An Eddy-Resolving Labrador Sea Modeling Studied by a Coupled Sea Ice-Ocean Circulation Model

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Qualitative comparison between observed and simulated fields over the Labrador Sea is performed. The model simulates the observed mean horizontal circulations of the surface cyclonic subpolar gyre and the mid-depth (~ 700 m) cyclonic recirculations. The distribution of the eddy kinetic energy shows good agreement with the observed evidence over the surface in annual average. The model captures the observed typical vortical structures of a pair of vortices and a cluster of vortices offshore West Greenland. For the vertical motion, on the other hand, winter convection reaches about 1000 ~ 1500 m consistent with the observed mixed-layer depth over the Labrador Sea. The model captures the wintertime convection columns.

Keywords: Labrador Sea, coupled sea ice-ocean circulation model, mesoscale eddies, intermediate water formation, deep convection

1. Introduction

The Labrador Sea is one of the most extreme ocean convection sites in the World Ocean characterized by weak density stratification, in each wintertime, exposed to intense buoyancy loss to the atmosphere and broken down by deep-reaching convection (see, for review, Marshall and Schott, 1999). The open-ocean convection in the Labrador Sea mixes the surface waters to great depth (about 1000 ~ 2300 m during the 1990s, Lazier et al., 2002) to form the intermediate water mass called Labrador Sea Water (LSW). The formation of LSW in the northern North Atlantic is considered to have a significant influence on global climate through the thermohaline circulation, global meridional-overturning circulation of the ocean, responsible for roughly half of the net poleward heat transport demanded of the atmosphere-ocean system (Macdonald and Wunsch, 1996).

It has been speculated that transport of water mass of different properties from the background by mesoscale eddies might stabilize/destabilize the near-surface density stratification to prevent/enhance the open-ocean deep convection in wintertime. Recent rapid advances in computer science make it possible to simulate the Labrador Sea with an eddy-resolving resolution (~ 5 km) under realistic topography and forcings by the use of a coupled sea ice-ocean circulation model (CCSR Ocean Component Model, COCO version 4, Hasumi, 2006). In this circumstances we are interested in understanding roles of mesoscale eddies on the LSW formation under relatively realistic conditions.

In this report, as a preliminary step, we compute a basic flow field qualitatively consistent with the available observed field in the Labrador Sea. Section 2 briefly describes about a coupled sea ice-ocean circulation model employed in this study. Section 3 devotes to the numerical results, which consist of mean horizontal circulations in §3.1, deviation field in §3.2, and vertical convection in §3.3. We summarize this report in section 4.

2. Model Description

In this study we employ a coupled sea ice-ocean general circulation model called Center for Climate System Research (CCSR) Ocean Component Model (COCO version 4, see, for detail, Hasumi, 2006). The previous version of COCO version 3 has been used to investigate the Atlantic deep circulation (Komuro and Hasumi, 2005). The ocean component is based on the hydrostatic primitive equations (see, for example, Haidvogel and Beckmann, 1999) formulated in orthogonal curvilinear horizontal coordinates and hybrid sea-surface-following (σ-) and geopotential (z-) vertical coordinate. Fig. 1 shows the configuration of orthogonal curvilinear horizontal coordinates in a model domain prescribed. The grid points are drawn every 8 grids so as to see their arrangement. Black lines denote isobaths of 1000, 2000, 3000, 4000 meters. The horizontal grid intervals are about 5 km, nearly equal to the Rossby radius of deformation, in the Labrador Sea. The vertical, on the other hand, has 30 layers: the top 5 layers are σ-levels, the others z-levels. The model is initialized to a rest

