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WIND ENERGY POTENTIAL OF COASTAL ERITREA: AN ANALYSIS OF SPARSE WIND DATA

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Abstract—This paper describes an analysis of historical surface wind data for the small country of Eritrea, in northeastern Africa. Winds in this region are directed by summer and winter monsoons in addition to diurnal land–sea effects. An analysis of national Eritrean and historical Italian wind records indicated marginal wind resources in the central highlands near the Eritrean capital of Asmera. An analysis of wind speed records recorded at two sites in the southern port city of Aseb indicate mean annual 10-m wind speeds of 9.5 m s^{-1} at the windier site. Surface wind speed records for the Red Sea suggest that similar potential may be found along the lower 200 km of the Eritrean coastline. Based on these findings, wind-generated electricity in this region should be substantially cheaper than the current supply generated from imported diesel.

1. INTRODUCTION

The Eritrean Department of Energy is currently investigating the availability of a variety of power sources needed to rebuild the Eritrean infrastructure after several decades of war with Ethiopia. This report is based on a study that was undertaken to supply the Eritrean Department of Energy with information about wind-energy resources in Eritrea (Rosen, 1998).

Some introductory studies of wind resources in and around Eritrea have previously been conducted. Studies of the region surrounding the Red Sea and Gulf of Aden have issued promising results, especially for coastal areas (Elliott and Renne, 1987; Pallabazzer and Gabow, 1991; Radwan, 1987). Mulugetta and Drake (1996) conducted a study of wind potential for Ethiopia that included Eritrea. Their analysis included four Eritrean sites: three in the central highlands, and one at Aseb on the southern coast.

This study reports mean annual wind speed estimates for nine sites not included in previous studies, including a detailed wind assessment based on a combined total of 13 years of wind data for two sites at the windy southern port city of Aseb. In addition, an analysis of surface wind speeds over the southern Red Sea is provided to assist in predicting wind potential along the Eritrean coastline.

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2. STUDY AREA

Eritrea occupies the southernmost 1200 km of the western Red Sea shoreline, including hundreds of islands near the major ports of Mitsiwa'e (Massawa) in central Eritrea and Aseb (Assab) in the south (see Fig. 1). The capital, Asmera (Asmara), is located in central Eritrea on a plateau at over 2000 m elevation. This high plateau and the surrounding hillsides are known as the central highlands. To the west and east are the western and coastal lowlands, respectively. The western lowlands have a semiarid climate and consist chiefly of desert hills and savanna. On the eastern border with the Red Sea lies a wide arid coastal plain that stretches the entire length of Eritrea. About 100 km south of the main Eritrean port at Mitsiwa'e, the coastal plain dips to 100 m below sea level at the Danakil Depression, an uninhabitable desert that divides the central highlands in the west from a much smaller range of mountains in the east. This second mountain range parallels the shoreline from the Danakil Depression to beyond the Djibouti border, reaching almost 2000 m at its highest point.

The estimated population of Eritrea is 3.6 million (Central Intelligence Agency, 1997). Of

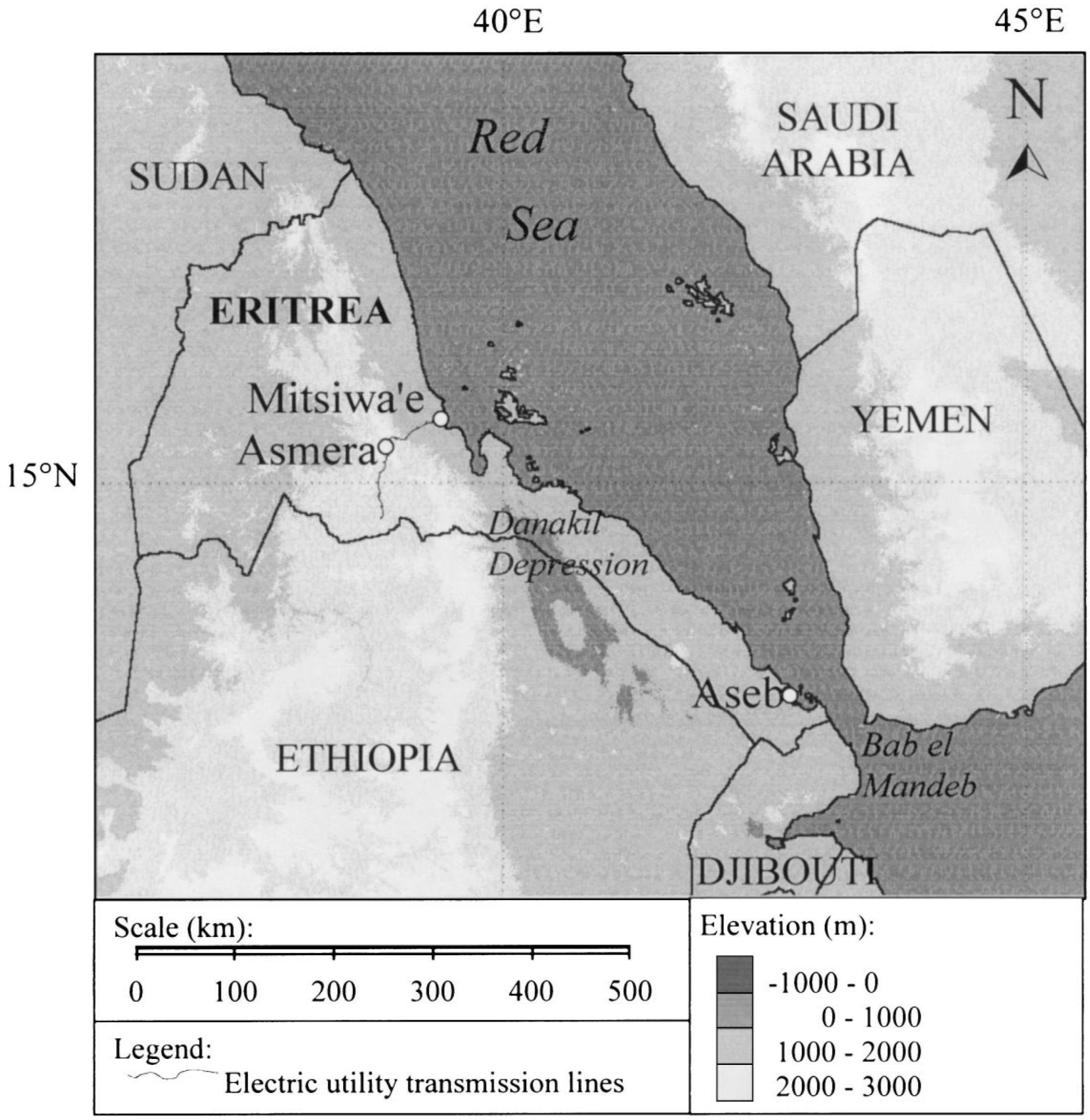


Fig. 1. Map of Eritrea showing topography, major cities, the national electrical grid, surrounding countries, and major bodies of water.

that number, roughly 20% inhabit the capital, Asmera. Although accurate population counts for other major cities are not available, it is estimated that more than half of the Eritrean populace lives in the towns and cities of the highlands, due in part to the wetter and cooler climate found there. Because of the heat and aridity of the lowland areas, settlements below 1000 m are relatively sparse. The largest city in the coastal lowlands is Aseb, a port city of about 50 000 people located at the southernmost tip of the Eritrean coastline, where summer temperatures average 35–45°C and annual rainfall averages about 4 cm.

