WIND ATLAS FOR EGYPT: MEASUREMENTS, MICRO- AND MESOSCALE MODELLING

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ABSTRACT

The results of a comprehensive, 8-year wind resource assessment programme in Egypt are presented. The objective 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. The regional wind climates of Egypt have been determined by two independent methods: a traditional wind atlas based on observations from more than 30 stations all over Egypt, and a numerical wind atlas based on long-term reanalysis data and a mesoscale model (KAMM). The mean absolute error comparing the two methods is about 10% for two large-scale KAMM domains covering all of Egypt, and typically about 5% for several smaller-scale regional domains. The numerical wind atlas covers all of Egypt, whereas the meteorological stations are concentrated in six regions. The numerical wind atlas database, in combination with SRTM 3 elevation data and satellite imagery, provide the means for immediate WAsP wind resource assessments anywhere in Egypt. In addition to the very high wind resource in the Gulfs of Suez and Aqaba, the wind atlas has discovered a large region in the Western Desert with a fairly high resource – close to consumers and the electrical grid. The KAMM simulations seem to capture the main features of the wind climate of Egypt, but in regions where the horizontal wind gradients are large, the uncertainties are large as well and additional measurements are required. The results are now published in a Wind Atlas for Egypt.

INTRODUCTION

The wind resources of Egypt have recently been assessed by the New and Renewable Energy Authority, the Egyptian Meteorological Authority and Risø National Laboratory; the results are reported in detail in a *Wind Atlas for Egypt* [1]. 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. The regional wind climates of Egypt have been determined by two independent methods: a traditional wind atlas based on observations from more than 30 stations all over Egypt, and a numerical wind atlas based on long-term reanalysis data and a mesoscale model, KAMM. The observations have been analysed using the WAsP microscale model [2], and the two approaches may be described in the following simple way:

WAsP microscale model:	*Observed wind climates*	⇒	*Observational wind atlas*
KAMM mesoscale model:	*Simulated wind climates*	⇒	*Numerical wind atlas*

The observational wind atlas covers only those parts of Egypt where meteorological stations have been erected or exist already, whereas the numerical wind atlas covers the entire land area of Egypt – as well as offshore. The two approaches may be compared on the regional wind climate level, since the wind atlas data sets are independent of the exact measuring and modelling conditions. The purpose of the present paper is to provide an overview of the results obtained in the Wind Atlas for Egypt project, in particular a preliminary comparison of the regional wind climates derived by the observational and numerical wind atlas approaches, respectively. The work is a continuation of the work that led to the publishing of a *Wind Atlas for the Gulf of Suez* [3, 4].

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OBSERVED WIND CLIMATES

Meteorological observations from almost 50 stations all over Egypt have been analysed in the course of the project; of these eight standard (WMO) stations operated by the Egyptian Meteorological Authority and 22 dedicated wind atlas stations erected and operated by the project were selected for the final Atlas. The meteorological stations were chosen to cover six regions: Northwest Coast, Northeast Coast, Gulf of Aqaba, Gulf of Suez, Red Sea and Western Desert. Figure 1 shows an elevation map of Egypt in which the meteorological stations of the Atlas are shown.

