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STRATIFIED FLOW OVER RIDGES AND VALLEYS

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FLOW VISUALIZATION EXPERIMENTS ON
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1. INTRODUCTION

Meteorological conditions within a valley frequently result from the interaction between local conditions and large scale atmospheric circulations. Local conditions such as nocturnal cooling and confinement by the valley walls tend to produce stable conditions within the valley. Large scale atmospheric circulations produce upper-level winds which sometimes pass over the ridges without disturbing the stable flow within the valley and sometimes sweep down into the valley producing breakup of the stable valley flow. This interaction between the local and ambient flows is determined by the meteorological conditions and the geometry of the valley. However, its exact nature and the importance of the various meteorological and geometric parameters is not well understood.

In laboratory experiments it is not possible to simulate all of the phenomena which affect the flow within a valley. It is especially difficult to simulate Coriolis effects which may be important for large valleys and thermal effects associated with diurnal heating and cooling. However, many aspects of this problem can be studied using nonrotating, isothermal flow over geometrically simple models. This paper summarizes a series of such experiments on the flow over a cosine-shaped ridge and within a valley formed by a pair of such ridges when there is a stable ambient flow normal to the axis of the ridge. Three experimental parameters were varied during the study: the steepness of the ridges, the separation distance between the ridges and the Froude number. A more detailed description of the experiments and an extensive set of photographs are presented in Lee, Lawson and Marsh (1986).

2. EXPERIMENTAL FACILITY AND MODELS

The experiments were conducted in the large stratified towing tank at the EPA Fluid Modeling Facility in Research Triangle Park, North Carolina. A detailed description of this facility is presented in Hunt, Snyder and Lawson (1978). The tank is 1.2 m deep, 2.4 m wide and 22 m long. Arbitrary stable density profiles can be established in the tank using salt water with specific gravity of 1.0 to 1.2. Linear density profiles were used for all of the experiments in this study. The nominal value of the Brunt-Vaisala frequency, $N = [-(g/\rho)(dp/dz)]^{1/2}$, was 1.33 s^{-1} . The Froude number, $F = U/Nh$, was varied by changing the tow speed U which can be varied from 2 to 50 cm/s.

Cross-sections of the models drawn to scale are presented in Fig. 1. Each ridge has a cosine cross-section given by the relation $z = (h/2)[1 + \cos(2\pi x/W)]$ where z is the vertical coordinate and x is the horizontal coordinate measured from the crest of the ridge. Models were built with maximum slopes of 40° , 27° and 13° and are referred to as the steep, intermediate and gentle ridges respectively. Two identical ridges were used for the valley tests, and the separation S between the crests of the ridges was varied over the range of $S/W = 0.75$ to 3 where W is the width of a single ridge. The geometric parameters for all of the models tested are listed in Table 1.

The models were mounted on a baseplate that is 2.8 m long and 2.4 m wide. This baseplate was inverted and mounted beneath a towing carriage which runs along the top of the tank. During a tow the model was upside down and completely submerged, but throughout this paper the experimental procedures and

results are discussed as though the model were in the normal upright position. Each ridge has a constant-cross-section region that is 1 m long with caps on each end. These end caps have the same cross-section as the ridge in vertical planes and a circular cross-section in horizontal planes. In all of the experiments the ridges were mounted normal to the flow. The crest of the upstream ridge was 90 cm from the leading edge of the base plate, and the separation distance between the ridges was varied by moving the downstream ridge. The maximum cross-sectional area along the length of the ridge divided by the product of the ridge height and the tank width was 0.5. Based on previous experiments, Snyder et al. (1984), this blockage is believed to be small enough to avoid interference from the walls of the tank.

Neutral density streamers of blue dye were released from a rake of tubes suspended from the leading edge of the baseplate along the centerline of the model. Each tube was bent 90° toward the model and the dye was injected parallel to the ambient flow. Red dye was injected directly into the valley through surface ports located along the centerline of the model on the lee side of the upstream ridge. This red dye was used to define separation from the ridge and flow within the valley. The flow field was photographed using video and still cameras attached to the tow carriage.

