EOSC 579 - Chapter 1 - Lecture 7: Gulf Stream Separation

1.6.1 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

1.6.2 Gulf Stream Separation

The Gulf Stream is observed to separate at Cape Hatteras (Figure 1.1), even though the main wind stress curl goes to zero much further north (Figure 1.2).

Figure 1.1 *Sea surface temperature in the North Atlantic as observed by Satellite. Originally from NASA this version from wikipedia.*

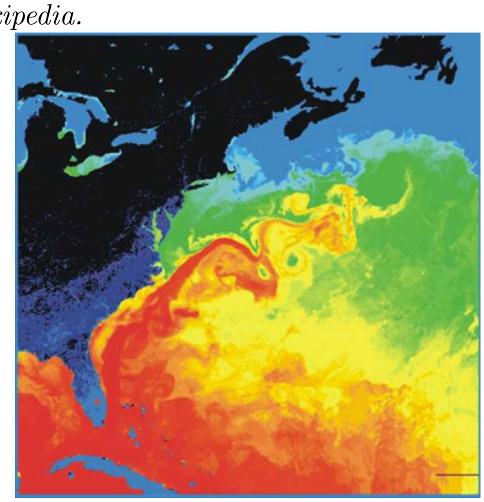
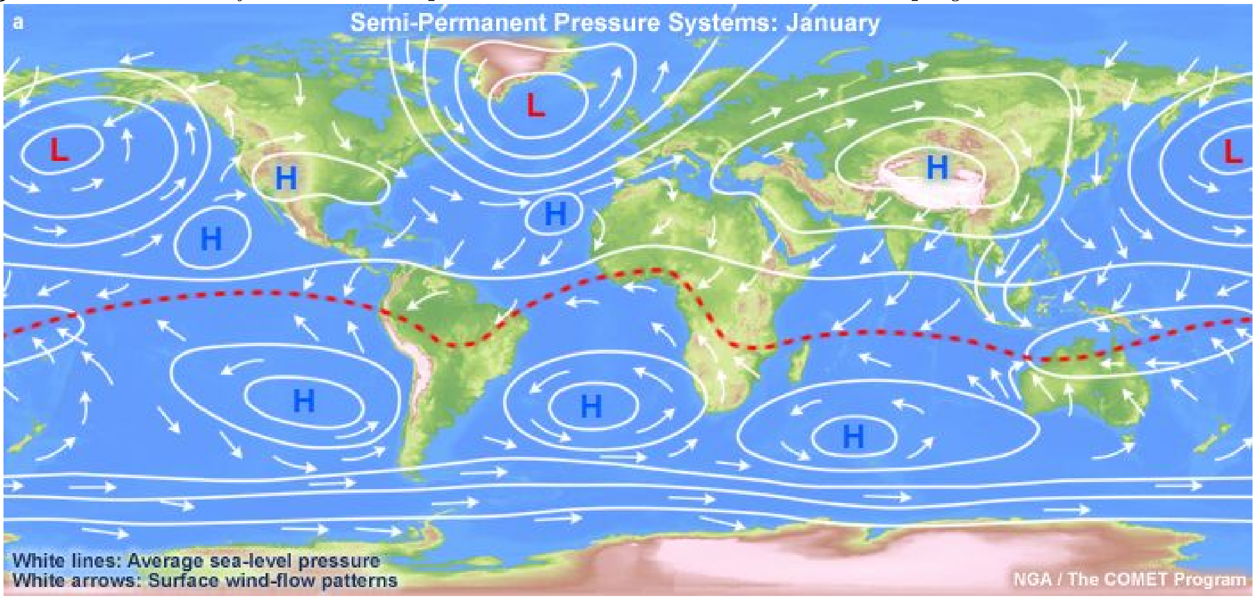
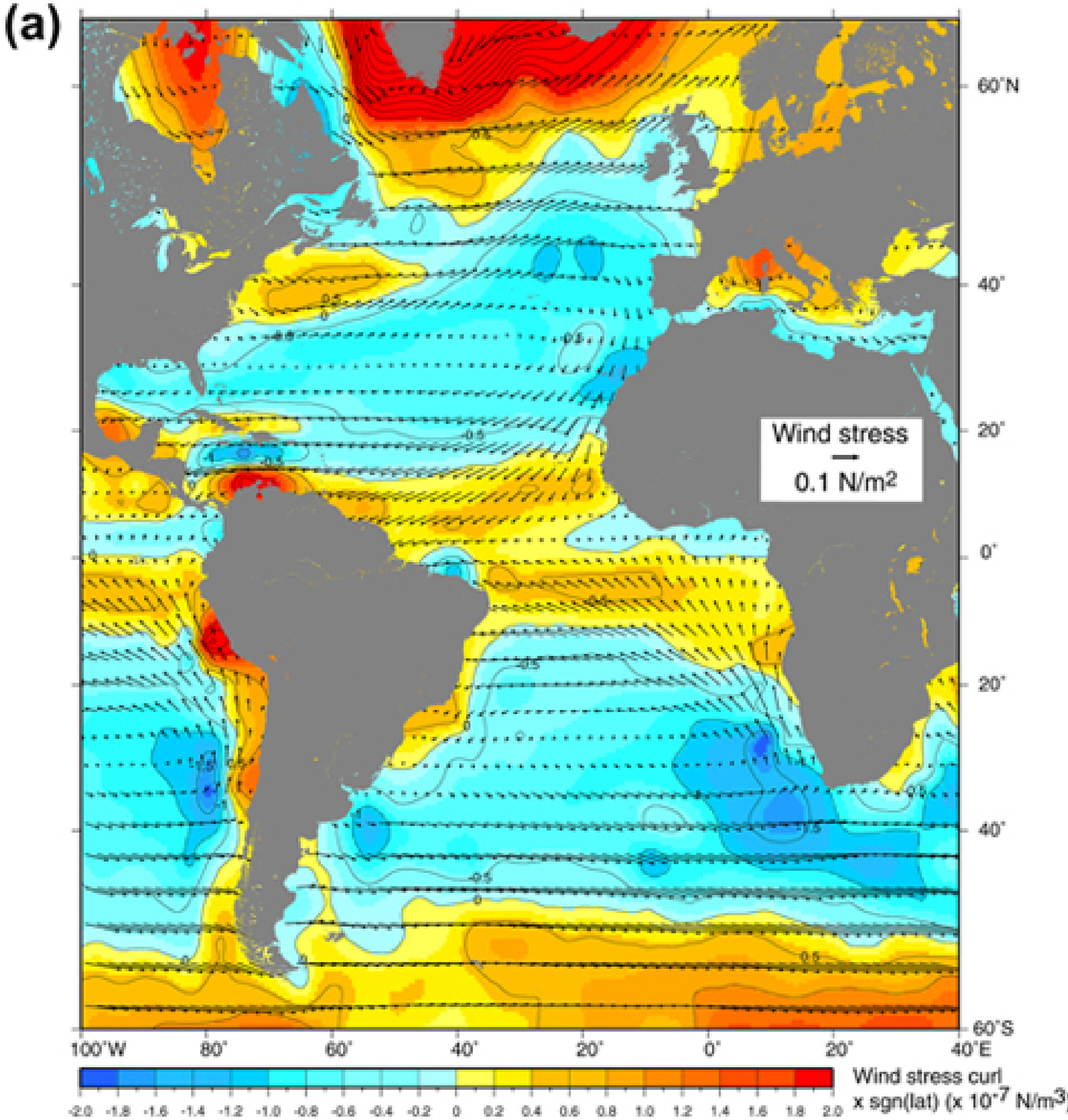


