type of structure (*1*), in which the sulfur atoms approximate the face-centered cubic packing: $a' = a\sqrt{2} = 5.197$ Å $\approx c = 5.035$ Å. The iron atoms, which occupy layers of adjacent tetrahedral holes at distances of 2.60 Å, make close contact with one another as well as with sulfur. The excess iron ($x = 0.05$ to 0.06) occupies the remaining unused tetrahedral holes randomly (*5*).

In cubic FeS the sulfur atoms are arranged on the nodes of a face-centered cubic lattice; one-half of the tetrahedral holes are occupied by the iron atoms. The lattice parameter is only 4.3 percent greater than the a' value of the tetragonal sulfide. Thus, the similarity in atomic arrangement and in lattice parameters facilitates the epitaxial nucleation and growth of cubic FeS.

Although hexagonal FeS is a more stable phase (*6*), it appears as a corrosion product long after cubic FeS, because its growth requires a reconstructive transformation of the tetragonal sulfide. There are some major differences between hexagonal FeS and the cubic and tetragonal structures: the iron atoms occupy all of the octahedral holes of the hexagonal closest packing of sulfur and form trigonal-prismatic clusters.

Interatomic distance $Fe(II)_{tetrahedral}$–S in cubic FeS, 2.348 Å, is in good agreement with the other known values: 2.36 Å in stannite, Cu_2FeSnS_4; 2.33 Å in $FeCr_2S_4$; 2.36 Å in $FeLu_2S_4$; and 2.38 Å in $FeYb_2S_4$ (*7*). According to Pauling (*8*), the tetrahedral covalent radius of sulfur is 1.04 Å; by subtraction of this value from the Fe–S distance, the value 1.31 Å for the tetrahedral covalent radius of iron(II) in sulfides is obtained.

It is clear that in the first structure determination the interatomic distance Fe–S in tetragonal $Fe_{1+x}S$ was not known with precision, because the sulfur coordinate $z(S)$ was assumed to be 0.25 (*1*). On the basis of more precise intensity measurements and calculations, I found that $z(S) = 0.28 \pm 0.01$ and Fe–S $= 2.32 \pm 0.02$ Å. The covalent radii for this compound are 1.30 Å for iron (half the interatomic Fe–Fe distance) and 1.02 ± 0.02 Å for sulfur, in good agreement with the previously calculated values.

RINALDO DE MÉDICIS
Department of Chemistry,
University of Sherbrooke,
Sherbrooke, Quebec, Canada

References and Notes

1. R. A. Berner, *Science* **137**, 669 (1962).
2. ———, *J. Geol.* **72**, 293 (1964).
3. Dr. B. J. Skinner has communicated to me recently that he and Dr. R. A. Berner have already observed this phase with $a = 5.426$ Å (unpublished result). I have just received the announcement of an article by S. Takeno, H. Zôka, and T. Niihara, to be published in *Amer. Mineral.*, in which this phase is reported to have a value of $a = 5.417 \pm 0.004$ Å.
4. P. B. Barton and P. Toulmin, *Econ. Geol.* **61**, 815 (1966).
5. The excess iron must occupy tetrahedral holes and not octahedral ones, as assumed by G. Hägg and A. L. Kindström [*Z. Phys. Chem. Abt. B* **22**, 453 (1933)] for tetragonal $Fe_{1+x}Se$, because the octahedral holes are too near to the occupied tetrahedral holes, 2.23 Å, as compared with the following distances: Fe–empty tetrahedral holes, 2.52 Å; Fe–Fe in $Fe_{1+x}S$, 2.600 Å; Fe–Fe in metal, 2.483 Å. This occupation of tetrahedral roles is also confirmed by intensity calculations.
6. R. A. Berner, *Amer. J. Sci.* **265**, 773 (1967).
7. L. O. Brockway, *Z. Kristallogr. Kristallgeometrie, Kristallphys. Kristallchem.* **89**, 434 (1934); P. M. Raccah, R. J. Bouchard, A. Wold, *J. Appl. Phys.* **37**, 1436 (1966); M. Patrie, J. Flahaut, L. Domange, *C.R. Hebd. Séances Acad. Sci. Paris* **258**, 2585 (1964).
8. L. Pauling, *The Nature of the Chemical Bond* (Cornell Univ. Press, Ithaca, N.Y., ed. 3, 1960), p. 246.
9. Supported by the National Research Council of Canada.

