Statistics of Wind over the Red Sea with Application to the Exodus Question

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ABSTRACT

This paper supplements an earlier article by Nof and Paldor that offered a possible explanation for the biblical crossing of the Red Sea in terms of natural phenomena. In that article, it was suggested that sustained winds (of 20 m s^{-1}) could have caused a receding of the shoreline (of the Gulf of Suez) of more than a kilometer from its original prewind position. Such a wind would also be associated with a sea level drop of more than 2.5 m that would expose a swath of Red Sea bottom and make a crossing possible. The present article puts this nonlinear theory on firmer ground by providing a statistical analysis of the actual wind pattern in the area.

The authors used the Weibull distribution, the known duration of typical storms in the area, and direct measurements in the region. On the basis of the Weibull distribution applied to winds in the part of the Indian Ocean adjacent to the Red Sea, it is argued that the likelihood of a storm sustaining winds of 20 m s^{-1} and lasting, as required, for the entire night is roughly once every 2000 years. Direct measurements along the Gulf of Suez suggest, on the other hand, a somewhat lower probability—once every 2400 years or so. When the application of the direct measurement calculation is restricted to a specific time of the year, such as the spring, when the crossing presumably occurred and when the area is usually more stormy than the rest of the year, the likelihood of the event increases to once every 1400 years. However, the relatively high likelihood associated with the last calculation is at least partially a result of the fact that one of the stations was situated in the mountains a few hundred meters above sea level. When this station is excluded from the computation, the likelihood of the storm occurring in April decreases to once every 2400 years.

Given the sensitivity of the above predictions to the distribution of the measured values and the fact that both the Weibull distribution method and the direct measurement prediction are based on two quite different datasets, the agreement between our predictions is considered to be good. It implies that the overall likelihood of the event is once in a period of $O(1000\text{ yr})$.

1. Introduction

Recently, Nof and Paldor (1992, hereafter NP) proposed an oceanographic explanation for the biblical parting of the Red Sea. The essence of the proposed nonlinear process is that, owing to the unique geometry of the Gulf of Suez (long, narrow, and shallow), a northwesterly wind of 20 m s^{-1} blowing for 10–14 h is sufficient to cause a sea level drop of about 2.5 m. Such a drop could presumably expose an underwater ridge, making a passage on "dry land" possible. The present article represents an attempt to determine the likelihood of such an event.

a. Background

The purpose of both our earlier study and the present one is not to prove (or disprove) that a crossing and exodus did in fact occur, but rather to examine whether or not a crossing phenomenon is plausible from a physical point of view. Similarly, our aim is not to address all the details of the biblical description, because some aspects of the Exodus are clearly impossible from a natural point of view.

For instance, it has been argued that an exodus of millions of people could not have been feasible because of the harsh climate in the area. Consequently, it has been suggested that a migration of perhaps a few hundred people (or a few thousand people) is a more reasonable estimate. Naturally, counterarguments have been put forward stating that several thousand years ago the climate was much more accommodating than it is today, and this could have enabled large groups to survive in the area. Our current understanding of climatic change suggests, however, that even though the past climate was indeed more accommodating than it is today, the climatic changes that have occurred during the last few thousand years are relatively small and are not sufficient to have produced a fundamentally different climate (e.g., see Lamb 1972). As mentioned,

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such aspects are not addressed here, and we accept the biblical account as a possible "qualitative" description of an event. Namely, in our opinion, it is quite possible that an event resembling the biblical story did in fact occur.

For clarity, we will briefly review the results of NP. Our wind setdown model of the Gulf of Suez (Fig. 1) consists of a long and narrow channel with a linearly sloping bottom (Fig. 2) connected to an infinitely deep basin that represents the Red Sea proper. We have shown in NP that the oceanic response to wind action is governed by the following nonlinear balance equation:

$$-g(H + \xi)\frac{\partial \xi}{\partial x} + \frac{\tau_x}{\rho_w} = 0, \qquad (1.1)$$

where g is the gravitational acceleration, H the undisturbed depth $[H = H(x)]$, ξ the free surface vertical displacement (measured upward from the undisturbed depth; i.e. $z = 0$), τ_x the stress induced by the wind (in the x direction), and ρ_w the density of the water. The nonlinearity of (1.1) results from the fact that, in the vicinity of the receding zone, $\xi \sim O(H)$; along the receding point itself $H + \xi = 0$ so that $\partial\xi/\partial x$ goes to infinity there.

We have also shown that even though (1.1) is highly nonlinear, it has the *exact* solution

$$x = \left[L + \frac{\tau_x}{g\rho_w(D/L)^2}\right]\exp\left[\left(\frac{g\rho_w D}{L}\right)\frac{\xi}{\tau_x}\right] - \frac{\xi}{D/L} - \frac{\tau_x}{g\rho_w(D/L)^2}, \qquad (1.2)$$

which satisfies the boundary condition $\xi = 0$ at $x = L$ as required. As expected, $\partial\xi/\partial x \rightarrow \infty$ (i.e., $\partial x/\partial\xi \rightarrow 0$) along the receding line, creating a "wall" of water.

