North Atlantic Subtropical Gyre: SOFAR Floats Tracked by Moored Listening Stations
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Reports

North Atlantic Subtropical Gyre: SOFAR Floats Tracked by Moored Listening Stations

Abstract. *In 1980, SOFAR (sound fixing and ranging) floats were tracked acoustically in the western North Atlantic entirely by means of moored autonomous listening stations. During a 5-month period 17 float trajectories were obtained in the eastern (45° to 65°W) Gulf Stream and subtropical gyre interior at depths of 700 and 2000 meters. These mid-depth trajectories suggest a time-varying Gulf Stream with instances of both a narrow, swift, westward recirculation south of the stream and a northeastward penetration into the Newfoundland Basin. A hundredfold increase of eddy kinetic energy was observed at 2000 meters from the gyre interior (south of 30°N) to the Gulf Stream.*

During the last decade SOFAR (sound fixing and ranging) floats were tracked in the western North Atlantic by means of shore-based listening stations (*1*), but the geographical coverage of these stations was limited and many of them no longer exist. In 1980 for the first time SOFAR floats were remotely tracked entirely by means of an array of moored autonomous listening stations (ALS's) (*2*). With the ALS's it is possible to track SOFAR floats anywhere in the oceans where a deep sound channel allows long-range acoustic propagation. The SOFAR floats passively follow the horizontal circulation at a preset depth and thus describe nearly the same trajectories as the water itself. This new system has great potential for the study of ocean circulation as well as for the study of the dispersion and advection of water properties by means of Lagrangian techniques (*3*). We present here a description of the 1980 SOFAR float experiment and its first results. Our main scientific achievement is the first measurement of ocean trajectories at mid-depths in the eastern Gulf Stream region, an area vital to the understanding of the Atlantic Ocean circulation and its variability. We found a strong northward increase in eddy kinetic energy toward the Gulf Stream, evidence that the Gulf Stream can flow into the Newfoundland Basin, and found the Gulf Stream recirculation flowing swiftly to the west.

During April 1980, 19 floats were launched along a meridional line (55°W) extending from the slope water region north of the Gulf Stream down to the interior of the subtropical gyre near 24°N (Fig. 1). An array of six ALS's was deployed during April and recovered (and replaced) in October 1980 (Fig. 2). Despite the loss of two ALS records, there was sufficient redundancy in the ALS net so that all 17 of the floats that operated correctly were successfully tracked.

A striking result is the clear depiction of the northward increase in mean and eddy kinetic energy toward the Gulf Stream (Fig. 2b). At 2000 m, the eddy kinetic energy increases from 1.5 cm^2/sec^2 in the subtropical gyre interior south of 30°N (floats 9D and 10D) to 140 cm^2/sec^2 near the Gulf Stream axis at 40°N (floats 2D, 3D, and 4D). Kinetic energy also increases toward the sea surface (Fig. 2a). The 700-m floats are nearly twice as energetic as the deep ones in the Gulf Stream (243 cm^2/sec^2) and 12 times as energetic in the south (17 cm^2/sec^2). The kinetic energy distribution as determined from the floats is consistent with the distribution computed from moored current meters along 55°W (*4*).

Two distinct varieties of eddies (inferred from closed loops) contributed to the eddy kinetic energy (Fig. 2a). Beginning in June, float 4S was trapped for 4 months in a cold core Gulf Stream ring that had just pinched off from the stream near 38°N, 50°W. Float 4S made 12 counterclockwise loops with periods of from 4 to 20 days and diameters of from 10 to 200 km as the ring moved southward at 2 cm/sec. An energetic clockwise rotating eddy is apparent in the trajectory of float 7S, which was trapped for over 4 months. This eddy, which was observed from conductivity-temperature profiles to have a deep (> 2000 m) warm core, translated westward along 33°N with a mean speed of 4 cm/sec. [Two similar clockwise rotating eddies which propagated westward were observed in this region with surface buoys (*5*)]. The average period of the loops was 18 days, and the average diameter was approximately 100 km. The second loop was coherent with a loop of float 6D; this finding indicates that the eddy's circulation penetrated to at least 2000 m, although the 2000-m mean speed in the loop (9 cm/sec) was much less than the speed at 700 m (25 cm/sec). The trajectory of float 5D over a 2-month period also seems consistent with the motion of this translating eddy and its deep circulation.

