

Orographic precipitation

Common ingredients of heavy orographic precipitation

The total precipitation (P) is determined by the average rainfall rate (R) and the duration (D),

$$P = RD. \quad (1)$$

The rainfall rate can then be determined by the *precipitation efficiency*, E , and the *vertical moisture flux*, wq_v ,

$$R = E(\rho / \rho_w)(wq_v), \quad (2)$$

where ρ_w is the liquid water density, ρ and q_v are the lower moist layer average air density and the water vapor mixing ratio.

Substituting (2) into (1) leads to

$$P = E (\rho / \rho_w)(wq_v) D. \quad (3)$$

The duration of heavy rainfall may be estimated by

$$D = L_s / c_s, \quad (4)$$

where L_s and c_s are the horizontal scale of the convective system and its propagation speed in the direction of the system movement, respectively. Combining (3) and (4) leads to

$$P = E(\rho / \rho_w)(wq_v)(L_s / c_s). \quad (5)$$

Equation (5) implies that when the value of any combined factors on the right hand side is large, there is a potential for heavy rainfall.

Based on (5), a set of essential ingredients for flash floods over a flat surface have been proposed (Doswell et al. 1998).

For flow over a mountain range, the low-level upward vertical motion is induced by either orography or the environment (e.g., upper-tropospheric divergence),

$$w = w_{oro} + w_{env} \quad (6)$$

The orographically-forced upward vertical motion may be roughly estimated by the lower boundary condition for flow over mountains,

$$w_{oro} = \frac{Dh}{Dt} \approx \mathbf{V}_H \cdot \nabla h, \quad (7)$$

where $h(x, y)$ is the mountain height, and \mathbf{V}_H is the low-level horizontal wind velocity.

The environmentally-forced upward vertical motion (w_{env}) can be determined by the transient synoptic setting, such as the divergence associated with an approaching trough or conditional instability.

Combining (5) – (7) gives

$$P = E(\rho / \rho_w) (\mathbf{V}_H \cdot \nabla h + w_{env}) q_v (L_s / c_s). \quad (8)$$

Based on the above equation, extremely heavy orographic rainfall requires significant contributions from any combination of the following common ingredients:

- (1) high precipitation efficiency of the incoming airstream (large E),
- (2) a low-level jet (large $|\mathbf{V}_H|$),
- (3) steep orography (large ∇h),
- (4) favorable (e.g., concave) mountain geometry and a confluent flow field (large $\mathbf{V}_H \cdot \nabla h$),
- (5) strong synoptically forced upward vertical motion (large w_{env}),
- (6) a moist unstable low-level flow (large w_{env}),
- (7) a high moisture flow upstream (large q_v),
- (8) presence of a large, pre-existing convective system (large L_s),
- (9) slow or impeded movement of the convective system (small c_s).

The precipitation efficiency may be controlled by several different factors, such as the advection of hydrometeors, evaporation associated with rainfall below the cloud base, entrainment rate of environmental air into the cloud, and environment wind shear (e.g., Fankhauser 1988).

Large CAPE is not consistently observed for the US and Alpine historical events of extremely heavy orographic precipitation.

Formation and enhancement mechanisms

Formation and enhancement mechanisms of orographic precipitation are complicated and are highly dependent on the dynamical and thermodynamic conditions of the upstream airflow, interactions between different layers of clouds, interactions between dynamical and cloud microphysical processes, and mountain geometry.

In the past, several major formation and enhancement mechanisms have been proposed:

- (1) stable ascent,
- (2) release of moist instabilities,
- (3) effects of mountain geometry,
- (4) combined thermal and orographic forcing,
- (5) seeder-feeder mechanism, and
- (6) interaction of dynamical and microphysical processes.

These mechanisms are sketched in the following figure and will be discussed in the following section.

