5.6 INITIATION OF PRECIPITATING CONVECTION IN MOUNTAINOUS REGIONS

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1. INTRODUCTION

Mountainous regions are known for large horizontal precipitation variations and the Rocky Mountains in the United States are a classic example. This variablility is especially evident during the summer months when the precipitation is primarily from convective storms. Days with precipitation are common during the summer - parts of the central Rocky Mountains receive an average of 70 thunderstorms per year. Management of the water supply is especially important as the Rocky Mountains receive more precipitation than the surrounding lowlands. These lowlands have a higher population density and depend on the mountain precipitation for a large part of their water supply.

Unfortunately, this planning process is made difficult because there is little predictability of the horizontal precipitation variations on either a seasonal or daily basis. A significant part of this difficulty results from the large number of ways that mountains can act to aid in the generation of convective storms. Mechanical lifting may cause air parcels to reach their level of free convection or may cause the creation of instability in a potentially unstable layer. Mountains can generate convergence by acting as an obstacle. Examples include channeling by narrowing mountain valleys, air going around a mountain and converging on the lee side, blocking, and down- stream eddies such as the Denver cyclone (Szoke et al. 1984). Gravity waves generated by mountains can encourage the development of convection especially if they interact with other mountain generated flows (Tripoli and Cotton 1989a,b). In addition, mountains can act as an elevated heat or cold source. This process causes upslope and upvalley winds during the day. With upslope winds on both sides of the mountain, convergence can trigger convective activity. When the upslope flow opposes the large scale flow, convection may be generated by lee side convergence. At night, downslope flows into a valley surrounded by mountains can generate thunderstorms (Tucker, 1993). Over larger time and space scales this elevated heating and cooling can cause plateau circulation systems (Tang and Reiter 1984;Reiter and Tang 1984).

This paper will concentrate on the daily thermal forcing of the mountains, although resolvable mechanical effects are included in the simulations. We will show how this thermal forcing on the locations where precipitating convection initiates.

2. THE MODEL AND ITS INITIALIZATION

This investigation employed the numerical model described by Clark and Hall (1991). The model is anelastic and nonhydrostatic. It has a terrain following stretched grid (Clark and Hall 1996) so that it can represent the effects of fine-scale topography. A grid structure has been chosen with two grids. The inner grid has a spacing of 2.6 km and covers central and western Colorado and northern New Mexico. The outer grid has a spacing of 7.8 km and covers a wider portion of the western United States. The inner grid is located off center to the east in the outer grid as no simulations with easterly winds are done. Output will be shown from the inner grid only. The vertical grid has 48 levels. The topography of the inner grid with key features annotated is shown in Fig. 1.

All experiments are initialized from a single sounding, see Fig. 2. For simplicity, the wind profile has no directional shear, only speed shear. Experiments are then performed with the wind direction varying from southerly to northwesterly in order to examine the sensitivity of the precipitation field on the wind direction. The speed shear represents an approximate average over all flow types (some wind directions are associated with more shear than others) without regard to how often each flow type occurs. The sounding is somewhat more unstable (CAPE= 57 J kg^{-1}) than the average summer sounding in eastern Colorado at this time, 0600 LT (12 UTC) but well within the normal

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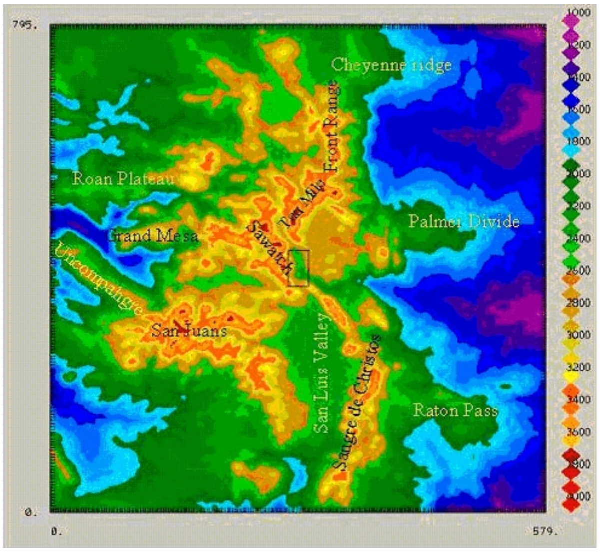


Figure 1. Orography of the inner grid with elevations in meters and key features annotated.

