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Basic Studies of Flow and Diffusion Over Hills

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BASIC STUDIES OF FLOW AND DIFFUSION OVER HILLS

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ABSTRACT

This research program was initiated with the overall objectives of gaining a better understanding of flow and diffusion of pollutants in complex terrain under both neutral and stably stratified conditions, providing a sound data base for testing existing theories and developing new theories of flow and diffusion around isolated hills and ridges. To this end, experiments were conducted with models of a bell shaped hill and a 2-D steep ridge in EPA's meteorological wind tunnel and salt-water stratified towing tanks. Measurements were made of the flow structure, as well as the concentration patterns around the hills due to point sources located at different heights and positions relative to the hills.

The experiments on stably stratified flow over a 3-D hill verify and establish the limits of applicability of Drazin's theory for small Froude numbers. The location of the surface impingement point from an upwind pollutant source can be identified under a wide range of atmospheric conditions.

The experiments on the neutral boundary layer flow over a 2-D ridge show that significant ridge effect is felt by turbulence structure to distances greater than eighty ridge heights downstream. Ground-level concentrations in the lee of the ridge are very sensitive to the source height and position relative to the ridge.

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CONTENTS

FIGURES

SYMBOLS

$f(r)$ -- height of hill as a function of radius

F -- Froude number $\equiv U_\infty/Nh$

F_L -- Froude number $\equiv U_\infty/NL$

g -- acceleration due to gravity

h -- maximum height of hill or ridge

H_d -- height of the dividing streamline or plume impingement

H_s -- source height above the level surface

L -- half-length of the hill in x-direction

N -- Brunt-Vaisala frequency = $(\frac{g}{\rho}\frac{\partial \rho}{\partial z})^{\frac{1}{2}}$

r -- radial coordinate in horizontal plane

$\overline{u}$ -- mean velocity in x-direction

u' -- velocity fluctuation in x-direction

$\overline{U}(h)$ -- mean velocity at z = h in the absence of hill

U_∞ -- ambient uniform velocity

w' -- velocity fluctuation in z-direction

x -- longitudinal coordinate axis; also the distance from the hill

x_s -- distance of the source from the ridge

z -- vertical coordinate

$\Delta\overline{u}_{max}$ -- maximum perturbation in mean velocity

$\Delta(-\overline{u'w'})_{max}$ -- maximum perturbation in the Reynolds stress

$\Delta(\overline{u'^2})_{max}$ -- maximum perturbation in the variance of longitudinal velocity fluctuations

$\Delta(\overline{w'^2})_{max}$ -- maximum perturbation in the variance of vertical velocity fluctuations

θ -- angle in the polar (r, θ, z) coordinate system

λ -- wavelength of lee wave

ρ -- density

χ -- normalized concentration

δ -- boundary layer thickness

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SECTION 1

INTRODUCTION

A series of laboratory experiments on neutral and stably stratified flows over isolated topographical features was conducted in 1977 under a grant from the Environmental Protection Agency. For these experiments, we used the meteorological wind tunnel, salt-water stratified towing tank and other support facilities and instrumentation of the EPA Fluid Modeling Facility in Research Triangle Park, NC. This report gives a summary of the research work done. More detailed and fuller descriptions are given in the following technical reports and papers:

1. "Flow structure and turbulent diffusion around a three-dimensional hill - Fluid modeling study on effects of stratification, Part I - Flow Structure". By J.C.R. Hunt, W.H. Snyder and R.E. Lawson, Jr. U.S. EPA Report EPA-600/4-78-041, Environmental Sciences Research Laboratory, Research Triangle Park, NC.

2. "Flow structure and turbulent diffusion around a three-dimensional hill - Fluid modeling study on effects of stratification, Part II - Surface concentrations due to upstream sources". By J.C.R. Hunt and W.H. Snyder, EPA report under preparation.

3. "A model study of boundary layer flow and diffusion over a ridge". By S.P.S. Arya and M.S. Shipman; Preprints, Fourth Symposium on Turbulence, Diffusion and Air Pollution, January 15-18, 1979, Reno, Nevada, American Meteorological Society, pp. 584-591, 1979.

In addition to the work reported above, Dr. J.C.R. Hunt also authored or co-authored the following papers while working on this project:

4. "A review of the theory of rapidly distorted turbulent flows and its applications". By J.C.R. Hunt, paper presented at XIII Biennial Fluid Dynamics Symposium - Advanced Problems and Methods in Fluid Dynamics, Warsaw, Poland, September 5-10, 1977.

5. "Turbulent diffusion from sources near obstacles with separated wakes. Part I. An eddy diffusivity model". By J.S. Puttock and J.C.R. Hunt. J. Fluid Mech., 1978.

6. "Distortion of turbulence by a circular cylinder." By R. E. Britter, J. C. R. Hunt and J. C. Mumford. J. Fluid Mech., 92, 269-301, 1979.

7. "A Lagrangian statistical analysis of diffusion from a ground-level sorce in a turbulent boundary layer." By J. C. R. Hunt and A. H. Weber. Quart. J. Roy. Meteor. Soc., 105, 423-443, 1979.

8. "Highway modeling. Part I: Prediction of velocity and turbulence fields in the wake of vehicles." By R. E. Eskridge and J. C. R. Hunt. J. Appl. Meteor., 18, 387-400, 1979.

9. "Highway modeling. Part II: Advection and diffusion of SF_6 tracer gas. By R. E. Eskridge, F. S. Binkowski, J. C. R. Hunt, T. L. Clark and K. L. Demerjian. J. Appl. Meteor., 18, 401-412, 1979.

SECTION 2

CONCLUSIONS

The most significant conclusions that can be drawn from our physical modeling studies of flow and diffusion over an isolated bell-shaped hill and a 2-D steep triangular ridge are as follows.

Flow and Diffusion Around a 3-D Hill

1. For the stratified flow past an isolated hill, the criteria for the occurrence and location of separation on the lee side are governed by the gross slope of the hill and the ratio of the wavelength of lee waves to the length of the hill in the direction of flow. For hills of moderate slopes, the Froude number (F) essentially governs the phenomena of separation, hydraulic jump, lee waves and rotors.

2. The Froude number based on the hill height (h) also determines the criterion of whether the approach flow at some level will go over the top of the hill, or it will go around the sides. According to our flow visualization studies, the height of the dividing streamline $H_d \simeq h(1-F)$, which gives a simple criterion for the impingement of plumes from upwind sources. If the source height (H_s) is smaller than $h(1-F)$ and the source is located on the stagnation streamline, then the plume will impact on the hill surface, bifurcate, and go around the sides, causing probably the highest ground-level concentrations (g.l.c.) along the area of impaction. However, slow oscillations in the flow direction will cause the area of impingement to increase and hence lower the maximum concentration.