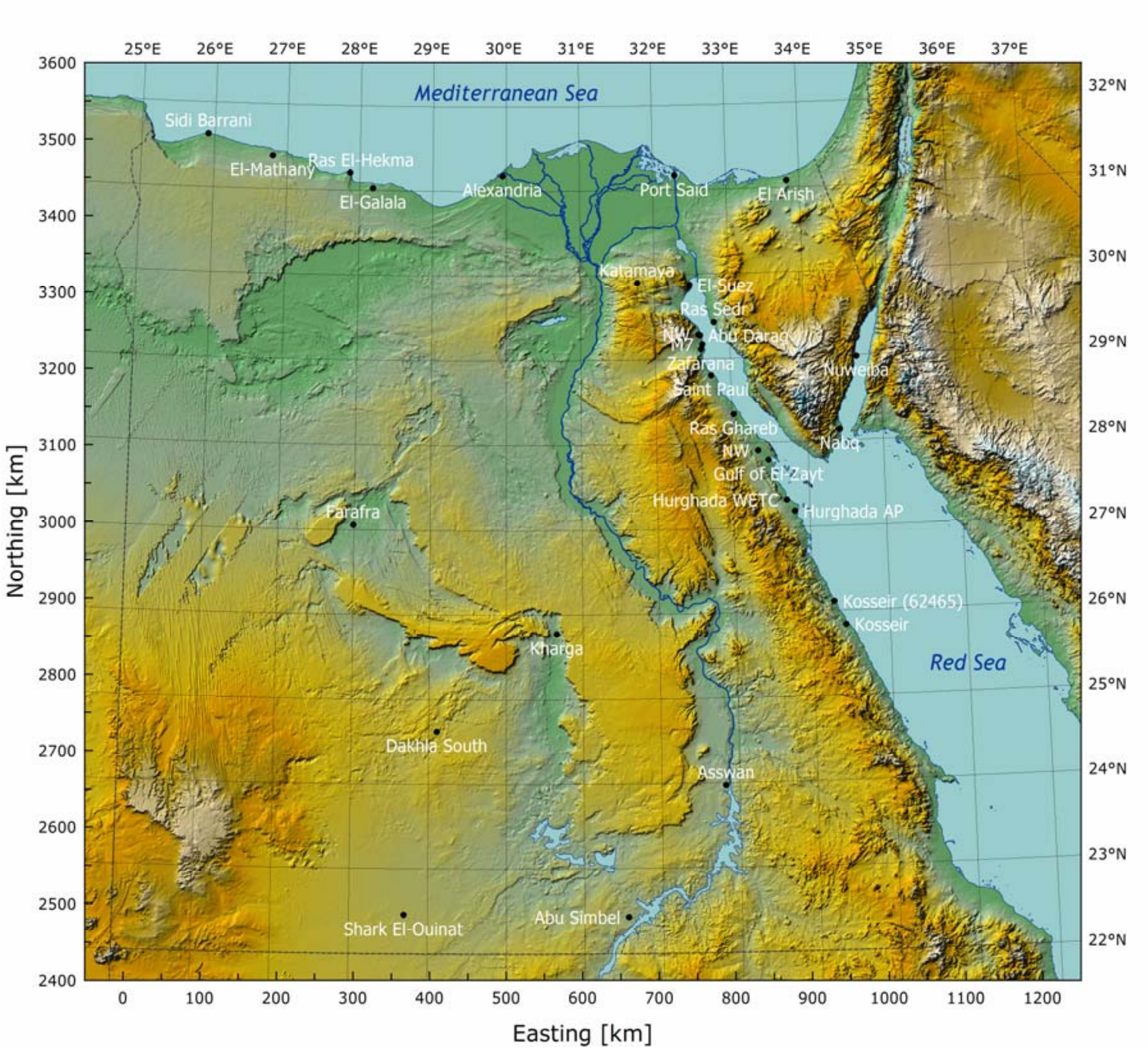

Figure 1. Elevation map of Egypt showing the meteorological stations used for the Wind Atlas for Egypt. The geographic and Cartesian (UTM) coordinates are referenced to the World Geodetic System 1984.

The meteorological instrumentation used for the 22 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 and by careful mounting of the wind sensors: a slender top tube was employed for the top anemometer at 25 m and extension poles were used for boom-mounted sensors.

The wind data recorded at the wind atlas stations are: mean wind speed, standard deviation of wind speed, gust wind speed, lull wind speed and mean wind direction. Primary 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 at the 30 stations are listed in Table 1.

Table 1. Summary of wind observations at the meteorological stations: Data-collecting period, height above ground level of anemometer, data recovery rate (R), Weibull A- and k-parameters, mean wind speed (U), mean power density (E), and direction (D_U) and magnitude ($|\boldsymbol{U}|$) of the mean wind vector.