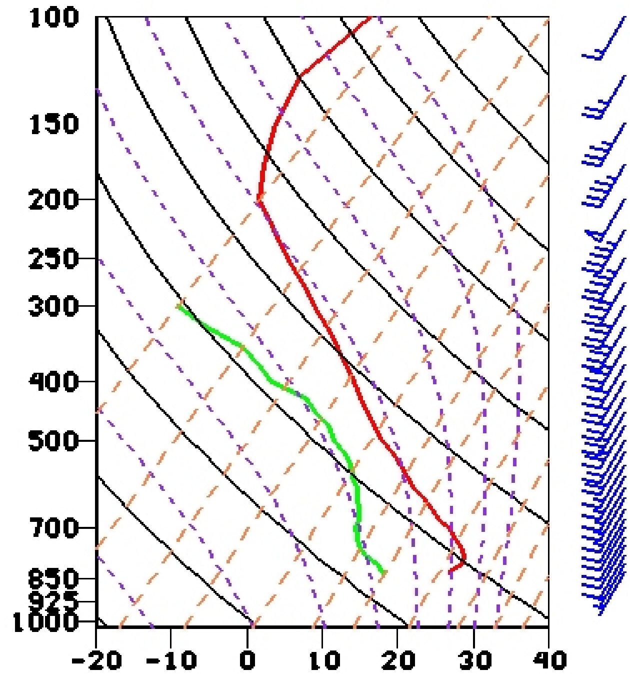


Figure 2. Skew-T-Log P diagram showing the temperature, dew point and wind profile used in model simulations

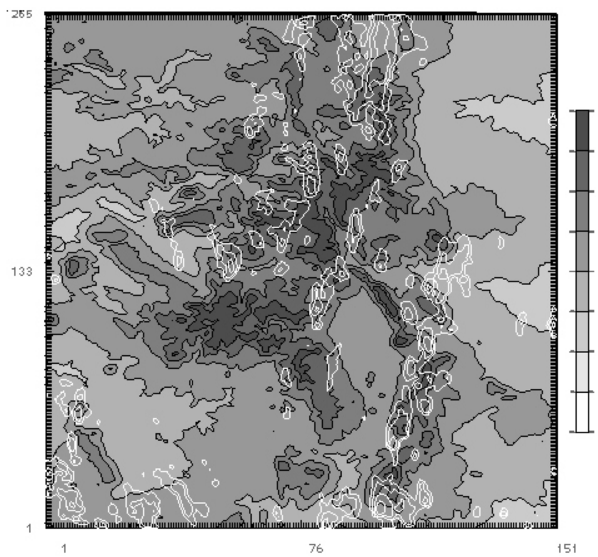
range. This slightly unstable sounding was chosen to maximize the amount of precipitation and reveal the greatest number of convective initiation points. It should be noted that the CAPE of 57 J kg^{-1} is for a surface parcel at 828 mb — pressure at the elevation of the mountains would be less. In addition, surface heating and moistening significantly increases the value of CAPE during the day. Generally, in the Rocky Mountain region in the summer, more northerly flow is associated with less moisture, greater stability, and stronger winds than the more southerly flows. We have not included these differences in this work and have sought to examine all flows on an equal basis. In experiments where the direction of the wind was varied, the speed shear in the sounding remained the same as that in Fig. 2. A diurnal cycle was included in the simulations and all simulations started at 12 UTC.