3. When $F < 1$, and $H_s \leq h$, the ratio of the maximum concentration on the surface of the hill to the maximum concentration in the plume in the absence of the hill lies between 0.5 and 1.2; for $F > 1$, the above ratio decreases rapidly with increasing Froude number.

4. If a plume goes over the hill, its vertical width is reduced by the converging streamlines in the vertical plane, and the lateral width is amplified by the divergence in the horizontal plane. There is also an indirect effect due to the density gradient being increased by the convergence of streamlines in the vertical plane.

Flow and Diffusion Over a Steep Ridge

1. The separation bubble or cavity region behind the ridge extends to a distance of 13h in the longitudinal direction and 2.5h in the vertical and is characterized by greatly reduced but circulating mean flow and very high intensities of turbulence.

2. Beyond the cavity region there is an extensive wake region whose height varies as $x^{\frac{1}{2}}$. It is also characterized by reduced mean flow and increased turbulence, but the perturbations caused by the ridge decay monotonically with distance (x) behind the ridge.

3. The maximum perturbations in the mean velocity, the Reynolds stress and variances of velocity fluctuations in the wake all decay with distance as x^{-1}, while the heights of maxima vary as $x^{\frac{1}{2}}$. Even for this ridge of low height (about 1/10 of the boundary layer thickness), the perturbations caused by the ridge are very large in the near wake region and remain significant to a distance of as large as 80h.

4. When an elevated source of height $\geq$ h is located upwind of the ridge or at the ridge top, the effect of the ridge is generally to reduce g.l.c. downwind of the ridge. For the ground sources, however, a good part of the plume may impinge on the separation streamline and get trapped in the cavity region, so that the maximum g.l.c. in the cavity region may become much larger than the g.l.c. at the same distance in the absence of the ridge. Thus the ground-level concentrations downwind of the ridge are very sensitive to both the source height and its position relative to the ridge.

5. When the source is located downwind of the ridge, the increased turbulence in the wake results in much lower concentrations aloft, but higher concentrations at the ground-level. The highest ground-level concentrations occur when the source is located within the cavity region near the base of the ridge. The peak g.l.c. decreases and its position shifts farther downwind from the source, as the source height and its distance from the ridge increase.

SECTION 3

EXPERIMENTS AND APPARATUS

The experiments were conducted in the towing tanks and the meteorological wind tunnel of the EPA Fluid Modeling Facility. In towing tanks, models of three-dimensional polynomial hills were towed at various speeds and for various degrees of stable stratification. In the wind tunnel two types of experiments were conducted to study (1) the flow and diffusion over and around a three-dimensional hill of height much larger than the surface boundary layer thickness, and (2) the flow and diffusion over a two-dimensional ridge of height much less than the surface boundary layer thickness. The wind tunnel experiments corresponded to neutral stability.

3.1 LARGE TOWING TANK EXPERIMENTS

The large towing tank is 25m long, 2.4m wide and 1.2m deep. A towing carriage mounted on rails allows models to be towed the length of the tank at variable speeds between 5 and 50cm/sec. The tank can be filled layer by layer with salt water to obtain a desired stable density profile in about four hours (Thompson and Snyder, 1976). The density profiles are measured by withdrawing samples from various depths in the tank and measuring their specific gravity with precision hydrometers or an electronic balance.

The 3-D model hill was made of an acrylic plastic sheet by vacuum molding onto a wooden former. The hill profile was close to a fourth order polynomial

$$f(r) = h/[1+(\frac{r}{L})^4],$$

where h is the maximum height in the center and L is a horizontal length scale of the hill such that at $r = L$, $f(r) = h/2$. With our particular choice of $h = L \approx 0.23$m, the bell-shaped hill had a maximum slope of about unity. The hill was mounted on a flat base plate and towed upside-down across the water surface. Twenty-eight sampling ports were fixed on the surface of the hill along each of the radial lines $\theta = 0, -90, -165$ and $180°$.

Flow visualization

As part of our study of diffusion and dispersion over the polynomial hill, a neutrally buoyant dye was emitted from a model stack located at 4h upstream of the center of the hill. The stack height H_s was varied from 0 to 1.2h. In other tests, dye was released from the surface sampling ports on the windward and leeward hill lines ($\theta = 180°$ and $0°$) to study the surface flow patterns, or alternately, through an injection rake emitting dye at several levels above ground to study the centerplane streamlines.

Color photographs and motion pictures were taken of the surface dye releases and black and white photographs were taken of the upstream multi-level dye releases. In some cases, shadowgraphs were taken of the flow patterns behind the hill.

In order to visualize the surface flow patterns, granules of potassium permanganate ($KMnO_4$) were cemented to the hill surface. These granules dissolved rather slowly as the hill was towed through the tank, yielding bright purple streamers indicating the surface flow patterns.

One series of tests was run for various combinations of stratifications and stack heights in order to determine (a) whether the plume went over the hill or around it, (b) the impingement height (H_d) where the maximum concentration on the upstream centerline on the hill surface is expected to occur, and (c) the streamline deflection at the side of the hill ($\theta = -90°$). Samples were drawn during the tow simultaneously through all the surface ports. The collected sample jars were then visually inspected to determine which contained the highest concentration of dye.

Concentration measurements

In our studies of diffusion and dispersion from a model stack upstream of the hill, the ground-level concentrations on the hill were measured by drawing samples of the dye mixed fluid through the various ports on the hill surface. For concentration measurements in the wake of the hill, the samples were collected by drawing the fluid through sampling ports of the rake, whose height and lateral position were adjusted as desired. Dye concentrations in the collected samples were measured by passing a beam of light through a test tube filled with the sampled fluid and measuring the intensity of the light coming on the other side of the tube by means of a photo cell.

In order to bring out the effect of the hill, the concentration measurements were also made in the absence of the hill for the same stratifications and for the same source heights as used in the hill study.

3.2 SMALL TOWING TANK EXPERIMENTS

In the large towing tank the residual flow requires about an hour to settle down after a tow, and it takes at least two hours to change a model. For some quick qualitative experiments a small towing tank was found to be more desirable. Smaller tank was also considered more suitable for flow visualization with hydrogen bubbles. We used a 2.0m long, 0.20m wide and 0.10m deep tank. The tank was filled with a stratified salt solution with specific gravity varying from 1.0 at the surface to 1.2 at the bottom. Model hills were mounted on a base plate suspended from a carriage and towed at speeds ranging from 2 to 25cm/sec. The polynomial hill used here had about the same shape as the large hill, but only 2cm in height.

