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Observations of wind flow and tracer gas dispersion over sand dunes

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Abstract Measurements of the wind profile and the rate of vertical dispersion from a ground-level source in flow over a rough and visually inhomogeneous plain of sand dunes yielded results which were not detectably different from the corresponding profiles in flow over a horizontally uniform surface with a roughness length of about 1 cm.

Keywords Wind; air flow; air pollution; dispersing; profiles; surface roughness.

INTRODUCTION

During April 1982 a group from the New Zealand Meteorological Service carried out several tracer gas experiments to help members of the Sea/Air Exchange Program (SEAREX) evaluate a proposed site for monitoring oceanic air chemistry. SEAREX (Duce 1981) is an ongoing multi-institutional project supported by the U.S. National Science Foundation, in which atmospheric chemistry experiments are conducted in clean marine air at carefully selected sites. During April 1982 preparations for the 1983 SEAREX experiment were being made at a site on Ninety Mile Beach, on a southwest facing coast near the northern tip of New Zealand.

The primary purpose of the tracer gas dispersion experiments was to determine the height necessary for proposed air sampling towers in order to minimise collection of contaminants emitted by surf or beach. Detailed wind profile measurements were made during the dispersion experiments to aid interpretation of the results. A report on these tracer gas studies and their implication for the suitability of the site for the SEAREX project is given by Clarkson et al. (1984).

A secondary aim of these experiments was to make use of the tracer gas facility and wind profiling equipment to study the nature of the offshore flow while conditions were unsuitable for the primary aims. This paper reports on a tracer gas experiment performed on the dunes during offshore flow and shows that, in spite of the inhomogeneous appearance of the dunes, the observed wind and concentration profiles differ negligibly from profiles for an infinite flat plain with a roughness length of about 1 cm. This is not presented as a comprehensive study but as an observation of a surprising characteristic of wind flow over sand dunes.

THE SITE

The experiments were performed 1.3 km north of Te Paki Stream, Ninety Mile Beach, New Zealand. Fig. 1 is a map of the locality showing the configuration of equipment for the experiment. A triangular tower 20 m tall fitted with an 8 m extension mast was erected at the site to support the meteorological instruments and the air sampling gear. The tower is 20 m inland from the beach on the first line of foredunes. The site is approximately 2-dimensional in that the cross-section of the dune topography is very similar inland from any point along the beach. The beach is terminated by a sharp rise of about 5 metres to a foredune followed by a plain of rough sand dunes which are sparsely and erratically covered by grasses and shrubs and randomly cut by stream beds. Approximately 1.5 km inland the dune plain rises slowly to larger sand hills which peak at around 100 m.

Fig. 2 and 3 are views from near the tower looking upwind (in the context of observations to be presented) towards 78° from true north. They are included to show one of the stream beds and to indicate the random and very rough appearance of the dune plain. A topographic survey from the tower out to 624 m upwind (towards 78°) yielded 30 estimates of local height at 20 m intervals. The surface along this line has an upward trend of 0.50° with a vertical standard deviation of 1.1 m.

