Diurnal Wind, Relative Humidity and Temperature Variation in the Stellenbosch-Groot Drakenstein Wine-Growing Area*

V. Bonnardot[1], O. Planchon[2], V. Carey[3]** and S. Cautenet[4]

1) ARC Institute for Soil, Climate and Water, Private Bag X5026, 7599 Stellenbosch, South Africa
2) COSTEL, UMR 6554/LEGT-CNRS, University of Rennes-II, 6 Avenue G. Berger, 35043 Rennes Cedex, France
3) ARC Infruitec-Nietvoorbij, Private Bag, X5026, 7599 Stellenbosch, South Africa
4) LaMP, UMR 6016-CNRS, Blaise Pascal University, 24 Avenue des Landais, 63177 Aubière, France

Submitted for publication: March 2002
Accepted for publication: September 2002
Key words: Atmospheric modelling system, sea breeze, relative humidity, temperature, wine-growing area, South Africa

Numerical simulations were performed for 2000-02-03 and 2000-02-04 over the Western Cape in order to observe the alternating sea and land breeze circulation and its effects on diurnal relative humidity and temperature variation, as well as to identify wine-growing areas characterised by high humidity and cool temperature during the maturation period. The Regional Atmospheric Modelling System (RAMS version 4.3) was used at a 1 km resolution. The study domain for the simulation covered a small area from False Bay up to 35 km from the coast. Results are presented using horizontal cross-sections at surface level as well as two south-north cross-sections at longitudes 18°40'E and 18°47'E in order to examine vertical profiles of the atmosphere above the Stellenbosch / Groot Drakenstein wine-growing area. Modelled results agreed with observed data in the vineyards. The sea breeze penetrated at least 35 km inland, but the cooling effect declined rapidly with distance from the sea. Temperature differences between southern and northern slopes near the sea could be significant enough to be important for viticulture.

In order to remain competitive in an ever-expanding international wine market, the South African Wine Industry considers terroir identification for viticulture as a high priority and fosters research on this topic as it corresponds with research priorities stipulated by the Office International de la Vigne et du Vin (http://www.oiv.org/Resolutions/frames.htm). The ARC Infruitec-Nietvoorbij Institute has been running a research project on terroir (the interaction between climate, geology, soil and topography (Falcetti, 1994) since 1993. Climate (meso-climate) is an important component of the terroir concept. The Stellenbosch-Groot Drakenstein wine-growing area, situated in the extreme South-Western Cape, has a warm temperate climate described as "*Mediterranean*" with mild, rainy winters and warm, dry summers (Schulze, 1972), similar to the Mediterranean basin, coastal California, South-Western Australia and Central Chile. Using various indices for viticulture (Winkler *et al*., 1974; Huglin & Schneider, 1998; Tonietto, 1999), this region can be described as having no climatic constraint for ripening of cultivars (Carey, 2000; Carey & Bonnardot, 2000). This global picture, however, has finer climatic aspects due to the complexity of the topography, as shown in research on natural terroir units for viticulture in the Bottelary-Simonsberg-Helderberg wine-growing area (Carey, 2001) as well as the proximity of the ocean. Water and land surfaces have different properties and energy balances. The sea is a fluid in continual motion; any heating or cooling is distributed to a considerable depth and so the rise or fall of water surface temperature is only slight. Conversely, the land has very low thermal conductivity and heats and cools rapidly, resulting in marked diurnal variation. The land-water temperature differences produce corresponding land-water pressure differences in the lower atmospheric layer, which result in a system of breezes along a coastline. Onshore flow during the day is known as a *sea breeze,* while offshore flow at night is referred to as a *land breeze* (Abbs & Physick, 1992). The cooling effect of the sea breeze during the afternoon, amongst other factors (altitude, aspect, soil, viticultural practices) could influence wine quality and character as cool temperatures are advantageous for aroma development of most cultivars, especially white cultivars (Becker, 1977; Huglin & Schneider, 1998).

As there is no doubt that sea breeze effects play a significant role in the environment, preliminary studies on the sea breeze in the Stellenbosch wine-growing area have been performed using surface data from the ARC Infruitec-Nietvoorbij automatic weather station network (Bonnardot, 1997; 1999). The climatic observations in the vineyards definitely showed signs of sea breeze effects, but it is difficult to separate the effects due to the sea breeze circulation from those due to the complex topography and local airflow within valleys (up-slope winds) on a surface data basis only. The use of a meso-scale meteorological model was therefore necessary to examine the vertical profiles and explore the sea breeze-induced patterns in a scientific way for ter-

**Results were partially presented at the Second International Congress of the South African Society for Enology and Viticulture, Cape Town, November 2000.*

***Present address: Department of Viticulture and Oenology, Stellenbosch University, Private Bag X1,7602 Matieland (Stellenbosch), South Africa.*

Acknowledgements: This work uses the RAMS model, which was developed with the support of the National Science Foundation (NSF) and the Army Research Office (ARO). Computer resources were provided by CINES (Centre Informatique National de l'Enseignement Supérieur), project amp2107. The authors wish to thank the Wine Industry Network of Expertise and Technology (Winetech) and the Centre National de la Recherche Scientifique (CNRS) for partial funding of the research, as well as Prof. G. Cautenet, A.M. Lanquette and F. Besserve (CNRS-LaMP), I. Ganzetti (CNRS-COSTEL) and A. Schmidt (ARC Infruitec-Nietvoorbij) for technical assistance.

roir identification. A preliminary simulation for 4 February 2000 (during the maturation period of the grapes) was performed using a 5 km grid resolution in order to determine the local circulation over the wine-growing region (Planchon *et al.*, 2000; Bonnardot *et al.*, 2001). The diurnal variation in land and sea breezes was clearly shown. The thermal threshold resulting from the penetration and subsequent disintegration of the sea breeze appeared to be situated in the environs of the Bottelaryberg, 10-15 km from False Bay. Even though the sea breeze penetrated further north from the direction of False Bay, the associated temperature effect was not experienced beyond the Bottelaryberg. In order to ascertain the contributing effects of topography to the sea breeze circulation in more detail, further simulations were performed using an additional grid of larger resolution (1 km). Results are presented in this paper. The diurnal wind, relative humidity and temperature variation over the wine-growing area is studied in order to identify the coolest areas resulting from the sea breeze effect.

MATERIALS AND METHODS

Numerical simulations over the South-Western Cape were performed using the Regional Atmospheric Modelling System (RAMS, non-hydrostatic, parallelled, 4.3 version), which was developed by the Colorado State University (Pielke *et al.*, 1992) and used in co-operation with CNRS-France (Laboratoire de Météorologie Physique, University of Clermont-Ferrand and COSTEL, University of Rennes). It is a numerical model based on the basic physical equations which govern the processes operating in the atmosphere. It assimilates observed data to adjust the model state towards observations. The RAMS takes many factors into account: six-hourly meteorological data at 30 levels in the atmosphere up to 9000 m (humidity, wind speed and direction, air pressure and temperature), sea surface temperature (SST) and the topography. The RAMS operates using 30 land cover classes, which are mostly characterised by its vegetation type, or defines whether the surface is water, bare ground or urban. Each of these classes is assigned a set of land surface parameter values including leaf area index, vegetation fractional coverall, vegetation height, albedo and root depth. It also takes soil data into account. A total of 12 classes of different soil texture are parameterised, but in this specific study it was assumed that the soil was homogeneous and the soil class used was sandy loam because of the high frequency of this type of soil in the vineyards (Landtype survey staff, 1995).

