Are There Oceanographic Explanations for the Israelites' Crossing of the Red Sea?

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Abstract

Two relatively simple physical oceanographic processes are suggested as plausible explanations for the biblical description of the Israelites' crossing of the Red Sea during their exodus from Egypt. The first involves strong wind that blows along the Gulf of Suez and pushes the water a considerable distance away from the regular shoreline. This process is examined with the aid of a simple conceptual model consisting of a shallow, narrow, and long channel (corresponding to the Gulf of Suez) connected to a large body of water (corresponding to the main body of the Red Sea). Uniform wind is allowed to blow over the entire gulf for a period of about a day and the resulting phenomena are examined by solving the appropriate governing equations.

It is shown that, in a similar fashion to the familiar wind setup in a long and narrow lake, the water at the edge of the gulf slowly recedes away from its original prewind position. The receding distance of the shoreline and the associated sea level drop are computed by solving the nonlinear equation that governs the motion resulting from the wind. It is found that, even for moderate storms with wind speed of about 20 m s^{-1}, a receding distance of more than 1 km and a sea level drop of more than 2.5 m are obtained. These relatively high values are a result of the unique geometry of the gulf (i.e., its rather small width-to-length and depth-to-length ratios) and the nonlinearity of the governing equation. Upon an abrupt relaxation of the wind, the water returns to its prewind position as a fast (nonlinear) gravity wave that floods the entire receding zone within minutes. It is suggested that the crossing occurred while the water receded and that the drowning of the Egyptians was a result of the rapidly returning wave.

The second possible mechanism that is considered is a tsunami (i.e., a flood resulting from an earthquake under the sea) that arrived at the Gulf of Suez from the main body of the Red Sea. In a similar fashion to the wind setup mechanism, a fast nonlinear gravity wave that could be responsible for the drowning is involved.

Of the two possible mechanisms, the wind setdown appears to be a more plausible explanation, because it is more closely related to the biblical description in terms of the strong wind prior to the event, the receding water, and the crossing in the midst of the sea.

1. Introduction

The ancient flight of the Israelites from Egypt into Canaan and the unusual events associated with it are of utmost historical and biblical importance. It is, therefore, of interest to examine whether events, such as the Red Sea crossing, can be explained in terms of natural phenomena. Furthermore, because of the significant advancement of physical oceanography during the past 50 years, such an examination appears to be appropriate at this time. We shall not be concerned here with the question of whether a flight and crossing actually occurred in the past but rather with the issues of providing a possible scientific explanation for such a crossing. We shall do so by using an analysis of the possible oceanographic processes that the Red Sea can be subject to as a result of strong winds acting on it or as a result of an earthquake. With the aid of these analyses, we shall argue that the Israelites' crossing and the Egyptians' drowning could have been a result of known natural phenomena. Furthermore, it will be shown that, although such events are probably not very common, they are certainly possible from a scientific point of view.

a. General background

It is perhaps appropriate to begin our detailed description with the biblical quotation relevant to the crossing:

> . . . the Lord caused the sea to go back by a strong east wind all the night, and made the sea dry land, and the waters were divided. And the children of Israel went into the midst of the sea upon the dry ground; and the waters were a wall unto them on their right hand, and on their left. And the Egyptians pursued, and went in after them into the midst of the sea, all Pharaoh's horses, his chariots, and his horsemen . . . And the Lord said unto Moses: 'Stretch out thy hand over the sea, that the waters may come back upon the Egyptians, upon their chariots, and upon their horsemen.' And Moses stretched forth his hand over the sea, and the sea returned to its strength when the morning appeared; and the Egyptians fled against it; and the Lord overthrew the Egyptians in the midst of the sea. And the waters returned, and covered the chariots, and the horsemen . . . . (Ex. 14: 21–23; 26–28)

In this quotation, special attention is given to the strong east wind prior to the event, the receding water, and the abrupt return of the water. It is of interest to note that in the Old Testament in the Hebrew language, the wind prior to the crossing is described as *Ruach kadim,* which can also mean *northeasterly* (*or southeasterly*) wind, because in the biblical Hebrew