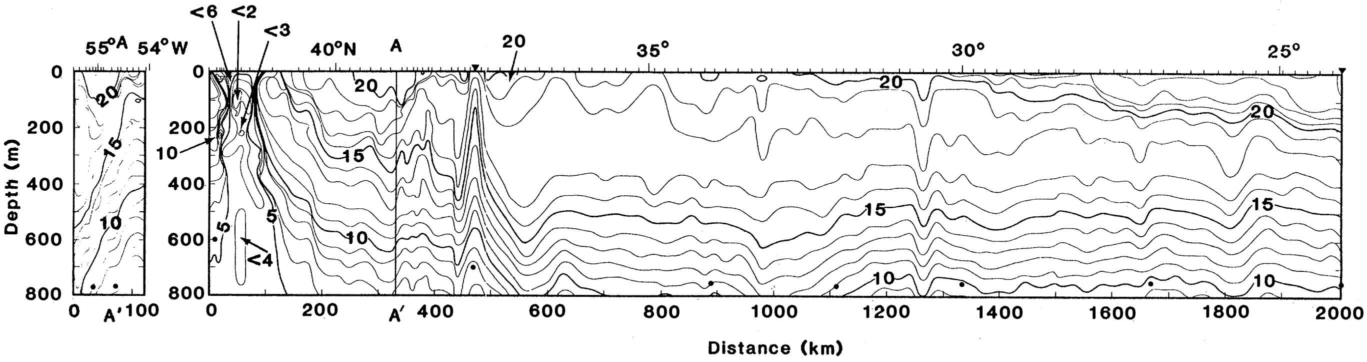

Fig. 1. North-south temperature section along 55°W, 28 April to 4 May 1980. Dots show the launch locations of shallow SOFAR floats; triangles show the locations of surface drifters. The Gulf Stream was running south parallel to the section from 41° to 38°N. A short east-west section (*A*–*A'*) normal to the stream is shown on the left. A cold core ring was attached to the southern side of the stream near 37.5°N, and a warm eddy was located near 33°N. Cold, fresh (1.91°C; salinity, 33.67 per mil at 110 m) Labrador Current water was found on the northern edge of the stream near 41.5°N.

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A second result is the Lagrangian picture of the complex and time-variable motion in the Gulf Stream system. Individual trajectories support both a tight westward recirculation immediately south of the stream (floats 3S and 8S) and a stream that (at times) branches into the Newfoundland Basin (float 1S). A point of controversy has been whether a branch of the Gulf Stream flows around the Grand Banks into the Newfoundland Basin (*6*). We have found that the northward flow exists, but it is intermittent.

Three sets of floats (floats 2, 3, and 4) and a surface drifter were launched directly into the Gulf Stream as it meandered south along 55°W (Fig. 1). During the first 2 weeks, all of the floats moved coherently in the meander. The pattern of the 700-m floats showed that the Gulf Stream meandered northward along 52° to 53°W and then south along 50°W where two floats (3S and 4S) reached their eastern limit and began to drift westward. The surface drifter also followed this pattern to 50°W but continued eastward, as have numerous others (*7*), and crossed 45°W near 37°N. Float 3S moved westward in the recirculation toward the New England Seamount chain. Float 4S became trapped in a cold core ring which drifted southward. Float 2S moved due north out of the meander and into the slope water region to 44°N. Almost from the start, the 2000-m floats (2D, 3D, and 4D) set in the stream diverged widely; their trajectories give no obvious indication of a continuous subthermocline Gulf Stream jet. Float 4D moved northward into the slope region, float 3D moved northeastward toward the Newfoundland Basin, and float 2D moved northwestward, passing 50 km southwest of float 1S as it moved southeastward.

One can determine the time variability of the Gulf Stream by contrasting these 700-m trajectories with that of float 1S, which moved eastward across 55°W 40 days after the other Gulf Stream floats were launched there. Float 1S cut across the locations of the earlier meanders (both of which had formed cold core rings, one near 54°W and one near 50°W) and continued eastward around the Grand Banks into the Newfoundland Basin. Thus, only one of the four 700-m floats launched in or near the Gulf Stream penetrated eastward a substantial distance.

