An Aircraft Study of Mesoscale Surface Wind Patterns and Associated Meteorological Conditions over Cape St. Francis, South Africa

MARK R. JURY

Oceanography Department, University of Cape Town, South Africa

ROSEANNE D. DIAB

Geographical and Environmental Sciences Department, University of Natal, Durban, South Africa

MARK SCHORMANN

Cloud Quest, Nelspruit, South Africa

(Manuscript received 21 September 1992, in final form 18 March 1993)

ABSTRACT

Aircraft surveys have been conducted to assess the mesoscale pattern of wind and weather over Cape Saint Francis, South Africa, on the southern tip of the African continent. Ten surveys were flown at a level of 100 m above ground during November 1991, and wind velocity, turbulence, and temperature were monitored. Results were stratified into composites according to the mean direction and speed of the wind. Under the prevailing westerly wind, three areas of high speed were found that may constitute optimal sites for wind energy turbines. These areas of high velocities lie along the tops of low rolling hills in the vicinity of the Krom River at Cape Saint Francis. The usefulness of aircraft surveys in developing an understanding of the mesoscale pattern of winds and associated meteorological fields is emphasized.

1. Introduction

The mesoscale pattern of wind and weather can exhibit sharp gradients across hilly subtropical coasts that are exposed to stratified alongshore flow. The distribution of the wind speed and the inland penetration of cool marine air has wider impacts: for example on human comfort, coastal ocean currents, and air pollution transport, as well as on wind energy, the focus of this paper. Wind energy conversion is most efficient within areas of sustained acceleration. Historical evidence has demonstrated that the southern and southwestern coastal belt of South Africa, like many Mediterranean climatic zones, holds significant potential for wind energy conversion (Diab 1988). Minimal utilization of the wind resource has taken place, however, due to an abundance of nonrenewable energy sources. In recent years, though, the environmental costs of transforming South African coal reserves to energy (20 000 MW) have mounted (Tyson et al. 1988) and renewable resources such as wind have become more viable alternatives. Further, wind energy technology has matured over the past decade to the extent that it is now reliable and cost effective (EWEA 1991).

Corresponding author address: Dr. Mark R. Jury, Oceanography Department, University of Cape Town, Private Bag, Rondebosch, 7700, South Africa.

In South Africa, preliminary screening of historical wind data has indicated numerous sites for wind energy conversion along the southern and southwestern coast (Diab 1990). The winds are driven by the continual eastward passage of midlatitude synoptic pressure systems, and accelerated by the steep upward slope of the land. At many points along the coast, mean wind speeds approach 7 m s^{-1} at 10 m. The Cape Saint Francis area (34°10′S, 24°40′E, Fig. 1) has been identified as one of three viable "hot spots" (Jury and Diab 1989) where further mesoscale research is needed for the optimal siting of wind turbines.

To better understand the mesoscale distribution of wind and associated meteorological conditions over Cape Saint Francis, low-level instrumented aircraft surveys were conducted from 3 to 12 November 1991 as part of a research project sponsored by the National Energy Council of South Africa. Here, these survey results are presented.

2. Background

The Cape Saint Francis area is characterized by low rolling hills and 200-m ridges with a 295°–115° alignment as shown in Fig. 1. The ridges lie across the prevailing west-southwest–east-northeast winds at a 45° angle. The cape extends seaward into the southwest

