EOSC 579 - Chapter 3 - Lecture 6: Gulf Stream Separation

Learning Goals

At the end of this lecture you will be able to:

- describe where the Gulf Stream is observed to separate
- describe, theoretically, where it should separate according to Stommel, Munk and Moore
- describe the processes that need to be included to get good Gulf Stream Separation in a numerical model

Gulf Stream Separation

The Gulf Stream is observed to separate at Cape Hatteras (Figure 3.1), even though the wind stress curl goes to zero much further north (Figure 3.2).

Figure 3.1 Sea surface temperature in the North Atlantic as observed by Satellite. Originally from NASA this version from wikipedia.
Figure 3.2 Sketch of Global Atmospheric Patterns. From UCAR Comet program.

Note that more detailed pictures paint a slightly different picture of the wind stress curl. Here the wind stress curl is positive along the eastern seaboard, pretty much to Cape Hatteras (Figure 3.3).
Kirk Bryan (1963) wrote and ran some of the earliest numerical models. His model allowed time dependence (a step beyond Moore) and here, using the same Reynolds number as Moore we see the time average solutions for a number of higher Rossby numbers (Plate 3.4)
As the nonlinearity increases we see stronger North-South asymmetry and a push to the north. If he included a sub-polar gyre as well, the separation point occurs, once again at the zero curl line, at least if the gyres are even.

Looking at the clear change of coastline at Cape Hatteras (Figure 3.1), Byran and others felt that the coastline might cause the separation. However, even in the nonlinear case this is not true. The gyre is very happy to follow the bathymetry although you do get a very strong recirculation cell (Figure 3.5).
Going back to the real wind stress (Figure 3.3), Bryan also tried a much more realistic wind stress. Here he does get a more realistic pattern including the Gulf Stream going off at an angle. However note that in the nonlinear case, do to the realistic ratio of the gyres, the separation is north of the zero wind stress curl line.
Getting the Gulf Stream to separate at the right point became a “holy grail” of ocean modeling. It was possible to get it to do so by some arbitrary choices but it remains extremely sensitive to numerical choices, particularly in coarser models. A nice summary paper is Chassignet and Marshall (2008) (https://ora.ox.ac.uk/objects/uuid:88dd03f2-eed5-48d9-a29c-fcb86786004c)

I will quote a couple of sections:

"The early linear frictional models [e.g., Stommel, 1948; Munk, 1950] suggest that separation takes place as a result of the change in sign of the wind stress curl. This theory is further supported by the fact that the observed mean path of the Gulf Stream roughly overlies the zero wind stress curl line (ZWCL). The ZWCL, however, shows considerable seasonal variation [e.g., Isemer and Hasse, 1987], while the point of separation shows remarkable consistency. Inclusion of the nonlinear terms and associated boundary conditions (no-slip or
free-slip) induces considerable variations in the separation latitude [Blandford, 1971; Moro, 1988; Verron and Le Provost, 1991; Cessi, 1991; Chassignet and Gent, 1991; Haidvogel et al., 1992; Verron and Blayo, 1996; Adcroft and Marshall, 1998]. Other mechanisms have been put forth as being important in the separation process, such as potential vorticity crisis [Kamenkovich, 1966; Ierley and Ruehr, 1986; Ierley, 1987, Cessi et al., 1987; Ierley and Young, 1988; Cessi, 1990; Kiss, 2002], a region of adverse pressure gradient [Haidvogel et al., 1992; Baines and Hugues, 1996; Marshall and Tansley, 2001; Kiss, 2002], collision with another western boundary current [Cessi, 1991; Agra and Nof, 1993], out-cropping of isopycnals [Parsons, 1969; Kamenkovich and Reznik, 1972; Veronis, 1973; Moore and Niiler, 1974; Anderson and Moore, 1979; Ou and de Ruijter, 1986; Huang, 1987; Huang and Flierl, 1987; Gangopadhyay et al., 1992; Chassignet and Bleck, 1993; Chassignet, 1995], interaction with the DWBC [Thompson and Schmitz, 1989; Spall, 1996a, 1996b; Tansley and Marshall, 2000], surface cooling [Veronis, 1976, 1978; Pedlosky, 1987; Nurser and Williams, 1990; Ezer and Mellor, 1992; Chassignet et al., 1995], and multiple equilibria [Jiang et al., 1995; Nauw et al., 2004]. Most of the cited studies, however, do not include any coast-line geometry or bottom topography. Separation can be influenced by a change in coastline orientation or by a change in bottom topography [Warren, 1963, Greenspan, 1963; Pedlosky, 1965; Kamenkovich and Reznik, 1972; Smith and Fandry, 1976; Stern and Whitehead, 1990; Spitz and Nof, 1991; Salmon, 1992; Dengg, 1993; Salmon, 1994; Thomp-son, 1995; Myers et al., 1996; zkkmken et al., 1997; Stern, 1998; Tansley and Marshall, 2000, 2001; Munday and Marshall, 2005]. Eddy-topography interactions have also been surmised to play a role in the separation process [Holloway, 1992; Cherniawsky and Holloway, 1993; Eby and Holloway, 1994; Hurlburt et al., 2008; Hurlburt and Hogan, 2008].”
“High resolution appears to be necessary, but it is not nec-essarily sufficient for a proper Gulf Stream separation. As stated by Bryan et al. [2007], substantial uncertainties remain about the robustness of the results obtained at a resolution of 1/10q or higher. The Gulf Stream separation, indeed, turns out to be quite sensitive to a variety of other factors such as subgrid scale parameterization, subpolar gyre strength and water mass properties, DWBC strength, representation of topography, and the choice of model grid (C. Bning, R. Bourdallé-Badie, F. Bryan, M. Hecht, J. McClean, and T. Penduff, personal communication). It is not always clear why certain model configurations lead to a correct western boundary current separation while others do not.”
Chassignet and Marshall (2008) finish with a model data comparison. The data come from TOPEX altimeter data (Figure 3.8)

**Figure 3.8** Data location. *From Chassignet and Marshall*

**Figure 3.9** Model Data Comparison. *From Chassignet and Marshall*
The best model, #14 is the highest resolution model from the US Navy at 1/32\degree, even though it is missing thermal forcing.

They conclude:

“There is yet no single recipe that would guarantee a correct separation of all western boundary currents in a global model. While it can be firmly stated that a resolution on the order of at least 1/10\degree is a necessary condition for a western boundary current to realistically separate from the coast.” details of the best numerical dissipation and the boundary conditions (bottom and lateral) are still unclear.

References
