WHOI-78-3

ON THE DEEP GENERAL CIRCULATION IN THE
WESTERN NORTH ATLANTIC

by

William J. Schmitz, Jr.

WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

April 1978

TECHNICAL REPORT

*Prepared for the Office of Naval Research
under Contracts N00014-66-C-0241; NR 083-004
and N00014-74-C-0262; NR 083-004 and for the
International Decade of Ocean Exploration of
the National Science Foundation under Grant
OCE75-03962.*

*Reproduction in whole or in part is permitted
for any purpose of the United States Government.
In citing this report in a bibliography, the
reference given should be given to the
"Journal of Marine Research, Volume 35, 1,
1977".*

*Approved for public release; distribution
unlimited.*

Approved for Distribution: Valentine Worthington, Chairman
Department of Physical Oceanography

On the deep general circulation in the Western North Atlantic

by William J. Schmitz, Jr.¹

ABSTRACT

Very large ($5\text{--}10\text{ cm s}^{-1}$) long-term averaged zonal flows have been observed near 4000 m depth in the vicinity of a recently hypothesized (Worthington, in press) horizontally restricted subtropical gyre in the deep western North Atlantic. The Reynolds stresses associated with low frequency fluctuations may play a significant role in the dynamics of this deep mean flow, possibly inducing a significant downstream increase in transport of the Gulf Stream, perhaps driving the deep gyre.

The shape of the general circulation of the North Atlantic as hypothesized by Worthington (1976) contains a subtropical gyre that is more north and northwestward concentrated and smaller than previously suggested. Worthington (Fig. 42) proposes a medium horizontal scale gyre (confined to the west of the mid-Atlantic Ridge) transporting about $30 \times 10^6\text{ m}^3\text{ s}^{-1}$ (the transport through the Straits of Florida), with a smaller gyre transporting about $120 \times 10^6\text{ m}^3\text{ s}^{-1}$ embedded in the northern and western corner of the larger gyre. The smaller scale gyre is presumed to contain all of the so-called downstream increase in transport of the Gulf Stream and all of the deep general circulation (Fig. 1) of the entire subtropical gyre. Long-term moored current meter data have been accumulated over the past several years in order to examine this suggestion, and also to investigate the relationship between the structure of the mean flow and the properties of the eddy field (the terms eddy and low frequency variability are used interchangeably to denote fluctuations with frequencies less than one cycle per day).

One particularly controversial element of the circulation patterns drawn by Worthington is the violation of approximate geostrophic balance in the westward return flow (Fig. 1) offshore of the Gulf Stream. A possible source of this difficulty might be that Worthington's assignment of reference level (or deep mean flow) is too low. The deep easterly flow found to be associated with the Gulf Stream is comparable in magnitude ($5\text{--}10\text{ cm s}^{-1}$) to that suggested by Worthington, although displaced 100-200 km to the south in the moored data, with a countercurrent under

1. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 02543, U.S.A.

Figure 1. Location of the line of moorings along 55° W relative to volume transport streamlines for the deep (potential temperature less than 4° C) general circulation of the North Atlantic according to Worthington (1976). The contour interval for the transport streamlines is $5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ and numbers denote volume transports at key locations.

the axis of the Gulf Stream. In the return flow near 4000 m depth, westerly velocity components are about 3 times as large as assigned by Worthington, and the width of the return flow is roughly 3 times smaller.

The earliest long-term moored instrument data indicated strong horizontal inhomogeneity in the intensity of the eddy field at 4000 m depth (Schmitz, 1976), related to some extent to the structure of the general ocean circulation. The newer data described below lead to the same general conclusion.

1. Data along 60° W long

The southerly extent of the deep westward return flow in the vicinity of 60° W in Fig. 1 is near the latitude of Bermuda, approximately 32° N. Two moorings were deployed near 60° W for about nine months starting in July, 1974, one to the south of Bermuda in the vicinity of 31° N, and one north of Bermuda near 34° N. The time-averaged east-west velocity component ($\bar{u}$) at 4000 m depth near 31° N was found to be small ($.3 \text{ cm s}^{-1}$). In sharp contrast, near 34° N (Mooring 549, Fig. 2) $\bar{u}$ at 4000 m depth was observed to be -7.0 cm s^{-1} , and at 2000 m depth, -2.8 cm s^{-1} . The sensitivity of these averages to averaging duration is indicated in Fig. 2. $\bar{u}$ is always negative. Data from moorings deployed along 28° N in the W long. range 55-65° yield estimates of $\langle u \rangle$ (the brackets denote a mixed space-time average) at 4000 m depth that are 1 cm s^{-1} or less and eastward. The sharp increase in mean kinetic energy from 28 and 31° N to 34° N up to 60° W is also associated with rapid changes in the averaged properties of the eddy field (Fig. 3).