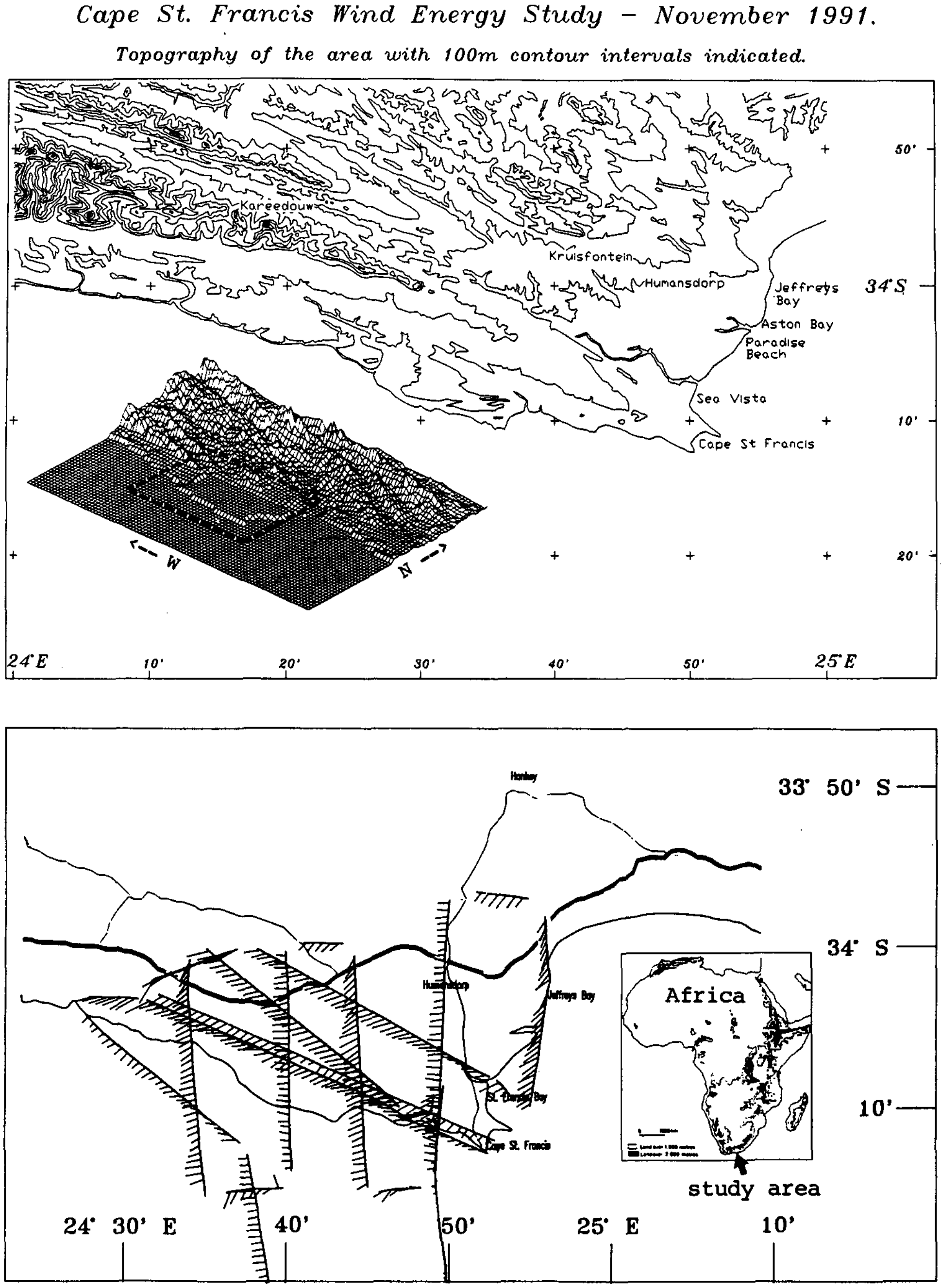

FIG. 1. Topographic map of the Cape Saint Francis area (top). Inset is a 3D perspective. Residential areas are labeled. The plan of flight 9 is show together with wind vectors at bottom. Lines refer to roads. Inset places the study area in the geographical context of Africa.

Indian Ocean some 20–30 km and accelerates the alongshore wind field as noted off California (Caldwell et al. 1986; Beardsley et al. 1987) and along the southwest coast of South Africa (Jury 1987, 1989). Along the eastern seaboard of the cape are the residential areas of Sea Vista (Saint Francis Bay), Jeffreys Bay, and Aston Bay. Other residential areas include Oyster Bay on the south coast and Humansdorp in the center of the cape. The largest river in the area is the Krom, which provides a potential channel for winds. Most of the land is cleared for grain, cattle, and sheep farming, while farther to the west commercial pine forests have been developed. About 100 km to the east is the major urban and industrial center of Port Elizabeth, a large electricity demand point with no local source of power. Jury and Diab (1989) have reported on surface wind patterns from four surveys conducted in January, March, and June 1983 in the Cape Saint Francis area using hand-held anemometers. Highest winds were found over the tip of the cape and the Krom River mouth.

Details of wind statistics for Cape Saint Francis have been provided in Hunter (1987) and Jury and Diab (1989), and are reviewed here briefly. Data have been taken from historical records of the South African Weather Bureau, and from short-term records of the Council for Scientific and Industrial Research and the University of Port Elizabeth. The mean wind speed at the 10-m level at the tip of the point at Cape Saint Francis is 6.9 m s^{-1}. Seasonally, winds are less than 6.5 m s^{-1} in the early winter in May and June. Highest winds prevail in the summer from September to January. Diurnally, winds are weakest near sunrise and strongest in the midafternoon (1500 LST). The amplitude of diurnal change is largest in summer (2–3 m s^{-1}) and almost flat in the winter. Wind speed probability distributions at Cape Saint Francis are almost normally distributed in summer with 45% in the 5–10 m s^{-1} class. In summer only 10% of winds are less than 2 m s^{-1}. In winter more than 20% of winds are less than 2 m s^{-1} and the probability distribution is skewed to lower speeds. In both seasons approximately 5% of winds are above 15 m s^{-1}. It should be noted that a mean power-law exponent of 0.2 is suggested from data collected at nearby meteorological towers (Jury and Diab 1989); hence, mean speeds of 7 m s^{-1} translate to 11 m s^{-1} at the 100-m flight level.

From wind statistics, Cape Saint Francis is suited to wind energy conversion; however, little is known about the mesoscale distribution of winds across the cape. For this purpose an instrumented aircraft was employed to fly low-level surveys.

3. Methods

a. Data collection and processing

The aircraft used for the Cape Saint Francis surveys was an Aero Commander Shrike 500 equipped with a Trimble TNL 2000 global positioning system (GPS). The GPS provided, at 1-s intervals (80 m alongtrack), updates of position, aircraft track, and ground speed. Combining the track and ground speed data from the GPS with the true airspeed (TAS) and heading from standard aircraft instrumentation and resolving the vectors, a computation of the wind direction and speed was made. According to the specifications of the navigation system, wind vector errors are of order 20%. In addition, air and dewpoint temperature sensors were mounted on the fuselage. Surface temperatures were monitored by means of an IR sensor. All sensors were linked to an IBM compatible 16-MHz 80386SX personal computer via a 16-channel analog-to-digital converter. Data taken from the sensors at 1-s intervals were stored on an 8-mm helical scan tape unit (Exabyte) with a hard disk used for backup storage. The computer software enabled a real-time analysis of all parameters measured. Parameters of particular interest (i.e., wind speed) were graphically displayed during surveys.

The wind velocity, surface, air, and dewpoint temperature data were converted from 1- to 10-s averages to smooth out some of the high-frequency details. Quality checks were imposed to remove all data associated with turns. Turbulence was estimated from the standard deviation of the TAS over 10-s intervals. The GPS occasionally lost full accuracy due to a decrease in the number of satellites available for tracking. Data were removed manually during these brief periods.