Region/Station	Period	Height [m]	R [%]	A [ms^{-1}]	k	U [ms^{-1}]	E [Wm^{-2}]	D_U [deg]	$|\boldsymbol{U}|$ [ms^{-1}]
Northwest Coast									
Sidi Barrani (62301)	10 y	10.0	n/a	7.0	2.16	6.2	254	324	2.8
El-Mathany	1 y	24.5	99.5	6.4	2.33	5.7	190	284	2.0
Ras El-Hekma	1 y	24.5	99.8	7.2	2.23	6.4	275	309	3.1
El-Galala	1 y	24.5	97.2	6.7	2.41	5.9	206	324	2.6
Alexandria (62318)	10 y	10.0	n/a	5.2	2.42	4.6	99	329	2.9
Northeast Coast									
Port Said	1 y	24.5	66.2	5.3	2.32	4.7	105	301	1.6
El Arish (62337)	10 y	8.5	n/a	3.0	1.44	2.8	37	303	1.0
Gulf of Aqaba									
Nuweiba	1 y	24.5	80.9	6.2	2.58	5.6	161	027	4.0
Nabq	1 y	24.5	97.6	7.7	2.04	6.8	367	009	5.9
Gulf of Suez									
Katamaya	1 y	24.5	79.5	6.0	2.66	5.4	143	357	2.8
El-Suez (62450)	10 y	10.0	n/a	6.2	3.17	5.5	140	350	3.9
Ras Sedr	5 y	24.5	84.1	8.5	3.06	7.6	368	341	6.0
Abu Darag NW	3 y	47.5	82.3	9.6	3.34	8.6	519	352	6.9
Abu Darag	14 y	24.5	82.5	10.1	3.50	9.1	598	355	7.6
Zafarana M7	7 y	47.5	79.1	11.1	3.57	10.0	788	356	8.4
Zafarana	14 y	24.5	85.2	10.2	3.19	9.1	626	358	7.0
Saint Paul	5 y	24.5	82.7	9.4	3.25	8.5	498	332	7.0
Ras Ghareb	5 y	24.5	85.5	11.0	3.40	9.9	775	322	8.7
Gulf of El-Zayt NW	5 y	24.5	82.0	11.8	3.70	10.7	950	313	9.4
Gulf of El-Zayt	7 y	24.5	83.8	11.5	3.29	10.3	900	322	9.0
Red Sea									
Hurghada WETC	11 y	24.5	79.6	7.6	2.32	6.7	308	322	4.9
Hurghada (62463)	10 y	10.0	n/a	7.6	2.66	6.7	285	325	5.4
Kosseir (62465)	4 y	10.0	97.1	5.1	2.03	4.6	178	334	3.5
Kosseir	4 y	24.5	88.7	6.5	2.32	5.8	197	321	4.3
Western Desert									
Farafra (62423)	2 y	10.0	98.6	3.9	1.79	3.5	53	342	2.0
Kharga	1 y	24.5	99.8	7.4	2.57	6.6	268	345	5.8
Dakhla South	1 y	24.5	81.5	7.3	3.31	6.6	229	352	5.5
Shark El-Ouinat	3 y	24.5	100.0	7.2	3.29	6.5	222	355	5.5
Asswan (62414)	10 y	10.0	n/a	5.4	2.61	4.8	102	346	3.8
Abu Simbel	1 y	24.5	99.9	6.4	2.76	5.7	166	356	4.8

OBSERVATIONAL WIND ATLAS

For each of the stations, the time-series of wind measurements was used to derive the observed wind climate statistics at the station [2]. In addition, accurate descriptions of each station and its surroundings were collected from elevation data, maps, satellite imagery, aerial photographs and during field trips:

- land use and terrain roughness lengths (Google Earth Pro, maps, aerial photography, site visits)
- nearby sheltering obstacles such as buildings (Google Earth Pro and site visits)
- terrain elevation variations (Shuttle Radar Topography Mission 3 arc-sec. elevation data, digitised topographical maps)

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
- measurements had been taken at heights of 10, 25, 50, 100, and 200 m a.g.l.

As an example, one of the transformed data sets represents wind speed and direction distributions at 50 meters above roughness class 1 (z_0 = 0.03 m), see Figure 2.