Surface stress patterns

Shear stress patterns on the surface were observed by coating the hill model with a gelatinous solution of dye and KNOX brand gelatin. As the model was towed, the dye was sheared away in regions of high stress and tended to collect along the stagnation areas, leaving a visual record of the surface flow patterns. Due to certain difficulties, however, this technique was found to be much less satisfactory than the corresponding wind tunnel technique using zinc oxide powder and oil.

Hydrogen bubble visualization

A hydrogen bubble wire system was developed to study the streamline pattern and the velocity field on the centerline of the hill. A 0.025mm diameter chromel thermocouple wire was kinked by running it between two gears. This provided a very uniform spacing of streaks. The bubble size could be varied by varying the current flow through the wire. Photographs were taken with a 35mm camera, and velocities were obtained from these photos by determining the distance between successive bubble streaks.

3.3 WIND TUNNEL EXPERIMENTS

The EPA meteorological wind tunnel (Thompson and Snyder, 1976) has a test section 18m long, 3.7m wide and 2.1m high. The air speed in the test section may be varied from 0.5 to 10m/sec. The tunnel ceiling was adjusted to obtain a zero pressure gradient in the core region.

Two basically different types of experiments were conducted in the wind tunnel. In the first category a three-dimensional polynomial hill identical to that used in the large towing tank was placed near the entrance to the test section. The boundary layer over the smooth tunnel floor was approximately 65mm thick at the center of the hill (but in the absence of it) of height 230mm.

In the second category of experiments in the wind tunnel, a symmetric triangular ridge of the height to base ratio of unity was placed within an artificially thickened turbulent boundary layer developed on the rough tunnel floor. The ridge height of 0.1m was about 1/10 the undisturbed boundary layer thickness at the location of the ridge (8.2m from the entrance). The boundary layer was artifically thickened by placing a 0.15m fence at the entrance to the test section.

In both cases, measurements were made of the mean velocity, variances of the longitudinal and vertical velocity fluctuations and the Reynolds stress at various positions in the boundary layers with respect to the hill. With a point or line source located at various positions upstream and downstream of the ridge, measurements were also made of the longitudinal ground-level concentrations as well as of the lateral and vertical concentration distributions. Similar measurements were made in the absence of the hill or the ridge.

Mean velocity and turbulence measurements

Turbulence measurements were made with two hot-film anemometers whose outputs were digitized and processed on a PDP 11/40 minicomputer. Averaging time of one minute was found to yield reasonably repeatable results. Probes were calibrated next to a pitot tube in the free stream flow in the core section of the wind tunnel. A computer program calculated the average velocity $\overline{u}$, the longitudinal and vertical velocity variances $\overline{u'^2}$ and $\overline{w'^2}$, the Reynolds stress $-\overline{u'w'}$ and the flow angle.

Flow visualization

A paraffin oil-fog generator was used to produce smoke for the qualitative flow visualization studies. In this generator, paraffin oil is aspirated onto a heating element which creates a fine oil-fog. A separate air supply then carries the smoke into the wind tunnel.

One phase of this study involved visualization of smoke emitted from the stack upstream of the hill. Plume centerlines were traced from photographs at various stack heights in order to obtain an idea of the centerline streamline pattern over the hill.

Photographs were also taken of the smoke being emitted at low speed through the surface sampling ports to obtain an idea of the surface flow pattern. Finally, drops of titanium tetrachloride were placed at various positions on the hill surface. This created a dense white smoke that was also helpful for understanding the surface flow pattern.

Concentration measurements

The source used in the wind tunnel was an air-methane or air-ethylene mixture emitted as a tracer gas located at various heights and positions with respect to the hill. Concentrations were measured at each selected position by passing a sample of air mixed with tracer gas through a Beckman Model 400 Hydrocarbon Analyzer. The sampling rate and source parameters were fixed on the basis of previous experiments (Huber and Snyder, 1976; Huber et al, 1976) using the same system.

SECTION 4

RESULTS AND DISCUSSION

Here we present only a summary of our experimental results, which have been discussed in considerably more detail in our other reports referred to earlier in section 1.

4.1 FLOW AROUND A 3-D HILL

Flow Visualizations

Hunt et al (1978) have presented photographs of various types of flow visualizations around the polynomial or bell-shaped hill for various values of Froude number in the range 0.2 to ∞. Here the Froude number, $F = U_\infty/Nh$, is based on the ambient flow speed or towing speed U_∞, the hill height h and the Brunt-Vaisala frequency

$$N = \left(\frac{g}{\rho}\frac{\partial\rho}{\partial z}\right)^{\frac{1}{2}} .$$

For illustration purposes, shadowgraphs of flow at various values of F are shown in Figure 1.

At low Froude numbers ($F = 0.1 - 0.2$), the flow is constrained to move in essentially horizontal planes around the hill, except in a narrow region near the hill top where it can go over the top. In the middle region, the centerline plume bifurcates after its impingement on the upstream face of the hill, it dips slightly as it goes around the sides, then rises again as it separates from the surface of the hill. Separation occurs at an angle of approximately 110° from the upstream stagnation line. The wake region behind the hill has more of a 2-D rather than 3-D character; it has a symmetric pair of more or less vertically oriented vortices. The flow structure and the observed streamline deflections in going around the sides of the hill are found to be consistent with Drazin's (1961) theory, which is asymptotically valid for $F \to o$. This theory breaks down, however, within a distance of the order of Fh from the submit. In this top region the flow is largely three dimensional and the streamline passing over the submit separates within a short distance on the lee side followed by the appearance of a slight hydraulic jump (see Figure 1).

As the Froude number is increased, beyond 0.2 the region where the flow goes over the top becomes increasingly broader, the separation of the centerline streamline passing over the hill top occurs farther and farther downstream, and the hydraulic jump becomes more prominent (Figure 1). At $F = 0.9$, almost all the flow in the center-plane goes over the top of the hill, and does not separate until well beyond the lee side base of the hill. At $F = 1.0$, however, the flow is again at the verge of separating just past the top of the hill.

As the Froude number is increased farther ($F > 1$), the flow separates near the top of the hill, the size of the cavity or recirculating region grows and the wake region also grows in both the lateral and vertical directions. At $F = 1.7$, there is a strong resemblance with the neutral flow ($F = \infty$) except that in the slightly stratified case the streamlines are more closely spaced and they lose elevation much faster in the wake region than those in the neutral flow.