Once the quality checks were complete, an averaged "clean" dataset was produced for each day. These data were then normalized with respect to the average values of the various scalar parameters for each day. Thus, the mesoscale pattern for each dataset could contribute equally in the construction of composites. The normalized 10-s-averaged data were grouped on the basis of the predominant wind direction and speed (see Table 2) and multiplied by the average for the group for each parameter. This produced a set of three composites with common wind characteristics. At this point the datasets were still nonuniformly spaced.

To obtain a more uniform data distribution (1-km resolution) the data were gridded using a program that considered the 40 closest data points weighted according to the inverse square of the distance to the desired grid point. Graphical analyses of these gridded data still contained some "bull's-eyes" due to irregularities in the original data density. The gridded data were then passed through a finite impulse response filter (Hamming 1983). All data were passed twice through the filter, except the inherently noisy turbulence index (standard deviation of TAS) which was passed five times through the filter. These data were then contoured with an overlay on a map of the area.

b. Sampling strategy and background weather

The aircraft traversed the smooth, low-lying hills of the Cape Saint Francis area first in a north–south pattern every 5′ of longitude (10 km), and then in a northwest–southeast diagonal pattern along the hilltops (flight plan shown in Fig. 1). A radar altimeter was used to ensure that measurements were taken approximately 100 m above local ground level. Additionally, profiles were made over Sea Vista for comparison with radiosonde data collected at the Port Elizabeth airport by the South African Weather Bureau (SAWB). Table 1 is a sample listing of flight data and Table 2 gives details of the flights and observed weather at Cape Saint Francis.

The synoptic-scale weather during the surveys was characterized by light westerly winds and mostly cloudy skies. Local weather forecasts emphasized gentle winds

TABLE 1. Sample of aircraft data.

Date	Time (UTC)	Latitude (°N)	Longitude (°E)	Wind Speed (kt)	Wind Direction (°T)	Temperature (°C)	Differential pressure (mb)	Pressure (mb)	IR surface temperature (°C)	Radar altimeter (m)	Dewpoint (°C)
12 November 1991	0717:40	34.1737	24.7850	34.7	257	18.7	24.5	993.1	16.1	81	10.6
12 November 1991	0717:41	34.1737	24.7837	33.3	260	18.8	24.5	992.3	16.2	83	10.6
12 November 1991	0717:42	34.1737	24.7837	36.2	257	18.8	25.2	993.0	16.6	84	10.6
12 November 1991	0717:43	34.1737	24.7832	33.6	258	18.8	24.8	993.1	16.1	84	10.6
12 November 1991	0717:44	34.1737	24.7823	32.1	264	18.9	25.4	993.3	16.1	85	10.6
12 November 1991	0717:45	34.1737	24.7820	31.4	265	18.9	25.7	993.1	16.5	85	10.6
12 November 1991	0717:46	34.1737	24.7812	29.0	271	18.8	25.1	993.1	16.5	85	10.6
12 November 1991	0717:47	34.1737	24.7807	31.7	270	18.9	26.5	992.5	16.2	84	10.6
12 November 1991	0717:48	34.1737	24.7802	30.4	270	19.0	26.4	993.1	16.2	85	10.5
12 November 1991	0717:49	34.1737	24.7793	28.5	268	18.8	25.9	992.0	16.3	86	10.6
12 November 1991	0717:50	34.1737	24.7793	27.9	268	18.8	25.7	992.5	17.0	85	10.5

and warm temperatures. A sequence of SAWB weather maps for the survey period (Fig. 2) indicates the repeated passage of midlatitude troughs and relatively weak marine anticyclones. Over the period 3–6 November 1991 a marine anticyclone ridged eastward giving pressure gradients favoring easterly winds. During the remainder of the period, with the exception of 9 November, pressure gradients favored westerly winds of varying strength. Port Elizabeth radiosonde profile data for the two lowest standard levels are listed in Table 3.

Table 3 highlights the wide variety of weather experienced during the survey period. Conditions ranged from warm inversion (6 November) to cool unstable conditions (12 November), from easterly winds (4 November) to westerly (7 November). Tables 2 and 3 provide the basis for the grouping of flight data into composites of easterly (flights 2, 3, 4), weak westerly (flights 6, 7, 9), and relatively strong westerly (flights 5, 8, 10) wind regimes.

4. Results of aircraft surveys

Three composite sets, each representing the average of three individual flights, are analyzed for mesoscale structure of winds and meteorological parameters. The spatial patterns for the easterly wind regime are shown in Figs. 3 and 4, the light westerly wind regime in Figs. 5 and 6, and the strong westerly wind regime in Figs. 7 and 8.

a. Easterly wind regime

With an easterly direction, the wind speed map (Fig. 3) identifies three zones of sustained high velocities: southwest of Humansdorp, at the point on the Cape Saint Francis headland, and in the southwest (inland from a river mouth). Easterly wind speeds along the northwest–southeast ridge south of the Krom River are lower than the surrounding areas. The variations in speed over the headland reflect channeling of flow in the river valley and wave motions over the undulating ridges. Along the south-facing coast, easterly winds increase in speed. Strong winds apparent in the northwest corner of the domain may not be realistic, being near an aircraft turning point over rough and high terrain.

Figure 4 shows that turbulence (standard deviation of TAS) is relatively low (0.5) in areas where east winds accelerate. Turbulence is reduced over the sea (0.3),

TABLE 2. Cape Saint Francis weather and flights. Weather data taken from SAWB operational reports at Cape Saint Francis.

