Numerical Simulation of Wind Distributions for Resource Assessment in Southeastern Eritrea, East Africa

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ABSTRACT

We present the results of a simulation study of the wind energy resources of Southeastern Eritrea. In this study, we simulate the three dimensional wind fields during typical, steady conditions of the Southern Red Sea southeast monsoon season. The simulations verify the existence of a low level jet (LLJ) contained within the highly stratified marine layer over the Southern Red Sea. The LLJ is cause by the channeling and acceleration of marine layer flow as it passes throught the straight of Bab el Mandeb on its way from the Indian Ocean to the Eastern Sahara. The LLJ extends from 12.5^o N to 14.5^o N latitude in the Southern Red Sea and has peak velocities at 300 – 600 m elevation above the Red Sea. Sea-land breezes advect the high speed flow of the LLJ onshore along a 200 km streatch of Southeastern Eritrean coastline, producing an excellent wind energy resource that peaks daily at 3 PM. This resource is currently under development for both grid-connected and decentralized village wind energy applications.

Keywords: wind resource assessment, Africa wind resources, meteorological modeling

OUTLINE

1. Introduction

Eritrea, an African country along the Red Sea coast, needs a rapidly growing supply of energy in order to satisfy the increasing electricity demand of its people. In providing for the rapidly expanding electricity needs of its population, Eritrea faces two major constraints: environmental impacts, and cost. Wind energy holds the potential of providing a significant contribution to Eritrea's electricity needs using a means that is both environmentally friendly and low cost (Garbesi et al. 1996). Another major benefit of wind energy for Eritrea given the recent rise in oil prices is that it can help decrease the national reliance on the expensive, imported diesel fuel and fuel oil that is currently used for electricity production.

An essential component of wind energy development is determining the geographic distribution of wind energy resources. This involves determining wind speeds to a high degree of accuracy. The power density of the wind determines the amount of power that can be produced by a given wind generator, and the power density is proportional the third power of the wind speed. Therefore, a 10% increase in wind speed produces a 33% increase in wind power.

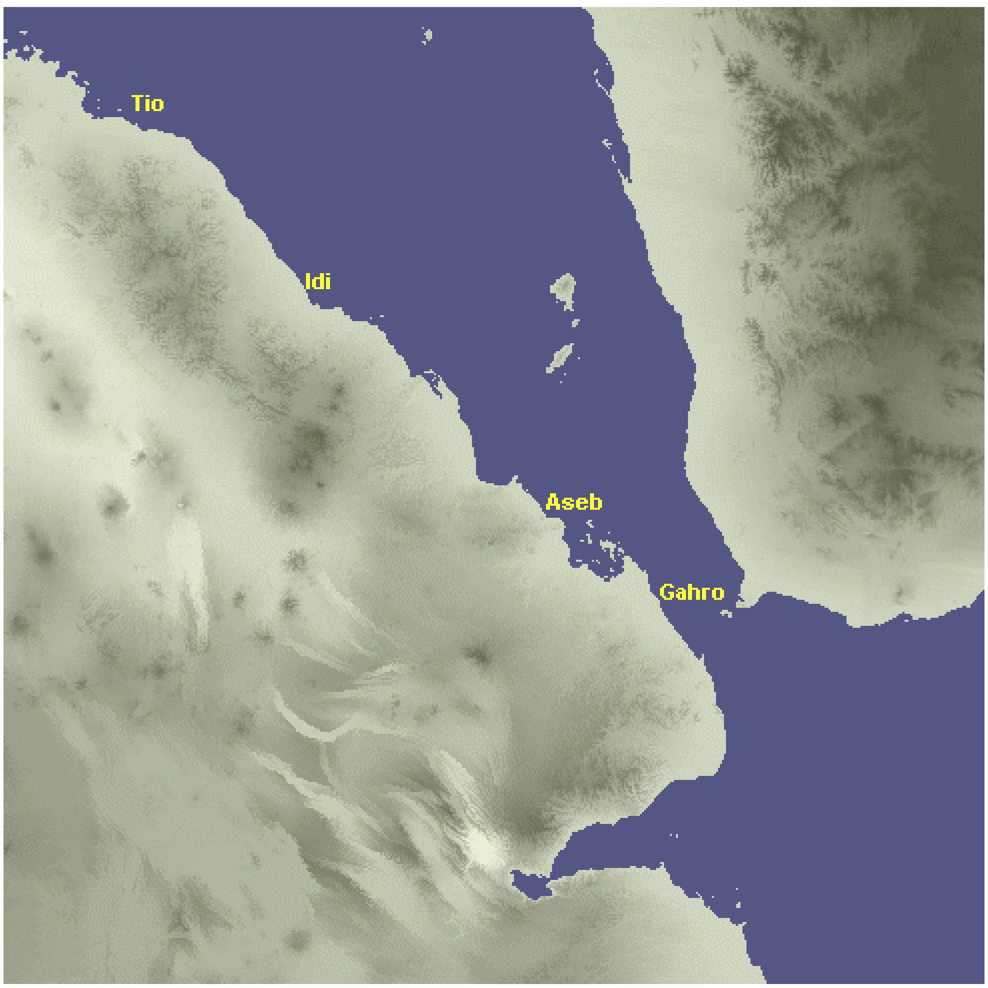

Figure 1: Map of the extreme southern Red Sea study area. Water is shown as blue or dark grey

while elevations are shown as shades of grey with darker colors corresponding to higher elevations. The highest elevations are approximately 3000 m.

Eritrea is a country located in the eastern part of Africa, with one thousand kilometers of coastline along the southwestern shore of the Red Sea. Our research is focused on the southern part of the Eritrean coast, which has been identified as the country's best wind energy resource region (EDOE report 2000). We show the southern extreme of the Red Sea in figure 1. At the southwestern boundary of the Red Sea is Southeastern Eritrea. Adjacent to the coast is a flat coastal plain; while parallel to the coast and 5-50 km inland is a range of coastal hills that vary from 1000 to 2000 m in elevation. West of the meridian at 40 degrees east, we have the 2000 meter Eritrean highland plateau, which extends from the north to the south of the country. In the southeast, at the extreme southern end of the Red Sea lies the straight of Bab el Mandeb, which is a constriction of about 35 km between Aden and Djibouti that connects the Red Sea and the Indian Ocean. The locations of the meteorological stations in the southern coast are also shown in figure 1 (Tio, Idi, Aseb, and Gahro).

The goal of this investigation is to increase knowledge of the distribution of wind energy resources of Southeastern Eritrea through simulation of the the mesoscale meteorology of the region. Some key questions regarding the Southeastern Eritrea wind energy resource include following:

- **Hills or Coastline**: Are the wind resources better on the hills or in the sea?
- **Extent of Resources**: How far along the coastline do excellent wind resources extend?
- **Vertical Wind Shear**: How does wind power depend on altitude? And is it very beneficial to have extremely tall wind turbines?
- **Best Wind Resources Location**: Where are the highest performance wind energy generation sites?

In the following sections, we review previous studies, describe the particular case that we simulate, describe the simulation set-up and methodology, present simulation results, and conclude with implications for further wind energy resource studies.

