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# MESO- AND MICRO-SCALE FLOW MODELLING IN THE GULF OF SUEZ, ARAB REPUBLIC OF EGYPT

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**SUMMARY**

The results of a comprehensive, 10-year wind resource assessment programme in the Gulf of Suez are presented. The primary purpose has been to provide reliable and accurate wind atlas data sets for evaluating the potential wind power output from large electricity producing wind-turbine installations; a secondary purpose has been to evaluate the applicability of current wind resource estimation and siting tools – in particular the European Wind Atlas methodology – to this region where the meso-scale effects are pronounced and the climatic conditions (e.g. atmospheric stability) somewhat extreme. The wind data are analyzed using the Wind Atlas Analysis and Application Program (WAsP).

The Karlsruhe Atmospheric Meso-scale Model (KAMM) has been used to model the wind flow as well as to establish the magnitude and spatial variation of the wind resource in the Gulf of Suez – based on the NCEP/NCAR global reanalysis data set. Results are compared to long-term measurements of wind speed and direction at 13 meteorological stations along a 250-km stretch of the Gulf of Suez and the northern Red Sea.

The simulations of the wind climate in the Gulf of Suez with the KAMM meso-scale model capture the main features of the complicated flow patterns and of the observed wind climates; however, the mean wind speeds and power densities are somewhat underestimated. The wind resource is found to be very high in the Gulf of Suez – with capacity factors of up to about 70% – at the same time the horizontal gradients of wind speed and power density are quite steep. The combination of meso- and micro-scale flow models – here the KAMM/WAsP methodology or the Numerical Wind Atlas – seem necessary in order to make reliable wind resource assessments in all parts of the Gulf of Suez.

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## INTRODUCTION

The wind resources in the Gulf of Suez in Egypt have recently been assessed by the New and Renewable Energy Authority and Risø National Laboratory; the results are reported in detail in the *Wind Atlas for the Gulf of Suez* [1, 2, 3]. The primary purpose of the Atlas is to provide reliable and accurate wind atlas data sets for evaluating the potential wind power output from large electricity-producing wind farms [1]. The assessments are based on wind speed and direction data from 15 locations along the Gulf of Suez and the northern Red Sea, micro-scale modeling of these 15 met. stations, as well as meso-scale modeling of the overall regional wind climate. Figure 1 shows an elevation map of the Gulf of Suez in which the met. stations of the Atlas are shown.