Flight	Date	Time	Wind direction	Speed (m s^{-1})	Maximum/minimum temperature (°C)	Rainfall (mm)	Cloud (pm)
1*	3–11	afternoon	WSW	10	19/15	0	1/8
2	4	afternoon	S–E	5	20/14	0	8/8
3	5	afternoon	E	15	21/15	0	4/8 turbulent
4	6	afternoon	ESE	5	22/15	0	1/8 sea breeze
5	7	morning	WSW	15	—		frontal transition
6	7	afternoon	WSW	7	19/16	1.3	8/8
7	8	morning	WSW	7	18/16	0	8/8
8	10	morning	WSW	10	22/16	2.5	8/8
9	11	afternoon	SSW	7	21/11	0	8/8
10	12	morning	WSW	12	20/13	0	8/8

* Instrument problems encountered.

TABLE 3. Port Elizabeth radiosonde profile data.

Date	T (°C)	T_d (°C)	Geopotential height (m)	Wind direction (°)	Wind speed (m s^{-1})
1000 hPa					
3 November	19.9	8.8	153	240	12.0
4 November	18.6	11.7	149	100	4.0
5 November	21.5	17.6	118	60	6.5
6 November	25.0	17.6	94	360	3.0
7 November	20.0	14.7	398	230	5.5
8 November	16.5	10.5	189	240	5.6
9 November	20.9	15.8	129	50	3.5
10 November	20.4	14.8	122	230	8.5
11 November	16.8	11.4	166	230	5.0
12 November	17.8	11.0	169	240	4.0
925 hPa					
3 November	15.1	6.8	817	230	14.4
4 November	13.0	11.3	812	120	8.9
5 November	18.4	11.1	789	80	8.0
6 November	28.7	−0.1	785	195	1.5
7 November	18.0	10.8	783	285	7.6
8 November	12.0	8.7	847	205	9.3
9 November	17.7	13.0	800	360	5.7
10 November	16.3	12.9	790	190	5.8
11 November	11.9	10.4	825	180	4.3
12 November	10.7	6.9	827	240	7.5

as would be expected, and is increased inland. The land–sea gradient is strongest in the northeast part of the domain in the vicinity of Jeffreys Bay. The east wind composite is characterized by generally high surface and air temperatures (26°C) over the headland. Dewpoint temperatures are around 17°C. The topographic orientation is well reflected in the air temperature pattern, as is the isolated urban heat island of Humansdorp, which casts a "warm wake" southwestward. It is noted that higher wind speeds coincide with the wake. Air temperatures at 100 m over the sea are 24°C in the east wind composite, while sea surface temperatures are 18°C. Hence, a low-level inversion is developed over the sea and heat fluxes are negative. Surface temperatures rise rapidly at the coast with solar insolation causing positive heat fluxes over the cape. Land temperatures are about 2°C warmer than the air at 100 m; hence, conditions are somewhat unstable. The dewpoint pattern reflects increased values (>18°C) just to the east of Sea Vista, coincident with largest gradients in surface temperature. A tongue of moist air penetrates the Krom River valley, while driest air is noted in the vicinity of Humansdorp. The topographic orientation and the depth of the marine boundary layer is reflected in the contour pattern of dewpoint. The easterly wind regime exhibits the most stratified characteristics (Table 3 profiles) and consequently the meteorological patterns are dynamic and variable.

b. *Weak westerly wind regime*

Under weak westerly winds (Fig. 5), areas of sustained acceleration include the ridge to the west of Sea Vista (Saint Francis Bay), the headland at Aston Bay, and seaward of the tip of Cape Saint Francis. Reduced wind speeds are noted to the north of the Krom River, near Kruisfontein, and Humansdorp, and in the southwest corner. Unreliable bull's-eyes can be seen at the southern and western edges of the composite domain, in spite of the filtering procedure.

In light westerly winds, turbulence is 0.6, surface and air temperatures are approximately 20°C, and dewpoints are 14°C (Fig. 6). Again the marine areas experience less turbulence (0.4) where sea temperatures are 2°C less than 100-m air temperatures. Over the land, air temperatures do not increase under westerly winds, remaining about 20°C throughout. A tongue of relatively warmer air lies over the Krom River in contrast to the ridge to the west and the hills to the north near Humansdorp. Surface temperatures only increase by 2°–3°C from the sea to the land, in response to reduced insolation in cloudy unstable weather condi-

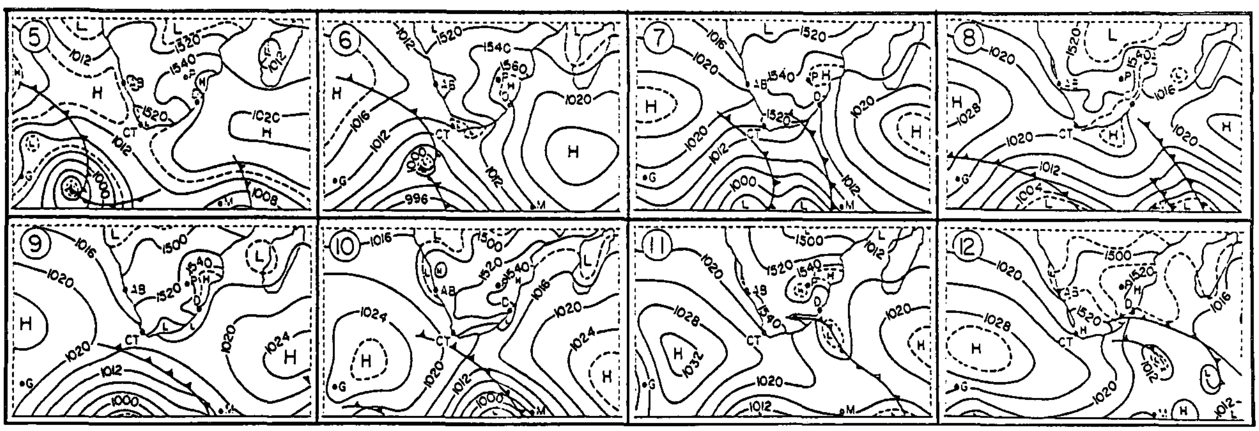

FIG. 2. Sequence of synoptic weather maps for the first half of November 1991. Isobar contours are drawn every 4 hPa (after SAWB 1991).