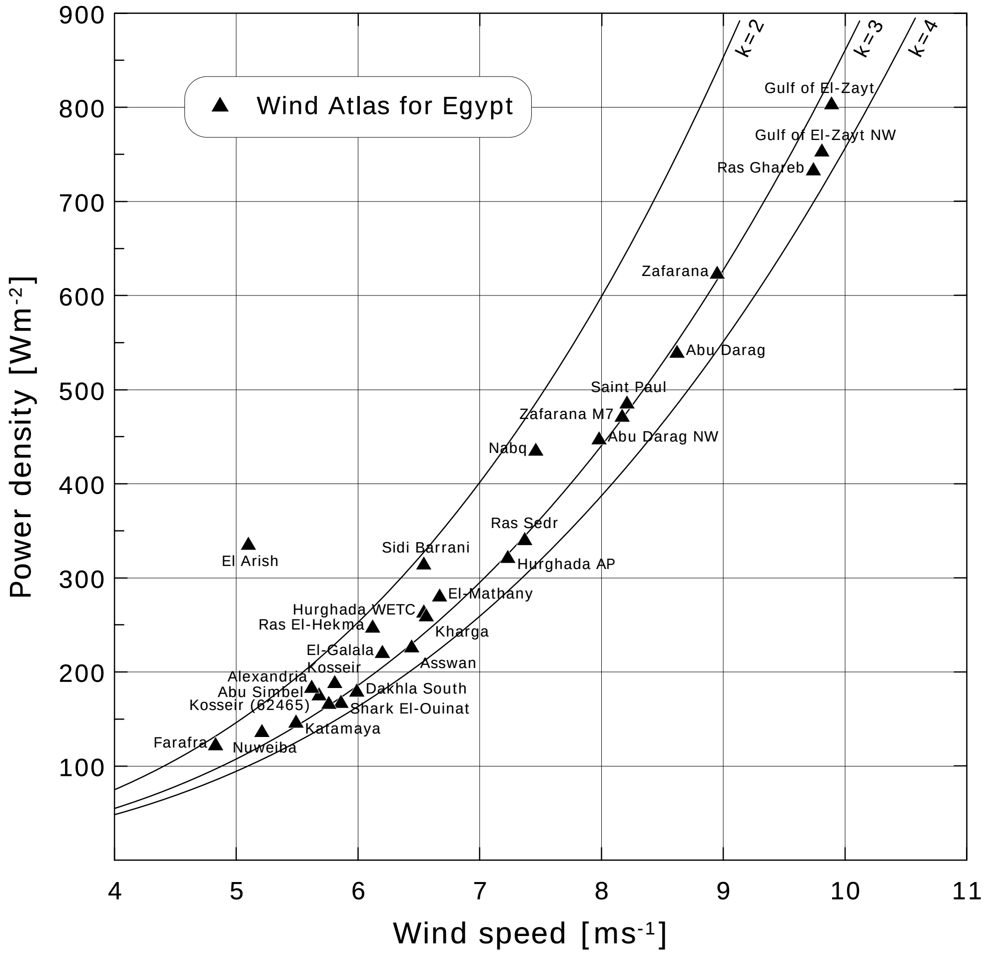

Figure 2. Mean wind speeds and power densities at a height of 50 m over roughness class 1 (z_0 = 0.03 m) for the 30 stations in the Wind Atlas for Egypt. Curves represent equal Weibull *k*-parameters.

The wind resources vary significantly over the land area of Egypt, from fairly low values at the Northeast Coast and parts of the Western Desert to the extraordinary high values found in the Gulf of Suez.

KAMM SIMULATED WIND CLIMATES

As described above, the conventional method employed to produce estimates of the wind resource on a national scale is to analyse wind measurements made at a number of sites around the country. In order for this method to work there needs to be a sufficient quantity of high quality data, covering the entire country. It is not possible to satisfy this criterion for Egypt and therefore other methods are required.

Numerical wind atlas methodologies have been devised to solve the issue of insufficient wind measurements. For Egypt, we have applied the KAMM/WAsP method developed at Risø National Laboratory [5, 6]. In this methodology an approach called statistical-dynamical downscaling is used [7]. The basis for the method is that there is a robust relationship between meteorological situations at the large scale and meteorological situations at the small scale. This method may not meet bankable accuracy in resource estimates, but on the other hand will typically give good indications of the geographical distribution and magnitude of the wind resource. It is also useful for decision making, planning of feasibility studies and for actual project preparation.

Information about the long-term, large-scale meteorological situation over Egypt was obtained from the NCEP/NCAR reanalysis data-set [8]. Time-series data of wind and temperature profiles for the period 1965 to 1998 were used to create around 100 different large-scale wind situations or wind classes. These wind classes form a representative set of wind conditions for the region and represent different wind speeds, wind directions, atmospheric stability or shear.

In order to make these wind classes meaningful at a smaller scale, a mesoscale model is used to find out how the large-scale wind forcing is modified by regional-scale topography. Therefore, a mesoscale model simulation is performed for each wind class using the Karlsruhe Atmospheric Mesoscale Model [9, 10]. Data concerning terrain surface elevation and land-use (roughness length) were obtained from United States Geological Survey GTOPO30 global elevation data set [11] and Global Land Cover Classification [12], respectively. Egypt's large size means that it is not possible to perform the numerical wind atlas calculations for the whole country at a reasonable resolution in one go. Therefore it was decided to split the numerical wind atlas effort into several calculation domains, see Figure 3.