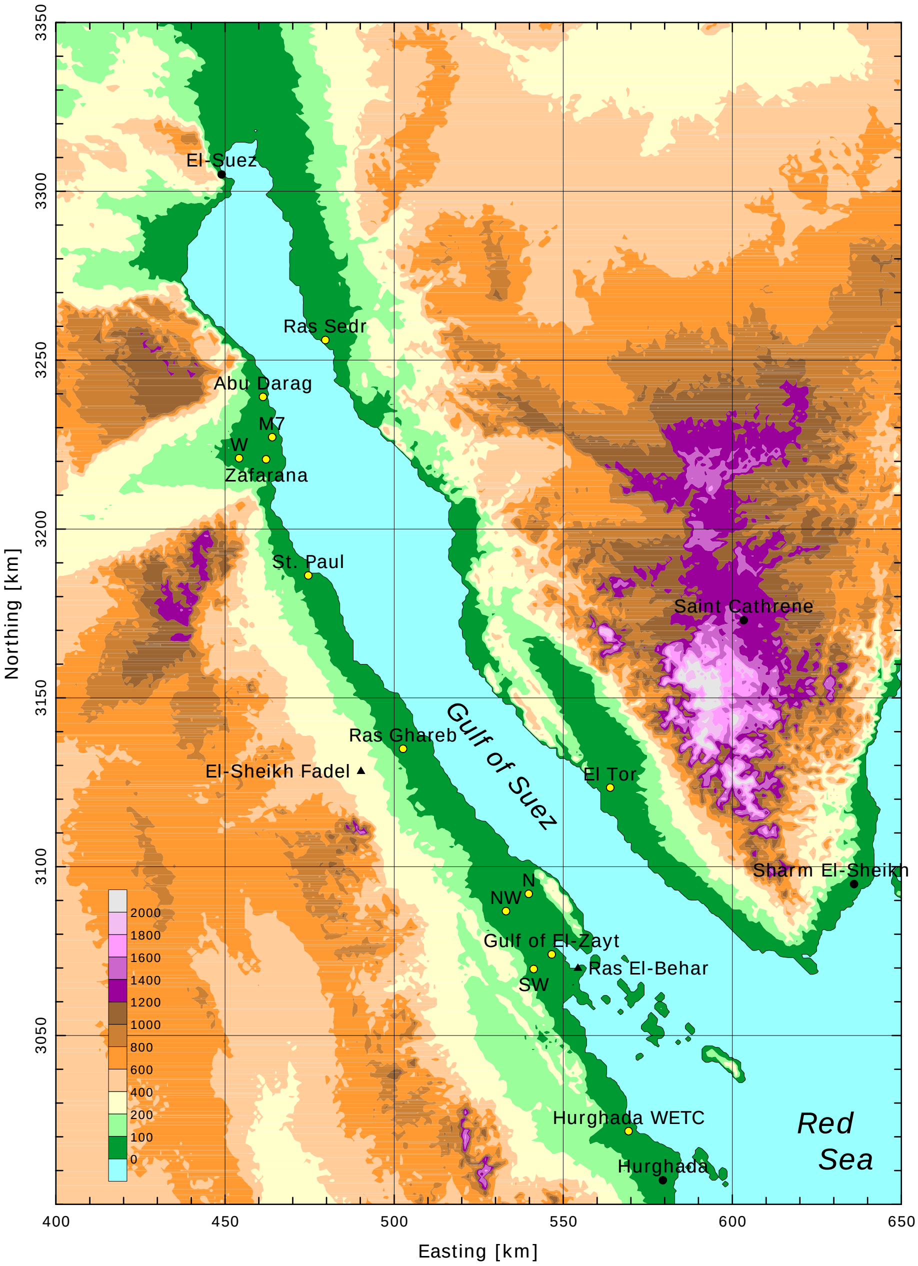


*Figure 1. Elevation map of the Gulf of Suez, Egypt; elevations are given in meters above mean sea level. Meteorological stations are marked with yellow symbols. Cartesian UTM coordinates are referenced to World Geodetic System 1984 (WGS 84).*

The purpose of the present paper is to present an overview of the results obtained so far, in particular a preliminary comparison of the results of the micro- and meso-scale modeling efforts.

## OBSERVED WIND CLIMATES

The meteorological instrumentation used for the 13 wind atlas stations consists of a data-logger with a data storage unit, as well as sensors to measure wind speed, wind direction, air temperature, atmospheric pressure and solar radiation. The sensors and data-logger are mounted on 25-m high triangular, lattice towers. The accuracy of the wind speed measurements have been secured by individual calibration of the cup anemometers used.

The wind data recorded at the stations are: mean wind speed, standard deviation of wind speed, gust wind speed, lull wind speed and mean wind direction. Measurements are done at 25 m a.g.l. and the averaging and sampling time is 10 minutes. Standard deviation is calculated from 1-Hz samples and the gust and lull wind speeds are sampled in 2-second windows over the 10-minute period. The main statistics of the observed wind climates for the two-year period 2000-01, where all 13 masts have been in operation, are listed in Table 1.