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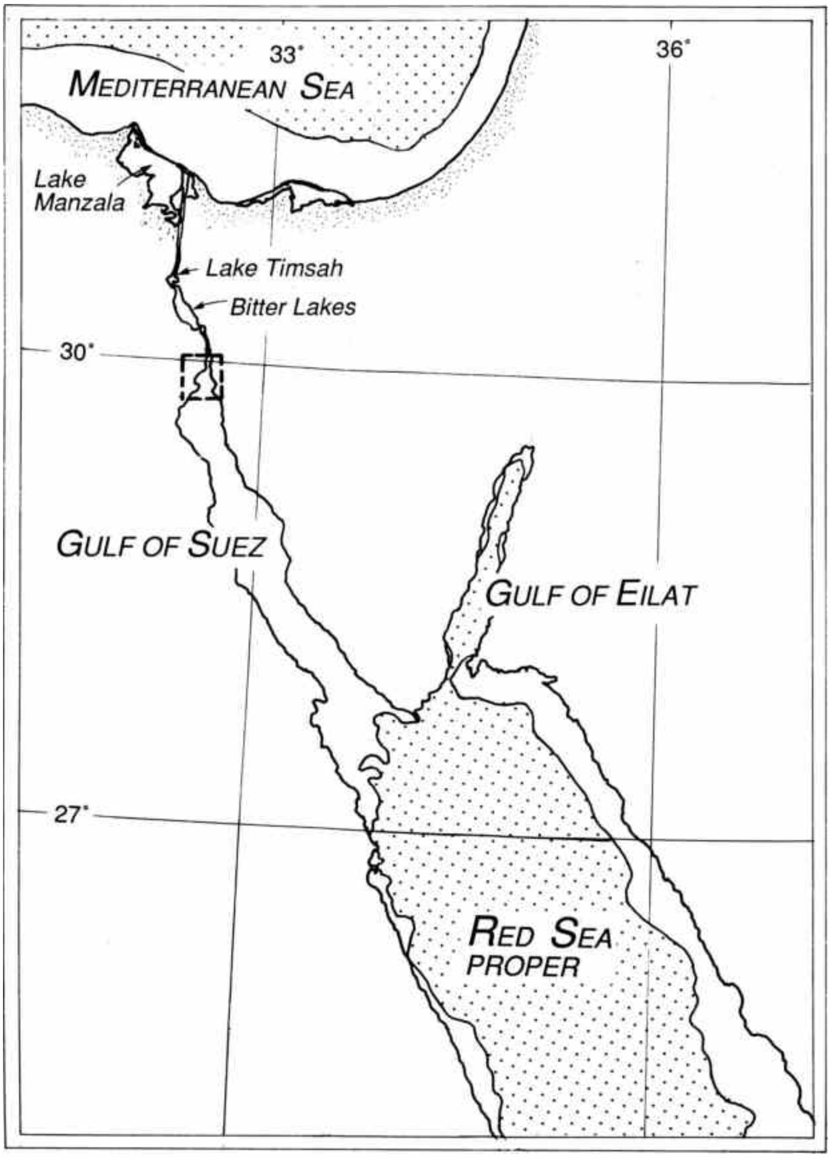


FIG. 1a. A general map of the Red Sea, including the Gulf of Eilat (sometimes referred to as the Gulf of Aqaba) and the Gulf of Suez. The main body of the Red Sea, which does not contain two gulfs, will be referred to as the "Red Sea proper" (after Morcos 1970). The shaded portion indicates a depth of >200 m. The Suez Canal, which connects the Mediterranean and the Red Sea, was built in 1869. A detailed map of the area bounded by the small dashed square is shown in Fig. 1b.

there are only four wind directions (N,E,S,W). In addition, it should be pointed out that, according to the biblical description, the wind had an important role also in other plagues that befell the Egyptians. For example, it is said that the locusts were driven by the wind from and back to the sea (Ex. 10: 12, 19).

b. Historical and geographical background

A rather thorough summary of the region's physical geography and a description of the crossing from a historical point of view can be found in Har-el (1983). Most of the details described there need not be repeated here. For our purpose, it is sufficient to describe some aspects of the crossing as given in Har-el (1983), and the climate and physical oceanography of the gulf.

1) CROSSING AREA

Although many scholars believe that the crossing occurred in the vicinity of the northern edge of the (present) Gulf of Suez (see Fig. 1), some suspect that it actually occurred much farther to the north, somewhere in the vicinity of Lake Manzala. This disagreement results from two considerations.

The first is related to a possible error associated with the translation of the original name *Yam Suf,* which in Hebrew means *Sea of Reeds,* but is later mistakenly referred to as the *Red Sea* (i.e., one *e* was dropped). Since there are no reeds or papyrus near what is known today as the Red Sea, some scholars believe that the original biblical reference was made with regard to one of the lakes farther north, where such plants are common. A counter argument is based on the idea that the Hebrew name *Suf* could have possibly originated in the Hebrew word *Sufa,* which means "a storm." If this explanation is accepted, then one can also accept the present location of the Red Sea as that of the ancient Red Sea.

The second consideration that leads scholars to believe in a crossing farther to the north is based on the suggestion that in biblical times the Gulf of Suez extended much farther to the north than it does today. None of the above considerations can be unequivocally proven and we shall, therefore, regard the northern edge of the (present) Gulf of Suez as the place of crossing. We shall see later that both of the mechanisms that might explain the parting of the sea support this choice of crossing area.

2) CLIMATE AND PHYSICAL OCEANOGRAPHY

The Gulf of Suez is about 350 km long and 20–30 km wide. Its average depth is about 36 m

(Morcos 1970, p. 92) and on its northern side the bottom slope is very gentle (2:1000). The salinity of the gulf is higher (~40%) than that of most seas, mainly because of strong evaporation; its typical temperature is about 22°C. Because of the high mountain chains that run on both sides of the gulf, the wind is usually directed along the gulf. The dominant wind is from the NNW during the entire year, although a SSE wind occasionally blows during the winter. For instance, during the spring and summer (the period of the year when the crossing had presumably occurred) the wind is from the NNW 70% of the time and its average value is about 5 m s^{-1} (Sharaf El Din 1975). The maximum monthly winds during the summer as given by the Comprehensive Ocean–Atmosphere Data Set (COADS) are about 8 m s^{-1} (see e.g., Woodruff et al. 1987). Unfortunately, the entire Red Sea and the Gulf of Suez in particular are not well studied from an oceanographic point of view, and only a relatively small number of reliable observations have been made.

Qualitative descriptions of the water behavior in the northern edge of the gulf is given in Har-el (1983). These descriptions suggest that when strong winds blow from the southeast, the waters of the Gulf of Suez spread some 8 to 9 km northward along the Suez Canal. Har-el suggests that this happens every 20 years or so and is typically associated with a sea level rise of almost 2 m. In contrast, when a strong wind blows from the northwest, the low tide is exaggerated. There are also reports that Napoleon was almost killed (during a crossing at a shallow region) as a result of a "sudden high tide." The Suez Canal company states that the usual difference between high and low water is 80 cm and that the maximal difference is more than 3 m. A scientific analysis of the sea level fluctuations for the period 1956–1966 was made by Sharaf El Din (1975). He speaks of tides, varying atmospheric pressure, and sea level variations of up to 140 cm, but it is not clear what are the direct causes of those variations. It is unfortunate that additional scientific attempts to rigorously examine the sea level variations over extended periods of time have never been made.