3. SIMULATIONS OF PRECIPITATION

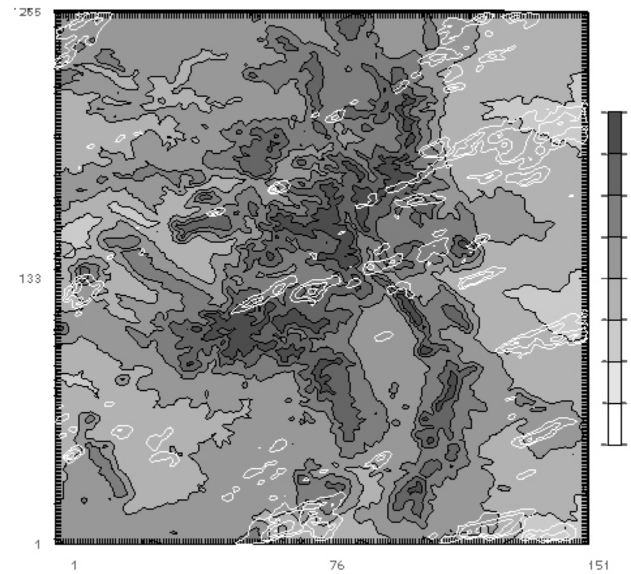
Twelve hour accumulated model precipitations amounts are shown in Fig. 3 for five wind directions. The directions were chosen to illustrate the most common wind directions and greatest differences between precipitation patterns. The locations of precipitation clearly vary greatly with the wind direction. The precipitation spreads downwind from the initiation location. In many cases, initiation sites are located downwind of the highest terrain. This behavior is what we would expect if the main trigger for convective activity is located downwind of the high terrain. But not all areas of high terrain act as initiation sites. Furthermore, the direction of the wind is important. Some areas act as initiation sites in one direction but not in others. Therefore it is not simply the absolute height of the terrain that determines whether a precipitating thunderstorm will be triggered. One general area in the northern San Juan Mountains appears to be able to trigger convection from any direction. The San Juan Mountains are more isotropic and also cover more area than most other mountain ranges in the domain. The places that are able to initiate convection have the axis of highest terrain parallel to the wind direction. For example, the southern Sangre de Christos Mountains act as a trigger only for southerly wind flows. Northern parts of the same mountain range act as a trigger for the northwesterly flow.

We believe these results occur because the mountain acts as an elevated heat source. When the axis of highest terrain is parallel to the wind direction, air parcels crossing the mountain remain over higher terrain for a longer period of time and receive more heat transfer from the mountain. If the length of time is an important factor then the wind speed as well as the wind direction should be important for determining whether a particular location can initiate precipitating convection.

Fig. 4 shows a simulation with the wind from 210 degrees but the wind speeds are halved or doubled

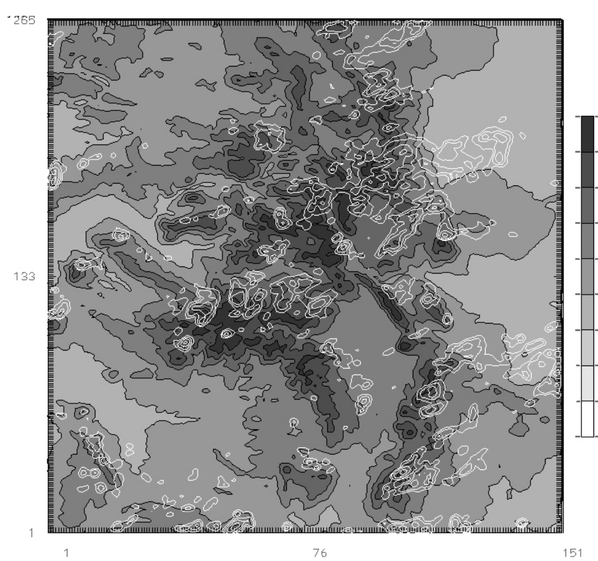


a - Southerly flow

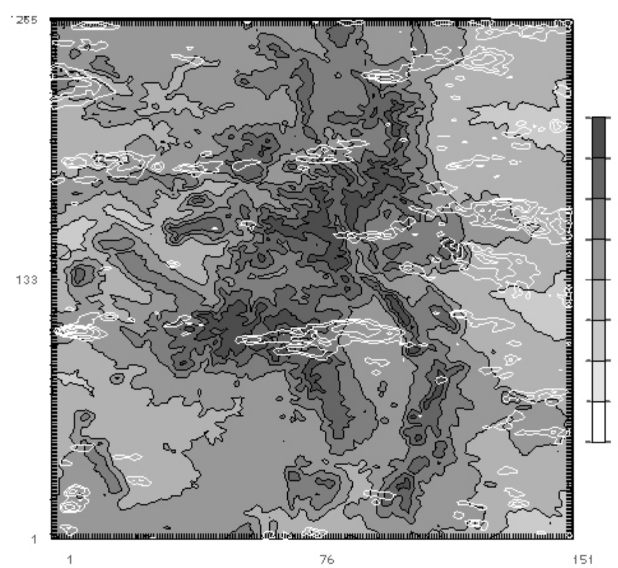


c - Southwesterly flow

Figure 3. Cummulative model simulated precipitation over a period of 12 hours. Solid shading shows surface elevation. White contours are precipitation at 2, 4, 8, 16 and 32 mm. Wind directions are a) 180°, b) 210°, c) 225°, d) 270° and e) 315°