The main national electric grid has a formal capacity of 40 MW. Transmission lines stretch from Mitsiwa'e to Asmera, and then continue to the south for a combined length of about 500 km (see Fig. 1). A second grid with a formal capacity of 17 MW is located at Aseb. In practice, however, the actual generation capacity in Eritrea is approximately one half the formal generation capacity because many generators are old and inefficient.

Wind patterns in the Red Sea region are controlled to a large extent by two distinct monsoons that are separated by 30 to 45 days each. During the Northeast Monsoon from November to March, the combined effects of the African Equatorial Low and the Siberian High pressure systems create a strong southeast wind

Table 1. Approximate (±1 m s^{-1}) mean annual 10-m wind speeds (MAWS) based on data recorded at seven stations in the Eritrean highlands and western lowlands, 1994–1995

Station	Geographical coordinates		MAWS (m s^{-1})
Asmera	15° 17′ N	38° 55′ E	3
Filfil	15° 36′ N	38° 57′ E	1
Kerkebet	16° 18′ N	37° 24′ E	3
Omhajer	14° 20′ N	36° 39′ E	2
Shambiko	14° 57′ N	37° 53′ E	2
Sh'eb	15° 51′ N	39° 03′ E	2
Tsorena	14° 39′ N	39° 13′ E	2

that is pulled through the narrow Bab el Mandeb at the southern mouth of the Red Sea. This wind slows as it continues toward Mitsiwa'e where it converges with the ever-present northwest wind, a result of the Azores High, at about 16° north latitude. Much of this air mass is drawn southwestward across the Eritrean highlands toward the African Low centered in southern Sudan. During the Southwest Monsoon from May to September, the Azores High and the Pakistani Low cause surface winds along the entire length of the Red Sea to blow from the northwest down the length of the Red Sea and out into the Gulf of Aden (United States Naval Oceanography Command Detachment, 1993).

3. STUDY OVERVIEW

In our initial search, four sources of wind speed data were found: recent Eritrean data, historical Italian data, United States Air Force (USAF) surface records, and a US Naval climatic study of the Red Sea. These data sources are described below.

Eritrean data (1994–1995). In 1994, the Eritrean Department of Water Resources began recording 15 min wind speed averages at seven stations located in towns and cities scattered throughout the highlands and western lowlands of Eritrea. Less than one year of data was available for this study; however, rough (±1 m s^{-1}) mean annual wind speed estimates were derived and are summarized in Table 1.

Italian data (1930–1933). During the Italian occupation in the early 1930's, daily average wind speeds were recorded at stations along the Italian-built railroad line from Mitsiwa'e to Keren. Mean annual wind speeds at four of these stations are provided in Table 2.

US Air Force Surface Records (1973–1992). Twenty years of hourly meteorological records were available for several Eritrean cities, including Aseb (42° 43′ E, 12° 58′ N), for which a data set containing 13 discontinuous years of observations (1973–1980, 1982–1991) was obtained. The arithmetic mean of wind speeds in this data set indicated a mean annual wind speed of 8 m s^{-1} at Aseb.

US Navy Climatic Study of the Red Sea. A 1982 climatic study of the Red Sea conducted by the United States Navy mapped monthly averages with 1° spatial resolution. For seven of the 12 months (October–April), the report shows mean annual speeds of between 6 and 10 m s^{-1} off the southern half of the Eritrean coastline. For the remaining months (May–September) the report indicates mean wind speeds between 3 and 5 m s^{-1}.

While these estimates suggest that wind resources in the highlands may be inadequate for utility-scale wind generation, one must keep in mind that the highland stations were not sited for wind prospecting purposes, and so are unlikely to have recorded the highest wind speeds in the region. VanBuskirk et al. (1997) argue that the channeling of wind through the hills and valleys of the highlands is likely to create areas in which wind speeds are significantly enhanced. The Eritrean Department of Energy has been collecting additional wind data in the mountain passes near Asmera in an attempt to locate such sites. Estimates based on preliminary measurements indicate the existence of sites with mean annual wind speeds exceeding 5 m s^{-1}.

Wind data obtained for Aseb and the Red Sea produced more promising results than did data for central Eritrea. The USAF surface records for Aseb indicated a mean annual wind speed of 8 m s^{-1}, while the Naval report for the Red Sea indicated mean monthly wind speeds as high as

Table 2. Mean annual 10-m wind speeds (MAWS) based on historical Italian data for four stations in the Eritrean highlands, 1930–1933

Station	Geographical coordinates		MAWS (m s^{-1})
Asmera	15° 17′ N	38° 55′ E	2.7
Faghena	15° 10′ N	39° 28′ E	2.1
Keren	15° 46′ N	38° 27′ E	1.9
Mitsiwa'e	15° 37′ N	39° 27′ E	3.7

10 m s^{-1} just off the southern coast. Although electricity demand in Eritrea is highest in the capital city of Asmera, we chose to pursue a more detailed study of the Aseb area based on the wind speeds recorded there. Analyses of winds at two Aseb sites and of winds over the Red Sea are presented below.

4. ASEB DATA AND ANALYSIS

The Eritrean Civil Aviation Department maintains two meteorological stations at Aseb, one at the Aseb Airport about 15 km northwest of Aseb and one at the Seaport within the city.[1] The Airport station is located in a flat, open plain at about 10 m elevation. The Seaport station is at the shoreline, sheltered by buildings on the northwest side (see Fig. 2).

The wind speed observations in the USAF data set for Aseb were estimated and recorded by personnel of the Eritrean and/or Civil Aviation Department. Although these wind speed estimates were based on the rotation of standard 10-m anemometers, wind speeds were visually estimated by personnel rather than mechanically estimated by a data logger. A recent comparison between simultaneous human wind speed estimates and 10-m anemometer readings showed an average error of 3% and an average absolute error of 11%.

Until 1991, weather observations recorded every 3 h were archived by the United States Air Force Environmental Technical Application Center, 1986 (USAFETAC). Observations reported before 1986 were taken at the Airport station, while observations reported after 1986 were taken at the Seaport station. The National Climatic Data Center (NCDC) provided a data set containing thirteen years (1977–1979, 1982–1991) of US Air Force surface observations for Aseb. After removing incomplete or otherwise inconsistent data records, over 5000 observations remained for each station.