The European Centre for Medium-Range Weather Forecasts (ECMWF), National Oceanic and Atmospheric Administration (NOAA), ARC Institute for Soil, Climate and Water and the South African Weather Service (SAWS) supplied data. Local sea surface temperatures (from SAWS) measured along the coast from Table Bay to False Bay (Koeberg, Sea Point, Hout Bay, Kommetjie, Fish Hoek, Kalk Bay, Muizenberg and Gordon's Bay) were added to those obtained from the ECMWF in order to take the large variation in local SST into account.

The RAMS uses nested grids to provide high spatial resolution while covering a large domain at lower resolution. Three nested grids were used for this study. Grid 1 was the coarse parent grid covering Southern Africa and its contiguous ocean at a horizontal resolution of 25 km. Grid 2 was nested to Grid 1 to cover a large area of the South-Western Cape and its surrounding ocean with a horizontal resolution of 5 km (previously used by Planchon *et al.*, 2000 and Bonnardot *et al.*, 2001). Grid 3 was nested to Grid 2 at a horizontal resolution of 1 km. It included a large portion of the ocean, the Cape peninsula, the coastal plain, inland hills (Tygerberg: 457 m, Bottelaryberg: 476 m) and the steep mountain ranges (Helderberg, Simonsberg: 1100 m to 1400 m) on the eastern side (Fig. 1a). It extended from 33°43'S to 34°23'S and from 18°08'E to 18°57'E; resulting in 5494 grid points of 1 km^2 (Fig. 1b). Results are shown for Grid 3. The sea breeze movement can be observed over the ocean and up to 35 km inland. Wind speed and direction, relative humidity and temperature were defined on the three-dimensional grid and were plotted in either horizontal or vertical cross-sections. Two south-north cross-sections at 18°40'E (X_1) and 18°47'E (X_2) (Fig. 1b) representing different relief in the wine-growing area (Fig. 1c) were used to assess the influence of the relief on the sea breeze motions: X_1 passed through the coastal and inland plain and X_2 passed through the Stellenbosch wine-growing district in the direction of the Bottelaryberg slopes. The nearest automatic weather stations were located approximately along the cross-sections (Fig. 1c).

Simulations were performed for 3 and 4 February 2000 on a trial basis as for the previous simulations obtained at the resolution of 5 km. The meteorological conditions over this period were close to average with a moderate southerly wind in the boundary layer and a weak northerly wind at the 900 hPa and 850 hPa air pressure levels (altitude of ca. 1000 m to 1500 m) on 2000-02-03 at Cape Town International Airport (CPT). It was also a typical sunny summer period in the Western Cape, with a clear sky over the South-western part of South Africa (Bonnardot *et al.,* 2001). This allowed the development of the sea breeze circulation, especially along the Atlantic coast of South Africa as described by Jackson (1954). The high diurnal increase in temperature intensified the thermal gradient between the hot land surface and the remarkably cool sea surface. This was intensified to an even greater degree at places due to significant sea surface temperature differences: 21.5°C at Muizenberg (False Bay) and 15.2°C at Koeberg (Table Bay) due to the cold Benguela current.

The diurnal variation of wind, relative humidity and temperature were analysed. Simulated results were compared to upper-air data from Cape Town International Airport and observed data *in situ* using hourly data from the ARC Infruitec-Nietvoorbij automatic weather station network (Fig. 1b). Seven automatic weather stations located in the wine-growing area and next to a vineyard were available for the study. Their characteristics with respect to altitude, slope and aspect are given in Table 1.

RESULTS AND DISCUSSION

Diurnal wind variation

The alternating sea and land breeze

At night the simulated surface winds were weak inland, less than 4 m.s^{-1} (Fig. 2ab), except for the down-slope winds, above 5 m.s^{-1}, coming from the mountains in the east (Fig. 2a). The land breeze formed a small layer, less than 200 m high, flowing from the land towards and over the sea (Fig. 2c).

During the morning and later on the surface wind strengthened and the direction reversed over the land from northerly to southerly inland, due to a sea breeze from False Bay (Fig. 3a). The sea breeze originating from the Atlantic Ocean did not penetrate inland at the latitude of Table Bay, but further north, probably due to the southerly wind flow present up to 1000 m to 1500 m of alti-

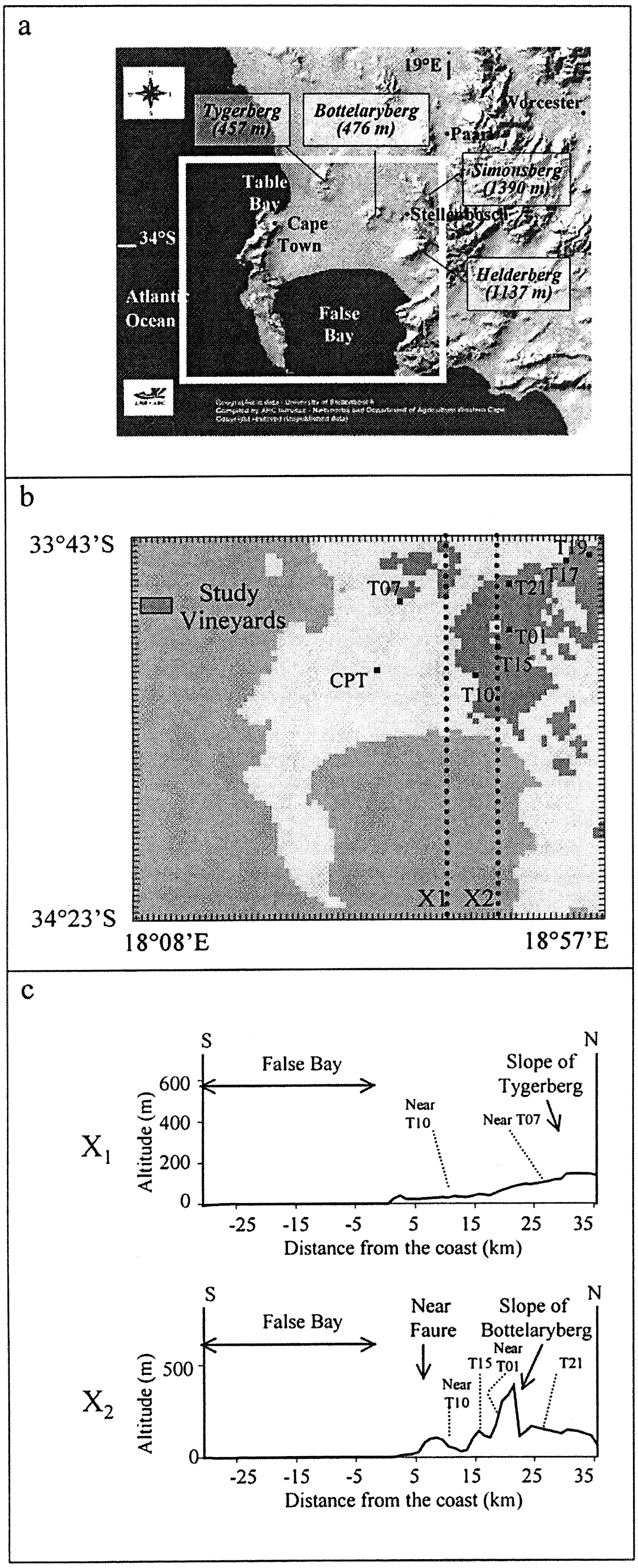

FIGURE 1
(a) = Study domain for simulation; (b) = Location of the vineyards, automatic weather stations (CPT stands for Cape Town International Airport) and cross-sections; (c) = Profiles of cross-sections X_1 (top) and X_2 (bottom).

