecise introduction, the deficient design of study cases, and the ambiguous choice of parameters may reduce its potential value. So I suggest the authors should better clarify their framework of studies in generally, and focus on their problem more precisely.

Major comments

The title is vague. Some critical information may be appended to the title, such as "with f-plane" or "β-plane", "Island size", "seamount submergence depth", etc.

As an ideal simulation, the authors should not be constrained by the background or previously study on the South China Sea (e.g., Wang et al., 2003, 2005). Otherwise, the authors can directly simulate the observed eddy-island interaction events near Dongsha Island.

Reply: Our study is motivated by eddy-splitting in the South China Sea. We, therefore, emphasize the South China Sea in our paper. Then we expand our experiments to different size islands and seamounts with different submergence depths. As a result, we decide this title including main components without many details.

The study is in f-plane or β-plane? Since the present study zone is relatively small, it is better to use f-plane rather than β-plane approximation for simplification. For example, supposing 100 km with $\beta = 2 \times 10^{-11} m^{-1} s^{-1}$, the Coriolis parameter only varies about $2 \times 10^{-6} s^{-1}$, which is only 2% of the local Coriolis parameter $f = 2 \times 10^{-5} s^{-1}$. And the eddy motion in this study has notable different from that in β-plane (e.g. Early et al., 2011). The study on eddy splitting in f-plane itself is a valuable work. This can also be a baseline for further study with β-plane approximation.

Reply: The study is on β-plane. The β effect is the primary force in the movement of the eddy, even though the study area is relatively small. On the f-plane, without any external forcing, the eddy will not move. This is why we used β-plane.

The eddy is mesoscale or sub-mesoscale? As mentioned in first sentence, the mesoscale eddies (scale of 100 km) and sub-mesoscale eddies (scale of 10 km) have different scales. Although the choice of ideal

Gaussian-type profile (e.g., Zhang et al. 2013, Wang et al., 2015) is valid for this study, the choice of L=15 km is subtle. It might be better to choose a typical value either for mesoscale eddies (e.g., L=50 km) or for sub-mesoscale eddies (e.g., L=5 km) in this study.

Reply: The eddy in the study can be regarded as mesoscale. The scale of the eddy used in the model is based on statistics properties of ACEs in the northern SCS (e.g., Nan et al., 2011; Zhang et al., 2013; Chen et al., 2010, see references in the manuscript). Although the study is an idealized simulation, we prefer a more realistic size of the eddy (here reflected in the eddy scale) for better applications in the future.

There are lots of physical effects and control parameters in eddy-splitting due to eddy-island interaction. The authors introduce two dimensionless parameters R and S. They are important, but they may not enough. According to our previous study (unpublished work), the eddy amplitude/strength, the speed of eddy motion, and the distance between eddy and island will play the comparable role as R and S. In present study, the authors may want to give a comprehensive review of these effects, then focus their study only on one or two of them by fixed other parameters.

Reply: There are indeed many factors influencing eddy splitting during the eddy-island interaction. The parameters mentioned in your comments are all important and we have added the relevant discussion on these issues in the last section of the paper. Here we only investigate fully developed eddies; therefore the topography (dimensionless parameter R and S) will be the most important factor. The other parameters will be explored in the future work.

Minor comments

Page 2, line 1 Guihua et al. 2005 ->Wang et al., 2005. And the reference is corrected as below. And another pioneer paper (Wang et al 2003) should be better cited here.

Page 2, line 3, The paper in Science (Zhang et al., 2014) should be better cited here.

Page 3, line 10 “there are few cases of eddy-splitting found by satellite images so far.” our recent published paper in this journal (GEM: a dynamic tracking model for mesoscale eddies in the ocean) just illustrates such kind of case.

Reply: Thank you for your suggestions, we have studied these papers carefully and added their references in the revision.

Page 4, line 10, "Fig.1 shows the temperature and azimuthal velocity distribution on the cross section through the eddy center." Page 6, line 10 At the beginning of the model integration, the eddy will adjust itself to a dynamic balance. It is better to show the balanced eddy structure rather than the initial eddy structure in Fig.1.

Reply: Changes of the structure of the eddy are insignificant before the eddy-island interaction, we, therefore, omitted the details in the manuscript.

Page 5, line 9, "parameter$\beta = 2 \times 10^{-11} m^{-1} s^{-1}$ and the Coriolis parameter $f = 9 \times 10^{-5} s^{-1}$, which are the typical values in the SCS, are used in model." This is not correct. Such values suit for 38°N are taken from Wei and Wang (2009). While at Dongsha Island (20 °N) in SCS, the parameter$\beta = 2.15 \times 10^{-11} m^{-1} s^{-1}$ and the Coriolis parameter $f = 9 \times 10^{-5} s^{-1}$.

Reply: Thank you for your correction and we removed the sentence "which are the typical values in the SCS" in the revision. The results are not sensitive to these two different values of f or β.

A modelling study of eddy-splitting by an Island/Seamount

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Abstract. A mesoscale eddy's trajectory and its interaction with topography under the planetary β and nonlinear effects in the South China Sea are examined using the MITgcm. Warm eddies propagate to the southwest while cold eddies propagate to the northwest. The speed of both warm and cold eddies is about 2.4 km/day in the model. The eddy trajectory and its structure are affected by an island or a seamount, in particular, some eddies may split during the interaction with an island/seamount. Eddy-splitting is related to the size of the island and the submergence depth of the seamount. The results of sensitivity experiments of the interaction between an idealized eddy and an island/seamount indicate that the eddy would split in the qualitative range of $1/4<R<2$, $S<1/5$ (where R and S are two dimensionless parameters of the island size and submergence depth; R is the ratio of the island radius to the eddy radius, and S is the ratio of the seamount submergence depth to the eddy vertical length). ~~And~~ The scale of the secondary eddy split out decreases as the island diameter or the seamount depth increases. In the splitting process, integrated angular momentum (IAM) is transferred from water around the eddy to the eddy core. As a result, some filaments or eddies with opposite vorticity appear around the eddy. Eddy-splitting, therefore, is an important way to transform energy from mesoscale to sub-mesoscale in the ocean.

1 Introduction

Eddies are common in oceans, both at surface and deep layers, including mesoscale eddies (scale of 100 km) and sub-mesoscale eddies (scale of 10 km) (Itoh et al., 2011; Oey, 2008; Olson et al., 2007). In particular, mesoscale eddies occur frequently in the South China Sea (SCS) (Hwang and Chen, 2000; Chang et al., 2012; Zhang et al., 2013; Nan et al., 2011; Wang et al., 2003; Wang et al., 2005). Eddies have gained much attention since they are an important form of material and energy transfer in the ocean (Zhang et al., 2013; Kersalé et al., 2013; Waite et al., 2007; Zhang et al., 2011; Jacob et al., 2002; Wang et al., 2005; Zhang et al., 2014). Although isolated eddies in open oceans are affected by different factors, many of them have similar kinematic characteristics in general. As many researchers have pointed out, an isolated warm eddy in open oceans moves southwestwards or moves northwards along the western boundary in the northern hemisphere under the planetary β and nonlinear effects (Chang et al., 2012; Wei and Wang, 2009; Nof, 1981; Itoh et al., 2011; Itoh and Sugimoto, 2001; Nan et al., 2011; Cushman-Roisin et al., 1990; Korotaev and Fedotov, 1994). Sutyrin (2003) came to conclusions that β-induced propagation of surface anticyclone drives lower-layer eddies which add a significant southerly component to surface eddy propagation.