*Table 1. Summary of observed wind climates @ 25 m a.g.l. in the Gulf of Suez: data recovery rate R, Weibull A- and k-parameters, mean wind speed U, mean power density P, and mean direction of the wind vector D. Observation period 2000-2001.*

| | $R$ [%] | $A$ [$ms^{-1}$] | $k$ | $U$ [$ms^{-1}$] | $P$ [$Wm^{-2}$] | $D$ [deg] |
|---|---|---|---|---|---|---|
| Abu Darag | 94.7 | 10.1 | 3.59 | 8.8 | 586 | 348 |
| Zafarana, mast 7 | 88.9 | 10.4 | 3.45 | 9.2 | 664 | 355 |
| Zafarana | 92.4 | 10.2 | 3.23 | 9.0 | 630 | 354 |
| Zafarana West | 81.9 | 8.7 | 2.63 | 7.5 | 429 | 359 |
| St. Paul | 85.1 | 9.7 | 3.49 | 8.4 | 524 | 332 |
| Ras Ghareb | 91.8 | 11.2 | 3.54 | 10.0 | 819 | 322 |
| Gulf of El-Zayt N | 84.6 | 11.8 | 3.67 | 10.4 | 952 | 313 |
| Gulf of El-Zayt NW | 83.6 | 12.1 | 3.84 | 10.5 | 998 | 313 |
| Gulf of El-Zayt | 83.4 | 11.8 | 3.52 | 10.3 | 947 | 319 |
| Gulf of El-Zayt SW | 83.6 | 12.4 | 3.57 | 10.8 | 1105 | 315 |
| Hurghada WETC | 84.9 | 7.6 | 2.36 | 6.7 | 310 | 320 |
| Ras Sedr | 94.0 | 8.5 | 3.04 | 7.5 | 371 | 342 |
| El Tor | 90.2 | 6.4 | 1.93 | 5.6 | 221 | 291 |

Long-term data further exist for the stations Abu Darag (1991-2001), Zafarana (1991-2001), Gulf of El-Zayt (1995-97 and 2000-2001) and Hurghada WETC (1991-2001); these are reported in the Wind Atlas for the Gulf of Suez [1]. A simple, flat-file database of time-series data and observed wind climates is available from the New and Renewable Energy Authority or Risø National Laboratory.

## REGIONAL WIND CLIMATES

For each of the stations data were taken every ten minutes over a period of two to 10 years. In addition, accurate descriptions of each station and its surroundings were collected from maps, aerial photographs and during field trips, which included:

- terrain roughness, i.e. water areas, desert surfaces etc.
- nearby sheltering obstacles such as buildings
- terrain elevation variations (orography)

For the calculation of regional wind climates (wind atlas data sets), the station descriptions and the WAsP models were used to transform the measured data sets of wind speeds and directions from each station to what would have been measured at the location of the station if the surroundings were as follows:

- flat and homogeneous terrain
- no nearby obstacles
- and measurements had been taken at heights of 10, 25, 50, 100, and 200 m above ground level.

As an example, one of the transformed data sets represents wind speed and direction distributions at 50 meters above smooth desert surface, see Figure 2.