21 April 1970; revised 12 October 1970

Bottom Velocity Observations Directly under the Gulf Stream

Abstract. *Speeds as high as 44 centimeters per second were observed 200 meters above the ocean bottom under the Gulf Stream at 70°W longitude and were associated with time-dependent motion that had a speed range of 40 centimeters per second and a time scale of about 30 days. These deep current fluctuations appear to be coupled with fluctuations in the surface position of the Stream and with surface and bottom current fluctuations 200 kilometers to the north.*

Two-month records of the bottom velocity directly under the Gulf Stream have been obtained from current meters moored 35 km apart. The records are very similar and exhibit large speed variations; a fluctuation of 40 cm/sec occurred on a time scale of about 30 days. The mean velocity components were 2 and 10 cm/sec in the eastward and northward directions. Both near-surface and near-bottom currents from moorings located about 200 km north of the position of the Stream axis show variability somewhat similar to that observed near the bottom under the Gulf Stream, with amplitudes reduced by a factor of 2 to 5. A current meter record of short duration from a bottom mooring located under the inshore edge of the Stream showed a similar reduction in amplitude. Measurements were simultaneously obtained of the varying position of the surface Gulf Stream as inferred from the surface and near-surface temperature structure. A comparison of the surface and bottom variability is of great interest, although the physical interpretation of the speeds obtained from the movement of near-surface features is moot (see below), and the horizontal as well as vertical separation of the measurements must be kept in mind. The north-south variability in path and in near-bottom currents was essentially in the same direction at nearby times on similar time scales; the amplitudes of the speed fluctuations as inferred from variations in path position are at least a factor of 2 smaller than near-bottom speed amplitudes. The time-averaged orientation of the surface Stream path was almost due east; the near-bottom current directions were normally in the same quadrant as the orientation of the surface path, but with a time lag and with directions offshore (onshore) of the surface path for offshore (onshore) path orientation.

Observations of the path and structure of the Gulf Stream from 75° to 60°W were completed in May to July 1969 as a cooperative effort among several groups (at Harvard University, the Naval Oceanographic Office, the Naval Research Laboratory, and the Woods Hole Oceanographic Institution). This program of observations included measurements of the position of the surface temperature gradient (an indicator for the location of the Stream, hereafter denoted by ΔT_S) as determined by airborne radiation thermometry (20 flights); repetitive tracking (from the R.V. *Chain*) of the position of the 15°C isotherm at 200 m (the standard indicator for the Stream location, hereafter denoted T_{15}) between 71° and 69°W with a final track from 69° to 64° (in addition, a hydrographic section was taken and drogues were tracked); four current meters, one on each of four moorings, were set for 2 months along 70°W near the bottom under the Stream. This program of observations is unique in its diversity, simultaneity, duration, and sampling rate. The composite experiment was designed to study the time dependence of meander scale phenomena in one region of the Gulf Stream and to obtain the variety of data necessary to test theoretical models of meandering at their present stage of development (*1*). The relationship of the totality of these data to prevailing theory, and more detailed discussion of the various types of data, will be presented at a later date. The purpose of this report is to make known some of the more prominent features of the observed near-bottom currents, their relationship to the Stream position at 70°W, and their relationship to currents observed at locations away from the immediate vicinity of the Stream.

Long time series of measurements of near-bottom currents at locations known to be under (or with known relation to) the (varying) position of the Stream have not been obtained previously. Short series of Swallow-float trajectories have been obtained at middepths (*2*). These data, in conjunction

Table 1. Location and duration of current meter records.