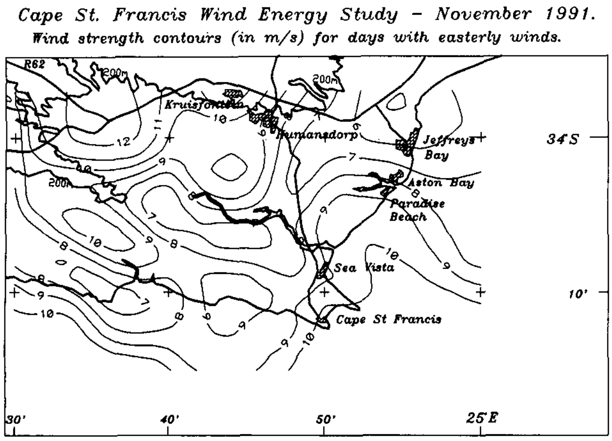

FIG. 3. Wind speed distribution at approximately 100 m above ground level for the composite easterly wind regime. Contour interval is 1 m s^{-1}.

tions (see Tables 2 and 3). Dewpoint temperatures decrease from 14° to 13°C from sea to land, with some contrasts between Humansdorp and Sea Vista. In general, meteorological gradients for the westerly wind regimes are weakened by the unstable character of the marine weather.

c. *Strong westerly wind regime*

An important wind regime from an energy availability and demand perspective is the strong westerly. Figure 7 reveals that near-surface flow is of a higher speed along the ridge south of the Krom River to the west of Sea Vista, at the Aston Bay headland, and over the northern tip of Cape Saint Francis. The wind maximum to the south of the Krom River extends about 40 km inland and could host a long line of large wind turbines. Being situated across the 250° direction of the prevailing wind, wake effects of adjacent turbines

