GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L05302, doi:10.1029/2003GL019015, 2004

Dissipation effects in North Atlantic Ocean modeling

D. E. Dietrich,[1] A. Mehra,[2] R. L. Haney,[3] M. J. Bowman,[4] and Y. H. Tseng[5]

Received 6 November 2003; accepted 4 February 2004; published 5 March 2004.

[1] Numerical experiments varying lateral viscosity and diffusivity between 20 and 150 m^2/s in a North Atlantic Ocean (**NAO**) model having 4th-order accurate numerics, in which the dense deep current system (**DCS**) from the northern seas and Arctic Ocean is simulated directly show that Gulf Stream (**GS**) separation is strongly affected by the dissipation of the DCS. This is true even though the separation is highly inertial with large Reynolds number for GS separation flow scales. We show that realistic NAO modeling requires less than 150 m^2/s viscosity and diffusivity in order to maintain the DCS material current with enough intensity to get realistic GS separation near Cape Hatteras (**CH**). This also demands accurate, low dissipation numerics, because of the long transit time (1–10 years) of DCS material from its northern seas and Arctic Ocean source regions to the Cape Hatteras region and the small lateral and vertical scales of DCS. *INDEX TERMS:* 4263 Oceanography: General: Ocean prediction; 4546 Oceanography: Physical: Nearshore processes; 4255 Oceanography: General: Numerical modeling. **Citation:** Dietrich, D. E., A. Mehra, R. L. Haney, M. J. Bowman, and Y. H. Tseng (2004), Dissipation effects in North Atlantic Ocean modeling, *Geophys. Res. Lett.*, *31*, L05302, doi:10.1029/2003GL019015.

1. Introduction

[2] Modeling the GS, especially its separation near CH, is a challenging problem that is affected by a number of factors including the DCS [*Dengg et al.*, 1996]. Northern seas and Arctic Ocean buoyancy sinks that fuel the DCS give it a complex small-scale multi-band structure [*Watts*, 1991] that reflects the strong nonlinearity of the GS/DCS interaction. This suggests, as shown herein, that very small numerical dissipation is needed for realistic NAO decadal and longer time scale modeling. Decadal time scale NAO simulation is of major interest because of ongoing climate warming and known strong decade-time-scale global warming at the end of the last glacial maximum; a main cause of the latter may involve the NAO through highly nonlinear GS/DCS interaction [*Rossby and Nilsson*, 2003].

[3] NAO modeling has progressed by using higher resolution as supercomputing power increases [e.g., *Chao et al.*, 1996; *McClean et al.*, 2002]. Herein, using a model having robust 4th-order-accurate numerics running ~200 model days per clock day on a PC based on a 2 GHz P4 processor, we show, through dissipation sensitivity experiments, that very small dissipation is needed for realistic decadal time scale modeling of the DCS and its interaction with the GS. The DCS importance is amplified by its contact with the ice-like methane hydrates on the ocean floor that contain more heat energy than oil and gas resources combined: DCS changes may lead to rapid methane hydrates gasification and biogeochemical-induced deep ocean warming, with positive feedbacks leading to potentially disastrous rapid climate change (Lai, personal communication, 2003).

2. Model and Experiment Design

[4] We use the DieCAST [*Dietrich*, 1997; *Dietrich et al.*, 1997] ocean model. Among full-featured ocean models, DieCAST is appropriate for analysis of wakes and recirculations relating to GS separation in that it has been quantitatively validated by laboratory experiments and observations in the closely related physical problem of 2-D and 3-D island wake vortices [*Dietrich et al.*, 1996]. DieCAST has also been validated in the Black Sea whose coastal circulation is dominated by persistent energetic meanders and eddies embedded in the wakes of coastal abutments [*Staneva et al.*, 2001], such as the Crimean Peninsula.