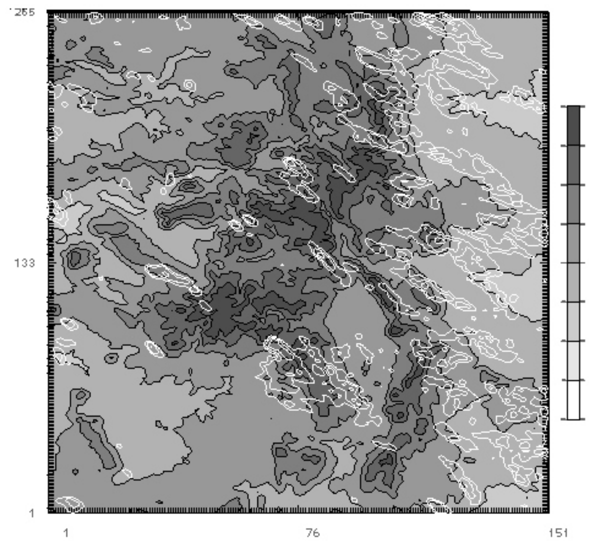
b - flow from 210°



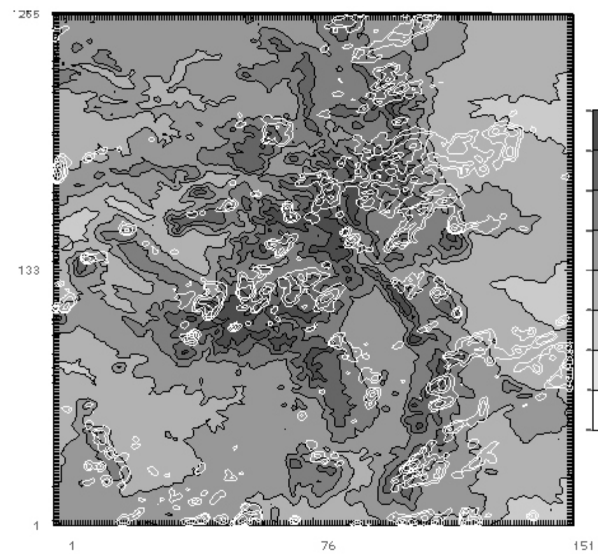
d - Westerly flow

from that used for Fig. 3b. Indeed, when the wind speeds are halved the number of convective initiation locations increases substantially over those in Fig. 3b and when the wind speeds are doubled, convective initiation locations are far fewer than those in Fig. 3b. In addition, for slower wind speeds, convection does not move downwind as quickly and thus more precipitation falls in each location.

Table 1 presents the total and maximum amount of precipitation over the domain for 10 simulations (not all are shown in Figs 3 and 4). Since all simulations are performed with the same moisture and stability conditions, these numbers are a measure of the potential of each wind direction to produce precipitation. The

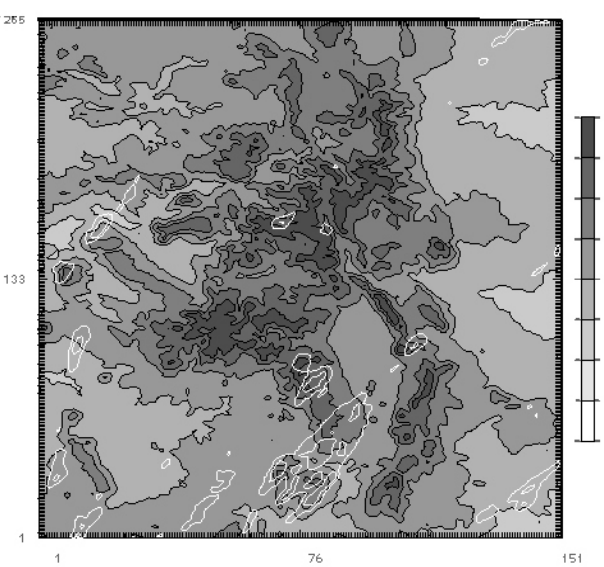


e - Northwesterly flow



a - halved wind speeds

Figure 4. As in Fig. 3 with winds from 210 degrees. Wind speeds are a) half and b) double those used for simulation shown in Fig 3b.