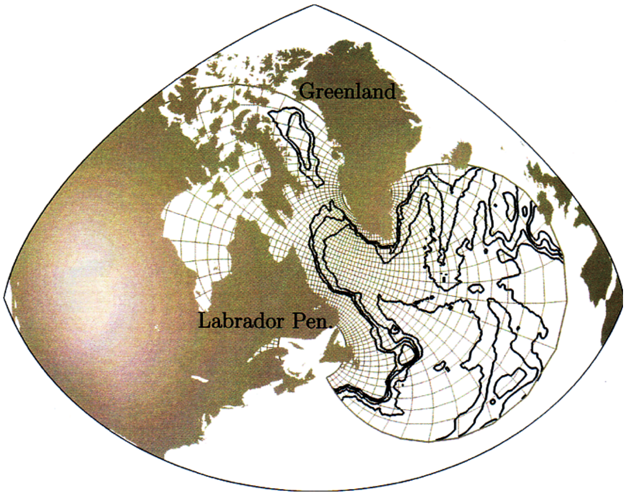

Fig. 1 Configuration of the system. Black isobaths are 1000, 2000, 3000, 4000 m.

state with the potential temperature and salinity of Polar Science Center Hydrographic Climatology (PHC 2.1, Steele et al., 2001) and forced by using the monthly forcing dataset of Ocean Model Intercomparison Project (Röske, 2001). The model is numerically integrated for 8 years with time increment 3 minutes.

3. Numerical Results

3.1 Mean Horizontal Circulations

Fig. 2 shows horizontal circulations of the Labrador Sea at (a) near-surface 2.5-meter depth and (b) mid-depth 800-meter depth both averaged over all the integration period. The velocity vectors are drawn every 3 grids so as to see the circulation pattern. Color scale on the vectors denotes their magnitude, i.e., current speed. The near-surface circulation pattern shows the observed typical structure of relatively strong (~ 30 cm/s) East Greenland Current (EGC) and West Greenland Current (WGC) along the shelf break offshore South Greenland, Labrador Current (LC) along the shelf break offshore North Labrador Peninsula, and North Atlantic Current (NAC) in Fig. 2a. All of these comprise the surface cyclonic subpolar gyre in the northern North Atlantic. We also observe the relatively strong (~ 30 cm/s) current on the Labrador Shelf from Hudson Bay and the relatively weak (~ 10 cm/s) circulation of complex pattern interior Labrador