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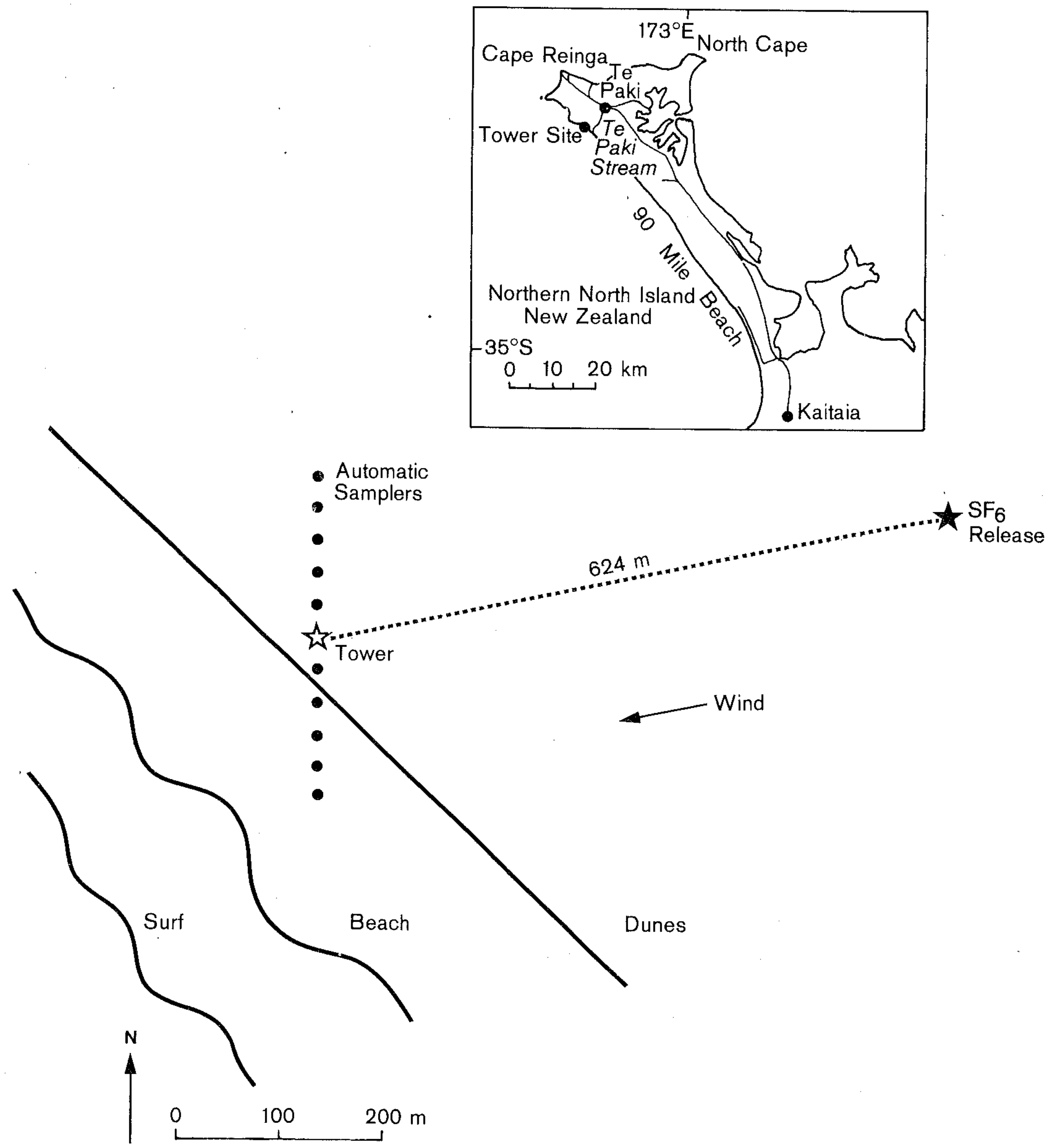

Fig. 1 The configuration of the tower, air samplers, and tracer gas release equipment at Ninety Mile Beach.

OBSERVATIONS

Wind profile

Horizontal windspeeds were measured using cup anemometers which were individually calibrated against a pitot tube and sensitive manometer prior to the experiments.

Over 5 consecutive overcast windy days of offshore flow 11 hours of windspeed data were obtained at 6 levels between 1.5 and 20 m. Each day there were only small deviations from the logarithmic wind profile:

$$u = (u_*/0.4)\ \ln(z/z_0)$$

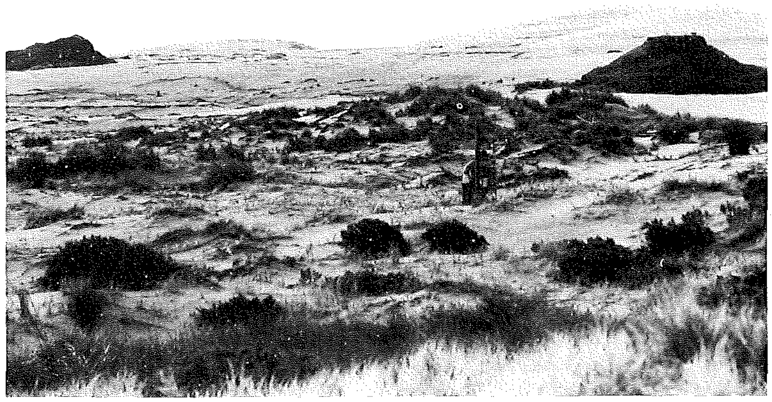

Fig. 2 View from tower in the upwind direction for reported measurements. Centre of view 78°, scrub-clad hills at 73° and 83°. The peak of the broad dune in the middle right of the photograph was 10 m above and 443 m upwind from the base of the tower. The tracer gas source lay a further 181 m behind this dune.

Fig. 3 View from near the tower in the upwind direction for reported measurements showing a stream bed and typical dune terrain.

with (u_*, z_0) = (41, 0.41), (37, 0.76), (42, 1.3), (46, 1.4), and (32, 1.3) (cm/s, cm), where z is height, z_0 is roughness length, u is horizontal wind speed, and u_* is the friction velocity. Fig. 4 shows the plot of log$z$ versus u from which these parameters for the first day were derived. That no displacement height is needed in fitting these profiles is coincidental. Had the tower base been higher or lower a displacement height would have been necessary. The differing roughness lengths can probably be attributed to small differences in wind direction from day to day. A roughness length of about 1 cm is surprisingly small for this surface, and more in line with expected values for rough pasture on a flat plain.

Flow over very rough surfaces is not well-understood. Lettau (1969) proposed an empirical formula derived from observations of flow over surfaces artificially roughened by arrays of geometrically uniform obstacles:

$$z_0 = 0.5h^*s/S$$

Here h^* is the effective obstacle height, s is the average obstacle frontal area, and S is the average horizontal area occupied by each obstacle ('specific area'). This formula has proven useful in cases where well-defined values of the geometric parameters occur. For example, Jackson & Carroll (1978) used Lettau's formula to explain wind direction-

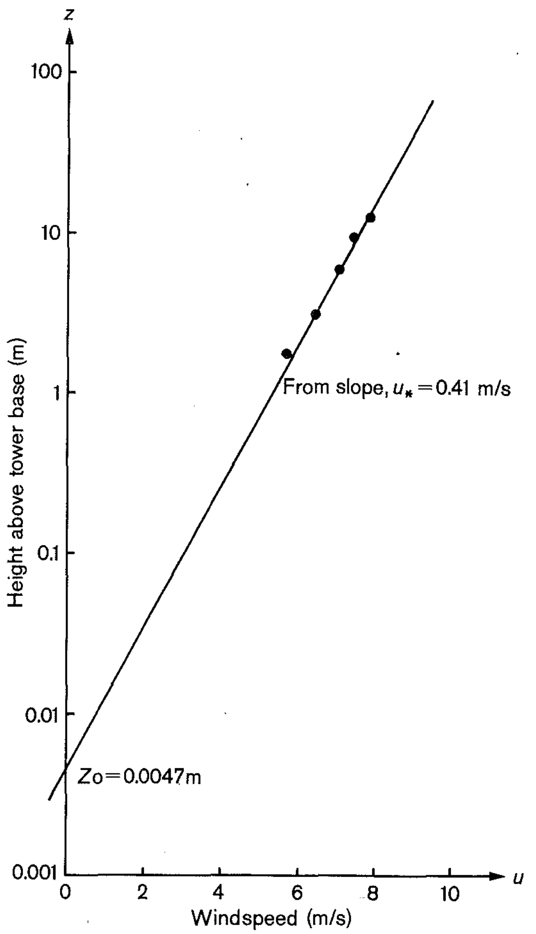

Fig. 4 Plot of log$z$ versus u used to derive u_* and z_0 for the experiment of 22 April 1982.