Smoke visualization in the wind tunnel ($F = \infty$) show the plumes to spread broadly to cover the entire hill surface. Flow separates slightly upwind of the top and there is up-slope flow on the lee side of the hill. The mean velocity vectors show significant vertical components as far as 2h upstream and well above the level of the summit. Directly above the hill top and on the sides, however, the vertical components are essentially zero.

Criteria for Separation

An important consideration is the existence and position of the separation of flow on the lee side of hill. Flow separation is expected to be governed by the gross slope (h/L) of the hill, as well as by the ratio of the fundamental wavelength of the lee waves ($\lambda = 2\pi U_\infty/N$) to the half length of the hill (typically, 2L). The latter ratio is proportional to the Froude number $F_L = U_\infty/LN$, defined on the basis of the length scale L.

When the gross slope is small ($h/L \ll 1$), separation is not likely to occur and when it is large ($h/L \gg 1$), separation is almost certain to occur. For hills of moderate slopes ($h/L \simeq 1$), as in our case, the occurrence and location of separation is critically dependent on the Froude number $F_L \simeq F$. When the stratification is such that $\lambda \simeq 2L$, separation of the flow over a rounded hill ($h/L \lesssim 1$) will be suppressed. If these two lengths (λ and 2L) differ considerably from each other, separation would occur on hills of moderate slope. If $\lambda \ll 2L$ (or, $F_L \ll 1$), separation is controlled by the pressure distribution produced by the lee wave pattern. But, if $\lambda \gg 2L$ (or, $F_L \gg 1$), separation on the hill is controlled by the boundary layer flow. These criteria for the occurrence of separation have been suggested by recent experimental and theoretical work on stratified flow over 2-D hills (Brighton, 1977; Sykes, 1978). Our experimental results for the 3-D polynomial hill with $h/L = 1$ are found to be in general agreement with the above criteria.

4.2 DIFFUSION AROUND A 3-D HILL

Plume Growth and Impingement

The flow patterns not only indicate the path of the center line of the plume but also its growth in the vertical and the lateral directions.

Observations of plumes in the absence of the hill clearly show that the stronger the stratification, the narrower becomes its vertical dimension and the wider becomes its lateral dimension.

Over the hill the vertical plume width is reduced by the streamlines converging in the vertical plane, and the horizontal width is amplified by the divergence in the horizontal plane. There is also an indirect effect due to the density gradient being increased by the convergence of the streamlines in the vertical plane. For a plume starting upstream the latter effect mainly reduces the growth of the plume width (σ_z), while the former effect actually reduces the width of the plume.

In stably stratified flows around 3-D hills, of great practical importance is the height H_d of the dividing streamline, above which the flow goes over the hill and below which it goes around the sides. The criterion for determining whether the plume will impact on the hill surface and go around the sides is given by the relation $H_d \approx h(1 - F)$, which was suggested by Hunt et al (1978) on the basis of Drazin's (1961) theory and confirmed by our towing tank experiments. If the plume height upstream, which is the same as the source height H_s, is smaller than $h(1 - F)$, the plume will impact on the hill surface; otherwise it will go over the top. The former situation is likely to result in the highest ground-level concentrations.

Although no source was placed downstream of the hill in our experiments, it is evident from the mainly horizontal circulation patterns in strongly stratified flow ($F < 0.3$) that a plume below $h(1 - F)$ would also impinge on the hill surface. For weaker stratifications, the plume could also be brought down to the ground as a result of lee waves and rotors induced by the hill.

Concentration Distributions

Because it was of considerable interest to compare concentrations measured on the hill with those in the plume in the absence of the hill, the baseline concentration distributions in the plume were measured for the same source heights and Froude numbers. The lateral concentration profiles are very close to Gaussian. The vertical profiles for large stack heights ($H_s > 0.5h$) are roughly Gaussian, but for the smaller stack heights they are not Gaussian, as one would expect. Since there is a turbulent boundary layer growing along the base plate, the concentration profiles for the sources inside and outside this boundary layer are quite different.

With the hill in place, concentrations were measured on the hill surface along various sectors. Concentrations were also measured in the wake region downstream of the hill, the height and the lateral position of the sampling rake being adjusted to measure maximum concentrations. At low Froude numbers, the lateral concentration profiles in the wake show two distinct maxima - one on each side of the wake, due to the plume impinging on the surface, going around the sides and separating from the surface. At large Froude numbers there is greater vertical and horizontal mixings and the concentration is approximately constant in the whole cavity region.

Of considerably greater interest is the ratio of the maximum concentration χ_{max} on the surface of the hill to the concentration χ_o in the center of the plume in the absence of the hill. The broadest conclusion we could draw is that when $F \leq 1$ and $H_s < h$, χ_{max}/χ_o lies between 0.5 and 1.2. When $F > 1$ and $H_s > 0.5h$, the ratio χ_{max}/χ_o decreases rapidly with increasing F.

At low values of F, when $H_s < H_d$ (the height of impingement), the maximum concentration occurs at the upstream face. A small displacement of the source off the stagnation streamline does not change the magnitude of χ_{max}, but generally moves its location to the side of the hill. Thus slow oscillations in the flow direction, whether caused by the wake or upstream eddying, affect the plume upwind of the hill so as to increase its area of impingement on the hill and hence lower the maximum concentration.

4.3 BOUNDARY LAYER FLOW OVER A STEEP RIDGE

Distributions of mean velocity, the Reynolds stress and variances of velocity fluctuations in the absence of the ridge were quite typical of a well-developed equilibrium boundary layer. The surface stress did not change noticeably with distance along the tunnel floor.

Mean Flow

When a symmetric ridge of slope 2:1 was placed at the floor in the middle of the test section, the boundary layer thickness (δ) increased somewhat, but it remained more or less constant ($\delta \simeq 10h$) behind the ridge. As expected, the flow separated at the ridge top and reattached to the surface at a distance of about 13h. The recirculating cavity or bubble region is comparable, in size and shape, to that behind a normal bluff plate.

The mean velocity profiles at various positions relative to the ridge indicate that, in the lower layer, the flow decelerates slightly as it approaches the ridge, accelerates by about 10% while passing over the ridge and then considerably decelerates in the wake region behind the ridge. With increasing distance (x) behind the ridge, the height of the wake grows as $x^{\frac{1}{2}}$, and so does the height of the maximum deficit (as compared to the case of no ridge) in the mean velocity. The velocity deficit in the wake decreases in inverse proportion to the distance from the ridge and, surprisingly, it takes a distance of more than 80h for a full recovery of the undistrubed velocity profile (see Figure 2).