Current meter record No.	Latitude (N)	Longitude (W)	Depth (m)	Bottom depth (m)	Approximate duration (days)
3041	36°23.4′	70°00.4′	4286	4486	60
3051	36°43.0′	70°00.4′	4226	4426	60
3061	37°01.1′	70°00.3′	4168	4368	Flooded
3071	37°20.0′	70°00.0′	4081	4281	17
3021	39°05.9′	69°59.5′	2585	2685	125
3096	39°09.0′	70°00.2′	108	2678	60

with estimates of vertical shear based on geostrophic calculations with hydrographic station data, indicate that currents penetrate to the bottom under portions of the Gulf Stream. Knauss (*3*) reported one short-term (about 20-hour) estimate from a current meter moored 3.5 m above the bottom under the Stream, approximately 60 nautical miles (111 km) downstream from Cape Hatteras. Observed velocities were about 10 cm/sec in the direction of the surface currents.

The recent moorings were set on 12 June 1969 in a north-south line along 70°W with 35-km spacing (nominal): one approximately under T_{15}, one to the north, and two to the south. The geographic positions are listed in Table 1 (records 3041, 3051, 3061, and 3071). The current meters were placed 200 m above the bottom; the "bottom" velocities in the nonviscous meandering models refer to velocities outside any type of boundary layer. Aircraft path determinations began on 26 May 1969 and continued while the meters were moored until the surface temperature gradient faded; the sampling interval was conditioned by practical constraints but was planned to be short compared with anticipated fluctuation time scales. Between 4 and 17 July, the R.V. *Chain* made repetitive tracks between 69° and 71°W following T_{15}.

All the moorings that were set were recovered. The current meter on mooring 306 had flooded, owing to a pinched

