Ocean Modelling 104 (2016) 15–27

Contents lists available at ScienceDirect

Ocean Modelling

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

Revisiting the problem of the Gulf Stream separation: on the representation of topography in ocean models with different types of vertical grids

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A R T I C L E I N F O

Article history:
Received 29 January 2016
Revised 18 May 2016
Accepted 23 May 2016
Available online 24 May 2016

Keywords:
Gulf Stream
Ocean model
JEBAR
Bathymetry
Western boundary current

A B S T R A C T

The difficulty of simulating a realistic Gulf Stream (GS) that separates from the coast at Cape Hatteras has troubled numerical ocean modelers for a long time, and the problem is evident in different models, from the early models of the 1980s to the modern models of today. The source of the problem is not completely understood yet, since GS simulations are sensitive to many different factors, such as numerical parameterization, model grid, treatment of topography and forcing fields. A curious result of early models is that models with terrain-following vertical grids (e.g., "sigma" or "s" coordinates) seem to achieve a better GS separation than z-level models of similar resolution, so the impact of the vertical grid type on GS simulations is revisited here. An idealized generalized coordinate numerical model is used to compare between a sigma-coordinate grid and a z-level grid while maintaining the same numerical code and model parameters. Short-term diagnostic–prognostic calculations focus on the initial dynamic adjustment of the GS from a given initial condition and imposed boundary conditions. In diagnostic calculations, wherein the three-dimensional flow field is adjusted to time-invariant temperature and salinity data, the GS is quite realistic independent of the grid type. However, when switching to prognostic calculations, the GS in the z-level model tends to immediately develop an unrealistic GS branch that continues along the continental slope instead of separating from the coast at Cape Hatteras. The GS is more realistic in either a sigma-coordinate model or in a z-level model with a vertical wall replacing the continental slope. Increasing the vertical resolution in the z-level model reduces numerical noise, but it does not solve the GS separation problem. Vorticity balance analysis shows that the Joint Effect of Baroclinicity and bottom Relief (JEBAR) and its associated bottom pressure torque are very sensitive to the choice of vertical grid. A stepped topography grid may disrupt the local vorticity balance near steep slopes; this vorticity balance may be important to develop a counterclockwise circulation north of the GS that pushes the GS offshore. Therefore, the study suggests that a smooth representation of bottom topography in ocean models by using either a terrain-following coordinates or a z-level grid with partial cells may allow a more realistic treatment of flow–topography interactions and potentially a better simulation of the GS.

1. Introduction

The Gulf Stream (GS) is a western boundary current with a complex three-dimensional structure that is difficult to directly measure (e.g., Fuglister, 1963; Richardson and Knauss, 1971; Johns et al., 1995) and as difficult to realistically simulate with numerical models. One interesting aspect of the GS dynamics is that from the Florida Straits until Cape Hatteras it flows along the coast, but then it separates from the coast and turns farther eastward into the deep North Atlantic Ocean, rather than continue along the coast. Unfortunately, in many numerical models the simulated GS often tends to unrealistically loop toward the coast north of Cape Hatteras, and separates from the coast farther north than observed (Bryan and Holland, 1989; Semtner and Cherving, 1988; Thompson and Schmitz, 1989; Chassignet et al., 2003; Schoonover et al., 2016). Attempts to study the "Gulf Stream separation" issue started early on with simple idealized models that show, for example, the important role of wind and stratification on model results (Parsons, 1969; Nurser and Williams, 1990). Other early models with an idealized topography and a simplified vertical structure such as barotropic models (e.g., Dengg, 1993) or quasigeostropic models (e.g., Özgökmen et al., 1997) evaluated the role of wind, eddies, the shape of the coastline, the GS inertia and the slip/no-slip model boundary conditions. Primitive equations models with an idealized topography were also used to demonstrate the impact of the Deep

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http://dx.doi.org/10.1016/j.ocemod.2016.05.008
1463-5003/

Western Boundary Current (DWBC) and recirculation on GS separation (e.g., Spall, 1996). How much can be learned from these idealized models about the real GS is questionable, given, for example, the fact that some early models represented the continental slope by a vertical wall and neglected the coastal ocean. Therefore, studies of the GS separation were extended to coastal ocean models; these models show for example that to achieve a realistic GS separation, models may need to include local surface heat flux over the shelf and need to resolve the recirculation gyre between the GS and the coast (Ezer and Mellor, 1992). In the late 1980s models' resolution became fine enough to resolve the GS front and mesoscale eddies, at least to some degree and to include more realistic topography and coastline. Nevertheless, unrealistic GS separation has been a lingering problem in many models even today, though simulations do improve when very high horizontal resolution is used (Smith et al., 2000; Bryan et al., 2007; Chassignet et al., 2008; Hurlburt and Hogan, 2000, 2008; Hurlburt et al., 2011; Schoonover et al., 2016).

Two secondary problems of unrealistic GS path in ocean models include: (1) simulated temperatures in the Mid-Atlantic Bight may be warmer by several degrees than observed, causing problems in coupled ocean-atmosphere models, and (2) the southward flowing cold Slope Current (Rossby et al., 2010) may be missing or be too weak, and the northern recirculation gyre north of the GS (Mellor et al., 1982; Hogg, 1992) is thus not well simulated. The two aspects above are especially important for climate modeling. For example, a recent study (Saba et al., 2016) demonstrates how a mislocated GS in coarse resolution climate models affect climate simulations, so that a higher resolution ocean and atmospheric models with more realistic GS representation results in enhanced warming in the northwest Atlantic Ocean in future climate change simulations. Moreover, recent studies connect climate-related variations in the GS to coastal sea level rise and increased flooding along the U.S. East Coast (Ezer et al., 2013; Yin and Goddard, 2013; Sweet and Park, 2014; Ezer, 2015), thus reemphasizing the need of climate models to more accurately represent the GS, if coastal sea level rise is to be accurately predicted.