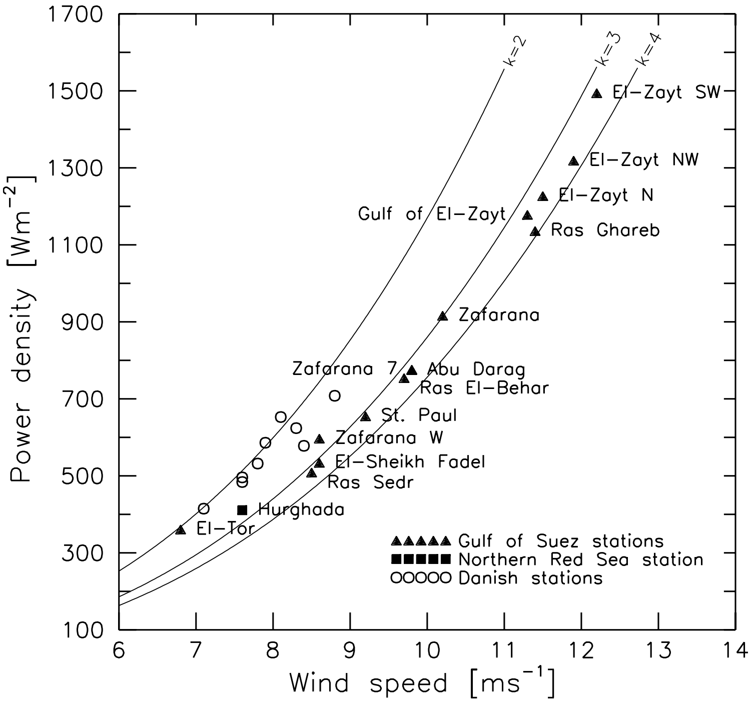


*Figure 2. Mean wind speeds and power densities at a height of 50 m over roughness class 1 (smooth desert surface) for 15 stations along the Gulf of Suez and in the northern Red Sea. For comparison, the Danish stations of the European Wind Atlas are also shown.*

The wind resources vary significantly over the 270-km stretch from Ras Sedr in the north to Hurghada in the south; for comparison, the Danish stations cover an area with a diameter of approximately 400 km. Mean wind speeds range from 7.6 $ms^{-1}$ at Hurghada to 12.2 $ms^{-1}$ at Gulf of El-Zayt SW, a factor of 1.6, and mean power densities from 411 $Wm^{-2}$ at Hurghada to 1494 $Wm^{-2}$ at Gulf of El-Zayt SW, more than 3.5 times the Hurghada value.

**PREDICTED WIND CLIMATES**

Another way of comparing the wind climates and wind power potential at the met. station sites – which are mostly located at prospective wind farm sites as well – is to compare the annual energy production from a sample wind turbine erected at the location of each station. Using the WAsP program, the regional wind climates described above can be employed to predict the actual wind climates at any given height at the met. station sites.

As an example, the wind turbine type which has been installed in several wind farms in the Zafarana area has a hub height of 40 m a.g.l. and a rated capacity of 600 kW. Given the power curve of this turbine, the annual energy production and corresponding capacity factor for each met. station site can be calculated. The capacity factor (CF) is the ratio of the actual annual energy output (AEP) to the theoretical maximum output, i.e. if the machine was running at its rated (maximum) power during all of the 8766 hours in a year:

$$CF = AEP/(365.25 \cdot 24 \cdot 600)$$

where the AEP is given in kWh. The theoretical maximum annual energy production for this turbine is thus 5260 MWh, corresponding to 8766 full-load hours (FLH). Table 2 shows the predicted wind climates, power productions, capacity factors and equivalent number of full-load hours for the met. station sites in the Gulf of Suez.

*Table 2. Summary of predicted wind climates and power productions 40 m a.g.l.: Weibull A- and k-parameters, mean wind speed U, mean power density P, mean annual energy production AEP, capacity factor CF and equivalent number of full-load hours FLH.*

| | $A$ [$ms^{-1}$] | $k$ | $U$ [$ms^{-1}$] | $P$ [$Wm^{-2}$] | AEP [MWh] | CF [%] | FLH [h] |
|---|---|---|---|---|---|---|---|
| Abu Darag | 10.7 | 3.24 | 9.6 | 726 | 2772 | 52.7 | 4620 |
| Zafarana, mast 7 | 11.1 | 3.15 | 9.9 | 822 | 2933 | 55.8 | 4888 |
| Zafarana | 10.9 | 2.99 | 9.7 | 784 | 2804 | 53.3 | 4673 |
| Zafarana West | 9.3 | 2.63 | 8.3 | 525 | 2105 | 40.0 | 3508 |
| St. Paul | 10.3 | 3.12 | 9.2 | 650 | 2564 | 48.7 | 4273 |
| Ras Ghareb | 12.2 | 3.71 | 11.0 | 1026 | 3457 | 65.7 | 5762 |
| Gulf of El-Zayt N | 12.6 | 3.36 | 11.3 | 1161 | 3512 | 66.8 | 5863 |
| Gulf of El-Zayt NW | 12.8 | 3.54 | 11.6 | 1224 | 3654 | 69.5 | 6090 |
| Gulf of El-Zayt | 12.6 | 3.37 | 11.3 | 1159 | 3516 | 66.8 | 5860 |
| Gulf of El-Zayt SW | 13.1 | 3.17 | 11.7 | 1346 | 3622 | 68.9 | 6037 |
| Hurghada WETC | 8.5 | 2.62 | 7.5 | 397 | 1733 | 32.9 | 2888 |
| Ras Sedr | 9.2 | 3.08 | 8.2 | 472 | 2069 | 39.3 | 3448 |
| El Tor | 7.0 | 2.06 | 6.2 | 269 | 1181 | 22.5 | 1968 |