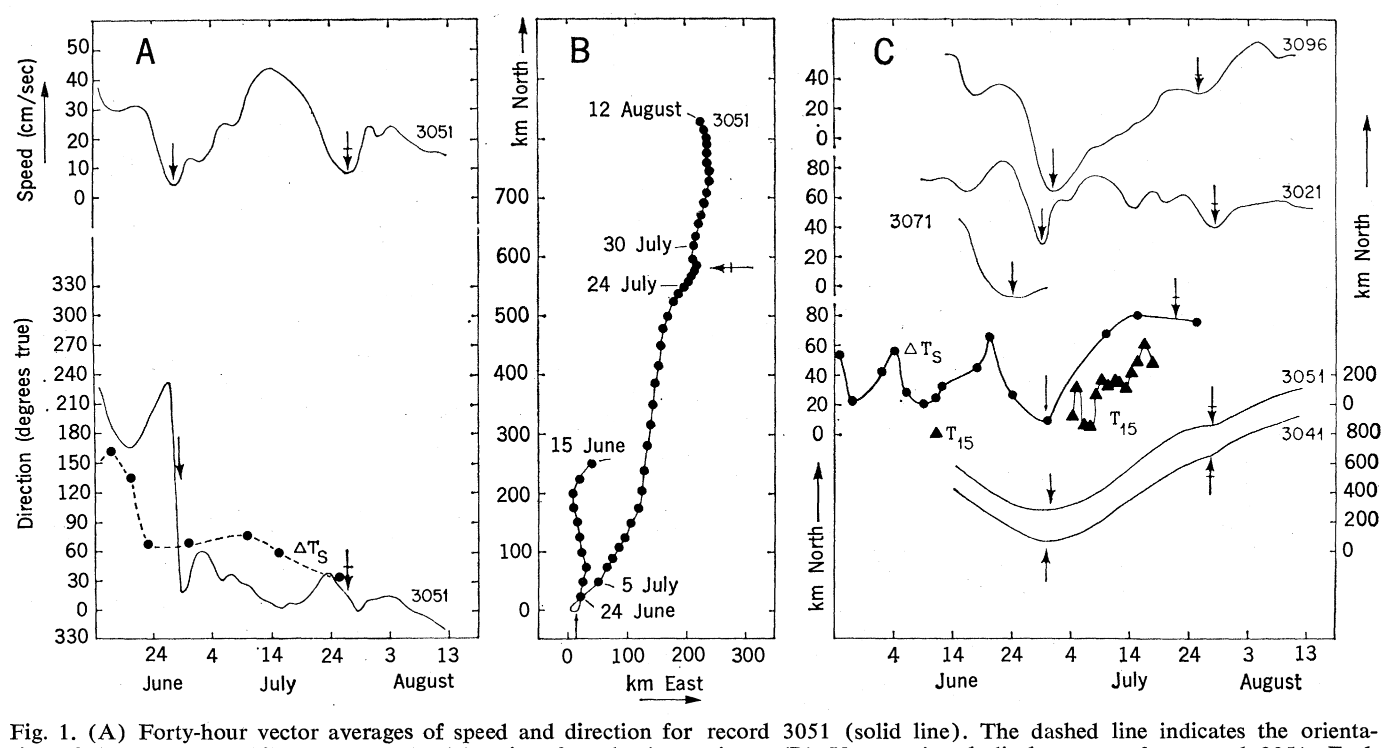

Fig. 1. (A) Forty-hour vector averages of speed and direction for record 3051 (solid line). The dashed line indicates the orientation of the stream at 70°W, as determined by aircraft path observations. (B) Vector virtual displacements for record 3051. Each circle denotes 1 day. (C) The north-south displacement component versus date for all records, as indicated by record number or identifying symbol (see Table 1 and text). The location of the records on this plot are in approximate north-south perspective with respect to locations at which data were obtained. The perspective is to true scale for the positions of surface temperature gradient (T_S) and 15-degree isotherm at 200 m (T_{15}) only. The ordinate scale for records 3041 and 3051 is on the right; for the other records the ordinate scale is on the left.

O ring. A switch failed after 17 days of recording in the current meter on mooring 307. The duration of good data for each record is listed in Table 1. [See (*4*) for a discussion of sampling and processing techniques.]

In addition to data from the current meters moored under the Stream, records are available from a long-term station (known as site D) located 200 to 300 km north of the Stream. Data from records 3021 and 3096 (see Table 1) will be used to investigate the relationship between meanders and associated motions away from the immediate vicinity of the Stream (*5*).

Records 3051 and 3041 are known to have been taken under the Gulf Stream. In Fig. 1A, 40-hour vector averages of speed and direction from record 3051 are plotted versus date. The minimum speed is 4 cm/sec, and the maximum is 44 cm/sec. The maximum speed of 44 cm/sec is associated with a low-frequency fluctuation; the mean speed for record 3051 is 23 cm/sec and the magnitude of the mean velocity is 11 cm/sec [the specification of a mean value for these records, even though comparatively long, should be accompanied by a cautionary statement: the averaging duration is neither commensurable with nor long compared with the fluctuation time scale(s)]. In any event, the fluctuation amplitude is of at least the same order as any reasonable mean. There is an abrupt direction shift of about 180 degrees associated with the first speed minimum toward the end of June. There is a change in direction associated with the second speed minimum in Fig. 1A, but it is much smaller and less abrupt than the first shift. For later comparison, the approximate times of the speed minima and direction shifts in record 3051 have been marked with arrows. These general features are also characteristic of record 3041, which is almost identical to record 3051.

In order to compare fluctuations in Stream path as determined by near-surface indicators with the observed near-bottom currents, we integrate the current meter velocities with time and compare the resulting north-south component of "virtual" displacement with the north-south variation in position for the upper-level path indicators along 70°W. "Virtual" displacements would be particle paths in the absence of shear. Figure 1B is an example of a vector displacement, plotted for record 3051 at equal time intervals of 1 day.

