THE ROLE OF MOIST PROCESSES IN MOUNTAIN EFFECTS

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1. INTRODUCTION

The effect of mountains on the hydrologic cycle is most clearly seen on maps showing the correspondence between patterns of precipitation amount and terrain height. Examples are shown in Figures 1 and 2. A less obvious effect is that the heat, moisture, and momentum transports in the locally intensified orographic clouds may influence the regional airflow. In this brief review we discuss both issues. Other general discussions of this problem are given by Bonacina 1945, Browning 1978, 1980, and Smith 1979.

2. MECHANISMS OF OROGRAPHIC PRECIPITATION

Orographic precipitation enhancement occurs in a wide variety of latitudes, climates, and weather conditions near terrain of differing size and shape. It appears almost certain that the enhancement mechanism varies from region to region. Four basic mechanisms have so far been identified. These are described below.

2.1 Smooth forced ascent

A common aspect of orographic precipitation is that the enhancement occurs on the upwind side of a mountain range. In some climates this relationship is so reliable that the precipitation pattern around a mountain range can be used as a crude indicator of regional wind direction. A recent study of R. Fjortoft (personal communication) suggests that the rainfall at three stations in Norway can be used to classify the Northern Hemisphere circulation features into distinct flow types. Each distinct circulation

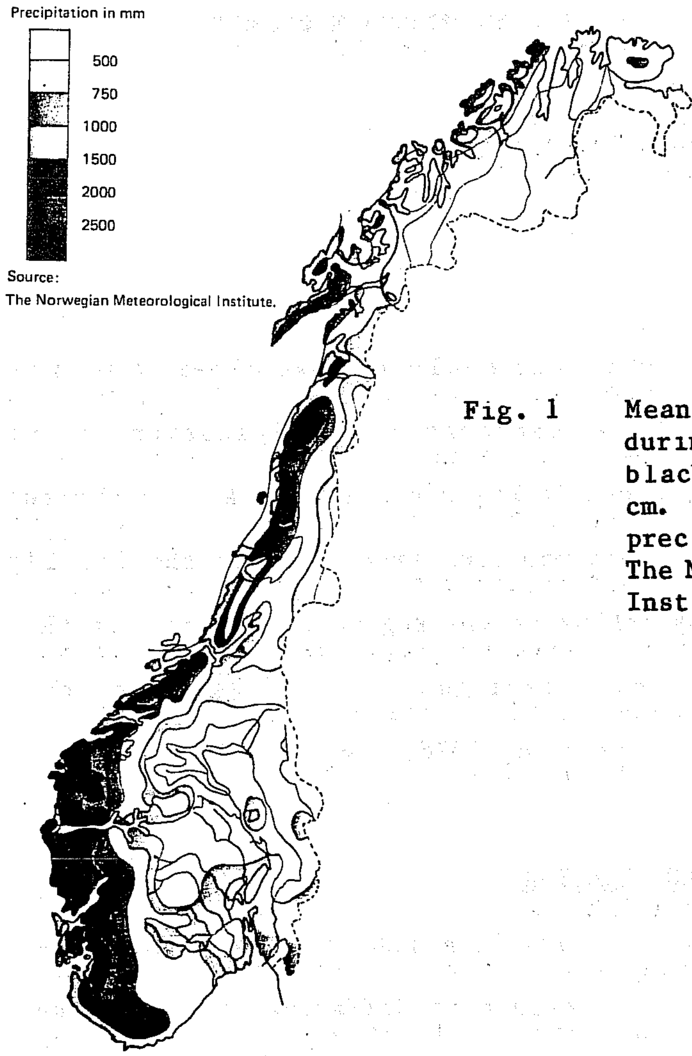

Fig. 1 Mean annual precipitation in Norway during the period 1931 - 1960. The black area receives more than 250 cm. The annual global average precipitation is 88 cm. (Source: The Norwegian Meteorological Institute)