3. RESULTS AND DISCUSSION

In planning these experiments it was anticipated that separation of the flow from the lee side of the upstream ridge would have a major effect on the flow in the valley. Under neutral flow conditions separation is controlled primarily by the steepness of the ridge. It may also be influenced by the

Reynolds number at low Reynolds number. However, this dependence on Reynolds number should be avoided in simulating atmospheric flows where the Reynolds number is always large. Under stable flow conditions separation is also strongly influenced by the Froude number as shown by the experiments of Hunt, Snyder and Lawson (1978).

The steep and gentle ridges were intended to be generic models with boundary layer separation near the crest of the steep ridge under neutral conditions and no separation from the lee surface of the gentle ridge under neutral conditions. Tests under neutral conditions showed that the flow separated from the lee side of the steep ridge very near the crest at all tow speeds of interest. However, similar tests of the gentle ridge revealed that the flow did not separate from the lee side of the ridge at high tow speeds, $U > 30$ cm/s, but it did separate at low tow speeds, $U < 20$ cm/s. This Reynolds number effect on flow separation was eliminated by covering the model with gravel and installing a 5-mm high boundary layer trip along the crest of the ridge. The gravel had an average diameter of about 4 mm and a density of approximately 30 stones per 100 cm². Under neutral conditions the flow separated near the crest of this modified gentle ridge for all tow velocities of interest. The same modifications were made to the intermediate ridge, and neutral-flow separation also occurred near the crest over the full range of tow speeds. For valley tests both ridges were covered with gravel, but the boundary layer trip was placed on the crest of the upstream ridge only.

The study of separation on three-dimensional hills under stable flow conditions by Hunt, Snyder and Lawson (1978) provided guidance in selecting the experimental conditions for the stable flow tests. These authors showed that

separation from the lee side of a steep hill in stably stratified flow is controlled by the parameter λ/W , where λ is the wavelength of the lee waves, $\lambda = 2\pi U/N$, and W is the width of the hill. For $\lambda/W \gg 1$, the flow over the hill approaches that for neutral conditions, and separation occurs near the top of the hill. When λ/W is of order unity separation is controlled by the pressure distribution induced by the lee waves. For $\lambda/W \approx 1$ the first lee wave matches the contour of the hill and separation is eliminated completely. For $\lambda/W < 1$ separation occurs near the first trough of the lee wave.

Based upon these results experiments were conducted at Froude numbers corresponding to λ/W in the range of 0.25 to 3. The relationship between these two parameters is simply

$$\lambda/W = 2\pi(h/W)F \quad (1)$$

where h/W is a measure of the steepness of the ridge. The gentle ridge was tested at higher Froude numbers than the steep ridge so that the two models would have the same values of λ/W . Principal values of F and λ/W used in this study are tabulated in Table 2; these parameters are based on h and W as listed in Table 1. For each experiment the exact tow speed for the desired value of F or λ/W was calculated using the Brunt-Vaisala frequency N as determined from a linear fit to the density profile measured just before the tow. Approximate values of the tow speed based on the nominal value of $N = 1.33 \text{ s}^{-1}$ are tabulated in Table 2.

Photographs of the flow fields for the intermediate-ridge models are shown in Fig. 2. This figure shows three different model configurations: a single ridge, a valley with $S/W = 1$ and a valley with $S/W = 1.5$. Each model configuration is shown for three values of $\lambda/W = 2, 1$ and 0.5 . These photographs illustrate the general types of flow field observed for all of the models. They were taken 2.4 m downstream from the starting point of the tow, which is an adequate distance to eliminate starting transients in the flow field.

