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.

P. L. RICHARDSON
J. F. PRICE
W. B. OWENS
W. J. SCHMITZ
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543
H. T. ROSSBY
Graduate School of Oceanography, University of Rhode Island, Kingston 02881
A. M. BRADLEY
J. R. VALDES
D. C. WEBB
Woods Hole Oceanographic Institution

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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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terize the global dust haze and are particularly valuable during the dustiest periods, when only lower bounds could be estimated from the VL1 imaging data (2).

Figure 1 (left half) compares the model-generated and the analyzed diurnal, terdiurnal, and quadridiurnal amplitudes and phases of the tidal surface pressure harmonics at VL1 for the 1977 period of storms. Comparison for the semidiurnal phase is also shown. (The VL1 semidiurnal amplitude is automatically reproduced by our choice of τ_0.) Considering that the model does not include differential (orographic) heating or dynamic coupling induced by the sizable martian relief (6, 7), the simulation is very good, even for the small-amplitude higher order tidal harmonics. There are three major exceptions to this general agreement: (i) the period near VL1 martian solar day 310, when the diurnal tide virtually vanished and went through a rapid change of phase; (ii) the increasing (with season) lag of the observed semidiurnal phase relative to the modeled phase; and (iii) the enhanced quadridiurnal amplitude during the second (1977b) great dust storm. This last discrepancy reflects the fact that the computed quadridiurnal component of the thermal forcing remains largely unchanged during the 1977b event, despite the large change in opacity of the global dust haze. The semidiurnal phase error may reflect the model's neglect of the viscous planetary boundary layer or of latitudinal variations in the atmosphere's basic state.

The virtual vanishing of only the diurnal component immediately before the 1977b storm also cannot be easily explained in the context of classical (that is, inviscid, linearized, separable, and nontopographic) tidal theory (8). This behavior may result from the sudden enhancement of a topographically induced, eastward-traveling diurnal tidal component that destructively interferes with the classical westward-traveling tide over the low-lying basins where the Viking landers are located (1). If only diurnal tides with longitudinal wave numbers $s = \pm 1$ were present, the amplitude of the composite diurnal tide

$$A(\lambda) = [a_E^2 + a_W^2 + 2a_E a_W \cos(2\lambda + P_W - P_E)]^{1/2}$$

would virtually vanish at VL1 ($\lambda = -48°$ east longitude) when the eastward and westward tides have comparable amplitudes ($a_E \approx a_W$) and the phase of westward component lags about one-quarter cycle behind that of the eastward tide ($P_E - P_W \approx 6$ hours). The model implies that $P_W \sim 18$ hours, so the optimum eastward phase is ~ 24 hours (midnight). Longitudinal variations of the martian terrain can produce a sizable eastward-traveling diurnal tide in one of three ways: (i) by dynamic coupling of the westward-traveling diurnal tide with the planetary-scale terrain variations, (ii) by strong modulation of the westward-traveling wave of solar heating, or (iii) by weak modulation of the thermal forcing and resonant enhancement of the subsequent tidal response. In any case, the eastward-traveling tidal mode most likely to appear is the diurnal Kelvin mode. Generation of this mode by topographically induced dynamic coupling would tend to produce an eastward-traveling pressure wave at the surface whose phase is much too early (7). Direct thermal forcing of this mode would yield the appropriate phase if that component of the thermal forcing were strongest over the martian highlands.

There are two obvious ways in which thermal forcing could have been enhanced over the highlands before the onset of the 1977b storm. As the dust opacity decreased to unity or smaller values at the end of the first (1977a) storm, heating of the atmosphere by the radiative-convective heat flux from the surface would have become important. This thermal forcing is stronger over high areas, since essentially the same amount of energy goes into heating less air mass. Alternatively, there may have been more airborne dust, and thus greater solar absorption, over the uplands. Many small dust storms were observed over the upland regions of Sinai and Solis Plana for several weeks preceding the 1977b event (9). Furthermore, an amplifying diurnal Kelvin mode and its associated wind field could have helped to raise dust above that same latitudinal zone (between 15° and 30°S), which historically is a region where the precursors of great (planetary-scale) dust storms originate.