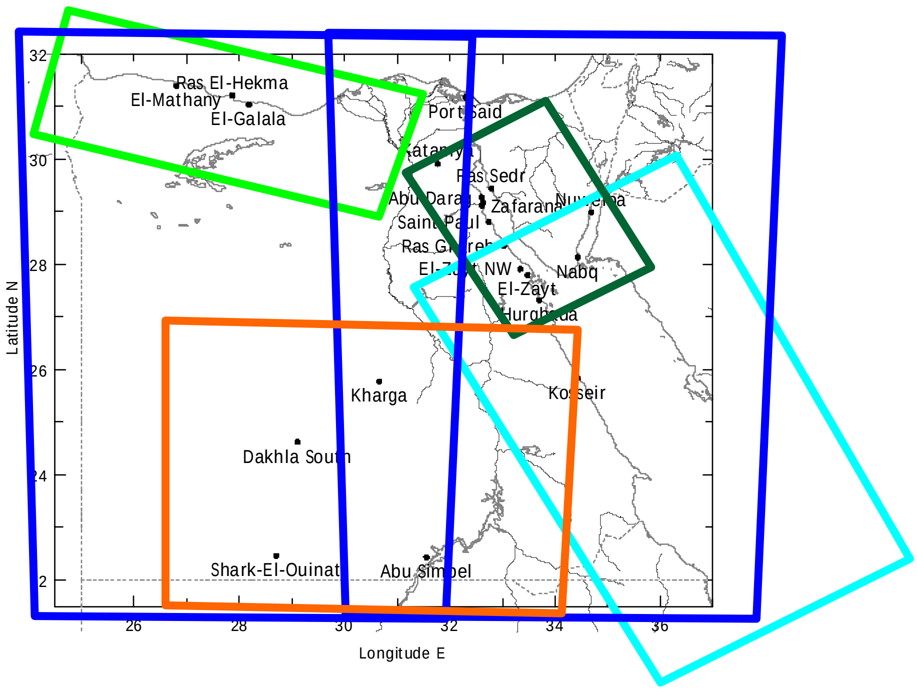

Figure 3. Map of Egypt showing the various modelling domains being used. A complete numerical wind atlas calculation is made for each domain. Horizontal grid point resolution is 7.5 km for the two large domains and 5 km for the Red Sea, Western Desert, Northwest Coast and Gulf of Suez domains.

NUMERICAL WIND ATLAS

After the mesoscale simulations are complete for all of the wind classes, the results are compiled in the post-processing stage of the methodology. First, a weighted mean of the wind class simulation results is calculated. This yields a simulated wind resource map at the resolution of the model simulations, as the one depicted in Figure 4.

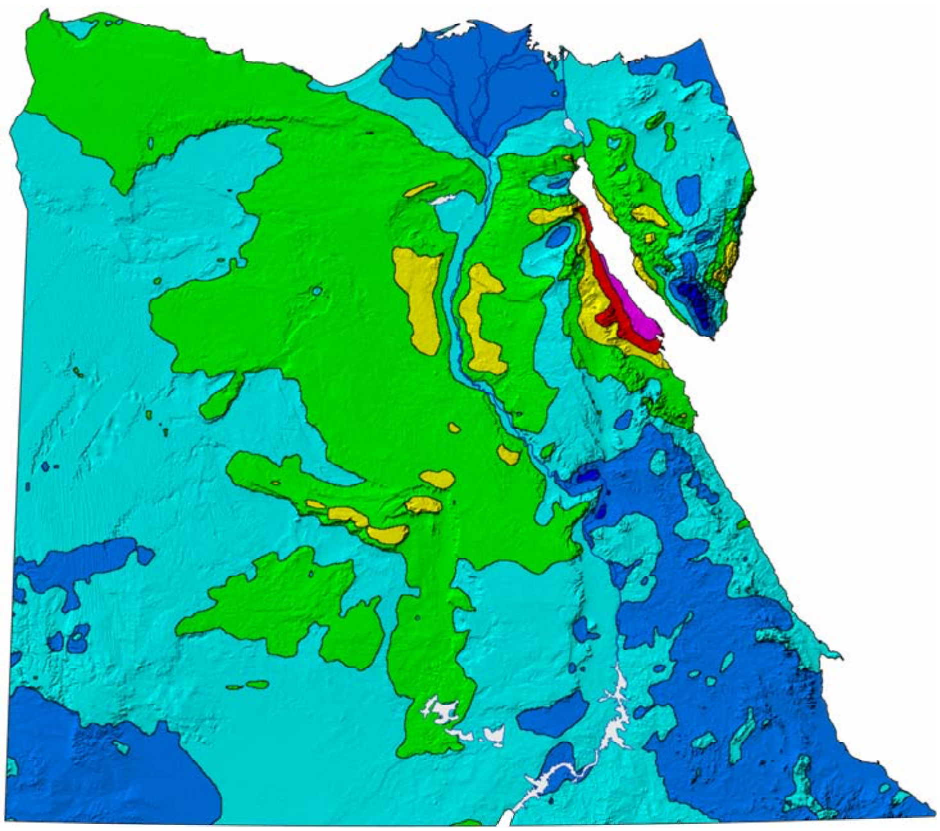

Figure 4. The predicted wind climate of Egypt determined by mesoscale modelling. Map colours show mean wind speeds in [ms^{-1}] at a height of 50 m over the actual (model) land surface: blue 4-5, cyan 5-6, green 6-7, yellow 7-8, red 8-9, magenta 9-10 ms^{-1}. The horizontal grid point resolution is 7.5 km.