The eddy propagation in the ocean is directly affected by topography. The eddy trajectory and structure would be changed due to the interaction with a continental slope, an island or a seamount. The interaction between a warm eddy and a continental shelf slope has been investigated by many researchers based on satellite observations, laboratory experiments and numerical models (Hyun and Hogan, 2008; Rennie et al., 2007; Sutyrin and Grimshaw, 2010; Wei and Wang, 2009; Herbette et al., 2003; Smith and O'Brien, 1983; Simmons and Nof, 2002; Dewar, 2002; Herbette et al., 2005; Luo and Liu, 2006; Itoh and Sugimoto, 2001; Cenedese, 2002). Studies on cold eddies are fewer than for warm eddies. The reason may be that warm eddies exist perennially in California Bay and Cape Basin which provide good opportunities to investigate the characters of warm eddies. In the SCS the number of cold eddies is similar to that of warm eddies. Therefore, it is of importance to find out the difference between the cold and warm eddies.

There are plenty of mesoscale and sub-mesoscale eddies existing in the northern SCS, and most of them propagate to the southwest (Chang et al., 2012; Nan et al., 2011). Furthermore, the SCS is populated with numerous islands and seamounts. Therefore, most eddies are affected by the topography variation in their movement. Chang et al. (2012) found from satellite observations that an anticyclonic eddy (warm eddy) with a diameter of 120 km was split by the Dongsha Atoll situated on the slope in the northern SCS. In addition, eddies may split during interaction with a curved continental slope. Kersalé et al. (2013) investigated a coastal anticyclonic eddy in the western part of the Gulf of Lion in the northwestern Mediterranean Sea, where eddies split in a similar pattern as in the case of Dongsha Atoll. This provides a wider application prospect for any eddy-splitting role in the interaction with topography. However, it is not clear whether an eddy can always be split by an island/seamount and how the scale of the isolated topography influences the eddy eddy-splitting.

Drijfhout (2003) discussed the eddy splitting mechanism, and Simmons and Nof (2000) obtained the essential conditions of eddy-splitting by a wall using a wall moving into the eddy. Using an isopycnal ocean circulation model Herbette (2003) analyzed the behavior of a surface-intensified anticyclonic eddy encountering an isolated seamount. However large differences have been found between an eddy colliding with an island and with a wall.

The change of eddy structure over topography has an important influence on its dynamics, while it is an important means of energy transfer among different scales and affects coastal ocean dynamics (Kersalé et al., 2013; Drijfhout, 2003; Dunphy and Lamb, 2014). Because of difficulties in catching the entire process of eddy splitting by both satellite observations and situ measurements, there are few cases of eddy-splitting found by satellite images so far. Recently, li et al. (2016) used the Genealogical Evolution Model (GEM) to track the dynamic evolution of mesoscale eddies in the ocean which can distinguish between different dynamic processes including merging and splitting. But the special processes and characteristics of splitting have not been elucidated completely. Particularly, the phenomenon of eddy-splitting reported in Dongsha SCS lacks sufficient measured data to systematically describe the process of splitting (Chang et al., 2012).

In this study, we constructed an idealized eddy in a numerical model according to the features of the observed eddies in the SCS to examine its kinematic characters and test eddy splitting process using numerical simulations. Moreover, inspired by the eddy splitting near the Dongsha Island in the SCS, we vary the island size and seamount submergence depth to investigate the influence of the island on the eddy, and then to analysis the effect of the island and the seamount on the mesoscale eddy evolution (weakening and destruction) as the eddy approaches the obstacles.

This paper is organized as follows: Sect.2 describes the eddy structure used in the model and the method of eddy identification. Sect.3 introduces the model. The model results, including a comparison of eddy trajectories between the warm eddy and cool eddy, and the effect of an island and seamount on eddy deformation will be presented in Sect.4. A summary and discussion is given in Sect.5.

2 An idealized mesoscale eddy

2.1 The eddy structure

Much previous research has explored the mesoscale eddy structure in the SCS, especially its three-dimensional density distribution (Wang et al., 2005; Nan et al., 2011; Hwang and Chen, 2000). The idealized mesoscale eddy is initialized with an axisymmetric Gaussian-type profile based on long term moored observations (Zhang et al., 2013), Argo float data and the merged data products of satellite altimeters (Chen et al., 2010). Temperature profiles from observations are abstracted to

$$\mathrm{T(z)} = \mathrm{T}_b\mathrm{(z)} + a_z e^{-\frac{x^2+y^2}{2L^2}} \tag{1}$$

where $\mathrm{T}_b\mathrm{(z)}$ is background temperature; a_z is a function parameter varying with depth (z) and L is constant 1.5×10^4 m; x, y and z are position coordinates.

The eddy's initial tangential velocity is calculated using the thermal wind balance with zero velocity at the ocean bottom. Fig.1 shows the temperature and azimuthal velocity distribution on the cross section through the eddy center. The initial eddy is 60 km in diameter and 500 m in depth with a total water depth of 2000 m. The maximum surface velocity is about 0.9 m/s, and the maximum surface elevation is 0.5m.

2.2 Eddy identification and definition of the eddy boundary

There are different methods to identify an eddy and here we use the Okubo-Weiss method (Okubo, 1970; Weiss, 1991) to identify the eddy which we constructed in the model and define the boundary of the eddy. The Okubo-Weiss parameter W is given by

$$\mathrm{W} = {s_n}^2 + {s_s}^2 - \omega^2 \tag{2}$$

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\ ;\ s_n = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\ ;\ s_s = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \tag{3}$$

where ω is the vertical component of relative vorticity; s_n and s_s represent the strain and shear deformation; and u and v are eastward and northward velocities respectively.

Because the velocity field within an eddy is dominated by its rotation, ocean eddies are generally characterized by negative values of W. In this study, we use $W < -0.2\sigma_w$ to define the core region of the eddy, where σ_w is the standard deviation of W in the study region. This way to identify an eddy has a tendency toward excess of eddy detection (Doglioli et al., 2007), so we combine the potential vorticity distribution, velocity field and temperature anomaly to determine the main eddy which we focus on, and ignore the smaller circulations due to the eddy-topography interaction.

3 Numerical model and initialization

The MITgcm (**MIT** **G**eneral **C**irculation **M**odel) (Adcroft et al., 2011) is used in this study. Its non-hydrostatic formulation enables us to simulate fluid phenomena over a wide range of scales. However, we only use the hydrostatic form of the model as we expect that the non-hydrostatic dynamics plays minor roles in our problem (to capture the non-hydrostatic dynamics we would have to use much finer resolution than used here). The model domain is 500 × 450 km^2, and the depth of the ocean used in the model is 2000 m. The horizontal resolution is 2.5 km; in the vertical, 28 levels are used with 50 m resolution in the upper 1000 m and the resolution gradually coarsens in the lower 1000m. ~~The planetary parameter $\beta = 2 \times 10^{-11} m^{-1} s^{-1}$ and~~ The Coriolis parameter $f = 9 \times 10^{-5} s^{-1}$ and the planetary parameter $\beta = 2 \times 10^{-11} m^{-1} s^{-1}$ (here the main reason to use β plane rather than f plane is the β effect being the main force for the movement of an eddy, see section 4). ~~, which are the typical values in the SCS, are used in model.~~ The model boundaries all are open, and the Orlanski radiation condition is used. In the horizontal, we use Smagorinsky viscosity with a parameter of 0.2. ~~The Laplacian diffusion of heat is used with a constant coefficient of $10^{-4} m^2/s$.~~ In the vertical, the eddy viscosity is $5.0 \times 10^{-4}\ m^2/s$. For the temperature equation, the vertical eddy diffusivity is 10^{-4} m^2/s and horizontal eddy diffusivity is set to zero.

In the model, both the warm eddy and the cold eddy are initialized with an axisymmetric Gaussian-type profile described in Sect.2. The temperature decreases with the depth in the upper 1000 m and is set to a constant value of 4℃ below 1000 m. A constant salinity of 35 psu is used which does not affect model results.