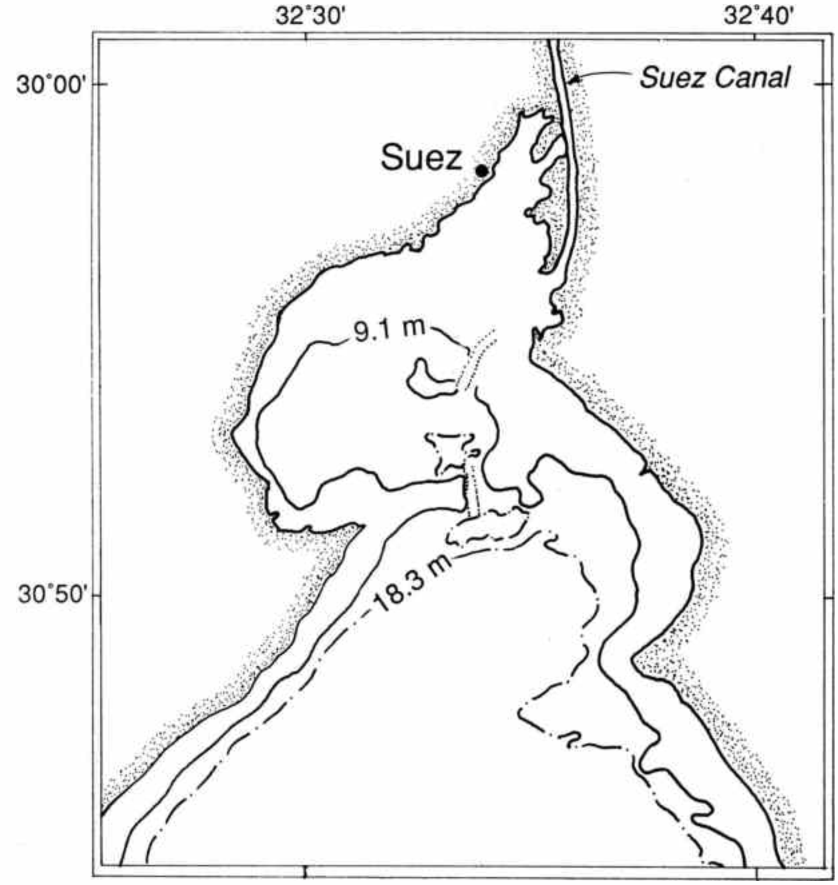
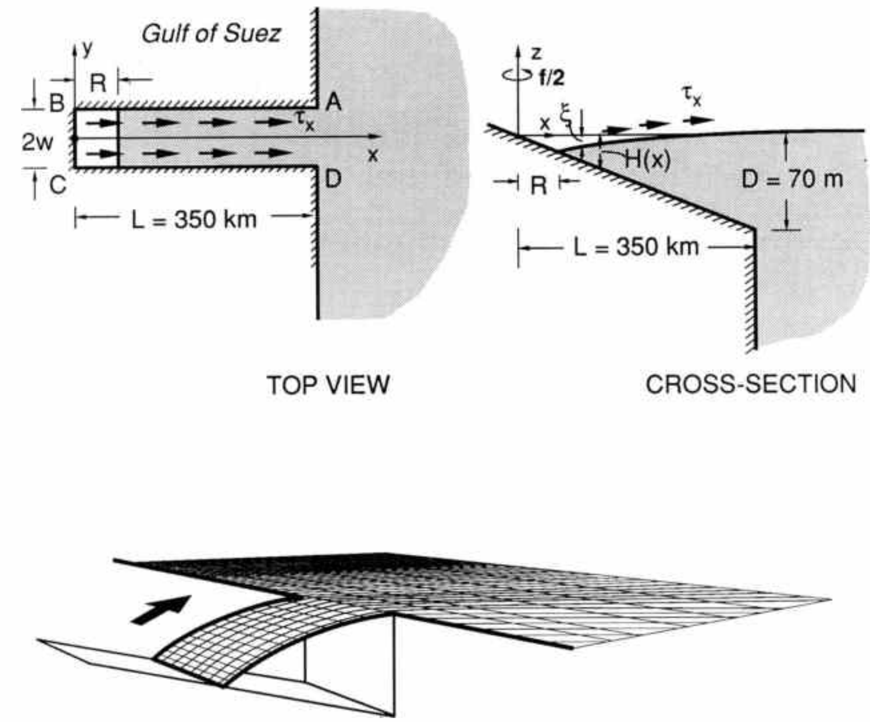


FIG. 1b. A detailed map of the Gulf of Suez's northern edge (corresponding to the small square bounded by the dashed line in Fig. 1a). A number of scholars believe that the crossing occurred somewhere north of 30°50' and south of 30°00' (Har-el 1983). Note that in the northernmost portion of the gulf the bottom slope is very gentle. (Unrounded depth contours result from a conversion of fathoms to meters.)