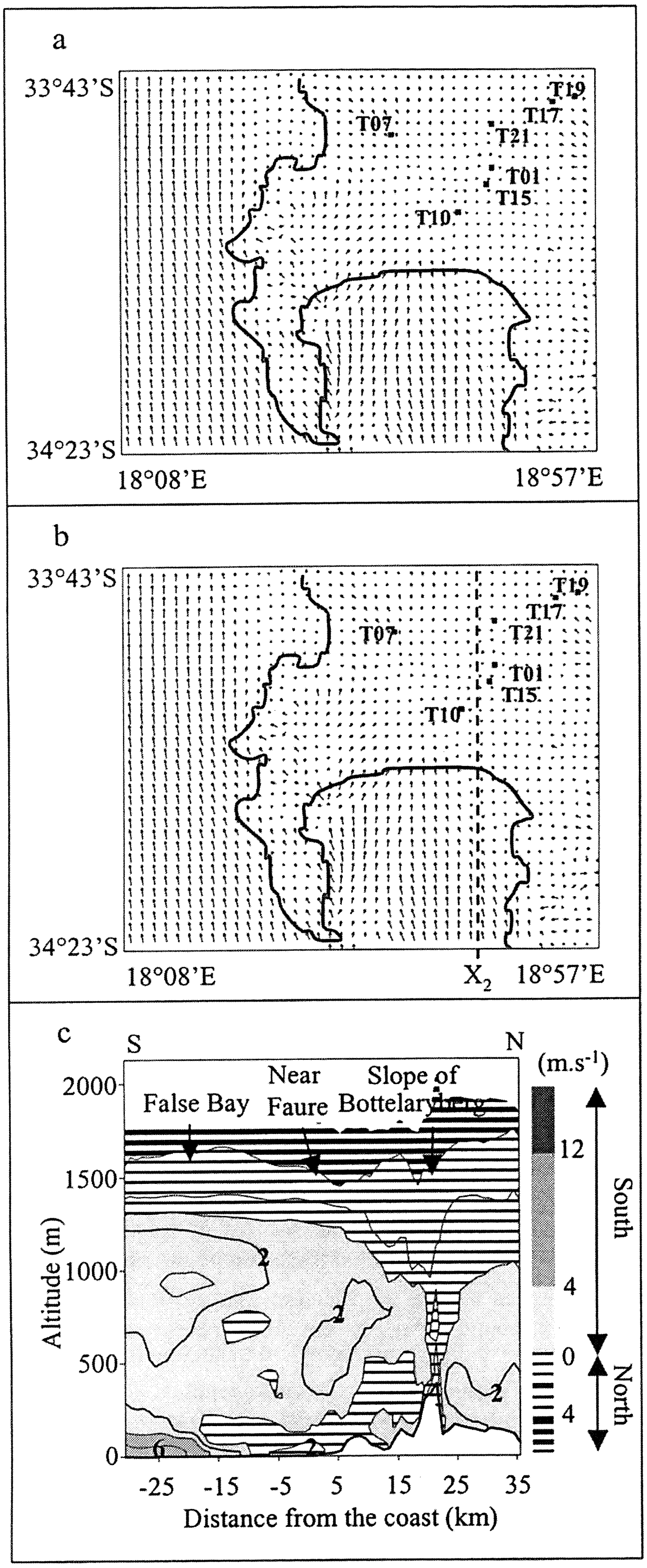

FIGURE 2
Land breeze: (a) Wind vectors at surface level on 2000-02-03 at 05:00 and (b) on the 2000-02-04 at 02:00. Length of vectors simulates wind velocity: maximum vector is 15.2 $m.s^{-1}$ (a), and 9.5 $m.s^{-1}$ (b). (c) = Meridian wind (v) for cross-section X_2 at 02:00 on 2000-02-04. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

TABLE 1
Characteristics of the automatic weather stations in the Stellenbosch-Groot Drakenstein wine-growing area.

Location	Altitude (m)	Aspect	Slope (%)	Distance from Table Bay (km)	Distance from False Bay (km)
T01	148	SSW	1.68	20	35
T07	230	SE	8.62	27	12
T10	130	SW	5.73	12	24
T15	150	S	9.59	16	28
T17	248	NNE	7.83	31	40
T19	160	E	1.43	32	43
T21	177	NW	4.3	27	32

tude. The sea breeze, usually developing between 300 m and 1000 m in temperate zones (Pédelaborde, 1987; Abbs & Physick, 1992), was directed by the southerly wind flow of the boundary layer, through which it is moving, and the upper northerly wind (at 1500 m) was not strong enough (< 4 m.s^{-1}) to oppose its development (Fig. 3b). Therefore the southerly wind flow favoured the strengthening of the sea breeze circulation with a maximum speed of 14 m.s^{-1} over False Bay and 10 m.s^{-1} at the coastline (Fig. 3b). This did not continue beyond a few kilometres inland because the increased surface friction resulted in a decrease in the horizontal wind speed as explained by Smith (1976) and Oke (1978). The simulated surface wind speed was at least 4 m.s^{-1} slower further inland than at the coastline, *i.e.* 6 m.s^{-1} at 5 km inland on the southern slope of the hill near Faure, below 4 m.s^{-1} at 12 km on the northern slope due to the sudden roughness of the land surface generated by dune ridges 80 m high, parallel to the coast and covered by evergreen shrub. This climatic effect of the coastal dunes corroborated the meteorological observations of Pita Lopez and Ojeda Zujar (1991) on the Atlantic coast of Andalusia in Spain.

A sudden change in wind direction and increase in velocity are the primary indicator of the onset of the sea breeze component of the land-sea breeze circulation system. In temperate zones the sea breeze velocity is usually 4 or 5 m.s^{-1}, but in warm temperate climates such as this study region, the sea breeze can reach 7 to 9 m.s^{-1} and sometimes more (Gentilli, 1971; Pédelaborde, 1987), especially when the sea breeze is combined with a valley wind or an up-slope breeze (Mahrer & Pielke, 1977; Alpert *et al.,* 1982). These modelled results also matched observed data. The wind velocity was weak at night (3 m.s^{-1} recorded at CPT at 08:00, below 3 m.s^{-1} at T10, below 2 m.s^{-1} at T01) except for the slope breezes, which occurred at stations close to the mountains located in the east, especially at T17 (above 5 m.s^{-1}) during the night of 3 February (Fig. 4a). Wind came from inland at night (from north, north-east at T10, south-east at T17) and suddenly reversed late in the morning (at 11:00 at T10) or in the afternoon further inland (at 16:00 at T17) coming from south-west and west (Fig. 4b).

Vertical motions and horizontal extent of the sea breeze

Considering the vertical component of the wind in the afternoon from 14:00 to 20:00 (Fig. 5), the sea breeze was originally stable, descending air over False Bay (Fig. 5a), which indeed modified its properties over the land due to the thermal convection. At

