WESTERN REGION TECHNICAL ATTACHMENT
NO. 96-16
July 30, 1996

THE EFFECTS OF MOUNTAINS AND COMPLEX TERRAIN ON AIRFLOW AND DEVELOPMENT OF CLOUDS AND PRECIPITATION

Daran L. Rife - NWSFO Great Falls, MT

Introduction

A distinguishing feature of the states which lie within the domain of the Western Region, is the existence of broad regions of mountains and complex terrain. These features have significant effects on airflow and the development of clouds and precipitation. A basic understanding of these effects can be very helpful when evaluating the synoptic and mesoscale weather patterns for forecast package generation.

This Technical Attachment (TA) is intended as a literature review to help bring forecasters in Western Region field offices up-to-date on the latest findings in the field of mountain meteorology. It will outline some of the important effects and some basic concepts of orographic influence on airflow, clouds and precipitation, and will be divided into to two parts: 1) the stable environment, and 2) the unstable environment.

[*Authors Note: Much of the material for this TA comes from Rife (1995)*]

Stable Environment

There are two major roles that mountains have in forming clouds and precipitation. First, mountains are obstacles to atmospheric flow. As stable approaching airflow encounters a mountain barrier, it is forced to ascend the mountain (Banta, 1990). If the necessary atmospheric conditions exist, particularly the stability and moisture content of the atmosphere, clouds and precipitation may be produced due to the forced-orographic uplift of the air.

To a large extent, the stability of the atmosphere determines how the obstacle will affect the flow. In particular, the stability determines the maximum orographic lifting realized by the air. If the atmosphere is more stable, there will tend to be less vertical displacement and more flow around the mountains.

Mountains also cause blocking of stable flow. As stable air approaches the mountain, it slows down due to the blocking effect of the mountain (analogous to the effect of large stones on water flow in rivers). Flow retardation can result in horizontal-mass convergence upstream of the mountain, and may produce upward air motion and cloud formation before the mountain slope is reached.

Similar to mountain blocking is flow deflection by a mountain. Airflow deflection can also produce regions of horizontal mass convergence, but in a different location. Stable airflow may be forced to split and flow around the mountain or obstacle. The airflow then converges on the lee side of the obstacle and may create a region of enhanced instability. Figure 1 illustrates this mechanism.

Finally, the stable airflow may be forced to flow upslope and over the mountain top on the windward side, and then descend to its original level on the lee side. Disturbances in the flow on the lee side and downstream of the mountains can play a major role in cloud and precipitation formation as well (Banta, 1990).

Flow over an obstacle may excite gravity waves. Bradley (1985) found that a major effect of gravity waves is to provide regions of enhanced upward motion that produce clouds with higher liquid water contents than simple orographic lifting. Bruintjes et al., (1994) presented similar results, indicating that to a large extent, gravity waves excited by flow over mountains can determine the distribution of clouds and precipitation. Figure 2 shows a schematic depiction of the typical gravity wave.

Airflow around orographic features, particularly isolated mesoscale mountains or hills, may cause vortices to form on the lee side of the obstacle. Figure 3 shows an example of lee vortices near the Hawaiian Islands. Recent airflow studies by Hjelmfelt and Farley (1992) found that vortices often form on the lee side of isolated mountain masses. The magnitude, number, and strength of the vortices were highly dependent on the speed and direction of the airflow, and the orthogonality of the flow. The convergence caused by lee vortices may enhance instability and convection (Hjelmfelt et al.,1994).

The second major role that mountains have on forming clouds and precipitation is that they are elevated heat sources (Banta, 1990; Orville 1965, 1968). The slopes of the mountain protrude into the atmosphere and air next to the mountain slopes is warmed by the heated slopes. Air next to the mountain becomes warmer than that at the same level away from the mountain and over the plains. This produces a relative low pressure in the air next to the mountain. The low pressure induces convergence of flow toward the mountain. Air begins to flow up the slope. Provided there is sufficient heating and low stability, the airflow will eventually rise over the peak and break away from the slope. Updrafts then form over the mountain. An illustration of this mechanism is depicted in Fig. 4.