3) PRESENT OCEANOGRAPHIC APPROACH

As mentioned, our approach in this study is to relate the Red Sea crossing to natural oceanographic phenomena. We shall show that a relatively simple oceanographic process related to a northwesterly wind pushing the water offshore and the water returning as a fast high-amplitude nonlinear wave (once the wind relaxes) can explain the "parting of the sea." The Gulf of Suez provides an ideal body of water for such a process because of its unique geography; as stated earlier, it is rather long, narrow, and shallow. The idea that the wind could possibly be responsible for the crossing has already been qualitatively mentioned by Bartlett (1879, p. 181; see also Har-el 1983, p. 147), but the quantitative scientific question of how such a process can actually occur has not been addressed.

After the completion of this study, it has been brought to our attention that, as early as 1924, Hellstrom attempted to explain the crossing using a 3-m–long



TOP VIEW

CROSS-SECTION

FIG. 2. Upper panels: Schematic diagram of the conceptual wind-crossing model. The gulf is taken to be a long and narrow channel with a linearly sloping bottom. Short and thick arrows represent the wind stress at the surface, τ_x. $H(x)$ is the undisturbed water depth, D the maximum depth, $2w$ the width, L the length, and R is the receding distance. Lower panel: Three-dimensional view of the water surface.

channel and a fan. No calculations are present in his original (unpublished) report (which was later translated to English in 1950) but his qualitative results are similar to ours; in particular, our idea of a ridge (described in section 6) has also occurred to him. It will become clear later that his ideas regarding the place of crossing (somewhere between Lake Timsah and the Bitter Lakes) cannot be supported by specific calculations. This is so because, according to the recent geography (which excludes, of course, the relatively new Suez Canal), his considered body of water (which is separated from the Gulf of Suez) is not long enough to produce a significant wind setdown. Ironically, 60 years later, Har-el (1987), who examined geographical and archaeological evidence for the crossing, came up with a similar suggestion even though he was not aware of Hellstrom's original work.

Another attempt to relate the crossing to natural phenomena was made earlier by Goedicke (see Goedicke 1991, and earlier remarks in popular literature such as *Newsweek,* 18 May 1981), who suggested that the crossing occurred near Lake Manzala and that the drowning of the Egyptians was a result of an earthquake-generated wave (tsunami) associated with a volcanic eruption in the Mediterranean Sea. While this idea is interesting, it appears that Goedicke's suggested crossing path is situated much too far inland (~50 km), so that any tsunami would dissipate long before reaching it. This difficulty could have been resolved had the sea level at the time of the crossing been much higher than it is today, but this is inconsistent with our present knowledge of sea level changes (Barnett 1990).

We shall begin our detailed analysis in section 2 by looking at a conceptual model consisting of a shallow channel (Fig. 2), closed at one end, connected to a much larger body of water. The narrow and long channel represents the Gulf of Suez, and the adjacent, much deeper and broader body of water represents the Red Sea proper and the Gulf of Eilat. In section 3, an expression for the distance that the water recedes in response to the action of northwesterly wind is derived by solving the differential equation that governs the water movement. Similar wind setup problems have been dealt with before and the solution for sea level displacements that are much smaller than the total water depth is well known (see, e.g., Csanady 1982). In our problem, however, the total fluid depth vanishes where the water recedes (see Fig. 2), so that a new nonlinear equation must be solved. Even though the problem is nonlinear (because, as just stated, near the edges of the gulf the amplitude of the disturbance is of the same order as the mean depth), an exact analytical solution relating the receding distance to the geometry of the gulf and the wind speed is derived. It is shown that, for the parameters relevant to the Red Sea, one obtains a receding distance of about 1 km—a distance that could certainly permit crossing.

We shall then proceed in section 4 and discuss the events that would occur when the wind relaxes. It is expected that, in most cases, the wind will relax gradually (over a period of, say, a day), allowing the water to gradually return to its prewind position. Obviously, such a return would not impose any danger to humans because one could easily escape its arrival. A sudden (i.e., within several minutes) relaxation of the wind or a sudden change in its direction would, however, cause a severe response. Under such conditions, a rapidly advancing nonlinear gravity wave will cover the exposed area within minutes, preventing any possible escape. After discussing these points in some detail, it will be argued that our proposed wind crossing mechanism has much in common with the original biblical description because it involves pre-event winds, receding water, and a rapidly returning wave.

We shall then continue in section 5 and look at the alternative possibility that a tsunami in the Red Sea was a cause of the Egyptians' drowning. We shall eventually argue that, even though such a tsunami is certainly possible, the mechanism is somewhat less appealing than the wind mechanism because the events associated with it are not that close to those mentioned in the biblical description.

2. The conceptual wind setdown model

This section, as well as section 3, contains the mathematical steps necessary for the computation of the receding distance and the height of the returning wave.

Consider again the model shown in Fig. 2. The narrow ($w/L \ll 1$) and shallow ($D/L \ll 1$) gulf represents the Gulf of Suez. A uniform steady northwesterly wind blows along the gulf toward the Red Sea proper. The maintenance of its direction and strength is assisted by the mountain chains on the two sides of the gulf, which are approximately parallel to the shoreline. We consider here a northwesterly wind, because this is the most common wind in the gulf (e.g., Sharaf El Din 1975). The apparent discrepancy between our choice of a northwesterly wind and the biblical description of an east wind (which, as mentioned earlier, can also mean northeasterly or southeasterly wind) prior to the crossing is attributed to the local variability of the wind. Given the region's geography and, in particular, the relatively low mountains near the northern edge and the much higher mountains along most of the gulf, it is quite possible that in the relatively small area of crossing the wind was indeed from the east, whereas over the much larger gulf the wind was from the northwest. As a result of the wind stress, acting for some time, a steady state is reached and the water recedes a distance R. We wish to compute this distance to see whether, for a storm of reasonable strength, it can provide a strip broad enough to allow crossing.