The single ridge experiments in Fig. 2 are in general agreement with the results of Hunt, Snyder and Lawson (1978) for separation on three-dimensional hills as described above. The flow separates near the crest of the ridge for $\lambda/W = 2$, there is no separation for $\lambda/W = 1$, and the separation point is located at a distance of approximately $\lambda/2$ from the crest of the ridge for $\lambda/W = 0.5$. These experiments are therefore consistent with the idea that separation occurs near the crest of the ridge for $\lambda/W \gg 1$ and near the first trough of the lee wave for $\lambda/W < 1$. Similar separation characteristics were observed for the steep and gentle ridges, although it was questionable whether the flow over the gentle ridge was separated at $\lambda/W = 2$. However, when this model was tested at $\lambda/W = 3$ the flow was clearly separated.

Valley experiments for $S/W = 1$ and 1.5 are compared to the corresponding single-ridge experiments in Fig. 2. For $\lambda/W = 2$ the flow separated near the top of the upstream ridge just as it did for the single ridge. The valley was filled with a highly-turbulent recirculating separation zone, and the ambient flow passed over the ridges with very little deflection down into the valley. For $\lambda/W = 1$ the flow did not separate from the lee side of the upstream ridge,

and the ambient flow swept down into the valley similar to the single ridge. For $\lambda/W = 0.5$ the flow separated about the middle of the lee side of the upstream ridge. The valley was filled with a rather stagnant separated flow with very little deflection of the ambient flow down into the valley.

It is seen in Fig. 2 that the flow over the upstream ridge in the valley experiments is very similar to the flow over the single ridge at the same value of λ/W . The presence of the downstream ridge does not affect the separation of the flow from the lee side of the upstream ridge. The flow field within the valley has the same general features as the flow field at the corresponding position downstream of the single ridge. This shows that the general structure of the flow in the valley is controlled by the upstream ridge. This was also true for the gentle-ridge model even when S/W was reduced to 0.75.

There were some notable differences in the flow fields over the steep-ridge models. For $\lambda/W = 0.5$ the presence of the downstream ridge caused the flow to separate near the crest of the upstream ridge as compared to about half way down the lee slope for the single ridge. This occurred for $1 < S/W < 3$. For $\lambda/W \approx 1$ the presence of the downstream ridge caused the separation of the flow from the upstream ridge to become unstable. This is illustrated in Fig. 3 which shows steep-ridge valley experiments for $\lambda/W = 1.1$ and $S/W = 1, 2$ and 3 at distances downstream of the starting position of $d = 2.4, 7.3$ and 12.2 m. For $S/W = 1$ and 2 the flow did not separate from the lee side of the upstream ridge during the early part of the tow, and the ambient flow swept down into the valley much as it did for the single ridge. Later in the tow, however, the flow did separate near the top of the upstream ridge. For the rest of the tow the valley was filled with a stagnant separated zone, and the ambient flow

passed over the ridges with very little deflection down into the valley. This change in structure of the flow field occurred at $d = 3$ to 5 m for $S/W = 1$ and at $d = 10$ to 12 m for $S/W = 2$. The change was accompanied by wave-breaking and general unsteadiness in the flow over the ridges. For $S/W = 3$ the flow appeared to be changing toward a separated condition near the end of the tow, but the change was less pronounced than for the smaller values of S/W .

Numerous tows were made to investigate the repeatability of this phenomenon and its sensitivity to small changes in Froude number. The details of the flow field were not completely repeatable, and the separation occurred at different positions along the tank. However, with the exception of the $S/W = 1$ model, the separation always occurred late in the tow at $d = 10$ to 15 m. During one experiment with $S/W = 2$ and $\lambda/W = 0.99$ the attached flow separated at $d \approx 10$ m and reattached at $d \approx 14$ m. The change from attached to separated flow was also observed for the intermediate-ridge valley with $S/W = 1$ and $\lambda/W = 0.75$. It was not observed for the intermediate-ridge valley for $S/W = 1.5$ or for any of the gentle-ridge valleys. It is not clear whether this instability of the separation is inherent to the flow over the model or is the result of wave motions and reflections that are peculiar to a finite-size towing tank. The fact that the instability occurs only for the valley model when $\lambda/W \approx 1$ suggests that it is inherent to the flow field.

