which, although stable against AF demagnetization, is thermally unstable. Natural remanent magnetization blocked below the collection temperature would be indicative of contamination acquired since the sample was picked up from the lunar surface and blocked during subsequent field cooling, wherever that may have taken place. The possibility that the soil carries NRM may be of interest in stratigraphic studies aimed at understanding soil dynamics. It also provides a mechanism for the generation of NRM on the moon, other than at the times of formation of the crystalline rocks and breccias. This magnetization may contribute to the surface fields observed by the astronauts using the surface magnetometers. It is hoped that measurements of the NRM of the soil may eventually be made on returned core tube material, so that we may see if it is greater than can be accounted for by random moments.

M. FULLER

Department of Earth and Planetary Sciences, University of Pittsburgh, Pittsburgh, Pennsylvania 15213

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12. I thank W. A. Cassidy and A. A. de Gasparis of the Department of Earth and Planetary Sciences, University of Pittsburgh, for helpful discussions on the magnetization of regolith material and D. W. Strangway and G. W. Pearce of the Manned Spacecraft Center, Houston, Texas, for their help in trying to arrange a measurement of the NRM of a returned core tube sample. I am also grateful to J. R. Dunn for help with the experimental work and to T. Nagata and F. C. Schwerer, who established the basic magnetic characteristics of the soil samples.

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North Atlantic Ocean: Preliminary Description of Normal Modes

Abstract. *The three lowest gravitational modes of free oscillation of the North Atlantic Ocean are estimated by numerical integration of Laplace's tidal equations. These modes have periods of approximately 21, 14, and 11 hours, and structures, respectively, of one, two, and three positive amphidromic systems. The phase distribution of the first mode resembles cotidal charts of the diurnal tide, and the period of the second mode is consistent with that inferred by Wunsch from tidal data in Bermuda and the Azores.*

By a method described previously (*1*) it is now feasible to calculate two-dimensional normal modes of the major ocean basins. Preliminary results for the North Atlantic are shown in Fig. 1. They are based on a numerical integration in which the lateral boundary and bathymetry are resolved on a grid of 4° squares on a Mercator projection. The boundary is assumed to be totally reflecting. In particular, on the boundary between the North and South Atlantic oceans a zero elevation of sea level is prescribed; on all other boundaries there is zero volume transport. The Caribbean Sea and Gulf of Mexico are excluded, as are the Norwegian Sea and Baffin Bay. The model thus defined is designated "model 401."

Figure 1d shows the bathymetry (*2*) of model 401, the most conspicuous features of which are the two major deep-sea basins and the intervening ridge system. The broad-scale shelving northward of 50°N accounts for most of the generally larger amplitudes of all modes in that region.