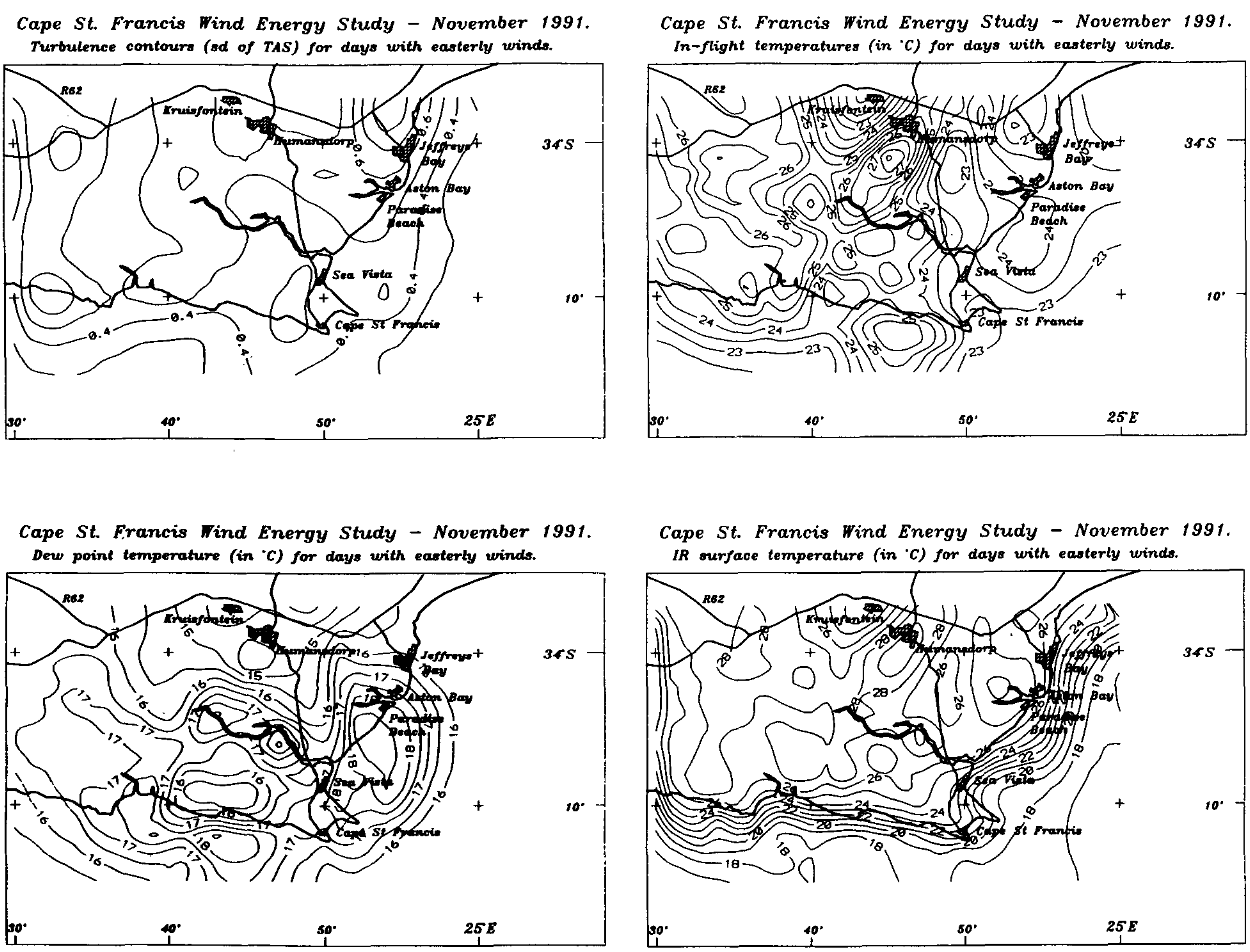

FIG. 4. Meteorological fields of turbulence, air temperature, surface temperature, and dewpoint temperature for the composite easterly wind regime, shown clockwise from upper left. Contours are labeled in units of standard deviation for turbulence and degrees Celsius for temperature.

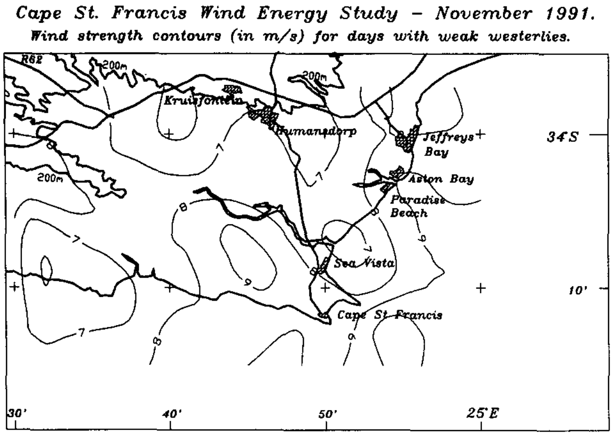

FIG. 5. Wind speed distribution for composite weak westerly wind regime as in Figure 3.

would be minimized. Areas to be avoided due to reduced wind speeds include the central northern third of the domain and the southwest corner.

Figure 8 shows that turbulence is higher in this regime (0.9). Peak values occur near Humansdorp and the mountainous area northwest of the domain. The generally high values are indicative of sharp gusts in the wind field produced by topography and embedded cloud circulations. A sharp gradient in turbulence is noted along the south coast where values decline from 1.0 to 0.5. Temperatures are similar to the light westerly composite, being in the range 20°C for land and air temperatures, 17°C for sea temperatures, and 13°C for dewpoint temperatures. Air temperatures decrease from the Krom River mouth to Humansdorp, due to increasing elevation and cool temperatures aloft. Sharp gradients are also seen in the surface temperature field east of the Krom River. Dewpoint gradients are very weak, indicative of a homogeneous, well-mixed air mass with minor continental–maritime contrast.

5. Summary

Aircraft surveys of wind velocity and associated meteorological parameters have been compiled for a brief