As discussed above, weather patterns at Aseb can be divided into two distinct seasons. For this analysis, mean monthly wind speeds calculated by the United States Naval Oceanography Command Detachment (1993) were used to divide the entire multi-year data set into two subsets corresponding to the two seasons. From this point on, May–September will be referred to as the summer season while October–April is referred to as the winter season.

Each seasonal subset was further divided according to whether the observations were recorded at the Airport or the Seaport station. The resulting four subsets were analyzed independently. A preliminary statistical analysis of the four data subsets is presented in Table 3.

Although the number of observations did not differ significantly on a month to month basis, observation patterns did vary widely on an hourly basis. Midnight and early morning observations were comparatively few, and for the first eight years were practically non-existent. To compensate for the fact that more observations were made during the daytime when wind speeds are highest, the four data subsets were each divided into eight 3-h bins that were analyzed separately. Because records for late evening and early morning hours were not recorded on a regular basis until after the observation site was moved to the Seaport, six of the 16 data subsets for the Airport contained insufficient data for analysis. Fig. 3 illustrates the data divisions and the number of observations in each subset.

To derive the mean annual wind speed at the Airport, it was necessary to estimate mean wind speeds for the 21:00, 0:00 and 3:00 data subsets. First, mean values were calculated for the Airport and Seaport data subsets that contained sufficient data. A scatter plot was then created using the Airport values as the abscissas and the Seaport values as the ordinates (see Fig. 4). Using regression analysis, a linear correlation was derived between the time-correlated pairs of mean wind speeds at the two stations ($R^2 = 0.96$). Each of the three missing values for the two seasons were then calculated as $\mu_a = m\mu_s + b$, where μ_a and μ_s are the mean wind speeds at the Airport and Seaport, respectively, and $m = 1.043$, and $b = 2.179$ are the slope and y-intercept, respectively, found in the regression analysis.

To provide accurate annual wind speed distributions for the two Aseb sites, it was necessary once again to estimate values for the empty data bins at the Airport. Therefore, we planned to calculate Weibull parameters for the subsets with sufficient data, and then use them to estimate the Weibull parameters for the subsets with insufficient data. From these estimated parameters, model distributions for the empty subsets could then be constructed. At this point, however, it

[1] The US Air Force database did not indicate the existence of two separate stations. An apparent change in mean annual wind speed and observation patterns late in 1986 alerted us to the situation. The existence of the two stations and date of transition were affirmed by visiting the two stations and reviewing the logs.

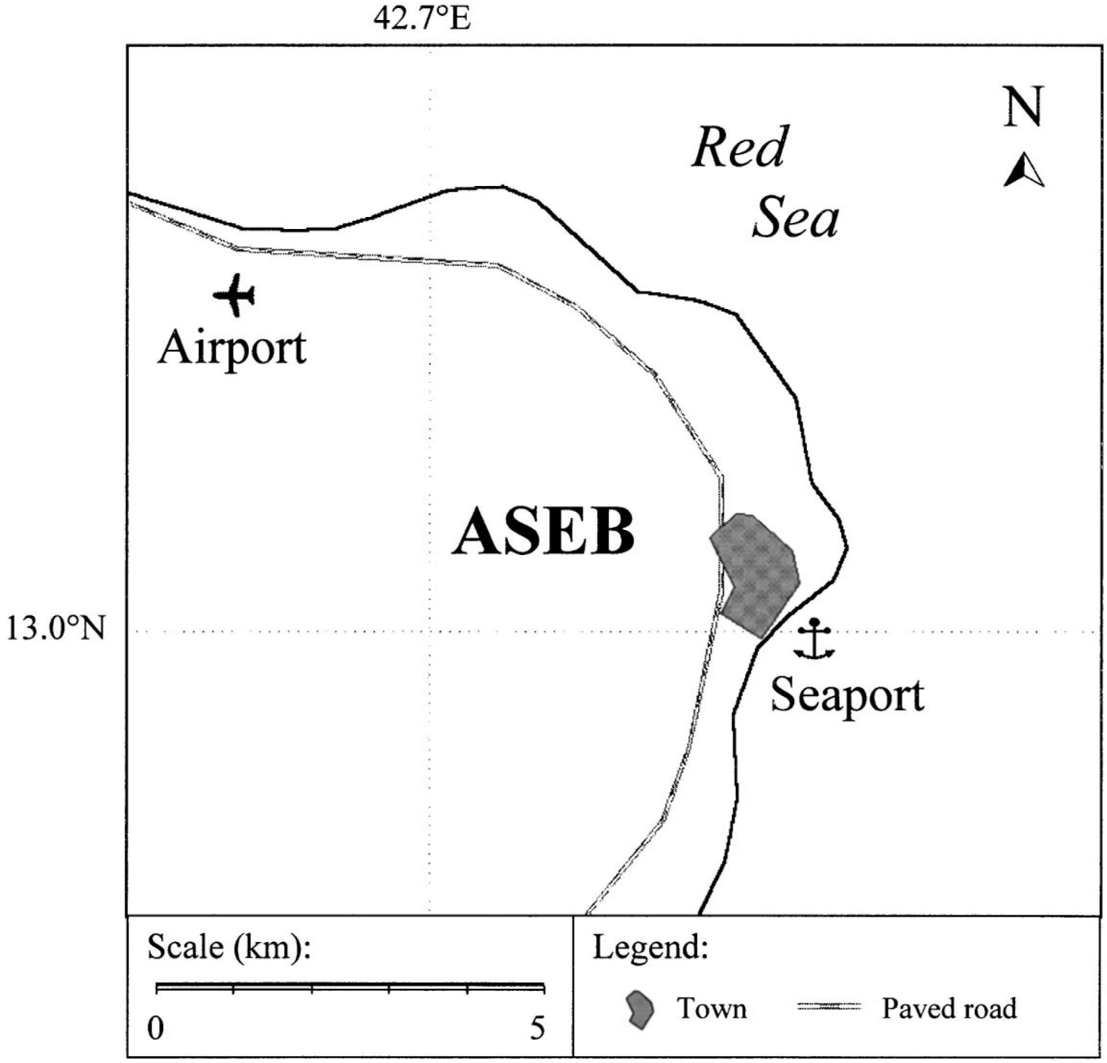


Fig. 2. Map showing the Airport and Seaport meteorological stations at Aseb, where the US Air Force data were recorded.