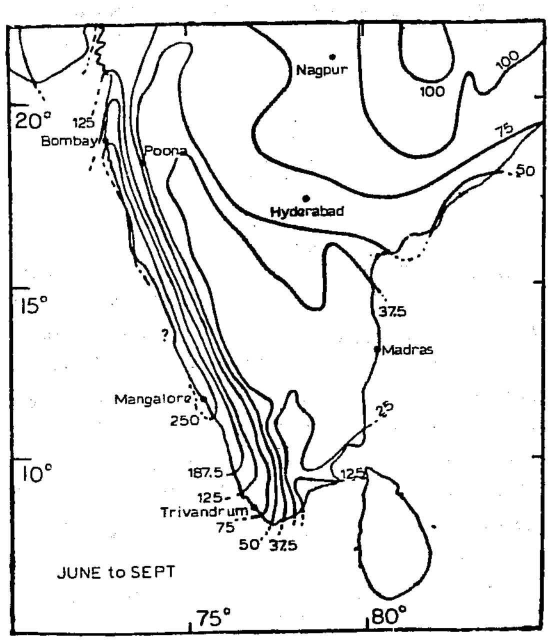

Fig. 2

Precipitation in India during the southwest monsoon season in centimeters. (Source: India Meteorology Department) type brings upslope conditions to the different stations in Norway. Such a correlation is remarkable considering that none of the detail of precipitation process, synoptic, mesoscale, or cloud physical, are considered.

The most often heard explanation for such observations is that smooth terrain-forced ascent will cool the air adiabatically producing condensation and perhaps precipitation (Figure 3a). Although this is the textbook explanation for orographic rain, it has a serious weakness. As pointed out by Bergeron (1960), if the mountain width and wind speed are moderate, there is not sufficient time for hydrometeor formation (HF). Both the collision-coalescence mechanism and the ice phase mechanism take time to work. Furthermore, supercooled water which is needed for the ice phase mechanism, may not be present in the low level air forced up by terrain. As research on these problems has advanced over the last 20 years, it has become more and more possible that the "textbook" mechanism may not be found anywhere on earth! Of course it is still a convenient way for teaching beginning students about the thermodynamics relating ascent and condensation.

One recently proposed location for the application of the smooth forced ascent model is the island of Hawaii. Data from the Hawaiian Warm Rain Project in 1985 suggest that very rapid HF is possible in ascending air upwind of the island (Al Cooper,personal communication). Perhaps salt crystals in the maritime air mass act as giant CCN and accelerate the collison-coalescence process. We must await a complete analysis of that data to rehabilitate the forced ascent model.

A modified version of smooth forced ascent is known to occur. Low level cloud droplets generated by forced ascent can be directly removed from the air by impact on tree foliage. The resulting precipitation is call "tree-drip". This can be a primary mechanism of precipitation on