This exact nonlinear solution enabled us to compute the desired receding distance R and the associated sea level drop for given geometry, D/L, and wind stress τ/ρ_w. We then argued that the ancient Gulf of Suez might have included a ridge (Fig. 3) that under similar conditions could have been exposed, making a crossing possible.

b. Purpose of the present study

Nof and Paldor (1992) left a number of important questions unanswered. The most important aspect ignored was the wind data statistics analysis. Specifically, it has not been demonstrated how often a wind of 20 m s^{-1} lasting for 10–14 h is likely to blow over the Gulf of Suez. By and large, this was because the only reliable detailed wind dataset for the area that we knew of was contained in an Israeli government report that was classified at the time. Fortunately, since the publication of NP two years ago, portions of wind data reports have been declassified, making our present study possible.

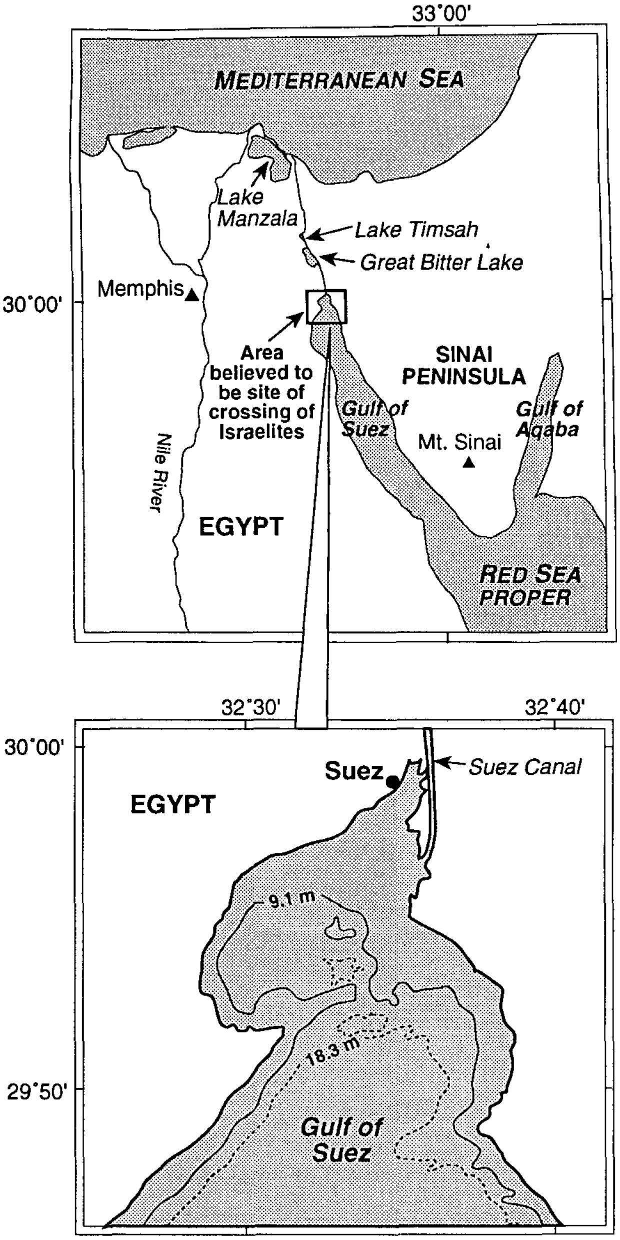

FIG. 1. The Gulf of Suez and the adjacent Red Sea proper.

Nevertheless, we were able to employ two different techniques (one is based on the so-called Weibull distribution and the other on direct measurements) and come up with similar answers (sections 2 and 3) indicating that, despite the loose-handed use of the statistics, our conclusions are probably valid. Note that we are mainly interested in determining the order of magnitude of the period between two consecutive storms, and we are not seeking more exact estimates. Both the term *probability* and the term *likelihood* are used throughout the article. The terms are not interchangeable—the term *probability* is used with regard