Quantitative differences in the flow fields were determined by tracing the dye streamer that was released upstream of the ridge at approximately the ridge height. The minimum height δ of this streamer above the surface of the baseplate anywhere within the valley or downstream of the single ridge was measured from the photographs. Values of δ/h are plotted versus λ/W and F for

the steep, intermediate and gentle ridge models in Figs. 6, 7 and 8 respectively. The minimum value of δ/h , which corresponds to the maximum penetration of the ambient flow into the valley, occurs at $\lambda/W \approx 1$ for all of the models tested. However, the three values of λ/W used for the steep-ridge tests, Fig. 6, are not adequate to define the precise value of λ/W corresponding to the minimum value of δ/h . Also, it appears that the minimum value of δ/h occurs at $\lambda/W = 0.75$ for the gentle-ridge models, Fig 8. For the single-ridge models the minimum value of δ/h decreases with increasing steepness of the ridge. This seems consistent with the lower Froude numbers and stronger lee waves associated with the steeper ridges. For the valley models with $S/W = 1$ the minimum value of δ/h is about equal for the gentle and intermediate ridges and increases slightly for the steep ridge. It is emphasized, however, that these measurements were made at $d = 2.4$ m which is before the flow over the steep-ridge valley models changes from an attached to a separated configuration. After the change occurs, δ/h for the steep-ridge valley models is approximately unity at $\lambda/W = 1$.

The δ/h values generally decrease with increasing S/W for most values of λ/W , and the valley curves appear to approach the single-ridge curve as S/W increases. However, this is not true for the steep-ridge models at $\lambda/W = 0.5$ where the downstream ridge causes separation near the top of the upstream ridge for all values of S/W tested resulting in δ/h values of order unity. The divergence of the δ/h curves as λ/W varies from 1 to 2 may be somewhat misleading. It is caused by the fact that δ is defined as the minimum height of the dye streamer downstream of the single ridge and anywhere within the valley. Therefore, δ can be measured further downstream as S/W increases and even further downstream for the single ridge. The large variation in δ/h at

$\lambda/W = 2$ is caused by measuring δ at different axial positions and not by large changes in the structure of the flow field.

Two previous studies of stable flow over valleys have provided theoretical and experimental results that can be compared to our data. Bell and Thompson (1980), hereafter referred to as BT, conducted numerical and laboratory experiments on two-dimensional flow over topography that had periodic triangular-shaped ridges in the flow direction. Based on their numerical models, they concluded that the width of the ridges and valleys in the flow direction is not important. The important parameter in their study was the Froude number F based on the ridge height. They also concluded that stagnant flow exists in the valley for $F < 1.3$ and that the valley is ventilated for $F > 1.3$. Their towing tank experiments were in agreement with their numerical results, but only one model was tested with a value of $h/W = 0.1$.

The experiments of BT correspond most closely to our gentle-ridge valley with $h/W = 0.082$. Our experimental results show that a separated, stagnant flow exists in the valley for λ/W less than about 0.5. This corresponds to F less than about 1, which is close to BT's result of $F < 1.3$. However, the critical parameter separating stagnant and ventilating flow in our experiments is λ/W and not F . For our steep, intermediate and gentle-ridge models, the maximum penetration of the ambient flow into the valley occurs at $\lambda/W \approx 1$ which corresponds to Froude numbers of 0.6, 0.9 and 1.9 respectively.