1.1 Previous Eritrean Wind Resources Studies

Recent wind energy research and resource assessment activities in Eritrea are carried out by the Energy Research and Training Center (ERTC) of the Minisitry of Energy and Mines in Eritrea where both of the authors have previously worked and with which they actively collaborate. The ERTC, is responsible for renewable energy technology in Eritrea and is active in studying assessing and developing renewable energy resources in Eritrea while promoting the efficient use of all energy sources. Since the establishment of the ERTC in 1995, the activities have included training, seminars, demonstration events , advisory and information services, and promoting the benefits of renewable and sustainable energy technology.

The ERTC has a fairly comprehensive wind data collection system with 25 stations around the country and in particular in southern coastal area of Eritrea. A wind information system WIS was developed and implemented at the ERTC. GIS and databases are also established in ERTC, which enable the ERTC to quickly provide information on the wind resources at selected locations. The result of the wind data analysis shows a high wind potential in and around Aseb and in the regions to the south of Aseb, though average wind velocities appear to decrease, to ward the north. Current wind energy assessments are being used for the identification and selection of suitable rural villages for wind stand alone and wind hybrid systems in the wind rich part of Eritrea. The data from ground-based monitoring is also used for the conceptual planning and economic assessment of a 750 kW wind park currently being implemented in Aseb.

In terms of methodology, revious research on wind energy resource assessment in Eritrea and the surrounding area has relied primarily on collecting and analyzing ground station data on wind speeds, with some preliminary efforts at performing mesoscale simulations for the southeastern coast. Some of the earliest studies (Mulugeta & Drake 1996) identified the Aseb area of Eritrea as an area of high wind potential. Further general assessment studies (Van Buskirk et al. 1998, Garbesi et al. 1996 and Rosen et al. 1999) provided more detail on the potential of the southeastern coast and central highland passes. In addition to meteorological data, these studies examined ship-based meteorological measurements (Rosen 1998), and satellite scatterometry data (Van Buskirk et al. 1999). More recent investigations (Habtetsion et al. 2002) have analyzed data from 25 recently installed meteorological stations. Consultant studies (Lehremeyer 2000) have performed simulations using the German mesoscale atmospheric model KLIMM, KLIma Model Mainz (Climatic model Mainz) in an effort to extrapolate meteorological station data to a wider geographic area. But these earlier simulations did not capture well-known wind dynamics of the southern Red Sea area. Other consultant studies (Swedish Consulting (SWECO 2002) attempted to geographically extrapolate station data using the Wind Atlas Analysis and Application Program (WAsP), but extrapolations based on land-based station data did not accurately forecast the wind speeds over the Red Sea that are indicated by ship-based measurements.

The current investigation is needed because the studies that have been performed to date have not provided consistent answers regarding the extent and features of the Southeastern Eritrea wind energy resources that are important for an accurate and well-resolved resource assessment.

With respect to whether or not the best wind resources are in coastal waters or at the tops of coastal mountains, different studies and investigations have provides varying results. Scatterometry and ship-based measurements (Van Buskirk et. al. 1999; Rosen 1998) indicate the existence of a low level jet (LLJ) that appears to be centered in the middle of southern portion of the Red Sea. Meanwhile WAsP calculations (SWECO 2002) indicate very high wind resources on the tops of hills and mountains. Furthermore, unpublished investigations indicate that low hills in the Aseb area can have wind speeds that are higher than the wind speeds in the nearby coastal plains (Eritrean Department of Energy 1997)

With regards to the extent of the high resource areas, simulations, the examination of ship-based meteorological measurements, station measurements and scaterometry data have provided significantly different answers. The KLIMM mesoscale simulations forecast a very limited area of high wind resources centered around Aseb Airport that did not extend far into the Red Sea and, which covered an area of less than 50 km radius. The ship-based measurements were largely limited to the main shipping lanes in the Red Sea and did not resolve the details of the wind speeds near the Eritrean coast. But these measurements did indicate 10 m annual average wind speeds of up to 8 m s^{-1} extending from 12.7 to 14 degrees N latitude in the Red Sea (Rosen

1999). Scatterometry measurements appear to indicate 10 m annual average wind speeds of slightly more than 6 m/s from about 13 to 14 degrees N latitude, but such measurements are known to be inaccurate near coastlines. Meanwhile more recent meteorological ground station measurements have indicated 10 m annual average wind speeds of approximately 7.1 m/s at along the coast at Gahro (12.8 degrees N) and 6.7 m/s at Aseb Airport (13.06 degrees N), but an annual average wind speed of only 4.7 m/s at Idi (13.93 degrees N) and 4.5 m/s at Tio (14.68 degrees N). It is currently unknown how much variability there might be in the wind speeds between the existing stations, or if there are some particular spots along the coast that have wind speeds higher than any of these stations.

And finally, because there is no vertical profile measurements of wind speeds in the high wind portion of the Southern Red Sea, very little is known regarding the three dimensional structure of the LLJ and its dynamics with local sea breezes and coastal topography.

In this study, we apply the Regional Atmospheric Modeling System (RAMS) in order to map specific wind energy resources in Southeastern Eritrea during a typical 4-day period during the high wind season. We find that RAMS reproduces well-know distinct features of the Eritrean wind meteorology much better than previous modeling efforts. We compare the results from RAMS with available surface data on winds and wind climatology. Given a good match between the model and available ground data, we use RAMS to produce wind speed maps for a typical high wind season day. Because annual wind power estimates are dominated by winds during the high wind season and because the winds during this period follow a consistent monsoonal pattern, we assume that the wind speed maps produced for a typical high wind period will correlate with annual wind power resources for the area.

With respect to our four Southeastern Eritrea wind resource questions: (1) Are the wind resources better on the hills or in the sea? (2) How far do excellent wind resources extend? (3) How does wind power depend on altitude? and (4) Where are the highest performance wind energy generation sites? We propose the following hypotheses: (1) Because the source of the high wind is a LLJ over the Red Sea, the highest wind locations will be coastal protrusions or hills that are closest to the center of the LLJ. (2) Approximately 200 kilometers of coastline from the Djibouti border north to Tio has very good wind resources except for bays and protected areas. (3) Vertical wind shear will be strongest near the coastline whereas further inland there will be a great variability of vertical wind shear due to topographic effects, and (4) the highest performance wind energy generation sites will be coastal hills near Aseb Airport and Gahro stations.

1.2 Simulation Case Selection and Synoptic Conditions

The winds along the Southeastern Eritrea coast are monsoonal in nature. From October to May, winds are largely from the southeast, while from June to September they are from the northwest. Figure 2 shows a scatterplot of daily average wind power density vector for Aseb Airport. This figure demonstrates that a large portion of the wind energy resource is provided under the conditions of the southeastern monsoon. Thus by characterizing the conditions of a typical strong southeastern monsoon we are likely to capture the meteorology that is most important for wind power production in this region.

