METEOROLOGICAL ASPECTS OF WINTER AIR POLLUTION EPISODES IN THE CAPE TOWN AREA

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ABSTRACT

Winter air pollution episodes in Cape Town are studied using observations, statistics and model simulations. Correlations between meteorological parameters and NO_x concentrations, and the vertical structure of the lower atmosphere are analysed. The surface inversion is best correlated (70%) with air pollution and derives from radiative heat loss during winter nights. The inversion has a mean strength of 11°C up to the 500 m level. Composite analysis of the episode surface weather features shows that a marine anticyclone ridges over the southern Cape and the continental high strengthens near Durban. The resulting surface flow is from the north to northeast, commonly referred to as a berg wind. Numerical model simulations show that the berg winds are channelled in the Diep river valley to the northeast to Cape Town and deflected to the west of the peninsula during the morning hours. A large calm develops in the lee of the Tygerberg Hills over the main industrial and traffic emission area.

INTRODUCTION

Increasing air pollution may threaten public health in subtropical regions experiencing urban-industrial expansion and poor atmospheric ventilation, such as the interior plateau near Johannesburg (Tyson *et al*, 1988). Cape Town, at the south-west tip of the African continent is located in an exposed coastal environment where pollutants can mix seawards. But even there, hourly concentration maxima of NO_x, SO_2 and hydrocarbons can rise to 3048, 322 and 558 ug m^{-3}, respectively and exceed local air quality standards. In this paper we examine meteorological aspects of air pollution episodes during the 1985 and 1986 winters.

Pollutants in the Cape Town area primarily originate from small industries and vehicular traffic. The industrial areas are located to the east of Cape Town at a radius of 5-15 km. Over 100 000 vehicles travel into Cape Town every working day along two major routes extending to the east and southeast. These heavy vehicle loads constitute the major emission source in the Cape Town basin (Lowenheim, 1988). An industrial complex located 10 km to the NNE of Cape Town provides additional emissions, some at effective stack heights up to 200 m.

The steep topography in the SW Cape area and the eastwards passage of transient cells of high and low pressure create, at most times, atmospheric conditions conducive to the mixing of near surface emissions, particularly during summer (Jury and Spencer-Smith, 1988). In winter northwesterly winds and rain cleanse the air. But the rainy spells are followed by anti-cyclones that ridge eastward over the southern Cape coast. Climatic conditions and the sheltering effect of Table Mountain then lead to the accumulation of atmospheric pollution.

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DATA AND EPISODE SELECTION

Since 1984 detailed hourly measurements of air pollution constituents have been recorded in metropolitan Cape Town and at a few outlying industrial sites (City Engineer's Report, 1984-1986). For episode selection here, the daily concentration of SO_2 and NO_x had to exceed twice the monthly mean for more than one day at more than one monitoring site. The episode criteria ensured that only cases which were sufficiently extensive in space and time were chosen for further analysis. Eleven episodes could be identified during the 1984-1987 period. Here we report on one case in 1985 and on three cases each lasting five days in the 1986 winter season.

Once the episodes were identified it was necessary to obtain meteorological data. Information on surface layer wind, turbulence and inversion conditions were obtained from the Koeberg Nuclear Power Station network. Details of this network have been provided by Jury and Mulholland (1988). Radiosonde profile data were available from the SAWB and DFM airport east of Cape Town. Synoptic analyses for the surface 850, 700 and 500 hPa levels were also obtained from SAWB publications. Use was made of an acoustic sounder data in August 1985 which overlapped with a pollution episode. Statistical analyses were performed to determine mean vertical atmospheric structure and cross-correlations between meteorological and pollution trends. The numerical model of Wilczak and Glendening (1988), which accounts for interactions between topography and vertical atmospheric stability, was utilised to simulate the structure of the urban circulation for the mean episode scenario.