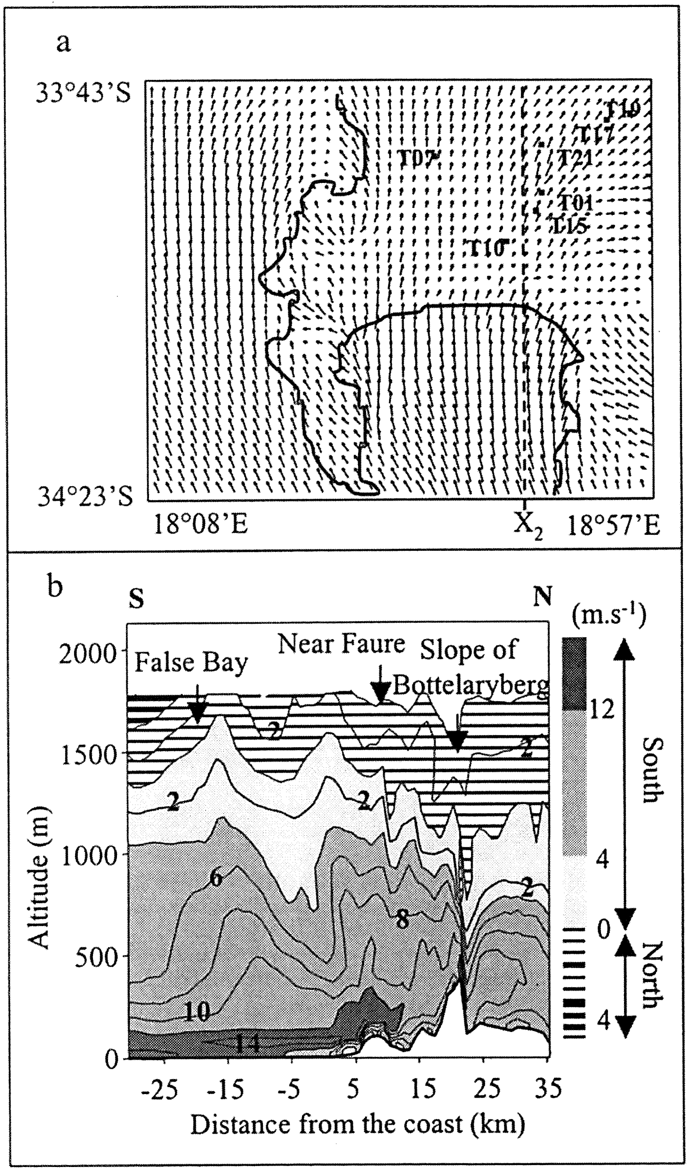

FIGURE 3
Sea breeze: (a) Wind vectors at surface level (Length of vectors simulates wind velocity: maximum vector is 13.9 m.s^{-1}); (b) Meridian wind (v) for cross-section X_2 at 17:00 on 2000-02-03. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

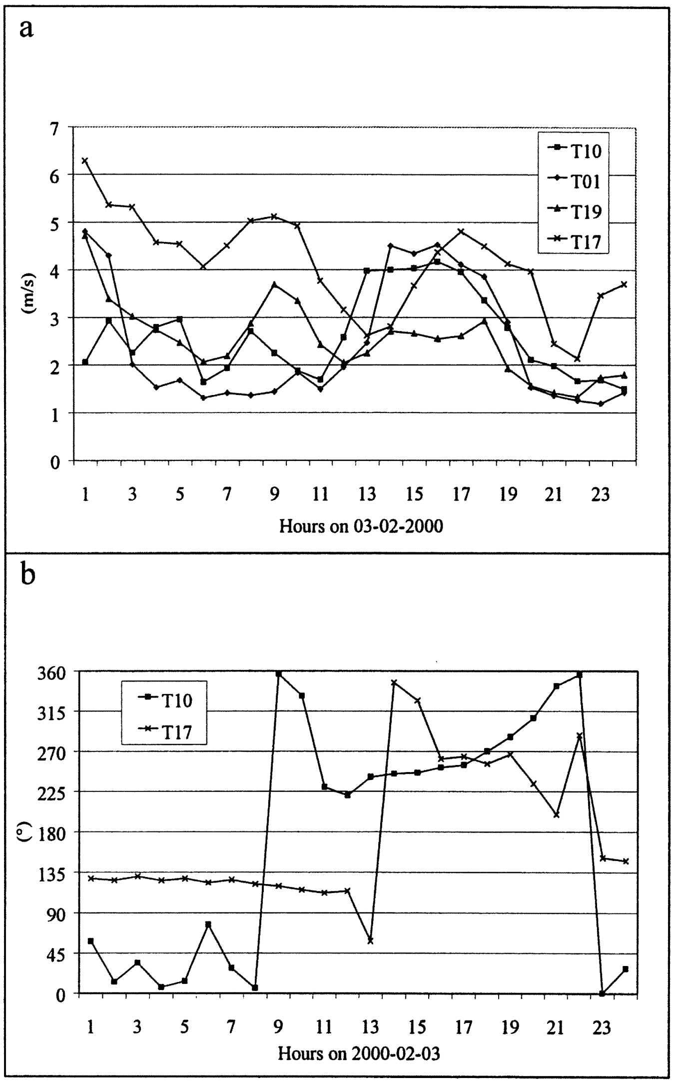

FIGURE 4

Observed wind speed (a) and direction (b) in the vineyards on 2000-02-03. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

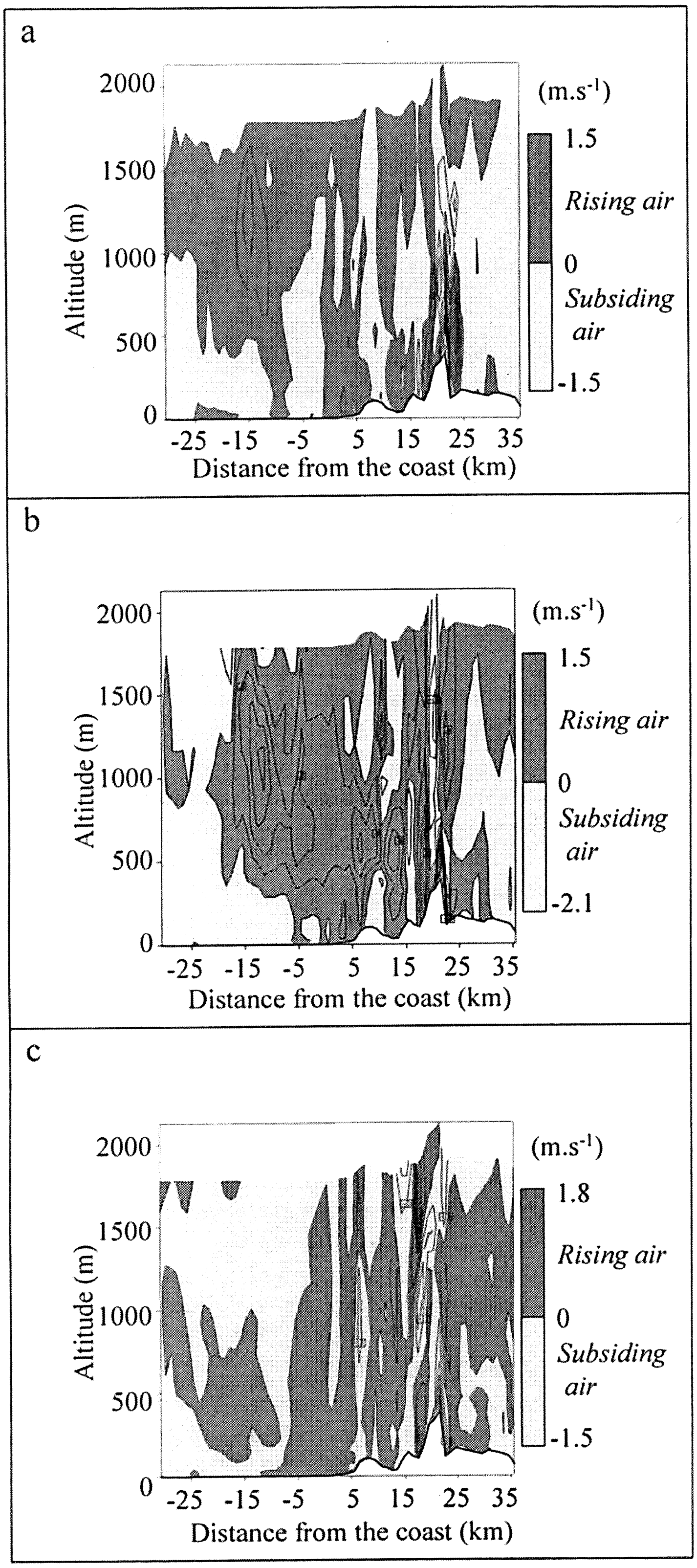

FIGURE 5

Vertical wind (*w*) for cross-section X_2 on 2000-02-03 at (a) 14:00; (b) 17:00 and (c) 20:00. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