Considerable care must be exercised in the comparison of variations in the bottom virtual displacements with variations in the near-surface indicator positions, primarily because of the ambiguity inherent in the interpretation of the latter quantities. The current meters measure Eulerian velocities, which contain both the velocities associated with the mean Gulf Stream profile and the velocities of the meandering of the Stream, if such a decomposition be meaningful. A surface drogue launched over T_{15} remains over T_{15} when tracked for several degrees of longitude; in this sense T_{15} is an indication of the near-surface velocity axis. It should also be noted that the two types of data were taken at a varying horizontal separation. The problem of interpretation of the near-surface data will not be further pursued here. Rather we ask the reader to exercise his discretion in the following comparisons.

The predominant north-south variability in surface path and near-bottom virtual displacements (see Fig. 1C) are in essentially the same direction at similar times on about the same time scales; however, the near-bottom displacement range is larger by a factor of about 10. Corresponding speed amplitudes (slopes of the trajectories) are at least a factor of 2 larger for the near-bottom data. Estimates from aircraft data of the orientation of the Stream at 70°W are plotted in Fig. 1A for the paths determined during the duration of record 3051. The Stream orientation changes from southeast to northeast a few days before the large direction shifts in the current meter records near the end of June.

For the 2-week period during which positions of T_{15} and ΔT_S were obtained, the general trend of the Stream position is consistent for both path indicators. The T_{15} data exhibit variability of higher frequency than do the ΔT_S data, but the sampling interval of several days for ΔT_S precludes a comparison.

The north-south displacement component for the current meters north of the Stream has also been plotted in Fig. 1C; these records exhibit variability with amplitudes and time scales similar to that of the near-surface indicators (*6*). A direction shift near the end of June (marked with an arrow) is present in all the records displayed. The date of the second speed minimum in records 3051 and 3041 is denoted by an arrow with a slash. Although well defined in the speed records, this second event is barely discernible on the north-south plots for records 3051 and 3041. A dip in the other records at nearby times may indicate the appearance of the same event.

Theoretical models of Gulf Stream meandering that include the process of topographic meandering in vertically integrated equations assume a coherent stream structure in depth. The comparisons of near-surface and near-bottom measurements presented here lend credence to that approach, but the structure of the fluctuations needs considerably more resolution. Although it has been demonstrated that all meanders are not predominantly topographic (*7*), vortex line stretching due to depth variations is an important contribution to the vorticity balance. A preliminary analysis of the data from this cruise (*1*) indicated that transient contributions to the vorticity balance are of the same order of magnitude as the contributions from the term included in the quasi-steady theory. In addition to the time-dependent effects that occur in an integrated theory (*1*), direct baroclinic processes isolated in the study of free baroclinic topographic (*8*) and unstable (*9*) waves may be of fundamental importance in the meandering phenomenon.

WILLIAM J. SCHMITZ, JR.
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

A. R. ROBINSON
Pierce Hall, Harvard University, Cambridge, Massachusetts 02138

F. C. FUGLISTER
Woods Hole Oceanographic Institution

References and Notes

1. A. R. Robinson and S. Gadgil, *Geophys. Fluid Dyn.*, in press.
2. B. A. Warren and G. H. Volkmann, *J. Mar. Res.* **26**, 110 (1968).
3. J. A. Knauss, *ibid.* **22**, 237 (1965).
4. F. Webster, *Deep-Sea Res.* **16**, 85 (1969).
5. The other current meters on mooring 309 were located between meter 3096 and the sea surface as part of an effort to study higher-frequency near-surface fluctuations in detail.
6. Similar behavior was inferred from the data previously available by D. V. Hansen [*ESSA Tech. Rep. ERL 164-AOML1* (1970)].
7. P. P. Niiler and A. R. Robinson, *Tellus* **19**, 601 (1967).
8. P. Rhines, *Geophys. Fluid Dyn.* **1**, 273 (1970).
9. I. Orlanski, *J. Atmos. Sci.* **26**, 1216 (1969).
10. Support for this work was provided by the Office of Naval Research. Contribution 2542 of the Woods Hole Oceanographic Institution.

19 August 1970