Figure 2. (left) Time averages of the east-west velocity component as a function of averaging duration for records 5494 (2000 m) and 5495 (4000 m), from the vicinity of 34° N, 60° W. For $\overline{u(t)}$, computation is from the start of the record, $\overline{u(-t)}$ indicates calculation from the end of the record toward the beginning.

Figure 3. (right) Latitudinal distribution of horizontal momentum flux ($\overline{u'v'}$) and eddy kinetic energy ($\overline{K_E}$) for observations along 60° W long.

The 60° W data support, in a general way, confinement of the intense deep mean gyre in Fig. 1 to comparatively northern latitudes, an increase in eddy intensity moving into this gyre, and raise the question of the existence of a weaker deep easterly flow or even another closed gyre south of the gyre in Fig. 1.

2. Data along 55° and 70° W long

An array of moored instrumentation was set (Fig. 1) in April-May, 1975 and recovered in December, 1975. Nine moorings, four with current meters near 4000 m depth, and five with current meters at nominal depths of 600, 1000, 1500, and 4000 m, were deployed along 55° W.

Two moorings (557 and 565, Fig. 4) were found to be located in the region of westward recirculation. The vertical structure of $\bar{u}$ for both 549 (60° W, return flow) and 565 is bottom intensified (Fig. 4), with 565 (35° 36' N) higher in amplitude than 549 (34° N) by about 50%. North of 565, $\bar{u}$ at mooring 557 (35° 56' N) is large, negative, and nearly depth independent in the deep water, becoming more

Figure 4. (left) Vertical distributions of mean east-west velocity component ($\bar{u}$) for moorings from the zone of westward return flow (557 is near 36° N, 55° W; 565 is near $35^\circ 30'$ N, 55° W; 549 is near 34° N, 60° W.)

Figure 5. (right) Time averages of the east-west velocity component as a function of averaging duration for records 5571 (600 m) and 5573 (1000 m) from the vicinity of 36° N, 55° W. For $\bar{u}(t)$, computation is from the start of the record, $\bar{u}(-t)$ indicates calculation from the end of the record toward the beginning.

westerly in the thermocline. The 55° W data are consistent with the results from mooring 549 in that they indicate the existence of large deep mean flows in the zone of westward recirculation. The vertical distribution of $\bar{u}$ below the thermocline at mooring 557 (Fig. 4) is much more dominated by the barotropic mode than postulated by Worthington for the return flow, although the weak vertical shear in the thermocline may be in qualitative agreement with his results. The settling down time for $\bar{u}$ in the thermocline for mooring 557 is indicated in Fig. 5.

The latitudinal distributions of mean east-west velocity components at 4000 m depth for the two longitudes at which data are available for a reasonably broad range of latitudes (Fig. 6) are qualitatively similar, with larger amplitudes found near 55° W. The data along 70° W were collected at intervals over several years (Schmitz, 1976) but only one good quality current meter record was obtained in the westward return flow, in the area south of 36° N and north of *Aries* Area A (latitude range $30^\circ 38' - 32^\circ 12'$ N) near 70° W. The means along 70° W are mixed space-time averages, denoted by the symbol $\langle \rangle$. The latitudinal distributions of momentum flux at the two longitudes are also qualitatively similar (Fig. 7) but again with larger values at 55° W than at 70° W, about the same ratio of amplitudes as for the mean flow in Fig. 6. Eddy kinetic energy distributions (Fig. 8) have nearly the same characteristic shape. At 70° W the eddy kinetic energy is characteristi-

Figure 6. (top left) Distribution of averaged east-west velocity components along 55° (time averages, $\bar{u}$) and 70° W (space-time averages, $\langle u \rangle$). ■, ● are 4000 m data, ⊙ 5000 m, □ 2000 m. The latitudes of the 70° W data have been shifted 2° N.