14:00 ascending cells developed on the southern slope of each escarpment with a maximum vertical motion of 1.5 $m.s^{-1}$ on the southern slope of Bottelaryberg, 20 km from the shoreline, which probably represented the sea breeze front combined with up-slope breezes. At 17:00 one main descending cell remained beyond 30 km (Fig. 5b). The sea breeze was well established for the entire domain and went over the Bottelaryberg hill up to 35 km inland (Fig. 5b) and even beyond this frame (100 km), as was shown in the previous numerical simulations at a 5 km resolution (Bonnardot *et al.*, 2001; Planchon *et al.*, 2001). Weak ascending and descending cells developed on every slope (Fig. 5c) associated with the beginning of the land breeze system at night.

Penetration of cool and moist air inland

The moist air penetrated from False Bay and moved landwards during the afternoon at 1 km to 4 km/h between 11:00 and 17:00, depending on the relief (Fig. 6).

The diurnal variation in simulated relative humidity (RH) due to the sea breeze circulation was studied in more detail using the two south-north cross-sections. The beginning of the sea breeze effect can be observed later in the morning at 11:00 (Fig. 7a), when the humidity dropped below 65% on land, except near the coast. A thin layer (50 to 100 m) of high humidity (> 80%), corresponding to a zone of high wind velocity, remained above False Bay and started to penetrate inland with the sea breeze development. A relative humidity value of 80% was simulated at 5 km inland on the southern slope of the hill near Faure (X_2), where the wind suddenly ceased, 65% between 10 km and 30 km inland, depending on the relief (X_1, compared to X_2). Relative humidity at the northern bottom slope of Bottelaryberg hill was below 50%. At 14:00 (Fig. 7b) the stable and moist air of the sea breeze (> 70%) passed under the dry "land" air (< 60%). The thin marine air layer (65 to 80 m) carried by the sea breeze exchanged heat and moisture with the sea surface and became a cool, humid film overlain by a deeper mass of warm dry air (Fig. 7b), similar to observations found in southern California (Edinger, 1963; Atkinson, 1981). The layer of humid air (> 70%) was thicker when there was no relief (X_1). The moist air (80%) did not advance much further inland compared to the situation at 11:00, but was stopped at 6 km inland and even before that by coastal relief, while relative humidity continued to drop inland as day-time temperatures increased and the land warmed up. Later in the afternoon (at 17:00), as the wind reached its maximum velocity, the humid air (> 70%) passed over the coastal hills and penetrated inland, depending on relief (Fig. 7c). The "limit" of high humidity, above 80% and between 70 to 80% RH, was found at 18 km and 30 km inland, respectively, when the relief was flat or of little significance (X_1) and before that, at 8 km and 14 km, respectively, before the southern slope of Bottelaryberg hill (X_2), where relief is higher. The highest values were still found on the coastline. It is noticeable that relative humidity was higher and the gradient was greater on the eastern side of False Bay (X_2) than on the western side (X_1) due to relief. At 20:00 the humid air continued to pass over the hills due to the sea breeze penetration landward as well as the beginning of radiative cooling (Fig. 7d).

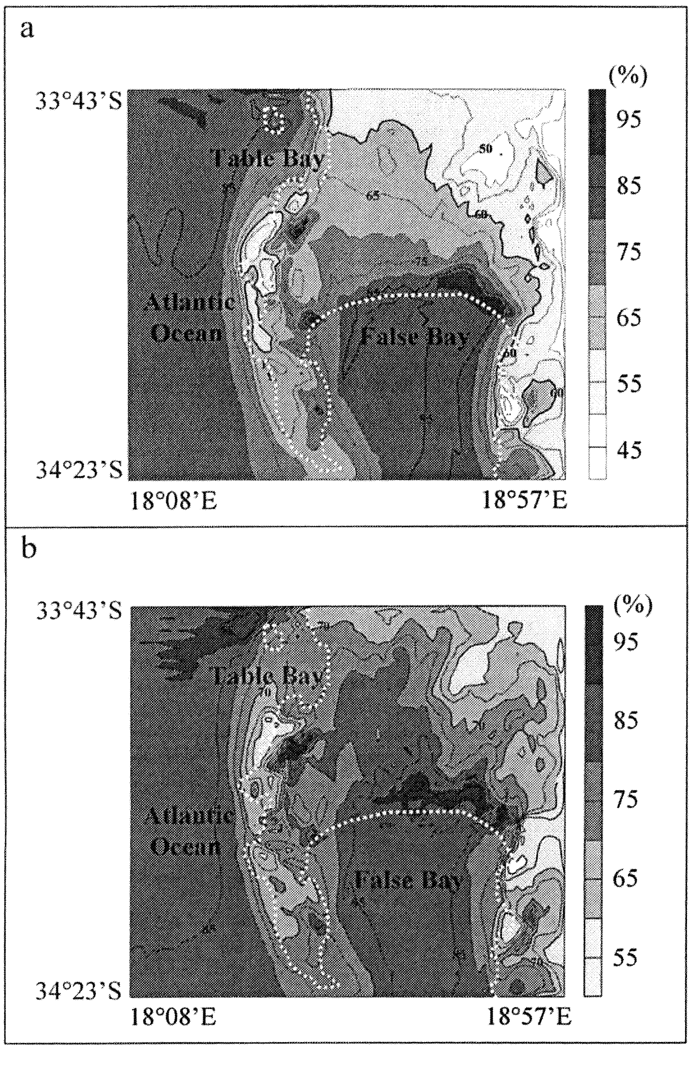

FIGURE 6

Simulated relative humidity (%) at surface level at (a) 14:00 and (b) 17:00 on 2000-02-03. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

Simulated values were similar to observed data early morning and late afternoon, but slightly over-estimated during the day using two references in the vineyard (T07 along X_1 and T15 along X_2) as shown in Table 2. Simulated and observed values did not differ more than 5 to 10%.

Consequences for temperature

At 05:00, before sunrise, simulated temperature was uniform. A minimum of 15 to 17°C inland and 19°C above the sea was recorded (results not shown), which was similar to data observed in the vineyard (15.7°C at T10 at 10 km and at T01 at 20 km).

The land warmed up during the morning and the cool moist air of the sea breeze started to penetrate inland. This has major consequences for temperature at the coastline due to the temperature difference between the sea and the land. Significant vertical and horizontal temperature gradients occurred, as well as notable temperature differences between southern and northern slopes.

Thermal inversion at the coastline

As the sea breeze was generated during the morning and started to penetrate inland, the cool moist air passed below the inland warm air (Fig. 8a-c). As a result, a thermal inversion began at 11:00 above the sea and the first kilometres inland and developed further inland as the maritime air progressed inland. This phenomenon can be clearly seen from 14:00 onwards, as the cool maritime air (air below 22-23°C) was a thin layer of a maximum of 120 m, overlaid by a thicker layer of warm air (above 23°C) over a distance of 35 to 40 km, *i.e.* 30 km over the sea and 10 km over the land at 17:00 (Fig. 8c). This phenomenon of thermal inversion is a usual feature in summer in warm temperate maritime climates on the western fringes of the continents, for example, in Portugal and Morocco (Atillah, 1993; Delannoy, 1997). It is due to the modification and stabilisation of the lower atmosphere by the cold ocean temperatures. The coastal upwelling of cold water intensifies the cooling of the air closest to its surface. During the day the sea breeze carries this relatively cool and stable surface air layer over the land and maintains the low-level temperature inversion (Oke, 1978; Abbs & Physick, 1992). However, the properties of the marine layer change inland over the warm land surface (Edinger, 1963; Janoueix-Yacono, 1995).