The lowest gravitational mode in this

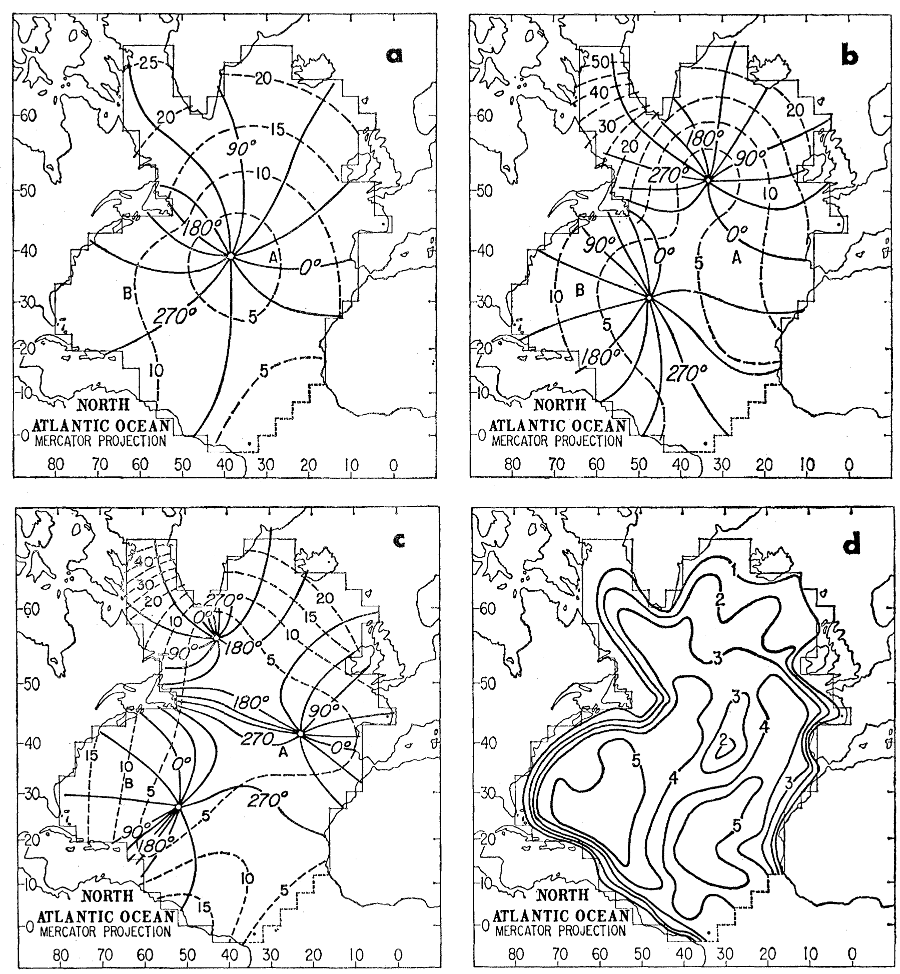

Fig. 1. (a to c) First, second, and third modes of free oscillation of the North Atlantic Ocean. The solid lines show the phase of maximum sea level in degrees (interval: 30°) referred to 0° at Lisbon; the broken lines show the amplitude of sea level normalized to root-mean-square 10 arbitrary units (interval: 5). (d) Bathymetry in kilometers.

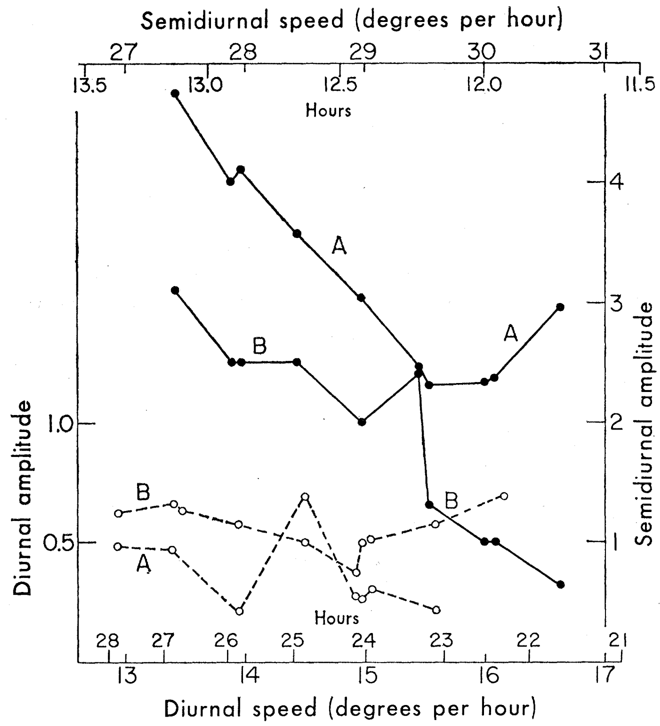

Fig. 2. Ratios of observed to local equilibrium amplitude of selected constituents of the semidiurnal tide (solid lines) and diurnal tide (broken lines) at a station in Bermuda (B) and one in the Azores (A). The constituents are ϵ_2, $2N_2$, μ_2, N_2, M_2, λ_2, L_2, S_2, K_2, η_2 and σ_1, Q_1, ρ_1, O_1, M_1, π_1, P_1, K_1, J_1, OO_1. From data given by Wunsch (5).

model has a period of 21.2 hours and a single positive amphidromic system (3) centered at 39°N, 38°W. The second mode has a period of 14.0 hours and two positive amphidromes, at 31°N, 48°W and at 52°N, 33°W. The period of the third mode is 11.5 hours; its amphidromes (all positive) are centered at 27°N, 52°W; at 42°N, 22°W; and at 56°N, 42°W. In the first mode the potential energy is 55 percent of the total energy, in the second it is 53 percent, and in the third 48 percent. Thus, all three are close to the equipartition characteristic of nonrotating basins (4).