**MESO-SCALE MODELLING**

In order to provide a more detailed and coherent overview of the spatial distribution of the wind resource in the Gulf of Suez, numerical simulations of the wind flow have been carried out with the Karlsruhe Atmospheric Mesoscale Model (KAMM) [5, 4]. The method and the results are described in more detail elsewhere [2].

The model domain has 60 by 81 grid points with a grid cell size of 5 km and thus covers an area of 300 by 400 $km^2$. The model uses 28 levels in the vertical from the surface to a constant height of 6000 m a.s.l. The resolution is higher near the surface than at the top of the model.

The method of statistical-dynamical down-scaling [6] is used to determine the wind climate on the meso-scale from large-scale data [7, 8]. Altogether, 128 simulations with a different base state, i.e. initial data, are made. The base state is given by the geostrophic wind and temperature at 4 heights: 0 m, 1500 m, 3000 m, 5500 m. The values are determined from the NCEP/-NCAR global reanalysis data set [9] for the years 1965-1998 at the pressure levels 1000 hPa, 850 hPa, 700 hPa, and 500 hPa. The 128 classes are determined from 16 sectors of the geostrophic wind at 0 m and positive or negative shear between the geostrophic wind at 0 m and 1500 m.

An overview of the wind climate and resource within the modeling domain can be established by combining the results of the 128 simulations. As an example, Figure 3 show the average wind speed at 25 m a.g.l. transformed to a uniform roughness length of 0.2 mm.