b - doubled wind speeds

lowest amount of total precipitation was for winds from 240 degrees. The greatest was for winds from 315 degrees which exceeded even the halved wind speeds at 210 degrees. In actuality, northwest flow does not generally have as much moisture associated with it as the more southerly flows. With winds from 315 degrees the maximum amount of precipitation produced is fairly small. Thus, 315 degrees has the potential to produce widespread beneficial rains with less threat of flash floods than other wind directions. In an actual situation, this potential must be balanced by the forecaster based on how much moisture the flow actually contains. Flows from 180 degrees and 270 degrees have moderate total precipitation amounts but high maximum precipitation amounts. With sufficient moisture and weak wind speeds these flows have the potential to produce heavy rainfall in a few locations.

4. COMPARISON WITH OBSERVATIONS

As we have seen, differences in the wind direction and wind speed cause considerable variablity in the location of convective precipitation. The question arises as to how much of the natural variablity in precipitation locations it accounts for. It is possible to do a rough qualitative comparison with the results of Schaaf et al (1986) They divided the midtropospheric wind patterns into three regimes they called curving southerly, southwest and northwest. This is a more coarse categorization than was used for the simulations in this paper but it can still yield some insights. Schaaf et al. used satellite data to trace thunderstorms back to their point of origin. They plotted each point of origin over a period of three summers. Their results are presented in Fig. 5.

Table 1. The total precipitation over the inner grid and the maximum precipitation over the inner grid for all cases.

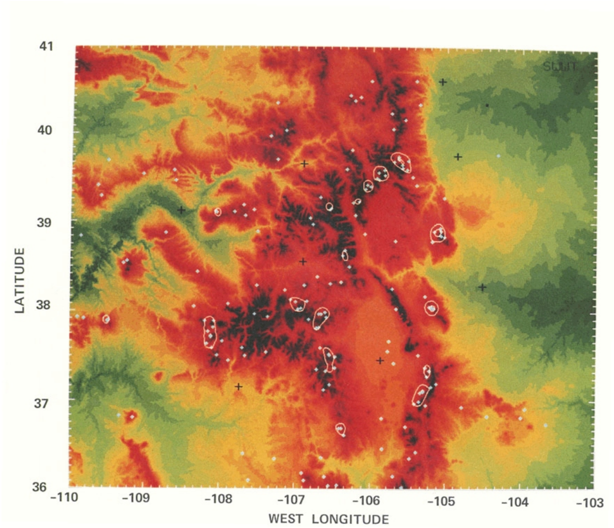
Case	Total Precipitation	Maximum Precipitation
180 degrees	3449	30.6 mm
210 degrees	3236	15.4 mm
225 degrees	2879	16.9 mm
240 degrees	2744	19.1 mm
270 degrees	3396	37.2 mm
285 degrees	3264	16.7 mm
300 degrees	3460	18.1 mm
315 degrees	4270	17.5 mm
210 degrees, doubled wind speed	1770	6.9 mm
210 degrees, halved wind speed	4234	23.0 mm

These observations have a number of common elements with the simulations presented in Fig. 3 and Fig. 4. The curving southerly flow is the only one to show significant initiation over Pikes's Peak. The simulations show initiation at this location occurs primarily for winds from 210 degrees. The strongest initiation observed over Ten Mile Ridge is also for curving southerly flow. The simulations also show this initiation primarily at 210 degrees. The observations with southwest winds show initiation mainly over the southern San Juan and Sangre de Christos Mountains. Some of these initiation locations show in the simulations at 210 degrees but not at 225 degrees. The observations with northwest winds also reveal initiation locations in the southern San Juan and Sangre de Christos Mountains. The simulation from 315 degrees has initiation locations in these areas but they are stronger in the northern than in the southern Sangre de Christos Mountains, in contrast to the observations. This discrepancy could be due to the greater specificity of the wind direction in the simulations or to a smaller scale process the simulations do not include.