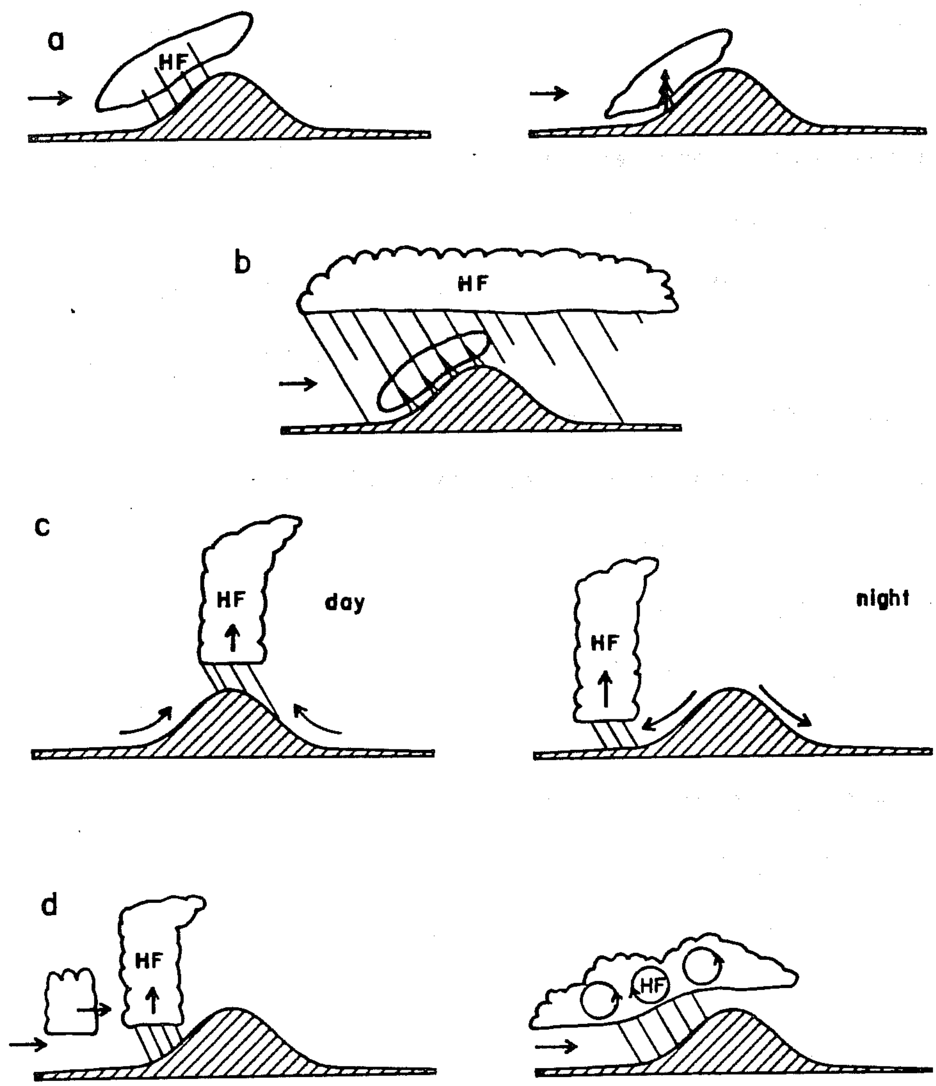

Fig. 3 Four idealized mechanisms for orographic rain. The region of hydrometeor formation (HF) is noted. a) smooth forced ascent with HF or scavenging by foliage; b) seeder-feeder; c) diurnal convection; d) triggering penetrative or shallow convection.

windward slopes in the subtropical high pressure belt where the descending branch of the Hadley cell discourages cloud formation. The Canary Island (Lat. 28°N) experience this phenomena as does the coastal range of Queensland, Australia (near Lat. 25°S).

Rejection of the smooth forced ascent mechanism implies that other factors are needed to explain orographic rain. This agrees with a most important observation: orographic precipitation, i.e., heavy rain on the windward slopes, is almost always accompanied by weaker precipitation over a larger region. Thus high terrain seems to enhance precipitation but not act as its sole cause.

2.2 The Bergeron seeder-feeder cloud mechanism

The difficulty in the rapid production of hydrometeors in low level orographically lifted air was addressed by Bergeron's suggestion of a two-cloud system of orographic precipitation enhancement. An upper "seeder" cloud is presumed to be precipitating with no influence from the terrain (Figure 3b). This cloud is associated with ascent in a regional synoptic scale disturbance. Its mid-troposphere position (and temperature) allows an ice phase formation of hydrometeors. The precipitation from the regional seeder cloud is partly evaporated on the way to the earth's surface. This decreases the rainfall rate at the surface and serves to moisten the low level air. When this air is locally lifted by the terrain, it reaches saturation quickly and a dense low level cloud or fog is formed, i.e., the feeder cloud. The falling hydrometeors collect cloud droplets from this "feeder cloud" and grow in size. Great droplet enlargement may lead to drop splitting and multiplication. Even on small hills (h ~ 100 m) significant rainfall enhancement may result.

The pure seeder-feeder mechanism is an idealization. In practice, the two clouds may be combined into one. Furthermore, the seeder cloud may be influenced by the terrain. A further description of the seeder-feeder mechanism can be found in papers by Bergeron 1960, Browning et al. 1974-1975, Storebo 1976, Bader and Roach 1977, Passarelli and Boehme 1983, and Carruthers and Choularton 1983.

2.3 Diurnally forced convection

One of the most regular and predictable types of orographic rain occurs in warm season conditions over high mountains. The daily heating of the hillsides generates warm upslope winds which continue rising after reaching the mountain ridge top and trigger deep convection (Figure 3b). These clouds produce precipitation in the afternoon over the peaks or downwind if there is cloud drift. This phenomena shows clearly in satellite movie loops and is part of the daily cycle for people who work or live in the high mountain areas during the summer. This mechanism dominates the precipitation patterns on islands and mountainous coastlines throughout the tropics.