EPISODE CORRELATION ANALYSIS

Time series of pollution concentrations and meteorological parameters for the 1986 winter are shown in Figure 1. Three distinct peaks (arrows) each lasting about 5 days can be noted in the NO_x plot. These pollution peaks coincided with winds from the east sector, reduced speeds, surface inversions, high 850 hPa geo-potentials and no rain; all indicative of anticyclonic influence. Statistical correlations were computed by

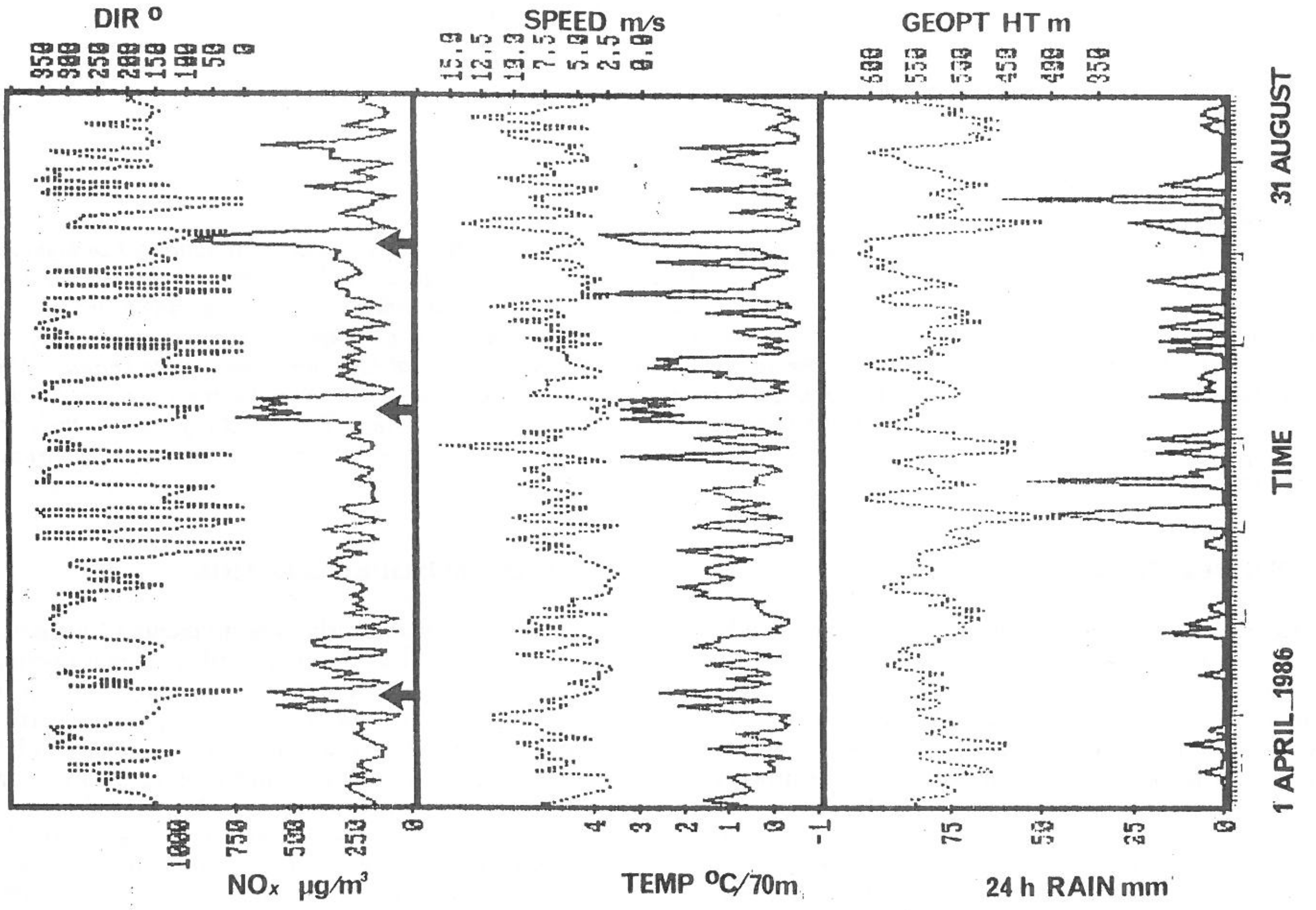

Figure 1: Time series of daily averaged 80 m wind direction, NO_x concentration, 80 m speed, 10-80 m delta temperature, 850 hPa geopotential height, and daily rainfall total. Arrows identify the pollution episodes.

comparison of meteorological and pollution time series. To view the wider atmospheric forcing, synoptic charts were composited for the period 6 days prior to 2 days following each episode. Autocorrelation analysis revealed cycles at 7 days in the first half of winter for NO_x and rainfall. Cross correlation of the various para-meters was performed for all possible combinations. Table 1 lists the pertinent results and identifies leads and lags.