The right half of Fig. 1 compares the observed tidal harmonics for VL2 to those computed with the classical atmospheric tidal model and the same g_a and τ_0 values inferred from the VL1 data. Usually the terdiurnal harmonic at VL2 is too small to be reliably determined. The amplitude of the quadridiurnal harmonic at VL2 is not much more reliable, but the failure of the model to reproduce its enhancement during the onset of the 1977b storm is similar to the result for the larger quadridiurnal amplitude at VL1. More significant is the considerable disagreement between the comput-

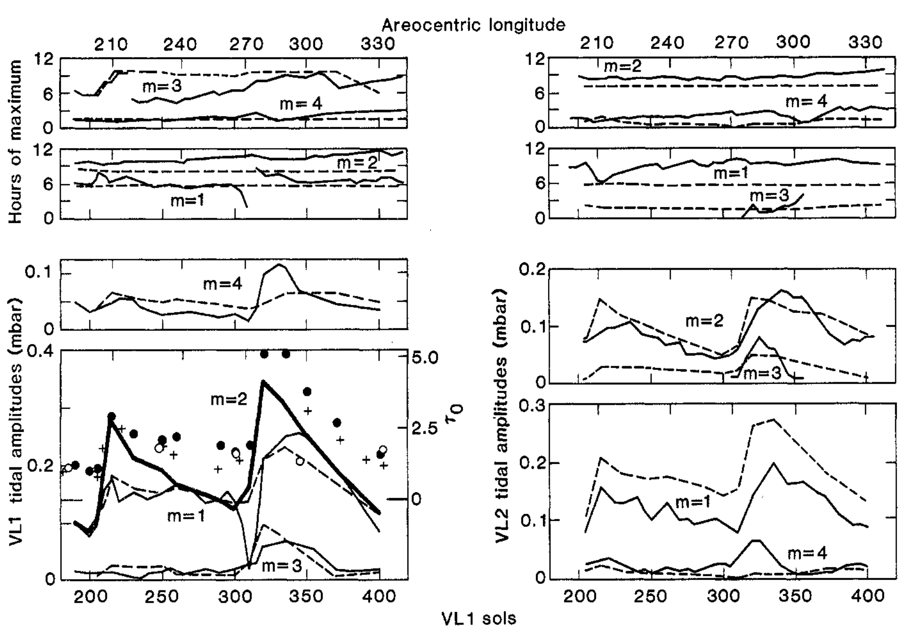

Fig. 1. Comparison of the observed (1) and model amplitudes (bottom) and times of maximum (top) of the surface pressure tidal harmonics derived for VL1 (left) and VL2 (right). By definition, 24 "hours" = 1 martian solar day (sol) = 1.027 Earth days. Noon = 12 hours. The diurnal, semidiurnal, terdiurnal, and quadridiurnal oscillations have μ = 1, 2, 3, and 4 cycles per sol, respectively. The abscissa is marked in martian days from arrival of VL1 (VL1 sols) and in Mars seasonal date (areocentric longitude, L_s). Northern fall and spring begin at L_s = 180 and 360, respectively. Model results are shown by the dashed lines and were computed for the model-inferred dust opacities τ_0 (●). Also shown are opacities inferred from the second year of VL1 pressure observations (○). For comparison, representative values of the opacity above VL1 (+), as derived from the VL1 imaging data (4), are given for 1977.

ed and observed phases of the diurnal component. Although the model appears to consistently overestimate the diurnal amplitude, it does closely follow the observed trends in amplitude. Furthermore, the model simulation of the semidiurnal surface pressure oscillation is remarkably good.

Considering both the simplifications used in the theory and the limitation of the data to only two sites, the overall agreement is surprisingly good. The classical atmospheric tidal theory used here was originally developed to explain the daily variations in surface pressure observed for the earth's atmosphere (*8*). Application of this theory to Mars was thought to be limited primarily by the effects of the martian relief (*10*). The present results demonstrate that the classical theory can simulate major features of the martian atmospheric tides during a great dust storm and that, in doing so, a reliable measure of the planet-wide opacity due to airborne dust can be inferred from the semidiurnal tide at VL1. Application of this technique to the second martian year of VL1 data reveals a less intense event (1979a) corresponding to the 1977a storm, but no opacity comparable to the second, more intense 1977b storm (Fig. 1). Viking Lander 1 continues to operate and may transmit surface pressure data as late as 1994. If so, the data will provide a unique record of the episodic great dust storms on Mars.

