# Dynamical downscaling of prevailing synoptic-scale winds over the complex terrain of Mariepskop, South Africa

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Locations where large altitudinal gradients exist have been shown to be a good early indicator of climate change. Mariepskop is a high mountain peak situated in the Mpumalanga province of South Africa. It is partly isolated from the rest of the Drakensberg mountain range, making it ideal to study the effects of flow dynamics and climate over the mountain without interference in the flow from adjacent topography. The flow dynamics of Mariepskop was studied by forcing averaged, long term synoptic observations at Mariepskop across the lateral boundaries of a Computational Fluid Dynamics (CFD) model. Although CFD models have traditionally been used for engineering applications, CFD models have been used more commonly in the meteorological realm over the last few years. Model results were verified by weather station observations and aerial photographs of the mountain. The model was able to simulate wind speed, wind direction and high rainfall areas relatively well.

*Keywords*: Computational fluid dynamics, climate modelling, Lowveld climate.

## 1. Introduction

When embarking on Mesoscale atmospheric modelling, it is often challenging to select the appropriate model for the spatial extension and study problem at hand. The size of the domain to be studied and the complex topography of the Mariepskop Mountain lead the authors to believe that a CFD model will be best suited for this study.

The model used in this study is called STAR-CCM+ and it recently became the first commercial CFD package in the world that could mesh and solve flow dynamics and thermodynamics problems with over one billion finite volume cells. It was chosen as the model of choice as it is capable of handling fine resolutions, complex geometry and because of its relative ease of operation.

## 2. Dynamical Downscaling of Climate

### 2.1 The Mariepskop Domain

The Mariepskop domain stretches over an area 27 by 27 km. The lowest point in the domain has an elevation of 520 m Above Mean Sea Level (AMSL) and the highest point is located just below 2000 m AMSL

### 2.2 The Mariepskop Volume Mesh

The Mariepskop volume mesh designed for this study consists of approximately 9 million volume cells.

A north-facing view of the Mariepskop volume mesh is depicted in Figure 1.

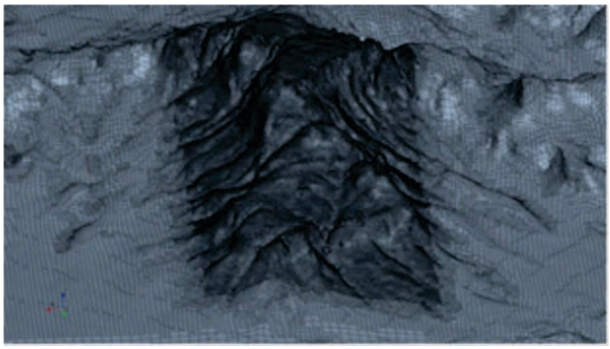

Figure 1: A north-facing view of the smallest volume block mesh with the highest resolution of approximately 6 m x 6 m around the Mariepskop mountain domain.

### 2.3 Boundary Types

The Mariepskop terrain was set to a “Wall” type boundary between the mountain and the atmosphere in contact with the mountain, which represents an impermeable, non-slip surface (see STAR-CCM+ user guide, 2011), whereas the lateral boundaries on the north, south, east and west were chosen to be velocity inlet boundaries (where air is pushed into the domain across the upwind boundaries and pulled out of the domain across the downwind boundaries. The top boundary in the upper atmosphere at a height of 8000 m above the lowest point in the terrain was set to a symmetry plane.

### 2.4 Boundary Conditions

Temperature, pressure, wind speed and wind direction were supplied to the model in the form of field functions. The name “Field Functions” is used for functions that supply the CFD model with boundary conditions that change as a function of some variable (or variables). In the case of this study the field functions describe temperature, pressure, wind speed and wind direction as a function of height AMSL.

Field functions were created from long-term averaged (1981 to 2011) wind speed, wind direction and surface temperature values obtained from National Center for Atmospheric Research/ National Center for Environmental Prediction (NCAR/NCEP) reanalysis data (Kalnay *et al*., 1996).