Figure 7. (top right) Distribution of the off-diagonal horizontal Reynolds stress along 55° (time averages, $\bar{u}'v'$) and 70° W (space-time averages, $\langle u'v' \rangle$). ■, ● are 4000 m data, ⊙ 5000 m, □ 2000 m. The latitudes of the 70° W data have been shifted 2° north.

Figure 8. (bottom left) Distribution of eddy kinetic energy along 55° (time averages, $\bar{K}_E$) and 70° W. (space-time averages, $\langle K_E \rangle$). ■, ● are 4000 m data, ⊙ 5000 m, □ 2000 m. The latitudes of the 70° W data have been shifted 2° north.

Figure 9. (bottom right) Averages of the east-west velocity component as a function of averaging duration for moored current meter data obtained near 36° N, 70° W. For $\langle u(t) \rangle$, computation is from the start of the record, $\langle u(-t) \rangle$ indicates calculation from the end of the record toward the beginning. The stability bars were set by computing the average after discarding the most and least energetic records.

cally an order of magnitude greater than the mean kinetic energy, but at 55° W the eddy and mean kinetic energies are of the same order of magnitude in the vicinity of the Gulf Stream and the westward return flow. In Figs. 6 through 8 the latitudes for the 70° W data are shifted north by 2° in order to make the comparison relative to the axis of the Gulf Stream [as indicated by the position of the 15° C

isotherm at 200 m depth (Fuglister and Voorhis, 1965), located near 39° 30' to 40° 30' N at 55° W, 37° 40' N at 70° W (Schroeder, 1963)].

Short zonal scale variations in the mean north-south velocity component and in momentum flux (but not eddy kinetic energy or mean east-west velocity component) were first observed by Luyten (1976) for the deep flow in the vicinity of the Gulf Stream along 70° W. This scale of variation is also found in the data in the westward return flow near 55° W, along 36° N. These shorter horizontal scale variations are observed primarily in the mean north-south velocity component near 55° W, and may be associated with the distribution of bottom topography (Nelson Hogg, personal communication). In addition, an example of possible shielding in the lee of a seamount was obtained.

3. Spatial inhomogeneity

A pronounced general descriptive characteristic of the data presented above is that the properties of the eddy field at 4000 m depth vary with position by about two orders of magnitude; distributions appear to be associated with the properties of the general circulation and, to some extent, the distribution of bottom topography. The *Aries* data (Swallow, 1971) contain the first hint of the type of spatial inhomogeneity described above (more energetic low-frequency fluctuations near the Gulf Stream), but do not imply the existence of energetic deep low-frequency variability throughout the ocean (for example, near 28° N, 55-65° W, the eddy kinetic energy is found to be less than 1 cm² s⁻²). The intensity and spatial variability of the eddy field is in sharp contrast to that of higher frequencies (1 c.p.h. → 1 c.p.d.). For example, along 55° W near 4000 m depth between 28° and 41° 30' N the kinetic energy of the higher frequency band varies between 2.1 and 6.5 cm² s⁻² with an average of 3.5 cm² s⁻², whereas the low frequency kinetic energy varies from less than 1 to 162 cm² s⁻², with an average of 85 cm² s⁻².

4. Discussion

The distribution of mean east-west velocity components in Figs. 4 and 6 have some features in common with Worthington's (1976) deep mean gyre, and there are also points of potential disagreement. There is a westward return flow in Fig. 6 at both 55° and 70° W. At 55° W, this zone is of narrow latitudinal extent (100-150 km) compared either to the 70° W data in Fig. 6 or Worthington's pattern (about 600 km) in Fig. 1. The eastward flow near the axis of the Gulf Stream in Fig. 6 is consistently present at a distance of 100-200 km south (offshore) of the axis of the Gulf Stream, in contrast to the patterns drawn by Worthington. A deep westward mean flow north of and under the Gulf Stream, stronger and broader than implied by Fig. 1, is a characteristic of the moored instrument data at both longitudes. The eastward flow south of the westward circulation at 55° W in Fig. 6,

poorly resolved by the data available, does not appear in Fig. 1. There is no indication in Fig. 1 that the zonal flows (Fig. 6) are 3 times larger at 55° than at 70° W. However, a diagram of the sub-tropical gyre below 2° potential temperature (located at nearly 4000 m depth), kindly communicated personally by Worthington, shows a transport of only $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ at 70° W, with about $7 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ at 55° W. A zonal flow of 2.0 cm s^{-1} (Fig. 6, 70° W) over 400 m depth range (the bottom depth is roughly 4400 m at the location of the deep Gulf Stream along 70° W) and 150 km horizontal extent gives a transport of $1.2 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. At 55° W, a zonal flow of 7 cm s^{-1} (Fig. 6, 55° W) distributed over 1000 m depth range (the bottom depth is roughly 5000 m at the location of the deep Gulf Stream along 55° W) and 150 km horizontal extent gives a transport of $10.5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. In addition, the return flow below 2° potential temperature according to Worthington is narrower than the pattern in Fig. 1.