Turbulence Structure

Changes in the Reynolds stress and the variances of velocity fluctuations are rather insignificant upwind of the ridge. But, in the wake behind the ridge turbulence is greatly enhanced. The vertical profiles of the Reynolds stress and velocity variances in the wake are all characterized by a maximum whose position moves gradually upwards with increasing distance from the ridge. The maximum perturbation in each of these quantities are found to decrease in inverse proportion to the distance (see Figure 3), similar to the variation of the mean velocity deficit. Even at a distance of 80h, the maximum perturbations in Reynolds stress and velocity variances caused by the ridge remain as large as the maximum values of these quantities in the undisturbed boundary layer. Thus the effect of a steep ridge on turbulence structure in its wake may persist for long distances.

The vertical distributions of the perturbation stress and variances are qualitatively very similar. The positions of maxima in their profiles at a given distance from the ridge lie within one ridge height of each other.

4.4 DIFFUSION OVER A STEEP RIDGE

Diffusion measurements were made in both the disturbed and the undisturbed boundary layers using the same point source. The ground-level concentrations (g.l.c.) downstream of the ridge are found to be very sensitive to the source height (H_s) and its location (x_s) relative to the ridge.

Source Upwind of the Ridge

For a point source or stack located upwind of the ridge, the surface concentration increases as the source is brought closer to the ridge and they decrease with the increase in source height. The concentrations in the cavity region are by no means uniform and seem to depend on where and how much of the plume comes in contact with the separation streamline.

Source at the Ridge Top

With a source located at the ridge top, the lateral diffusion on the lee side of the ridge is enhanced considerably. The width of the plume at the ground level at a distance 10h downwind of the ridge is about twice the width of the plume at the same distance from the source without the ridge.

The vertical concentration profiles are also considerably modified by the ridge. For an elevated source, the vertical profiles downwind show a substantial plumerise. The concentration profiles in the cavity region are remarkably uniform (see also Huber et al, 1976). The maximum concentrations in the presence of ridge are 1/3 to 1/2 of the maximum values in the absence of the ridge.

Source Downwind of the Ridge

For a source located in the cavity region, significant ground-level concentrations are found both upwind (relative to the overall flow direction) and downwind of the source. The position of the maximum g.l.c. is generally found to be some distance (depending on the source height) downwind of the source. For a near ground-level source, however, the recirculating flow towards the ridge in the lower part of the cavity may cause the maximum g.l.c. to occur slightly upwind of the source. The maximum concentration decreases rapidly as the source height is increased.

When the source is located outside the cavity region, the maximum g.l.c., for a given source height, decreases with increasing distance of the source from the ridge and the position of the maximum shifts farther away from the source. Thus the main effect of the ridge is to considerably enhance the ground-level concentrations.

Figure 4 summarizes the results for the maximum g.l.c. for various source heights and positions, and Figure 5 gives the distance of the maximum g.l.c. from the source. It is seen that the ridge has the most effect when the source is located about 5h downwind of the same and that the ridge effect becomes insignificant when the source is located beyond a distance of about 30h from the ridge.

The vertical concentration profiles in the plume from an elevated source located at about 10h downwind from the ridge are quite different from the concentration profiles taken in the absence of the ridge. The comparison of the two shows that, while the concentrations near the surface are enhanced, those at higher levels are considerably reduced. Thus the increased turbulence in the wake is very effective in diffusing the material down towards the wall region, where there is actually slight reduction in turbulence.

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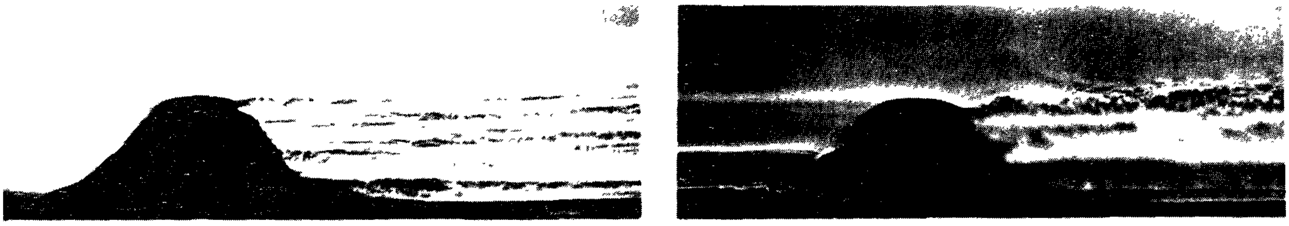
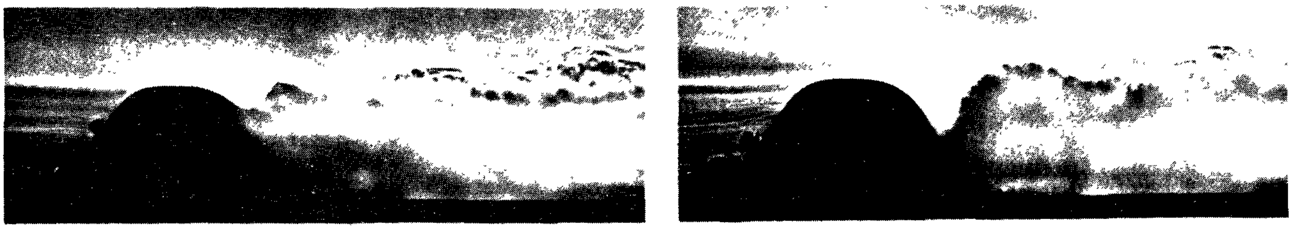