At night the thermally forced winds reverse and low level convergence may trigger convection some distance away from the mountains. On mountainous tropical islands this may produce a statistical nighttime precipitation maximum near the coast or off-shore. East of the Rockies thunderstorms may build over the Great Plains at night.

Further discussion on the subject of diurnally forced convection over mountains is found in papers by Lin and Orville 1969, Kuo and Orville 1973, Astling 1984, and Banta 1984.

2.4 Triggered convection by forced ascent or blocking

In an attempt to understand how terrain can so strongly influence precipitation it is often supposed that forced lifting can trigger some sort of instability which will then produce additional condensation and hydrometeor formation (Figure 3d). Three possibilities have been mentioned:

(i) blocking and upstream lifting triggers deep penetrative convection (e.g. Smith and Lin 1983, Grossman and Durran 1985, Smith 1985)

(ii) blocking and upstream lifting triggering conditional instability in strataform layers (e.g. Lee 1984)

(iii) blocking and differential advection will overturn sloping baroclinic zones triggering conditional instability in strataform layers (e.g. Smith 1982).

These suggested mechanisms are rather difficult to verify for at least two reasons. First, if the environment is close to instability, there are likely to be disturbances and precipitation already in the area. This agrees with the idea of orographic "enhancement" but makes it difficult to isolate the effect of the mountain. Second, in interpreting surface rainfall amounts, the effect of feeder cloud enhancement must be subtracted out. The question then is whether the seeder cloud is influenced by the terrain. Observationally this is best approached with aircraft penetration (Marwitz 1974, 1980) or radar (Browning et al. 1974).

As an example of these problems, consider the Western Ghats (Figure 2) on the west coast of India. The undisputed facts are these:

(i) during the Southwest Monsoon, the rainfall is much greater on the coast and the windward slopes than east of the mountains;

(ii) the rainfall is associated with deep convection.

One could postulate that an upstream blocking effect of the mountains could trigger convection in the approaching southwesterly air current, but verification of this idea is difficult as the statistics and synoptic meteorology of cloud clusters in the Arabian Sea are poorly understood and the upstream effect of the Ghats is difficult to estimate.

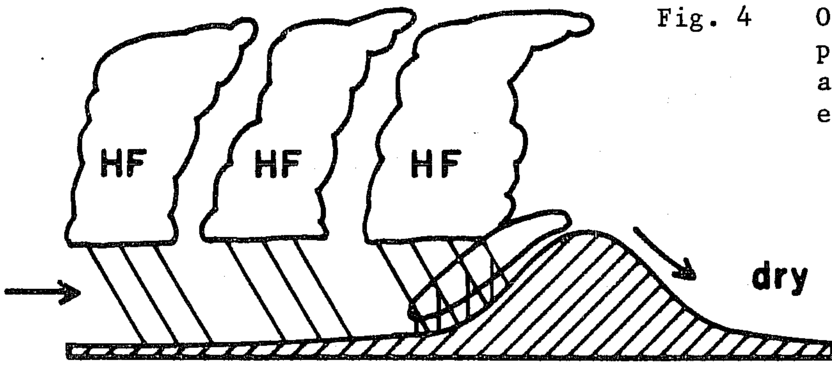

Fig. 4 Orographic control of precipitation by an air-mass modification effect.

An alternative solution to the Western Ghats problem is pictured in Figure 4. Naturally occurring convection over the sea and the coastline during disturbed or unstable conditions will be cut off at the mountain ridge due to an air mass modification effect. Low level air will be scavenged of its water by drops falling from a seeder cloud above. As the air descends beyond the mountain crest it is dry and cannot restore its water vapor by evaporation from the sea. Without the low level moisture, convective precipitation is suppressed.