became clear that the wind speed database for Aseb contained an unusually large number of calms. This presented a problem because the standard Weibull distribution does not allow for a wind speed of 0. To resolve this problem, we employed a method described by Mulugetta and Drake (1996) in which a Weibull distribution is fit to the observed distribution above 0 $m\,s^{-1}$, and calms are considered separately. This method tends to provide a more conservative estimate of mean wind speed by assuming that the reported frequency of calms is correct, whereas the standard Weibull distribution assumes that the frequency of calms is 0. This is particularly im-

Table 3. Results of a preliminary statistical analysis of US Air Force wind speed data for Aseb

	Airport		Seaport	
	Summer	Winter	Summer	Winter
No. of observations	2593	3258	1899	3244
Minimum ($m\,s^{-1}$)	0.0	0.0	0.0	0.0
Maximum ($m\,s^{-1}$)	31.0	42.2	30.0	44.0
Arithmetic mean ($m\,s^{-1}$)	7.7	12.1	4.8	9.1
Variance ($m\,s^{-1}$)	18.3	25.0	13.1	20.8
Standard deviation ($m\,s^{-1}$)	4.3	5.0	3.6	4.6
Standard error	0.08	0.09	0.08	0.08
Skewness	0.26	0.14	0.92	0.21
Kurtosis	0.19	1.33	1.64	0.92

Airport	0	3	6	9	12	15	18	21
Summer	-	-	214	836	633	666	224	-
Winter	-	-	320	1002	761	865	275	-

Seaport	0	3	6	9	12	15	18	21
Summer	32	96	206	452	227	401	255	229
Winter	51	207	324	724	392	696	407	440

Fig. 3. Division of the US Air Force data for Aseb, showing number of data points in each seasonal 3-h bin.

portant in the case of the Aseb data, where the observed frequency drops abruptly between 0 and 1 $\mathrm{m\,s^{-1}}$, and then follows the expected Weibull distribution closely.

To the standard Weibull parameters k and A is added a variable s denoting the frequency of calms. The equation of the three-parameter Weibull probability density function is:

$$f(v) = \begin{cases} s, \text{ at } v = 0 \\ (1-s)(kv^{k-1}/A^k)\exp^{-(v/A)^k}, \quad \text{for } v > 0 \end{cases} \tag{1}$$

where v is the wind speed, s is the observed frequency of calms, A is the magnitude parameter, k is the shape parameter, and $f(v)\mathrm{d}v$ is the fraction of time the velocity data is in a bin centered at v, with bin size $\mathrm{d}v$. Note that for $v>0$, the model distribution is simply $(1-s)$ times the standard Weibull distribution.

For each season, this three-parameter Weibull model was fit to the wind speed frequency distributions for the 13 subsets containing sufficient data. A best fit was obtained by minimizing the sum of the squared differences between points on the observed frequency distribution and the Weibull distribution. After calculating the three parameters of k, A and s for each subset, a scatter plot was then created using the Airport values as the abscissas, and the Seaport values as the ordinates (see Fig. 5).

As can be seen in Fig. 5(a), the scatter plot of k-values found at the Aseb Airport and Seaport did not indicate a clear linear correlation ($R^2=0.6373$); therefore, we used the average seasonal k value at the Airport to estimate the three missing values.[2] For both A and s, acceptable linear correlations were determined between the two stations ($R^2=0.9575$ and $R^2=0.9626$, respectively). The missing values were then calculated as $y=mx+b$, where y and x are the parameters at the Airport and Seaport, respectively, and m and b are the slopes and y-intercepts found in the regression analyses respectively. Mean wind speeds could then be estimated as (Mulugetta and Drake, 1996):

$$\mu = A\Gamma(1/k+1)(1-s) \tag{2}$$

Seasonal wind speed frequency distributions at the Airport were calculated as the average of the five observed and three estimated frequency distributions for each 3-h bin for each season. Seasonal wind speed frequency distributions at

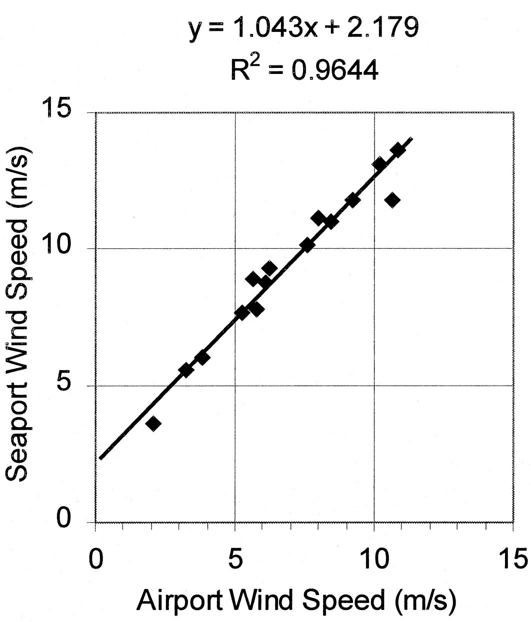


Fig. 4. Scatter plot showing the correlation between mean wind speeds at the Aseb Airport and Seaport.

[2]Many different methods were used to estimate the Weibull parameter of k for the empty bins, including averaging, linear correlations and non-linear correlations. All methods provided nearly identical mean annual wind speeds (± 0.5 $\mathrm{m\,s^{-1}}$). We chose to present the averaging k-value method because, of the methods tested, it resulted in the most conservative wind speed estimates.

