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Computer-Model Results for the Beach-Escarpment-Induced Distortion of Onshore Wind Flow at the Northwest Point of San Nicolas Island, California

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A computer model developed by the Atmospheric Environment Service of Canada concluded that the beach escarpment underlying the Naval Research Laboratory's micrometeorological tower facility at San Nicolas Island, California, induced wind-speed amplifications ranging from 1.00 to 1.25 and wind-direction perturbations ranging from −5° to +5°, depending upon the altitude and wind direction, for measurements made from the NRL tower. The altitudes considered ranged from 5 to 35 m above the beach for onshore winds ranging over a 180° arc cen-

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ABSTRACT

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COMPUTER-MODEL RESULTS FOR THE BEACH-ESCARPMENT-INDUCED DISTORTION OF ONSHORE WIND FLOW AT THE NORTHWEST POINT OF SAN NICOLAS ISLAND, CALIFORNIA

INTRODUCTION

A frequent fact of life for a marine atmospheric experimentalist is that the selection of a research platform is usually determined by funding and logistical constraints rather than by purely scientific considerations. Given the choice of something or nothing, a researcher must frequently attempt to make the best of a less than ideal measurement platform. A recent paper dealing with the particle aspects of flux measurements in the marine atmospheric surface layer (Blanc, 1983) concluded that an onshore tower was the most practical platform from which to make coastal measurements. Given the present state of turbulent flow distortion modeling, an understanding of the distortion produced by a relatively simple beach is more readily achievable in the forseeable future than a comprehensive model of the more complex distortion produced by a ship or large ocean tower. The paper further concluded that, no matter what type of platform is selected, a detailed flow-distortion study will need to be conducted to determine the influence of the platform. The question is no longer simply whether or not a platform will distort the measurements, but rather, to what degree are they distorted?

This report summarizes the results of a cooperative effort by the Atmospheric Environment Service (AES) of Canada to model the distortion produced at the Naval Research Laboratory's (NRL) Coastal Air-Sea Interaction Observatory (CASIO) facility located on the outermost upwind edge of San Nicolas Island, California. Earlier experiments (Blanc, 1981) employed a relatively unsophisticated model of escarpment effects to fashion an algorithm for correcting profile flux and stability observations made at the facility. The results presented in tables at the end of this report are intended to provide an improved correction algorithm for future experiments.

THE ONSHORE TOWER FACILITY

Because the prevailing weather in the region of the North American continent generally flows from west to east, it was considered highly desirable to have a coastal marine experiment site west (upwind) of the United States mainland. San Nicolas Island is the outmost of a coastal grouping of islands off the coast of California known as the channel islands. The 60 km^2 island is owned by the U.S. Navy and is located approximately 120 km southwest of the city of Los Angeles at 33° 15′ North latitude, 119° 30′ West longitude (see Fig. 1). Experienced observers on the island indicated that the weather in the vicinity of the island tends to occur in two- or three-day cycles, during which conditions remain relatively uniform, and that over a span of two or three weeks a diverse spectrum of such uniform periods could be observed. Surface and radiosonde weather observations have routinely been made from the island for more then 35 year. This would be of considerable assistance in planning experiments. From a logistical perspective, the island has a fully operational airport with a 2.6-km runway, twice daily weekday air service to and from the mainland, monthly barge service for large equipment, food and housing facilities for scientists, hardline electrical power to the experiment site, commercial telephone and data links to the mainland, and motor-vehicle transportation.

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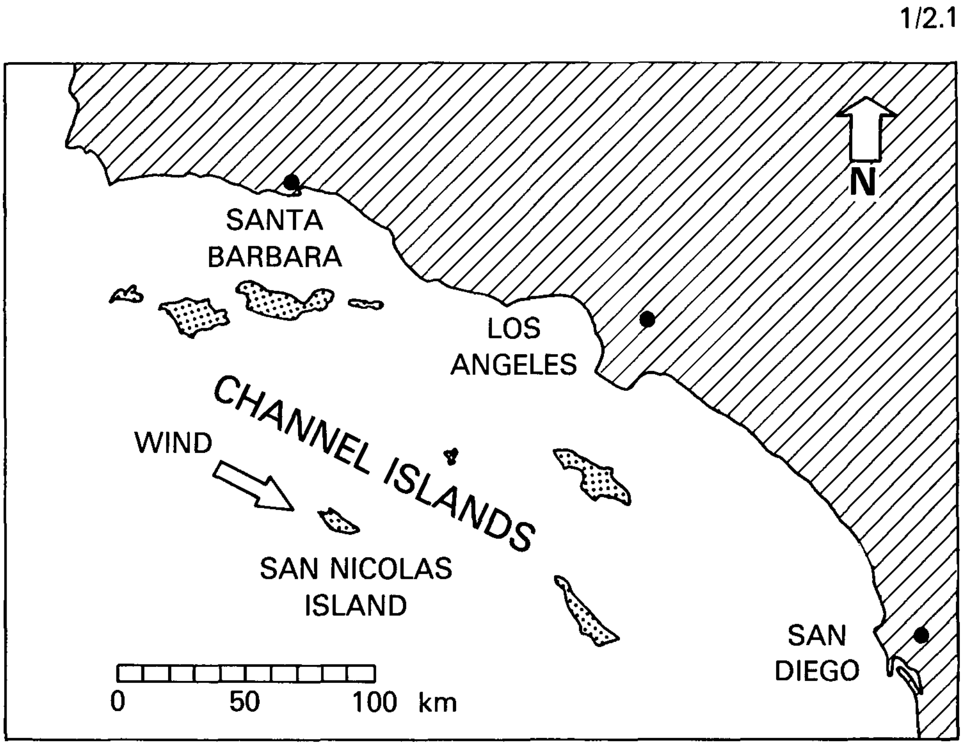

Fig. 1 — A map of the southern California coast showing San Nicolas Island and the prevailing wind direction in the vicinity of the island

The Naval Research Laboratory's micrometeorological tower facility is located on the leading edge of the island's major northwest promontory, Vizcaino Point, which protrudes directly into the prevailing wind (see Figs. 2 and 3). The promontory is a narrow 1.5-km-long low-profile peninsula with a mean net slope of approximately 1:20 (see Fig. 4). The 19.1-m tower is located on top of an escarpment, or beach embankment, approximately 6 m above mean sea level and is surrounded by the Pacific Ocean on three sides (see Fig. 5). When the tide is at mean sea level the tower is approximately 76 m from the water's edge. The specially designed tower is equipped with 6.7-m-long sensor arms to minimize the distortion produced upwind of the tower by the presence of the tower structure (see Figs. 6 and 7). A mobile field shelter is provided to house instruments and personnel when measurements are being made. Vedder and Norris (1963) described the beach material located between the high- and low-tide lines as a light-gray, very thick-bedded, concretionary, medium-grained sandstone, containing a few thin beds of intercalated sandstone and siltstone. They described the overlying escarpment material as a light-tan, unconsolidated, lime-cemented sand.

COLLABORATION AND THE SITE SURVEY

At the suggestion of the North Atlantic Treaty Organization (NATO) Air-Sea Interaction Program, the second author visited the Atmospheric Environment Service in July, 1981. During that visit, the AES offered its assistance to NRL in attempting to characterize the San Nicolas Island escarpment. Subsequently, during February of the following year, a low-altitude, high resolution aerial survey of the topography surrounding the NRL tower site at Point Vizcaino was conducted. The results of the stereophotographic survey are presented in Fig. 8. A 1-m by 1-m version of the figure was read into the AES computer by a large flatbed graphic digitizer.

Fig. 2 — An aerial view of San Nicolas Island looking east. The Vizcaino Point peninsula can be seen in the lower left hand corner of the photograph.