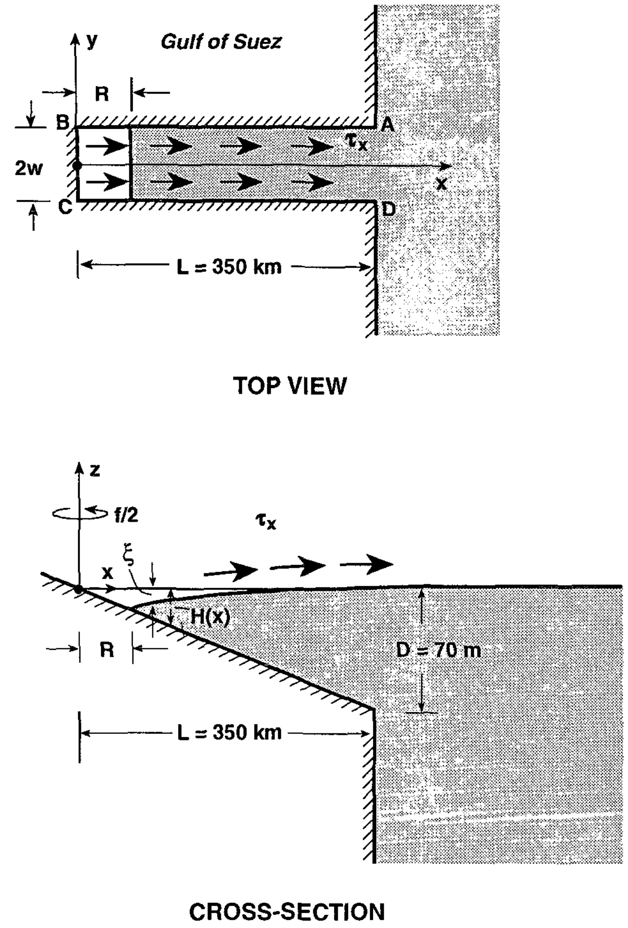

FIG. 2. Schematic diagram of the conceptual wind-crossing model. The gulf is taken to be a long and narrow channel with a linearly sloping bottom. Short, thick arrows represent the wind stress at the surface, τ_x. The variable $H(x)$ is the undisturbed water depth, D the maximum depth, $2w$ the width, L the length, and R the receding distance. Reproduced from Nof and Paldor (1992).

to the chance that a given storm would occur, whereas the term *likelihood* is used in reference to the time interval between two such consecutive storms. Our analysis demonstrates that the likelihood of the kind of event that we are proposing is once in a period of $O(1000\ \text{yr})$.

Another aspect considered in the present article is the relationship between the Nof and Paldor nonlinear mechanism and the linear study of Dayan (1978), which was previously unknown to us and was brought to our attention after the publication of our paper (section 4). Dayan employs a mechanism that involves a particular combination of wind and biweekly tides to produce the desired sea level drop. As we will see, because of this particular combination, the likelihood of such an event is much smaller than ours. Dayan did not publish his results in a scientific journal of natural sciences, but rather in a scholarly journal of biblical studies (in Hebrew, later translated into Spanish) that is not usually accessible to natural scientists in the West. Consequently, neither we nor Har-el (1983, 1987) nor Goedicke (1992) (all of whom dealt extensively with the question of the Exodus) were aware of it. Similarly, Dayan himself was not aware of either Bartlett (1879) or Hellström [1924 (later translated into English in 1950)], both of whom attempted to explain the crossing in terms of natural phenomena long before he did.

We will see that the likelihood of Dayan's mechanism is no more than once in 30 000–60 000 years, implying that, although the mechanism is certainly possible, it is less appealing than the NP mechanism in the sense that the NP mechanism is more likely to have indeed happened at least once during the past 3500 years.

2. Weibull statistics of wind speed

Determining the occurrence likelihood of a given storm (i.e., a storm that is consistently stronger than a threshold value for a particular duration) requires knowledge of the wind statistics in the area. If the storm in question is likely to appear within a period shorter than that of an existing wind record (e.g., suppose that a given storm is likely to happen once a year and we have a 10-yr record), then the prediction procedure is relatively simple. The computation becomes considerably more complicated, however, when the expected period of the storm (i.e., the time expected to elapse between two consecutive storms) is much greater than the existing record (e.g., suppose that a given storm is likely to appear once every thousand years and we have a record of only a few hundred years).

In our case, we require a wind of 20 m s^{-1}, blowing during the night from the north-northwest and lasting anywhere from 10 to, say, 14 h; we have a record of a

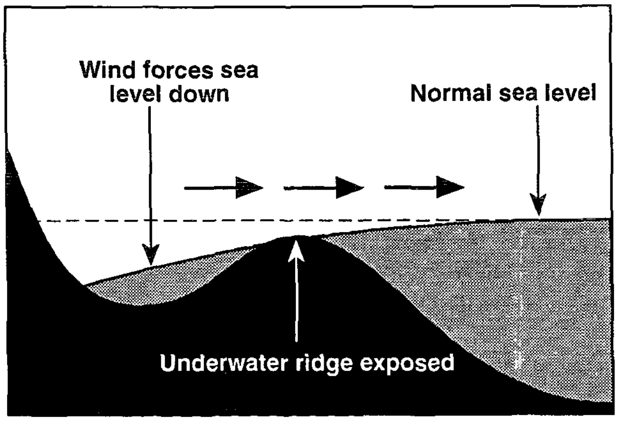

FIG. 3. Schematic diagram of an assumed underwater ridge exposed by wind action. Owing to various geographical changes that have occurred during the last several thousand years (including the construction of the Suez Canal), it is currently difficult to identify such a ridge. Bartlett (1879) and later Dayan (1978) suggest, however, that such ridges are common on the northern edge of the gulf.