Tampieri and Hunt (1985), hereafter referred to as TH, also conducted theoretical and experimental studies of stable flow over a single ridge and valleys formed by a pair of ridges. Their theoretical studies were based on a

linearized theory which assumes small perturbations to the ambient flow and a Froude number much larger than one. Using this model, TH concluded that the presence of the downstream ridge would probably cause separation on the lee side of the upstream ridge for $S/W < 1.5$ under conditions where the flow would not separate from the lee surface of a single ridge. This linearized theory appears to be most nearly applicable to our gentle-ridge experiments. For this model we saw no evidence of separation being caused by the presence of the downstream ridge for $0.75 < S/W < 1.5$ over the Froude number range of $F = 0.5$ to 3.9 . Separation from the upstream ridge occurred at the same conditions as for a single ridge, and the downstream ridge had only a small effect on the flow in the valley. For the steep-ridge model the downstream ridge did cause separation from the upstream ridge as discussed previously. However, the phenomenon appears to be more complicated than predicted by the linearized theory.

The experimental results of TH were reported in terms of the ratio of the deflection of the flow down into the valley to the deflection downstream of the second ridge. We have chosen instead to use the ratio of the deflection down into the valley to the hill height, which is a better indicator of valley ventilation. Therefore, a direct comparison of our data to that of TH is not possible, but some general comparisons can be made. TH correlated their data in terms of the ratio of the ridge separation to the wave length of the lee waves, S/λ . Our data suggest that λ/W is a more fundamental parameter. It was also concluded by TH that the flow in the valley is stagnant for F less than about 1.5 and $S/W > 1$. Our data suggest that a more appropriate criteria for stagnant flow in the valley is λ/W less than 0.5 to 0.75 which is the criteria for wave-induced separation on the lee side of a single ridge.

4. CONCLUSIONS

The flow visualization experiments described in this paper have shown that stable flow over a valley formed by a pair of ridges is more complex than depicted in previous theoretical and experimental studies. However, many characteristics of the flow can be explained using criteria for boundary layer separation from the lee side of a single ridge. In a broad sense, three general types of flow field were observed depending upon the ratio of the length of the lee waves to the width of the ridge, λ/W .

For $\lambda/W \approx 2$ the flow separates near the crest of the upstream ridge just as it does for a single ridge. The valley contains separated flow which, for the steep and intermediate ridges, is a highly-turbulent recirculating flow. There is little penetration of the ambient flow down into the valley for $S/W < 1.5$. For $\lambda/W \approx 1$ the flow does not separate from the lee side of the upstream ridge, and the ambient flow sweeps down into the valley. For λ/W less than 0.5 to 0.75 the flow separates near the first trough of the lee wave, i.e. at a distance of approximately $\lambda/2$ from the crest of the ridge. The valley is filled with a rather stagnant separation zone, and there is little deflection of the ambient flow down into the valley. These general features of the flow field are modified somewhat depending upon the steepness of the ridge and the separation distance between the ridges.

There were some notable exceptions to the general behavior described above. For the steep-ridge model the downstream ridge causes separation from the lee side of the upstream ridge under conditions where the flow would not be separated for a single ridge. This effect is most dramatic for $\lambda/W \approx 1$ where

the separation is unstable and changes from an attached to a separated condition during the tow. More research is needed to determine the cause and significance of this phenomenon.

It should be emphasized that our gentle ridge is actually rather steep since the boundary layer separates near the crest under neutral flow conditions. Many valleys are formed from ridges with even smaller slopes which would have no flow separation under neutral conditions. The separated flow observed in our valleys for $\lambda/W \approx 2$ would not exist in these valleys. The stagnant separated flow observed in our valleys for $\lambda/W < 0.5$ probably would exist in these valleys, but this needs to be investigated. Unfortunately, towing tank experiments for this case may be complicated by Reynolds number effects as discussed in Section 3.

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REFERENCES

- Bell, R. C. and R. O. R. Y. Thompson, 1980, Valley ventilation by cross winds, J. Fluid Mech., 96, part 4, p. 757-767.

Hunt, J. C. R., W. H. Snyder and R. E. Lawson, Jr., 1978, Flow structure and turbulent diffusion around a three-dimensional hill: Fluid modeling study on effects of stratification; Part 1, Flow structure, U.S. Environmental Protection Agency, EPA-600/4-78-041, Research Triangle Park, NC.