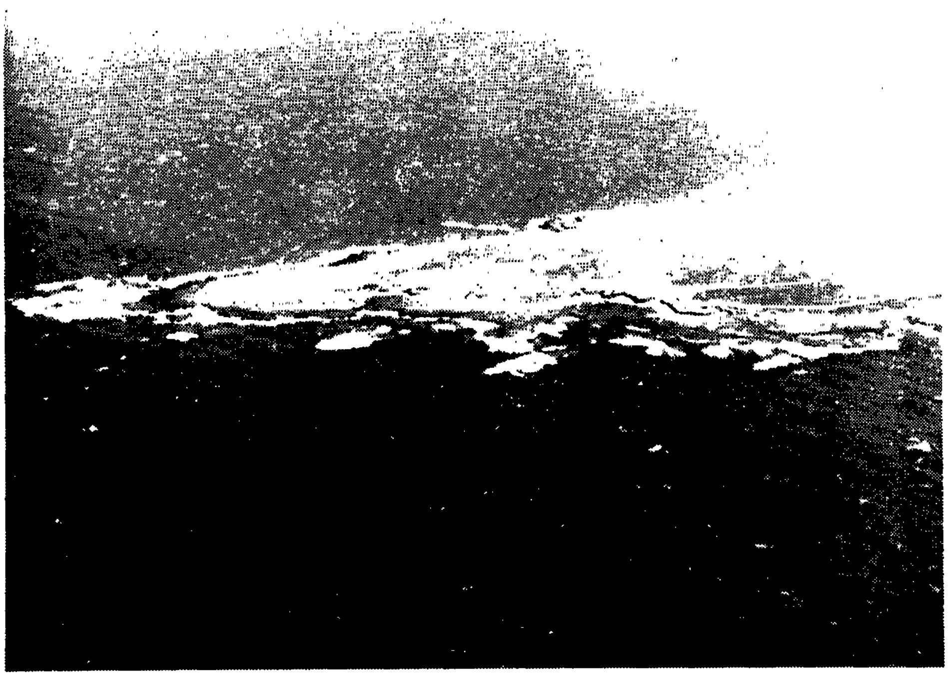

Fig. 3 — A view of the northwest end of San Nicolas Island looking to the northeast. The prevailing northwesterly winds approach the island from the left side of the photograph, parallel to the peninsula's axis of symmetry.

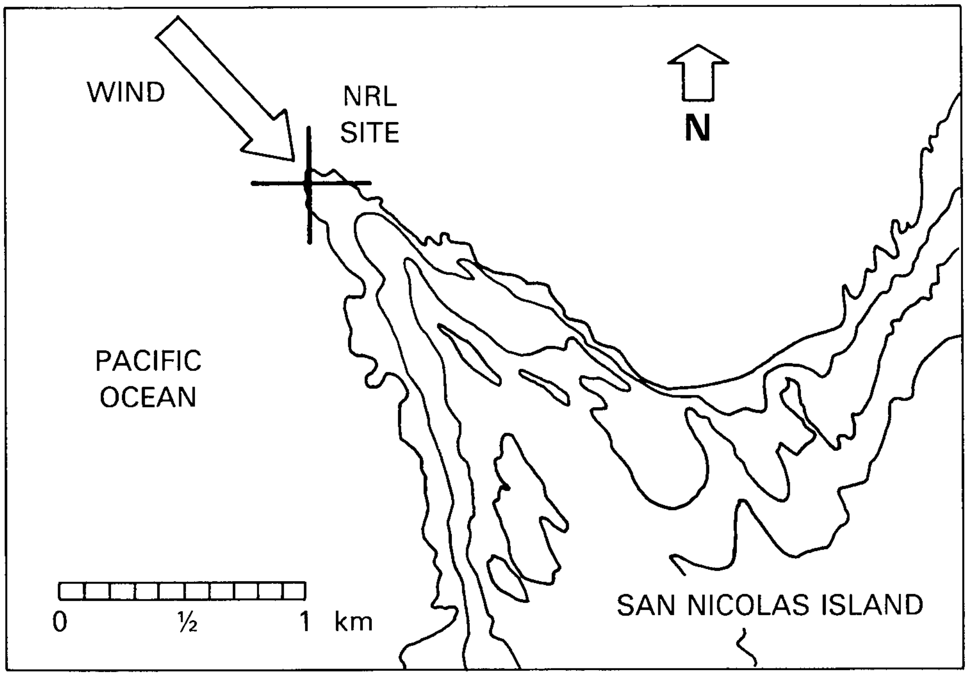

Fig. 4 — A 15-m-interval contour map of the entire Vizcaino Point peninsula

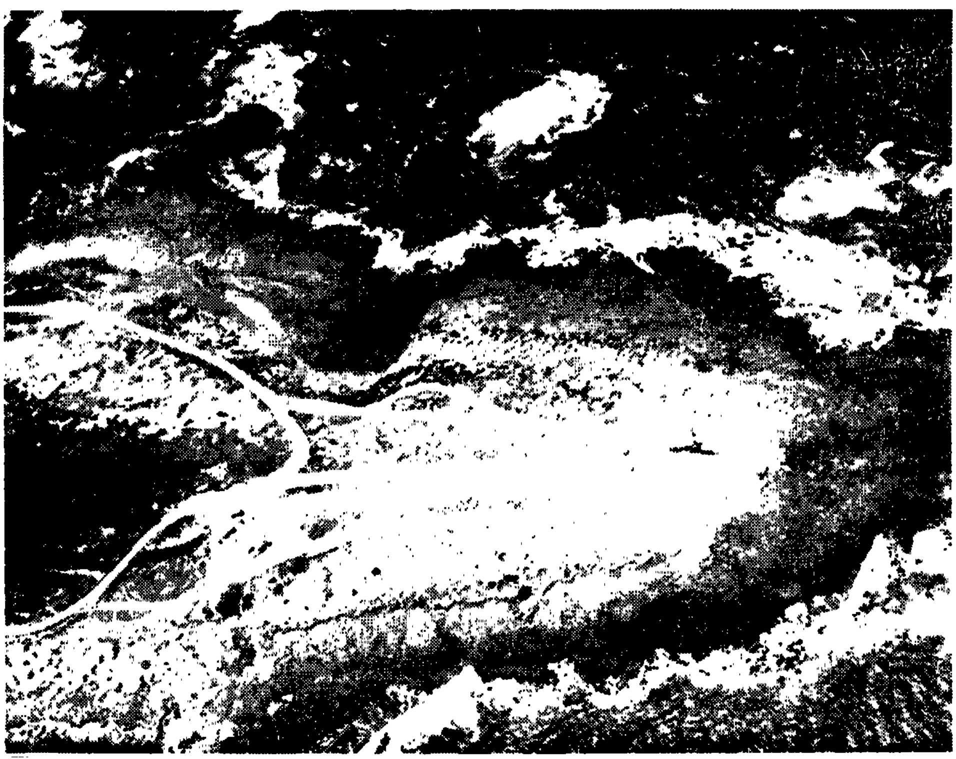

Fig. 5 — An aerial view of the NRL tower site at low tide
looking down towards the southwest.

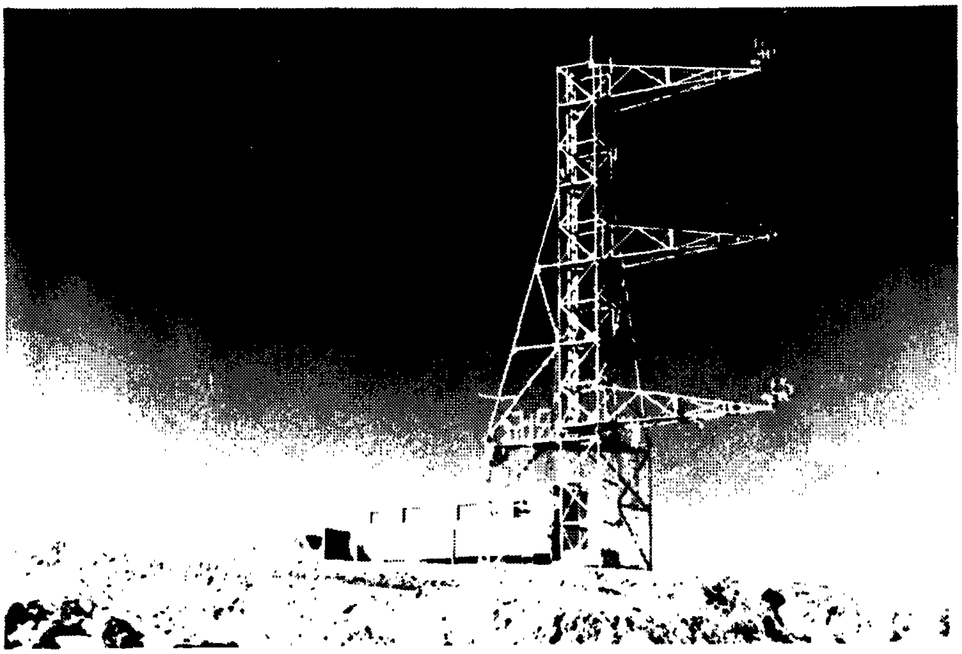

Fig. 6 — A view of the NRL micrometeorological tower and mobile field shelter on top of the beach escarpment looking south. The sensor arms point in the direction of the prevailing wind. During experiments, the mobile field shelter is located farther downwind of the tower to minimize any flow distortion produced by the shelter.