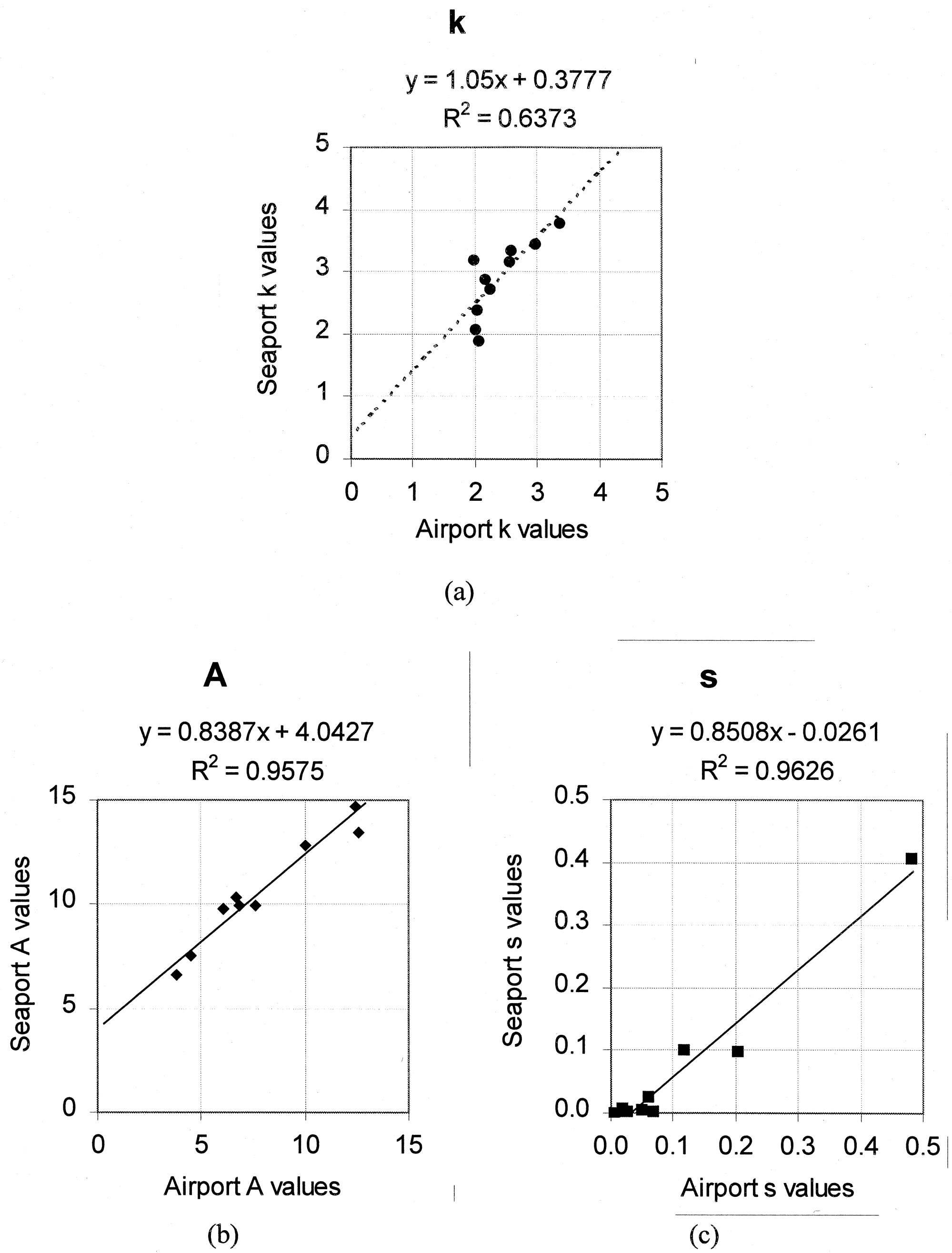


Fig. 5. Scatter plots showing correlations between Airport and Seaport *k*, *A* and *s* values.

the Seaport were simply calculated as the average of the eight observed frequency distributions. For this study, we defined the summer season as the five months from May to September and the winter season as the seven months from October to April; therefore, annual distributions for each station were calculated as:

$$f(v) = \frac{5}{12} f_s(v) + \frac{7}{12} f_w(v) \quad (3)$$

where $f(v)$ is the annual wind speed frequency distribution, and $f_s(v)$ and $f_w(v)$ are the summer and winter wind speed frequency distributions, respectively. Three-parameter Weibull distributions were then fit to the resulting annual wind speed distributions to derive Weibull parameters for the aggregated data at each site.

Wind power density is the amount of wind power available in a plane perpendicular to the direction of the wind. In this study we calculate the mean annual wind power density for each 3-h data bin as:

$$\sum \frac{1}{2} \rho v^3 f(v) \quad (4)$$

where ρ is the average observed air density, v is the wind speed, and $f(v)$ is the wind speed frequency distribution. Mean annual wind power density is calculated as the arithmetic average of the 3-h bin wind power densities.

5. RED SEA DATA AND ANALYSIS

The Comprehensive Ocean-Atmosphere Data Set (COADS) is a global collection of marine observations recorded between 1854 and 1993 that is widely used for studies of ocean winds, temperature, and heat budget. Due to insufficient spatial resolution (1°), observations recorded before 1940 were discarded. The portion of data set retained for this study contained over 650 000 observations.

To account for uneven temporal sampling in the data set, the data were divided into seasonal 6-h bins, resulting in eight data subsets. Mean wind speeds were calculated for each position containing data in all eight data subsets. The arithmetic average of wind speeds in each 0.1° bin was then calculated for each subset. Average seasonal wind speeds were derived as the average of the four 6-h subsets for each season for each 0.1° bin. Mean annual wind speeds were calculated for each 0.1° bin as the sum of 5/12 the summer average and 7/12 the winter average.

6. RESULTS

Unless otherwise noted, results presented here represent wind speed values at 10 m height. It is expected that wind speeds at typical turbine hub heights of 30 m or more would be higher than those presented here. In some cases, however, winds have been known to decrease with height, particularly in mountainous areas. Therefore, we have chosen to present the majority of values at 10 m without making any assumptions about the wind speeds at higher hub heights. Mean wind speed values based on USAF surface records are estimated to be accurate within 5% of given values.

Table 4 shows mean wind speeds calculated from observed wind speed values. Values in italics at 21:00, 0:00 and 3:00 at the Airport were estimated as described in Section 4.

Table 5 shows the parameters obtained using three-parameter Weibull fits to the observed 3-h wind speed distributions. Again, values for 21:00, 0:00 and 3:00 are estimated as described in Section 4, where mean wind speeds are based on Eq. (2). The majority of mean 3-h wind speed values presented in Table 5 are within 2% of the observed mean wind speeds. The greatest difference between calculated values and observed values was 3.3% at 0:00 at the Seaport.

Fig. 6 depicts the mean diurnal wind speed variations at the Aseb Airport and Seaport. Estimated values at 21:00, 0:00 and 3:00 are circled in Fig. 6(b). The higher midday wind speeds shown in both graphs suggest potential for increased power supplies during the peak demand period. Obvious similarities between Figs. 6(a) and 6(b) support the assumption that wind speeds at the two stations are closely related.

Fig. 7 shows the three-parameter Weibull fits to the wind speed distributions at the Aseb Airport and Seaport. In Fig. 7(a), the 'Observed' distribution at the Airport is actually the arithmetic average of the five observed distributions and three estimated distributions (see Section 4). The 'Observed' distribution in Fig. 7(b) is the arithmetic average of the eight observed 3-h distributions at the Seaport.

The amount of electricity that can be generated at Aseb depends on several factors, including the hub height, rotor size, and spacing of the wind turbines, and also the estimated efficiencies of the

Table 4. Results of the analysis of US Air Force data for Aseb, showing mean seasonal and annual 10-m wind speeds (in m s^{-1}) for 3-h periods at the Aseb stations

Eritrean time	Airport			Seaport		
	Summer	Winter	Annual	Summer	Winter	Annual
6:00	3.6	7.8	6.0	2.1	5.8	4.3
9:00	6.0	11.2	9.0	3.8	8.0	6.2
12:00	8.9	13.1	11.3	5.6	10.2	8.3
15:00	9.3	13.6	11.8	6.2	10.8	8.9
18:00	8.8	11.8	10.5	6.1	10.6	8.7
21:00	*7.9*[a]	*11.6*	*10.1*	5.2	9.2	7.5
0:00	*6.1*	*10.9*	*8.9*	3.9	8.4	6.5
3:00	*5.2*	*10.1*	*8.0*	3.2	7.6	5.8
Average	7.0	11.3	9.5	4.5	8.8	7.0

[a] Figures in italics represent values estimated by linear correlation between station wind speeds.