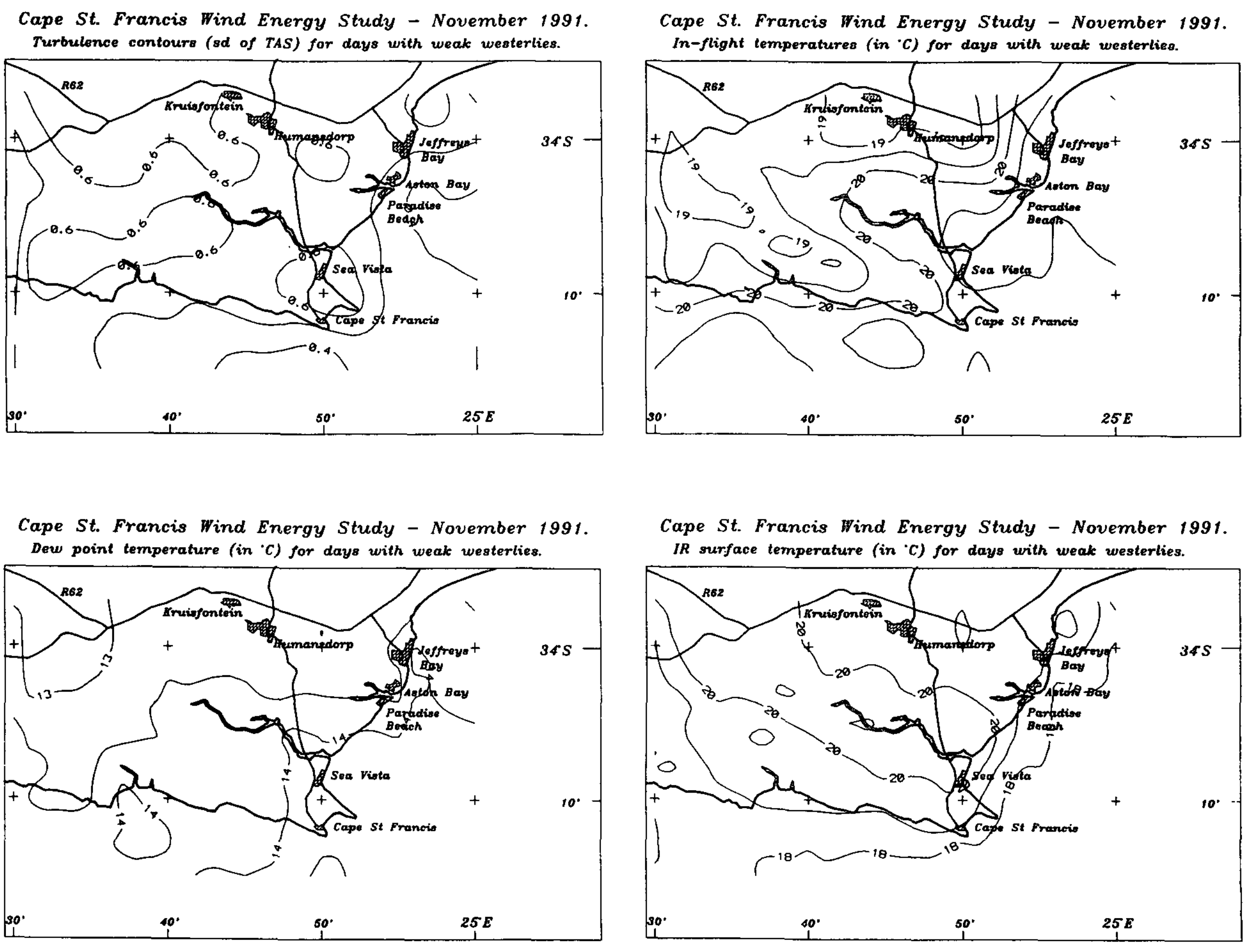

FIG. 6. Meteorological fields for the composite weak westerly wind regime as in Figure 4.

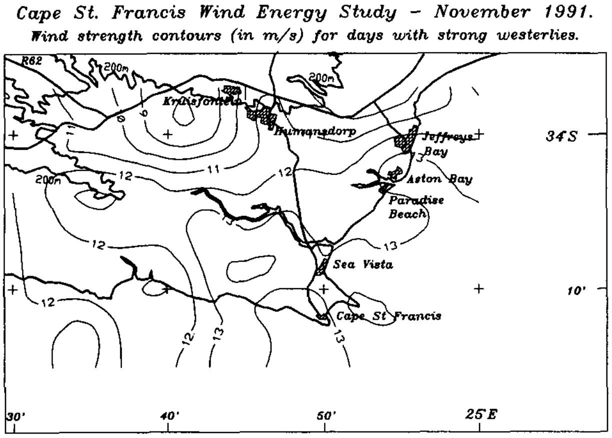

FIG. 7. Wind speed distribution for composite strong westerly wind regime as in Figure 3.

period in November 1991 in support of a siting investigation for wind energy conversion systems in the Cape Saint Francis area. The utility of aircraft in the analysis of low-level winds was confirmed under a wide variety of weather conditions.

Results have been composited into various wind regimes and demonstrate that wind speeds are highest under strong westerly winds along the northwest–southeast ridge south of the Krom River, near an access road to Oyster Bay (34°08′S, 24°42′E). Other zones of sustained westerly wind acceleration include the point at Cape Saint Francis and the headland near Aston Bay. During easterly winds (when temperatures are high and consumer heating energy demand is low) the southwestern flank of the cape and the area to the southwest of Humansdorp are zones of acceleration.

In general, the ridges of the Cape Saint Francis headland show up as areas of high wind speeds under all wind regimes. The flow is subcritical (Froude number less than 1) and acceleration is estimated to be 30% in excess of geostrophic, owing to vertical and horizontal flow compression over the cape. In contrast, marine wind speeds and turbulence over the adjacent sea to the south and east are not particularly strong.