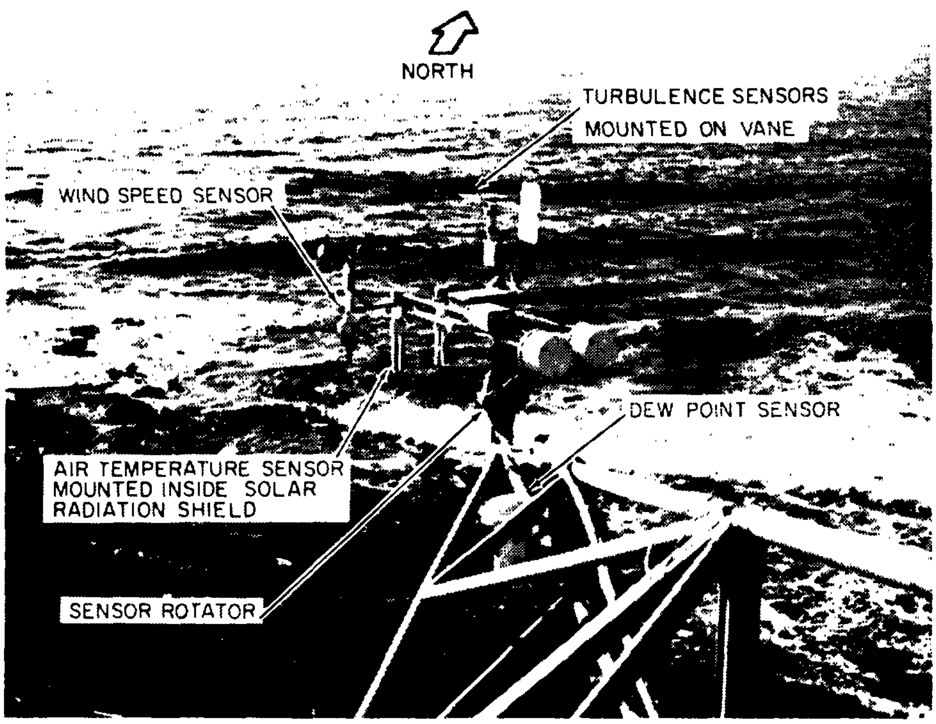

Fig. 7 — A view of a typical set of sensors located on the end of a tower arm. The arms are equipped with a hinge located midway out from the tower, which enables the sensors to be retrieved from the safety of the main tower structure. The hinge is located on the vertical arm support shown in the lower right foreground.

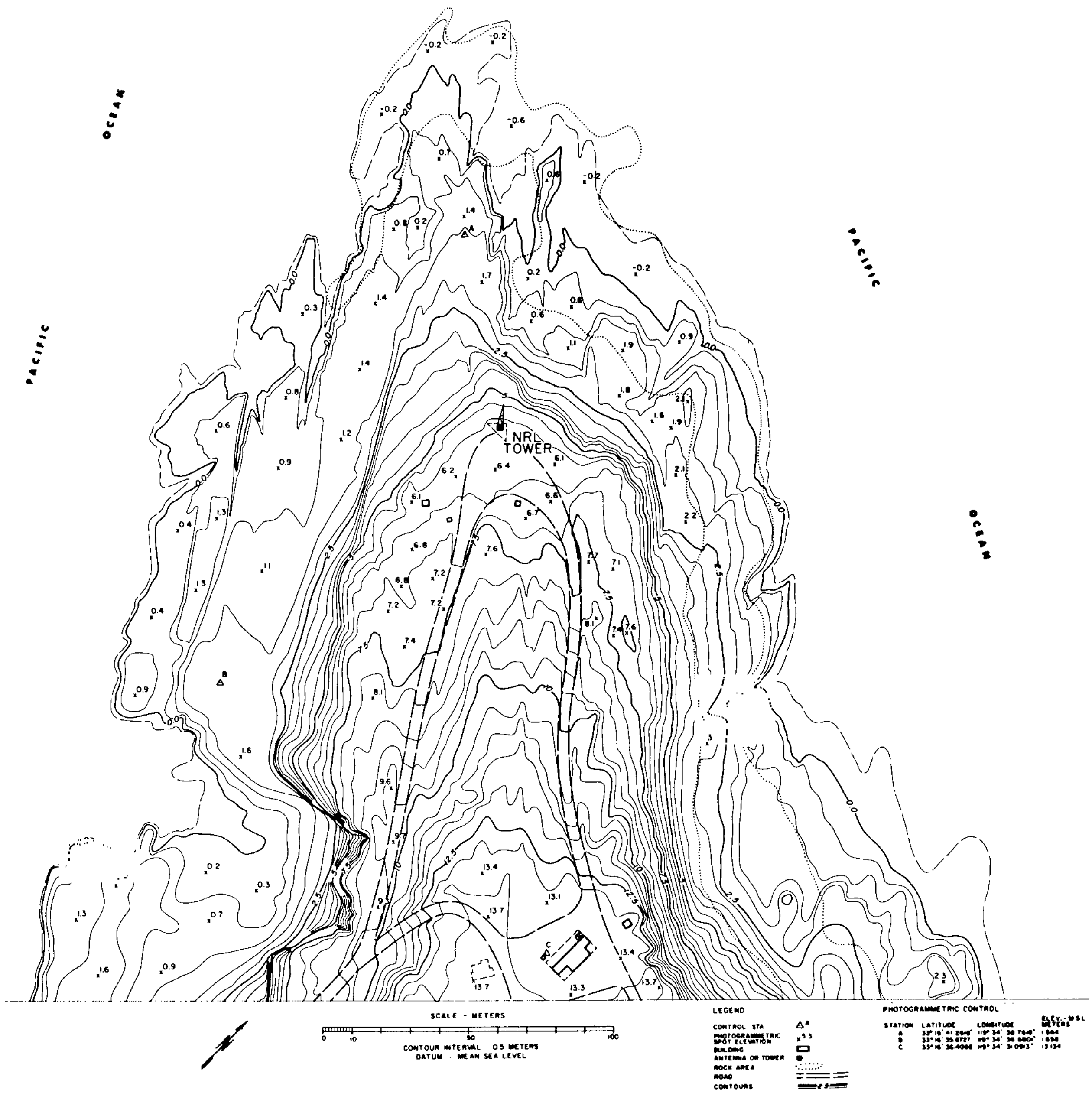

Fig. 8 — The 0.5-m-interval contour map of the first 300 m of the Vizcaino Point peninsula resulting from the February 1982 aerial survey

THE COMPUTER MODEL

The calculations of wind-speed and wind-direction changes induced by the beach escarpment at NRL's micrometeorological tower site were made using the MS3DJH/1.5 model. This is one of a series of models developed by scientists in the Boundary-Layer Research Division of the Atmospheric Environment Service to study near-surface flow in computer-simulated terrain. Details are given by Walmsley et al. (1982).

The models are based on Mason and Sykes' (1979) three-dimensional extension of Jackson and Hunt's (1975) approximate theory of flow over a low hill, hence the acronym MS3DJH/1.5. The Jackson-Hunt theory involves a number of limitations, approximations, and assumptions but has the significant advantage that it leads to analytic solutions for terrain-induced flow perturbations. Numerical methods are needed to perform required finite Fourier transforms and Bessel function evaluations, but the computer time necessary is at least three orders of magnitude less than for a finite-difference solution of the governing equations. The main limitations of the theory and model are that the terrain must be of low slope (up to about 1 in 5 is probably acceptable) and uniform surface roughness, z_0. Ideally the terrain considered should consist of an isolated feature in an otherwise flat plain, but this restriction can be relaxed if a sufficiently large domain is used.

The model assumes that the flow can be divided into an outer, inviscid flow region and an inner layer within which the turbulent shear stresses can be represented by mixing-length closure. The pressure gradients determined from inviscid, irrotational flow in the outer region are used to "drive" flow perturbations in the inner layer. All perturbations are assumed linear in a small, slope-dependent parameter, ϵ, and are also expressed as power series in

$$\ln^{-1}\left(\frac{L}{z_0}\right)$$

and

$$\ln^{-1}\left(\frac{l}{z_0}\right)$$

where L is a horizontal length scale for the terrain and l is the inner-layer vertical scale (see Walmsley et al., 1982). Only zero-order terms in these series appear in the MS3DJH model. This corresponds to the use of uniform advection velocities $u_0(L)$ and $u_0(l)$ in the approximations to the linearized outer- and inner-layer perturbation momentum equations. Here, $u_0(z)$ is the assumed velocity profile in the undisturbed, upstream flow. We will assume a logarithmic profile,

$$u_0(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0},$$

for the present computations, where u_* is the friction velocity, κ is the von Kármán constant, and z is the altitude. Version 1.5 of the model can be regarded as an approximation to version 2 as described by Walmsley et al. It gives essentially the same results with a substantial saving in computer time.