few years (Manes et al. 1980). It is expected that over the Gulf of Suez our desired storm will not happen every year or even every 10 years, so that our case belongs to the second, more complicated, predictive category. To compute the likelihood of our setdown storm, we will use the so-called Weibull distribution, which enables one to make predictions extending beyond the recording period. We will begin by introducing the properties of this statistical distribution.

a. The Weibull wind speed distribution

Recall that any wind speed measurement can be plotted against relative frequency, and that as the wind speed intervals are made smaller and smaller, the plot becomes the probability density function (PDF). The PDF is usually obtained by fitting a curve to the wind data. Usually, a Gaussian or Rayleigh distribution is used, but for wind data, the Weibull distribution is a better choice because it takes into account the fact that the winds are usually not isotropic but rather have preferred directions (e.g., see Conradsen et al. 1984; Pavia and O'Brien 1986). The Weibull distribution is a general model that includes the Gaussian and Rayleigh distributions as special cases. For a variable V with two parameters A and C, the Weibull PDF is given by

$$f(V; A, C) = \frac{C}{A}\left(\frac{V}{A}\right)^{C-1} \exp\left[-\left(\frac{V}{A}\right)^{C}\right], \quad (2.1)$$

where $V \geqslant 0$, $A > 0$, and $C > 0$.

Here, V is the wind speed, A is a scaling wind speed parameter, and C is a dimensionless parameter determining the shape of the distribution (Fig. 4a). For $C > 1$ the distribution has a maximum away from the vertical axis; for $C = 2$ it is precisely the Rayleigh distribution; and for $C = 3.6$ it yields an approximation to the Gaussian distribution. For our predictive storm, we will use the cumulative distribution function (CDF), which is the integrated version of (2.1) and is given by

$$F(V; A, C) = 1 - \exp\left[-\left(\frac{V}{A}\right)^{C}\right]. \quad (2.2)$$

b. Application of the Weibull distribution to the Red Sea

The nearest part of the World Ocean for which the Weibull constants have been computed (from long and reliable wind records) is the northwestern Indian Ocean (Pavia and O'Brien 1986). A reasonable choice for the parameters A and C from the Pavia and O'Brien (1986) computations is 7.5 m s^{-1} and 1.75, respectively (see their Figs. 10 and 11). For this choice (Fig. 4b), (2.2) gives the likelihood of 20 m s^{-1} as 0.38%.

Note that the computed Weibull distributions are based on measurements averaged over 3-h intervals.