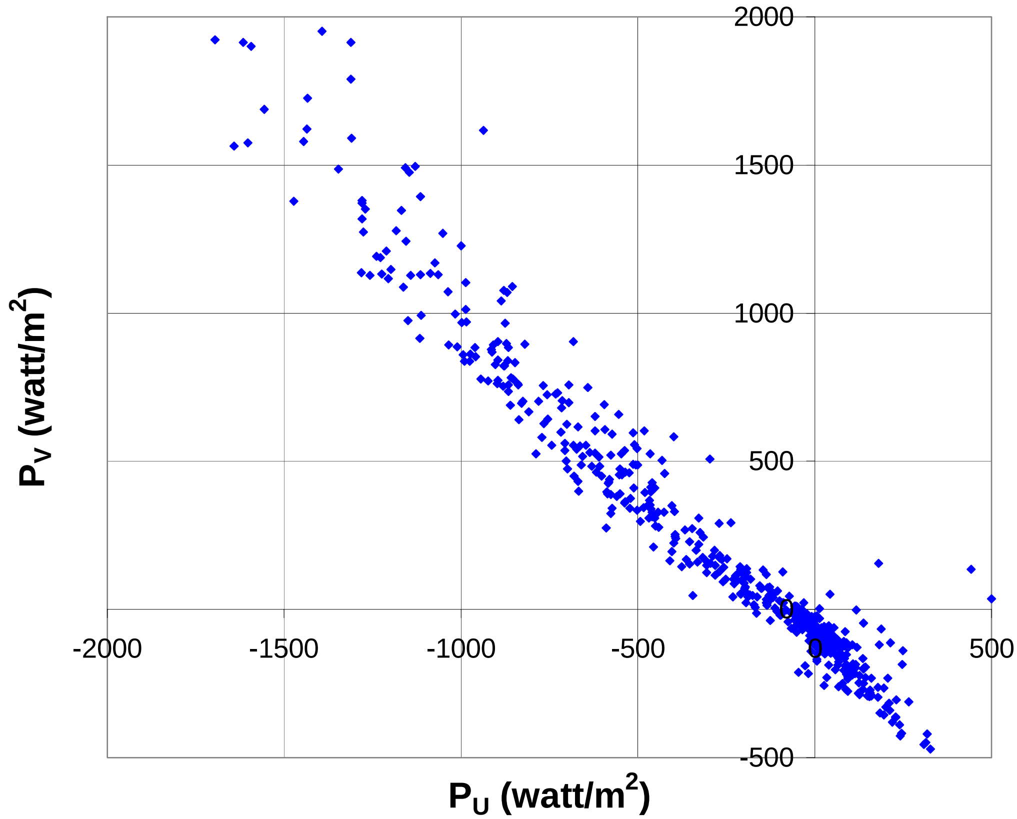

Figure 2: Scatterplot of daily average wind power density vector for Aseb Airport, Eritrea. Wind power density vectors are calculated from hourly data at 10 m, assuming an air density of 1.2 kg m^{-3}

The simulation period selected for this study is February 8-12, 2002 where the dynamics of the region is typically stable and consistent. The synoptic pattern changed very little, is characterized by the south east monsoon at the surface and a stable high pressure system over the South Red Sea at the 700 mb level (Flohn 1965). The stable, stationary high pressure produces a strongly stratified marine layer over the Gulf of Aden and the Red Sea and a heat low over Western Eritrea and Eastern Sudan. The strongly stratified, relatively cool marine layer provides a mass of dense air that is channeled and constrained as it travels from the Gulf of Aden to the Red Sea, and ultimately into the heat low in Eastern Sudan.

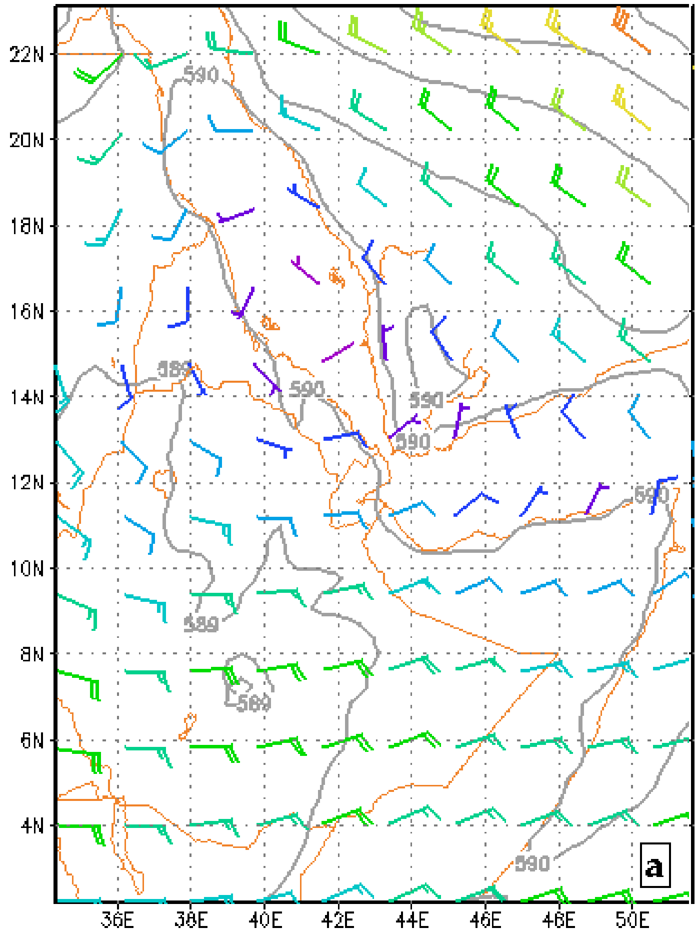

Figure 3: Synoptic conditions over the study area. A high pressure anti-cyclonic circulation is centered over Southeastern Eritrea at the 700 mb level.

We illustrate synoptic conditions in figures 3 and 4. The synoptic pattern changed very little over the Aseb bay region during this simulation period. The upper-level flow (700 mb) fields were characterized by a steady, stable high pressure ridge which lingers over the Red Sea, Eritrea, and the Gulf of Aden, and then drifts to the southeast over Somalia and the Indian Ocean. Westerly flow persists over the northern Red Sea and easterly flow is dominant over Ethiopia and Somalia. Mid-latitude westerlies of 10-50 knots extended from Sudan to Saudi Arabia to the north, while from Ethiopia to the Indian Ocean the equatorial easterlies can be seen in the southern part of the domain. The high pressure ridge produces a very stable marine layer and a heat low over Eastern Eritrea and Sudan. These features drive the planetary boundary layer mesoscale flows that create the Southern Red Sea LLJ.

At 0000 UTC 10 February 2002 (Fig. 3), 700 mb, the winds were characterized by an anticyclonic flow centered at the southern Red Sea and covering northwestern Sudan, the northern Red Sea and Yemen. Winds over the Southern Red Sea and Eritrean land-mass were weak and variable since the area was under the influence of an anticyclonic circulation bounded by the mid-latitude westerlies to the north and the equatorial easterlies to the south. The peak of the synoptic high pressure (5900 m) was located over the Yemeni plateau the Southern Red Sea and Gulf of Aden.

The surface (1000 mb) synoptic map is shown in figure 4 for 0000 UTC 10 February 2002, a synoptic high pressure system of 1015 hPa developed over Saudi Arabia and the Indian Ocean combined with a heat low of 1005 hPa west of the Ethiopian Plateau produces a general east to west surface level pressure gradient. This high pushes marine air through the strait of Bab el Mandeb. Winds are generally flowing from the southwest all over the Red Sea speeds ranging from 10 – 25 knots, the maximum being at Bab el Mandeb. Western Eritrea was characterized by calm winds (2-5 knots). The anticyclonic circulation around the eastern Sahara high (to the west of the illustrated domain) pushes northern Red Sea winds from the north and produces a low level convergence along the northern Eritrean coast. From here, air is pulled inland through a break in the mountains at Port Sudan to Western Eritrea by the heat low in that region. This creates a pattern that is characteristic of the wintertime steady monsoon circulation pattern in the region (Flohn 1965).