The basic inputs to the model are the wind direction, an estimate of surface roughness length and a detailed contour map of the area. In the central part of the domain used by the model, the terrain map is carefully digitized, while in the outer portions it is smoothed and blended into a surrounding flat plain; see Salmon et al. (1981) for details. In the application to the Vizcaino Point Peninsula on San Nicolas Island a total domain size of 768 m × 768 m was used with 3-m grid spacing. The inner region within which the terrain is faithfully represented is a circle of radius 194 m, centered on the tower site (or more specifically at the location for the sensors on the fully extended horizontal arms of the tower). The topography of the inner region is shown in Fig. 9. The original high-resolution contour map displayed elevations as low as 0.5 m below mean sea level. The normal variation in extreme tide

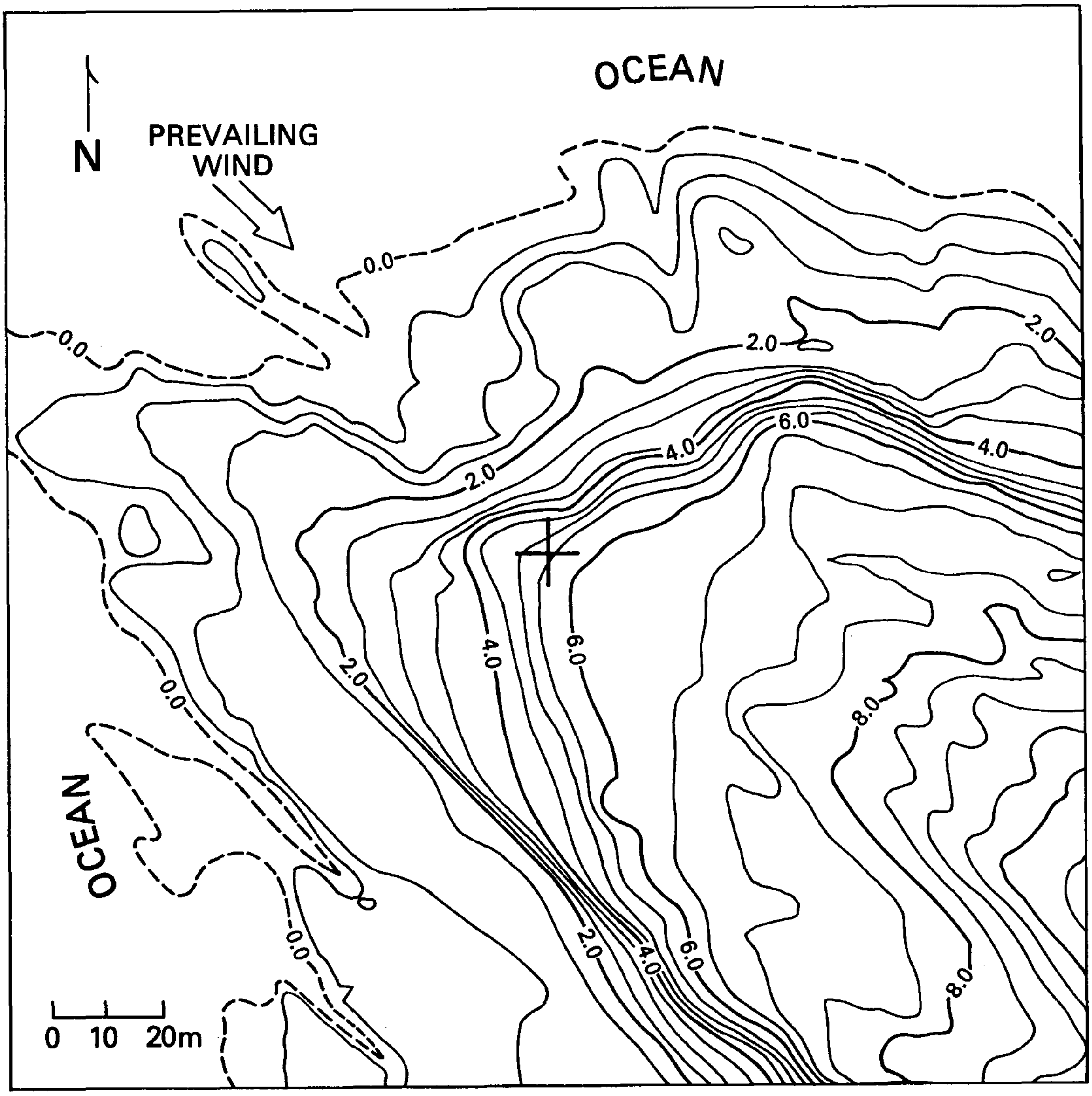

Fig. 9 — A contour map of the central portion of the modeled terrain. The contour intervals are 0.5 m. The dashed line depicts the outline of the peninsula at mean sea level. The cross at the center of the figure indicates the position of the sensor location at the end of the NRL tower arms. The horizontal domain shown is 192 m by 192 m.

heights is ± 1.2 m. As a final step in preparing the topographic input file, the terrain was "flooded" to mean sea level to eliminate any negative elevations over the sea. It should be noted that the model (in its present form) assumes a uniform surface roughness and cannot include changes due to the roughness differences between land and water. A roughness length of 0.01 m was assumed for both the water and the land for the San Nicolas Island computations. The atmospheric stability was assumed to be neutral. The length L, representative of the horizontal scale of the terrain, was set equal to 50 m, which gave an inner-layer depth of 2.83 m. This, in effect, implies that all the levels of interest at the tower site (5 to 35 m) lie in the outer region of the flow and that the perturbations predicted will be fundamentally the same as those that would be predicted by irrotational flow theory. A revised version of the model, version 3.1, is currently under development. Among other changes this calculates blended inner and outer layer solutions and should give better representation of the solutions in the outer layer. Test computations for the San Nicholas Island site with this model suggest that the MS3DJH/1.5 computations may overestimate the wind-speed amplification (unperturbed wind speed amplification = 1.0) by as much as 30 to 50% at the upper levels.

SAMPLE RESULTS

While our prime concern is with wind-speed and wind-direction perturbations at the sensor locations, it is instructive to consider the overall picture for a larger portion of the experiment site. Sample results for a wind direction of 015° for the terrain map shown in Fig. 9, are given in Figs. 10 to 13. Figures 10 through 12 show the normalized wind speeds at 5, 10, and 35 m above the terrain. The