Second, for each wind class simulation, the effects of elevation and roughness variation are removed with modules similar to those used in the WAsP software – corresponding to a 'WAsP analysis' procedure where the simulated wind climate is substituted for the observed wind climate. Then the weighted mean of the adjusted results from the wind simulations is made. This yields the regional wind climates, or generalized wind map for flat, uniform surface conditions of a specified roughness. Figure 5 shows a schematic diagram of the wind class simulations and the post-processing steps.

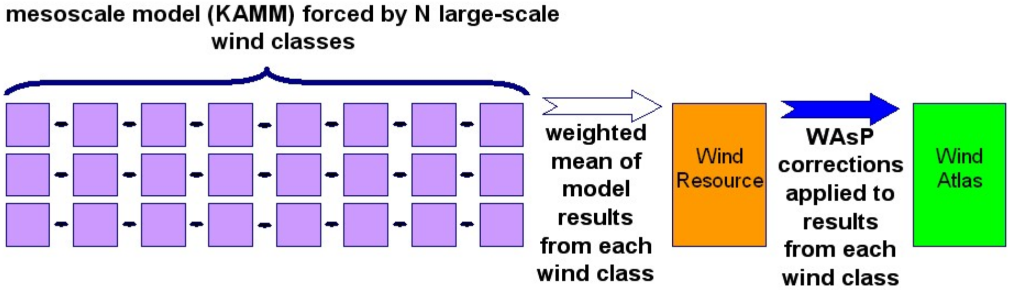

Figure 5. A schematic diagram showing the KAMM/WAsP numerical wind atlas methodology.

The regional wind climate estimates determined for the KAMM model grid points together form a database of regional wind climates covering the entire land area of Egypt. Files containing detailed information about the wind speed and direction distributions can be generated that are directly compatible with the WAsP software, the wind industry standard for site resource assessment calculations. More than 50,000 WAsP regional wind climates (*.lib files) have been generated in this way to cover all of Egypt.

VERIFICATION OF THE WIND ATLAS METHODOLOGY

In this section a comparison is made between the wind atlas wind speed values derived from the numerical wind atlas (KAMM/WAsP method) and the observational wind atlas (WAsP method using observations). For a given location, a wind atlas file can be used to provide an expected wind speed for a set of standard heights above a set of standard terrain roughnesses.

In Figure 6 and Figure 7 the mean wind speeds at 10, 25, 50, 100 and 200 m above a flat, uniform terrain surface with a roughness length z_0 of 0.03 m are used for the comparison; more comparisons are given in [1]. The legend to the right of each plot shows the names of the stations used, cf. Figure 1. Each figure shows the comparison within a single modelling domain; Figure 6 for the large Eastern Egypt modelling domain and Figure 7 for the smaller Western Desert domain. There is overlap of domains and therefore a few stations may appear in both plots. Where there is good agreement between KAMM/WAsP and observation and WAsP, the plotted points lie close to the one-to-one line in each plot.