The data was obtained for two atmospheric pressure levels (850 and 700 hPa) for the austral summer (DJF) and austral winter (JJA) seasons. NCAR-NCEP reanalysis data is one of the few data sets available for Mariepskop, exhibiting a consistent long record at different atmospheric levels in the vertical.

The temperature field function was supplied to the model in the form of the average environmental temperature lapse rate as is specified by the International Organization for Standardisation (ISO) (ISO, 1975).

The barometric formula was used to describe the decrease of pressure with an increase in altitude and the power law velocity equation was used to create an estimated field function of the wind speed profile. Wind directions changes with altitude were linearly interpolated from long term observations.

### 2.5 Model Parameterization

The time step simulation method that was selected for this study is referred to as “implicit unsteady”. The reason is because the CFD model failed to converge under steady conditions when a very large domain, such as in this study, is considered.

A turbulent viscous regime was modelled as the main aim of the study was to simulate turbulence.

The ideal gas model was chosen as the Equation of State model, whereas a segregated flow model was selected to simulate flow and energy.

The convection scheme chosen for this simulation is the second order upwind finite volume discretization scheme.

The Segregated Fluid Energy model that was selected for the Mariepskop simulation is known as the Segregated Fluid Temperature model.

Turbulence was modelled by means of the Reynolds-Averaged Navier Stokes (RANS) k-ε turbulence model.

## 3. Observations

Before and during commencement of this research, three Automatic Weather Stations (AWSs) were erected at different elevations on Mariepskop. The AWSs were erected at 1300 m, 1600 m and 1900 m AMSL. Each weather station electronically recorded rainfall, temperature, wind speed, wind direction, soil moisture and solar radiation data on hourly intervals.

The wind speed and wind direction data at each of the three elevations were used to verify the output of the CFD model used to model atmospheric flow over Mariepskop.

## 4. Results

### 4.1 Mesh Sensitivity Study

A mesh sensitivity study was done to compare the results of a model having 2 and 9 million volume mesh cells. Since the results of the two volume meshes varied less than 12% it was decided that a volume mesh size of 9 million cells was adequate for the purpose of this study.

A computer with a Random Access Memory (RAM) of 16 Giga Bytes was used to perform the simulations. Each of the simulations with a volume mesh size of nine million cells took between one and two months to complete (in actual time), depending on the simulation in question.

### 4.2 Wind Speed

Figure 2 shows the model simulated wind speed results at 1300 m, 1600 m and 1900 m AMSL cells as a function of model time for the summer simulation. A summer and winter simulation was done, but for the purposes of this publication, only the summer results are included.

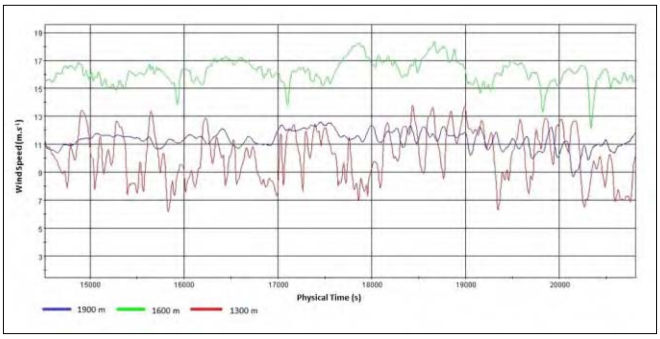


Figure 2: Model simulated wind speed results ($m.s^{-1}$) at 1300 m, 1600 m and 1900 m Above Mean Sea Level (AMSL) for the summer simulation over a period of approximately 4000 seconds.