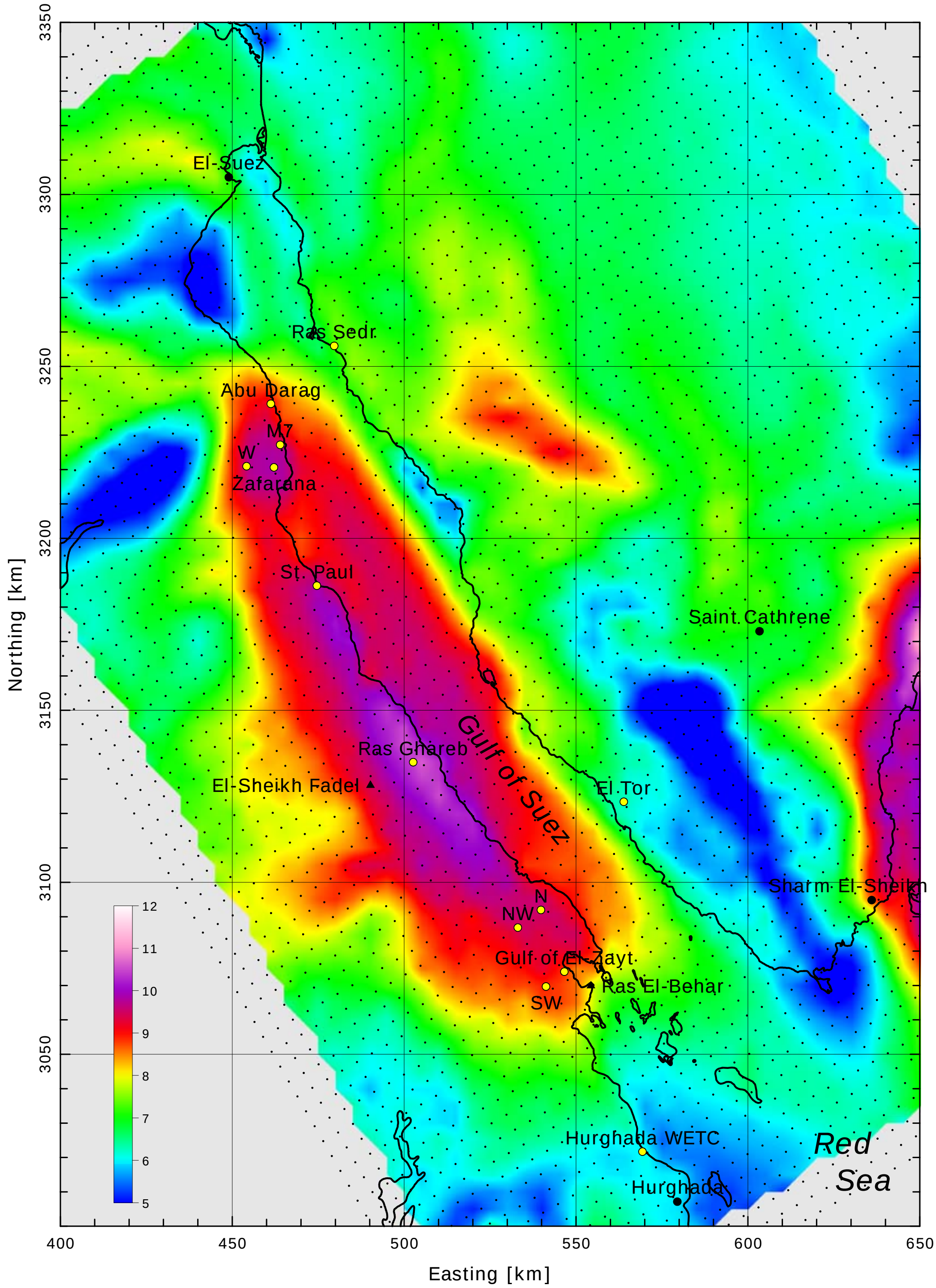


*Figure 3. Modeled mean wind speed in ms$^{-1}$ at 25 m a.g.l. over $z_0$ = 0.2 mm. The grid points of the KAMM model are shown by black dots. The wind atlas stations are shown with yellow symbols, other met. stations with black symbols.*

Correspondingly, Figure 4 show the average wind power density at 25 m a.g.l. transformed to a uniform roughness length of 0.2 mm.