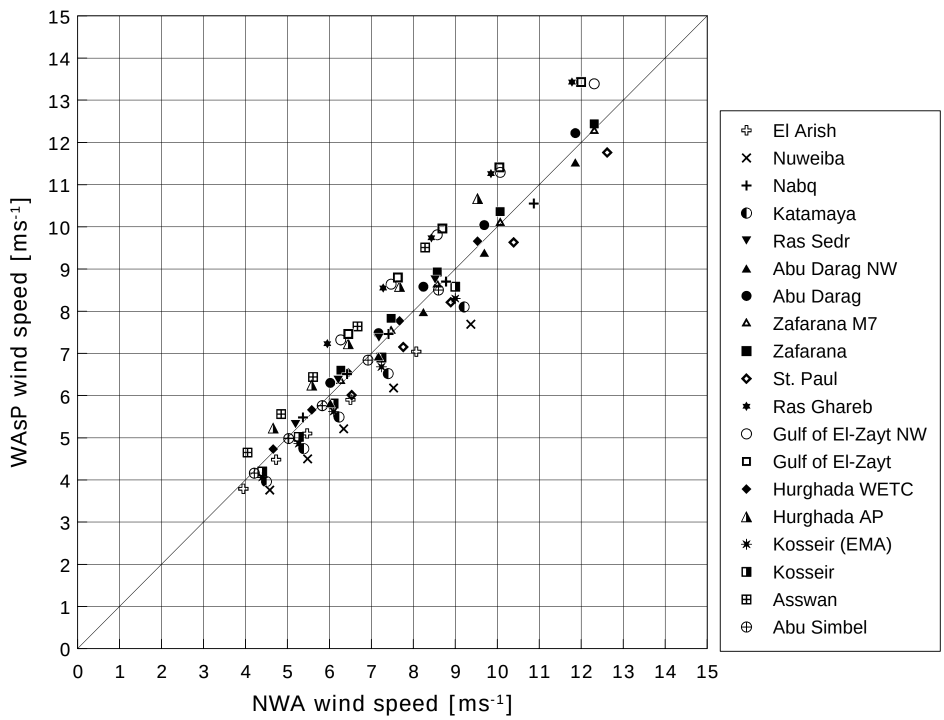

Figure 6. Eastern Egypt domain comparison of atlas wind speed values at 10, 25, 50, 100, 200 m calculated using KAMM/WAsP (*x*-axis) and observations/WAsP (*y*-axis), roughness is 0.03 m.

In many cases there is good agreement between the wind atlases derived from KAMM modelling and observations. The agreement at the station locations adds confidence to the KAMM-derived wind data for locations away from stations.

There are several possibilities why there may be poorer agreement between KAMM- and observation-derived wind atlases.

Close to the KAMM domain boundaries a less accurate wind atlas is usually derived. This is an unavoidable consequence of limited area modelling. The effect can be minimized by careful selection of the domain, keeping points of interest well within the domain and including the dominant topographic features in the domain as much as possible.

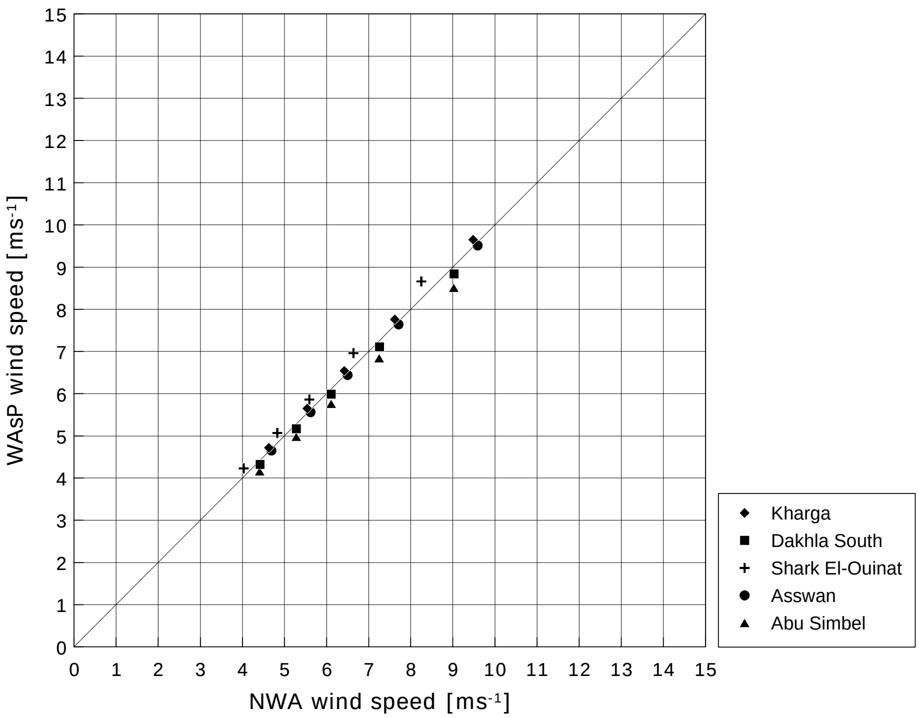

Figure 7. Western Desert domain comparison of atlas wind speed values at 10, 25, 50, 100, 200 m calculated using KAMM/WAsP (x-axis) and observations/WAsP (y-axis), roughness is 0.03 m.

The complexity of the flow modification by the topography influences the agreement between the KAMM results and the observations. For the Gulf of Suez and the Red Seas domains, the topography tends to be higher and have a stronger influence on the flow. For the Northwest Coast and Western Desert domains, the topography is less complex, and the flow modification due to terrain is less pronounced.

Correct selection of the wind classes used to force the mesoscale model has a very strong influence on the accuracy of the KAMM results. The use of more location-specific wind classes in the smaller domains tends to reduce the error from this source.

Other causes of error may be found within the WAsP analyses. The correct choice of surface roughness for instance has an influence on the wind atlas values. Also some of the stations are relatively close to sheltering obstacles. Obstacles can be difficult to model correctly. Comparison of the wind direction distributions also would help to highlight causes of errors, including errors due to incorrectly modelled influence of obstacles.