The initial velocity field is in geostrophic balance and it is calculated from the density distribution which we obtain from a state equation according to Jacket and Mcdougall (1995). For the model with flat topography the eddy is located at the center of the model domain to test the difference between warm- and cold-eddy trajectories. In the cases studying the interaction between an eddy and an island/seamount, the island/seamount with different sizes/depths is located in the central path of the eddy, and all islands and seamount are cylinder shaped. We run the model from the initial state of rest for 50 days in order to compare different effects of obstacles on eddies.

4 Results

Our main attention has been put on the eddy-splitting due to the interaction between eddies and obstacles, and a series of experiments based on the idealized eddy structure in the SCS have been carried out (Table 1.). The eddy diameter is 60 km, and the initial location of the eddy center is x=250 km, y=225 km.

We first examine the eddy trajectories and its characteristics without any island/seamount. Then we focus on the interaction between the eddy and island/seamount, and the sensitivity of eddy-splitting to the island size and seamount depth.

4.1 The trajectories of warm and cold eddies

In our first set of numerical experiments, an eddy (warm or cold) is located at the center (x=250 km, y= 225 km) of the domain with open boundaries and a flat bottom (Fig.2). When the eddy is a warm eddy (anticyclonic eddy in the northern hemisphere), it moves towards the southwest direction in a flat bottom ocean. At the beginning of the model integration, the eddy will adjust itself to a dynamic balance. As a result, the speed of the eddy movement is relatively small. After the model reaches its balance, the speed of the eddy increases, to a constant value of 2.4 km/day after 40 days. The speed of the warm eddy in the model is similar to that of the study of Wei and Wang (2009). The eddy speed is influenced by the eddy size and the β effect, which is a function of the local latitude. Therefore at different latitude, the eddy has different speed. Fig.3 shows that the average speed over 50 days of the warm eddy is 1.75 km/day which is smaller than the eddy speed in the natural conditions in the SCS region because of the adjustment in the early stage of the model run.

With a cold eddy (cyclonic eddy in the northern hemisphere) in the same situation, the movement direction is northwest under β and nonlinear effects. The speed increases from the beginning of the model integration which is the same as for the warm eddy. The speed reaches a constant value of 2.3 km/day after 40 days. From the trajectory and speed variation during the eddy movement, we can see that the warm and the cool eddy have similar kinematic characteristics. However, the cold eddy moves to a higher latitude in the northern hemisphere while the warm eddy moves to a lower latitude because of their different spin directions.

When an isolated eddy propagates in open oceans with a flat bottom, it is known that the movement is governed by the planetary β and nonlinear effects (e.g. Chang et al., 2012; Hyun and Hogan, 2008). While the β effect drifts the eddy westwards (Shi and Nof, 1994), nonlinearity provides the meridional component of movement. From the results of the model, the warm eddy generally moves in the southwest direction in the northern hemisphere which agrees with previous studies. The trajectory of the cold eddy is mirror symmetric with the warm eddy (Fig.2). Both eddies' propagation speed is about 2.4 km/day which is smaller than the value in previous numerical investigations which used mesoscale eddies with 100 km horizontal scale (Wei and Wang, 2009; Sutyrin et al., 2003). The eddy propagation speed associated with the eddy size, and the propagation speed increases with increasing eddy size but will be limited by the maximum Rossby wave phase speed.

4.2 Eddy-splitting

The influence of an island on the eddy deformation is explored in this study. According to the eddy-splitting at Dongsha Island in the SCS (Chang et al., 2012), we set an island on the path of the warm eddy based on the first case we have examined. The diameter of the island is 20 km. At the beginning of the model integration, the eddy is not influenced by the island because the distance between the eddy and the island is not sufficiently close. As the eddy moves towards the island along its trajectory, the edge of the eddy begins to contact the solid boundary of the island; and it continues to push slowly against the island under the β effect and inertia. Due to the blocking by the island, the circulation of the eddy is abruptly cut off, which can be interpreted from the conservation of integrated momentum and quality equations. As a result, the eddy loses mass along the edge of the island, creating a jet moving away from the eddy. Because of the conservation of vorticity, the separated water is dammed at the downstream of the jet and gradually evolves to an independent eddy and shed from the main body.

It is evident from Fig.4, when the eddy collides with the island, there is another weak warm eddy formed on the other side of the island. The two eddies have similar diameters, but the secondary eddy is weaker than the main one which can be seen from SSH (Sea Surface Height), temperature, PV (Potential Vorticity), and O-W field (Fig.5). In eddy-splitting, the temperature can be seen as a tracer. From the temperature distribution we can find that the water of the secondary eddy is derived from the original eddy, so we believe that the secondary eddy comes from eddy-splitting rather than being formed independently. After the eddy-splitting, the two eddies move away from the island along their own trajectories as independent eddies. When a cold eddy encounters an island with 20 km diameter in its trajectory, the eddy split in the same way with the warm eddy (Fig.6). Therefore, only the warm eddies are used to study the influence of an island/seamount on the eddy-splitting.

When the eddy encounters an obstacle, the trajectories and the speed are usually drastically altered. The results show that the speed of the eddy decreases significantly when the eddy interacts with the island. Shi and Nof (1994) pointed out that the image effect of the eddy usually dominates when colliding with an obstacle, and the effect would inhibit the original movement trend. At the same time, the generation of a weak cyclonic eddy during the interaction of warm eddies with an island/seamount adds a significant effect on the eddy propagation. ~~Fig.6 shows the cyclone inhibits the southward propagation of the eddies in eddy-splitting.~~

Actually, an ~~warm~~ eddy can never split on their own. Applying the conservation law of integrated angular momentum (IAM), Nof (1990) demonstrated this. As a result, when a warm eddy splits, the IAM has to increase as the newly formed eddies move away from their original center. When a warm eddy is forced by the solid boundary of an island or a seamount, in the lower layer there has to be a transfer of IAM from the surrounding fluid to the core region of the eddy (Drijfhout, 2003). We can see this from our model results shown in Fig.7, in which positive vorticity has increased at 1000 m depth ~~in both surface and lower layers~~.

~~On the sea surface, a cyclonic eddy is generated by a division of the warm eddy (anticyclonic eddy) due to the conservation of angular momentum. The cyclonic eddy is smaller than either of the two warm eddies, and the strength~~

~~of the cyclonic eddy is weak. By comparison.~~ At the deeper layer at day 50, there are ~~only~~ two circulations: one anticyclonic eddy which is the deeper part of the main body of the warm eddy, and the other cyclonic eddy beside the anticyclonic eddy. The secondary warm eddy is too weak to extend to the deep layer, so it does not show at this layer. ~~Comparing PV (Potential Vorticity) on the surface and the deeper layer, we can find that the deeper part of the warm eddy moves southwards slightly faster than the upper part.~~ The existence of the deep cyclonic eddy adds a southerly component to eddy propagation, and its influence is greater at the deep layer than on the surface. We speculate this is one reason for the vertical structure tilt of the warm eddy (Zhang et al., 2013).

4.3 The effect of island sizes on eddy-splitting

The observational data, including satellite images and situ measurements, points out that when an eddy collides with a continental slope or a small island, there is no eddy-splitting, only changes of its trajectory (Jacob et al., 2002; Wei et al., 2009; Nan et al., 2011). In order to find out the parameter ranges of eddy-splitting, we use a series of islands with different diameters at the same location in the model. Before that, interactions of different sized islands and eddies were investigated. Take for example the eddies with 90 km (Eddy_{90}) and 60 km (Eddy_{60}) in diameter, the eddy-splitting pattern of Eddy_{90} interacting with an island of 120 km diameter is similar to that of Eddy_{60} interacting with an island of 90 km (Fig.8). Although the islands and eddies all are different in size in comparison, they have an approximately same ratio of the island radius to the eddy radius in each experiment.