Figure 1.2 *Sketch of Global Atmospheric Patterns. From UCAR Comet program.*



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 1.3).

Figure 1.3 *Mean wind stress and wind stress curl from Descriptive Oceanography by Talley et al. Reproduced under Fair Dealing.*



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 1.4)

Figure 1.4 *Mean circulation in a rectangular basin for a range of Rossby Numbers*

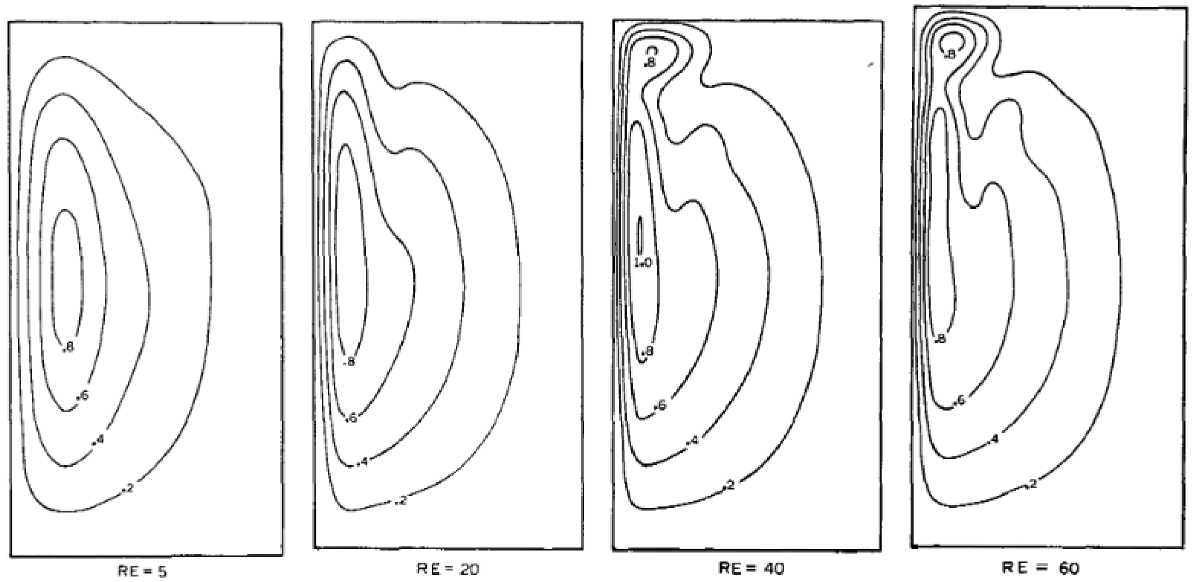


FIG. 4. Patterns of the transport stream function, Ψ', obtained from a time average of solutions with $\epsilon = 1.28 \times 10^{-3}$ and 4 values of Re. For the cases Re = 5 and 20 the finite difference interval was $\Delta S = 1/20$, for Re = 40 and 60, $\Delta S = 1/40$.

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 1.1), 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 1.5).

Figure 1.5 *Only showing the nonlinear case. Flow for a single gyre with an irregular coastline.*

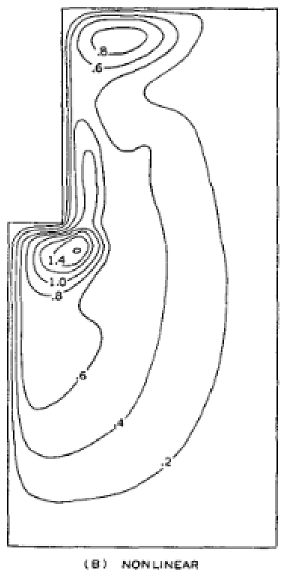


FIG. 9. Linear and non-linear flow patterns for $\epsilon = 1.28 \times 10^{-3}$, Re$=60$, curl of the wind stress proportional to $\sin[(\pi/2)y']$, and an irregular western boundary.

Going back to the real wind stress (Figure 1.3), 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, due to the realistic ratio of the gyres, the separation is north of the zero wind stress curl line.

Figure 1.6 *Only showing the nonlinear case. Flow for a single gyre with an irregular coastline.*