We infer from the cross-correlation analysis that the vertical temperature structure (delta temp, corr=.69) is most likely to control pollution levels, but peak NO_x concentrations will lead any increases in the strength of the surface inversion. Wind speeds are next most likely to control concentrations in an inverse relationship (corr=-.51). That the 850 hPa geopotential height is slightly better correlated at 1 day lag (corr=.39), indicates a possible useful relationship in the context of forecasting. Peak NO_x concentrations are therefore preceded by rises in the 850 hPa height. Cross correlations between concentration and direction, and speed and direction imply that winds turn to easterly (warm advection) with the advent of an episode.

TABLE 1: Cross Correlation

	Parameter	Correlation at zero lag	1 day lag	1 day lead
No_x vs	direction	-.28	-.11	-.18
	delta temp	.69	.27	.39
	wind speed	-.51	-.23	-.20
	850 hPa ht	.38	.39	.18
	rainfall	-.23	-.13	-.07
Direction vs	delta temp	-.39	-.06	-.22
	wind speed	.23	.18	-.00
	850 hPa ht	-.37	-.37	-.08
	rainfall	-.39		
Delta temp vs	wind speed	-.54	-.41	-.13
	850 hPa ht	.44	.51	.09
	rainfall	-.26	-.26	-.01
Wind speed vs	850 hPa ht	-.48	-.32	-.29
	rainfall	.30		
Rainfall vs	850 hPa ht	-.45	-.40	-.21

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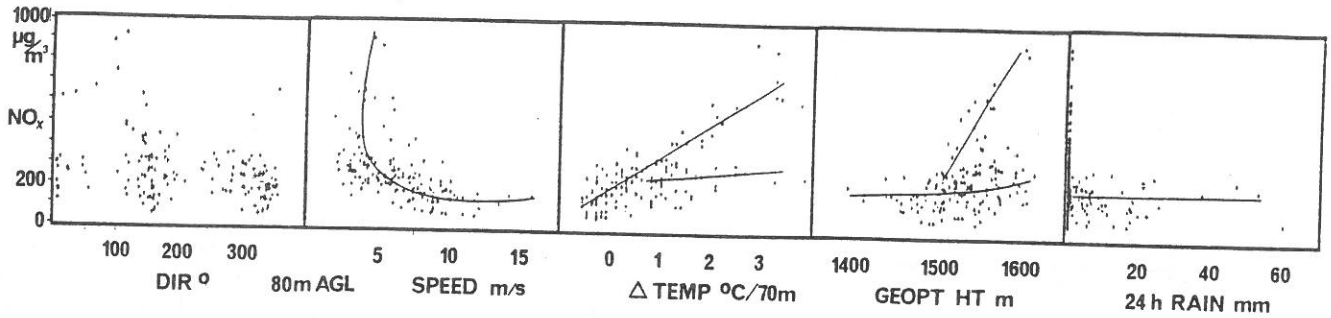

Figure 2: Scatterplots of daily averaged NO_x concentration versus (left to right) daily averaged wind direction, speed, delta temperature, 850 hPa geopotential height and daily rainfall total. Curves are subjectively fit. Data cover the period 1 April - 31 August 1986

Figure 2 shows scatterplots of the cross correlations of NO_x vs all meteorological parameters for the entire 1986 winter season. As can be seen in the direction plot, clustering of the observations occurs for SE and NW sectors indicating topographic channelling of the flow. Highest concentrations arise when winds are in the NE sector. The relationship between pollution concentration and surface inversion intensity is somewhat linear, while the NO_x vs speed scatterplot appears more exponentially sloped. The 850 hPa geopotential height scatterplot is poorly structured with the exception of peak concentrations which assume a linear tendancy. Interestingly, the amount of daily rainfall does not have much impact on NO_x concentrations and the trend is almost flat.