In a similar fashion to known wind setup problems (see, e.g., Csanady 1982), we begin by considering the vertically integrated linearized equations of motion with no horizontal friction; keeping the nonlinear terms resulting from the integration:

$$\frac{\partial U}{\partial t} - u_s\frac{\partial \xi}{\partial t} - fV = -g(H+\xi)\frac{\partial \xi}{\partial x} + \frac{\tau_x}{\rho_w} \qquad (2.1)$$

$$\frac{\partial V}{\partial t} - v_s\frac{\partial \xi}{\partial t} + fU = -g(H+\xi)\frac{\partial \xi}{\partial x} + \frac{\tau_x}{\rho_w}, \qquad (2.2)$$

where U and V are the vertically integrated (from the bottom to the free surface) horizontal transports in the x and y directions (which are pointing along and across the gulf), u_s and v_s are the velocities at the surface, t is time, f the Coriolis parameter, g the acceleration of gravity; ξ the free surface vertical displacement (measured upward from the undisturbed depth), H the undisturbed depth [$H = H(x)$], τ_x and τ_y the stresses induced by the wind (in the x and y directions), and ρ_w the density of the water; the bottom stresses have been ignored. The relationship between the wind stress and the speed of the wind above the water is discussed in the next section [Eq. (3.6)]. It is assumed here that the gulf is approximately barotropic. Indeed, observations suggest that, with the exception of the southern part of the gulf, the density does not vary significantly with depth [see Morcos 1970, (his) Fig. 10].

Since our gulf is rather narrow and $\tau_y \equiv 0$, it is reasonable to assume that, in a steady state, the walls prevent any horizontal transport, so that $U \equiv 0 \equiv V$ (see, e.g., Csanady 1982). Note, however, that even though the integrated horizontal transport vanishes, the local speed is not zero because the interior stress does not vanish. In a steady state, the following balance will hold:

$$-g(H+\xi)\frac{\partial \xi}{\partial x} + \frac{\tau_x}{\rho_w} = 0. \qquad (2.3)$$

This first-order nonlinear equation is subject to the boundary condition,

$$\xi = 0; x = L, \qquad (2.4)$$

which states that the sea level of the much larger and deeper Red Sea proper is fixed.

Three points should be made with regard to (2.3). First, note that away from the receding zone, $\xi \ll H$, but in the vicinity of the receding zone, $\xi \sim O(H)$ so that, in contrast to most wind setup problems, (2.3) cannot be linearized by ignoring ξ compared to H. Also, note that along the receding shoreline the sea level slope $\partial\xi/\partial x$ goes to infinity, because $H + \xi$ goes to zero, whereas τ_x/ρ_w is, obviously, finite. Because of the nonlinearity, one would tend to solve (2.3) numerically but, as we shall shortly see, it is possible to derive an exact analytical solution even though the problem is highly nonlinear. Second, it is important to realize that the effect of the earth's rotation (i.e., f) does not enter (2.3) because of the proximity of the side walls. This is consistent with the fact that the gulf is mainly barotropic so that the Rossby deformation radius $(gH)^{1/2}/f$ is about 200 km, which is much greater than the gulf's width (~20 km). Third, in reality, bottom stress could also play a role, but it cannot, of course, be included in (2.3) without including nonvanishing transports, which are beyond the scope of this study.

3. The wind setdown solution

Before discussing the nonlinear solution of (2.3), it is appropriate to briefly present the classical linear solution, which is valid for similar problems. When $\xi \ll H$ and H is a constant (i.e., the bottom is flat) the solution of (2.3) is,

$$\xi = \tau_x(x-L)(gH\,\rho_w)^{-1}, \text{ so that } \xi_e = -\frac{\tau_x L}{gH\rho_w}, \quad (3.1)$$

where ξ_e is the sea level change along the edge (i.e., the maximum sea level change). This sea level change increases with increasing wind stress, increasing length, and a decreasing depth, implying large sea level changes for long and shallow basins. In what follows it will be demonstrated that these tendencies are also present in our nonlinear case, although the sea level change is much greater in the nonlinear case.

To solve (2.3) we note that (since our simplified model has a linearly sloping bottom) $H = (D/L)x$ (where D is the gulf's maximum depth and L is the gulf's length) and rewrite (2.3) in the form,

$$\frac{d\xi}{dx} = \left(\frac{\tau_x}{g\rho_w}\right)\frac{1}{(D/L)x + \xi}, \quad (3.2)$$

which can also be expressed as

$$\frac{dx}{d\xi} - \left(\frac{D}{L}\right)\left(\frac{g\rho_w}{\tau_x}\right)x = \left(\frac{g\rho_w}{\tau_x}\right)\xi. \quad (3.3)$$

Surprisingly, with this simple manipulation, the governing equation has been changed from a nonlinear equation in ξ *(2.3) to a linear equation in* x.

The exact general solution of (3.3) is now easily found to be

$$x = Ae^{(g\rho_w D/L\tau_x)\xi} - \frac{\xi}{D/L} - \frac{\tau_x}{g\rho_w(D/L)^2},$$

where A is to be determined from the boundary condition (2.4). One ultimately finds

$$x = \left[L + \frac{\tau_x}{g\rho_w(D/L)^2}\right]e^{(g\rho_w D/L)\xi/\tau_x} - \frac{\xi}{D/L} - \frac{\tau_x}{g\rho_w(D/L)^2} \quad (3.4)$$

The dependence of ξ on x and the other parameters is shown in Fig. 3, which illustrates that the nonlinear sea level drop is considerably *greater* than the linear drop, because $d\xi/dx \to \infty$ along the receding line. The expression for the receding distance R is now found by setting $\xi = -(D/L)x$ and $x = R$ (equivalent to $\xi + H = 0$ at $x = R$) into (3.4). The result is,

$$R = \frac{\tau_x}{g\rho_w(D/L)^2}\ln\left[1 + \frac{g\rho_w D^2}{L\tau_x}\right], \quad (3.5)$$

which enables one to compute R in terms of the wind's stress and the gulf's geometry.