Table 5. Three-parameter Weibull parameters and mean 10-m wind speeds derived from them for seasonal 3-h periods at the Aseb stations

Eritrean time	Airport				Seaport			
	k	A	s (%)	Wind speed ($m\ s^{-1}$)	k	A	s (%)	Wind speed ($m\ s^{-1}$)
Summer								
6:00	2.1	6.6	0.41	3.5	2.0	3.8	0.49	1.7
9:00	1.9	7.5	0.10	6.0	2.0	4.5	0.21	3.2
12:00	2.9	9.8	0.00	8.7	2.2	6.1	0.07	5.0
15:00	2.7	10.3	0.00	9.2	2.2	6.7	0.02	5.8
18:00	3.2	10.0	0.00	8.9	2.0	6.9	0.05	5.8
21:00	*2.6*[a]	*8.7*	*0.06*	*7.3*	2.0	5.6	0.10	4.5
0:00	*2.6*	*8.1*	*0.11*	*6.4*	2.1	4.8	0.16	3.6
3:00	*2.6*	*7.9*	*0.25*	*5.2*	2.3	4.5	0.32	2.7
Summer averages	2.3	8.8	0.12	6.9	2.0	5.5	0.18	4.0
Winter								
6:00	2.4	10.0	0.10	8.0	2.0	7.6	0.12	5.9
9:00	3.2	12.8	0.02	11.2	2.5	10.0	0.06	8.3
12:00	3.3	14.7	0.00	13.2	2.6	12.4	0.03	10.7
15:00	3.5	15.3	0.00	13.7	3.0	12.9	0.01	11.4
18:00	3.8	13.4	0.01	12.0	3.4	12.6	0.02	11.1
21:00	*3.2*	*13.3*	*0.00*	*12.0*	3.2	11.1	0.03	9.6
0:00	*3.2*	*12.1*	*0.02*	*10.6*	4.1	9.7	0.06	8.2
3:00	*3.2*	*12.1*	*0.02*	*10.6*	3.2	9.6	0.05	8.2
Winter averages	3.4	13.2	0.02	11.4	2.4	10.3	0.05	8.7
Annual averages	2.4	11.5	0.06	9.6	1.8	8.9	0.10	7.1

[a] Figures in italics represent values estimated using correlations between station parameters k, A and s.

turbine, array and power system. The calculations presented in Table 6 use the following assumptions: (i) The rotor diameter (D) is 20 m; (ii) the turbine spacing is $10D \times 5D$; (iii) the array and system efficiency is 75%.

A typical annual average wind power density for utility scale energy production is 450 $W\ m^{-2}$ at turbine hub height (Cavallo et al., 1993). The wind power densities shown in Table 6 are high because of the very high wind speeds during the winter months at Aseb. It should be noted, however, that the wind power supply between May and September is expected to be considerably lower.

Fig. 8 shows approximate ($\pm 1\ m\ s^{-1}$) mean annual wind speeds in the Red Sea along the southern Eritrean coastline. According to these results, mean annual wind speeds along the lower 200 km of the southern Eritrean coastline are in excess of 6 $m\ s^{-1}$. This suggests that sites with high wind power potential may be found along much of the lower Eritrean coastline.

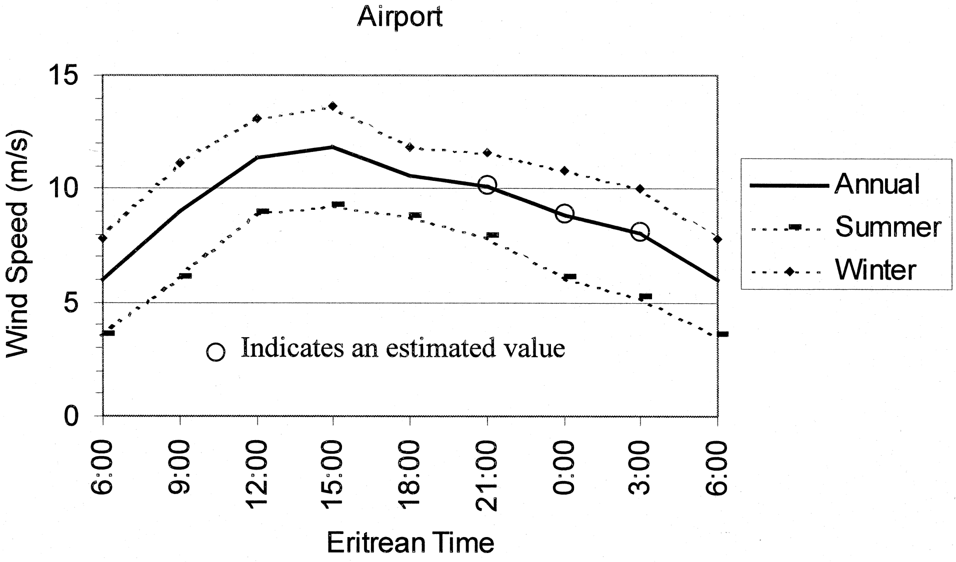
7. DISCUSSION

The results of this study indicate that the mean annual wind speed difference between the Airport and the Seaport is about 2.5 $m\ s^{-1}$. We attribute this to the different levels of wind exposure at the two stations: the Airport is located outside the city and has excellent wind exposure, whereas the Seaport station is located in a developed area within the town. This suggests that the Seaport estimate is not representative of the high wind power potential in the surrounding region.