2. Mesoscale Simulation

2.1 Methodological Overview

The Regional Atmospheric Modeling System (RAMS) model (version 4.4) was used to perform a simulation of the wind patterns over the selected four-day period in February 2002 for the Southeastern Eritrean coast. As described above, this period was chosen because February is within the high wind season of the Southern Red Sea region based on observational studies. The particular period was selected because it showed steady, consistent strong winds from the southeast that are typical for this period, and because steady conditions increase the potential accuracy of the mesoscale simulation. The simulated winds and temperatures were validated by comparing with the observations from ground-based meteorological stations. The automatic stations at Aseb Airport and Gahro (Habtetsion et.al. 2002) were used for the model validation. Finally, the simulation results were analyzed to both characterize the structure of the wind patterns and to find the best sites for wind energy production. Wind speed maps and verticle cross-sections of the Red Sea LLJ are produced for this anlaysis.

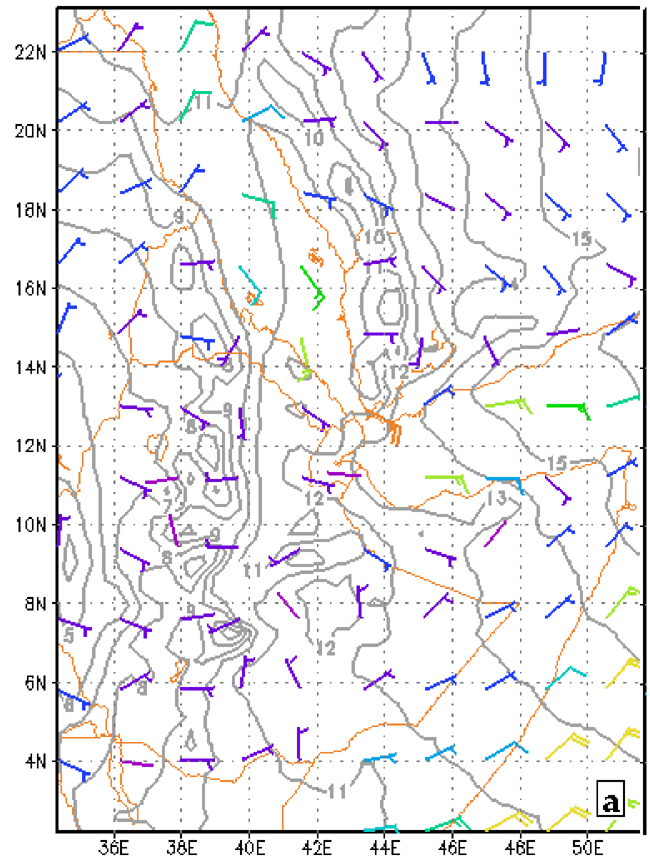

Figure 4: Synoptic conditions over the study area. A general pressure gradient exists between the Gulf of Aden and Western Eritrea due to a heat low over Eastern Sudan. Peak winds occur at Bab el Mandeb where flows are channeled as they pass from the Gulf of Aden to the Red Sea.

2.2 Model Setup

Our RAMS simulations focused on an analysis of the coastal wind dynamics in order to locate the best sites for wind power generation in Southeastern Eritrea. For this purpose, a nested-grid configuration of four grids was used in RAMS. The outer model domain was extended westward to include Eritrea, parts of Sudan, and Ethiopia. Meanwhile, on the eastern side of the domain the Red Sea, parts of Saudi Arabia and Yemen were included. Finer nested grids were used applied to the area of interest in order to obtain meteorological fields of high resolution (Fig. 5).

In order to select the most suitable nested grid configuration, several test simulations were performed. The configuration that was finally been selected and applied for the selected periods of simulation is the following:

- Grid 1: A coarse grid with a mesh of 50x60 points and 40 km horizontal grid increment.
- Grid 2: A medium grid with a mesh 42x42 points and 10 km horizontal grid increment.
- Grid 3: A small grid with a mesh 62x50 points and 2.5 km horizontal grid increment.
- Grid 4: A fine grid with a mesh 42x42 points and 0.7 km horizontal grid increment

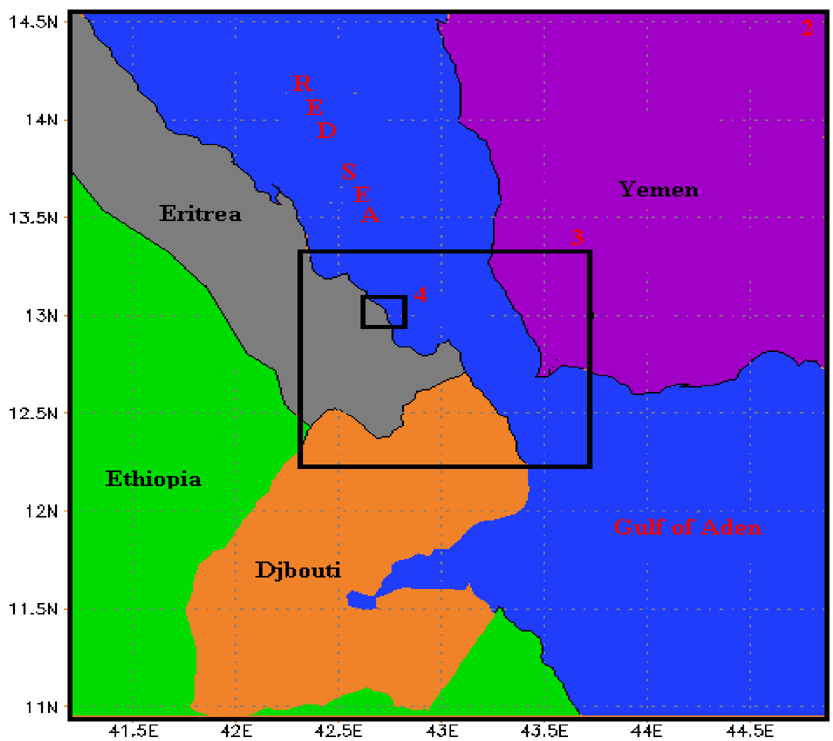

Figure 5: Boundaries of grids 2 – 4 used for the computational domain of the numerical simulation.

Grids one, two and three were centred at the domain coordinate of 12.791° N and 43.071° E (Aseb city), while the centre of grid four was adjusted to slightly south of Aseb Airport to include the hills near Aseb Airport. Concerning the vertical structure, the grids were identical. In detail, 50 vertical layers with a first grid spacing of 40 m and a grid stretch ratio of 1.12 have been used. The vertical structure was dense in the lower levels, and became increasingly coarse toward the top of the domain, which was at 30 km.

2.3 Model Initialization and Input Data

The data available for validating and calibrating meteorological simulations in Eritrea consist of ground station data, historical and current radiosonde data, satellite-based scatterometry data, and historical ship-based measurements in the Red Sea. Station data exists for 25 first and second-class stations recently installed by the Eritrean Department of Energy (Habtetsion et al. 2002). These stations measure temperature, wind, humidity, pressure, and solar radiation. Historical radiosonde data measurements exist for Asmara, and for nearby stations at Addis Abeba, and Khamis Saudi Arabia. Recent radiosonde data exists for Abha and Jedda, Saudi Arabia (University of Wyoming web site). Historical ship-based measurements from the Red Sea are available from the Comprehensive Oceanographic and Atmospheric Data Set (COADS). In addition, satellite-based measurements of wind using radar scatterometry exist for the Red Sea and Gulf of Aden areas.