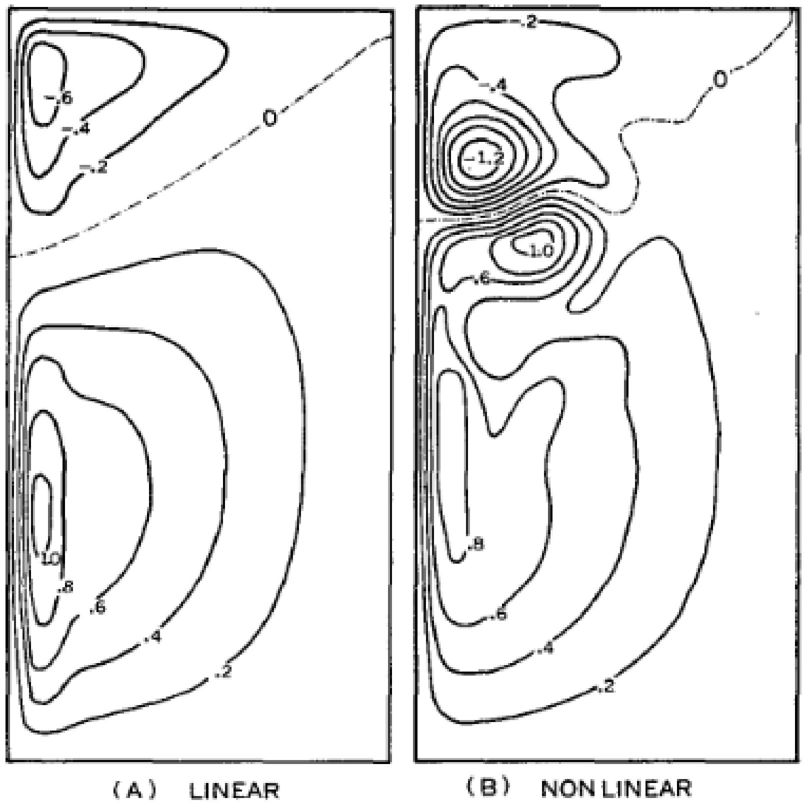


FIG. 11. The same as for Fig. 9 except that the curl of wind stress is proportional to $\sin[(\pi/2)(2-x')y']$ and the western boundary is straight.

Getting the Gulf Stream to separate at the right point became a "holy grail" of ocean modelling. 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 coastline 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; Thompson, 1995; Myers et al., 1996; zgkmen 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; Hulburt and Hogan, 2008]."

Figure 1.7 *A NEMO model results showing good separation. From Chassignet and Marshall*