We, therefore, define two dimensionless parameters R and S to represent the size and submergence depth of an obstacle, namely,

$$\mathrm{R} = \frac{R_{ob}}{R_{ed}} \tag{4}$$

$$\mathrm{S} = \frac{D_{sb}}{D_{ed}} \tag{5}$$

where R_{ob} is the radius of an obstacle; R_{ed} is the radius of an eddy; D_{sb} is the seamount submergence depth and D_{ed} is the vertical extent of an eddy.

The eddy collides with the islands in 20 days and interacts with them as we have described previously. Fig.9 shows that when the island is small enough, namely R < 1/4, the eddy does not split. Instead, the eddy will move through the obstacle, although the eddy structure deforms during the interaction process, and then recovers back after the interaction. As the island diameter increases, the 'passing through' eddy gradually turns to splitting as a result of the eddy-island interaction. The eddy-splitting happens in the parameter range of 1/4 <R< 2. As the island diameter increases to R>2, a filament splits out from the eddy. This phenomenon is not considered as eddy-splitting in this study. In the last example, when the eddy collides with a solid wall (which can be seen as a circle with an infinite diameter), the eddy propagates to the higher latitude along the boundary which agrees with previous studies (Wei et al. 2009).

From the eddy-splitting processes with different sizes of islands, we can find that the locations of the secondary eddy split out are related to the island size. Fig.10 shows the position relationship of the two eddies and the island. The angle (θ) between the secondary eddy and the position of collisional origin varies with the different island sizes (R). The distribution of the angle (θ) and the island size (R) are shown in Fig.11. The fitting curve demonstrates that the empirical relation between the angle and the island size can be written by

$$\theta \sim f(R) = 2.6R^{-0.663} \qquad (6)$$

where $f(R)$ is the angle (rad) between the two split eddies related to the island; R is a dimensionless parameter of the island size.

4.4 Effect of a seamount on eddy-splitting

In natural oceans, islands are just part of topography and there are more seamounts which are submerged under the sea surface. The effect of seamounts on ocean dynamics is different from that of islands. The submergence depth and the size of a seamount are key factors in the eddy-splitting. During the interaction between an eddy and a seamount, the lower part of the eddy is affected directly by the solid seamount while the upper part is not, then the vertical structure of the eddy is deformed significantly. As a result, its trajectory and splitting process is different from that of the interaction between an eddy and an island.

4.4.1 The effect of the seamount submergence depth

Here we investigate the effect of the seamount submergence depth on eddy-splitting. The experiments are set up based on the cases of R=1/4, 1, 2, which have typical eddy splitting. Model results for the seamount with a diameter of 60 km are presented in Fig.12. When the submergence depth is 50 m which is shallow, the interaction process between the eddy and the seamount is similar to that of the interaction between an eddy and an island. With the increase of depth, eddy-splitting becomes weaker and weaker. When the seamount submergence depth is 100 m, the upper layer of the eddy moves under the inertia effect while the lower part is hindered by the seamount; this leads to the change of eddy vertical structure and the upper water of the eddy is stranded by the seamount. At the same time, the filament which sheds from the eddy is closer to the main body of the eddy compared with the case of an island.

When the seamount submergence depth is 200 m, the effect of the seamount on the eddy structure has weakened greatly compared with the seamount submergence depth of 100 m. Apart from the filament shedding, there is no significant change in the main structure of the eddy. The result also shows that the seamount with S=2/5 cannot induce the eddy-splitting. When the submergence depth is 500 m (S ≈1), the seamount only affects the bottom of the eddy. The eddy trajectory changes under this circumstance. Fig.12 (e) shows that the eddy will bypass the obstacle from the left side under the effect of the secondary circulation in the deep layer. When the seamount submergence depth is 1000 m (S>1), the existence of the seamount does not impact the eddy motion, and the warm eddy moves toward southwest which is similar to the case with a flat bottom.

Above all, we find that eddy-splitting happens roughly in the range of S <1/5 when the seamount diameter is 60 km. Similarly, from the result of numerical experiments when the seamount is 10km in diameter, the eddy-splitting occurs at S <1/10. Actually, the range of eddy-splitting in the seamount cases is related to the seamount horizontal size as discussed in Sect. 4.4.2.

4.4.2 The effect of the seamount size

When an eddy collides with a seamount, the effect of the seamount on eddy-splitting is weaker than that of an island. The effect of the seamount on eddy-splitting is not only determined by the submergence depth but also influenced by the seamount horizontal scale. Here we test three different sized seamounts with the same submergence depth (Fig.13). During the interaction between the eddy and the seamount with 15 km diameter, the eddy does not split, and when the seamount diameter is 60 km, a small eddy is split out while the main eddy deforms. For the seamount with 120 km diameter, intense deformation occurs to the eddy without splitting.

For the seamount, the eddy-splitting happens in a narrower band of horizontal scale compared with the island. As the seamount submergence depth increases, the influence of the seamount on eddy deformation decreases. So the band of seamount horizontal scale for which the eddy-splitting occurs is narrower and narrower as the submergence depth increases. ~~This is the reason why the area where eddy-splitting occurs is triangle shaped.~~

Concerning eddy evolution in the ocean, we have explored the effect of topography such as islands and seamounts on eddy-splitting. According to the results we obtained, the dependence of eddy-splitting on the parameters R and S is summarized in Fig.14. This diagram illustrates the main settings of experiments and the red area is where eddy-splitting occurs.

5 Summary and discussion

Motivated by the eddy-splitting near Dongsha Island in the SCS, we explored the eddy's trajectory and effect of topography on an idealized eddy evolution. MITgcm is used in the study of the effect of topography on eddy evolution including eddy trajectory and its structure, particularly the eddy-splitting when the eddy collides with an island/seamount. The topography used in the numerical experiments includes a flat bottom, islands with different diameters and seamounts with different submergence depth. Eddies colliding with the topography all have the same initial structure. The simulation results of PV, SSH, temperature and O-W parameter are analyzed.

The model eddies (both warm and cold) move at a speed of 2.4 km/day in open oceans under the planetary β and nonlinear effects. The warm (cold) eddy moves southwestward (northwestward). The eddy speed and trajectory are influenced by topography. Generally speaking, the effect of topography starts when the eddy is some distance away from the island. The island leads to the eddy's trajectory changing and slows down the movement of the eddy. Because of the inertia of the eddy movement, eddies interact with obstacles by the collision. By defining two dimensionless parameters R and S representing the scale and submergence depth of an obstacle, we have shown the qualitative range of eddy-splitting using the results of numerical model experiments. During the eddy-splitting, the location of a secondary eddy detached from the main eddy is related to the size of the island or the seamount. Results of the model experiments show that the relationship between the angle of two eddy directions f(R) and the dimensionless parameter R can be written as $f(R) = 2.6R^{-0.663}$.

Because observational data of eddy-splitting in oceans is scarce, we need more and comprehensive measurement data and combine with numerical models to explore the dynamic mechanism of eddy-splitting further. ~~As Sheng and Tang (2003) pointed out the monthly varying wind stress and boundary flows also play an important role in simulating general circulation and variability in the Caribbean Sea~~. In addition to the dimensionless parameters R and S, there are other physical effects and control parameters in eddy-splitting such as the strength of an eddy which depends on the stratification (Thiem et al., 2006), and the movement speed of the eddy. In this paper, a single eddy interacts with an island or seamount was studied. However, there may be other scenario that a sequence of eddies hit an island. The result of the first eddy interacting with the island may be different from that of the eddy behind. In our study the island is placed in the middle of the trajectory of the eddy. Results can be much more complicated when eddies hit more to one side of the island. In short, the eddy-topography interaction is a systematic and complex problem and many factors need to be explored in order to understand the issue fully. Meanwhile, an investigation using more realistic model settings, such as the real topography, density stratification and forcing of the northern SCS is in progress.