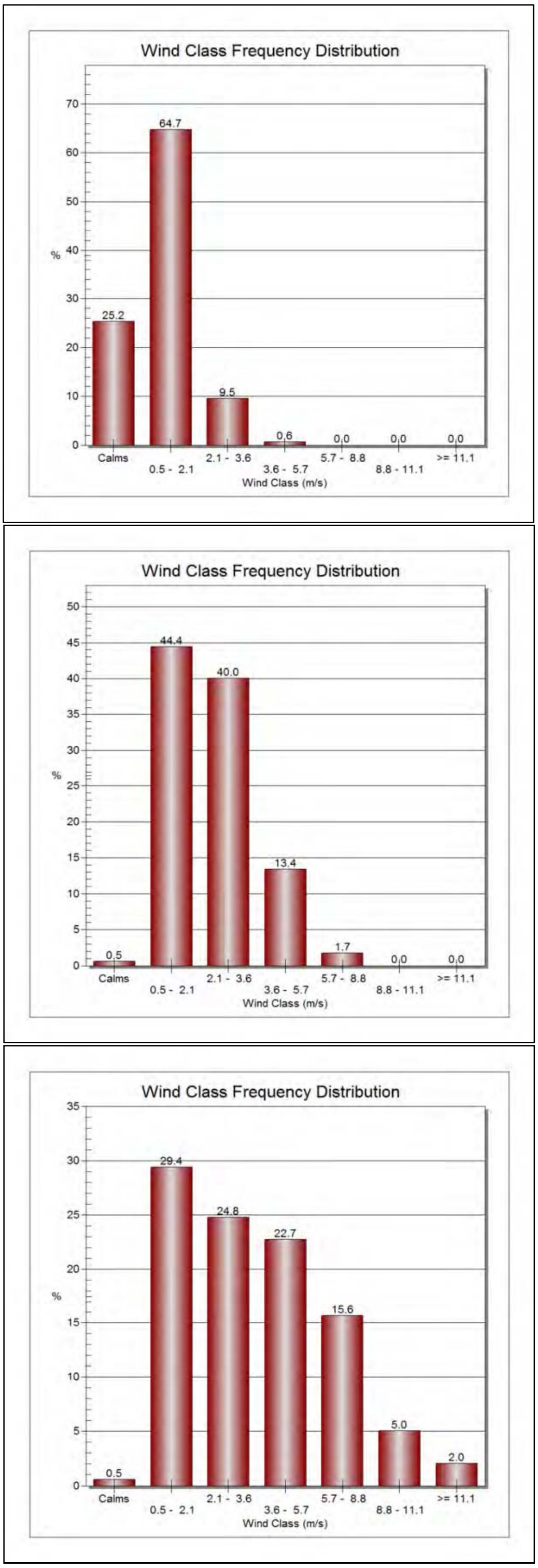


Figure 3: Wind class frequency distribution (%) for the 1300 m (top), 1600 m (middle) and 1900 m (bottom) Above Mean Sea Level (AMSL) weather stations on Mariepskop during the months of December, January and February (DJF) in the 2010-2011 season.

It is clear that the CFD model over predicted wind speeds at all three levels (1300 m, 1600 m and 1900 m). The reason for this inaccuracy is most probably related to the fact that a constant averaged wind speed was forced across the boundary of the model and that calm conditions could therefore not be modelled.

### 4.3 Wind Direction

Figure 4 provide a graphic representation of the modelled wind directions for the summer simulation at 1300 m (top left), 1600 m (top right) and 1900 m (bottom) AMSL on Mariepskop.

The position of the weather stations are indicated by a coloured circles whereas a wind rose representing observed conditions for the specific season in question can be seen in the top right corner of each figure.

From the figures it can be seen that modelled and observed wind directions agree very well.

### 4.4 Rainfall

The modelled flow of air over Mariepskop was compared to aerial photographs in order to see if modelled ascending flow of air over Mariepskop correlates with high density vegetation on the Mountain (indicating high precipitation zones). It was found that such a correlation exists.

## 5. Conclusions and Recommendations

CFD studies have been limited in the meteorological realm in the past mainly because of computing expense. As computing power becomes more accessible it is possible to use this extremely powerful tool to simulate meteorological problems.

The STAR-CCM+ model performed well in this study and could model flow conditions over Mariepskop relatively successfully even though a simple set of averaged boundary conditions were used. This makes a strong case for using CFD models in similar studies in the future.