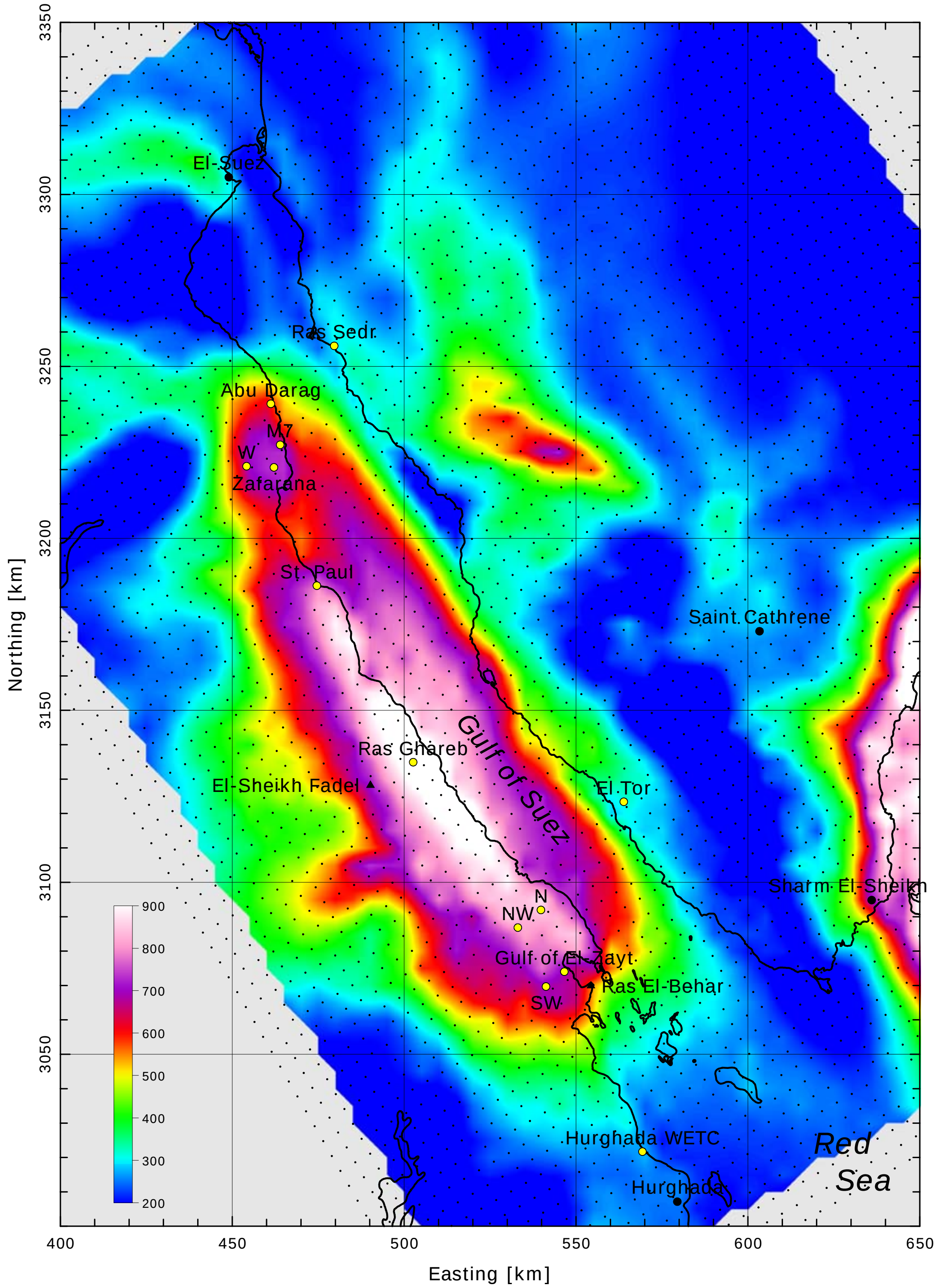


*Figure 4. Modeled mean power density in $Wm^{-2}$ at 25 m a.g.l. over $z_0$ = 0.2 mm. The grid points of the KAMM model are shown by black dots. The wind atlas stations are shown with yellow symbols, other met. stations with black symbols.*

The highest wind resource occurs in the central and southern parts of the Gulf of Suez: towards the western side of the Gulf and over the coastal plains between Ras Issaran to the north and Gulf of El-Zayt to the south. The simulations predict even higher wind resources for the Gulf of Aqaba; however, these results are less reliable, because this valley is not fully included in the simulation domain; the north-eastern part of the Gulf of Aqaba is cut off at the right side of the domain. The wind resource is significantly lower in the northern and eastern parts of the Gulf of Suez.

A preliminary comparison of mean wind speeds at the met. station sites – estimated from the observed wind climates and from the KAMM results – is shown in Figure 5. The "WAsP wind speed" is calculated using the WAsP program – from the wind climates observed in the period 2000-2001 and descriptions of the surroundings of each station. No attempt has been made to account for missing data at the stations, even though the data recovery at some stations is below 90% and this may bias the data somewhat. The "KAMM wind speed" is based on re-analysis data from the period 1965-1998; the two wind speed data sets thus do not cover the same period.