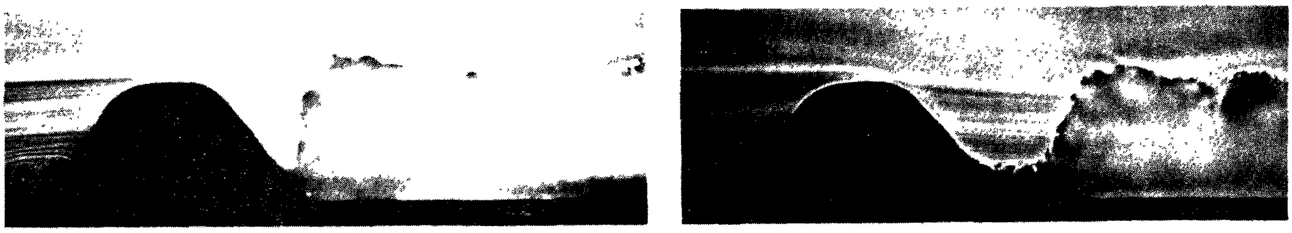
(A) F = 0.1, Re = 6870

(B) F = 0.2, Re = 13740



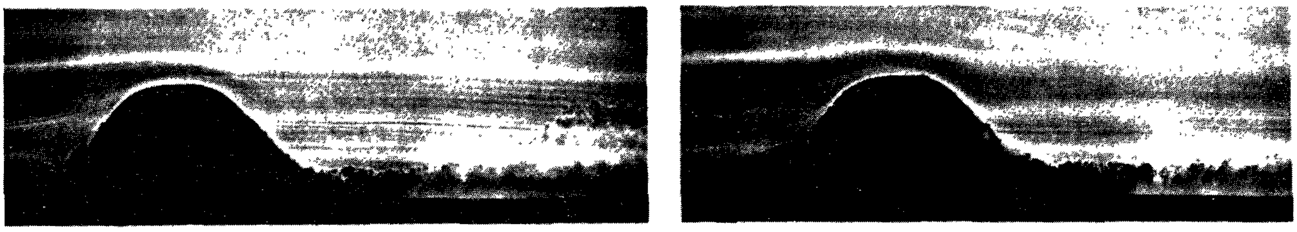
(C) F = 0.3, Re = 20610

(D) F = 0.4, Re = 27480



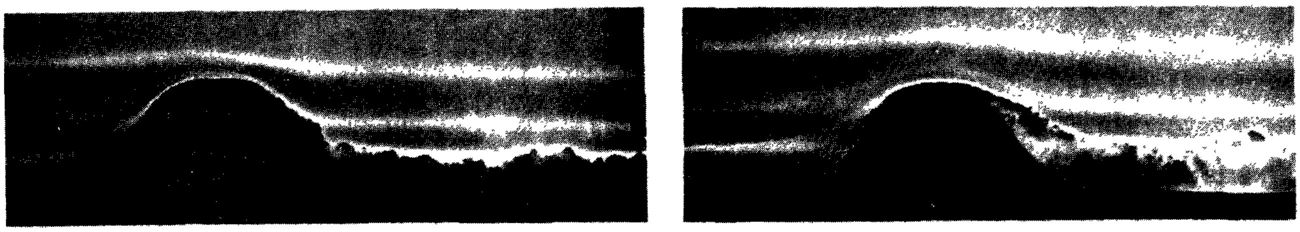
(E) F = 0.5, Re = 34400

(F) F = 0.6, Re = 41200



(G) F = 0.8, Re = 55000

(H) F = 1.0, Re = 68700



(I) F = 1.2, Re = 81600

(J) F = 1.7, Re = 117000

Figure 1. Shadowgraphs of flow over hill (N = 1.33 rad/sec).

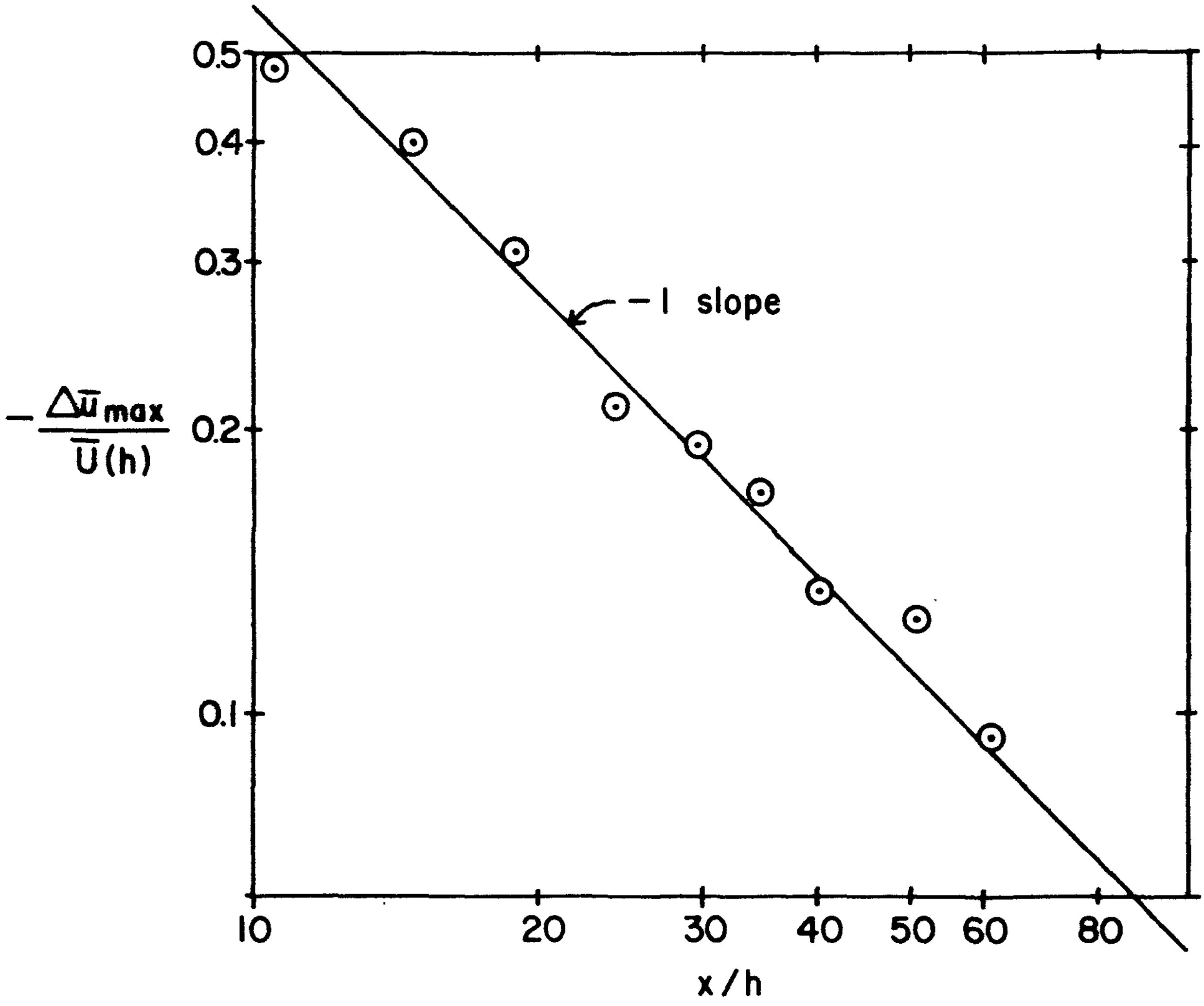


Figure 2. The variation of the maximum deficit in mean velocity in the wake with distance behind the ridge.