Acknowledgements

The authors would like to express their sincere gratitude to the insightful comments from Prof. J Huthnance of NOC (UK). The very constructive comments from referees, in particular, Dr. Y. Liu (Bedford Institute of Oceanography), and Prof. J. Berntsen (University of Bergen) have greatly helped to improve the manuscript. This work was supported by the National Key Basic Research Program of China (Program 973) (grant 2014CB745001), the Environmental Protection Special Funds for Public Welfare (201309006), the Shenzhen Special Funds for Future Industry Development (201411201645511650) and S. Chen is supported by the China Postdoctoral Science Foundation (2016M591159).

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Tables

Table 1. List of different topography used in the experiments

Case	Type	Diameter	Submerge Depth	Center Location	Outcome
1	flat	-	-	-	No Splitting
2	Island	10 km	0	(213 km, 176 km)	No Splitting
3	Island	15 km	0	(211 km, 174 km)	Split
4	Island	25 km	0	(207 km, 170 km)	Split
5	Island	60 km	0	(195 km, 158 km)	Split
6	Island	90 km	0	(184 km, 147 km)	Weak Splitting
7	Island	120 km	0	(173 km, 136 km)	Weak Splitting
8	Island	150 km	0	(162 km, 125 km)	Weak Splitting
9	Island	300 km	0	(109 km, 72 km)	Filament
10	Island	Infinite	0	-	Filament
11	Seamount	15 km	50	(211 km, 174 km)	No Splitting
12	Seamount	15 km	80	(211 km, 174 km)	No Splitting
13	Seamount	15 km	100	(211 km, 174 km)	No Splitting
14	Seamount	60 km	50	(195 km, 158 km)	split
15	Seamount	60 km	80	(195 km, 158 km)	split
16	Seamount	60 km	100	(195 km, 158 km)	Weak Splitting
17	Seamount	60 km	200	(195 km, 158 km)	Filament
18	Seamount	60 km	500	(195 km, 158 km)	No Splitting
19	Seamount	60 km	1000	(195 km, 158 km)	No Splitting
20	Seamount	90 km	50	(184 km, 147 km)	split
21	Seamount	120 km	100	(173 km, 136 km)	No Splitting
22	Seamount	120 km	150	(173 km, 136 km)	No Splitting
23	Seamount	150 km	100	(162 km, 125 km)	No Splitting

Figures

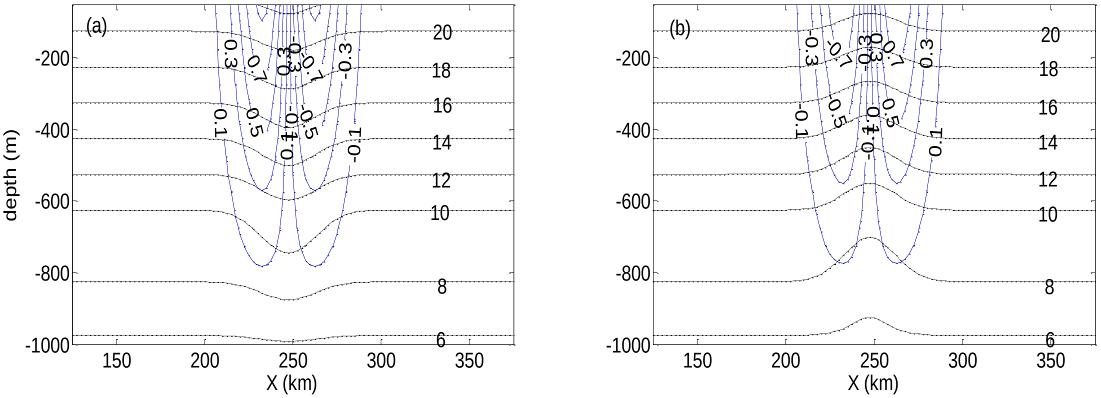

Figure 1. Initial velocity (m/s) and temperature (℃) profiles of the model warm eddy (a) and cold eddy (b).

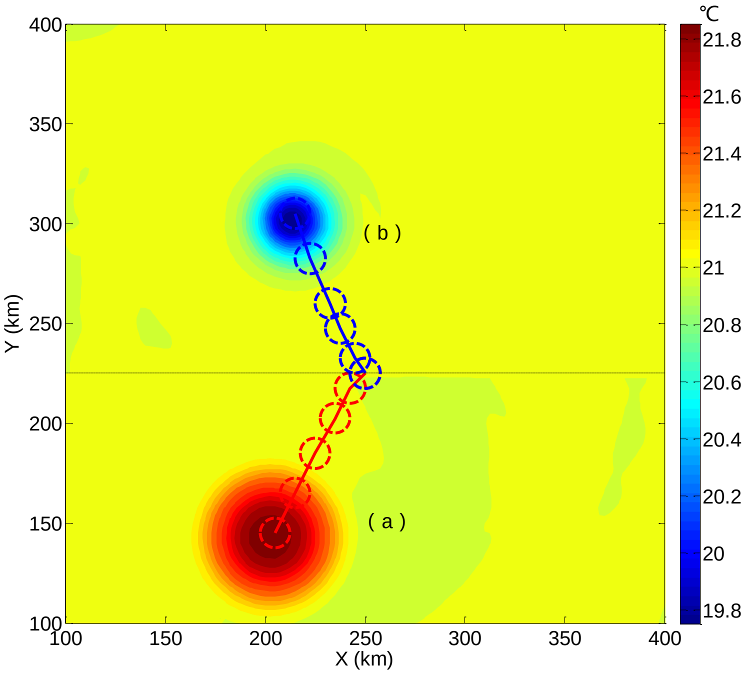

Figure 2. Eddy trajectory over a flat bottom: (a) warm eddy; (b) cold eddy) for 50 days. The trajectory of the eddy centers are depicted by circles every 10 days. The temperature field is shown in colors.

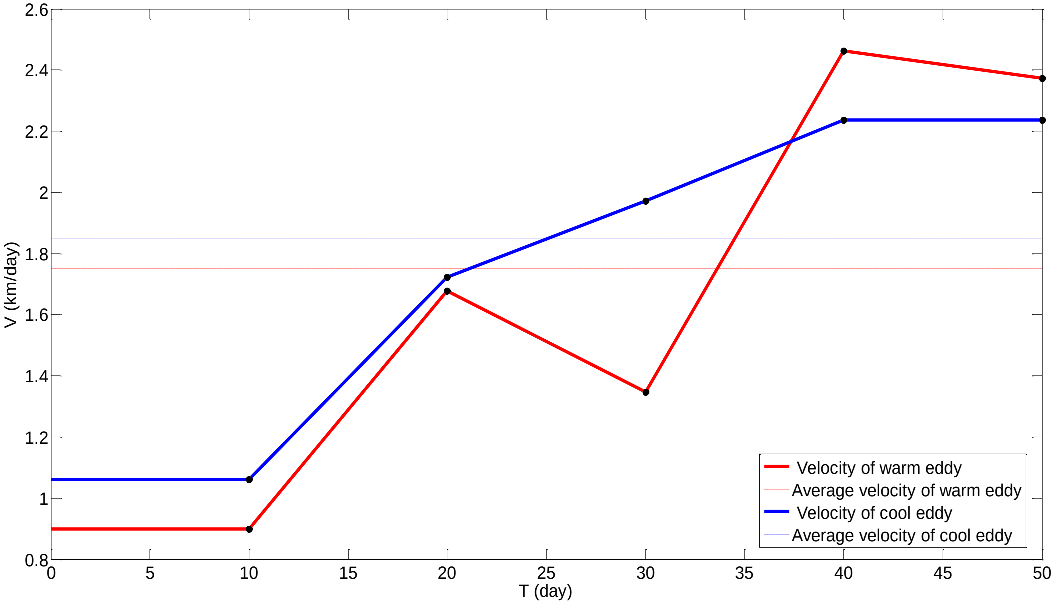

Figure 3. The speed of eddies over a flat bottom ocean. Solid lines: time series of speed; dashed lines: the speed averaged over 50 days.