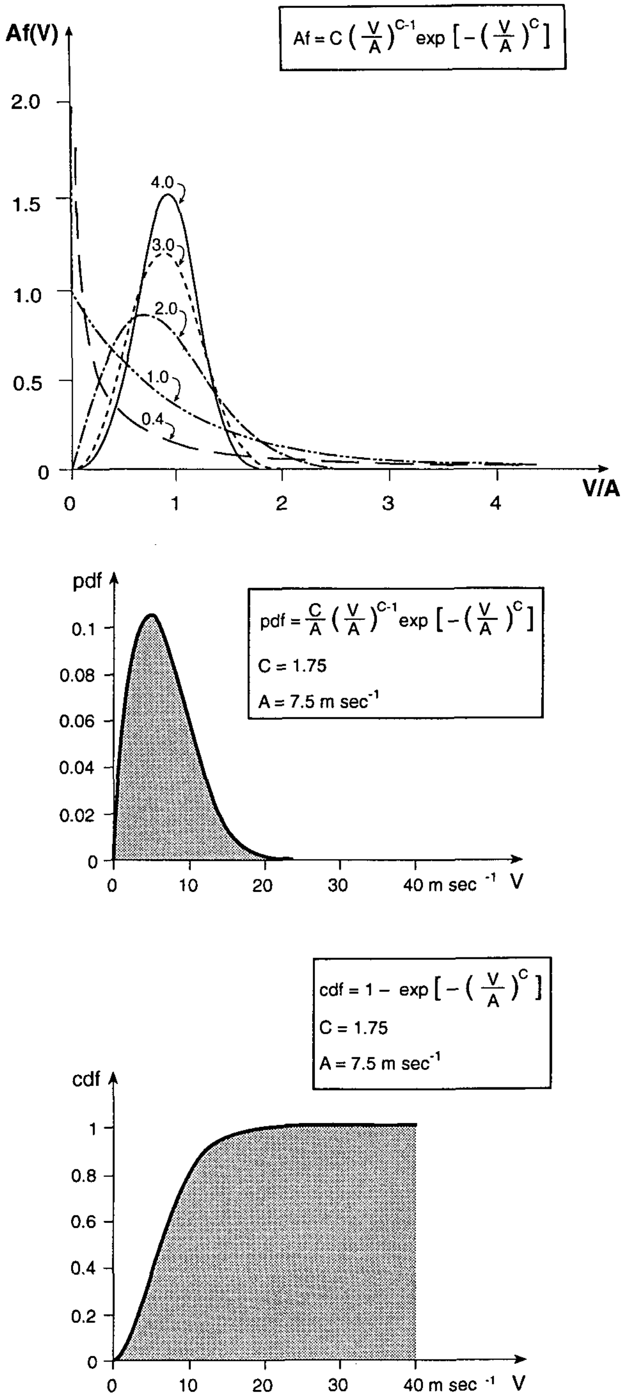

FIG. 4. (a) The shape of the probability density function (PDF) for different values of the Weibull parameter C (ranging from 0.4 to 4.0). (b) The PDF and the cumulative distribution function (CDF) for the specific values of C and A determined from Pavia and O'Brien (1986).

This implies that the probability of, say, a 12-h storm is somewhere between 0.0038 and $(0.0038)^4$. The large probability (0.38×10^{-2}) corresponds to a situation where all storms in the area are long and last for 12 h or more, so that a single measurement is always associated with a 12-h storm. Since the probability represents the ratio between the length of the storm and the time interval between these consecutive storms, it follows that such a storm would occur approximately every 4 months $[12/(0.0038 \times 24 \times 30)]$.

The small probability, on the other hand, corresponds to a situation where the typical storms are relatively short (say, 3 h) so that a continuous 12-h storm requires the appearance of four *independent* storms, one right after the other. The latter situation is analogous to the probability of a 1 turning up in each of four consecutive tosses of a fair die $[(1/6)^4]$. It assumes, of course, that no physical process has any influence on the occurrence of the storms—that is, that the occurrence of one storm does not increase or decrease the probability of another storm. Since the length scale of the Gulf of Suez is considerably smaller than the meteorological synoptic scale, it is reasonable to assume that the occurrence of one storm may perhaps increase, but certainly does not decrease, the probability of additional storms, implying that the independence assumption will indeed give the lower probability bound.

Local meteorologists argue that typical storms in the area in question are neither short nor long and last, on the average, 4–6 h. This is supported by direct measurements taken by the Israeli Nuclear Research Center at Dimona, located approximately 300 km northeast of the Gulf of Suez at roughly 31.23°N, 34.30°E (see Table 1). Hence, it is reasonable to consider a storm of 12 h as if it consists of two independent storms of 6 h each, and this gives us a probability of $(0.0038)^2$. Such a probability corresponds to a likelihood of once in approximately 100 years $\{12/[(0.0038)^2 \times 24 \times 365]\}$. The apparently trivial multiplication corresponding to the 100-yr period has been presented in detail because it is not necessarily obvious how the time intervals are taken into account.

In addition to requiring that our 20 m s^{-1} wind will last for 12 h, we also require that it will blow during the night rather than the day (in accordance with the biblical description), and that it will blow from the north-northwest (as required by our model). Direct wind measurements in the area (Manes et al. 1980) suggest that the wind blows from the north-northwest 30% of the time. (Note that this percentage corresponds to an average over the year and is smaller than the averages over the spring or summer, which are typically the stormiest periods of the year.) In view of the above requirements, we find that the likelihood of our desired storm is approximately once every 700 years $(100 \times 2/0.3)$. It is implicitly assumed in the above analysis that, for a random variable x, the mean of the inverse $\langle 1/x \rangle$ is of the same order as the inverse of the mean, $1/\langle x \rangle$.

Interestingly, however, the above once-every-700-yr likelihood is not the final answer to our question because the Weibull distribution prediction is sensitive to the choice of the parameters A and C. In the above calculation, we took A and C to be 7.5 m s^{-1} and 1.75 (respectively) from the Pavia and O'Brien computations and argued that this is a reasonable choice. An equally reasonable choice, however, is 7.0 m s^{-1} and 1.77, and these give a period of 3400 years which is five times greater than the previous estimate of 700 years. Consequently, at this point we can say only that the likelihood of our storm is once in a period that is $O(1000 \text{ yr})$. In the following section, this result will be confirmed using direct wind measurements along the Gulf of Suez.

TABLE 1. Duration of storms that took place once during 1967–73 at Dimona, which is located approximately 300 km northeast of the Gulf of Suez. Courtesy of Dov Skibin, Israel Nuclear Research Center, Dimona.