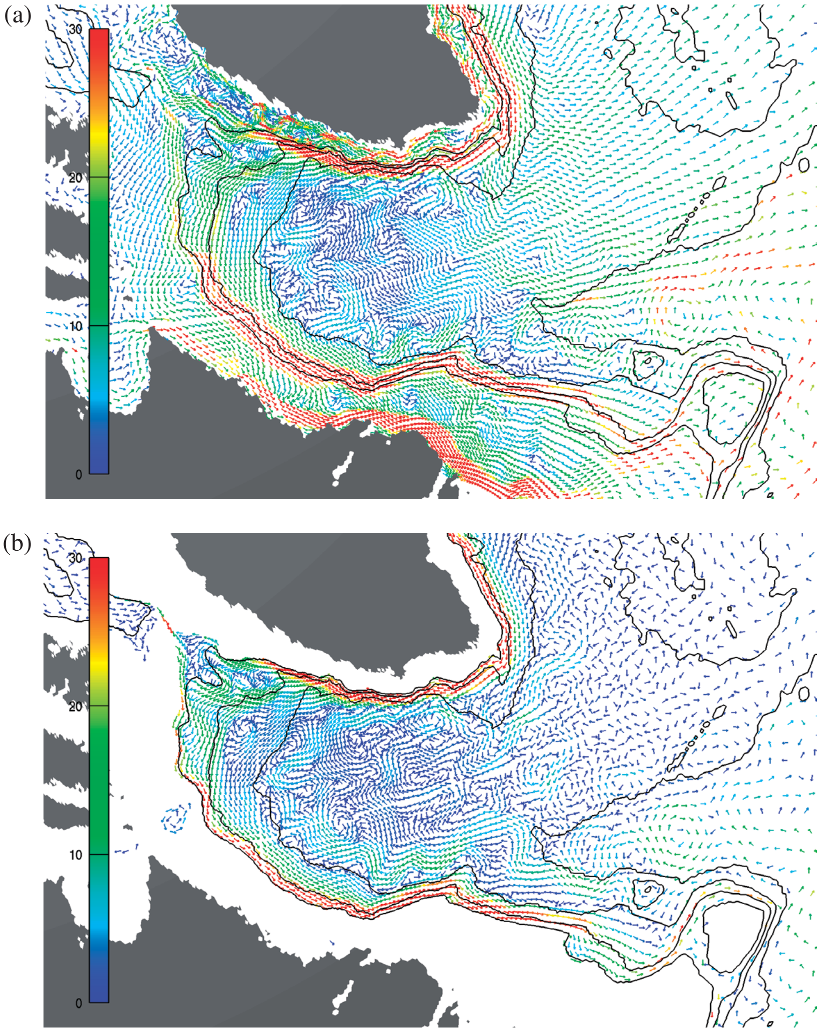

Fig. 2 The 8-year mean horizontal circulations of the Labrador Sea at depths (a) 2.5 and (b) 800 m. Color scale on the velocity vectors denotes their current speed.

Sea. The mid-depth circulation pattern, on the other hand, also shows the strong (~ 30 cm/s) cyclonic boundary currents on the Greenland and Labrador shelf breaks in Fig. 2b. Moreover, we clearly see the weak (~ 15 cm/s) cyclonic recirculations, observed by Lavender et al. (2000), comprising the anticyclonic countercurrent interior Labrador Sea along the cyclonic boundary currents. This recirculation pattern is considered to let near-surface water masses reside within the pattern for circulation timescale and expose to intense cooling in wintertime to initiate the open-ocean deep convection in the Labrador Sea.

3.2 Mesoscale Eddies

Strong deviation field from the mean surface circulation has been observed in the Labrador Sea. Brandt et al. (2004), for example, shows the strong (~ 600 cm^2/s^2) distribution of eddy kinetic energy (EKE), energy density of the deviation field, offshore West Greenland at the sea surface. Fig. 3 shows the EKE distribution at depth 2.5 meters averaged over all the integration period. The contour levels are 250, 500, 750, 1000 cm^2/s^2. The mean near-surface EKE distribution shows the observed typical structure of strong (~ 500 cm^2/s^2) triangular pattern offshore West Greenland. The mean EKE distribution, however, does not show the observed relatively strong (~ 400 cm^2/s^2) pattern along the Labrador Shelf break. We also observe the relatively strong (~ 250 cm^2/s^2) EKE distribution on the Labrador Shelf from Hudson Bay.

The strong triangular distribution of the mean near-surface EKE offshore West Greenland is caused by creation, advection, and annihilation of time-varying mesoscale eddies in the Labrador Sea. We observed (not shown in this report) that the strong (~ 0.8 × 10^{-4} s^{-1}) relative vorticities are created along EGC and WGC, advected into the central Labrador Sea around the 3000-meter isobath separating from the West Greenland coast, and annihilated out in the Labrador Sea. This process of the mesoscale eddies produced the strong triangular EKE distribution over the 3000-meter isobath offshore West Greenland (see Fig. 3).

An example of those mesoscale eddies is shown in Fig. 4, a snapshot of distribution of vertical component of relative vorticity over the Labrador Sea at depth 2.5 meters. Red denotes cyclonic vorticity, blue anticyclonic. The strong distribution of relative vorticity is observed offshore West Greenland, especially around the 3000-meter isobath. The strong relative vorticity distribution successfully captures the observed typical vortical structures of a pair of vortices and a cluster of vortices (see Fig. 2 in Prater, 2002) offshore West Greenland (see regions A' and B' in Fig. 4). We also observe the strong vortical distribution on the Labrador Shelf from Hudson Bay and the weak vortical distribution of complex pattern in the central Labrador Sea. The mesoscale eddies transport water masses of different properties from the background; therefore, this transport might stabilize/destabilize the near-surface density stratification, depending on water mass properties of the mesoscale eddies and background, so as to prevent/enhance the open-ocean convection in wintertime.