4. CONCLUSIONS

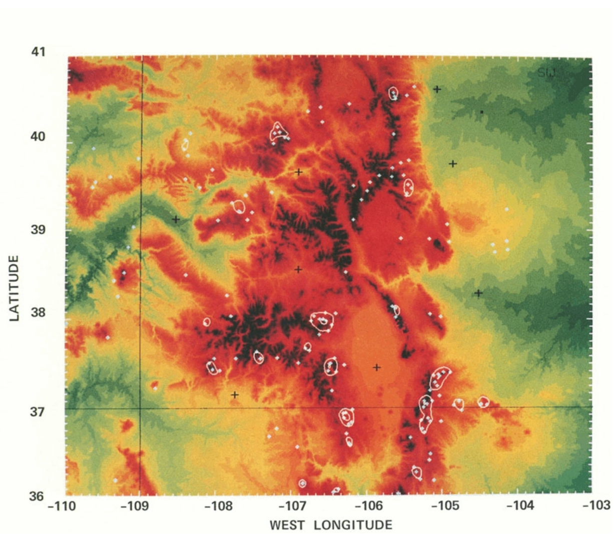
This study has shown that, under horizontally homogeneous conditions, the locations where precipitating convection initiates in the Rocky Mountains in the summer are strongly controlled by the wind direction and speed. Mountain ridges which have their highest terrain oriented parallel to the wind direction are most likely to generate convection. The longer the time air parcels have to gain heat from the mountain ridges, the more likely convection is to occur. The elevated heating also causes convergence and lifting, which is important for convection initiation. Weak winds generate many initiation locations but the convection does not move downwind very quickly. Northwest wind have the potential to produce the largest total amount of rain over the domain yet the amount of rain produced in any one location is moderate.

It is important to note that the simulations presented in this paper were done without any synoptic forcing. Frontal systems and vorticity maxima could alter the patterns illustrated in these simulations significantly. There are many days during the summer in this region, however, when synoptic forcing is weak and yet a fair amount of precipitation falls. In addition, thunderstorm initiation can be influenced by topographic features or processes not resolved by the size of the model grid used in this study. Evaporation from reservoirs or lakes is a process that was not included. Forcing mechanisms associated with convective initiation become more complicated on the adjacent High Plains where thunderstorm outflow is a significant initiation mechanism. Whether thunderstorm outflow will initiate a new cell depends on a number of factors many of whose daily variations are not well known (Tucker and Crook 1999).In spite of these limitations, the variations in wind direction and speed account for a number of observed variations with wind direction in the convective initiation locations. The frequency with which the different wind directions and wind speeds occur in the Rocky Mountains varies from year to year. If a wind direction predominates which is favorable for a particular location to have precipitation it will be more likely to have greater precipitation than another location for which that wind direction is unfavorable for precipitation. Finally, these results can be helpful for day to day weather forecasting when synoptic forcing is weak. By examining the mid-tropospheric wind direction the forecaster may anticipate what regions will be most favorable for precipitation on a particular day.

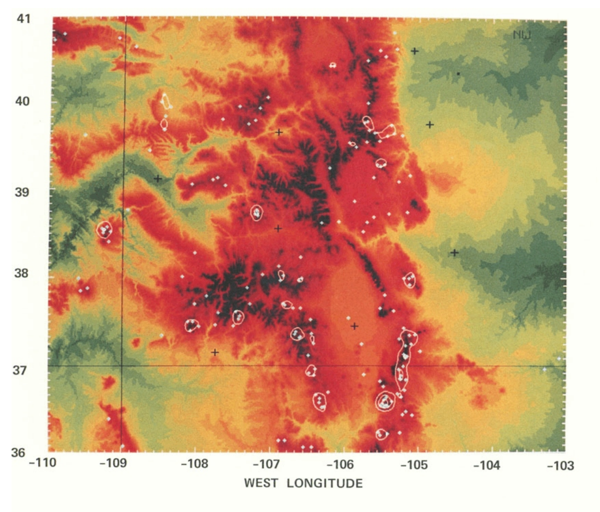


a - curving southerly winds

Figure 5. Thunderstorm initiation sites for 1983 - 1985 for a) curving southerly winds, b) southwest winds and c) northwest winds. Surface elevation is given by the color shading. (From Schaaf et al. 1986)



b - southwesterly winds



c - northwesterly winds

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