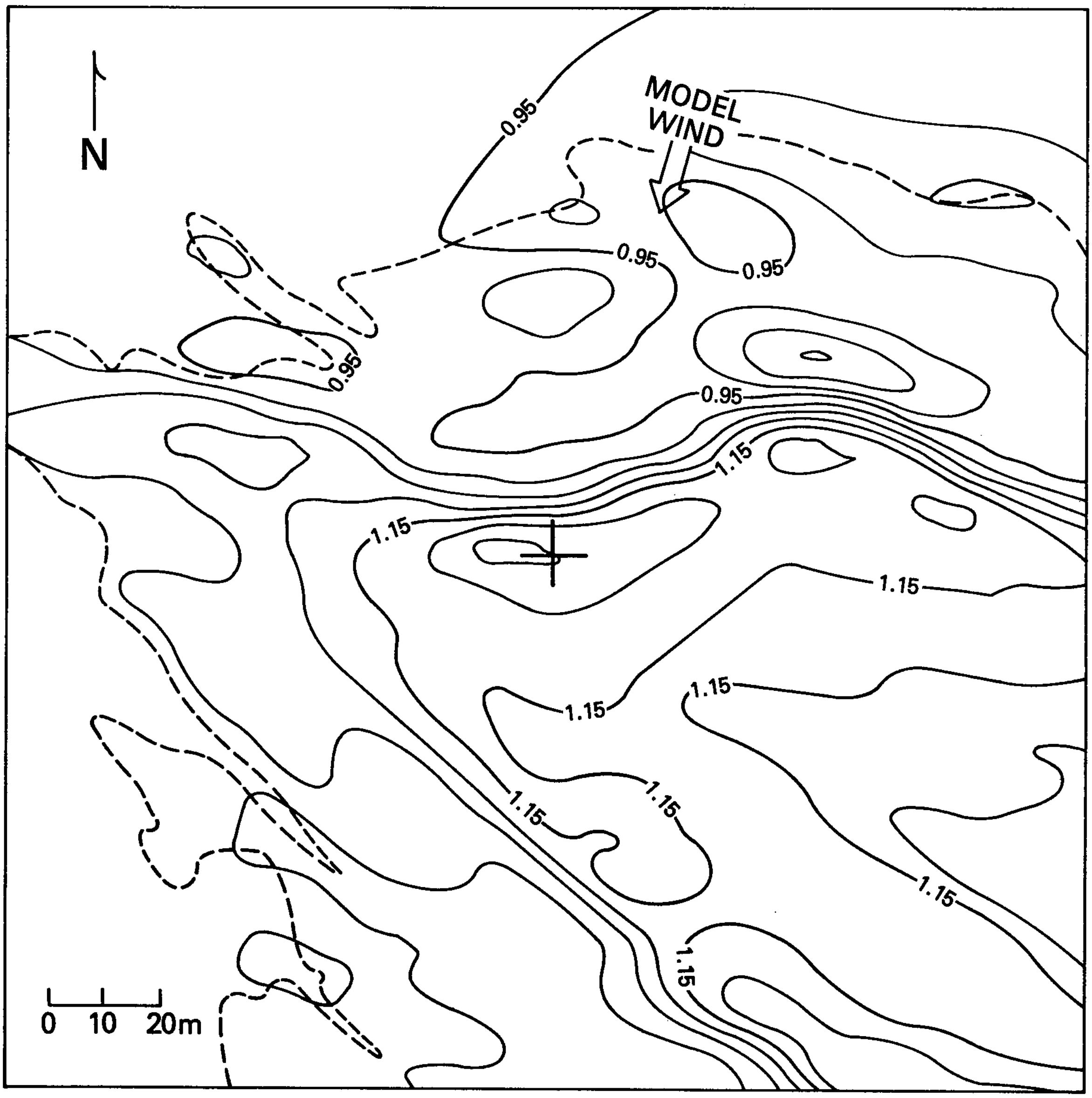

Fig. 10 — Wind speed amplification results for the MS3DJH/1.5 model at an altitude of 5 m, as referenced to the terrain beneath the end of the NRL tower arms, for a wind direction of 15° (true). The wind speed amplification isopleth intervals are 0.05. Wind speed upwind of island = wind speed observed at the island/amplification. The horizontal domain shown is the same as in Fig. 9. The dashed line shows the outline of the peninsula at mean sea level. The cross at the center of the figure denotes the sensor location at the end of the tower arms.