[5] The model domain covers the North Atlantic basin from 10°N to 73°N and from 97.5°W to 0°W. To reduce the computation, a duo grid approach is used. West of 60°W, 1/6° resolution is used where it is needed to resolve the GS separation; east of 60°W, 1/2° resolution is used (D. E. Dietrich et al., Nonlinear Gulf Stream interaction with deep currents: A numerical simulation, submitted to *Ocean Modelling*, 2004, hereinafter D04). The grids are fully two-way-coupled each time step, with only a single coarse grid cell overlap (3 × 3 fine grid cells). The results are virtually seamless at the duo grid interface (D04). There are 30 model layers, geometrically expanding from 41.6 m thick at the top to 738 m thick at the bottom (maximum depth 5000 m). This is less resolution than used by *Chao et al.* [1996] and by *McClean et al.* [2002].

[6] The wind forcing is by monthly average Hellerman winds [*Hellerman and Rosenstein*, 1983]. It is noteworthy that *Hurlburt and Hogan* [2000] report that when sufficient resolution is used to address nonlinear GS separation dynamics using the Navy Layered Ocean Model (NLOM), realistic GS separation and other inherently nonlinear features are well simulated using these winds even though the linear version of the same model shows unrealistic GS separation [*Townsend et al.*, 2000].

---

[1] AcuSea Inc., Albuquerque, New Mexico, USA.
[2] Geo Resources Institute, Mississippi State University, Stennis Space Center, Mississippi, USA.
[3] Department of Meteorology, Naval Postgraduate School, Monterey, California, USA.
[4] Marine Sciences Research Center, State University of New York at Stony Brook, Stony Brook, New York, USA.
[5] Department of Mechanical Engineering, Johns Hopkins University, Baltimore, Maryland, USA.

0094-8276/04/2003GL019015$05.00

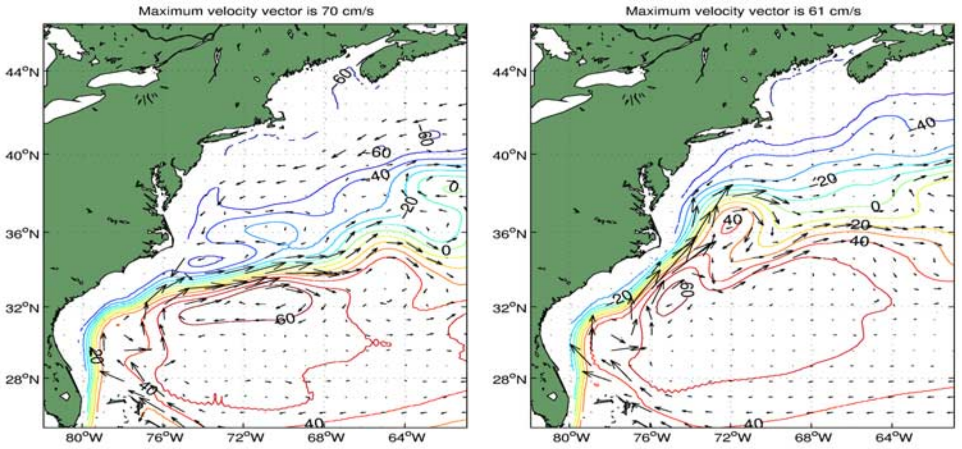

Figure 1. Twenty years mean sea surface height (cm) and 700 m depth velocity vectors in the 1/6 degree resolution western domain. Viscosities are 20 m^2/s (left) and 50 m^2/s (right).

[7] Levitus climatology (Levitus World Ocean Atlas, available at http://www.cdc.noaa.gov/cdc/data.nodc.woa94.html, hereinafter L94) is used for initial conditions. Surface heat and freshwater fluxes are based on an improved (less smoothed) surface climatology (Yashayaev, personal communication, 2002) using a new surface buoyancy flux computation methodology (below). The annual mean surface temperature in the GS region from the latter climatology is more consistent with the observed GS separation near Cape Hatteras than is L94. In a buffer zone 20 grid-points wide along latitudinal open boundaries, the model temperature is restored toward climatology. Salinity is not restored. Instead, a 0.2 Sv inflow of freshwater is spread uniformly along the open northern GINSEA boundary to parameterize Arctic Ocean net river inflow [*Bacon et al.*, 2002]. We also specify 0.018 Sv Gulf of St. Lawrence freshwater volume source [*Chapman and Beardsley*, 1989]. Heat and freshwater fluxes at the sea surface are constructed such that the model multi-year mean annual cycle of surface temperature and salinity precisely follow the observed climatological annual cycle [*Dietrich et al.*, 2004]. This new surface flux condition avoids some of the problems (e.g., erroneous phase lags and excessive damping of surface fronts) attributed to conventional restoring [*Killworth et al.*, 2000].

