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Morning Breakup of a Nocturnal Cold Pool

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Local flow patterns in areas of complex topography are driven by diurnal heating and cooling. If the topography is basin-shaped, then the drainage flows occurring at night accumulate in the lower valleys of the basin, causing the development of a pool of cold stable air that traps pollutants. These cold pools are destroyed during the day by rising convective boundary layer and upslope flows, leading to the dilution of pollutants. In order to understand mechanisms of cold pool destruction, a series of laboratory experiments were conducted, focusing on the identification of flow phenomena, rather than dynamic modeling of a particular atmospheric situation. The experimental configuration consisted of a V–shaped water tank, subjected to either bottom heating, cooling or a heating/cooling cycle. The working fluid was initially stably stratified (thermally) with a pronounced inversion layer. Bottom heating with a specified heat flux was initiated and dye visualization, temperature and particle tracking velocity (PTV) measurements were used to monitor the flow field. It was found that cold pools are destroyed by the combined influence of along-slope flow, horizontal intrusions emanating from the slope flows and entrainment of these intrusions into the growing bottom convective boundary layer. This scenario is different from previously held view of cold pool destruction. Field data taken during the VTMX field campaign (Salt Lake City, Utah, October 2000) were interpreted in light of laboratory observations.

1. INTRODUCTION

During the night, cold air carried by katabatic flows starts pooling on valley floors, forming the so-called *Cold Pool* characterized by a basin potential temperature inversion (Figure 1). A basin potential temperature inversion is defined as a surface-based layer of stable cold air or, alternatively, a surface-based layer in which the potential temperature increases with height (Whiteman *et al*. 1998). The morning transition begins when the incoming radiation from the sun is greater than the outgoing radiation from the surface of the Earth, whence the basin begins to warm. At this point, the surface begins to increase in temperature and the heat is transferred to the surrounding atmosphere. The heated air has a density less than that of the stable inversion core above the valley floor. Convective currents begin to rise along the valley slopes. The currents continually absorb heat from the valley walls, forming a growing convective boundary layer. To satisfy continuity requirements, air is entrained from the base of the elevated stable core. Several different mechanisms of the morning transition are noted (Whitman (2000), Brehm and Freytag (1982), Vergeiner (1982), Whiteman and McKee (1982)). To investigate the feasibility of different inversion break-up mechanisms laboratory experiments were conducted.

Laboratory experiments designed to investigate the morning inversion are described in Section 2, followed by laboratory results in Section 3. Field application is given in Section 4 and conclusions are presented in Section 5.

2. LABORATORY SETUP

A laboratory model of a simple 2-D valley was constructed with hollow walls made from aluminum (see Figure 1a and the schematic shown in Figure 1b). Inside the walls were the flow deflectors to evenly distribute the warm water. The angle β could be changed by replacing the front and back end panels to the valley. The valley walls were heated by pumping warm water through the walls. The discharge from the valley slopes (walls) was run back into the water heater, before cycling through the slopes another time, Figure 2.

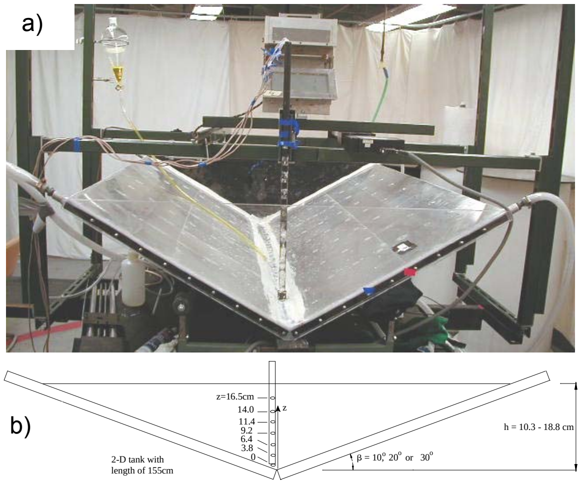

FIG. 1. a) Photo and b) schematic of the “V” shaped water tank used for laboratory

The morning transition period was simulated in the valley by beginning with a “cold-pool” of stably stratified

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water. The stratification was achieved by filling the bottom half of the tank with water at a temperature near 0°C, and then pouring tap water at room temperature into a floating platform that facilitated layering of the water. In some cases a very strong gradient was required, so the top centimeter of the tank was filled with hot water, initially at 50°C. A smooth temperature gradient was achieved by slightly mixing the water with aluminum mesh before the initiation of the experiment. The temperature measurements in the pool and of the coming and outgoing water from/to the heater were recorded. The vertical temperature profile of the water in the tank was measured with seven 'two-terminal integrated circuit temperature transducers' (type AD590JF, manufactured by Analog Devices).

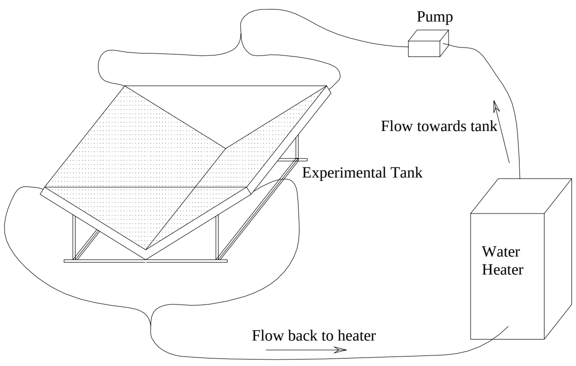

FIG. 2. Circulation of the warm water used for the slope heating.