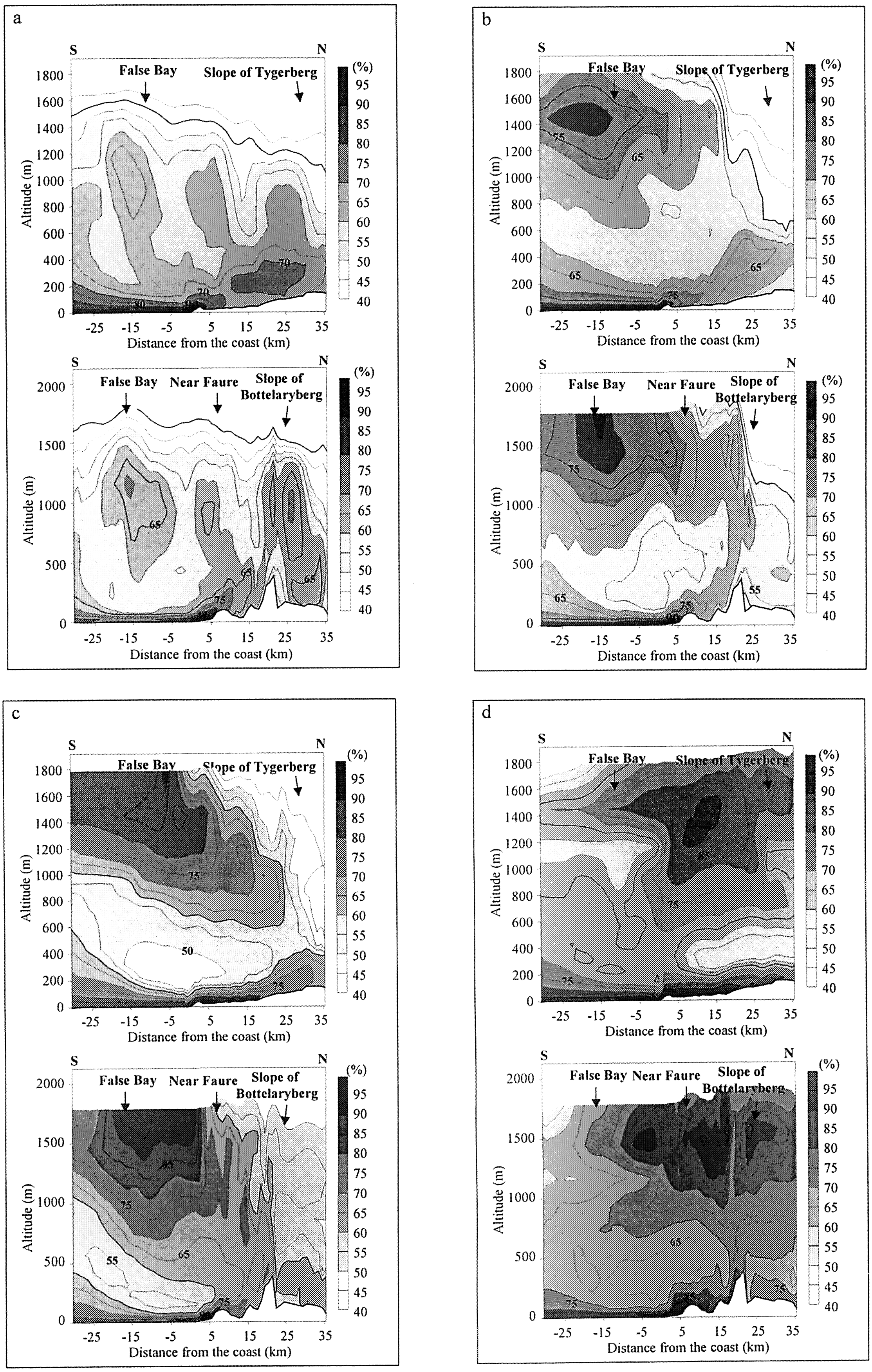

FIGURE 7

Simulated relative humidity (%) at (a) 11:00; (b) 14:00; (c) 17:00 and (d) 20:00 on 2000-02-03. South-north cross-sections at 18°40'E (X_1) on top and 18°47'E (X_2) at the bottom. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

TABLE 2

Relative Humidity (%). Comparison between observed and modelled data at T07 and T15 on 2000/02/03. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

Location	Data	Time (SAST)				
		05:00	11:00	14:00	17:00	20:00
	Observed	99	68.8	62.7	67.9	80.3
T07	*Modelled*	*[85-90]*	*[75-80]*	*[65-70]*	*[80-85]*	*[75-80]*
	Difference	-10	+5	+5	+10	-5
	Observed	84.4	64.3	61	60.9	76.6
T15	*Modelled*	*[80-85]*	*[55-60]*	*[55-60]*	*[65-70]*	*[80-85]*
	Difference	0	-5	-5	+5	+5

Temperature gradient at the maritime/inland air interface

On the land surface the simulated temperature rapidly increased with distance from the sea. Using the cross-section X_1 at 11:00 (Fig. 8a), a simulated temperature of 20°C was found on the coastline, 22°C at 2 km inland, 23°C at 4 km and 24°C at 26 km, a difference of 3°C over the first 4 km, and a difference of only 1°C over the following 22 km inland. Using the vertical profile of X_2 at the same time, the simulated temperature was 20°C at the coast, 21°C at 4 km inland, 23°C at 8 km and 24°C at 14 km, a difference of 3°C over the first 8 km, and a difference of 1°C over the following 6 km inland. This gradient in temperature intensified as the land warmed up. At 14:00 the simulated temperature was 21°C on the coastline, 25°C at 5 km inland, 26°C at 12 km and 27°C at 30 km, a difference of 4°C over the first 5 km, and a difference of only 2°C over the following 25 km inland (Fig. 7c, X_1). Using the cross-section X_2, this gradient was even greater with a difference of 5°C over the first 5 km and of 2°C over the following 6 km inland. To summarise, there was a temperature increase of 6°C over a distance of 30 km (X_1) and 7°C over a distance of 11 km (X_2) at 14:00. Data recorded *in situ* on 2000-02-03 at 14:00 at three stations located on southern slopes – subject therefore to the cooling effect of the sea breeze – showed a difference of 1.1°C over a distance of 6 km between T10 at 10 km (28.2°C) and T15 at 16 km, a difference of 0.7°C over a distance of 4 km between T15 and T01 (30.1°C at 20 km). It was therefore a temperature gradient of 1.9°C between 10 and 20 km from the coast. For this specific location, even though the modelled values were under-estimated compared to observed data at this time (Table 3), the modelled gradient at the approximate longitude of X_2 was also 2°C. We cannot accurately verify this gradient near the coast with observed measurements due to a lack of weather stations with no environmental interference and close to the sea. If we consider the isotherm 23°C, which corresponded to a relative humidity of 80% at 14:00, the "limit" between cool and warm air was located at 3 to 4 km inland (Fig. 8b). At 17:00, when the wind was at its maximum, the cool maritime air penetrated a couple of kilometres further, up to 6 to 7 km (Fig. 8c). It was still blocked on the southern slopes of the first topographical features near the coast on the second cross-section (X_2), showing the significant effect of even very low relief (152 m).