Each of the regions of zonal mean flow in Fig. 6 is defined by data obtained from at least two horizontal positions. The sensitivity of estimates of the mean east-west velocity component at the location on the offshore side of the Gulf Stream axis where $\bar{u}$ near 4000 m depth is the maximum eastward along 70° W may be seen in Fig. 9. The stability bars in Fig. 9 were set by computing the average without the most and least energetic records and taking the maximum difference.

The distributions of momentum flux (off-diagonal component of the horizontal Reynolds stress tensor) in Fig. 7 indicate that the dynamics of the mean flow may be significantly influenced by the structure of the deep eddy field. The momentum transport by the eddy field is neglected relative to the momentum transport by the mean flow in inertial models of the Gulf Stream or of the subtropical gyre. Taking one term as an indicator of the potential relevance of this assumption, the latitudinal derivatives of $\overline{u'v'}$ and $\overline{uv}$ are of the same order for the 4000 m data along 55° W. In purely frictional models, the momentum transport by the mean flow is neglected relative to the momentum transport by the fluctuations, and a constant positive eddy viscosity is often used. Again looking at one term as an example, the ratio (eddy viscosity) of $-\overline{u'v'}$ to the latitudinal derivative of the zonal mean flow is both positive and negative and varies by an order of magnitude for the data along 55° W. This ratio is negative in the region of eastward mean flow to the offshore side of the axis of the Gulf Stream and in the westward return flow. The corresponding term (the negative product of $\bar{u}$ and the latitudinal derivative of $\overline{u'v'}$) in the energy budget for the mean flow, based on the 4000 m data at 55° W, is the largest (and, if the average were spatial, from low-frequency fluctuations to the mean flow) in the regions of eastward mean flow offshore of the axis of the Gulf Stream and in the westward return flow to the south.

Recent gyre-scale numerical models capable of resolving eddies (Holland and Lin; 1975a,b) yield a deep mean circulation driven by the eddies. This class of models and the data described above are qualitatively similar in some respects; de-

tailed quantitative comparisons await more thorough analysis, a more substantial data base, and more realistic models. Nevertheless, it seems possible that the directly wind-driven segment of the North Atlantic subtropical gyre is confined to the approximately $30 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ moving through the Straits of Florida, with a sizeable fraction of the downstream increase [$120 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ according to Worthington (1976)] in transport of the Gulf Stream system induced by the spatial inhomogeneity in the eddy field, especially at depths below the main thermocline.

Acknowledgments. The research described was supported primarily by the Office of Naval Research under contracts N00014-66-CO241 NR 083-004 and N00014-74-CO262 NR 083-004. Funds in partial support of the POLYMODE observations were obtained from the International Decade of Ocean Exploration Office of the National Science Foundation under grant OCE75-03962. I am grateful for permission to use part of a diagram of the deep general circulation of the North Atlantic Ocean, kindly made available by L. V. Worthington prior to publication. Drs. R. E. Davis and M. N. Koshlyakov are thanked for their early encouragement of the efforts described above. Portions of these results were presented in a Memorial Lecture to William S. Richardson in March, 1976, sponsored by the American Meteorological Society. This work is dedicated to Bill Richardson. This is Contribution No. 3779 from Woods Hole Oceanographic Institution, and Contribution No. 66 from the Mid-Ocean Dynamics Experiments, MODE and POLYMODE.