Although these modes are well defined in calculations with model 401, the model is affected by computational approximations that could cause the computed periods to differ from the true periods by as much as 1.0 hour. Chief among these is truncation (discretization) error, caused by the coarseness of the grid. This reduces the number of degrees of freedom and so, by Rayleigh's principle, may be expected to diminish the period. Probably more important are the exclusion of adjacent seas, which increases the period, and especially the imposition of zero sea level on the boundary between the North and South Atlantic (which implies no disturbance in the South Atlantic). The latter condition is a constraint analogous to the clamping of a membrane, and therefore should diminish the period.

There seems little hope of detecting gravitational modes of oceanic scale by looking for spectral peaks in sea level at the modal frequencies, because their excitation by atmospheric transients is likely to be ineffectual owing to a mismatch of both space and time scales. On the other hand, as pointed out by Wunsch (5), the tidal force spans a fairly broad band of frequencies even within each species so that, by analyzing sea-level data for as many constituents as possible in the tidal bands, and then comparing observed and equilibrium amplitudes, one can deduce useful segments of the frequency response of the ocean, at least at the tide-gage location. Wunsch's results for a gage in Bermuda (8 years of record) and one in the Azores (5 years) are shown in Fig. 2. The strong indication of a resonance below the low-frequency end of the semidiurnal band is apparent in the amplitude at both locations (6). Wunsch estimated the resonance period to be 14.8 hours. In view of the uncertainties in this estimate and in the 14.0-hour period of model 401, the near-agreement of the two values is encouraging.

Wunsch also inferred a resonance at 9.3 hours on the basis of the terdiurnal constituent M_3. Calculations with model 401 have not yet come to that part of the spectrum, but the tidal response at Bermuda does not indicate the third mode of 11.5 hours found in model 401. At the Azores station there is an enhanced response of the fastest semidiurnal constituent, but inspection of Fig. 1 (where the two stations are marked A and B) reveals the proximity of the Azores to an amphidromic point in the third mode. Hence we should expect greater enhancement at Bermuda, in contradiction to Fig. 2. Thus, Wunsch's analysis does not appear to support the existence of the third mode.

At B there is a slight upswing of amplitude at the high-frequency end of the diurnal band, suggestive of the first-mode period of 21 hours, but the trend depends almost entirely on one weak line (OO_1). Somewhat better observational support for the first mode comes from the cotidal chart of the K_1 tide, inferred from coastal data (7). Like the 21-hour mode, K_1 has a single amphidromic system centered near the middle of the North Atlantic.

Despite the tentative nature of these preliminary results, the way seems open to a modal synthesis of the large-scale features of the ocean tide. Many difficulties remain to be overcome, such as the calculation of rotational modes and the inclusion of dissipation, but I believe the effort is worthwhile because it promises a hitherto inaccessible elucidation of tidal phenomena.

GEORGE W. PLATZMAN

Department of the Geophysical Sciences, University of Chicago, Chicago, Illinois 60637

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2. The depths used in this study were derived from values on 1° squares compiled on tape by S. M. Smith, H. W. Menard, and G. Sharman [*Scripps Inst. Oceanogr. Ref. 65-8* (1966)]. A copy of the tape was obtained from the National Oceanographic Data Center, Washington, D.C.
3. Owing mainly to Coriolis forces, a region of zero or small displacement of sea level is usually localized at a nodal point rather than along a nodal line, in slow oscillations of the type considered here. The crest of the wave rotates around such an amphidromic point and the amplitude increases with distance from it.
4. If the earth were not rotating, modes one and two would each have a single nodal line approximately bisecting the North Atlantic, in an orientation roughly northwest-southeast for the first mode and southwest-northeast for the second. Taking the Mid-Atlantic Ridge as the principal axis of the North Atlantic, we may refer to these modes respectively as the lowest longitudinal and transverse oscillations.
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6. Magnifications 4.8 at B and 6.5 at A are assigned by Wunsch to Doodson line 217, period 13.4 hours. Although it is consistent with the trend toward resonance, I have not included this line in Fig. 2 because its equilibrium coefficient is very small, 0.0011. A few diurnal lines used by Wunsch are omitted for the same reason. The most apparent anomalies of amplitude in Fig. 2 are in λ_2 at B, and O_1 or M_1 at A.
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8. Research supported by the Oceanography Section of the National Science Foundation under grant GA-15995. Programming was done by G. A. Curtis.

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