Three comments should be made with regard to (3.5). First, it is clear that this expression is valid for both a wind setup [resulting from a wind blowing toward the closed end of the gulf (i.e., southeasterly)] and a wind setdown (resulting from a northwesterly wind). It should be clear by now that we shall be mainly interested in the setdown case ($\tau_x > 0$, $R > 0$) rather than the setup case ($\tau_x < 0$, $R < 0$), because only the former causes a receding shoreline. However, even though it is of no direct interest to us, it is worth pointing out that, in a wind setup case with $\tau_x \to -g\rho_w D^2/L$, the sloping sea surface is parallel to the sloping bottom so that, theoretically, the entire beach is flooded. Second, when τ_x is negative (i.e., wind setup) and smaller in magnitude than $g\rho_w D^2/L$, the solution breaks down, probably because a steady state cannot be reached. Third, it so happens that, according to our solution, the free surface at the receding point ($x = R$) is vertical ($d\xi/dx \to \infty$), which is "in agreement" with the biblical description of "waters that were a wall." Although the actual sea level slope would probably be large, friction would, no doubt, prevent the water from becoming vertical.

The dependence of the wind stress, τ_x, on the wind speed is given by

$$\tau_x = \rho_a C_D |w^2|, \quad (3.6)$$

where ρ_a is the density of air, C_D is the drag coefficient (empirically defined), and w is the wind speed. For a "typical wind" of 7 m s^{-1}, the surface stress τ_x/ρ_w is 10^{-4} m^2 s^{-2}, whereas a hurricane gives (τ_x/ρ_w) of 30×10^{-4} m^2 s^{-2} or more (see, e.g., Csanady 1982, pages 12 and 26).

For the Gulf of Suez, we take $L \sim 350$ km and

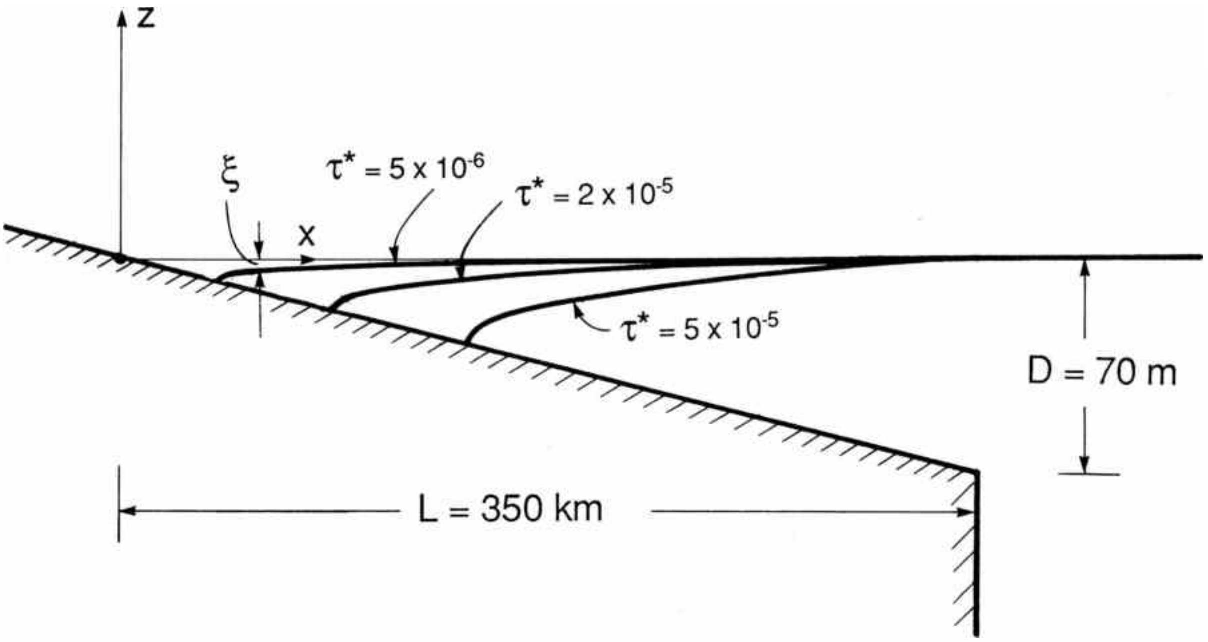


FIG. 3. The nonlinear dependence of the sea surface vertical displacement ξ on x, and the wind stress τ_x ($\tau^* \equiv \tau_x/g\rho_w D$). To demonstrate this dependence clearly, extremely high values for the wind stress were chosen (in addition to the realistic values). The highly unrealistic values are included merely for demonstration purposes.