At the large scale, the model simulation obtains boundary condition information and large scale synoptic forcing information from data provided by the National Centers for Environmental Predication (NCEP). The NCEP data is available at a frequency of once every six hours and includes: temperature, pressure, wind speed, wind direction, and relative humidity data with a resolution of 2.5 x 2.5 degrees. The simulation model was initialized at 0000 UTC 08 February 2002 and was allowed to spin up for 12 hours.

3. Results

3.1 Model Validation

To have confidence in the model results, validation of model results against observations was carried out. To gain insight into how well the model simulation depicted the thermal forcing of the low-level flow, the model surface temperature and wind speed fields were compared to surface observations. For the time period simulated, there are detailed meteorological measurements for only two stations located in the higher resolutions grids three and four: Aseb and Gahro. Time series plots of surface temperature and wind speed for stations at Aseb Airport and Gahro were compared to model results and observations.

Differences between direct model output and observations can largely be explained by possible errors in near-surface extrapolation of model parameters due to local, subgrid characteristics of surface roughness. In our comparisons, we compared the time series model results of the 10 m wind speed at Aseb Airport and Gahro, and 2 m temperature at the Aseb Airport station.

When we compare model output with observations for the Aseb Airport station, there was a consistent underestimate of the wind speed by the model output. Given the systematic underestimation of wind speed, the surface roughness assumptions of the 10 m wind speed estimate was reexamined. The model used a total roughness length of 0.05 m in the Aseb area, which is a level desert. A review of typical roughness lengths for level desert indicated that a roughness parameter adjustment for the 10 m estimate was needed given the local roughness characteristics of the meteorological station site. To make this adjustment, the log law (Jacobson 1999) was used and the roughness- length was set 0.0003 m (Jacobson 1999) for level desert. The adjusted estimate of the 10 m wind speed vs. time was recalculated for Aseb Airport from the surface grid cell average wind speed and plotted in figure 6. The roughness-adjusted estimate of 10m wind speed now shows a very good match with the observational data (Fig. 6).

For the Gahro station, similar discrepancies were observed between model results and the observations, but the adjustment in the 10 m wind speed estimate was made in a slightly different manner. The meteorological station at Gahro is located less than 10m from the water's edge at a location where the winds are onshore during the entire simulation period. The model grid did not resolve these subgrid characteristics of the meteorological station site well. Thus the appropriate surface for the Gahro station is water, but at the model resolutions, RAMS shows Gahro to be on land. Thus, the model wind speeds used to compare with observations are those at the next grid cell east of Gahro, which has water surface characteristics in the model. These recalculated comparisons show approximately the same level agreement as seen for the Aseb Airport comparison.

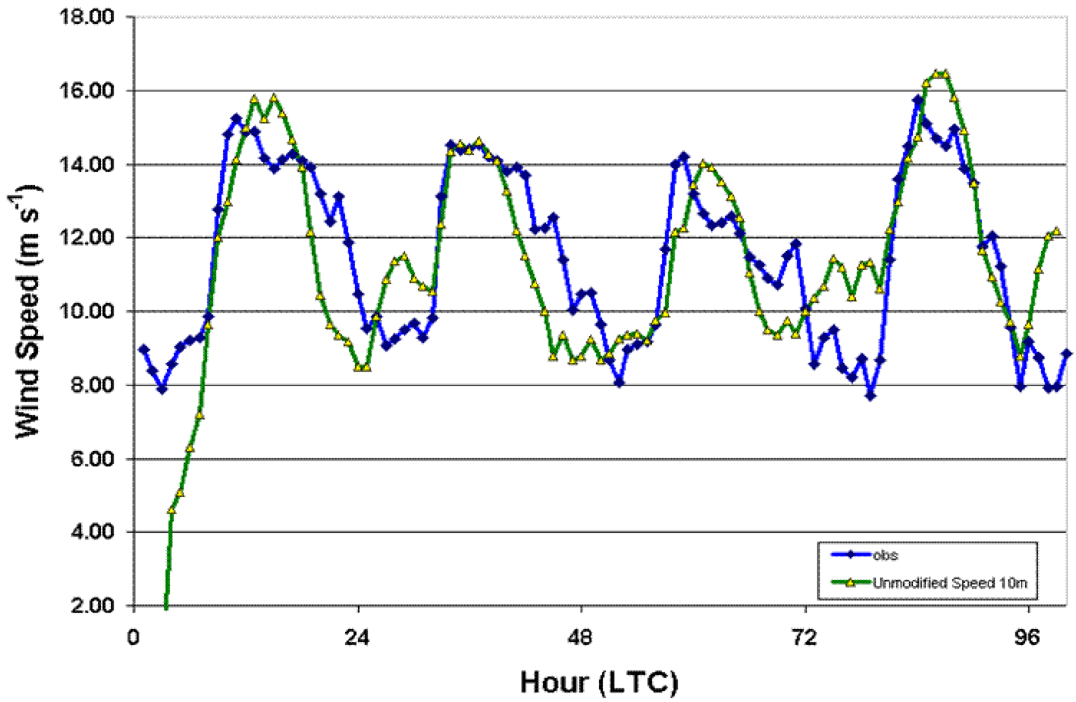

Figure 6: Wind speed comparison of adjusted model output and wind speed observations. Model output is adjusted to compensate for local roughness characteristics of meteorological station.

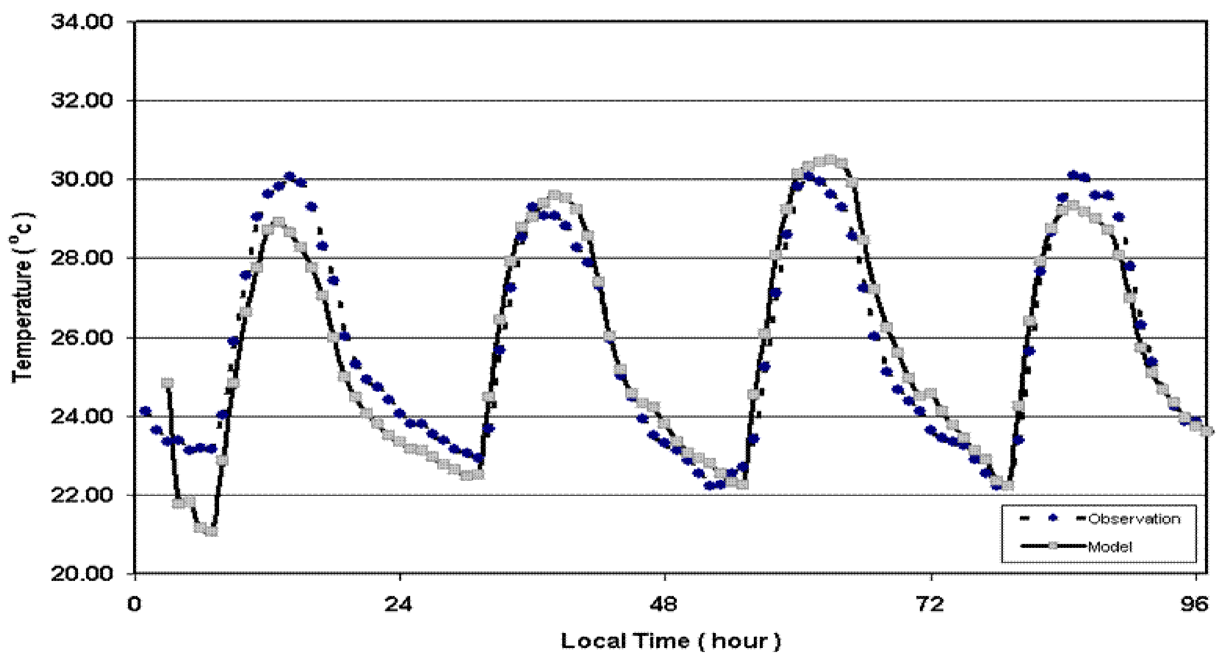

Figure 7: Temperature comparison of adjusted model output and wind speed observations. Model output is adjusted for local roughness characteristics of meteorological station.