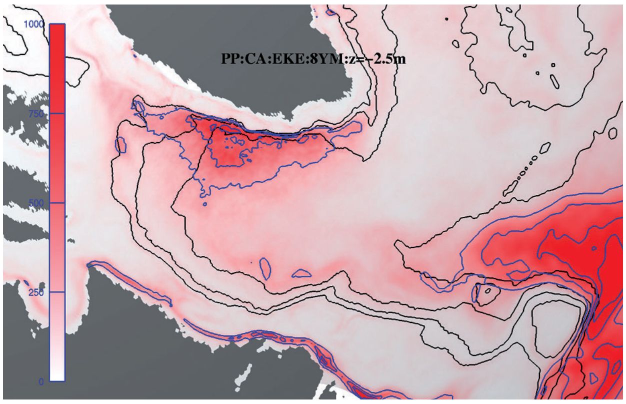

Fig. 3 Distribution of the 8-year mean eddy kinetic energy over the Labrador Sea at depth 2.5 m. Contour levels are 250, 500, 750, 1000 cm^2/s^2.

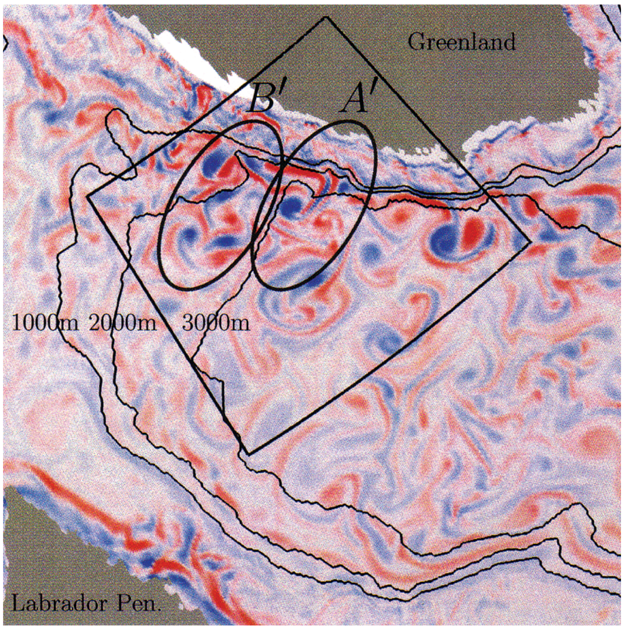

Fig. 4 A snapshot of distribution of vertical component of relative vorticity over the Labrador Sea at depth 2.5 m. Red denotes cyclonic vorticity, blue anticyclonic.

3.3 Vertical Convection

In §3.1 and §3.2 we compared the horizontal motion of the mean circulations and the deviation field with the available observations. In this section we look into the vertical motion of winter convection. One of the quantities to see the vertical convection is the mixed-layer depth (MLD), depth at which potential density becomes 0.01 kg/m^3 heavier than the surface. Fig. 5 shows a snapshot of the MLD distribution over the Labrador Sea in wintertime. The winter convection reaches about 1000 ~ 1500 m, consistent with the observed MLD distribution (for example, Pickart et al., 2002), in the central Labrador Sea. The winter MLD distribution, however, does not show the observed localization in the western part of the Labrador Sea. We also observe the deep MLD distribution along the band between 1000-meter and 3000-meter isobaths in the northern part of the Labrador Sea. It is interesting to note that the MLD distribution is relatively shallow where the EKE distribution is relatively high offshore West Greenland. Fig. 6 shows a snapshot of isovolume of the potential density σ_o larger than or equal to 27.75 kg/m^3 inside the Labrador Sea in wintertime. Black lines denote the isopycnals every 0.05 kg/m^3-interval between 27.50 kg/m^3 and 28.00 kg/m^3. The potential density distribution successfully captures the wintertime convection columns in the central Labrador Sea.