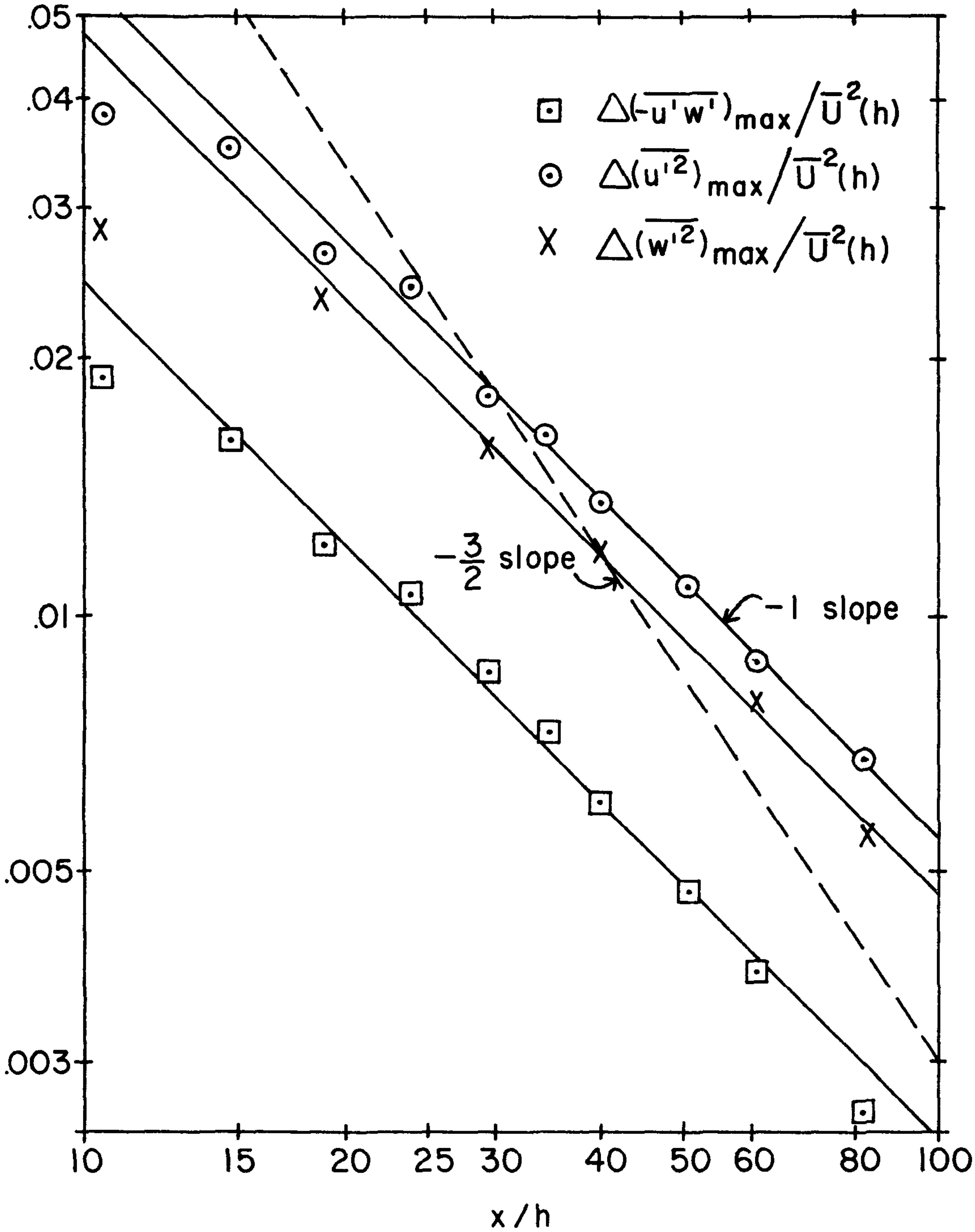


Figure 3. Variations of the maximum perturbations in Reynolds stress and velocity variances in the wake with distance behind the ridge.