Mountains are elevated moisture sources as well (Orville 1965, 1968). Mountains typically have fairly dense vegetation that holds moisture in the vegetation itself and facilitates moisture retention in the topsoil on the mountain slopes (Oke, 1987). The addition of water vapor to the atmosphere from evaporation and evapotranspiration at the surface of the mountain slope creates enhanced buoyancy effects. This causes air flowing up the mountain slope to be more moist and less dense than that at the same level away from the mountain and over the plains (Orville, 1968). In addition, the moisture is a critical component for the formation of clouds.

Cotton and Anthes (1989) and Dennis (1980) outline some of the more important factors that affect orographic enhancement of precipitation. Those relevant to this discussion are: the moisture content of low-level air, the stability of the atmosphere, the shape of the mountain, the slope of the hill perpendicular to the wind direction, the strength of the wind normal to the mountain, and cloud water content. Cotton and Anthes (1989) also state that the heaviest precipitation events in mountainous terrain in the winter are associated with extratropical cyclones.

Unstable Environment

The picture is somewhat different for unstable airmasses. The effects of mountains noted for stable orographic clouds apply to unstable clouds as well. This discussion will focus on two basic types of unstable orographic situations: thunderstorms and unstable snow clouds.

Summertime initiation of thunderstorms in the vicinity of mountainous terrain, an example of unstable conditions, is caused by three main mountain effects. These are orographic lifting, thermal forcing, and obstacle effects which include mountain blocking, flow deflection, and the production of lee-side flow disturbances (Banta, 1990).

Unstable cumulus clouds form when forced lifting releases moist instability that is latent in a column of the atmosphere. Forced lifting of moist air up the slopes of a mountain barrier can lift air directly to its LFC when the LFC is located at some inflow level near or below the mountain summit. According to Banta (1990) there are two ways in which this can happen: when a potentially unstable layer of air is forced to ascend a mountain, and by orographically-forced thunderstorms.

Thermally-generated mountain circulations also produce updrafts that can initiate cumulus cloud growth. As discussed previously, the elevated heat source effect of mountains drives thermally-generated mountain circulations, which initiates flow up the mountain slope and updrafts somewhere over the mountain (see Fig. 4).

Obstacle effects for the unstable case are very similar to those for the stable case. The main difference between the stable and unstable cases is that when an unstable atmosphere is subjected to obstacle effects induced by mountainous terrain, these effects can increase the instability of the atmosphere and enhance convection.

Unstable wintertime clouds can be formed by the same processes that apply to unstable summertime clouds. They are usually formed by destabilization of an otherwise stable air mass by differential thermal advection (Banta, 1990). This can occur when there is cold air advection over warm or neutral advection.

Banta (1990) outlines the main processes involved in differential thermal advection. Destabilization of the atmosphere by differential thermal advection can be caused by large-scale processes. This normally occurs when cold and warm air masses from two different source regions (with different trajectories) are advected over the same point. If the cooler air is advected over the warmer air the atmosphere in this region will become unstable.

An important process that creates differential thermal advection is mountain blocking of an approaching cold front. As the stable cold air mass behind the cold front approaches the mountain, the cold air in the lowest layers is forced upslope. The low-level cold air that is forced upslope is cooler than the environmental air at its new level. As a result, a mesoscale high pressure region forms against the mountain slope, which retards the progress of the cold front near the ground. However, the cold front aloft continues to move over the mountain. Thus, cold air is advected over warmer low-level air on the leeward side of the mountain. The resulting destabilization of the lee-side air may initiate embedded convection or deep convective clouds (Banta, 1990). Figure 5 shows a schematic of this mechanism.

Banta (1990) summarizes the most important roles that mountains have on unstable clouds. First, the depth of unstable clouds is usually related to the depth of the unstable layer. Second, mountain-induced flows to a large extent determine where convective cells will initiate, and how the precipitation from the cells will be spatially distributed. Finally, when storms initiate by thermally-forced solenoidal circulations caused by the high-level heat source effect of mountains, the circulations regulate the location and timing of storm initiation.

Summary

This TA has discussed the important role that mountains and complex terrain play in the formation of clouds and precipitation, by providing the necessary lifting mechanism. The kinds of lift that mountains and complex terrain provide can be direct, such as forced orographic ascent when airflow encounters an obstacle, or more indirect, such as when stable flow produces blocking or waves or when mountain slopes are heated and the mountain acts as a high-level heat and moisture source (Banta, 1990). Clouds are not formed by mountains themselves, but require inputs of moisture, proper stability, and some supportive synoptic or mesoscale environment.