$D \sim 70$ m; this depth corresponds to an average depth of 35 m, which is almost identical to the actual average depth of 36 m (Morcos 1970, page 92). Hence, for moderate winds (7 m s^{-1}), (3.5) gives a sea level drop of ~37 cm at the coast and a receding distance of ~2 km. This value for the receding distance has to be reduced by a factor of 10 because the slope near the northeast edge of the gulf is actually 2:1000, compared to the more gentle 7:35,000 average slope taken into account in our model with a linearly sloping bottom. The corrected value is then about 200 m, which corresponds, of course, to the *same sea level drop* of approximately 40 cm. Similarly, one finds that hurricane winds of ~35 m s^{-1} would give a rather high sea level drop of about 5.8 m and a (corrected) receding distance of about 3 km, whereas a wind of ~20 m s^{-1} (corresponding to a strong storm) would give a sea level drop of about 2.5 m and a (corrected) receding distance of about 1.2 km. It should be stressed that *all of these numerical values would have been reduced by a factor of 2 to 3 had the linear case been considered.*

Two additional comments should be made before proceeding and discussing the behavior of the returning water, which begins once the wind relaxes. First, it is appropriate to address the question of how long it would take for the wind to create the setdown situation mentioned above. An estimate for this time (T) can be easily computed by noting that, during the establishment of the setdown, the wind stress term τ_x/ρ_w in (2.1) is of the same order as the time-dependent term so that

$$\frac{\partial U}{\partial t} \sim O(\tau_x/\rho_w),$$

which, in view of the scale $U \sim O(LD/T)$, gives,

$$T \sim O\left(\frac{LD}{\tau_x/\rho_w}\right)^{1/2}.$$

It corresponds to a Gulf of Suez setdown time of about ten hours for moderate winds and several hours for strong winds. This is in agreement with the biblical description of a wind blowing the entire night prior to the crossing. Second, it is appropriate to point out that the tides in the Gulf of Suez are probably no more than 50 cm (see, e.g., Morcos 1970). Hence, a combination of tides and wind effect of the kind considered by Wang (1979) will not differ much from the setdown considered above.

4. The returning wave

As mentioned in the Introduction, it is expected that in most cases the wind that originally caused the setdown (discussed in sections 2 and 3) will gradually relax over a period of, say, several hours or days. This would cause a gradual return of the water to the prewind state and would present no threat to humans. However, if the wind relaxes or changes its direction abruptly (say, within several minutes) then the water returns as a fast nonlinear gravity wave or a "bore." Namely, since the water behind the front of the nonlinear wave has larger depth than the water ahead, the back travels faster than the front and the wave ultimately breaks (e.g., Stoker 1957; Lighthill 1978). Even though the wave is highly nonlinear, its propagation speed is still given by $(gh)^{1/2}$, where h is the total depth of the water. This implies that for a wind setdown of 2.5 m (corresponding to a storm), the wave would travel at 5 m s^{-1}, so that the entire receding area would be flooded in just 4 min. In reality, breaking waves, decreasing depth, and friction would slow down the advancement of the wave, but these effects might be offset by the neglect of overshooting that is discussed below.

The main weakness of our theory of a wind setdown and a returning wave is that the time-dependent aspects of the problem have been partially ignored. A suddenly imposed wind stress will actually cause the water to overshoot its equilibrium position (3.4) initiating a cycle of seiches superimposed on the steady-state solution. This corresponds to a bottom [associated with a receding distance greater than that given by (3.5)] that is periodically exposed. It is difficult to say at this stage, but it is quite possible that the seiche period is just such as to allow the return of the water after the crossing. For such conditions, it is not necessary to postulate the abrupt cessation of the wind after the crossing. These important aspects will be examined in the future and, hopefully, will be reported elsewhere.

5. Could a tsunami be a possible explanation?

To answer this question, it is recalled that the Red Sea proper is about 2000 km long, 180–370 km wide, and 2000 m deep (at the troughs). From a geologic point of view, the area is very active, and the reader is referred to Simkin et al. (1981) and Fairhead and Girdler (1970) for a survey of the volcanic activity during the past 10 000 years. Sea-floor spreading occurs along four known troughs (located in the southern half, along the sea's main axis) where most of the seismic activity takes place. The activity associated with this spreading is accompanied by both gravity and magnetic anomalies (Phillips et al. 1969) and by large heat fluxes from beneath the troughs (Erickson and Simmons 1969).

In the open ocean, tsunamis typically have an initial amplitude (i.e., an elevation of the sea surface) on the order of one meter, but their wavelength is on the order of several hundred kilometers (Murty 1977; Voit 1987). The precise way these tsunamis are initially generated is not quite clear, but their subsequent propagation into the coast and the ensuing amplitude increase are fairly well understood from linear as well as nonlinear wave theories. The main result of these theories that is supported by observations is that, as a simple gravity wave, the tsunami's speed of propagation is given by $(gh)^{1/2}$. Also, it is known that the total energy of the wave (kinetic plus potential) per unit width (i.e., per unit length in the direction perpendicular to the direction of the wave's propagation) is proportional to the square of the wave's amplitude (ξ^2). Therefore, the energy flux per unit width associated with a tsunami propagating in the open water far from its region of generation is proportional to $\xi^2 h^{1/2}$. In the absence of any sources (or sinks) of energy, this flux has to remain constant, which implies that when the ocean's depth, h, decreases, the wave's amplitude, ξ, has to increase as $h^{-1/4}$.

In the case of a tsunami generated in the southern part of the Red Sea (say, by some volcanic activity in one of the spreading troughs where the depth is over 2000 m) and propagating northward into the Gulf of Suez (with its average depth of about 30 m), the amplitude increases by a factor of $(30/2000)^{-1/4} \equiv 2.9$. Thus, if the initial tsunami's amplitude is a mere 1 m in the Red Sea, it will be nearly 3 m once it enters the Gulf of Suez. Further, if we consider the decrease in width, then energy conservation requires, in addition, a similar increase of the wave's amplitude.