EPISODE VERTICAL ATMOSPHERIC STRUCTURE

The vertical structure of meteorological conditions during episodes is provided in Figure 3 from night time radiosonde ascents over the periods 21-25 April, 23-27 June and 29 July - 2 August, 1986. The temperature structure confirms the presence of a strong surface inversion. Temperatures increase (11° on average) linearly to the 500 m (953 hPa) level. Conditions above the surface inversion are relatively neutral. The dewpoint structure is linearly sloped throughout the lower troposphere and there appears to be no particular marine-continential or upper subsidence layer transition. Rather the dry air becomes gradually mixed down to the surface. Surface layer dewpoints are less than 10°C and average 7°C at the 1000 hPa level. The direction structure is disorganised. Some topographic channelling is evident, but the wide scatter above the inversion suggests that the upper level anticyclone moves across the area during the episode, providing winds from all sectors and the possibility of low net transports for pollutants. The speed structure is well sheared. Winds in the surface layer are less than 3 m s^{-1}, but increase rapidly aloft above the inversion. Mean 925 hPa winds are 030° at 3.3 m s^{-1}.

COMPOSITE WEATHER CHARTS

The composite sequence of the surface synoptic pressure field is shown at 2 day intervals in Figure 4 for the period 6 days before to 2 days after the episode. The pattern is dominated by the gradual ridging of the South Atlantic anticyclone following a trough in the westerlies. As the anticyclone moves across the southern tip of the continent, the interior high over the Limpopo Valley migrates towards Durban and intensifies on day A. A separate marine high develops off Durban causing a berg wind circulation over the west coast. A second westerly trough approaching Cape Town acts to terminate the episode. Standard deviations are particularly large over the land during anticyclogenesis (day -2 to A) indicative of some variability in the interaction of the continental and marine highs.

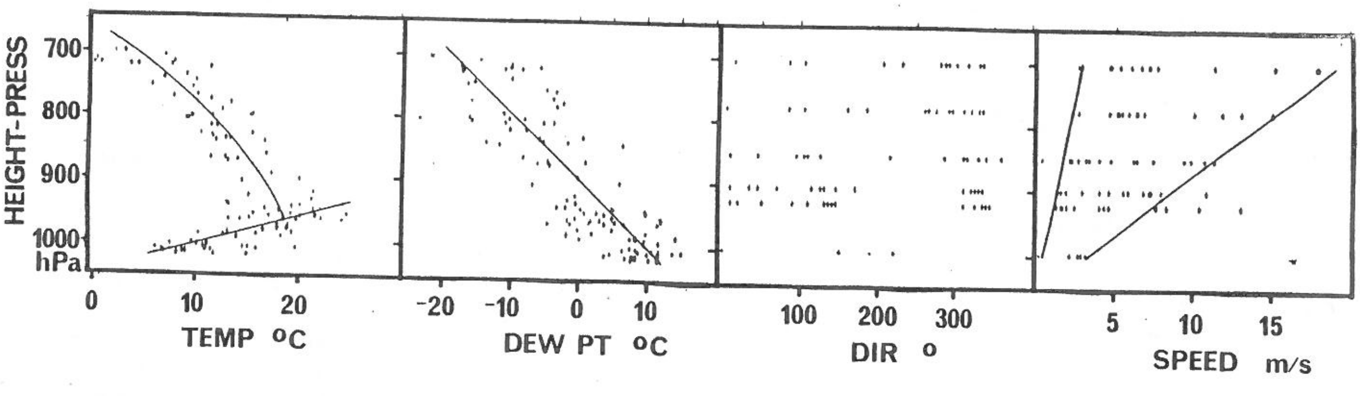

Figure 3: Detailed nocturnal vertical atmospheric structure for 15 episode cases in 1986. Left to right: temperature, dewpoint, wind direction and speed.