3. LABORATORY RESULTS

Figure 3 presents schematics of the flow patterns observed in laboratory experiments. The results of the experiments can be presented using the governing parameters for this problem, which are the initial stratification N, surface buoyancy flux q_0, inversion height h and slope angle of the valley sides β (see Figure 4).

The dimensionless parameters that include all important governing parameters were selected as

$$B = \frac{N^3 h^2}{q_o} \tag{1}$$

and the slope angle β.

In the case of initial neutral stability (homogeneous fluid in the tank), which corresponds to the value of the parameter $B = 0$, simple circulation was observed after initiation of heating. Simple circulation consisted of the circulation following the slope, flowing horizontally toward the center of the tank after reaching the inversion and finally subsiding at the central region.

For small values of $B > 0$, a similar pattern was observed but in this case upslope flow is significantly slower due to the blocking effect of the stable stratification. Owing to this blocking effect, thickening of the upslope flow can be noticed. Eventually, after reaching the inversion height, flow continues horizontally towards the tank center, and finally subsides to the valley bottom. In this way, the fluid becomes completely mixed, completing the transition.

Further increasing of the parameter B results in a pattern similar to the one described above but with more horizontal intrusions that peel off from the upslope flow into the stable core. Again, the stable core sinks down, transports heat upward from the valley bottom and is advected by the already fully developed upslope flow, thus completing the mixing process.

At some critical value of the parameter B ($B > 1000 – 2000$), heat flux will not be strong enough to provide enough buoyancy for the fluid parcels to flow against the "blocking" imposed by stable stratification. In this case, instead of flowing upslope and recirculating back from above into the stable core, trapped heated fluid slowly moves upslope, while penetrating the stable core from below until, eventually, the inversion is well mixed.

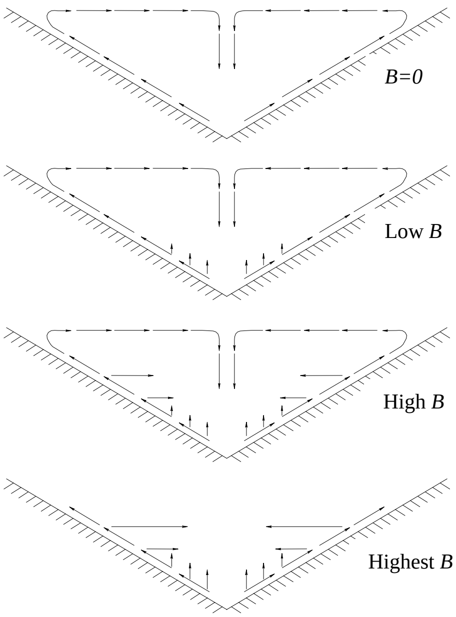

FIG. 3. Observed flow patterns during cold pool destruction for different values of B.

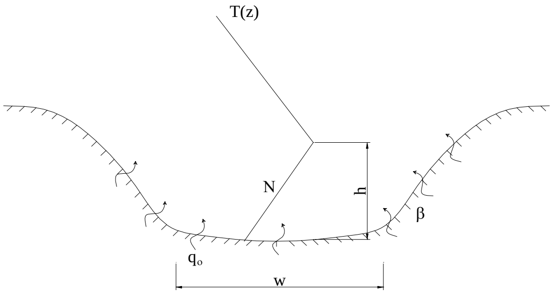

FIG. 4. Governing parameters: q_o – buoyancy flux, N – initial buoyancy frequency (stability), h – inversion height, β – slope angle, w – width of the valley. In the present case w = 0.

4. FIELD APPLICATION

Data taken from several sites around the valley during the VTMX campaign were employed to test the laboratory results given in Section 3.

In order to calculate the parameter B for the Salt Lake City valley, the morning inversion height was determined using radiosonde data. These radiosondes were released from the Wheeler Farm site. Using data from seven Intensive Observational Periods (IOPs), it was determined that the inversion height h ranges from 600 to 800 meters, with the growth rate of the cold pool ranging from 0.6 cm/s to 1.3 cm/s. The same radiosonde temperature profiles were used for the estimation of the initial (morning) stability N. It was found that the average N just before sunrise is on the order 0.015 s^{-1}. The buoyancy flux q_0, which is highly variable during the morning transition presented the biggest uncertainty for the comparison between laboratory and field results (Figure 3). After averaging data taken during several mornings, an estimate of $q_0 \sim 1.4 \cdot 10^{-3}\, m^2/s^3$ was made. Using these values, the parameter B was calculated as $B \approx 1000$. According to this B and our laboratory findings, the third case of the inversion break-up shown in Figure 3 is expected to occur within the Salt Lake City Valley.

5. CONCLUSION

The morning inversion break-up was investigated using laboratory experiments. Four different patterns were delineated: 1) pure upslope advection of the valley air consequently followed by the inversion subsidence; 2) upslope advection, convective destruction of the stable core and inversion subsidence; 3) upslope advection accompanied by the horizontal intrusions in the stable core; and 4) convective destruction with horizontal intrusions in the stable core. It was found that the type of inversion break-up is determined by the new parameter $B = N^3 h^2 / q_0$. Higher values of the parameter B are leading to the destructions with horizontal intrusions (type 3 and 4).

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