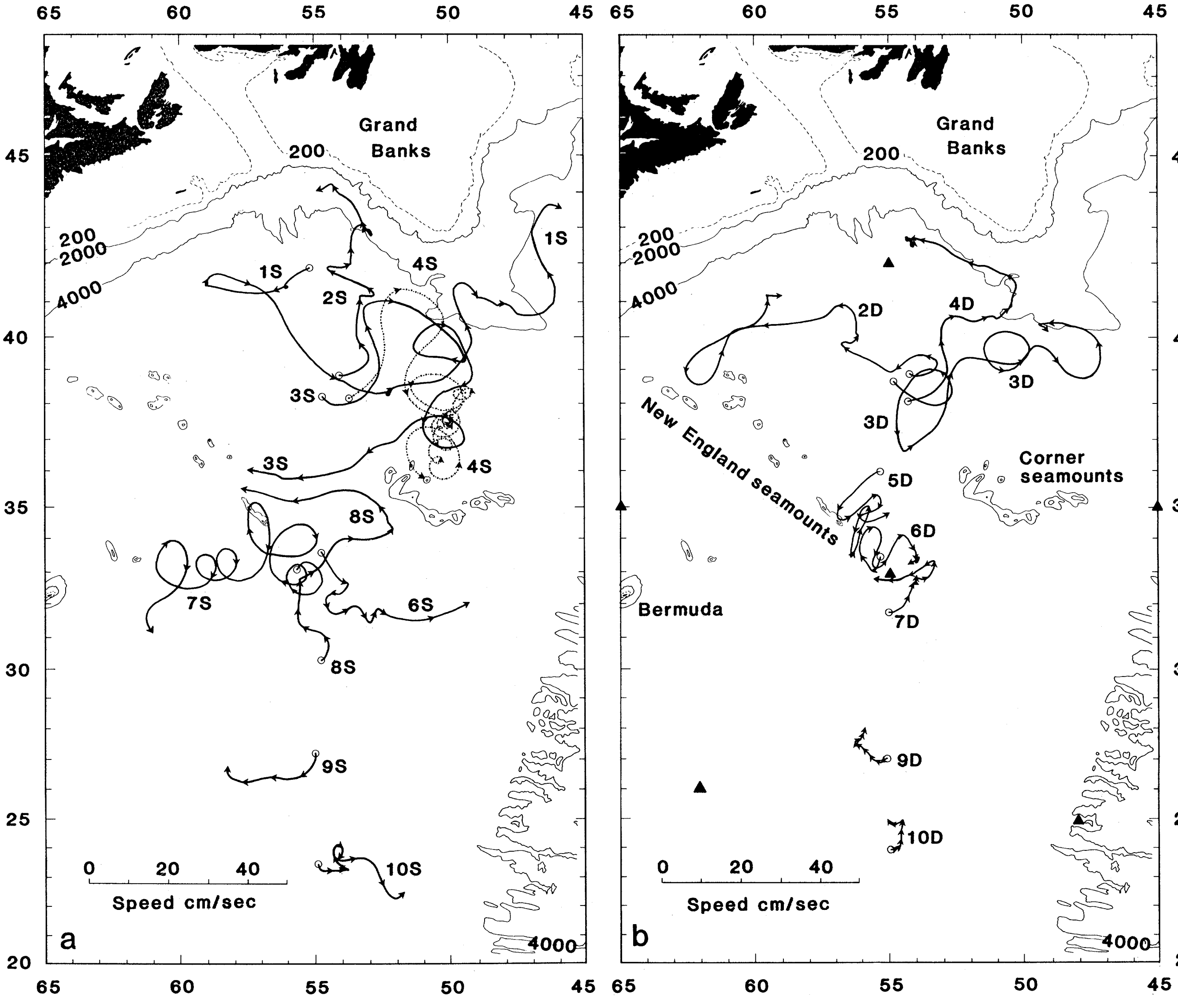

Fig. 2. Trajectories of SOFAR floats at nominal depths of (a) 700 and (b) 2000 m for the period 7 May to 4 October 1980. Floats are numbered from north to south, with *S* indicating shallow and *D* deep. Three sets of floats (floats 2, 3, and 4) were launched in the Gulf Stream near 38° to 39°N. The speed between arrowheads, which are spaced at 15-day intervals, can be obtained from the scale at the lower left. Triangles show the locations of ALS's, which were used to track the floats. The frequent occurrence of trajectories that cross each other is evidence of the time dependence of the flow.

The recirculation was recorded by two 700-m floats (3S and 8S), which moved coherently westward between 35° and 36°N; these float tracks give a clear, synoptic view of this current. These two floats moved westward side by side for 30 days with mean speeds of 16 and 18 cm/sec and a characteristic separation of 70 km. Their daily speeds peaked near 30 cm/sec as the floats crossed 54°W. The recirculation observed here is in remarkable agreement with its mean location and speed as determined by long-term moored current meters (*8*); the floats may have given a Lagrangian determination of the intense (nearly barotropic) bursts in westward velocity recorded by current meters.