Surface temperature comparisons of model and observation at Aseb Airport station were also carried out. The model calculates the grid cell average temperature of the surface grid cell and uses a surface boundary layer equation to calculate the estimate of the 2 m temperature. Before any roughness adjustment was done to the equation that estimates 2 m temperatures from the grid cell average temperature, the model under-estimated the surface temperature by an average of 2.5^{o}C. After a roughness an adjustment was made to the equation for estimating 2 m temperatures using the value of 0.0003 m appropriate for the level desert at Aseb Airport, the surface temperature matched very well with the observations at the Aseb Airport station (Fig. 7).

3.2 Wind Speed Maps

Given that the model reliably reproduces daily wind patterns and temperatures with appropriate roughness adjustments, and that RAMS is a well-test mesoscale simulation model, it is likely that the model may also reproduce many of the key physical and geographic features of the winds in the area. In this section we illustrate the larger geographic features of the simulated wind fields as a candidate forecast of the wind speed patterns that are likely to be found in the Southern Red Sea during the southeastern monsoon season.

Figure 8 shows a 10 m average wind speed map for the south coast of Eritrea for the simulation period generated from the RAMS model results. This map shows a zone of average wind speeds of 9 - 11 m s^{-1} at 10 m and 13 – 15 ms^{-1} at 60 m stretching from approximately 12.8 to 14.6 degrees north latitude over the Red Sea. Coastal wind speeds reached 7-10 m s^{-1} at 10 m and 10 – 14 m s^{-1} at 60 m, while inland wind speeds were 4-7 m s^{-1} at 10 m and 5 – 13 m s^{-1} at 60 m .

Higher resolution maps of the average wind speed distribution of the area (grid 3), were also analyzed to show more detailed wind speed structure of the region. Figures 9 shows the higher resolution the wind speed distribution around Aseb and Gahro.

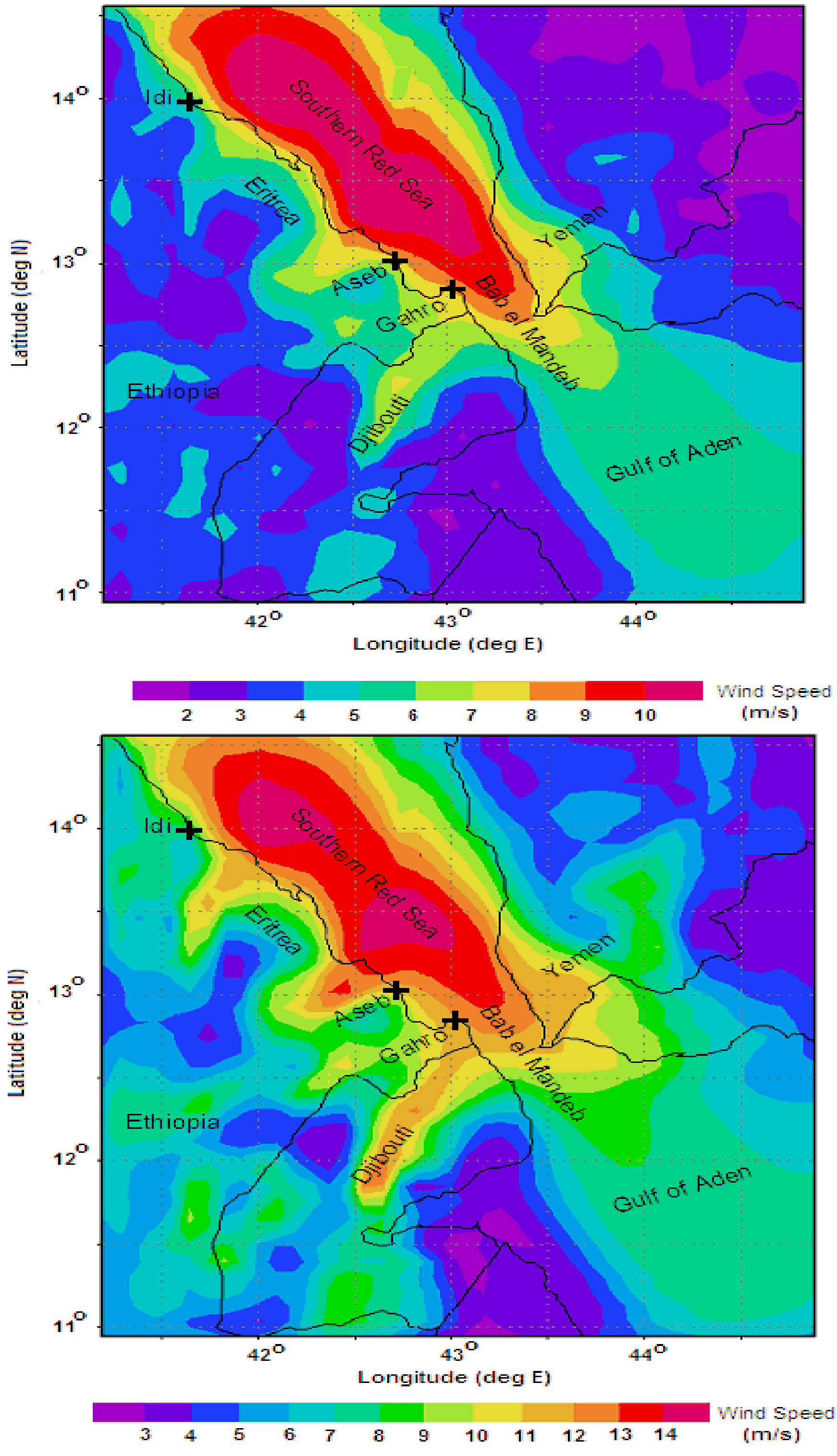

Figure 8: Average 10 m (above) and 60 m (below) wind speed for the simulation period for grid 2. Results how a strong LLJ of 9 – 11 ms^{-1} over the Southern Red Sea for 10 m, and an LLJ wind speed of 13 – 15 ms^{-1} at 60 m height.