Wind duration (h)	4	5	6	7	8	12	17
Maximum average hourly wind speed (km h^{-1})	87	82	70	64	60	54	48

3. Direct wind measurements

A summary of frequency of velocity observations presented by Manes et al. (1980) for the stations shown in Fig. 5 is given in Table 2. From the given annual averages of the frequencies, it can be seen that the annual average likelihood of a 20 m s^{-1} wind or stronger (for the four stations) is 0.2% [i.e., the average of the annual (boldfaced) percentages shown in Table 2 $(0.002 \times 3 + 0.001 \times 2 + 0.001)/4$]. Note that in contrast to the Weibull distribution for winds in the Indian Ocean (discussed in section 2), which is based on 3-h averages, the present analysis is based on hourly observations. As before, we now take into account the fact that each strong storm in the area is expected to last about 6 h, so that we require two such storms (one immediately after the other) and regard the two storms as two independent variables. In view of this, we obtain that the likelihood of our storm is one out of 250 000 measurements. Taking into account that this is based on hourly observations and that we require the wind to blow (i) during the night and (ii) from the north-northwest, we find that the likelihood of our storm is once in approximately 2400 years $\{2 \times 12/[(0.002)^2 \times 24 \times 365 \times 0.3]\}$.

If we limit our attention to the month of April rather than the entire year, the likelihood of our desired storm is greater because April is usually stormier that the rest of the year. The average frequency for a storm sustaining winds of 20 m s^{-1} (or stronger) occurring in April is found from Table 1 to be 0.9%. This gives the likelihood of our storm as once in approximately 1400 years $\{2 \times 12/[(0.009)^2 \times 24 \times 30 \times 0.3]\}$. Both of the above computations probably overestimate the

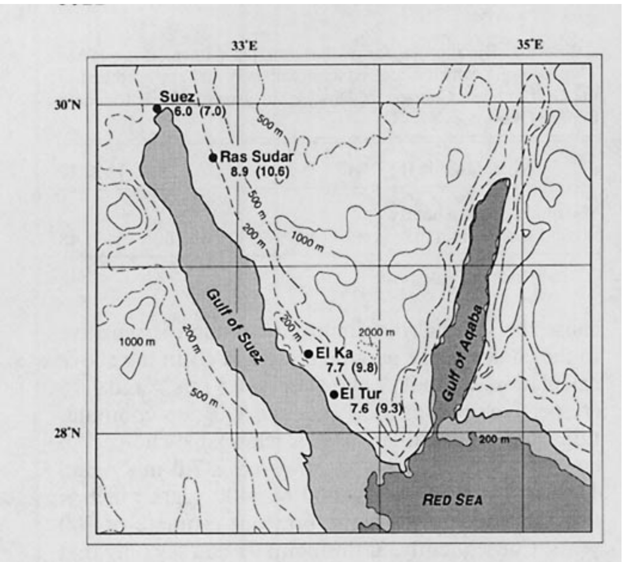

FIG. 5. *Distribution of annual mean wind speed and root-mean-cubed wind velocity in four stations along the Gulf of Suez.* Numerals indicate the annual mean wind speed (m s^{-1}) and the root-mean-cubed wind speed (in parentheses). Record periods are: Suez (29°57′N, 32°36′E), 1970–73; Ras Sudar (29°37′N, 32°53′E), 1976–77; El Ka (28°30′N, 33°25′E), 1970–72; El Tur (28°15′N, 33°37′E), 1970–76. Stations Suez, El Ka, and El Tur were approximately at sea level, whereas Ras Sudar was about 200 m above mean sea level. Adapted from Manes et al. (1980).

TABLE 2. Frequency velocity computations of wind data (%) from four stations along the Gulf of Suez: (a) Suez, (b) Ras Sudar, (c) El Ka, and (d) El Tur. Locations of stations are shown in Fig. 5. Note that all stations are situated approximately at mean sea level except Ras Sudar (b) which was located about 200 m above mean sea level. This may have contributed to the relatively high readings in (b). Frequencies were computed from hourly observations obtained from various records. The Suez station (a) was in operation during the period 1970–73, Ras Sudar 1976–78, El Ka 1970–72 and El Tur 1970–76. Reproduced from Manes et al. (1980).