This possible explanation of a sudden flooding of a coastal region by a tsunami has two shortcomings. First, it totally ignores the effect of strong wind mentioned in the biblical description. Second, it affords no difference between the inundation of land and the subsequent recession of water from it; both are gravity waves moving in and out at the same speed. From the biblical description, it seems, on the other hand, that the process was not symmetrical. Namely, the water gradually receded over some period of time but returned abruptly. On the other hand, a tsunami is more in line with a rare catastrophic event.

6. Discussion

We have looked at two possible natural processes that might explain the "parting of the sea." First, we examined the possibility that the water receded as a result of a northwesterly wind that blew along the gulf

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[1] For a comparison, it is pointed out that a hurricane produces winds of 35 m s^{-1} or more, whereas a moderate wind typically has a speed of 7 m s^{-1} or so.

(Figs. 2 and 3). We found that even a storm of moderate strength with wind speeds of about 20 m s^{-1} could generate a sea level drop of about 2.5 m and a receding shoreline of roughly 1.2 km along the northern edge of the gulf.[1]

By and large, these high values are a result of the *particular geometry* of the Gulf of Suez (which is a rather long, narrow, and shallow body of water) and *the nonlinearity of the equation governing the motion.* Such variations will obviously allow crossing in an area that was covered with water a day earlier. Furthermore, if, due to natural geological processes, the bottom topography in biblical times were slightly different than it is today and contained a ridge as shown in Fig. 4, then crossing in "the midst of the sea" with *water on both sides* is certainly possible. In this context, it is appropriate to point out that sea level variations on the order of meters also occur from time to time in some of the Great Lakes. For instance, Lake Erie, which, similar to the Gulf of Suez, is long and narrow, is regularly subject to fluctuations of about 1 m during winter storms (see, e.g., Csanady 1982). However, in the Great Lakes the bottom slope is much greater than that of the Gulf of Suez so that no significant receding of the shoreline is associated with these sea level fluctuations. Wind-generated fluctuations of about 1 m were also observed in the Delaware estuary (e.g., Galperin and Mellor 1990).

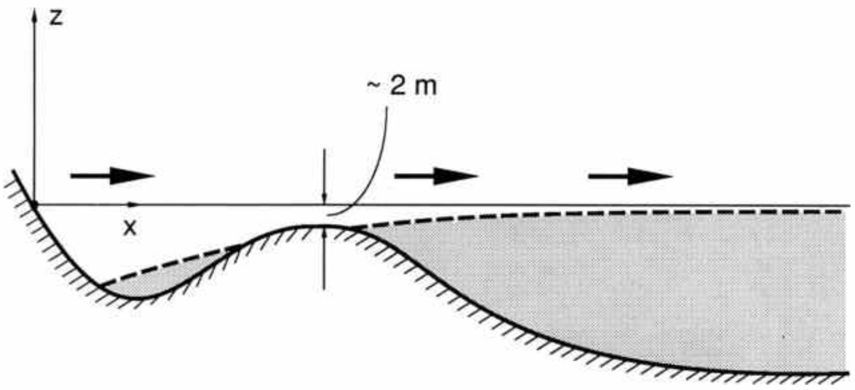

FIG. 4. Schematic diagram of a wind setdown in a gulf with a ridge (as before, *x* is directed along the gulf and *z* is directed upward). Thick arrows denote the wind direction. In the absence of any wind stress, the sea level is, of course, flat (thin line). In a similar fashion to the situation in a gulf with a linearly sloping bottom, due to the wind stress along the gulf, the sea level drops and, consequently, a portion of the bottom becomes exposed. It is suggested that, in biblical times, the northern edge of the Gulf of Suez could have had a similar structure and that the crossing occurred along the exposed bottom. Such a situation corresponds to a crossing in "the midst of the sea" with water on both sides.

The biblical description specifically addresses a strong wind that blew for the entire night prior to the crossing. The estimates based on our model (section 4) suggest that, indeed, about 10 hours of wind action are necessary in order to produce the sea level drop and the receding distance mentioned above. There is an apparent disagreement between the biblical description of an east wind and our choice of a northwesterly wind, but we have attributed this discrepancy to the local variability of the wind (see section 2).

We then proceeded and suggested that if the wind changed its direction abruptly (i.e., within several minutes), then the water could have returned as a fast nonlinear gravity wave. Such a wave would advance rapidly at a rate of about 5 m s^{-1} and would flood the entire exposed area within minutes. It is difficult to establish the likelihood that the wind will change abruptly in that part of the world because of the lack of sufficient observations. For the same reason, it is also difficult to establish the likelihood that a 20 m s^{-1} northwesterly wind will blow for 10 hours over the entire gulf. Namely, it is not clear whether such events are likely to happen every 50, 100, or 500 years. However, it seems that an occurrence of such events is certainly possible. Moreover, it should be stressed that a rapidly changing wind is not required in the case of a long ridge of the kind shown in Fig. 4. Specifically, if the ridge is long, so that crossing the sea by walking on the exposed bottom would take, say, 10 hours, then even gradually returning waters could cause drowning.

We then examined the possibility that a tsunami occurred during the crossing. We have shown that, although it is technically feasible, such an event does not agree with the biblical description of either the wind or the crossing in the midst of the sea. Finally, it should be said that, whether the above theory explains the crossing or not, it should not affect the religious aspects of the exodus. Believers can find the presence and existence of God in the creation of the wind with its particular properties just as they find it in the establishment of a miracle. Some may even find our proposed mechanism to be a supportive argument for the original biblical description of this event.

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