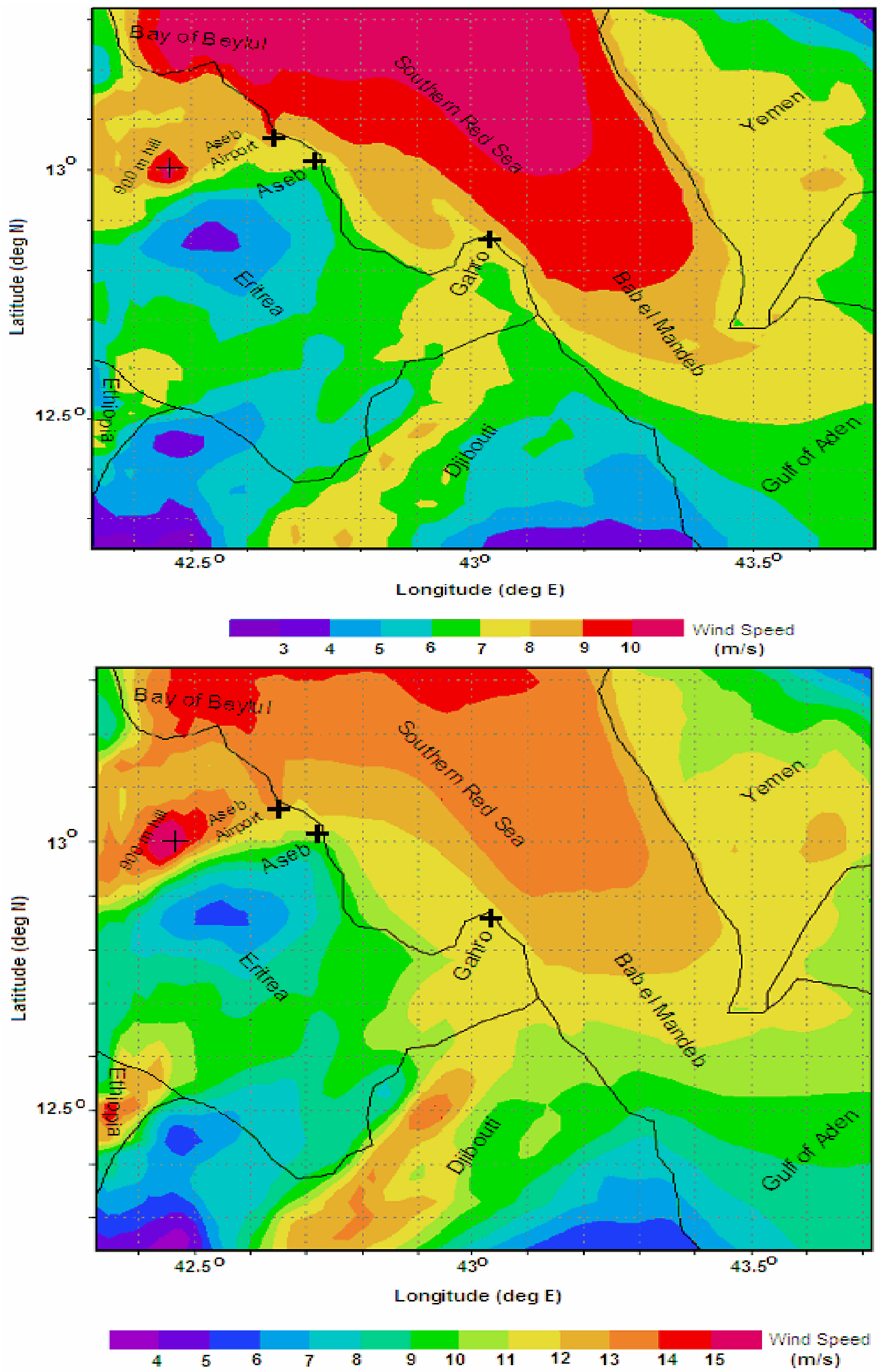

Figure 9: Average 10 m (above) and 60 m (below) wind speed for the simulation period for grid 3. Results how a strong LLJ of 9 – 11 ms^{-1} over the Southern Red Sea for 10 m, and an LLJ wind speed of 12 – 14 ms^{-1} at 60 m height. Both images show peak wind speeds n the Bay of Beylul and on the top of the 900 m hills west of Aseb

3.3 Lower Level Jet Vertical Structure

The "Eritrean Low Level Jet" is a relatively narrow wind stream along the East African Red Sea Coast and is part of the larger South West Monsoon circulation pattern. A conceptual model of the LLJ that shows a horizontal slice across southern Red Sea is shown on figure 10. The LLJ is a strong, sustained low-level wind systems produced by the channeling of strongly stratified marine air through the straight of Bab el Mandeb. This marine air is driven by a persistent east to west surface synoptic pressure gradient produced by a heat low on the western side of the Ethiopian Highlands in Eastern Sudan during the southeast Southern Red Sea monsoon.

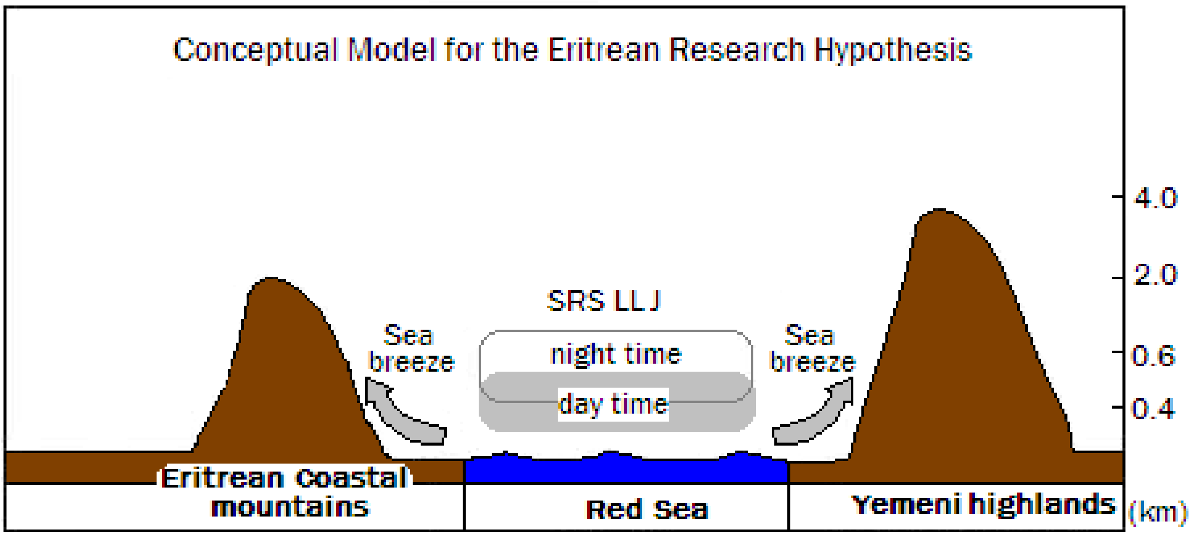

Figure 10: Conceptual model for Southern Red Sea Low Level Jet (SRS LLJ). Daily solar heating produces sea-land and upslope flow that draws the jet that is funnelled through Bab el Mandeb down to lower altitudes and advects high speed Red Sea winds onshore.