[8] Another novel feature of the present approach is to replace the conventional vertical wall approach at open northern boundaries by an idealized shelfbreak; this avoids unphysical vortex stretching of the strong North Atlantic current when it turns near the northeastern corner of the model domain, and is more consistent with a shortcircuited Arctic Ocean. Such artificial vortex stretching generates great vertical and horizontal mixing for the wrong physical reasons. Further details on the model setup are given by D04.

[9] We perform two model experiments that differ only by horizontal viscosity and diffusivities (all being equal in a given experiment) used to address the effects of unresolved "turbulent" fluctuations on the predicted control volume averaged quantities: a low dissipation experiment using 50 m^2/s in the 1/6° resolution western domain and 150 m^2/sec in the 1/2 deg resolution eastern domain; and an even lower dissipation experiment using 20 m^2/sec and 60 m^2/sec in the two domains. The smallest dissipation is smaller than estimates based on observations [*Rajamony et al.*, 2001], but the "ideal" values depend on: model resolution and resolved eddy activity admitted by the model; and model robustness with low dissipation as further discussed below.

3. Sensitivity to Dissipation

[10] Based on the scale of the CH abutment curvature (~100 km) and GS velocity (~1 m/sec), the Reynolds number for the primary dissipation scale in our two experiments is $O(10^3 \sim 10^4)$. The Rossby number for these scales is $O(10^{-1})$. Thus, in both cases, the inertia terms are large enough for highly inertial GS separation to occur near CH.

[11] Figures 1–3 show 20-year time averaged flow results of our two cases. The left panels in Figures 1–3 show the lower dissipation case results; the right panels show the low (compared to most other models) dissipation case results. Figure 1 compares the surface pressure with superposed 700 m depth velocity vectors in the 1/6 deg resolution western domain; Figure 2 compares the western domain 1474 m depth pressure and velocity; Figure 3 compares the surface pressure and with superposed 700 m depth velocity vectors in the 1/2 deg resolution eastern domain. Figure 3 also shows the strong bottom density current overflow (DCS source) from the Denmark Strait between Greenland and Iceland.

[12] The DCS volume flux per unit depth is proportional to the horizontal pressure difference across this southwestward dense current along the New England shelfbreak. The flow at all levels having a strong DCS along the New England shelfbreak, from ~1000 m to >2000 m, is similar to Figure 2 (D04). The vertically integrated volume flux over all levels is ~20 Sv for the lower dissipation case and ~5 Sv for the higher dissipation case. Thus, the larger dissipation greatly reduces the DCS volume flux and results in GS separation north of the observed CH separation point (Figure 1 (right)), as in other models using comparable resolution [*Chao et al.*, 1996; *Dengg et al.*, 1996]. Noting the high Reynolds number for the GS separation scale in both cases, our results suggest that the main cause of its sensitivity to dissipation may be the strong effect on the DCS, which in turn affects the GS path. This is