Acknowledgments

The author wishes to thank Mr. Ken Mielke for reviewing this paper and providing editorial guidance to improve its overall quality.

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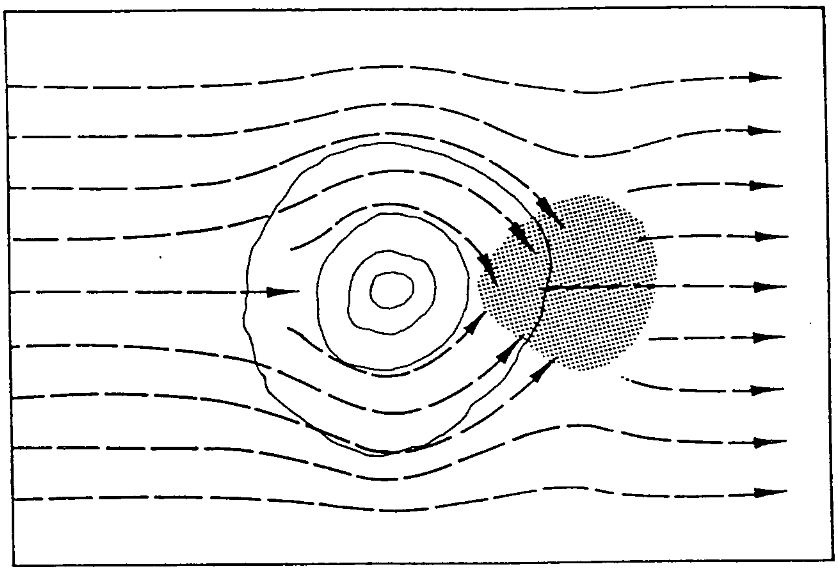

Figure 1. Schematic of horizontal flow patterns showing flow deflection by a mountain range nearly parallel to the flow, and the confluence in the wake in the obstacle. The stippled area on the lee side of the obstacle indicates the region of maximum convergence. [From Banta, (1990).]

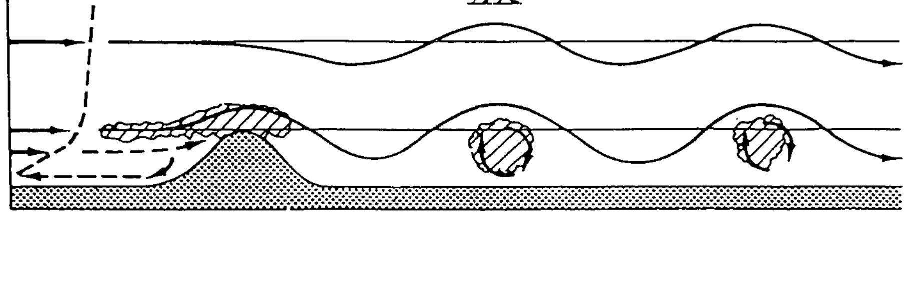

Figure 2. Schematic of gravity wave airflows lee of a mountain range. Dashed line on left indicates vertical profile of horizontal wind speed. [From Atkinson, (1981), after Förchtgott, (1949).]