		Wind speed interval (m s^{-1})										
	Month	20.0	20.5	21.0	21.5	22.0	22.5	23.0	23.5	24.0	24.5	25.0
(a)	Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mar	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Apr	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sep	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Oct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Annual	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(b)	Jan	0.2	0.2	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0
	Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mar	0.1	0.4	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0
	Apr	0.4	0.7	0.1	0.5	0.4	0.1	0.1	0.1	0.0	0.0	0.1
	May	0.5	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1
	Jun	0.3	0.4	0.3	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0
	Jul	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Aug	0.5	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sep	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Oct	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Dec	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Annual	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	0.0	0.0	0.0	0.0	0.0	0.0
(c)	Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Feb	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mar	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
	Apr	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Jun	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Jul	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sep	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Oct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Annual	**0.1**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(d)	Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mar	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Apr	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Jun	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sep	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Oct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Annual	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

likelihood of our storm because the Ras Sudar station, which was situated at a height 200 m above mean sea level, poorly represented the conditions along the sea surface at the gulf. If this station is excluded from the computation, then the likelihood of our desired storm to occur in April decreases to once every 2400 years. Note that, although it is known that during April the likelihood of a wind blowing from the north-northwest is greater than the annual 30% likelihood, we have not taken such an increase into account because we did not have any reliable data on which to base such a computation.

Given the limitations of our calculations and the fact that the Weibull distribution predictions (section 2) were based on data taken outside the Red Sea, the agreement between the two methods of calculation is good. The probability computations based on direct data that exclude the Ras Sudar station provide probably the most accurate approximation.

4. The linear response to wind

As mentioned in NP, attempts to explain the crossing of the Red Sea in terms of natural phenomena and wind action can be traced at least as far back as the nineteenth century (e.g., see Bartlett 1879). Since the Exodus was always a subject that intrigued scholars, it is reasonable to suppose that attempts to explain the crossing had been made even earlier, but that their records did not survive. An excellent review is provided by Bartlett (1879), who actually traveled from Egypt to Palestine attempting to personally identify the exact route of the Israelites. Bartlett notes that the tip of the Gulf of Suez is the most likely site for the crossing. He disputes the arguments that the biblical Red Sea was used in reference to another body of water (where reeds are common) on the ground that it is inconsistent with the Septuagint Version of the Bible, the translation of which to Greek clearly identifies the Red Sea as our present Red Sea. Furthermore, Bartlett notes that the tides are relatively high at Suez, and that the crossing was probably a result of a strong northwest wind. Also, following others, he identified a ridge in the northern part of the gulf and argues that the crossing might have occurred along that ridge (Bartlett 1879, pp. 161 and 168).

Dayan (1978) made the first attempt to actually compute the necessary conditions for crossing. He used the well-known linear oceanic response to wind stress:

$$\xi = -\frac{\tau L}{gH\rho_w}, \qquad (4.1)$$

where, as before, ξ is the sea level drop, τ the wind stress, L the length of the gulf, H the depth, g the gravitational acceleration, and ρ_w the density of the water. Recognizing that the likelihood of a wind of, say, 20 m s^{-1} over the Gulf of Suez is very small and that it gives a linear wind setdown of merely 1.5 m, Dayan suggested that a combination of wind and extremely low tide could perhaps expose a submerged ridge.

He argues that extreme low tides reach values as low as one meter below the mean sea level. This is somewhat higher than the value given by Morcos (1970) for the entire Gulf of Suez (quoted in NP) but is in agreement with the calculation of Arad (1971), who showed that in the tip of the gulf (i.e., at Suez), the tides are considerably higher than in the rest of the gulf. Assuming that the tides at the time of the crossing can be determined from the tides today, Dayan goes as far as to identify the day and the time of the day when the crossing presumably took place. Furthermore, using hydrographic maps from the period prior to the construction of the Suez Canal, he identified a ridge where the crossing presumably occurred. Dayan claimed to be the first to identify such a ridge, but in fact the same ridge was identified by Bartlett 100 years earlier.

Three comments should be made with regard to Dayan's analysis. First, Dayan based his computations on the fact that the Hebrew calendar is a lunar calendar, so that a given day of the month 3500 years ago corresponds to the same phase of the moon that it does today. He therefore considered his tidal computation for 1959 as also being adequate for 3500 years ago. The assumption that the topography and geography have not changed during the last 3500 years is, of course, inherent in the above considerations. Although it is technically possible to determine the tides 3500 years ago from the tides today, it seems that Dayan's computations are not sufficiently accurate to make any statement regarding a specific tide in a given day or a given hour.

This is so because (i) he neglects the effect of the sun, which is out of phase with the moon and which in Suez constitutes 20% of the total tidal effect (Arad 1971); (ii) he neglects the sea level rise, which in the Mediterranean[1] has been a few meters (Barnett 1990), an amount that is not at all negligible compared to the mean depth of the gulf (36 m); and (iii) he neglects the fact that the rules governing the Jewish calendar were determined in the fourth century; prior to this period, each lunar month was declared following eyewitness testimony. This implies that a given biblical month does not necessarily correspond to the same (lunar) month today, and consequently one cannot relate events accurately.