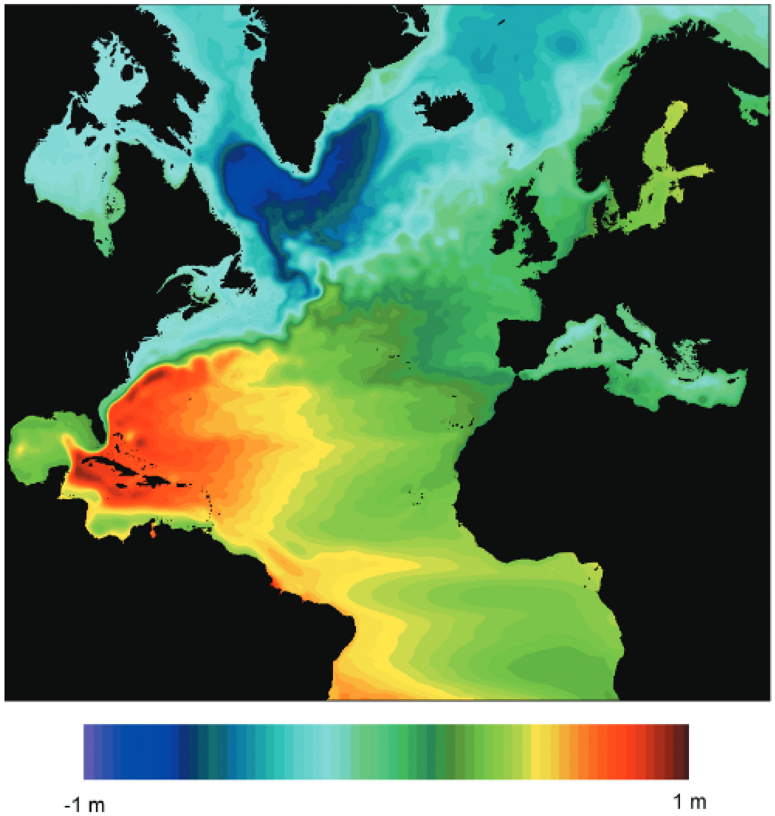


Plate 2. Three-year mean sea surface height from the 1/12° North Atlantic depth coordinate [Nucleus for European Modelling of the Ocean (NEMO); *Madec*, 2006] configured over the North Atlantic between 20°S and 80°N including the Mediterranean Sea (R. Bourdallé-Badie, Y. Drillet, and O. LeGalloudec, personal communication). There are 50 levels in the vertical with an increased vertical resolution near the surface. The bathymetry is a combination of ETOPO2 bathymetry for the deep ocean and GEBCO bathymetry for the continental shelf. The north and south boundaries are buffer zones where the temperature and salinity fields are damped toward a climatological monthly mean [*Levitus et al.*, 1998]. A free surface that filters high-frequency features is used for the surface boundary condition [*Roullet and Madec*, 2000]. An isopycnal Laplacian operator (125 m^2/s) is used for the lateral diffusion on the tracers, and a horizontal biharmonic operator (1.25×10^{-10} m^2/s^2) is used for the lateral viscosity on momentum. A partial slip lateral boundary condition is prescribed along the coast.

"High resolution appears to be necessary, but it is not necessarily 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 $1/10^o$ or higher. The Gulf Stream separation, indeed, turns out to be quite sensitive to a variety of other factors such as subgrid scale parameterization, subopolar gyre strength and water mass properties, DWBC strength, representation of topography, and the choice of model grid (C. Böning, 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 1.8)

Figure 1.8 *Data location. From Chassignet and Marshall*

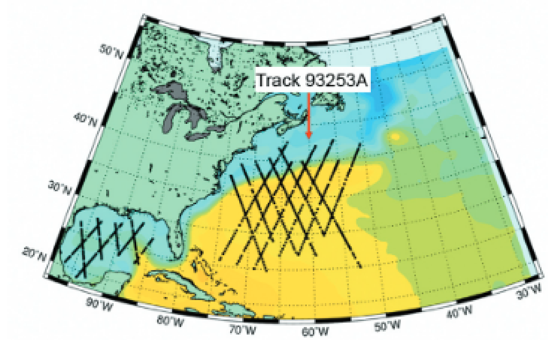


Plate 5. Location of the bathythermographic (BT) data taken during flights under the TOPEX altimeter ground tracks in September 1993. The red arrow points to track 93253A, which is used in Plate 6 to compare various mean dynamic topographies.

Comparison:

Figure 1.9 *Model Data Comparison. From Chassignet and Marshall*

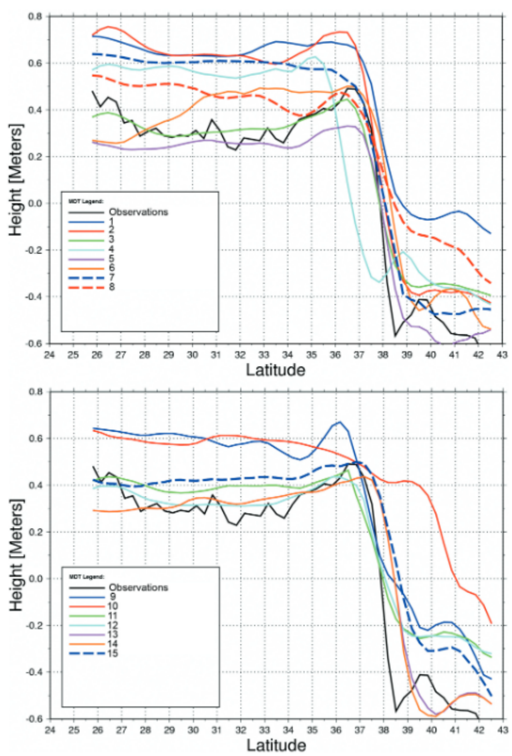


Plate 6. Mean dynamic topography (or sea surface height) in meters from four climatologies (1, 2, 11, and 12) and 11 numerical simulations (3, 4, 5, 6, 7, 8, 9, 10, 13, 14, and 15). The solid line represents the mean dynamic topography derived from the bathythermographic data and altimetry for the track identified in Plate 5.

The best model, #14 is the highest resolution model from the US Navy at $1/32^o$, 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 $1/10^o$ 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

Bryan, K. (1963). A numerical investigation of a nonlinear model of a wind-driven ocean. Journal of the Atmospheric Sciences, 20(6), 594-606.

Chassignet, E. P., & Marshall, D. P. (2008). Gulf Stream separation in numerical ocean models. Geophysical Monograph Series, 177, 3961.