South of the Gulf Stream the tracks of the 700-m floats suggest a predominantly zonal mean flow, except for float 8S which initially went northward. The motion was eastward between 22° and 24°N (2.7 cm/sec) and at 31° to 34°N (4.2 cm/sec); it was westward at 26° to 27°N (5.1 cm/sec), in the warm core eddy near 33°N (3.2 cm/sec), and in the recirculation jet between 35° and 36°N (17 cm/sec).

The southern 2000-m trajectories (floats 9D and 10D) had a weak mean north-to-northwest velocity of about 0.8 cm/sec, in agreement with the current meter velocities at 1500 m from POLYMODE array III-A at 27°N, 48°W (*9*) and POLYMODE array II at 35°N, 55°W (*8*). The low level of eddy kinetic energy and the agreement with the results derived from current meters suggest that the long-term mean flow might already be emerging from these southern deep trajectories.

These first 5-month-long trajectories are just beginning to reveal the complex Lagrangian general circulation and eddy field of the North Atlantic subtropical gyre. During the next 2 years as these and other new floats continue their drift, we expect to acquire a more than tenfold increase in data and a sharper, more quantitative picture of the currents.

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2. These SOFAR floats transmit three 250-Hz acoustic signals per day. The signals travel horizontally along the deep sound channel, a layer of minimum sound speed lying near a depth of 1200 m in the western Atlantic. The ALS's, which are moored in the sound channel, record the times of arrivals and the amplitudes of the four largest signals in each 10-minute window. Float positions are obtained by triangulation, using the time differences between signal arrivals at three ALS's. In practice, the continuous track of a float is obtained by using the distance from each of two ALS's.
3. A SOFAR float is really a quasi-Lagrangian device since it moves along a nearly isobaric surface. A float trajectory may differ from a water parcel trajectory where strong vertical shear and vertical motion occur together.
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Thermal Tides in the Dusty Martian Atmosphere: A Verification of Theory

Abstract. *Major features of the daily surface pressure oscillations observed by the Viking landers during the two great dust storms on Mars in 1977 can be explained in terms of the classical atmospheric tidal theory developed for the earth's atmosphere. The most dramatic exception is the virtual disappearance of only the diurnal tide at Viking Lander 1 just before the second storm. This disappearance is attributed to destructive interference between the usually westward-traveling tide and an eastward-traveling diurnal Kelvin mode generated by orographically induced differential heating. The continuing Viking Lander 1 pressure measurements can be used with the model to monitor future great dust storms.*

The dynamic variability of the daily oscillation of surface pressure on Mars during two great dust storms has been analyzed (*1*) in terms of composite tidal harmonics determined from meteorological measurements by Viking Lander 1 (VL1; 22.5°N, 48°W) and Viking Lander 2 (VL2; 48°N, 226°W). An atmospheric tidal model was constructed (*2*) to compute the thermal tidal forcing of a dusty martian atmosphere and the resultant surface pressure oscillations at the lander sites. This report presents a detailed comparison between the model simulations and observational data for the first four tidal harmonics observed during two great dust storms on Mars in 1977.

The solar heating of a dusty atmosphere is calculated with a delta-Eddington approximation to the radiative flux transfer equations. The martian airborne dust is assumed to be uniformly mixed horizontally and vertically up to several scale heights. The atmospheric tidal model is based on the inviscid primitive equations linearized about a motionless, stably stratified basic state. The model does not include effects due to variable terrain. The lower atmosphere is taken to be isothermal (210 K), with a less stably stratified zone at the top of the dust haze near 55 km surmounted by a colder, isothermal basic state (151 K). The dust particles are characterized by a single scattering albedo of $\omega_0 = 0.86$ and a phase function asymmetry parameter $g_a = 0.79$ during the decay phases of the great dust storms (*3, 4*). Comparisons between the tidal model results and the observed amplitude of the diurnal surface pressure oscillation at VL1 indicate that, during storm onset, the solar heating is concentrated away from the surface; for those periods we use $g_a = 0.5$ (*2*).

The remaining free parameter is the vertical extinction optical depth (at visible wavelengths) τ_0 of the global dust haze. The variation of τ_0 during the 1977 period of storms is determined by choosing that sequence of optical depths for which the model reproduces amplitudes defining the observed variation of the semidiurnal surface pressure oscillation at VL1. This criterion was suggested by the close correspondence between the changing amplitude of the VL1 semidiurnal amplitude and the local overhead opacity determined from the VL1 imaging data (*5*). While comparable to the VL1 opacities (Fig. 1, lower left), the opacities derived with the model charac-

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