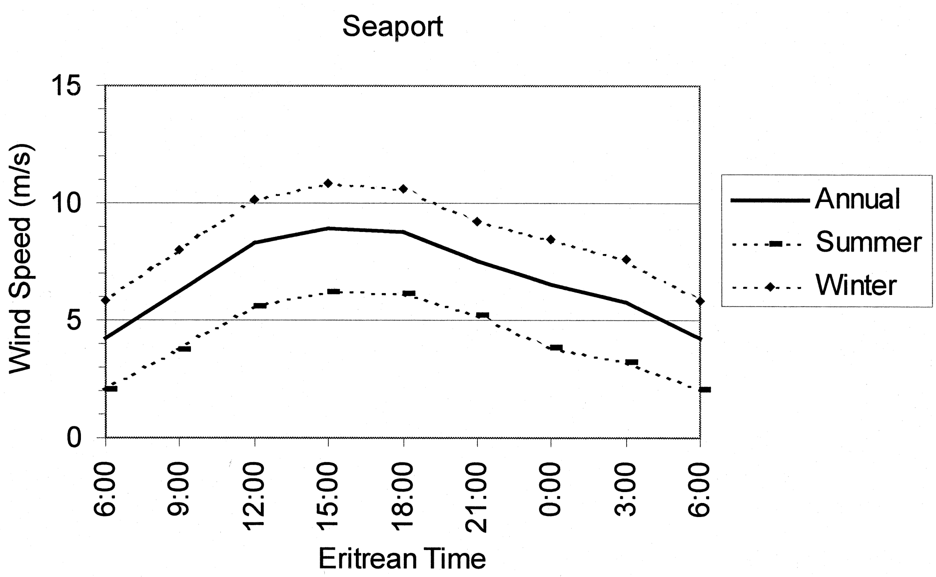
There were several confounding factors in the US Air Force data set for Aseb, including the location change in 1986, the lack of nighttime observations at the Airport and the high percentage of calms recorded at both stations. To account for these factors, several different methods of analysis were used as described in Section 4. It is interesting at this point to note the differences between these results. A summary of the results obtained using four different methods of analysis is presented in Table 7.

As noted previously, inconsistent sampling methods favored the higher daytime wind speeds, resulting in the artificially high values described as ‘Unbinned.’ Standard Weibull fits to the 3-h distributions also produced higher values because they failed to recognize the high percentage of calms recorded at Aseb. The linear correlation and three-parameter Weibull fit methods used in this analysis resulted in much more conservative and probably more accurate mean annual wind speed values.

Wind development at Aseb depends mainly on economic factors. Because of the uncertainties in wind speeds, cost estimates at this stage are highly unreliable; however, the cost of wind-generated electricity at Aseb will almost certainly be lower than the current diesel-generated electricity. The California Energy Commission (CEC)



(a)



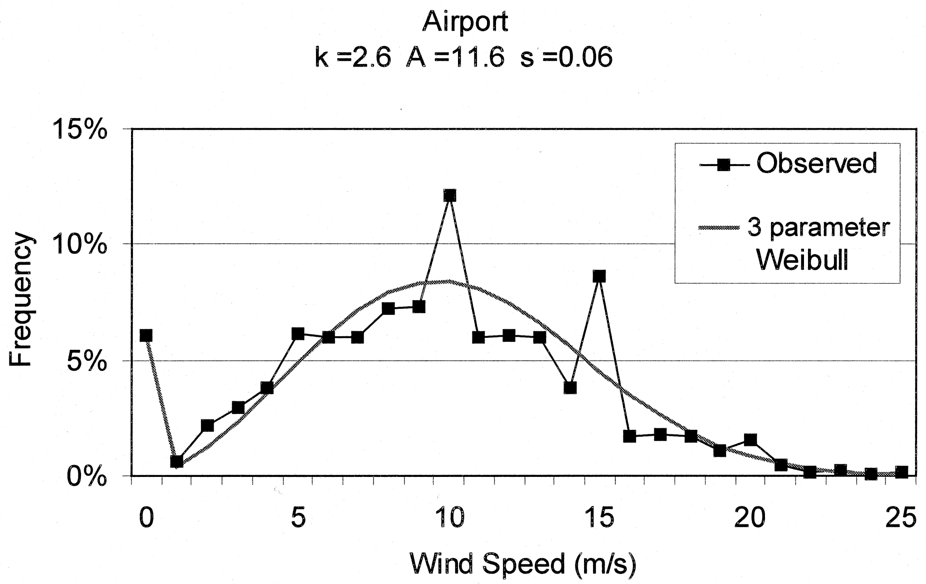
(b)

Fig. 6. Graphs showing mean diurnal wind speed variations at the Aseb Airport and Seaport.

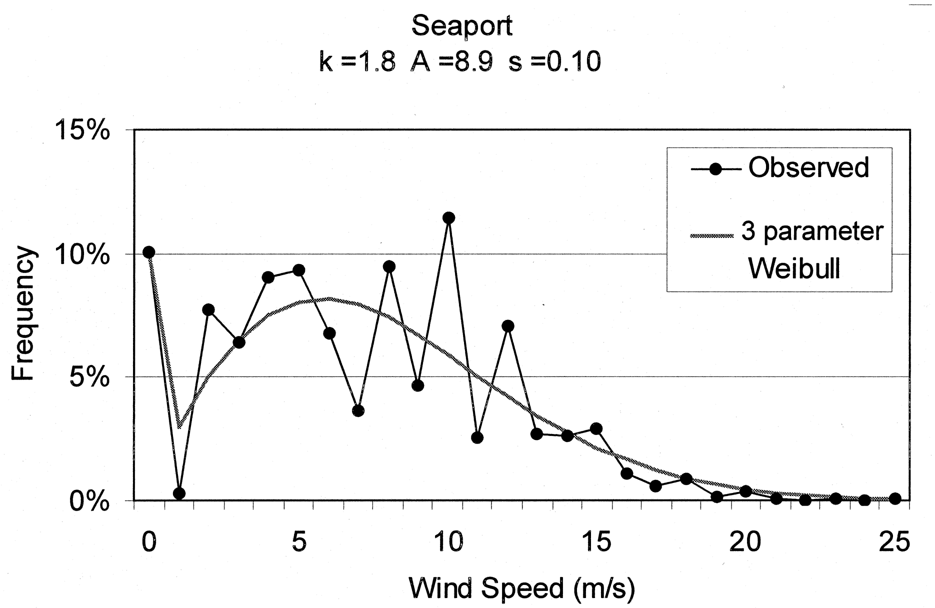
estimates that the cost of wind power at good sites is about US$13 per MJ (4.6 ¢/kW h) (California Energy Commission, 1997). All else being equal, this cost is already less than the cost of diesel fuel at Aseb, which is about US$18 per MJ (6.5 ¢/kW h). Based on the unusually high mean annual wind speed at Aseb, it is safe to assume that the cost of wind power would be even lower than the CEC estimate.

There are several problems associated with wind development at Aseb. The main factor constraining wind power development near Aseb is the relatively small capacity of the Aseb power system. Given that the combined capacity of the power system is only 17 MW, the Aseb utility without expansion could accommodate only about 3 MW of wind (Grubb and Meyer, 1993). This is a minute fraction of the total available wind power at Aseb (see Table 6).

The ample land and wind power resources at Aseb have the potential to offer more power than the entire country could absorb in the foreseeable future. It therefore seems worthwhile to consider options for maximizing utilization of this re-



(a)



(b)

Fig. 7. Graphs showing three-parameter Weibull fits to the observed annual wind speed distributions at the Aseb Airport and Seaport.