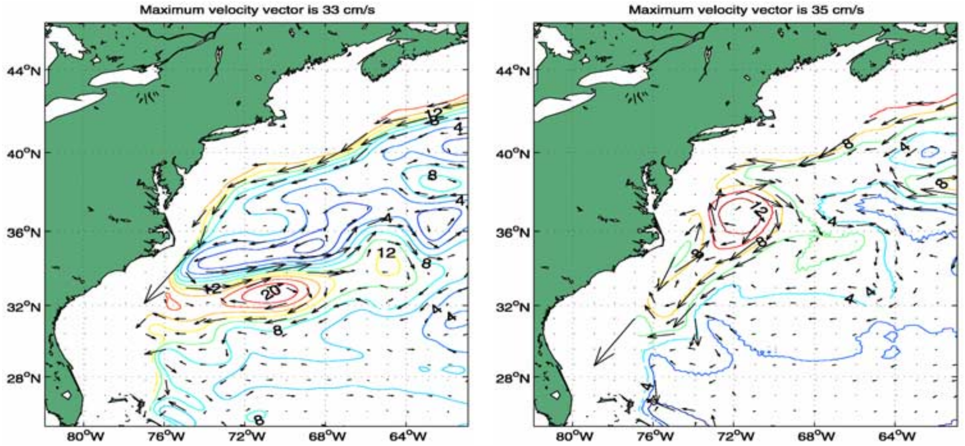

Figure 2. Twenty years mean pressure (cm) and velocity vectors in the 1/6 degree resolution western domain at level 1474 m. Viscosities are 20 m^2/s (left) and 50 m^2/s (right).

consistent with studies focusing on the GS separation region [*Thompson and Schmitz*, 1989] and with the observed significant annual cycle of the GS path that appears related to the DCS annual cycle [*Rossby*, 1999]. Noting the small scale and long travel time of the DCS material current from its northern seas and Arctic Ocean source regions, strong DCS sensitivity to dissipation is not surprising. If the GS separates too far north in a model using comparably low dissipation, this may be due to having larger numerical dispersion of the DCS than the present model. The DCS must have enough intensity to not be blocked by the energetic GS before the DCS reaches the CH region.

[13] The DCS is not resolved by initialization climatology. It takes a few years to reach full strength and achieve its full impact on the GS separation. During spin-up time, the GS separation is well north of the observed CH separation, further showing the major influence of the DCS on GS separation; these and further details on the DCS/GS interaction are given and discussed by D04. A highlight is that the iso-surfaces of time averaged potential density at depths >500 m in the wedge-shaped region between the GS and the DCS are remarkably flat in model results and climatology (Yashayaev, personal communication, 2002). The dramatic climatological isopycnal flatness between the steep isopycnals in the DCS and in the GS shows that the eddy field is NOT diffusive in nature. This flatness is more consistent with the small diffusivities used herein than with the excessive values used by some models. The observed very tight nature of the meandering GS jet gives further support for such small diffusivities. The isopycnal flattening is characteristic of an eddy field that is fueled by potential-energy-releasing nonlinear finite-amplitude effects of baroclinic instability occurring primarily along the GS and DCS; similar behavior occurs in the atmospheric index cycle and in rotating annulus experiments [*Pfeffer et al.*, 1974].

4. Concluding Remarks

[14] A good numerical model having small numerical dispersion and realistically small dissipation may simulate the GS/DCS system realistically using only marginally eddy-resolving resolution. This simulation required supercomputing power until very recently, but now is possible on a modern PC because of better computing technology and numerical modeling methodology. This is important in the study of the potential impact of GS/DCS interaction on

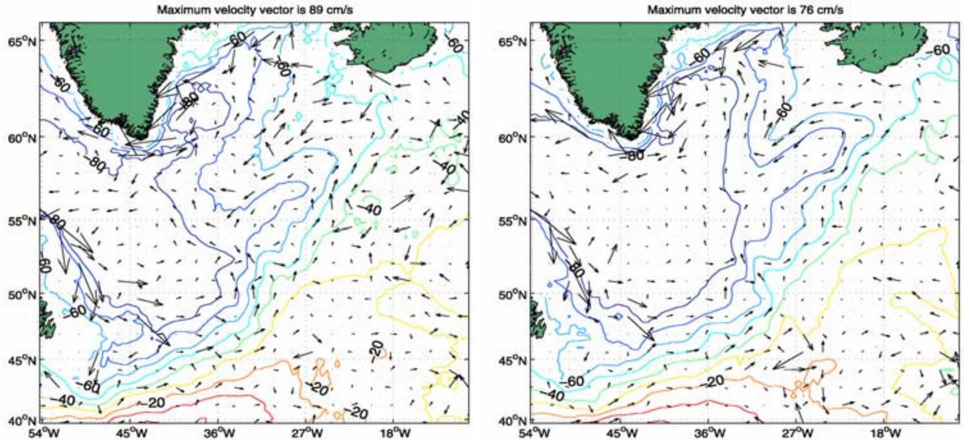

Figure 3. Twenty years mean sea surface height (cm) and 700 m depth mean velocity vectors in the Denmark Strait region. Viscosities are 60 m^2/s (left) and 150 m^2/s (right).

climate including potential rapid global warming and reliable risk assessment for such potential warming.