Temperature differences between northern and southern slopes

Temperatures varied with both distance from the sea and slope aspect. At 14:00 (Fig. 8b) a temperature difference of 2°C between northern and southern slopes of the Bottelaryberg was observed: 29°C at the foot of the northern slopes at about 23 km inland, and 27°C at the foot of the southern slopes at 18 km (X_2). Temperatures were much cooler closer to the coast (20°C on the coastline) and the temperature difference between northern and southern slopes was greater than on slopes further inland. The northern slope of the hill near Faure, 5 km from the coastline (X_2), was 4°C warmer than the southern slope. Temperature differences due to slope aspects remained until 17:00 (Fig. 8c) and decreased onwards. They were reduced to 1°C or 2°C at 20:00 due to the transition between day and night conditions (Fig. 8d).

Modelled temperature data were either under- or over-estimated compared to the observed data, depending on the time and location. The most important temperature difference of 3°C was found for the maximum temperature (14:00) at inland stations. This difference can be explained by the fact that the measure-

TABLE 3

Temperature (°C). Comparison between observed and modelled data on 2000/02/03. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

Location	Data	Temperature (°C) at 05:00	Temperature (°C) at 14:00	Temperature (°C) at 20:00
	Observed	16.28	28.2	21.9
T10	*Modelled*	*[16-17]*	*[25-26]*	*[22-23]*
	Difference	0	-2°C	+1°C
	Observed	17.53	29.28	24.41
T15	*Modelled*	*[17-18]*	*[26-27]*	*[22-23]*
	Difference	0°C	-2°C	-1°C
	Observed	16.02	30.01	24.2
T01	*Modelled*	*[17-18]*	*[26-27]*	*[22-23]*
	Difference	+1°C	-3°C	-2, -1°C
	Observed	20.1	31.27	26.86
T17	*Modelled*	*[17-18]*	*[28-29]*	*[24-25]*
	Difference	-2°C	-3°C	-2°C
	Observed	20.0	32.43	28.23
T19	*Modelled*	*[16-17]*	*[29-30]*	*[24.25]*
	Difference	-3°C	-3°C	-3°C

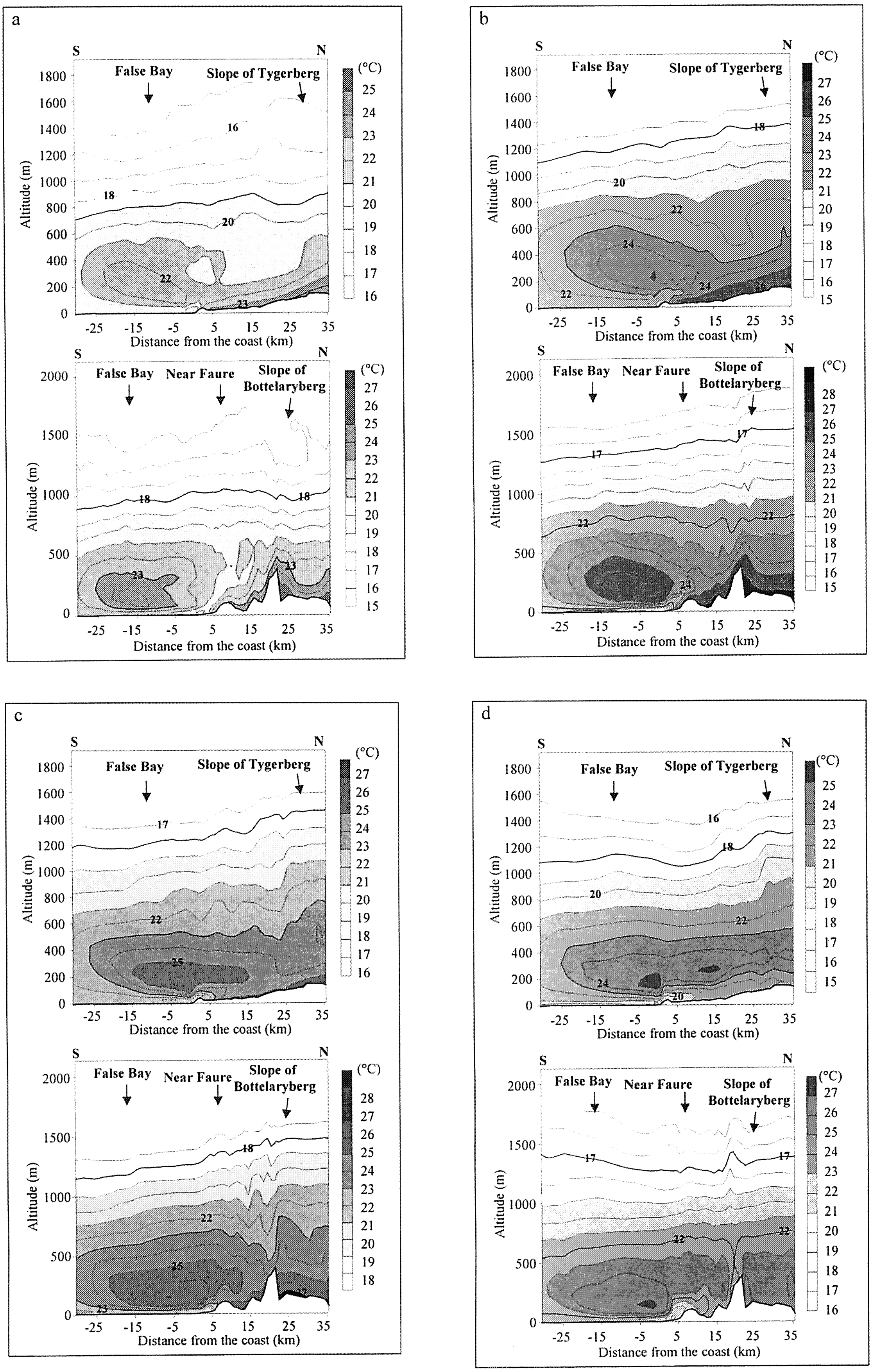

FIGURE 8

Simulated temperature (°C) at (a) 11:00; (b) 14:00; (c) 17:00 and (d) 20:00 on 2000-02-03. South-north cross-sections at 18°40'E (X_1) on top and 18°47'E (X_2) at the bottom. Time is given as South African Standard Time (SAST), *i.e.* Greenwich Meridian Time +02:00.

ments at each automatic weather station can be subject to micro-climatic peculiarities in the immediate vicinity of the station (Oke, 1978; White *et al.*, 1992). The stations are situated in the vineyards and represent different topographical locations in the area with the possibility of significant differences due, for example, to the soil (bare white sand has higher albedo than darker soil) or obstacles in the near environment (windbreaks or buildings close to the station). The topoclimatic effects on modelled data could also have been reduced due to the 1 km resolution grid as well as soil data, which was assumed to be uniform. However, the wind was adequately modelled and relative humidity differences between observed and modelled data did not exceed 5 to 10%, which can also be due to an instrumental fault.

CONCLUSIONS

Although this study is based on simulations from only two days and thus not necessarily representative of the effect and variability of the land/sea breeze circulations on the region, these preliminary results have highlighted the topographic effects on air movement and temperature in the region. Even very low topographical features resulted in large temperature differences between southern and northern slopes, especially close to the coast, which could be significant enough to be important for viticulture. The sea breeze front, strengthened by a moderate onshore upper wind, was located as far as 20 km inland in the Stellenbosch wine-growing area at 14:00. The sea breeze penetrated to at least 35 km inland at 17:00, but the cooling effect declined rapidly with distance from the coast. Besides altitude, the aspect and distance from the sea are also important factors with respect to temperature to be considered for cultivar recommendations. The effects of these two factors were cummulative on the southern slopes near the sea. These slopes were therefore cooler than the northern slopes, due to their lower sunlight interception, and also because they face the ocean, with the associated cool, moist sea breezes. Further inland, the cooling effect due to the sea breeze was non-existent or less important, and altitude and slope aspect were the main factors affecting temperature.