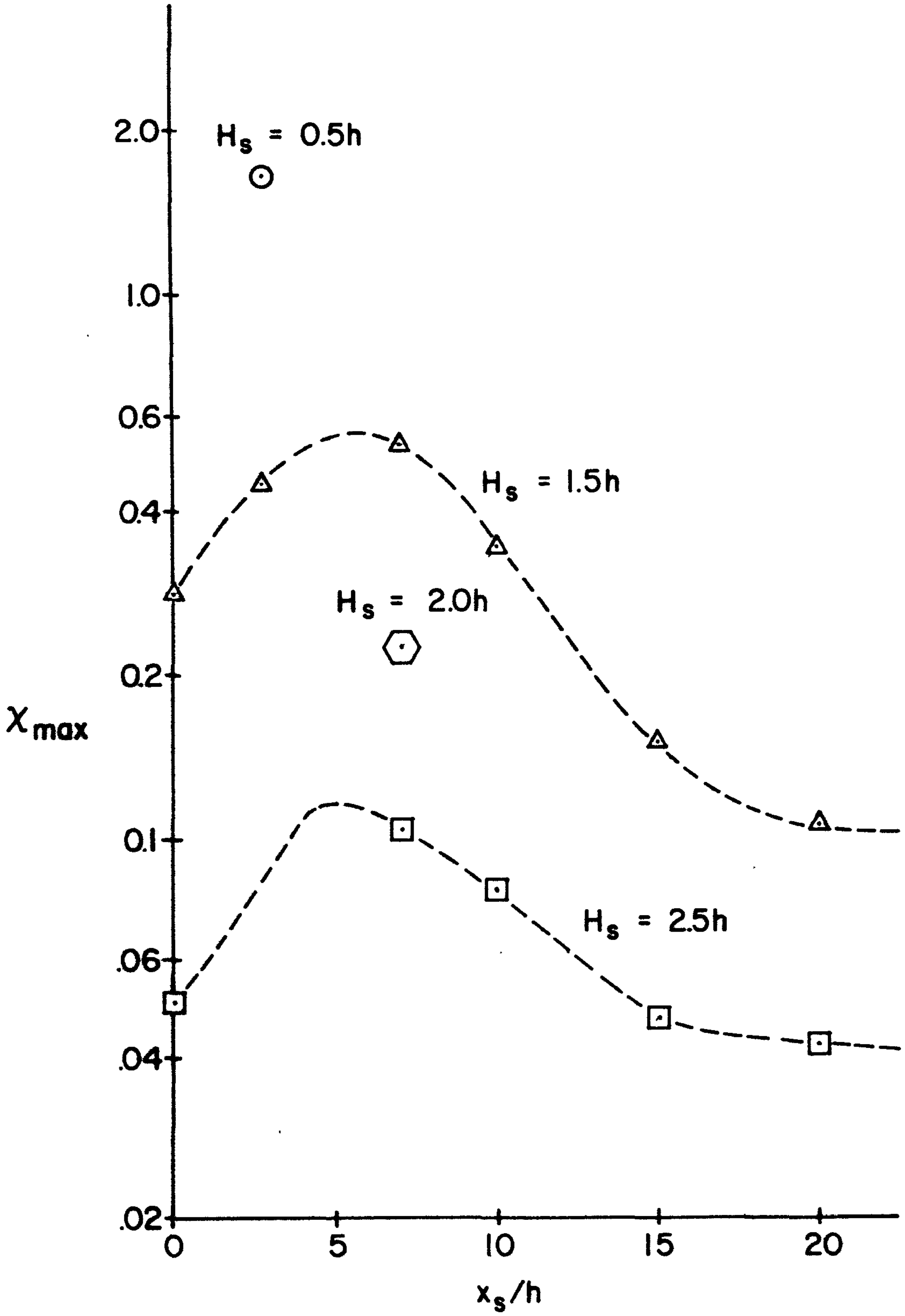


Figure 4. The maximum g.l.c. as a function of source height and its position relative to the ridge.

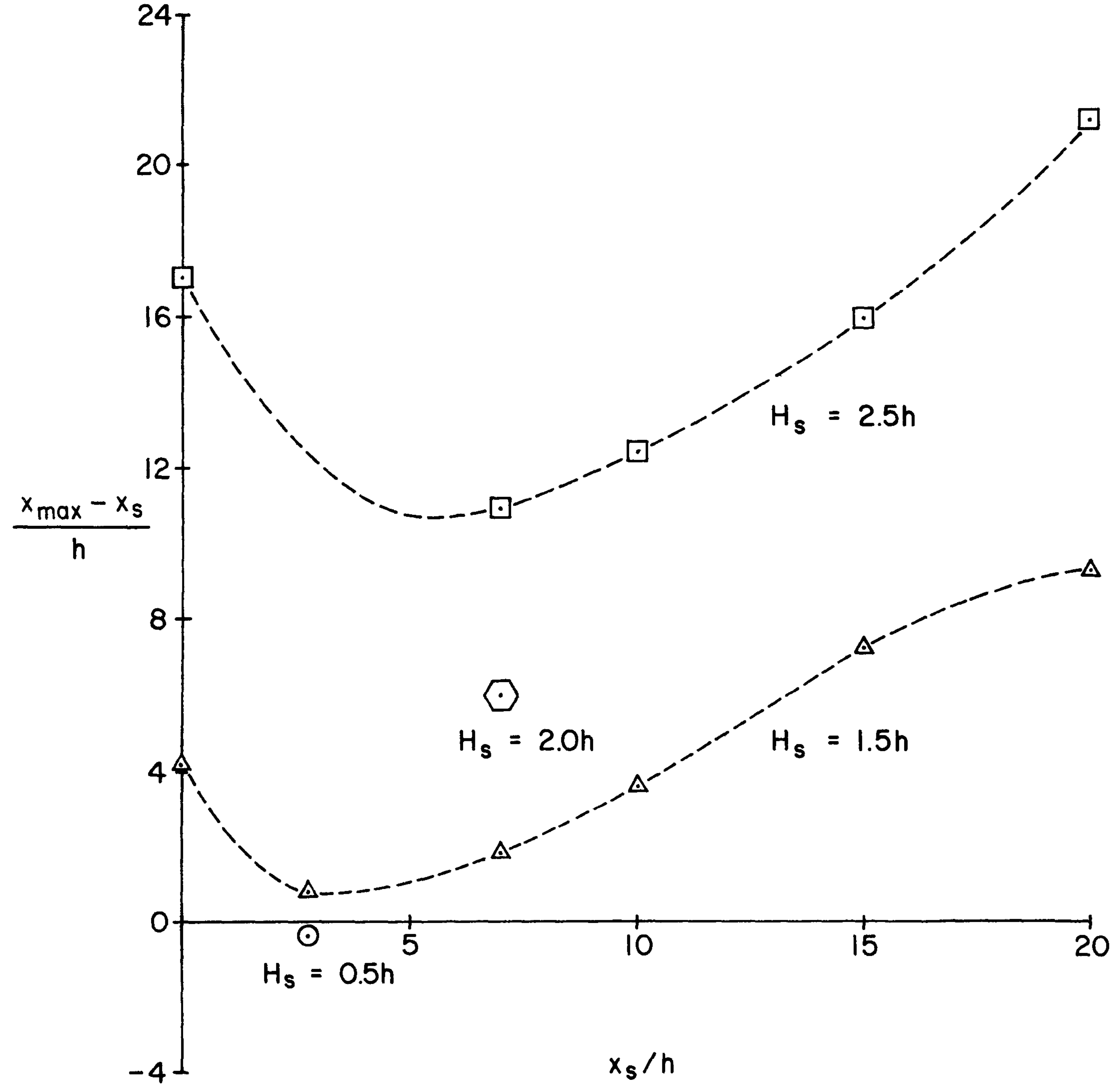


Figure 5. The distance of the maximum g.l.c. from the source as a function of source height and its position relative to the ridge.

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1. University of Cambridge, England

16. ABSTRACT

This research program was initiated with the overall objective of gaining a better understanding of flow and diffusion of pollutants in complex terrain under both neutral and stably stratified conditions, providing a sound data base for testing existing theories and developing new theories of flow and diffusion around isolated hills and ridges. To this end, experiments were conducted with models of a bell shaped hill and a 2-D steep ridge in EPA's meteorological wind tunnel and salt-water stratified towing tanks. Measurements were made of the flow structure, as well as the concentration patterns around the hills due to point sources located at different positions relative to the hills.

The experiments on stably stratified flow over a 3-D hill verify and establish the limits of applicability of Drazin's theory for small Froude numbers. The location of the surface impingement point from an upwind pollutant source can be identified under a wide range of atmospheric conditions.

The experiments on the neutral boundary layer flow over a 2-D ridge show that significant ridge effect is felt by the turbulence structure to distances greater than eighty ridge heights downstream. Ground-level concentrations in the lee of the ridge are very sensitive to the source height and position relative to the ridge.

17. KEY WORDS AND DOCUMENT ANALYSIS

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*Wind (Meteorology)		04B
*Wind Tunnel Models		14B
*Hills		08F
*Atmospheric Diffusion		04A
*Stratification		

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