REFERENCES

- Fuglister, F. C. and A. D. Voorhis. 1965. A new method of tracking the Gulf Stream. *Limnol. Oceanogr.*, 10, Sup. R115-R124.
- Holland, W. R., and L. B. Lin. 1975a. On the generation of mesoscale eddies and their contribution to the oceanic general circulation. I. A preliminary numerical experiment. *J. Phys. Ocean.*, 5, 642-657.
- . 1975b. On the generation of mesoscale eddies and their contribution to the oceanic general circulation. II. A parameter study. *J. Phys. Ocean.*, 5, 658-669.
- Luyten, J. R. 1976. Scales of motion in the deep Gulf Stream and across the Continental Rise, *J. Mar. Res.*, this issue.
- Schmitz, W. J., Jr. 1976. Eddy kinetic energy in the deep western North Atlantic. *J. Geophys. Res., Oceans and Atmospheres*, 81, 4981-4982.
- Schroeder, E. H. 1963. North Atlantic temperatures at a depth of 200 meters. *Serial Atlas of the Marine Environment. Folio 2*, American Geographical Society.
- Swallow, J. C. 1971. The *Aries* current measurements in the western North Atlantic. *Phil. Trans. R. Soc. Lond. A*, 270, 451-460.
- Worthington, L. V. 1976. On the North Atlantic circulation. *The Johns Hopkins Oceanographic Studies No. 6*, The Johns Hopkins University Press, Baltimore and London, 110 pp.

Received: October, 1976.

Printed in U.S.A. for the Sears Foundation for Marine Research,
Yale University, New Haven, Connecticut, 06520, U.S.A.
Van Dyck Printing Company, North Haven, Connecticut, 06473, U.S.A.

MANDATORY DISTRIBUTION LIST

FOR UNCLASSIFIED TECHNICAL REPORTS, REPRINTS, & FINAL REPORTS
PUBLISHED BY OCEANOGRAPHIC CONTRACTORS
OF THE OCEAN SCIENCE AND TECHNOLOGY DIVISION
OF THE OFFICE OF NAVAL RESEARCH

(REVISED FEBRUARY 1978)

1	Director of Defense Research
and Engineering
Office of the Secretary of Defense
Washington, D.C. 20301
ATTN: Office Assistant Director
(Research)	1	National Oceanographic Data
Center
National Oceanic & Atmospheric
Administration
3300 Whitehaven St., N.W.
Washington, D.C. 20235
	Office of Naval Research
Arlington, VA 22217	12	Defense Documentation
Center
Cameron Station
Alexandria, VA 22314
1	ATTN: (Code 460)		Commander
Naval Oceanographic
Office
Washington, D.C. 20373
1	ATTN: (Code 102-OS)	1	ATTN: Code 1640
6	ATTN: (Code 102IP)	1	ATTN: Code 70
1	ATTN: (Code 200)		
1	CDR J. C. Harlett, (USN)
ONR Representative
Woods Hole Oceanographic Inst.
Woods Hole, MA 02543	3	NORDA 430
NSTL Station, MS 39529
1	Office of Naval Research
Branch Office
495 Summer Street
Boston, MA 02210	2	CO NORDA
NSTL Station, MS 39529
	Director
Naval Research Laboratory
Washington, D.C. 20375		
6	ATTN: Library, Code 2620		

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER WHOI-78-3	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ON THE DEEP GENERAL CIRCULATION IN THE WESTERN NORTH ATLANTIC		5. TYPE OF REPORT & PERIOD COVERED Technical
7. AUTHOR(s) William J. Schmitz, Jr.		6. PERFORMING ORG. REPORT NUMBER WHOI CON. NO. 3779
9. PERFORMING ORGANIZATION NAME AND ADDRESS Woods Hole Oceanographic Institution Woods Hole, MA 02543		8. CONTRACT OR GRANT NUMBER(s) N00014-66-C-0241; N00014-74-C-0262; OCE75-03962
11. CONTROLLING OFFICE NAME AND ADDRESS NORDA National Space Technology Laboratory Bay St. Louis, MS 39529		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 083-004
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE April 1978
		13. NUMBER OF PAGES
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Reprinted from "Journal of Marine Research, Volume 35, 1, 1977".		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) 1. Deep general circulation 2. Western North Atlantic 3. Mesoscale eddies		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Very large (5-10 cm s ⁻¹) long-term averaged zonal flows have been observed near 4000 m depth in the vicinity of a recently hypothesized (Worthington, in press) horizontally restricted subtropical gyre in the deep western North Atlantic. The Reynolds stresses associated with low frequency fluctuations may play a significant role in the dynamics of this deep mean flow, possibly inducing a significant downstream increase in transport of the Gulf Stream, perhaps driving the deep gyre.