Further research in this field is necessary using different synoptic weather conditions in order to assess the variability of the sea breeze. The input of different soil data into the atmospheric model RAMS will probably give more accurate results. Using a finer resolution (200 m) model is also envisaged in order to assess the sea breeze effect in the Stellenbosch wine-growing area in greater detail together with the climatic requirements for viticulture. An extensive automatic weather station network is necessary in order to confirm the results of the simulations with even greater accuracy.

LITERATURE CITED

Abbs, D.J. & Physick, W.L., 1992. Sea-breeze observations and modelling: A Review. Aust. Met. Mag. 41, 7-19.

Alpert, P., Cohen, A., Neumann, J. & Doron, E., 1982. A model simulation of a summer circulation from the eastern Mediterranean past Lake Kinneret in the Jordan Valley. Mon. Wea. Rev. 110 (8), 994-1006.

Atillah, A., 1993. Les influences maritimes sur le climat du Maroc atlantique central: une analyse par télédétection spatiale. PhD. Thesis, University of Rennes-II, 6 avenue G. Berger, 35043 Rennes Cedex, France.

Atkinson, B.W., 1981. Meso-scale Atmospheric Circulations. Academic Press, London. 495 pp.

Becker, N.J., 1977. The influence of geographical and topographical factors on the quality of the grape crop. In: Proc. OIV International Symposium on the quality of the vintage, February 1977, Cape Town, South Africa. pp 169-180.

Bonnardot, V., 1997. Sea breeze effect on temperature in the Stellenbosch-Klein Drakenstein wine-producing district in South Africa. Research report, ARC Infruitec-Nietvoorbij, Stellenbosch, South Africa.

Bonnardot, V., 1999. Étude préliminaire des brises de mer pendant la période de maturation dans la région viticole du Cap en Afrique du Sud. Pub. Assoc. Int. Climatol. 12, 26-33.

Bonnardot, V., Carey, V.A., Planchon, O. & Cautenet, S., 2001. Sea breeze mechanism and observations of its effects in the Stellenbosch wine-producing area. Wynboer 147, 10-14.

Carey, V.A., 2000. The delimitation of macro-climatic regions in the Western Cape with the aid of a Geographic Information System and the determination of their potential for various cultivars. OIV Paris, Expert group "viticultural zoning" (March 2000).

Carey, V.A. & Bonnardot, V., 2000. Spatial characterisation of terrain units in the Bottelaryberg-Simonsberg-Helderberg winegrowing area (South Africa). In: Proc. 3rd Int. Sym. Viticultural Zoning, May 2000, Puerto de la Cruz, Tenerife.

Carey, V.A., 2001. Spatial characterisation of terrain units in the Bottelaryberg /Simonsberg/Helderberg winegrowing area. MSc Agric Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland(Stellenbosch), South Africa.

Delannoy, H., 1997. Remarques sur la climatologie de la façade atlantique ibéro-marocaine au sud de 40°N. In: Le climat, l'eau et les hommes, Presses Universitaires de Rennes, France. pp. 301-317.

Edinger, J.G., 1963. Modification of the marine layer over coastal southern California. J. Appl. Meteorol. 2 (6), 706-712.

Falcetti, M., 1994. Le Terroir. Qu'est-ce qu'un terroir? Pourquoi l'étudier? Pourquoi l'enseigner? Bull. O.I.V. 67, 246-275.

Gentilli, J., 1971. Climates of Australia and New Zealand. World Survey of Climatology, Elsevier Publishing Company, 13 (5-6), 53-184.

Huglin, P. & Schneider, C., 1998 (2nd ed). Biologie et Écologie de la vigne. Lavoisier TEC&DOC, Paris.

Jackson, S.P., 1954. Sea breezes in South Africa. S. Afr. Geogr. J. 36, 13-23.

Janoueix-Yacono, D., 1995. Rapports entre brise de mer ou de lac, structure de la couche-limite planétaire et pollution atmosphérique sur des plaines littorales urbanisées. In: Climat, pollution atmosphérique, santé. Dijon, France. pp. 177-201.

Landtype survey staff, 1995. Landtypes of the map 3318 CAPE TOWN. Mem. Agric. Nat. Resour, S. Afr., 24. Institute for Soil, Climate and Water of the Agricultural Research Council.

Lutjeharms, J.R.E. & Stockton, P.L., 1987. Kinematics of the upwelling front of Southern Africa. In: Payne, A.I.L., Gulland, J.A. & Brink, K.H. (eds). The Benguela and Comparable Ecosystems. S. Afr. J. Marine Sci. 5, 35-49.

Mahrer, Y. & Pielke, R.A., 1977. The effects of topography on sea and land breezes in a two-dimensional numerical model. Mon. Wea. Rev. 105, 1151-1162.

Oke, T.R., 1978. Boundary layer climates. Methuen and Co. Ltd. London.

Olivier, J. & Stockton, P.L., 1989. The influence of upwelling extent upon fog incidence at Lüderitz, Southern Africa. Int. J. Climatol. 9 (1), 69-75.

Pédelaborde, P., 1987. Sur les brises. Met-Mar. 136, 11-15.

Pielke, R.A., Cotton, W.R., Walko, R.L., Tremback, C.J., Lyons, W.A., Grasso, L.D., Nicholls, M.E., Moran, M.D., Wesley, D.A., Lee, T.J. & Copeland, J.H., 1992. A comprehensive Meteorological Modeling System – RAMS. Meteorol. Atmos. Phys. 49, 69-91. (http://rams.atmos.colostate.edu/detailed.html)

Pita Lopez, M.F. & Ojeda Zujar J., 1991. Les variations spatiales de l'amplitude thermique diurne au parc national de Doñana (Espagne). Pub. Assoc. Int. Climatol. 4, 121-126.

Planchon, O., Bonnardot, V. & Cautenet, S., 2000. Simulation de brise de mer dans la Province Occidentale du Cap (Résolution à 5 km): Exemple de la journée du 4 février 2000. Pub. Assoc. Int. Climatol. 13, 482-489.

Schulze, B.R., 1972. South Africa, World Survey of Climatology, Elsevier Publishing Compagny, 10 (15), 501-586.

Shannon, L.V., Walters, N.M. & Mostert, S.A., 1985. Satellite observations of surface temperature and near-surface chlorophyll – the Southern Benguela Region. In: Shannon, L.V. (ed). South African Ocean Colour and Upwelling Experiment, Sea Fisheries Research Institute, Cape Town. pp. 183-210.

Smith, K., 1976. The climates of coasts and inland water bodies. In: Chandler, I.J. & Gregory, S. (eds). The climate of the British Isles. Longman, London. pp. 248-263.

Tonietto, J., 1999. Les macroclimats viticoles mondiaux et l'influence du mésoclimat sur la typicité de la Syrah et du Muscat de Hambourg dans le sud de la France. Méthodologie de caractérisation. PhD thesis, Ecole Nationale Supérieure Agronomique de Montpellier, Place Viala, 34060 Montpellier Cedex 02, France.

White, I.D., Mottershead, D.N. & Harrison, S.J., 1992. Environmental systems. Chapman and Hall, London.

Winkler, A.J., Cook, J.A., Kliewer, W.M. & Lider, L.A., 1974. General Viticulture (2nd ed.). University of California Press.