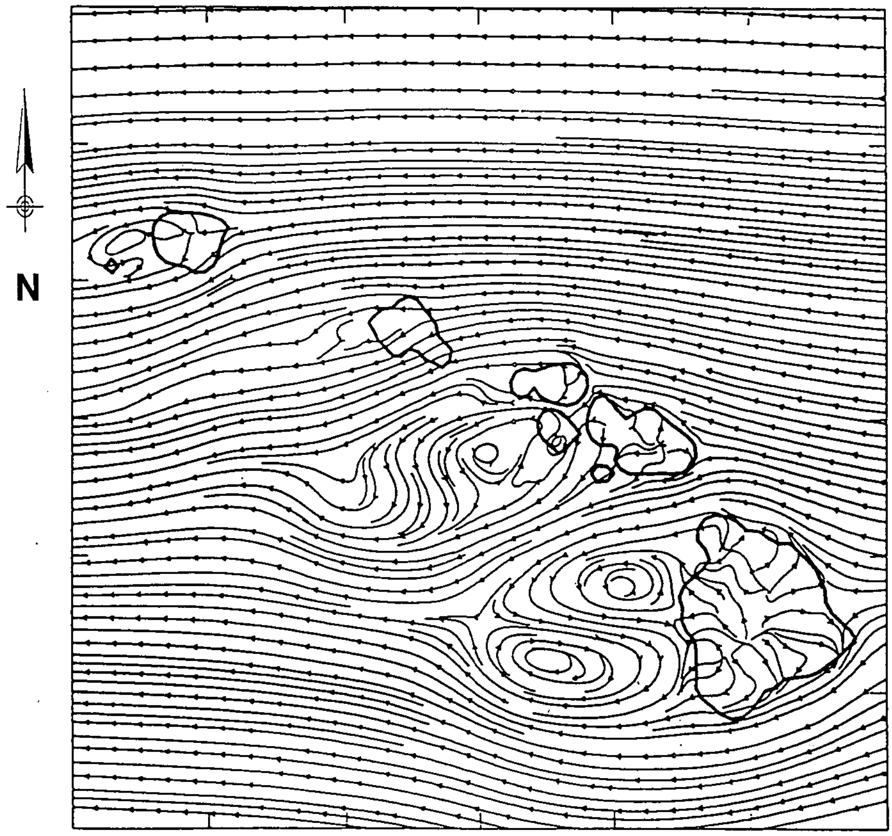

Figure 3. Lee Vortices in the streamflow west of the Hawaiian Islands. Thick solid lines indicate island boundaries. Thin solid (arrowed) lines are streamlines. [From Riesner and Smolarkiewicz, (1994).]

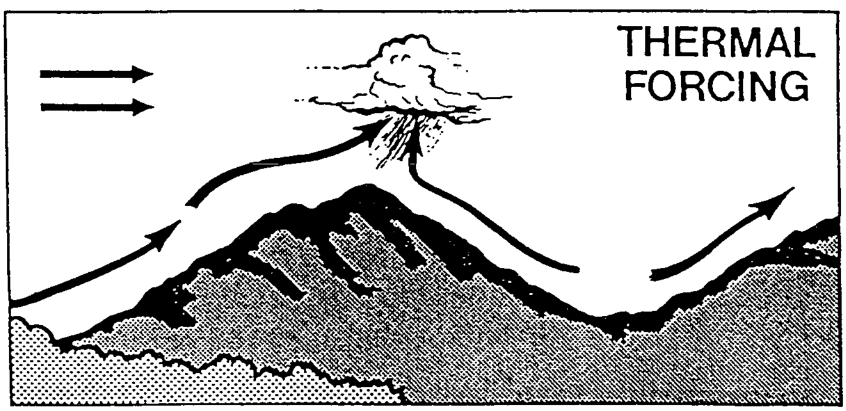

Figure 4. Illustration of the elevated heat and moisture source that mountains provide and its effect on thermal forcing. [From Banta, (1990).]

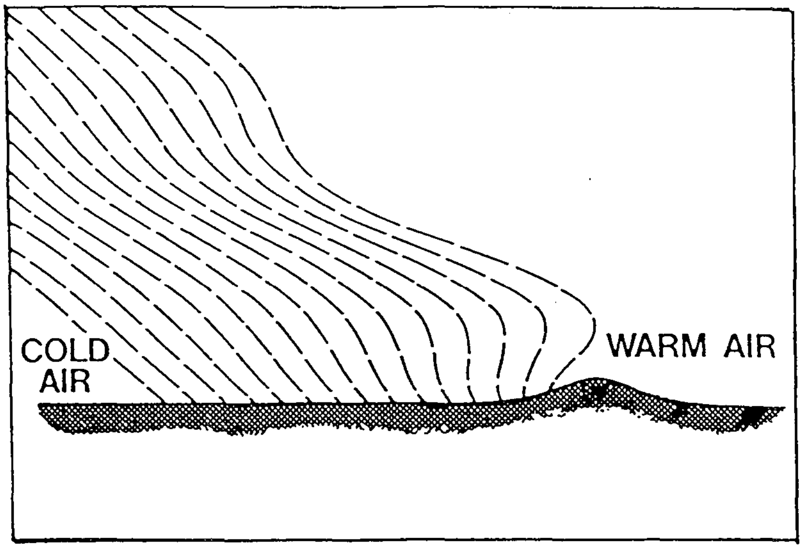

Figure 5. Distortion of a cold front (dashed lines) approaching a mountain range by retarding the low-level stable airflow as it is pushed up the slope. The cold front starts at the left of the figure and proceeds toward the mountain range; positions are at hourly intervals. [From Smith, (1982).]