* these figures differ in some cases by up to 2% from those in my log book. Tom must have revised them.

Table 1 Observed concentration profile.

Lateral		Vertical	
Distance from tower (m)	Concentration (μg/m³)	Height on tower (m)	Relative concentration *
−150	< 0.01	28	0.41
−120	0.35	24.5	0.45
−90	0.19	21	0.55
−60	1.24	17.5	0.62
−30	2.46	14	0.69
0	3.57	10.5	0.82
30	4.47	7	0.92
60	3.58	5	0.95
90	2.37	3.5	0.99
120	1.02	1	1.01
150	0.49	0.2	1.00

† accuracy of z_0 not critical because (1) same value is used to scale both simulation and data (2) generated log wind profile for simulation insensitive to z_0 (ie sensitive only to ln z_0)

dependent observed roughness lengths in flow over fields of sastrugi at the South Pole.

In the present case we estimate

$h^* \sim 3$ m

$s \sim 3 \text{ m} \times 30 \text{ m} = 100 \text{ m}^2$

$S \sim 10^3 \text{ m}^2$

which yields a value of z_0 of around 15 cm, an order of magnitude greater than the values of 1 cm that we have deduced from the wind profile.

A more complicated expression for the roughness length of an array of obstacles has been proposed by Arya (1975). Since we cannot assign meaningful values to at least 4 of the 7 parameters, Arya's formula cannot be applied here.

Dispersion from a ground-level point source

For the Te Paki tracer experiments, pure sulphur hexafluoride (SF_6) was emitted through a regulator at a monitored and manually controlled rate, and the source strength Q (g/s) was obtained by careful weighing of the cylinder. For the experiment discussed here the release site, 624 m upwind (78°) from the tower and 3.4 m higher in elevation than the base of the tower, was chosen as the site on the dune plain furthest upwind for which there was vehicle access for the heavy release equipment. Downwind, air samples were pumped into nylon bags by battery-operated automatically switched pumps. The pump controller switched to new bags every 10 minutes, to provide good time resolution of the concentration field.

Air samples were obtained at 11 levels on the tower and at 10 ground-level (z~35 cm) locations spaced at 30 m intervals along the line perpendicular to the source–tower line (i.e., crosswind).

Analysis of the samples was carried out immediately after each experiment using a gas chromatograph. The chromatograph had itself been calibrated against permeation tubes used in a dynamic dilution system. All sample bags were carefully flushed and checked with the chromatograph prior to each experiment. A detailed account of the equipment and procedures for the tracer gas experiment is available (Clarkson & Hadfield 1983).

Table 1 gives the mean concentrations observed over the 90 minute period 1200–1330 NZST, 22 April 1982. The rate of release of SF_6 was estimated to lie within the range $Q = 0.13 \pm 0.02$ g/s. The standard deviation of the wind direction over this period was 10°, a value representative of neutral stratification, which agrees with our subjective judgment of the stability during the experiment. The observed crosswind spread was characterised by standard deviation $\sigma_y = 54$ m, which is of the