2.5 <u>Climate type and orographic rain</u>

The relative importance of the mechanisms mentioned above is not known. The possibility of finding these mechanisms in each climate zone might be roughly as follows:

Tropics/Monsoon

Diurnal Convection	certain
Upstream triggering of convection	possible
Orographic air mass transformation	possible
Seeder-feeder	likely

Subtropics	
Smooth forced ascent	possible
Tree drip	certain
Mid-latitudes	
Seeder-feeder	certain
Upstream triggering of strataform convection (winter)	possible
Diurnal convection (summer)	certain

3. THE EFFECT OF STATIONARY HEAT SOURCES

It is of some interest to consider the effect of the enhanced precipitating clouds on the regional scale environment. This is a multifaceted question for which we will attempt only a partial answer. Consider a two-dimensional, inviscid, nonrotating, hydrostatic stratified flow past a region with a heating rate $q(x,z,t)$. The heating is presumed to come from condensation in a stationary precipitating orographic cloud. Small flow perturbations generated by the heat are governed by the linearized equation

$$\left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x}\right)^2 w_{zz} + N^2 w_{xx} = \frac{g}{c_p T} q_{xx} \quad (1)$$

(Lin and Smith 1986) where N is the buoyancy frequency and U is the approaching wind velocity. If the heating rate is independent of time ($q = q(x,z)$ only) as it might be in a stationary orographic cloud, then the field of vertical velocity will also reach a steady state ($w = w(x,z)$ only).

Using (1) a few simple conclusions can be reached. First, in a saturated atmosphere q is likely to be proportional to w and the equation becomes homogeneous with a modified stability. With no forcing in (1) the disturbance must come from another source, a mountain perhaps. The heating will not generate gravity waves, only modify them. Solutions of this type have been given by Barcilon et al. 1979 for hydrostatic mountain waves and by Durran and Klemp (1982) for trapped lee waves.

Only in cases when q is not proportional to w can there be heat-generated gravity waves. To understand this situation we form a steady state energy equation from (1)

$$\frac{\partial}{\partial x}(EU + pu) + \frac{\partial}{\partial z}(pw) = -(g^2/C_pTN^2)\rho q \quad (2)$$

where E is the energy $E = 1/2\, \rho[u^2 + (g\rho/N\bar{\rho})^2]$ and the pu and pw terms describe work associated with wave propagation. If waves propagate energy away from the source then

$$\iint \rho' q \, dxdz < 0 \quad (3)$$

Condition (3) implies that the heat must be added in regions which are already abnormally warm. Thus in a field of steady state heat-generated waves the parcels must descend and warm adiabatically before receiving their heat. Stated another way, the heating region will be a region of downward displacements. An example of this is shown in Figure 5 (Smith and Lin 1982). Similar arguments can be made for momentum sources in a flowing system.

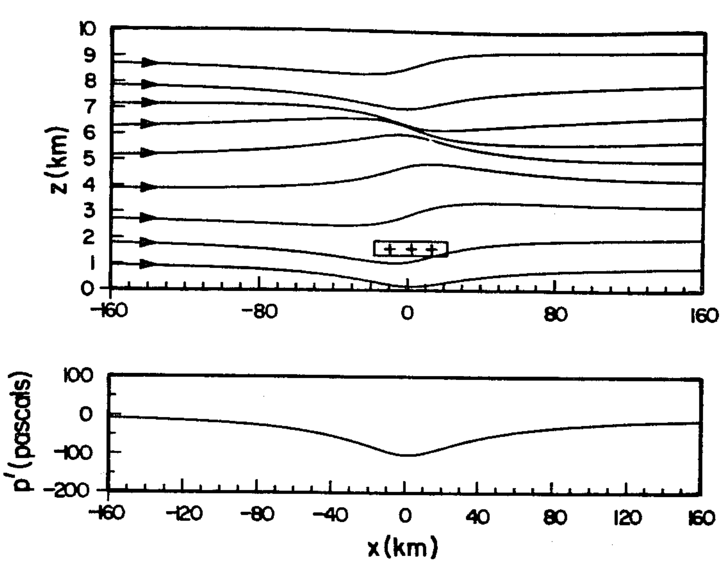

Fig. 5

Steady state stratified flow past a stationary source of heat. (from Smith and Lin 1982).

This result is surprising and troubling. It implies, for example, that if the wrong radiation condition were used (i.e., choosing incoming instead of outgoing radiation), positive displacements would be found near the heating. This mistake has been made in the literature. Furthermore it suggests that heating effects will be self-limiting as the response to heating is to suppress the vertical motion. The full implication of this result in nature is not yet clear.

4. REFERENCES

Astling, E.G., 1984: On the relationship between diurnal mesoscale circulations and precipitation in a mountain valley. J. Clim. Appl. Met., 23, 1635-1644.