The source of the GS separation problem in ocean models is still not completely understood since a model's GS depends on so many different factors such as surface forcing (Ezer and Mellor, 1994), model coastline (Dengg, 1993), wind and eddies (Özgökmen et al., 1997), grid resolution (Hurlburt and Hogan, 2000), boundary conditions (Thompson and Schmitz, 1989; Ezer and Mellor, 1994, 2000), eddy-driven abyssal circulation and DWBC (Hurlburt and Hogan, 2008) and various numerical aspects such as subgrid-scale parameterizations (Chassignet and Garraffo, 2001; Chassignet et al., 2003; Chassignet and Marshall, 2008; Schoonover et al., 2016). It is thus likely that the GS separation in each model is the result of not one factor, but a combination of several factors mentioned above. One of the factors that could significantly affect the GS separation in ocean models is the way bottom topography is represented by the model grid – this can influence the flow–topography interaction. For example, Myers et al. (1996) found that in ocean models the bottom pressure torque component of the Joint Effect of Baroclinicity and bottom Relief (JEBAR) was significantly different than that obtained directly by diagnostic calculations, and that the JEBAR term is crucial for the GS separation. The JEBAR may influence the flow in regions where vertical stratification and bottom slopes interact (for detailed discussions of the role of JEBAR in ocean models see Sarkisyan and Ivanov, 1971; Mellor et al., 1982; Greatbatch et al., 1991; Cane et al., 1998; Sarkisyan, 2006; Xu and Oey, 2011, and many others). The role of the bottom pressure torque in GS dynamics was also addressed in a recent study (Schoonover et al., 2016), suggesting that the GS separation is related to local dynamics rather than to the wind-driven basin-scale dynamics. The implication is that local flow–topography interactions may be important, but they may not be accurately simulated in some models. A curious related result in early simulations is that given the same moderate horizontal grid resolution (~20 km), GS separation is more realistic in models with smooth representation of topography, such as in models with terrain-following (e.g., sigma or *s* coordinates) vertical grids (Ezer and Mellor, 1992, 1994, 1997, 2000; Ezer, 1999; Haidvogel et al., 2000) than in models of similar resolution that use step-like z-level vertical grids (Bryan and Holland, 1989; Semtner and Cherving, 1988). Early models of the Atlantic Ocean using the Hybrid Coordinate Ocean Model (HYCOM) also show some deficiencies in GS simulations (Chassignet et al., 2003). The recent model intercomparison study of Schoonover et al. (2016) confirms the early results, by showing that the GS separation is quite realistic in a terrain-following model (the Regional Ocean Modeling System, ROMS) and in a model with partial cell representation of bottom topography (the MIT general circulation model, MITgcm), compared with an unrealistic northern GS separation in a z-level model (the Parallel Ocean Program, POP). However, the above study could not attribute the differences in GS separation to model grid types, because the models in the study use different numerical schemes, different subgrid-scale parameterizations and different horizontal grid sizes (POP, 10 km and 100 km; MITgcm, 3 km and 10 km; and ROMS, 2.5 km and 6 km).

The advantage of smooth representation of topography in sigma models (or other terrain-following models) is contrasted with the potential disadvantage of sigma models with regard to numerical errors associated with the pressure gradient term over steep topography (Mellor et al., 1998; Ezer et al., 2002). For the fine grid resolution and smooth topography of the sigma coordinate model used here, the numerical errors associated with pressure gradient errors were found to be small (order of mm s^{-1}) compared with the mean flow and other errors. The hypothesis that the different representation of bottom topography in z-level and in sigma models impact the GS separation is difficult to test, because different models often use very different numerical schemes and mixing parameterizations, so model-to-model inter-comparison studies (Willems et al., 1994; Chassignet et al., 2000; Ezer et al., 2002; Schoonover et al., 2016) cannot isolate the influence of the choice of vertical coordinate from among the other differences between models. A solution is to use a generalized-coordinate ocean model in which one can apply exactly the same model setup and numerical schemes except the vertical grid. Such comparisons of z-level and sigma models indeed show large sensitivity to vertical grid type in simulations of wind-driven ocean circulation (Mellor et al., 2002), in simulations of deep water formation (Ezer and Mellor, 2004) and in simulations of dense overflows (Ezer, 2005, 2006). Therefore, the same generalized-coordinate model developed by Mellor et al. (2002) (which is based on the Princeton Ocean Model, POM) will be used here. The main goal of the study is to test the hypothesis that the representation of topography in ocean models can strongly affect the GS separation, and if true to find the mechanism involved. Benefits of such a study are two-fold: first, to get a better understanding of numerical ocean models behaviors and the dependence of that behavior on the user's choices of grids, and second, to get a better understanding of the processes that control the GS dynamics and its interaction with topography.

The paper is organized as follows. First, the numerical model setup and the different experiments are described in Section 2, then a comparison of the results of different simulations are described in Section 3, following by analysis of the dynamical balances in Section 4. Finally, a summary and conclusions are offered in Section 5.