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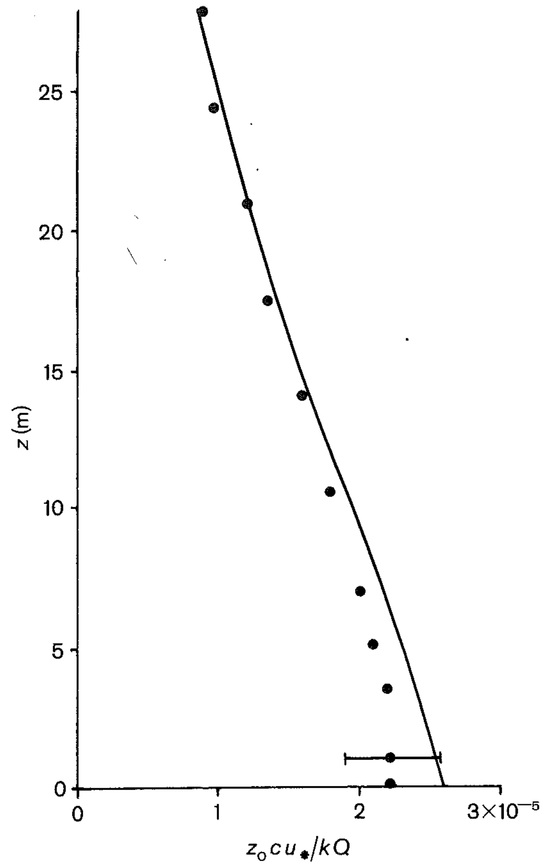

Fig. 5 Vertical profile of dimensionless crosswind integrated concentration $z_0 c u_*/kQ$. c = crosswind integrated concentration, $k = 0.4$ = von Karman's constant, $z_0 = 0.47$ cm, $u_* = 41$ cm/s.
Observation, ●; trajectory-simulation model, ———. The error bar on the observation at $z = 1$ m corresponds to the uncertainty in source strength, $Q = 0.13 \pm 0.02$ g/s.

expected magnitude for this downwind distance with neutrally stratified flow.

Fig. 5 shows the observed vertical profile of the dimensionless crosswind integrated concentration (XWIC), obtained by scaling the ground-level XWIC using the observed vertical concentration profile at the tower. Also given on Fig. 5 is the prediction of the trajectory-simulation model described by Wilson et al. (1981). To obtain this prediction it was assumed that $(\overline{w^2})^{1/2} = 1.25u_*$ and $\ell = 0.5z$, where $(\overline{w^2})^{1/2}$ is the root-mean-square vertical velocity, and ℓ is the Lagrangian length scale. The choice $\ell/z = 0.5$ was found by Wilson et al. to give best agreement with the Project Prairie Grass experiments on dispersion over an extensive flat plain. Note that the choice $\ell = 0.32z$, which implies that the eddy diffusivity is equal to the eddy viscosity, yields a predicted value for the dimensionless ground-level concentration of 4.03×10^{-5}, which is almost double the observed value.

The trajectory simulation model as applied here is strictly valid only for a horizontally uniform surface layer. Though the dunes at Te Paki did not give the appearance of a uniform flat plain, the logarithmic wind profile observed does indicate that perhaps the flow is not very different from flow over a large flat plain. The model prediction is satisfactory. The small discrepancy could be ascribed to:

(1) Departure of the turbulence statistics from the ideal behaviour embodied in the trajectory model. For example, although there was cloud cover during this experiment, and the impression was of strong winds and near-neutral stratification, in the absence of any measurement the possibility that vertical transport was enhanced by buoyancy effects cannot be ruled out.

(2) A systematic error in the experimental technique. Evaluation of the integral $\int_0^x uc\,dz$, where c [g/m²] is the crosswind integrated concentration, yielded a mass flux past the tower of 0.14 g/s, in good agreement with the estimated source strength. However, approximately 20% of the integral was contributed by an extrapolation of u and c above the top of the tower.

e.g. $\sigma_w/u_* = 1.5$ as observed 24/4. This gives $\chi_0 = 2.18$E-5 which is being off

CONCLUSION

Although the sand dunes over which these experiments were performed gave the impression of a highly inhomogeneous and very rough surface, the observed wind profiles differed little from those expected over an extensive flat plain with a roughness length of about 1 cm. Consistent with this, the rate of vertical dispersion from a ground-level source was found to be adequately described by a diffusion model which was developed for flow in a horizontally uniform ideal surface-layer and calibrated by a comparison with tracer experiments over a very large and uniform plain. The implication is that models derived for the ideal horizontally uniform case may remain useful even when the surface departs quite grossly from the original assumptions.

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