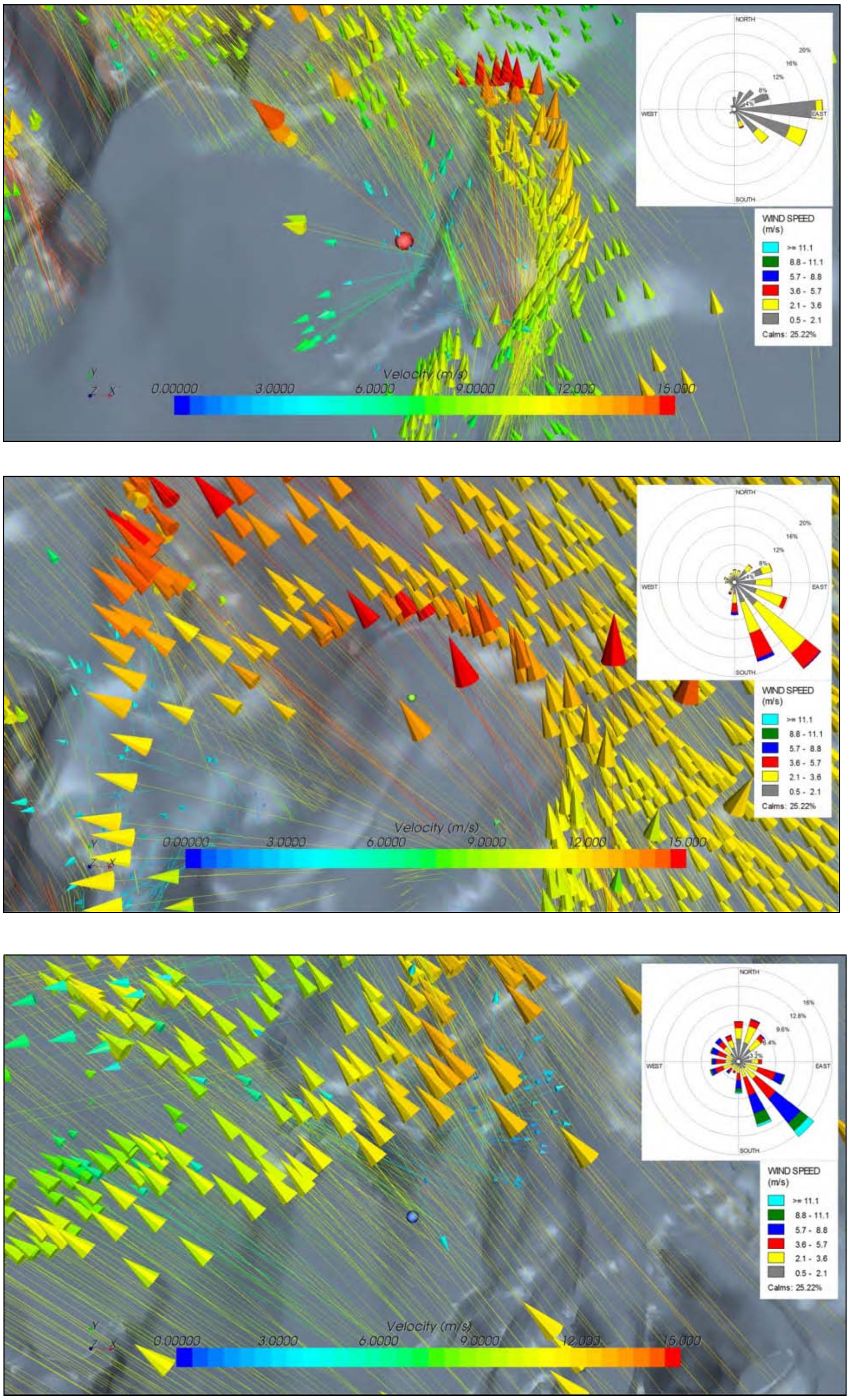


Figure 4: Simulated (arrows) and observed (wind rose – top right) results of wind speed and direction at 1300 m (top), 1600 m (middle) and 1900 m (bottom) Above Mean Sea Level (AMSL) on Mariepskop during the summer season. The coloured circles represent the positions of the weather stations.

## 6. Acknowledgments

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## 7. References

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