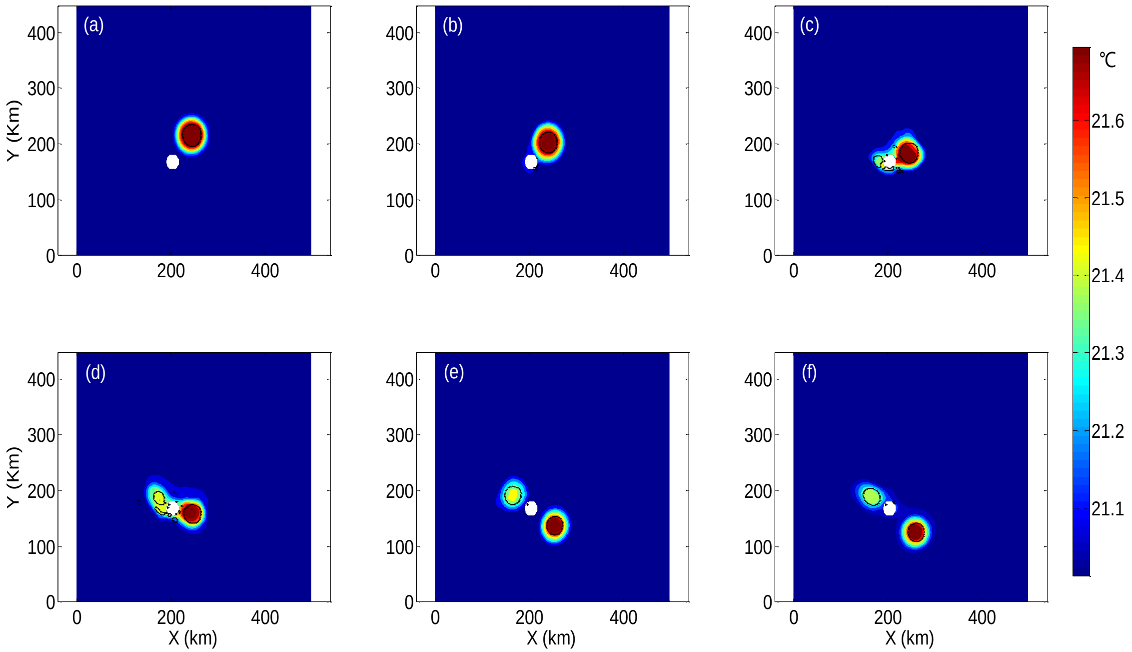

Figure 4. The process of eddy-splitting due to the interaction with an island of 20 km in diameter over 50 days. (a): the initial state; (b): 10 days; (c): 20 days; (d): 30 days; (e): 40 days; (f):50 days. The colors present temperature and the black solid lines are O-W parameter with value of $-0.2\sigma_w$.

5

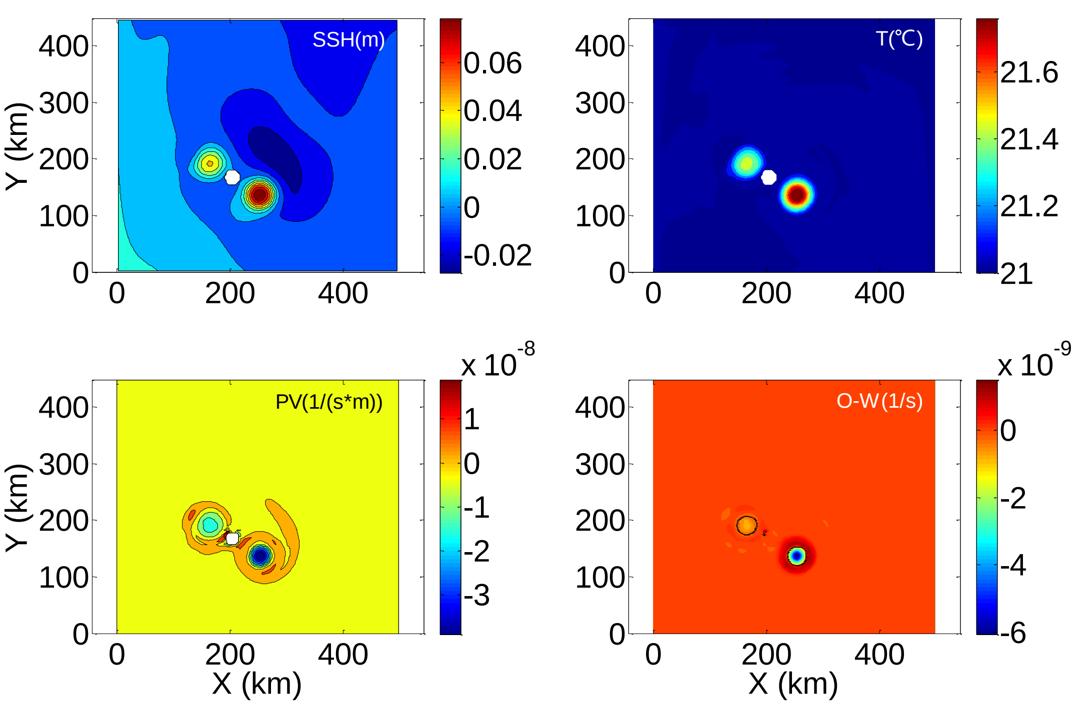

Figure 5. The warm eddy splits into two eddies during the interaction with an island of 20 km in diameter on day 50.

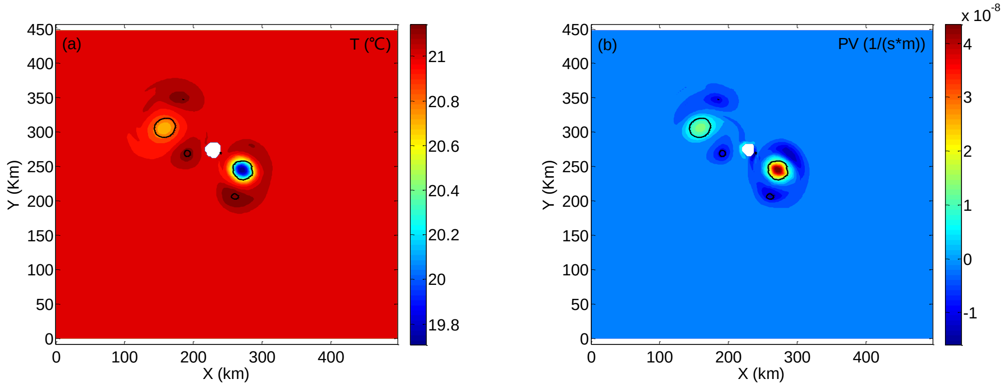

Figure 6. The cold eddy splits into two eddies during the interaction with an island of 20 km in diameter on day 50. The black solid lines are O-W parameter with value of $-0.2\sigma_w$.