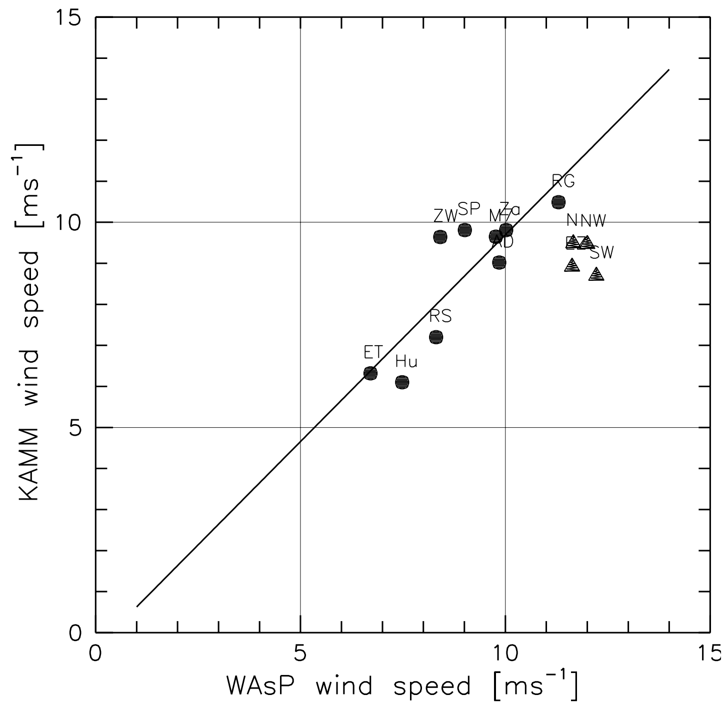


*Figure 5. Comparison of KAMM and WAsP modeled mean wind speeds. The symbols represent met. station sites in the Gulf of Suez; the four stations in the Gulf of El-Zayt area are represented by triangles. Full line is a least-squares fit to the black dots only.*

Overall, the mean speeds and power densities predicted by the meso-scale model are somewhat lower than the observed values. This is particularly obvious for the four stations in the Gulf of El-Zayt area (shown with triangles), where the predictions are significantly lower than the observed values. This may be caused be the limited resolution (5 km) of these meso-scale model runs.

## CONCLUDING REMARKS

The Wind Atlas for the Gulf of Suez project has established and operated a comprehensive network of wind-monitoring stations in the Gulf of Suez and northern Red Sea. A database of high-quality, reliable wind measurements now exists, and new information on turbulence intensity, gust wind speeds, lull wind speeds, atmospheric pressure and solar insolation has been obtained [1].

Furthermore, the first successful KAMM meso-scale modeling in Egypt has been carried out and novel wind resource maps for the Gulfs of Suez and Aqaba and the Sinai peninsula have been established. The simulations of the wind climate in the Gulf of Suez with the KAMM meso-scale model capture the main features of the complicated flow patterns and of the observed wind climates; however, the mean wind speeds and power densities are somewhat underestimated. The wind resource is found to be very high in the Gulf of Suez – corresponding to capacity factors of up to about 70% – at the same time the horizontal gradients of wind speed and power density are quite steep. The combination of meso- and micro-scale flow models – here the KAMM/WAsP methodology or the Numerical Wind Atlas – seem necessary in order to make reliable wind resource assessments in all parts of the Gulf of Suez. This methodology for regional resource assessment will be applied in other parts of Egypt over the next few years. The ultimate goal being to improve wind resource assessment and siting in all parts of Egypt.

The project results are available in the *Wind Atlas for the Gulf of Suez – Measurements and Modelling 1991-2001* [1]. A database of time-series data and observed wind climates is also available from the New and Renewable Energy Authority or Risø National Laboratory.


**ACKNOWLEDGMENTS**

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