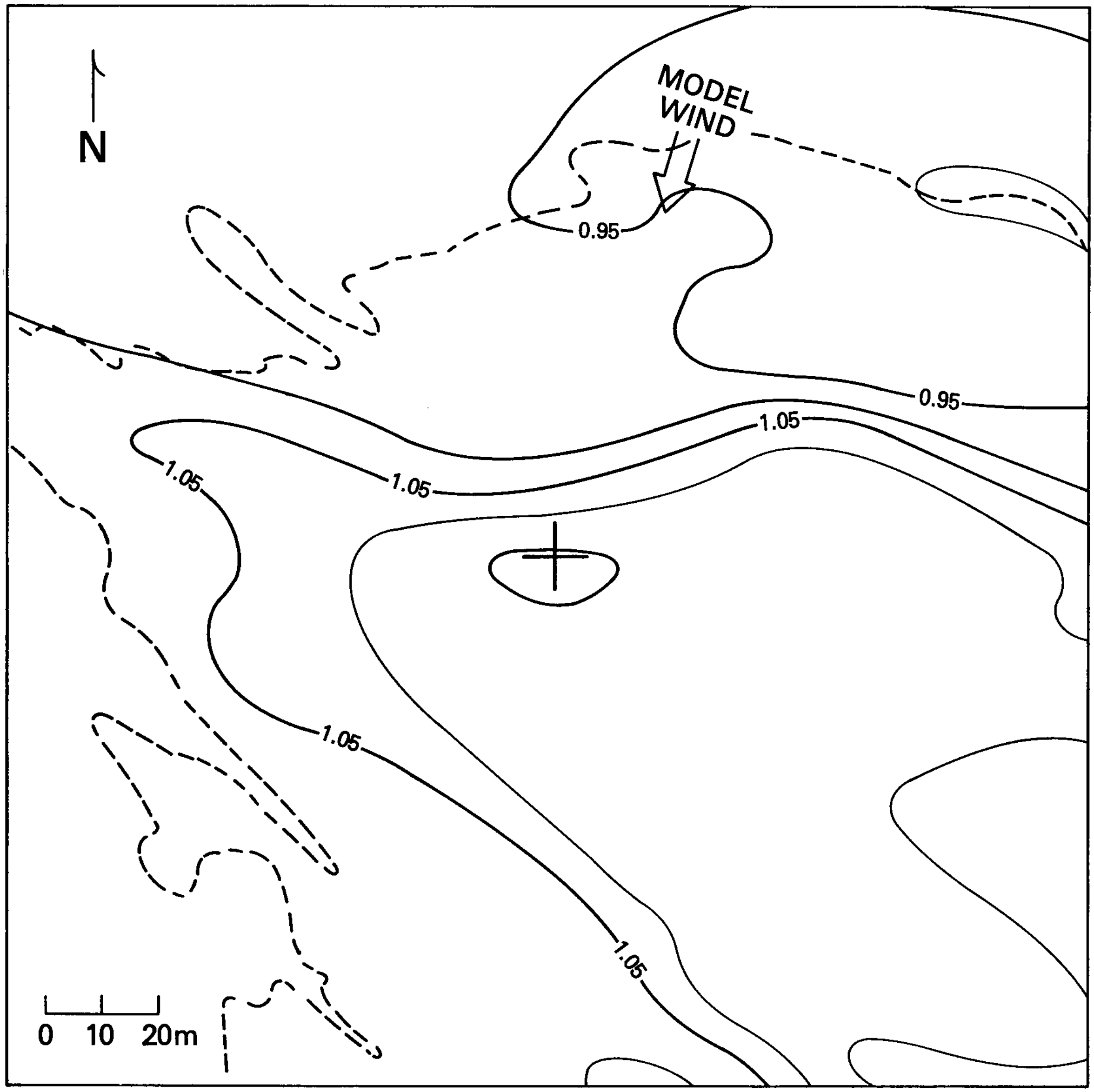

Fig. 11 — Same as Fig. 10 except for an altitude of 10 m

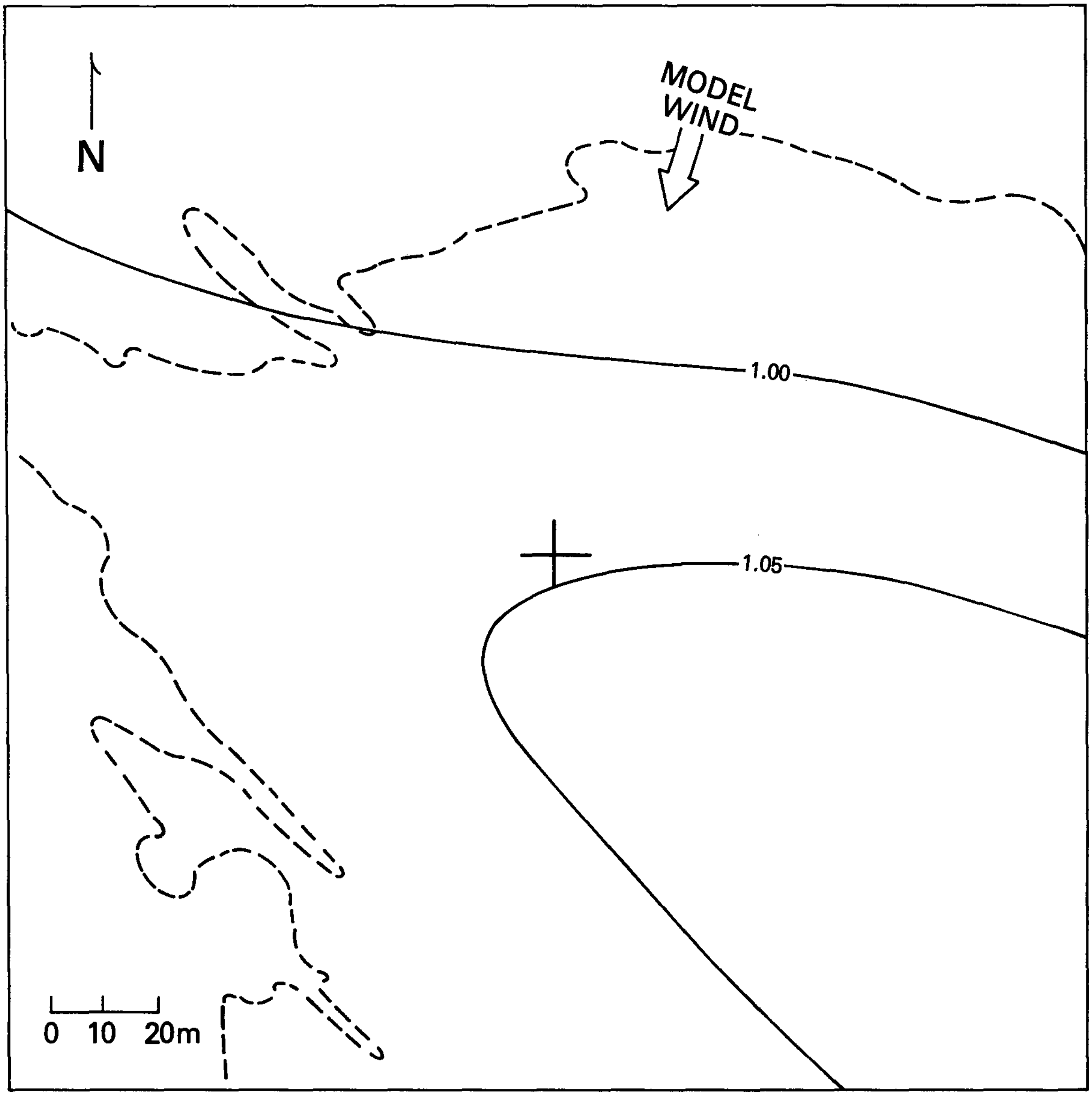

Fig. 12 — Same as Fig. 10 except for an altitude of 35 m

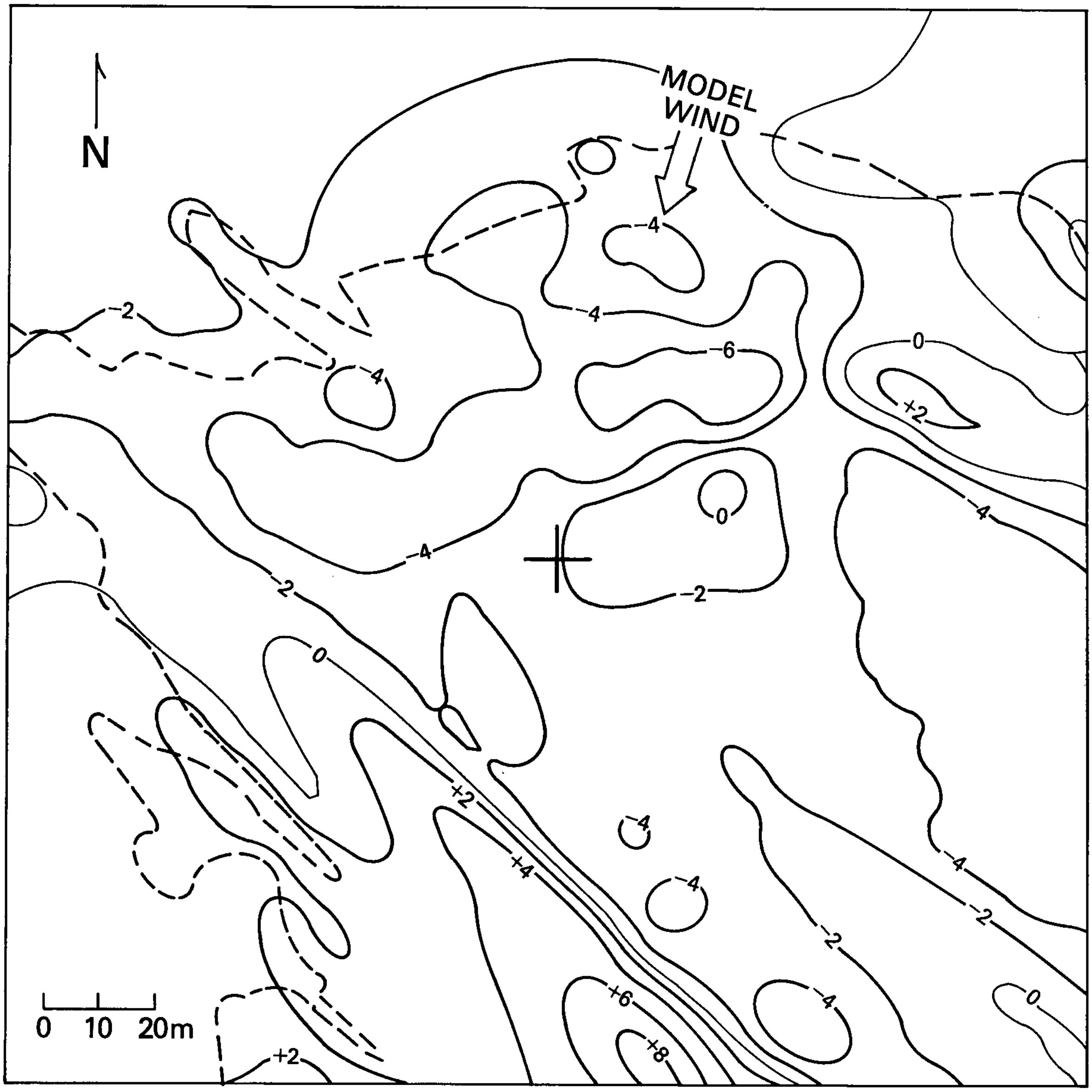

Fig. 13 — Same as Fig. 10 except wind direction perturbation results for an altitude of 5 m. The isopleth intervals are 2°. Wind direction upwind of the island = wind direction observed at the island + perturbation.

undisturbed, upstream flow is a logarithmic profile (neutrally stable) with $z_0 = 0.01$ m. At the 5-m level we can note the general relation between the terrain and the wind speeds. The magnitude of the perturbations falls quickly with height as can be seen from Figs. 11 and 12 with a maximum wind-speed amplification of only 1.08 at the 35-m level.

We can also see a shift in the location of the wind-speed maximum from the top of the near-shore escarpment at the 5-m level to the higher ground to the southeast (where the peninsula joins the rest of this island) at the 35-m level. Wind-direction perturbations at the 5-m level are shown in Fig. 13. The extreme perturbations are about −6° and +8° and occur close to the steepest parts of the terrain. There is a general tendency for the flow to deflect slightly to either side of the promontory. In Fig. 13 a positive value is an anticlockwise deflection of the wind vector from its undisturbed direction as observed from the perspective of the wind (left to right as observed from the perspective of the figure).

SUMMARY OF RESULTS

The results of the Atmospheric Environment Service calculations using the MS3DJH/1.5 model for sensors located at (or above) the end of the sensor arms on the Naval Research Laboratory's tower are presented in Tables 1 and 2 as a function of onshore wind direction and altitude. The model computations presented in the first two tables assumed that the tide height is at mean sea level, the horizontal scale length (L) is 50 m, the roughness (z_0) for both the sea and the island is 0.01 m, and the atmosphere is neutrally stable. The results of the site survey for the distances between the tower and the water's edge are presented in Table 3 as a function of wind direction and tide height.

Table 1 — Escarpment-Induced Wind-Speed Amplifications for the NRL Tower on the Northwest Point of San Nicolas Island at Mean Sea Level as a Function of Altitude and Wind Direction. Boldface values were calculated using the AES model, all others were interpolated logarithmically with altitude and linearly with wind direction. Wind speed upwind of the island = wind speed observed at the NRL tower/wind-speed amplification. For unperturbed wind speeds, amplification = 1.000.