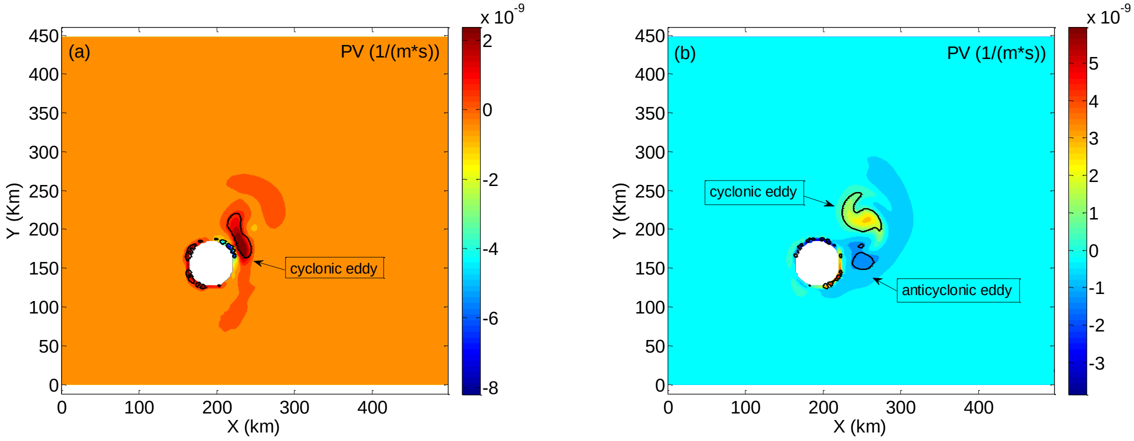

Figure 7. The potential vorticity distribution of the interaction between the warm eddy (anticyclonic eddy) and an island of 60 km in diameter at 1000 m below the sea surface at (a) day 30; (b) day 50. The colors represent PV and the black solid lines are O-W parameter with value of $-0.2\sigma_w$.

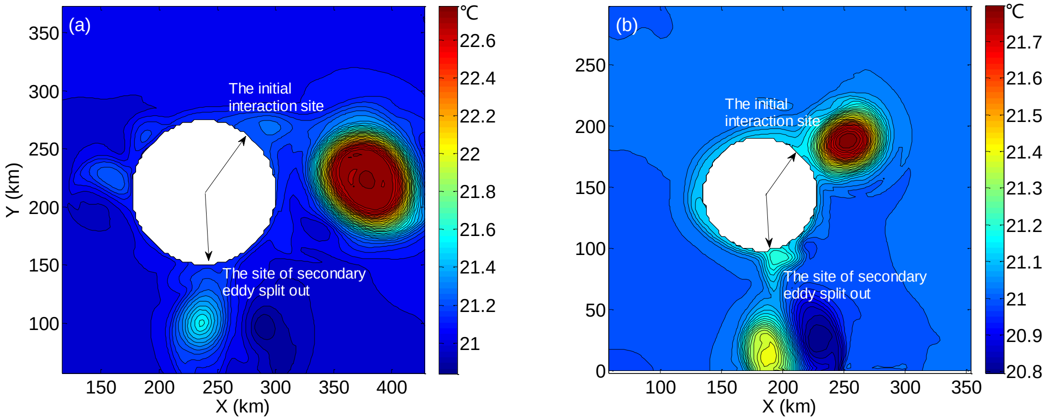

Figure 8. Comparison of the interactions between different sized islands and eddies (a) the island diameter is 120 km and the eddy diameter is 90 km; (b) the island diameter is 90 km and the eddy diameter is 60 km. the black arrows indicate the initial eddy-island interaction site and the site of secondary eddy split out.

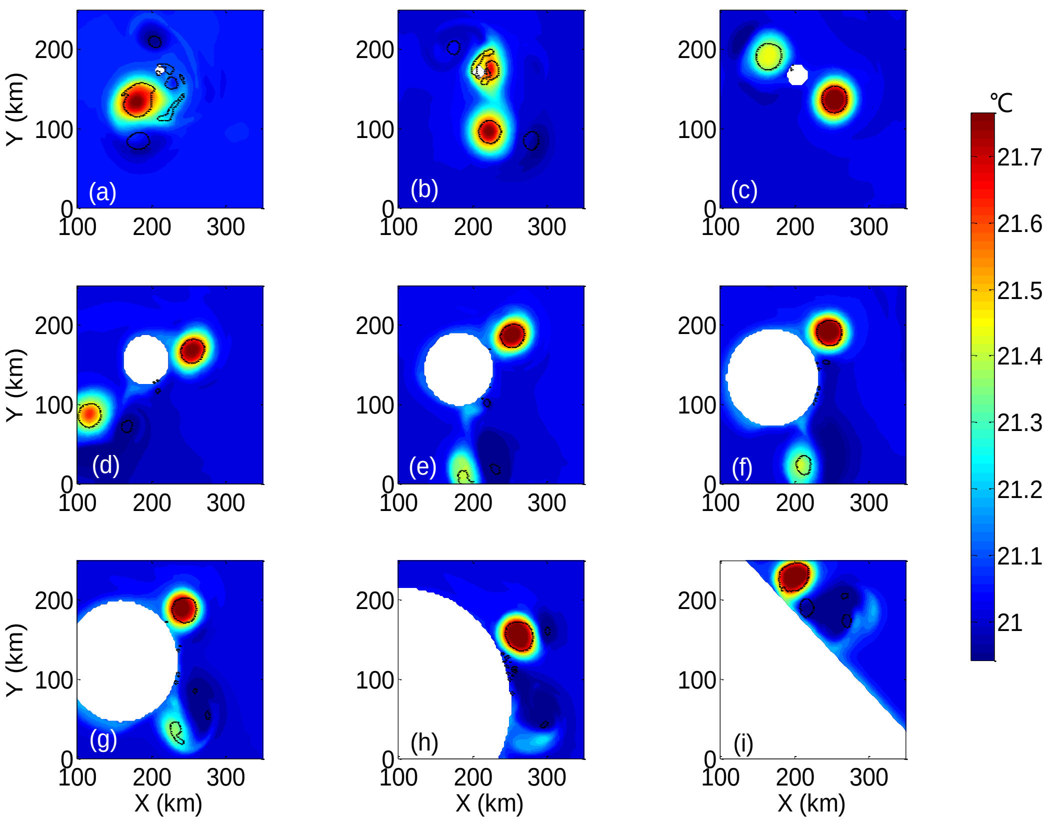

Figure 9. Eddy evolution after 50 days for islands with different diameter (a): 10 km; (b): 15 km; (c): 25 km; (d): 60 km; (e): 90 km; (f): 120 km; (g): 150 km; (h): 300 km; (a): infinite. The colors represent temperature and the black solid lines are O-W parameter with value of $-0.2\sigma_w$.

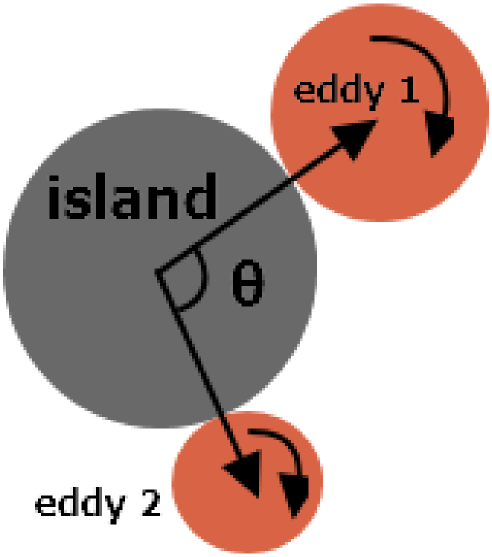

Figure 10. Sketch illustrating the position relationship of the two split eddies. When the eddy (eddy 1) encounters the island, the secondary eddy (eddy 2) splits out at angle θ during the splitting.