Lee, J. T., R. E. Lawson, Jr., and G. I. Marsh, 1986, Flow visualization experiments on stably stratified flow over ridges and valleys: Final Report, Los Alamos National Laboratory report, Los Alamos, NM, to be published.

Snyder, W. H., R. S. Thompson, R. E. Eskridge, R. E. Lawson, Jr., I. P. Castro, J. T. Lee, J. C. R. Hunt and Y. Ogawa, 1984, The structure of strongly stratified flow over hills: Dividing streamline concept. J. Fluid Mech., 152, p. 249-288.

Tampieri, F. and J. C. R. Hunt, 1985, Two-dimensional stratified fluid flow over valleys: Linear theory and a laboratory investigation, Boundary Layer Meteorology, 32, p. 257-279.

Ridge Model	h (cm)	W (cm)	h/W	Maximum Slope (degrees)	S/W Values Tested
Steep	10.4*	37	0.28	40	1, 1.5, 2, 3
Intermediate	7.5**	44	0.17	27	1, 1.5
Gentle	5.8**	71	0.082	13	1, 1.5, 0.75***

*Includes 0.4 cm step where model is fastened to baseplate.

**Includes 0.5 cm boundary layer trip on crest of ridge.

***Leading edge of downstream ridge was cut off and flared into the upstream ridge to obtain S/W = 0.75.

Table 1 Geometric parameters for ridge and valley models

Ridge Model	λ/W	F	U (cm/s)
Steep	2.12	1.2	16.6
	1.06	0.6	8.3
	0.53	0.3	4.2
Intermediate	2.0	1.87	18.6
	1.5	1.40	14.0
	1.0	0.93	9.3
	0.75	0.70	7.0
	0.5	0.47	4.7
	0.25	0.23	2.3
Gentle	3.0	5.84	45.1
	2.0	3.90	30.1
	1.0	1.95	15.0
	0.75	1.46	11.3
	0.5	0.97	7.5
	0.25	0.49	3.8

Table 2 Parameters used in experiments on stably stratified flow over ridges and valleys

Fig. 1 Nomenclature and cross-sections drawn to scale for ridge and valley models.

(a) RIDGE, $\lambda/W = 2$

(b) RIDGE, $\lambda/W = 1$

(c) RIDGE, $\lambda/W = 0.5$

(d) $S/W = 1$, $\lambda/W = 2$

(e) $S/W = 1$, $\lambda/W = 1$

(f) $S/W = 1$, $\lambda/W = 0.5$

(g) $S/W = 1.5$, $\lambda/W = 2$

(h) $S/W = 1.5$, $\lambda/W = 1$

(i) $S/W = 1.5$, $\lambda/W = 0.5$

Fig. 2 Intermediate ridge and valley models at $d = 2.4\text{m}$ downstream of starting point of tow.

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(a) $S/W = 1$, $d = 2.4\text{m}$

(b) $S/W = 1$, $d = 7.3\text{m}$

(c) $S/W = 1$, $d = 12.2\text{m}$

(d) $S/W = 2$, $d = 2.4\text{m}$

(e) $S/W = 2$, $d = 7.3\text{m}$

(f) $S/W = 2$, $d = 12.2\text{m}$

(g) $S/W = 3$, $d = 2.4\text{m}$

(h) $S/W = 3$, $d = 7.3\text{m}$

(i) $S/W = 3$, $d = 12.2\text{m}$

Fig. 3 Variation of flow field with distance d from starting point of tow for steep-ridge valleys with $\lambda/W = 1.1$

Fig. 4 Penetration of the ambient flow into the valley for the steep-ridge models.

Fig. 5 Penetration of the ambient flow into the valley for the intermediate-ridge models.

Fig. 6 Penetration of the ambient flow into the valley for the gentle-ridge models.