[15] The strongly inertial behavior of the GS/DCS indicated by observations and present model results shows the need for extremely low dissipation in NAO modeling. The DCS existence implies that GS separation must occur somewhere, but our results show that very low dissipation is needed to maintain the DCS intensity in order for it to flow all the way to the major CH abutment and not be blocked by the highly energetic GS on the way. The fourth-order-accurate "a" grid numerics used herein [*Dietrich*, 1997; *Sanderson and Brassington*, 1998] is a big advantage in minimizing numerical dispersion during the 1–10 year material transit time of the narrow, thin DCS water from its northern seas and Arctic Ocean source region to CH. Near CH, nonlinear boundary current separation dynamics associated with local bathymetric details take over; other separation mechanisms have been considered [*Dengg et al.*, 1996], but the major role of the DCS is shown by our results.

[16] The eddy-induced isopycnal flattening discussed herein adds to the body of theory, observations and model results e.g., *Hughes*, 2003; *Molemaker and Dukstra*, 2000; *Lin and Dietrich*, 1994, which suggest that horizontal and slantwise advection by resolved eddies is at least as important as vertical mixing by unresolvable surface mixed layer eddies.

[17] **Acknowledgments.** This work was supported by AcuSea, Inc. and Mississippi State University (contract No. N00014-00-1-0886). We thank Tom Rossby and the other (unnamed) reviewer, and Paul Martin, Tammy Townsend, Harley Hurlburt and Dan Wright for helpful suggestions and discussions; and Greg Lukeman for providing Yashayaev climatology and graphics help.

References

Bacon, S., G. Reverdin, I. G. Rigor, and H. M. Smith (2002), A freshwater jet on the East Greenland shelf, paper presented at 2002 Ocean Sciences Meeting, Honolulu, Hawaii, 11 –15 February.

Chao, Y., A. Gangopadhyay, F. O. Bryan, and W. R. Holland (1996), Modeling the Gulf Stream system: How far from reality?, *Geophys. Res. Lett.*, *23*, 3155–3158.

Chapman, D. C., and P. C. Beardsley (1989), On the origin of shelfwater in the Middle Atlantic Bight, *J. Phys. Oceanogr.*, *19*, 384–391.

Dengg, G., A. Beckmann, and R. Gerdes (1996), The Gulf Stream separation problem, in *The Warmwatersphere of the North Atlantic Ocean*, edited by Wolfgang Krauss, pp. 253–290, Borntraeger, Berlin.

Dietrich, D. E. (1997), Application of a modified "a" grid ocean model having reduced numerical dispersion to the Gulf of Mexico circulation, *Dyn. Atmos. Oceans*, *27*, 201–217.

Dietrich, D. E., M. J. Bowman, C. A. Lin, and A. Mestas-Nunez (1996), Numerical studies of small island wakes, *Geophys. Astrophys. Fluid Dyn.*, *83*, 195–231.

Dietrich, D. E., C. A. Lin, A. Mestas-Nunez, and D.-S. Ko (1997), A high resolution numerical study of Gulf of Mexico fronts and eddies, *Meteorol. Atmos. Phys.*, *64*, 187–201.

Dietrich, D. E., R. L. Haney, V. Fernandez, S. Josey, and J. Tintore (2004), Air-sea fluxes based on observed annual cycle surface climatology and ocean model internal dynamics: A non-dampening zero-phase-lag approach applied to the Mediterranean Sea, *J. Mar. Syst.*, in press.

Hellerman, S., and M. Rosenstein (1983), Normal monthly wind stress over the world ocean with error estimates, *J. Phys. Oceanogr.*, *13*, 1093–1104.