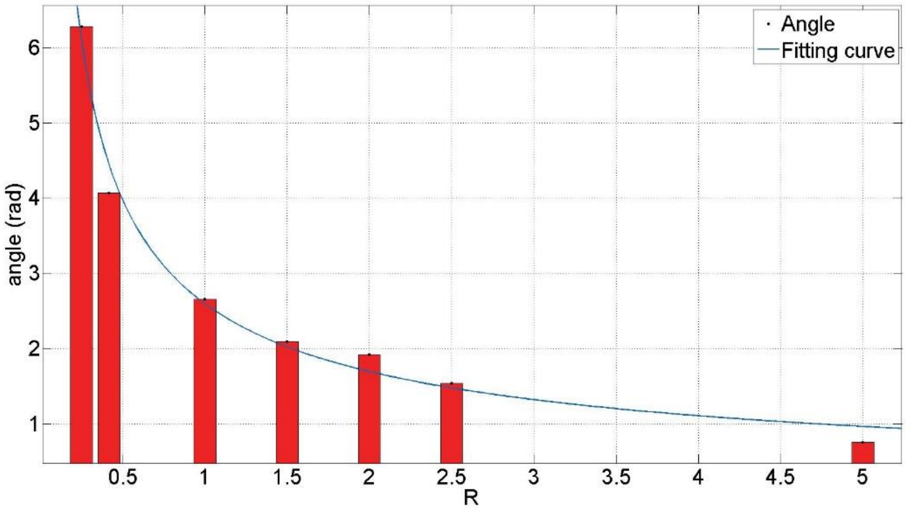

Figure 11. Distribution of relative angle (rad) with island size (R). The blue line is the fitting curve.

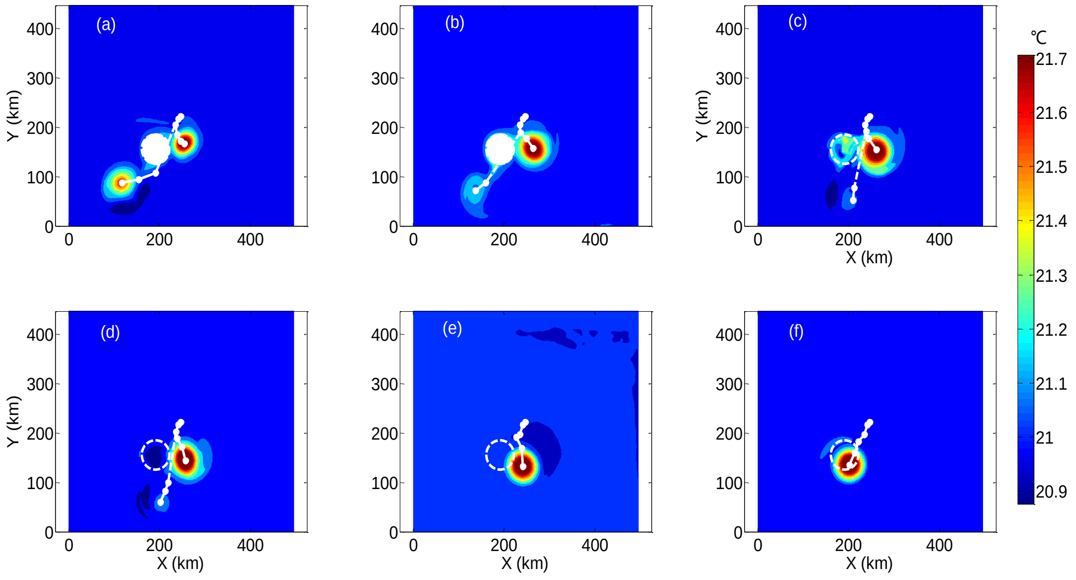

Figure 12. Eddy evolution in the case of the interaction with a seamount of 60 km in diameter at different submergence depths (a): 10 m; (b): 50 m; (c): 100 m; (d): 200 m; (e): 500 m; (f):1000 m. The temperature is shown in colors, and the trajectory of the eddy center is shown in white dotted lines.

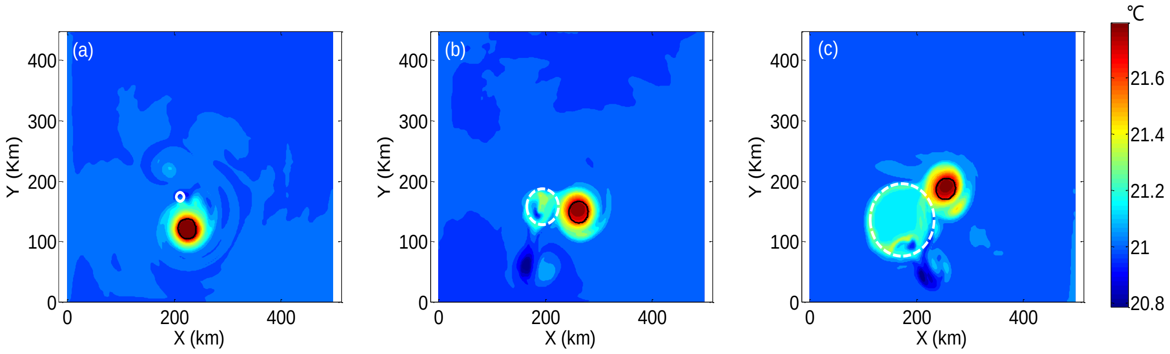

Figure 13. Eddy evolution during the interaction with different size seamounts with submergence depth 100 m. (a): 15 km; (b): 60 km; (c): 120 km. The temperature is shown in colors, and the white dashed lines are the position of seamount, the black solid lines are O-W parameter with value of $-0.2\sigma_w$.

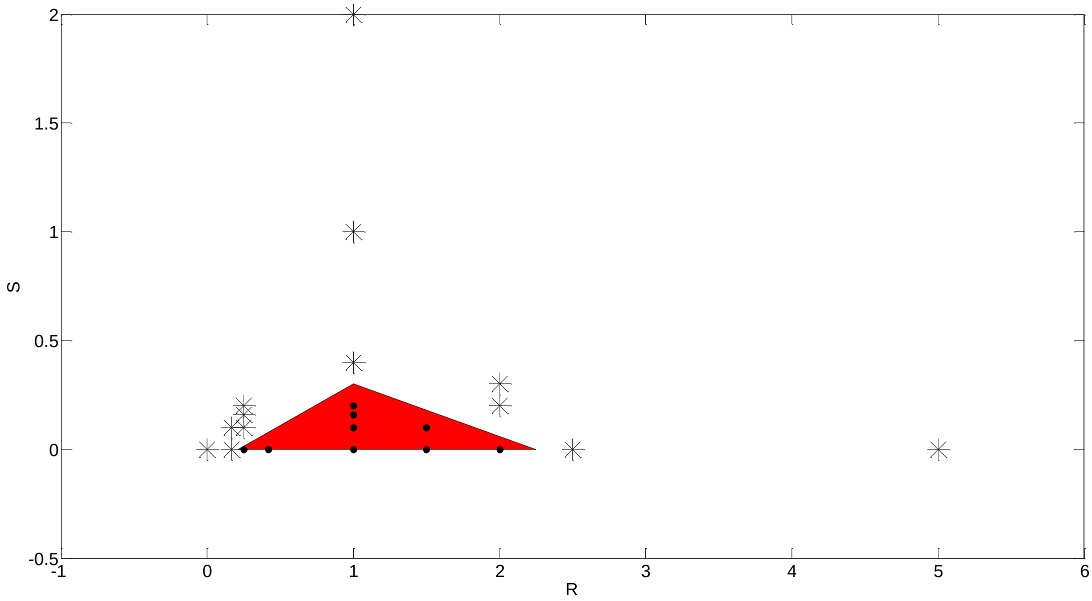

Figure 14. The range of parameters studied and dependence of qualitative features of the collision between eddies and obstacles for the range of R and S. The star marks represent no eddy splitting in the collision, and the solid dots represent eddy splitting. The red area is the range of eddy splitting.