Altitude Above the Beach Escarpment[*] (m)		Wind-Speed Amplification																		
z	ln *z*	225[†] (SW)	235	245	255	265 (W)	275	285	295	305	315 (NW)	325	335	345	355 (N)	5	15	25	35	45 (NE)
35	3.56	**1.058**	1.052	1.046	**1.040**	1.031	1.020	**1.009**	1.005	1.001	**0.997**	1.003	1.010	**1.016**	1.026	1.036	**1.046**	1.050	1.054	**1.058**
34	3.53	1.060	1.054	1.047	1.041	1.032	1.021	1.009	1.005	1.001	0.997	1.003	1.011	1.017	1.027	1.038	1.048	1.052	1.056	1.060
33	3.50	1.062	1.055	1.049	1.042	1.033	1.021	1.010	1.006	1.002	0.997	1.004	1.011	1.018	1.028	1.039	1.050	1.054	1.058	1.062
32	3.47	1.064	1.057	1.051	1.044	1.033	1.022	1.010	1.006	1.002	0.998	1.004	1.012	1.019	1.030	1.041	1.052	1.056	1.060	1.064
31	3.43	1.066	1.059	1.052	1.045	1.034	1.023	1.010	1.006	1.002	0.998	1.005	1.013	1.020	1.031	1.042	1.054	1.058	1.062	1.066
30	3.40	1.068	1.061	1.054	1.046	1.035	1.023	1.011	1.006	1.002	0.998	1.005	1.014	1.021	1.032	1.044	1.056	1.060	1.064	1.068
29	3.37	1.070	1.063	1.056	1.048	1.036	1.024	1.011	1.007	1.003	0.998	1.006	1.014	1.022	1.034	1.046	1.058	1.062	1.066	1.070
28	3.33	1.073	1.065	1.057	1.049	1.037	1.025	1.012	1.007	1.003	0.998	1.006	1.015	1.023	1.035	1.048	1.060	1.064	1.069	1.073
27	3.30	1.075	1.067	1.059	1.051	1.038	1.025	1.012	1.007	1.003	0.999	1.007	1.016	1.024	1.037	1.050	1.062	1.066	1.071	1.075
26	3.26	1.077	1.069	1.061	1.052	1.039	1.026	1.013	1.008	1.004	0.999	1.007	1.017	1.026	1.038	1.052	1.065	1.069	1.073	1.077
25	3.22	**1.080**	1.071	1.063	**1.054**	1.040	1.027	**1.013**	1.008	1.004	**0.999**	1.008	1.018	**1.027**	1.040	1.054	**1.067**	1.071	1.076	**1.080**
24	3.18	1.083	1.074	1.065	1.056	1.042	1.028	1.014	1.009	1.005	1.000	1.009	1.020	1.029	1.043	1.057	1.070	1.074	1.079	1.083
23	3.14	1.087	1.077	1.068	1.058	1.043	1.029	1.015	1.010	1.006	1.001	1.011	1.022	1.032	1.045	1.060	1.074	1.078	1.083	1.087
22	3.09	1.090	1.080	1.071	1.060	1.045	1.031	1.016	1.011	1.007	1.002	1.012	1.024	1.034	1.048	1.064	1.078	1.082	1.086	1.090
21	3.04	1.094	1.083	1.073	1.063	1.047	1.032	1.016	1.012	1.007	1.003	1.014	1.026	1.037	1.051	1.067	1.082	1.086	1.090	1.094
20	3.00	1.098	1.087	1.076	1.065	1.049	1.034	1.017	1.013	1.008	1.004	1.015	1.028	1.039	1.054	1.071	1.086	1.090	1.094	1.098
19	2.94	1.102	1.090	1.079	1.067	1.051	1.035	1.018	1.014	1.009	1.005	1.017	1.030	1.042	1.058	1.074	1.090	1.094	1.098	1.102
18	2.89	1.106	1.094	1.082	1.070	1.053	1.037	1.019	1.015	1.010	1.006	1.019	1.032	1.045	1.061	1.078	1.095	1.099	1.102	1.106
17	2.83	1.111	1.098	1.086	1.073	1.055	1.038	1.021	1.016	1.012	1.007	1.021	1.035	1.048	1.065	1.083	1.099	1.103	1.107	1.111
16	2.77	1.116	1.102	1.089	1.076	1.057	1.040	1.022	1.018	1.013	1.009	1.023	1.037	1.051	1.069	1.087	1.105	1.109	1.112	1.116
15	2.71	**1.121**	1.107	1.093	**1.079**	1.060	1.042	**1.023**	1.019	1.014	**1.010**	1.025	1.040	**1.055**	1.073	1.092	**1.110**	1.114	1.117	**1.121**
14	2.64	1.128	1.113	1.098	1.083	1.064	1.045	1.025	1.021	1.017	1.013	1.029	1.045	1.061	1.079	1.099	1.118	1.121	1.124	1.128
13	2.56	1.135	1.119	1.104	1.088	1.067	1.048	1.027	1.024	1.019	1.016	1.033	1.050	1.067	1.086	1.106	1.126	1.130	1.132	1.135
12	2.48	1.143	1.126	1.110	1.093	1.072	1.051	1.030	1.026	1.022	1.019	1.037	1.055	1.073	1.094	1.115	1.135	1.138	1.140	1.143
11	2.40	1.152	1.134	1.116	1.098	1.076	1.054	1.032	1.029	1.025	1.022	1.042	1.061	1.080	1.102	1.123	1.145	1.148	1.149	1.152
10	2.30	**1.161**	1.142	1.123	**1.104**	1.081	1.058	**1.035**	1.032	1.029	**1.026**	1.047	1.067	**1.088**	1.111	1.133	**1.156**	1.158	1.159	**1.161**
9	2.20	1.173	1.153	1.132	1.112	1.087	1.063	1.038	1.036	1.034	1.031	1.053	1.074	1.095	1.121	1.145	1.170	1.172	1.172	1.173
8	2.08	1.187	1.165	1.142	1.120	1.094	1.068	1.042	1.040	1.039	1.037	1.060	1.081	1.104	1.132	1.159	1.187	1.187	1.186	1.187
7	1.95	1.202	1.178	1.154	1.130	1.102	1.074	1.046	1.045	1.044	1.043	1.067	1.090	1.113	1.144	1.174	1.205	1.204	1.203	1.202
6	1.79	1.220	1.194	1.167	1.141	1.111	1.081	1.051	1.051	1.051	1.051	1.076	1.099	1.124	1.158	1.192	1.226	1.224	1.222	1.220
5	1.61	**1.241**	1.212	1.183	**1.154**	1.122	1.089	**1.057**	1.058	1.059	**1.060**	1.086	1.111	**1.137**	1.175	1.213	**1.251**	1.248	1.244	**1.241**

[*]As measured from below the end of the fully extended sensor arms of the NRL tower. Zero altitude is 5.5 m above mean sea level.

[†]Upwind wind direction (degrees, true). True direction equals magnetic direction plus 15°.

Table 2 — Escarpment-Induced Wind-Direction Perturbations for the NRL Tower on the Northwest Point of San Nicolas Island at Mean Sea Level as a Function of Altitude and Wind Direction. Boldface values were calculated using the AES model, all others were interpolated logarithmically with altitude and linearly with wind direction. Wind direction upwind of the island = wind direction observed at the NRL tower + wind-direction perturbation.