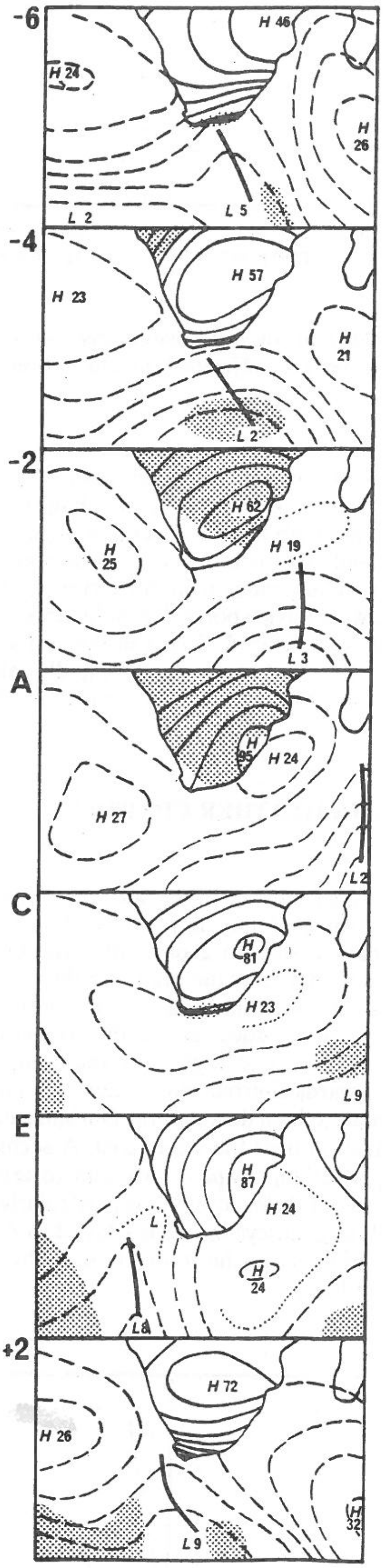

Figure 4: *Composite average structure of the synoptic weather sequence before (-6 to -2) during (A to E) and after (+2 days) the episode. Isobars over the land at 10 gpm. Locations and intensities of the high and low pressures are given. The bold line marks the cold front. Large standard deviations are shaded.*

ACOUSTIC SOUNDER CASE STUDY

The 26-28 August 1985 episode is highlighted here due to its overlap with acoustic sounder data. A background to the episode is provided by radiosonde data which indicate that 850 hPa heights at Cape Town rose to 1631 gpm on the 26th and were over 1650 gpm at Durban. The atmosphere was particularly dry as indicated by dewpoint temperatures of -30°C at 866 hPa (just above the level of the local mountains). Unlike most of the other episodes, this episode saw southerly winds start and end the period. Winds at the 500 hPa level reached 24 m s^{-1} from the west. The nocturnal surface inversion extended to 957 hPa with a strength of 13.5°C on 27-28 August. Pollution concentrations (Figure 5) show that values six to nine times the monthly mean were reached at 09h00 every morning during the three day episode with secondary maxima in the afternoon, both related to the sheltering effect of Table Mountain and traffic peaks.