R. W. ZUREK
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91109

C. B. LEOVY
Department of Atmospheric Sciences, University of Washington, Seattle 98195

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Circular Feature Among Dunes of the Great Sand Sea, Egypt

Abstract. *A circular crater, about 4 kilometers in diameter and located at 24.2°N, 26.4°E, was discovered in Landsat images among the linear dunes of the Great Sand Sea, Egypt. The crater has a sharp and crenulated rim crest, a terraced wall, a discontinuous inner structure (approximately 1.6 kilometers in diameter), and a few rim blocks. Its morphological and morphometric characteristics are similar to those of meteorite impact craters and other circular structures on the moon and the terrestrial planets. Because of its interaction with windblown sand, it is particularly comparable with craters on Mars.*

The Western Desert of Egypt has been the site of much of the basic research on dune classification and sand movement by the wind (*1*). It is part of the eastern Sahara, the driest large expanse of land on Earth, where received solar radiation is capable of evaporating 200 times the amount of rainfall (*2*). This vegetation-free, north-dipping plain of sedimentary rocks is crossed by numerous belts of sand dunes predominantly of the linear type; the largest accumulation of such dunes forms the Great Sand Sea (Fig.1) (*1*).

The southern part of the Western Desert was recently divided into two physiographic provinces, the Arba'in Desert in the east (*3*) and the Uweinat Desert in the west (*4*). The Arba'in Desert was named after the Darb El-Arba'in camel track that connects the Kharga Oasis in Egypt to El-Fasher in the Sudan. It contains numerous Paleolithic and Neolithic sites, which indicate episodic human habitation from 200,000 to 5000 years ago (*3*). Similar indications of former pluvial phases exist in the Uweinat Desert, which was named after the 35 by 20 km, 600-m-high mountain at the intersection of the borders of Egypt, Libya, and the Sudan (*4*).

Fluvial action in the geological past, followed by eolian activity under the extremely arid conditions of today, have produced a landscape in the Uweinat Desert that is comparable to that of

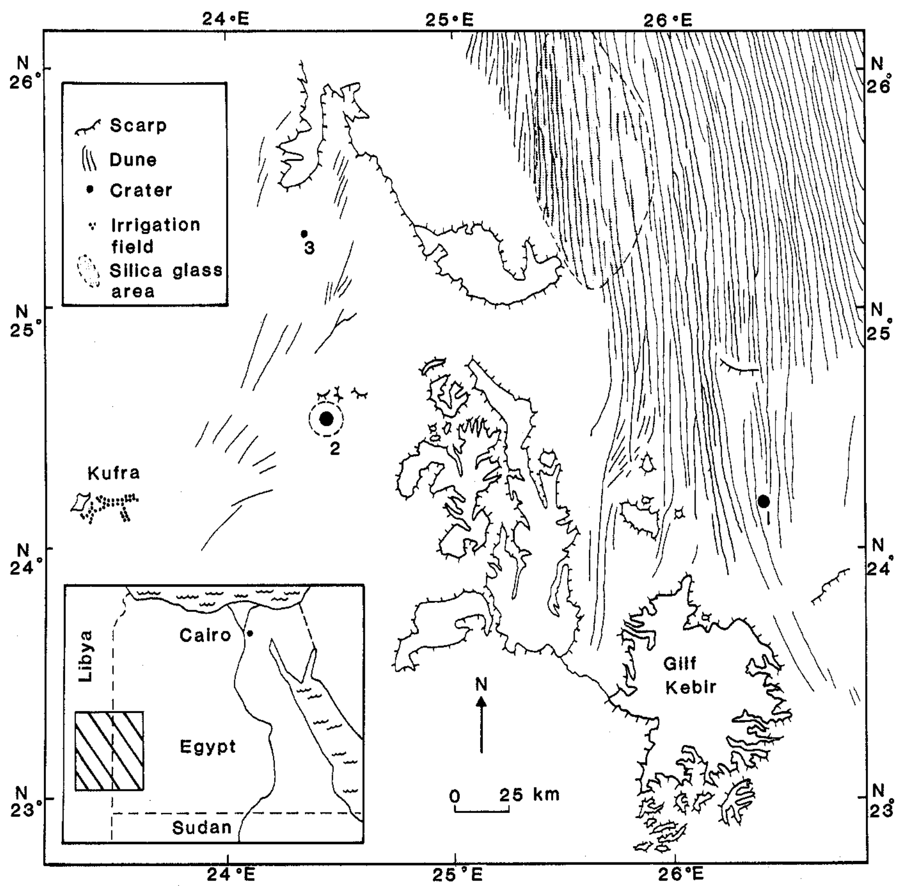

Fig. 1. Map showing the southwestern termination of the Great Sand Sea (upper right), north of the Gil Kebir plateau. Numbered dots are El-Baz Crater (site 1) and two craters, believed to be the result of meteorite impacts, named Oasis Astrobleme (site 2) and BP (British Petroleum) structure (site 3).

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