Altitude Above the Beach Escarpment* (m)		Wind-Direction Perturbation (deg)																		
z	ln z	225† (SW)	235	245	255	265	275 (W)	285	295	305	315 (NW)	325	335	345	355	5 (N)	15	25	35	45 (NE)
35	3.56	**0.2**	0.7	1.1	**1.6**	1.5	1.4	**1.4**	0.9	0.3	**−0.2**	−0.7	−1.1	**−1.6**	−1.5	−1.4	**−1.3**	−0.8	−0.3	**0.2**
34	3.53	0.2	0.7	1.1	1.6	1.5	1.5	1.4	0.9	0.3	−0.2	−0.7	−1.2	−1.6	−1.6	−1.5	−1.4	−0.8	−0.3	0.2
33	3.50	0.3	0.7	1.2	1.6	1.6	1.5	1.5	0.9	0.3	−0.3	−0.7	−1.2	−1.7	−1.6	−1.5	−1.4	−0.9	−0.3	0.2
32	3.47	0.3	0.7	1.2	1.7	1.6	1.6	1.5	0.9	0.3	−0.3	−0.8	−1.3	−1.7	−1.6	−1.5	−1.4	−0.9	−0.3	0.3
31	3.43	0.3	0.8	1.3	1.7	1.7	1.6	1.5	0.9	0.3	−0.3	−0.8	−1.3	−1.8	−1.7	−1.6	−1.5	−0.9	−0.3	0.3
30	3.40	0.3	0.8	1.3	1.8	1.7	1.6	1.6	0.9	0.3	−0.3	−0.8	−1.3	−1.9	−1.7	−1.6	−1.5	−0.9	−0.3	0.3
29	3.37	0.3	0.8	1.4	1.9	1.8	1.7	1.6	0.9	0.3	−0.3	−0.9	−1.4	−1.9	−1.8	−1.6	−1.5	−0.9	−0.3	0.3
28	3.33	0.4	0.9	1.4	1.9	1.8	1.7	1.6	1.0	0.3	−0.4	−0.9	−1.4	−2.0	−1.8	−1.7	−1.6	−0.9	−0.3	0.3
27	3.30	0.4	0.9	1.4	2.0	1.9	1.8	1.7	1.0	0.3	−0.4	−0.9	−1.5	−2.0	−1.9	−1.7	−1.6	−1.0	−0.3	0.4
26	3.26	0.4	1.0	1.5	2.0	1.9	1.8	1.7	1.0	0.3	−0.4	−1.0	−1.5	−2.1	−1.9	−1.8	−1.6	−1.0	−0.3	0.4
25	3.22	**0.4**	1.0	1.5	**2.1**	2.0	1.9	**1.7**	1.0	0.3	**−0.4**	−1.0	−1.6	**−2.2**	−2.0	−1.8	**−1.7**	−1.0	−0.3	**0.4**
24	3.18	0.5	1.0	1.6	2.2	2.0	1.9	1.8	1.0	0.3	−0.5	−1.1	−1.7	−2.2	−2.0	−1.9	−1.7	−1.0	−0.3	0.4
23	3.14	0.5	1.1	1.7	2.3	2.1	2.0	1.8	1.0	0.2	−0.5	−1.1	−1.7	−2.3	−2.1	−1.9	−1.7	−1.0	−0.3	0.5
22	3.09	0.6	1.2	1.7	2.3	2.2	2.0	1.8	1.0	0.2	−0.6	−1.2	−1.8	−2.4	−2.2	−2.0	−1.7	−1.0	−0.2	0.5
21	3.04	0.6	1.2	1.8	2.4	2.2	2.1	1.9	1.0	0.2	−0.6	−1.2	−1.9	−2.5	−2.2	−2.0	−1.8	−1.0	−0.2	0.6
20	3.00	0.7	1.3	1.9	2.5	2.3	2.1	1.9	1.0	0.2	−0.7	−1.3	−1.9	−2.6	−2.3	−2.1	−1.8	−1.0	−0.2	0.6
19	2.94	0.7	1.3	2.0	2.6	2.4	2.2	2.0	1.1	0.2	−0.8	−1.4	−2.0	−2.7	−2.4	−2.1	−1.8	−1.0	−0.2	0.7
18	2.89	0.8	1.4	2.1	2.7	2.5	2.2	2.0	1.1	0.1	−0.8	−1.5	−2.1	−2.8	−2.5	−2.2	−1.9	−1.0	−0.1	0.7
17	2.83	0.8	1.5	2.1	2.8	2.6	2.3	2.1	1.1	0.1	−0.9	−1.5	−2.2	−2.9	−2.5	−2.2	−1.9	−1.0	−0.1	0.8
16	2.77	0.9	1.6	2.2	2.9	2.6	2.4	2.1	1.1	0.1	−0.9	−1.6	−2.3	−3.0	−2.6	−2.3	−1.9	−1.0	−0.1	0.9
15	2.71	**1.0**	1.6	2.3	**3.0**	2.7	2.5	**2.2**	1.1	0.0	**−1.0**	−1.7	−2.4	**−3.1**	−2.7	−2.4	**−2.0**	−1.0	−0.1	**0.9**
14	2.64	1.0	1.8	2.5	3.2	2.8	2.5	2.2	1.1	−0.0	−1.1	−1.8	−2.5	−3.2	−2.8	−2.4	−2.0	−1.0	0.0	1.0
13	2.56	1.2	1.9	2.6	3.3	3.0	2.6	2.2	1.1	−0.1	−1.3	−2.0	−2.7	−3.4	−2.9	−2.5	−2.0	−1.0	0.1	1.1
12	2.48	1.3	2.0	2.7	3.5	3.1	2.7	2.3	1.1	−0.2	−1.4	−2.1	−2.8	−3.6	−3.1	−2.6	−2.1	−1.0	0.1	1.2
11	2.40	1.4	2.1	2.9	3.7	3.2	2.8	2.3	1.0	−0.3	−1.5	−2.3	−3.0	−3.7	−3.2	−2.6	−2.1	−0.9	0.2	1.4
10	2.30	**1.5**	2.3	3.1	**3.9**	3.4	2.9	**2.4**	1.0	−0.3	**−1.7**	−2.4	−3.2	**−3.9**	−3.3	−2.7	**−2.1**	−0.9	0.3	**1.5**
9	2.20	1.7	2.5	3.3	4.1	3.5	3.0	2.4	1.0	−0.5	−1.9	−2.7	−3.4	−4.1	−3.5	−2.8	−2.2	−0.9	0.4	1.7
8	2.08	1.9	2.7	3.5	4.3	3.7	3.1	2.5	1.0	−0.6	−2.2	−2.9	−3.7	−4.4	−3.7	−2.9	−2.2	−0.8	0.5	1.9
7	1.95	2.1	2.9	3.8	4.6	4.0	3.3	2.6	0.9	−0.8	−2.4	−3.2	−3.9	−4.7	−3.9	−3.0	−2.2	−0.8	0.7	2.1
6	1.79	2.3	3.2	4.1	5.0	4.2	3.4	2.6	0.9	−1.0	−2.7	−3.5	−4.3	−5.0	−4.1	−3.2	−2.2	−0.7	0.9	2.4
5	1.61	**2.6**	3.5	4.5	**5.4**	4.5	3.6	**2.7**	0.8	−1.2	**−3.1**	−3.9	−4.6	**−5.4**	−4.4	−3.3	**−2.3**	−0.6	1.1	**2.7**

*As measured from below the end of the fully extended sensor arms of the NRL tower. Zero altitude is 5.5 m above mean sea level.
†Upwind wind direction (degrees, true). True direction equals magnetic direction plus 15°.

Table 3 — Horizontal Distance over the Beach from the Water's Edge to the NRL Tower* on the Northwest Point of San Nicolas Island as a Function of Tide Height and Wind Direction. Values are integrated over ±5° and are based upon low-altitude aerial survey of February 1982. Normal tide extremes are ±1.2 m from mean sea level. Boldface values were obtained from the survey, all others are linearly interpolated. The lowest elevation observed at the time of the aerial survey was −0.5 m.

Tide Height from Mean Sea Level† (m)	Horizontal Distance (m)																		
	225‡ (SW)	235	245	255	265 (W)	275	285	295	305	315 (NW)	325	335	345	355 (N)	5	15	25	35	45 (NE)
−1.0	118	115	111	92	82	84	127	136	161	156	121	121	90	91	98	92	90	100	98
−0.9	117	111	108	91	82	83	122	133	155	146	116	115	87	88	94	90	88	98	97
−0.8	116	107	105	90	81	82	117	129	149	137	111	108	84	85	90	87	87	96	95
−0.7	116	103	101	90	81	82	113	126	142	127	105	102	81	81	87	85	85	94	94
−0.6	115	99	98	89	80	81	108	122	136	118	100	95	78	78	83	82	84	92	92
−0.5	**114**	**95**	**95**	**88**	**80**	**80**	**103**	**119**	**130**	**108**	**95**	**89**	**75**	**75**	**79**	**80**	**82**	**90**	**91**
−0.4	113	91	92	87	80	79	98	116	124	98	90	83	72	72	75	78	80	88	90
−0.3	112	87	89	86	79	78	93	112	118	89	85	76	69	69	71	75	79	86	88
−0.2	112	83	85	86	79	78	89	109	111	79	79	70	66	65	68	73	77	84	87
−0.1	111	79	82	85	78	77	84	105	105	70	74	63	63	62	64	70	76	82	85
0	**110**	**75**	**79**	**84**	**78**	**76**	**79**	**102**	**99**	**60**	**69**	**57**	**60**	**59**	**60**	**68**	**74**	**80**	**84**
0.1	105	74	76	80	76	75	77	98	96	59	63	54	58	57	59	66	73	79	83
0.2	101	73	73	76	74	74	75	93	92	59	57	51	56	54	58	63	72	79	81
0.3	96	73	69	72	72	74	73	89	89	58	50	48	54	52	56	61	71	78	80
0.4	92	72	66	68	70	73	71	84	85	58	44	45	52	49	55	58	70	78	78
0.5	**87**	**71**	**63**	**64**	**68**	**72**	**69**	**80**	**82**	**57**	**38**	**42**	**50**	**47**	**54**	**56**	**69**	**77**	**77**
0.6	82	69	63	64	67	70	67	77	81	56	36	39	46	44	53	56	67	76	76
0.7	78	68	62	63	66	67	64	74	80	54	34	35	41	42	51	55	64	76	76
0.8	73	66	62	63	66	65	62	72	80	53	31	32	37	39	50	55	62	75	75
0.9	69	65	61	62	65	62	59	69	79	51	29	28	32	37	48	54	59	75	75
1.0	**64**	**63**	**61**	**62**	**64**	**60**	**57**	**66**	**78**	**50**	**27**	**25**	**28**	**34**	**47**	**54**	**57**	**74**	**74**
1.1	60	59	57	58	60	58	56	65	74	45	27	24	27	32	45	54	56	73	73
1.2	56	55	53	54	56	56	55	63	70	40	26	24	25	29	43	53	55	72	72
1.3	52	50	49	51	53	53	54	62	67	35	26	23	24	27	40	53	54	70	71
1.4	48	46	45	47	49	51	53	60	63	30	25	23	22	24	38	52	53	69	70
1.5	**44**	**42**	**41**	**43**	**45**	**49**	**52**	**59**	**59**	**25**	**25**	**22**	**21**	**22**	**36**	**52**	**52**	**68**	**69**

*Distance measured from the end of the fully extended 6.7-m-long tower sensor arms, which point toward the northwest.

†Mean sea level (MSL) equals mean lower level water (MLLW) plus 0.76 m.

‡Upwind wind direction (degrees, true). True direction equals magnetic direction plus 15°.

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