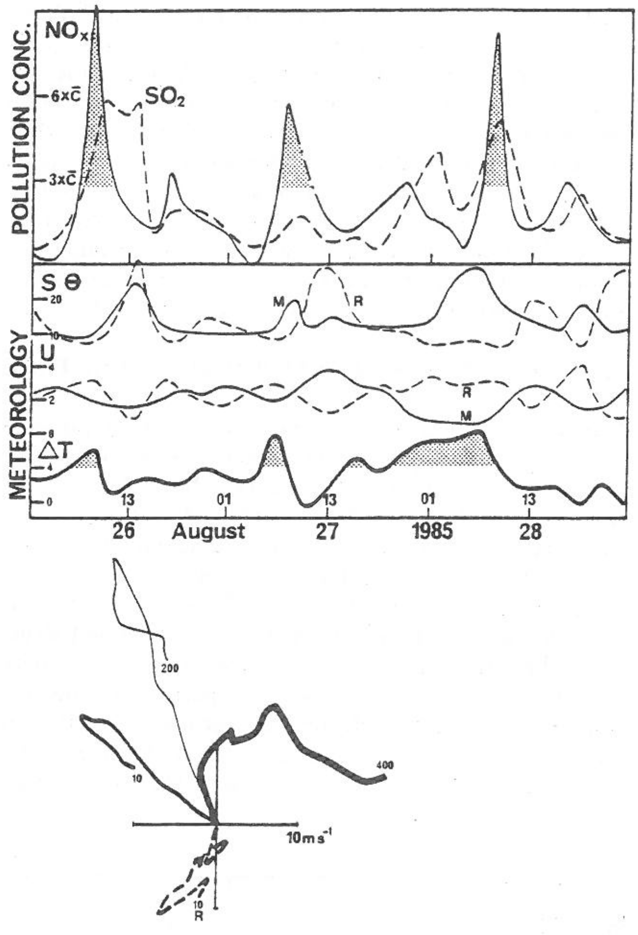

Figure 5: *Episode details for 26-28 August 1985 showing meteorological and pollution time series and progressive vector plots.*

Acoustic sounder results for the period 22h00 26 August to 18h00 28 August are shown in Figure 6. The episode saw diminishing southerly winds over the 27th, which decreased in depth from 450 to 150 m. A landbreeze component briefly interrupted southerly winds on the morning of the 27th. Turbulence values were particularly low during the southerly wind period and onlyincreased aloft. Subsidence was prevalent during the SE wind

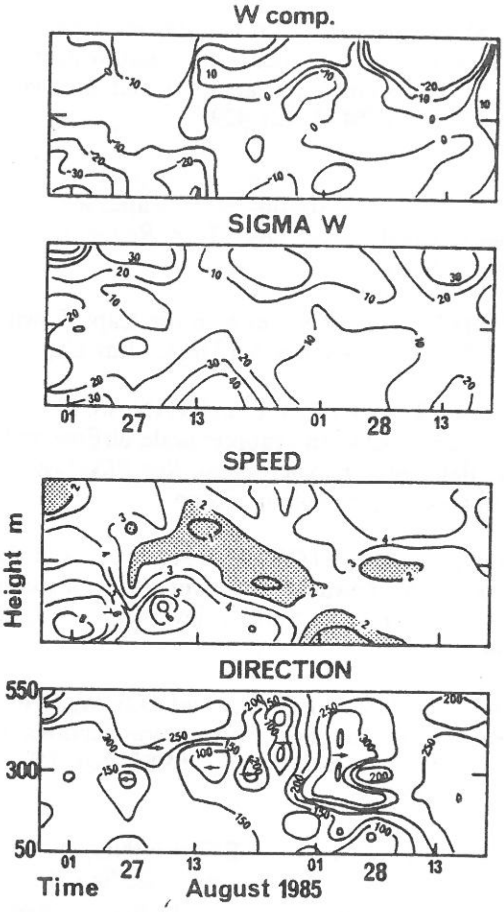

Figure 6: Acoustic sounder results over the period 20h00 27th August - 20h00 28 August 1985 showing wind speed, direction and turbulence.

period early in the episode. Weak surface landbreezes and upper boundary layer westerlies pulsed in a rhythm at the inversion top. The dominant feature was the reduction of wind speeds below 2 m s^{-1}.

Tower data and acoustic sounder progressive vectors (Figure 5) illustrate that reversals in wind direction in time, and with height and distance, resulted in a low net transport of pollutants. Surface nocturnal inversions increased in intensity and duration over the three days, exceeding 4°C from 10 to 80 m in the early morning hours. Channelling of the landbreeze at the inland site reduced turbulence (sigma theta) and brought cold air onto the coastal plain. Some evidence of seabreezes producing advection inversions along the coast and over the Cape Town basin is noted.