According to Dayan, the low tide necessary for his tide–wind mechanism occurs twice a day and lasts slightly more than an hour each time so that overall it occurs during approximately one-tenth of the day. Not all days, however, have the low tides required by the Dayan mechanism. Taking into account the fact that approximately one-third of the days are subject to high tides, one-third to no significant tides, and one-third to low tides required by the Dayan mechanism, we find that the likelihood of Dayan's mechanism is about $(1/3)(1/10) = 1/30$ the likelihood of our mechanism. This is so because the required tides are present only about 3% of the time. Namely, since both the time of the crossing and the specific times of the tide are uncertain, we must regard the possibility of crossing at a particular low tide as being entirely accidental. This implies that the Dayan event is likely to occur no more than once every 40 000–80 000 years, much greater than the NP nonlinear mechanism that is likely to occur once every 1000–3000 years.

Although the wind–tide combination is certainly possible, we find it hard to believe that tides were *crucial* to the crossing. This is not only because of the extremely low probability of the Dayan's mechanism, but also because we speculate that the Egyptians, who dug canals, built the pyramids, and were probably closer to the land than most civilizations today, could not have been ignorant of a tidal regime that repeats itself every two weeks. Being aware of such a tidal regime, they could easily avoid getting trapped on a temporarily exposed ridge.

The second comment that should be made with regard to Dayan's work is that, in contrast to both Hell-

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[1] Note that, even though the Red Sea and the Mediterranean were not connected at the time, it is reasonable to assume that sea level variations in these two close bodies of water were probably similar.

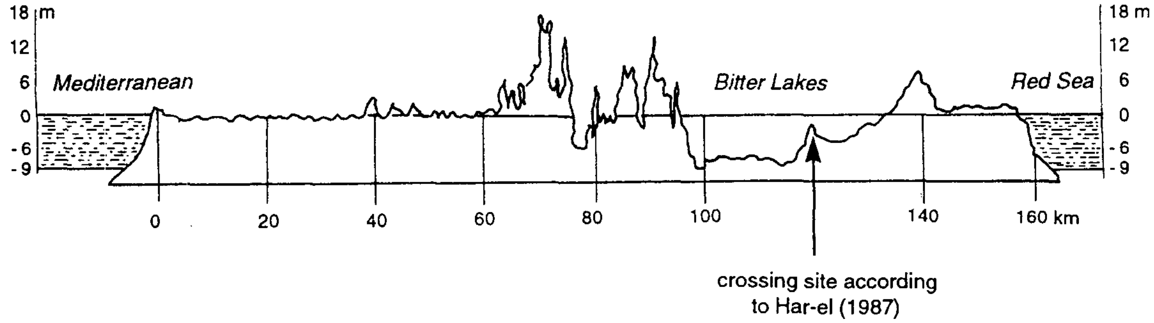

FIG. 6. A cross section from the Gulf of Suez (right) to the Mediterranean Sea (left) prior to the construction of the Suez Canal (adapted from Trumbull 1884).

ström (1950) and Har-el (1987), Dayan rejected the lakes situated between the Mediterranean and the gulf as a possible crossing area because of the absence of significant tides there. NP also rejected the area as a potential crossing site, but they did so for entirely different reasons. As already briefly alluded to in NP, the lakes are too small to allow a significant drop in the water level due to wind. For instance, the ridge that Har-el (1987) suggested as a possible crossing site (Fig. 6) is fairly close to the center of the (connected) lakes that, from basic theoretical considerations, is expected to be a nodal point. A south-southeast wind would indeed cause a drop of the water level, but because of the proximity of the ridge to the lake center ($\sim$4 km) and the fact that the average depth of the lake is 4–6 m, even a hurricane sustaining winds of 35 m s^{-1} (70 kt) will cause a sea level depression of only 30 cm above the ridge. Such a drop is certainly insufficient to expose the approximately 2-m-deep ridge.

Third, since the changes in both sea level and the level of the continents are estimated to be a few meters in a few thousand years and since erosion is common in the area in question, it seems that attempts to identify specific ancient underwater ridges with a height of a few meters will probably be unsuccessful.

5. Conclusions

We have demonstrated that the likelihood of the storm necessary to "part" the Red Sea (20 m s^{-1} north-northwest wind blowing for 8–14 h over the Gulf of Suez) is once in a period of $O(1000 \text{ yr})$. We suggest that the Red Sea crossing has been termed a "miracle" simply because the above likelihood period is greater than the human life span, so that even if it occurred at a given time prior to the legendary crossing, it was not remembered by later generations.

Both our earlier article (Nof and Paldor 1992) and the present one represent a departure from the traditional trend of physical oceanographic research, as their main aim is not limited to advancing physical oceanography per se. As one of the NP reviewers has pointed out, our exact nonlinear wind setdown solution could have been applied to many other situations and published as a more traditional physical oceanographic article. We chose to deal with this unusual type of research that advances archeology, biblical history, and religion as well as physical oceanography because we view the role of science as an aid not only in advancing its own cause but also in advancing other avenues of human endeavor.

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