Hughes, C. W. (2003), An extra dimension to mixing, *Nature*, *416*, 136–138.

Hurlburt, H. E., and P. J. Hogan (2000), Impact of 1/8 deg to 1/64 deg resolution on Gulf Stream model-data comparisons in basin-scale subtropical Atlantic Ocean models, *Dyn. Atmos. Oceans*, *32*, 283–329.

Killworth, P. D., D. A. Smeed, and A. J. G. Nurser (2000), The effects on ocean models of relaxation toward observations at the surface, *J. Phys. Oceanogr.*, *30*, 160–174.

Lin, C. A., and D. E. Dietrich (1994), A numerical study of low Reynolds number two-dimensional convective adjustment, *Geophys. Astrophys. Fluid Dyn.*, *74*, 123–134.

McClean, J. L., P.-M. Poulain, J. W. Pelton, and M. E. Maltrud (2002), Eulerian and Lagrangian statistics from surface drifters and a high-resolution POP simulation in the North Atlantic, *J. Phys. Oceanogr.*, *32*, 2472–2491.

Molemaker, M. J., and H. A. Dukstra (2000), Sensitivity of a cold core eddy in the presence of convection: Hydrostatic versus nonhydrostatic modeling, *J. Phys. Oceanogr.*, *30*, 475–494.

Pfeffer, R. L., G. Buzyna, and W. W. Fowlis (1974), Synoptic features and energetics of wave-amplitude vacillation in a rotating, differentially heated fluid, *J. Atmos. Sci.*, *31*, 622–645.

Rajamony, J., D. Hebert, and T. Rossby (2001), The cross-stream potential vorticity front and its role in meander-induced exchange in the Gulf Stream, *J. Phys. Oceanogr.*, *31*, 3551–3568.

Rossby, T. (1999), On gyre interactions, *Deep Sea Res. Part II*, *46*, 139–164.

Rossby, T., and J. Nilsson (2003), Current switching as the cause of rapid warming at the end of the Last Glacial Maximum and Younger Dryas, *Geophy. Res. Lett.*, *30*(2), 1051, doi:10.1029/2002GL015423.

Sanderson, B. G., and G. Brassington (1998), Accuracy in the context of a control-volume model, *Atmos. Ocean*, *36*, 355–384.

Staneva, J. V., D. E. Dietrich, E. V. Stanev, and M. J. Bowman (2001), Rim current and coastal eddy mechanisms in an eddy-resolving Black Sea general circulation model, *J. Mar. Syst.*, *31*, 137–157.

Thompson, J. D., and W. J. Schmitz (1989), A limited-area model of the Gulf Stream: Design, initial experiments and model-data intercomparison, *J. Phys. Oceanogr.*, *19*, 791–814.

Townsend, T. L., H. E. Hurlburt, and P. J. Hogan (2000), Modeled Sverdrup flow in the North Atlantic from 11 different wind stress climatologies, *Dyn. Atmos. Oceans*, *32*, 373–417.

Watts, R. (1991), Equatorward currents in temperatures 1.8–6.0 deg C on the continental slope in the Mid-Atlantic Bight, in *Deep Convection and Deep Water Formation in the Oceans*, edited by P. C. Chu and J. C. Gascard, pp. 183–196, Elsevier, New York.

M. J. Bowman, Marine Sciences Research Center, State University of New York, Endeavour Hall 215, South Campus, Stony Brook, NY 11794-5000, USA. (mbowman@notes.cc.sunysb.edu)

D. E. Dietrich, AcuSea Inc., 1421 Monte Largo Dr. N.E., Albuquerque, NM 87112, USA. (dietrich@nmia.com)

R. L. Haney, Department of Meteorology, Naval Postgraduate School, 589 Dyer Road, Room 254, Monterey, CA 93943-5114, USA. (rlhaney@nps.navy.mil)

A. Mehra, Geo Resources Institute, Mississippi State University, Bldg. 1103, Rm. 233, Stennis Space Center, MS 39529-6000, USA. (mehra@gri.msstate.edu)

Y. H. Tseng, Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21208, USA. (yhtseng@jhu.edu)