Bader, M.J., and W.T. Roach, 1977: Orographic rainfall in warm sectors of depressions. Quart. J.R. Met. Soc., 103, 269-280.

Banta, R.M., 1984: Daytime boundary-layer evolution over mountainous terrain. Part I: Observations of the dry circulations. Mon. Wea. Rev., 112, 340-356.

Barcilon, A., J.C. Jusem and P.G. Drazin, 1979: Geophys. Astrophys. Fluid Dynamics, 12, 1-16.

Bergeron, T., 1960: Problems and methods of rainfall investigation. Physics of Precipitation, Am. Geoph. Union, 5-30.

Bonacina, L.C.W., 1945: Orographic rainfall and its place in the hydrology of the globe. Quart. J.R. Met. Soc., 11, 41-55.

Browning, K.A., 1978: Structure, mechanism and prediction of orographically enhanced rain in Britain: A review. Res. Rep. No. 10, Met. Office Radar Res. Lab., Malvern, England.

Browning, K.A., 1980: Structure, mechanism and prediction of orographically enhanced rain in Britain, in Orographic Effects in Planetary Flows, GARP Publication Series #23, WMO, Geneva.

Browning, K.A., F.F. Hill, C.W. Pardoe, 1974: Structure and mechanism of precipitation and the effect of orography in a wintertime warm sector. Quart. J.R. Met. Soc., 100, 309-330.

Browning, K.A., C. Pardoe and F. Hill, 1975: The nature of orographic rain at wintertime cold fronts. Quart. J.Roy. Met. Soc., 101, 333-352.

Carruthers, D.J. and T.W. Choularton, 1983: A model of the feeder-seeder mechanism of orographic rain including stratification and wind-drift effects. Quart. J. Roy. Met. Soc., 109, 575-588.

Durran, D.R. and J.B. Klemp, 1982: The effects of moisture on trapped lee waves. J. Atmos. Sci., 39, 2490-2506.

Grossman, R.L. and D.R. Durran, 1984: Interaction of low-level flow with the Western Ghat Mountains and offshore convection in the summer monsoon. Mon. Wea. Rev., 112, 652-672.

Kuo, J.T. and H.D. Orville, 1973: A radar climatology of summertime convective clouds in the Black Hills. J. Appl. Met., 12, 359-368.

Lee, Robert R., 1984: Two case studies of wintertime cloud systems over the Colorado Rockies. J. Atmos. Sci., 41, 868-878.

Lin, Y.-L. and R.B. Smith, 1986: The transient dynamics of airflow near a local heat source. J. Atmos. Sci., 43.

Liu, J.Y. and H.D. Orville, 1969: Numerical modelling of precipitation and cloud shadow effects on mountain induced cumuli. J. Atmos. Sci., 26, 1283-1298.

Marwitz, J.D., 1974: An airflow case study over the San Juan Mountains of Colorado. J. Appl. Met., 13, 450-458.

Marwitz, J.D., 1980: Winter storms over the San Juan Mountains. Part I: Dynamical Processes. J. of Appl. Met., 19, 913-926.

Passarelli, R.E., Jr. and H. Boehme, 1983: The orographic modulation of pre-warm-front precipitation in southern New England. Mon. Wea. Rev., 111, 1062-1070.

Smith, R.B., 1979: The influence of mountains on the atmosphere. Advances in Geophysics, 21, 87-230.

Smith, R.B. and Y.-L. Lin, 1982: The addition of heat to a stratified airstream with application to the dynamics of orographic rain. Quart. J.R. Met. Soc., 108, 353-378.

Smith, R.B., 1982: A differential advection model of orographic rain. Mon. Wea. Rev., 110, 306-309.

Smith, R.B. and Y.-L. Lin, 1983: Orographic rain on the Western Ghats, Proc. First Sino-American Workshop on Mountain Meteorology. Ed. E.R. Reiter, Zhu Baozhen, Qian Yongfu. Pub. Science Press, Beijing, Amer. Met. Soc., Boston, 71-98.

Smith, R.B., 1985: Comment on "Interaction of low-level flow with the Western Ghat Mountains and offshore convection in the summer monsoon. Mon. Wea. Rev., 113, 2176-2177.

Storebo, Per B., 1976: Small scale topographical influences on precipitation. Tellus, 28, 45-59.