The progressive vector diagram at bottom in Figure 5 reveals a wide spread of winds at different levels and locations. At the coastal sounder site, 200 m vectors were northwestward from 01h00 on the 27th to 22h00. Winds then reversed during the morning of the 28th. At the 400 m level, sounder winds were initially northward and then eastward after 10h00 on the 27th. 10 m winds at the inland site (R) were slower and directed towards the southwest, directly opposite to the 400 m vector. The NE surface flow may have by-passed the Cape Town basin, and the southernly 200 m winds and the westerly 400 m winds would have been obstructed by Table Mountain. Hence some recirculation and convergence of pollutants in the Cape Town basin was likely.

MODEL SIMULATIONS AND DISCUSSION

A two layer mesoscale numerical model was adapted to suit local conditions and initialised with the episode meteorological data. Wilczak (1988) has described the application of the model to Santa Barbara, California, an area with quite similar environmental conditions to that found in Cape Town. For our simulation, observations were taken from the 80 m tower and airport radiosonde to construct a vertical profile consisting of a landbreeze layer of 30 m depth, an inversion at the 300 m level and a relatively neutral layer aloft. A surface flow of 2 m s^{-1} from the NNE was applied to the model domain, covering the area 33°30' - 34°30'S, 18° - 19°E. Terrain was specified at one minute intervals so that model calculations could be performed at a horizontal resolution of 1.7 km. Figure 7 shows the surface layer wind field at 09h00 when air quality is worst. Channelling of the nocturnal landbreeze in the Diep River Valley is prominent. The flow exits the valley mouth south of Tableview and swings seawards around the west side of the Cape Peninsula. A large calm area is developed just to the east of Cape Town where much of the industrial and traffic emissions are located. The calm area is indicative of topographic obstruction of the landbreeze by the Tygerberg hills. Jury *et al* (1990) discuss further model simulations in relation to other episode scenarios.

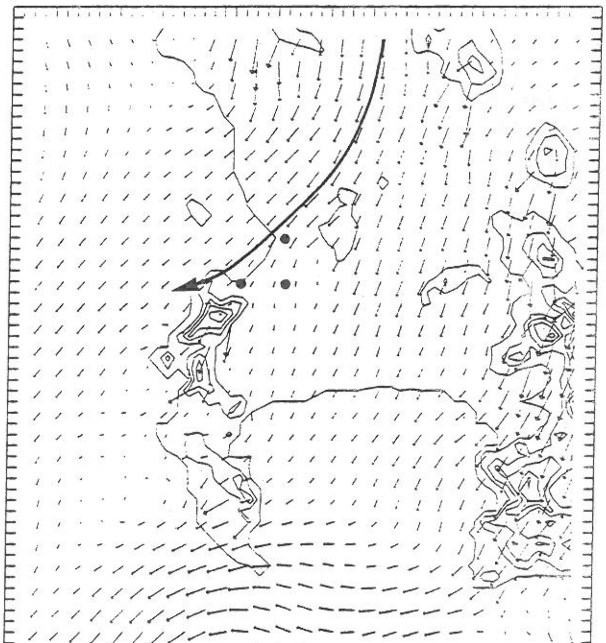

Figure 7: Surface velocities at 09h00 local time as simulated by the two layer numerical model. Channelling and deflection of the berg wind/-breeze leaves a large area of Cape Town under calm conditions. Traffic and industrial sources are shown by dots. The northernmost dot coresponds to the acoustic sounder site. Topography is given at 200 m contour intervals. Vector lengths represent speed.

CONCLUSION

The meteorological mechanism initiating air pollution episodes in Cape Town is the influx of dry continental air into the coastal zone. The berg winds occur about 10% of the time in the winter months (Redding *et al,* 1982) but seldom persist longer than 2-3 days. Through increased back radiation during the long winter nights, cooling of the surface layer leads to the development of a sharp inversion (Tyson *et al,* 1976) which prevents the transfer of northerly gradient winds to the surface. As weak landbreezes develop the inversion further strengthens. Topographic obstruction is accentuated and model results show that valleys and hills to the north-east of Cape Town have a channelling and deflecting influence. In the daytime, weak seabreezes can trap pollutants within the Cape Town basin (Keen, 1979).

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