Table 6. Projected wind speed, capacity factors, power, and energy output at Aseb, at 10 and 30 m hub height[a]

	Airport		Seaport	
	10 m	30 m	10 m	30 m
Average annual wind speed ($m\ s^{-1}$)	9.5	11.1	7.0	8.2
Wind power density ($W\ m^{-2}$)	905	1454	480	769
Capacity factor (%)		66		44
Wind power available per turbine (kW)		457		242
Electrical power generated per turbine (kW)		226		80
Annual energy output per turbine (TJ)		7.1		2.5
Annual energy output per km^2 ($TJ\ km^{-2}$)		356		126

[a] Height extrapolations to 30 m based on the 1/7 power law. Capacity factors based on the Flowind AWT-27 power curve.

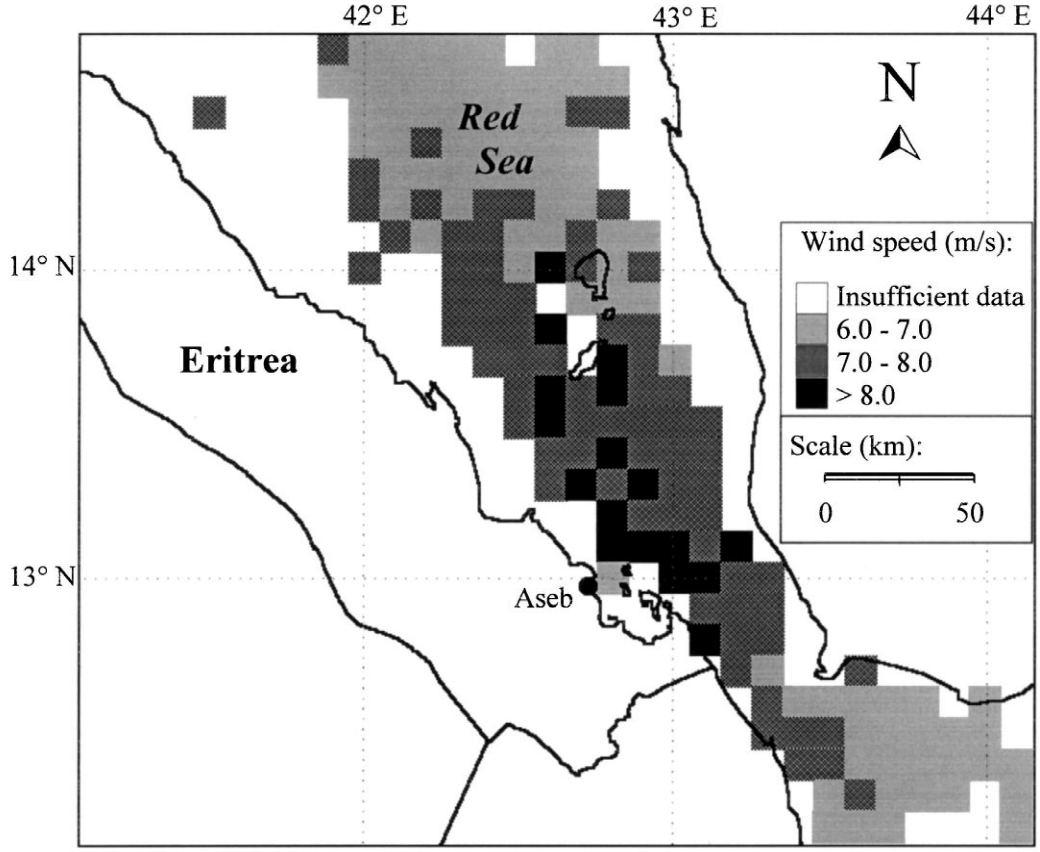


Fig. 8. Map showing mean annual wind speeds in the southern Red Sea off the Eritrean coastline.

source. A plan that would both further exploit the wind resource and level the seasonal loads is a cooperative effort with Ethiopia, in which winter wind power from Aseb is traded for summer hydropower from the Blue Nile region. However, this option may not be feasible due to recent political conflicts with Ethiopia. Another option for distributing excess supply may be to connect the power system at Aseb to the national grid in the central highlands. Although this option is preferable in many respects, construction of transmission lines may be prohibitively expensive and power losses unacceptably high. It may be possible, however, to find high-quality coastal wind power sites that are closer to the power supply system in the central highlands. The analysis of Red Sea winds indicates that high wind speeds may extend as far as 14.5° north latitude, about 300 km from the central grid at Mitsiwa'e. If current wind prospecting efforts in this region are successful, transmission between these two locations may be feasible. Research continues to be

Table 7. Results of different data analysis methods for the Aseb Airport and Seaport, showing Weibull parameters *k* and *A*, mean annual wind speeds (MAWS) and mean annual wind power densities (WPD), all at 10 m height

Method	Airport				Seaport			
	k	*A*	MAWS ($m\ s^{-1}$)	WPD ($W\ m^{-2}$)	*k*	*A*	MAWS ($m\ s^{-1}$)	WPD ($W\ m^{-2}$)
Unadjusted[a]			10.3				7.3	
Linear correlation[b]			9.5	920			7.0	480
Three-parameter Weibull[c]	2.4	11.6	9.6	915	1.8	8.9	7.1	538
Standard Weibull[d]	2.5	11.7	10.4	1025	1.8	9.3	8.3	688

[a] Unadjusted, unbinned arithmetic mean of all data.
[b] Data divided into subsets as shown in Fig. 6. Linear correlation between subset means used to estimate means for empty bins.
[c] Data divided into subsets as shown in Fig. 6. Correlations between three-parameter Weibull parameters, *k*, *A* and *s*, used to estimate parameters for empty bins.
[d] Data divided into subsets as shown in Fig. 6. Correlations between standard Weibull parameters, *k* and *A*, used to estimate parameters for empty bins.

conducted in the Eritrean highlands, but further investigation into power transmission from the southern Eritrean coast to the highland area is also warranted.

Further funding for this project has been procured from the Global Environment Facility (GEF), a joint program between the United Nations Development Program (UNDP), United Nations Environment Program (UNEP) and the World Bank. Results of a full scale wind prospecting effort undertaken under this grant are expected in 1999.

8. CONCLUSIONS

According to these results, the Eritrean coastline has an outstanding wind resource, particularly in the Aseb area. Of the two sites monitored at Aseb, the Aseb Airport site appears to be the more promising. Existing data sources indicate mean annual wind speeds of 9.5 $m\,s^{-1}$ at the Aseb Airport at 10 m height. Such winds can produce more power than the Aseb power system can absorb, but limited development may provide Aseb with a less expensive power source than the current diesel supply. The analysis of Red Sea surface winds presented in this study suggest that similar wind resource potential extends as far as 200 km north of Aseb along the Eritrean coastline.

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