Finally, the observed data sets have not been referenced to the same standard period of time so the scatter in Figure 6 and Figure 7 also simply reflect the climatic variability in the wind regimes.

For some groups of stations, the mean speeds and power densities predicted by the mesoscale model are somewhat lower than the observed values. This is particularly obvious for the four stations in the Gulf of El-Zayt / Hurghada region, where the predictions are significantly lower than the observed values. This may be caused be the limited resolution of these mesoscale model runs.

Table 2 summarises the comparisons between the KAMM- and WAsP-modelled regional wind climates. The absolute error is calculated as the difference between the two estimates (for the height of 50 m a.g.l.) divided by their mean value, and expressed as a percentage. The right-most column shows the mean absolute error for a subset of stations in the Red Sea and the Gulf of Suez. The scatter plots shown in Figure 6 and Figure 7 indicate that the largest differences between the KAMM- and WAsP-modelled regional wind climates are found for stations located close to the southern entrance of the Gulf of Suez. If Hurghada WETC and Hurghada AP are disregarded in the Red Sea comparison, the mean absolute error decreases from 10.5% to 4.4%.

Table 2. Comparison of atlas wind speed values at 50 m a.g.l. and a roughness of 0.03 m, calculated using KAMM/WAsP and observations/WAsP.

Domain	Grid size	Mean absolute error	Mean absolute error
		All stations	Selected stations
	[km]	[%]	[%]
Western Egypt	7.5	12.4	n/a
Eastern Egypt	7.5	7.6	n/a
Northwest Coast	5.0	5.2	n/a
Western Desert	5.0	3.1	n/a
Gulf of Suez	5.0	9.4	5.6
Red Sea	5.0	10.5	4.4

Likewise, if the Gulf of El-Zayt NW and Gulf of El-Zayt stations are disregarded in the Gulf of Suez comparison, the mean absolute error decreases from 9.4% to 5.6%. The typical mean absolute error is then about 10% for the large domains and about 5% for the small domains.

SUMMARY AND CONCLUSIONS

The Wind Atlas for Egypt project has established and operated a comprehensive network of wind-monitoring stations in six designated regions all over Egypt. 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]. The main result of the measurement campaign is an *observational wind atlas* which covers some of the most promising regions for wind power exploitation in Egypt. A successful continuation of the measurement programme has been secured by establishing a cup anemometer rehabilitation and recalibration facility in Egypt; the characteristics of this facility and the results obtained will be reported elsewhere.

The wind climate and wind energy resources of Egypt have furthermore been determined by applying the KAMM mesoscale modelling in two large and four regional domains. New wind resource maps for Egypt have been established which correct and update our knowledge about the wind resources of the country. The KAMM simulations capture the main features of the sometimes complicated flow patterns and of the observed wind climates; however, the mean wind speeds and power densities are underestimated in some regions. The main result of the mesoscale modelling is a *numerical wind atlas* which covers the entire land area of Egypt as well as adjacent offshore areas.

The Wind Atlas for Egypt confirms the existence of a widespread and particularly high wind resource along the Gulf of Suez. The Wind Atlas further indicates that the wind energy resource in large regions of the Western and Eastern Desert – in particular west and east of the Nile valley between 27°N and 29°N, but also north and west of the city of Kharga – are much higher than hitherto assumed. The mean wind speeds predicted here are between 7 and 8 ms^{-1} and the power densities between 300 and 400 Wm^{-2}, estimated at a height of 50 m a.g.l. There are no meteorological stations for verification in these regions; however, comparisons elsewhere in the Western Desert of predictions derived from the mesoscale modelling to those derived from measurements suggest that the mesoscale model is indeed able to resolve and predict the wind resource in this type of terrain.

The Wind Atlas for Egypt represents a significant step forward in the application of the wind atlas methodology in Egypt. Not only does it provide a coherent and consistent overview of the wind energy resource over the entire land (and sea) area of Egypt, the results of the mesoscale modelling are further available in a database (numerical wind atlas) that may be employed directly for detailed wind resource assessments and siting of wind turbines and wind farms. Utilising this database together with elevation maps derived from the Space Shuttle Topography Mission and land-use maps constructed from satellite imagery, the wind resource and likely power production of a given wind farm can be estimated in a matter of hours – anywhere in Egypt.

The project results are available in the *Wind Atlas for Egypt – Measurements and Modelling 1991-2005* [1]. In addition to the 258-page book, a comprehensive database of observed and regional wind climates is also available.

ACKNOWLEDGEMENTS

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