To examine the structure of this LLJ over the Southern Red Sea, we examine wind speed cross-sections at Aseb Airport from the simulation. In figure 11 we show XZ cross sections of the LLJ at the latitude of Aseb Airport for midnight and noon UTC (3 AM and 3 PM local time respectively) on the third day of the simulation, February 11, 2002. The jet is centered at about 600 m with a core speed of 25 m s^{-1} at 0000 UTC and there is a layer of relatively low winds at the surface below the jet, especially over land. Downslope winds from the Yemeni side of the Red Sea are flowing towards the jet which is proximate to the Eritrean coast. During 1200 UTC 11 February 2002, the sea breeze has fully developed on both sides of the coast resulting in subsidence of the marine layer air mass in the middle of the Red Sea. As a result, the jet has lowered to about 400 m strengthening the Eritrean coastal wind speeds and surface winds as the sea breeze and upslope winds mix the momentum contained in the core of LLJ throughout the basin contained between the Eritrean coastal hills and Yemeni highlands . The wind speeds ranged from 10-16 m s-1 at the Eritrean side of the coast and are more than 20 m s^{-1} at the core of the LLJ.

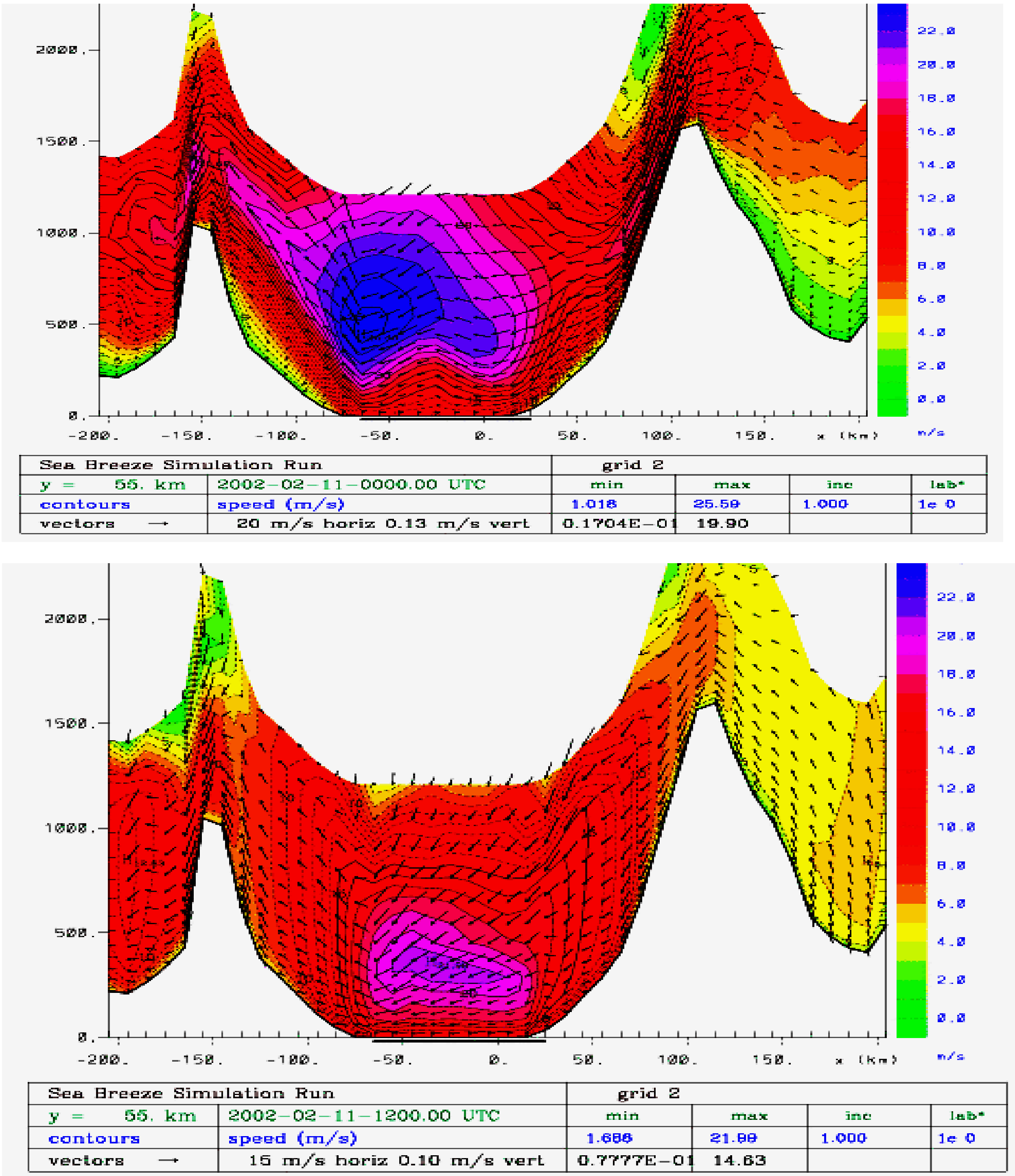

Figure 11: X-Z cross section of wind speeds in the Southern Red Sea for 0000 UTC (above) and 1200 UTC (below) February 11, 2002.

If we take our simulation results as indicative of mesoscale flows during the southeast monsoon in the Southern Red Sea, then we find that there is a persistent, 200 – 300 kilometer long LLJ in this region. The LLJ extends from Bab el Mandeb at 12.5 deg N to approximately 14.5 deg. N in the Southern Red Sea and is normally strongest in the period between November to March when core maximum speeds may reach up to 20-30 m s^{-1}. The LLJ is modified by the diurnal sea/land breeze dynamics of the region. The core is usually centered at an elevation of about 300-600 m, where it occupies the higher end of the elevation during nighttime hours and the lower range of the elevation during mid-afternoon. This semi-permanent low-level wind, which is particularly strong during the southeastern Southern Red Sea monsoon, is the key to the high wind speeds and excellent wind energy resources of observed in Southeastern Eritrea.

4. Conclusion

In this study, we posed four questions regarding the wind energy resources of Southeastern Eritrea that we attempted to answer through the simulation of a typical high wind period during the Southern Red Sea southeastern monsoon season:

(1) Are the wind resources better on the hills or in the sea?

(2) How far do excellent wind resources extend?

(3) How does wind power depend on altitude? and

(4) Where are the highest performance wind energy generation sites?

Since our simulation was conducted over a relative short time span, it cannot provide a definitive answer to these questions. But the simulation has revealed the three dimensional structure of the Southern Red Sea southeast monsoon low level jet. These results imply a set of provisional answers to our four wind resource questions:

- **Hills or Coastline**: The best wind resources are in the center of the Southern Red Sea LLJ at an elevation of 300 to 600 m above the eastern side of the Southern Red Sea along the Eritrean coastline. Those topographic features that can potrude closest to the center of this LLJ will be the locations with the best wind energy resources

- **Extent of Resources**: The SRS LLJ extends from Bab el Mandeb (at 12.5 deg N) to 14.5 deg N in the Southern Red Sea.

- **Vertical Wind Shear**: Vertical wind shear is strongest near the coast in the afternoon, or over coastal hills and mountains when the core of the SRS LLJ is closest to the land or sea surface.

- **Best Wind Resources Location**: There appears to be two maxima in the wind speeds in the SRS LLJ during the southeastern monsoon. One peak is near the Bay of Beylul and extends southwest toward a group of hills west of Aseb that rise to 900 m in elevation. The second peak in coastal wind speeds appears to be an area of coastline approximately 30-50 km ESE of the Eritrean town of Idi. Both of these locations have not yet had their wind speeds measured with a meteorological station.

RAMS appears to have successfully simulated the main characteristics of the distribution of wind energy resources for Southeastern Eritrea. Further research shall test these simulation results agains new meteorological measurements to determine if the characteristics and distribution of wind speeds and wind energy resources have been accurately forecast by this study.

Disclaimer

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