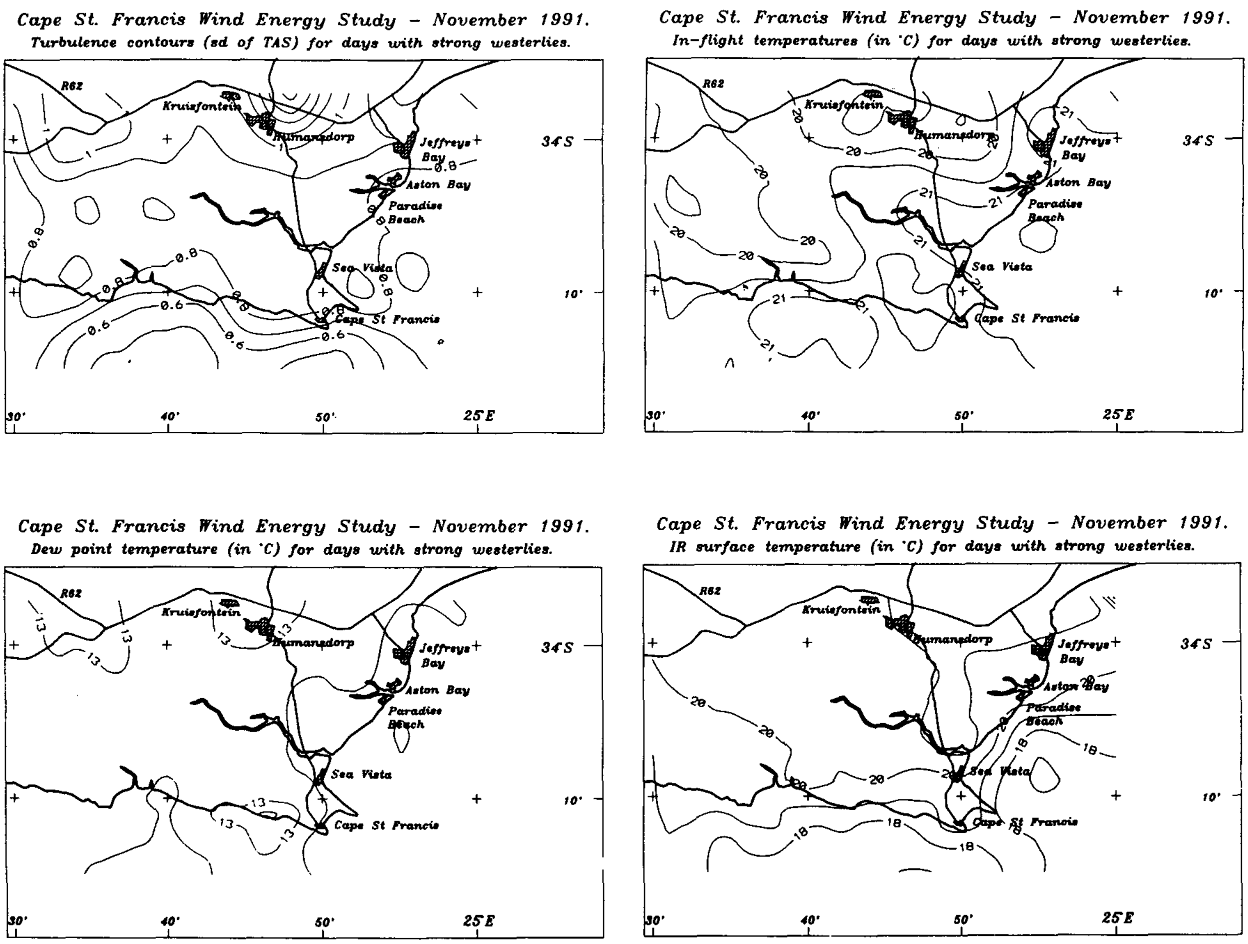

FIG. 8. Meteorological fields for the composite strong westerly wind regime as in Figure 4.

In previous aircraft surveys with a focus on marine weather to the south of Cape Saint Francis, Jury and Courtney (1991) have noted a calm wind zone just off the coast in contrast to strong winds over the coast and further offshore over the Agulhas Current.

In summary, a small set of aircraft data has provided some insight to the optimal siting of wind energy conversion systems at Cape Saint Francis, South Africa. Coupled with earlier information from hand-held anemometer surveys (Jury and Diab 1989) and recent numerical model simulations (Diab 1992), the Cape Saint Francis headland "looks a sure bet" for the siting of wind farms in the not too distant future. With over 200 million tons per annum of CO_2 being produced in South Africa by coal-burning power stations, renewable energy sources will be looked upon with increasing favor. Surveys as described here will assist in a more complete utilization of the wind resource.

Acknowledgments. The National Energy Council and the Foundation for Research Development of South Africa provided funding for this work. The surveys were expertly accomplished by staff of Cloud Quest using an instrumented aircraft supported by the Water Research Commission. The infrared sensor for surface temperature measurements was loaned by the Sea Fisheries Research Institute. Thanks are extended to the SAWB for forecasts and background data.

REFERENCES

Beardsley, R. C., C. E. Dorman, C. A. Friehe, L. D. Rosenfield, and C. D. Winant, 1987: Local atmospheric forcing during the coastal ocean dynamics experiment. I. A description of the marine boundary layer and atmospheric conditions over the northern California upwelling region. *J. Geophys. Res.*, **92,** C2, 1467–1488.

Caldwell, P. C., D. W. Stuart, and K. H. Brink, 1986: Mesoscale wind variability near Point Conception during spring 1983. *J. Climate Appl. Meteor.*, **25,** 1241–1254.

Diab, R. D., 1988: The wind energy resource in South Africa. *Renewable Energy Resources and Technology Development in Southern Africa,* A. Ebehard and A. Williams, Eds. Elan Press Cape Town, 157–181.

——, 1990: Wind energy climatology of southern and southwestern Cape. *Report National Energy Council,* Pretoria, 188 pp. [Available from National Energy Council, Department of Mineral and Energy Affairs, PBX59, Pretoria, 0001.]

——, 1992: Wind energy modelling: Southern Cape. *Report National Energy Council,* Pretoria, 82 pp. [Available from National Energy Council, Department of Mineral and Energy Affairs, PBX59, Pretoria, 0001.]

EWEA, 1991: *Wind Energy in Europe.* European wind energy association Technical Report, Amsterdam, 100 pp.

Hamming, R. W., 1983: *Digital Filters,* Prentice Hall.

Hunter, I. T., 1987: The weather of the Agulhas bank and the Cape south coast, M.S. thesis, Oceanography Dept., Univ. Cape Town, 231 pp. [Available from the University of Cape Town, Department of Oceanography, Rondebosch, 7700, South Africa.]

Jury, M. R., 1987: Aircraft observations of meteorological conditions along the west coast of Africa 30°–35°S. *J. Climate Appl. Meteor.*, **11,** 1540–1552.

——, 1989: Case studies of the response and spatial distribution of wind-driven upwelling off the coast of Africa 29–34°S, *Cont. Shelf Res.*, **8,** 11, 1257–1271.

——, and Diab, R. D., 1989: Wind energy potential in the Cape coastal belt, *S. Afr. Geogr. J.*, **71,** 3–11.

——, and S. Courtney, 1991: A transition in weather over the Agulhas Current. *S. Afr. J. Mar. Sci.*, **10,** 159–171.

South African Weather Bureau, 1991: *Monthly Newsletter,* **512,** Gov. Printers, Pretoria.

Tyson, P. D., F. J. Kruger, and C. W. Louw, 1988: Atmospheric pollution and its implications in the eastern Transvaal Highveld, *SANSP rep 150,* CSIR, Pretoria, 114 pp. [Available from CSIR, P.O. Box 395, Pretoria, 0001, South Africa.]