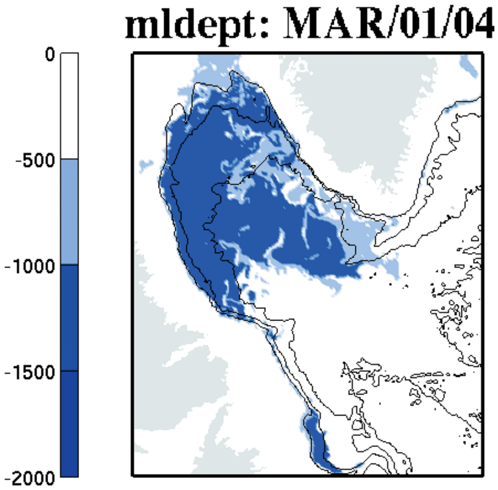

Fig. 5 A snapshot of distribution of mixed-layer depth over the Labrador Sea in wintertime.

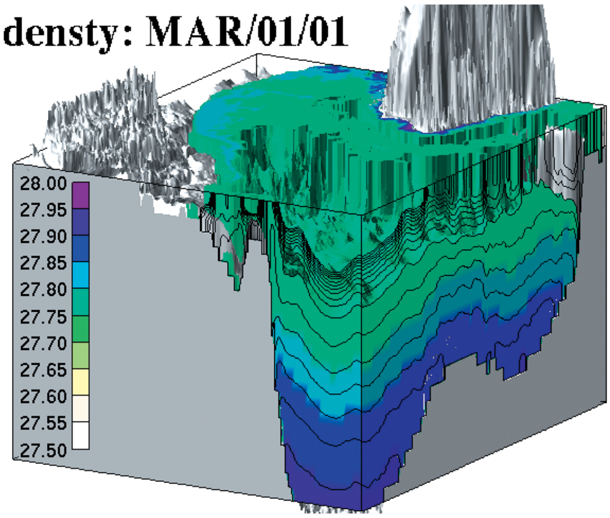

Fig. 6 A snapshot of isovolume of potential density $\sigma_o \geq 27.75$ kg/m^3 inside the Labrador Sea in wintertime. Black lines denote the isopycnals every 0.05 kg/m^3-interval between 27.50 kg/m^3 and 28.00 kg/m^3.

4. Summary

We performed qualitative comparison between the observed and computed fields by the use of an eddy-resolving coupled sea-ice ocean circulation model over the Labrador Sea. The mean near-surface circulation pattern shows the typical structure of EGC, WGC, LC, and NAC; all of these comprise the surface cyclonic subpolar gyre in the northern North Atlantic. The mean mid-depth circulation pattern shows the cyclonic recirculations comprising the anticyclonic countercurrent interior Labrador Sea along the cyclonic boundary currents.

The mean near-surface EKE distribution shows the typical structure of triangular pattern offshore West Greenland, but not relatively strong pattern along the Labrador Shelf break. The strong near-surface distribution of vertical component of relative vorticity is observed around this triangular pattern, suggesting that the time-varying mesoscale eddies are a source of the strong deviation field offshore West Greenland. We also observed the typical vortical structures of a pair of vortices and a cluster of vortices offshore West Greenland.

For the vertical convection, on the other hand, the winter MLD distribution shows about 1000 ~ 1500 m in the central Labrador Sea, but not the localization in the western Labrador Sea. The relatively shallow MLD distribution is observed around the triangular patter of the EKE distribution, suggesting that the time-varying mesoscale eddies stabilize the near-surface density stratification to prevent the winter convection offshore West Greenland. We also observed the wintertime convection columns in the central Labrador Sea.

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渦解像海洋海氷結合循環モデルを用いたラブラドル海のモデリング研究

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渦解像海洋海氷結合循環モデルで計算したラブラドル海の水平・鉛直場を、これまでに観測等により得られている知見と定性的な比較を行った。平均水平場に関して、モデルは表層反時計回りの亜寒帯循環と中層700m付近反時計回りの再循環を再現した。平均渦運動エネルギーの表層分布も観測事実とよく一致した。また、西部グリーンランド沖の特徴的な渦構造である渦対と渦群も表現した。一方、鉛直場に関して、冬季の対流が1000～1500mに達した。これは、観測された混合層深度と整合的である。モデルは、この冬季の対流柱の表現に成功した。

キーワード：ラブラドル海, 海洋海氷結合循環モデル, 中規模渦, 深層対流, 中層水形成