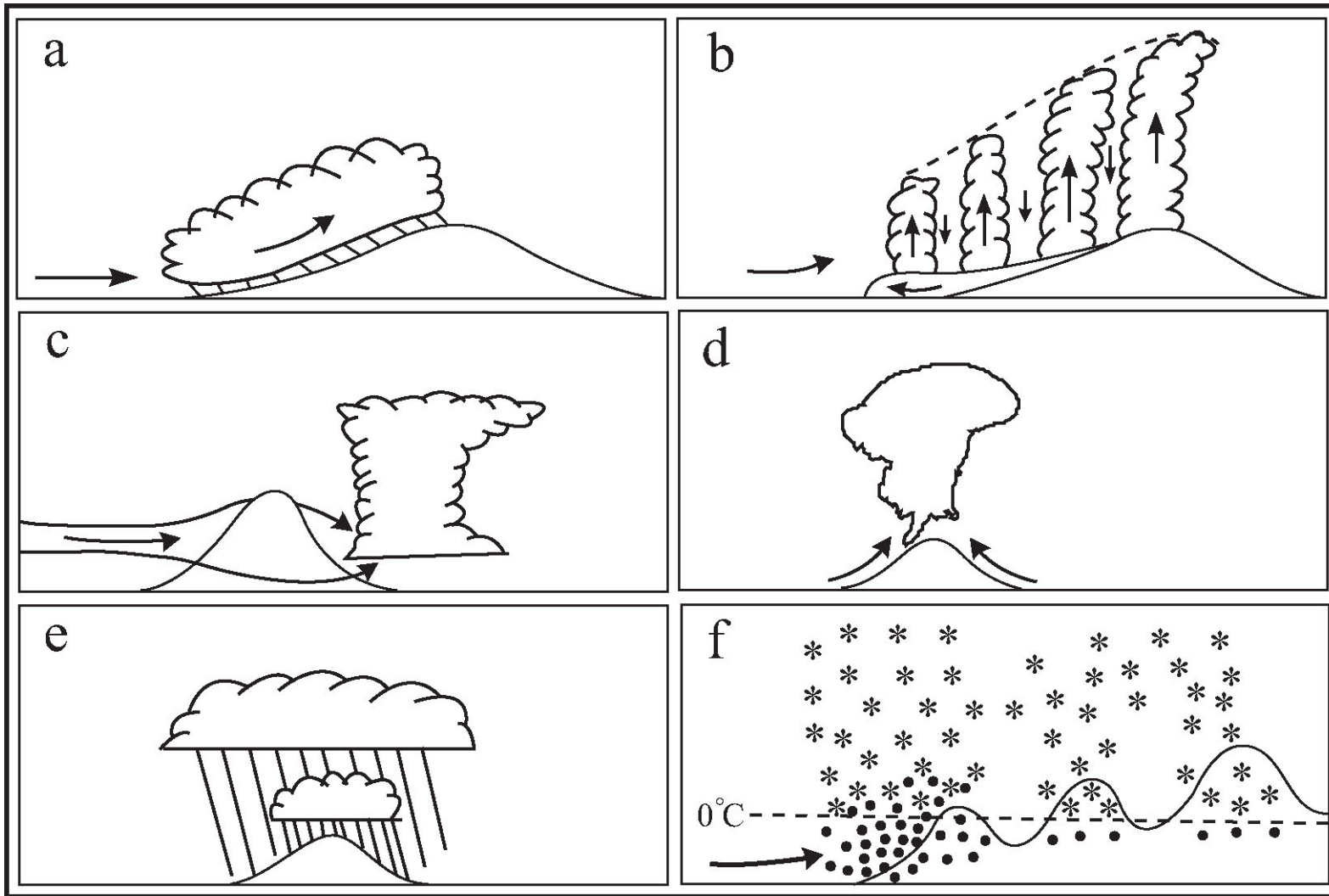


Figure. Conceptual models of the formation and enhancement mechanisms of orographic precipitation: (a) stable ascent, (b) release of moist instabilities, (c) effects of mountain geometry, (d) combined thermal and orographic forcing, (e) seeder-feeder mechanism, and (f) interaction of dynamical and thermodynamic processes.

Stable ascent mechanism

- The earliest and simplest mechanism proposed to explain the formation of orographic rain is the stable ascent mechanism, which assumes the precipitation is produced by the forced ascent of a stable, moist airstream along the upslope of a mountain.

Release of moist instabilities

- Most of the heavy orographic precipitation that often leads to flash flooding is produced by convective cloud systems triggered by orographic lifting on an incoming flow through the release of moist instabilities.
- The possibility that conditional instability may occur in an orographic precipitation system is often detected by inspecting whether there is positive CAPE, in a sounding observed upstream of the threat area.
- Occasionally extremely heavy orographic precipitation is produced by slantwise convection associated with symmetrically unstable airstream in an area of strong vertical shear. The symmetric instability is a concept that will be discussed separately later, if we have time.
- In addition to the above-mentioned instabilities, the wave-CISK mechanism might operate in the combined orographic forcing and latent heating in the orographic cloud and precipitation system, especially when both forcing are in phase along the upslope. The elevated thermal forcing and orographic forcing might interact with each other in a coherent manner to enhance the upslope response, and produce strong lee slope winds.

Effects of mountain geometry

Orographic forcing on incoming airstream is highly dependent on the detailed geometry of a mountain, which is often three-dimensional and complex.

- The geometry of the mountain, in turn, affects the amount and distribution of orographic precipitation if the incoming airstream is moist, especially in a moist unstable condition.
- The terrain geometry influences orographic precipitation in various ways, such as small-scale orographic features, large-scale terrain shapes, and three-dimensional flow blocking and splitting.
- When a low-Froude number airflow passes over a two-dimensional mountain ridge, it may produce wave breaking and severe downslope winds over the lee slope. In this situation, strong convergence is generated at the leading edge of the severe downslope winds and forms a hydraulic jump. When the air is moist, the hydraulic jump becomes visible as clouds form above their lifting condensation levels. Occasionally, these waves are trapped on the lee side and rotor clouds may form.
- If the mountain is isolated, steep and tall, orographic blocking is strong on the impinging moist airstream. In this situation, the flow tends to split and go around, instead go over, the mountain and may converge on the lee side and trigger convection, as sketched schematically in the conceptual model shown earlier. See also next figure as an example.
- Moist flow tends to converge in concave regions of a mountain range and initiate convection which may lead to heavy orographic rain or flooding.
- Complex terrain is often composed by numerous irregular peaks and valleys, resulting in fine-scale, complicated distribution of orographic precipitation.

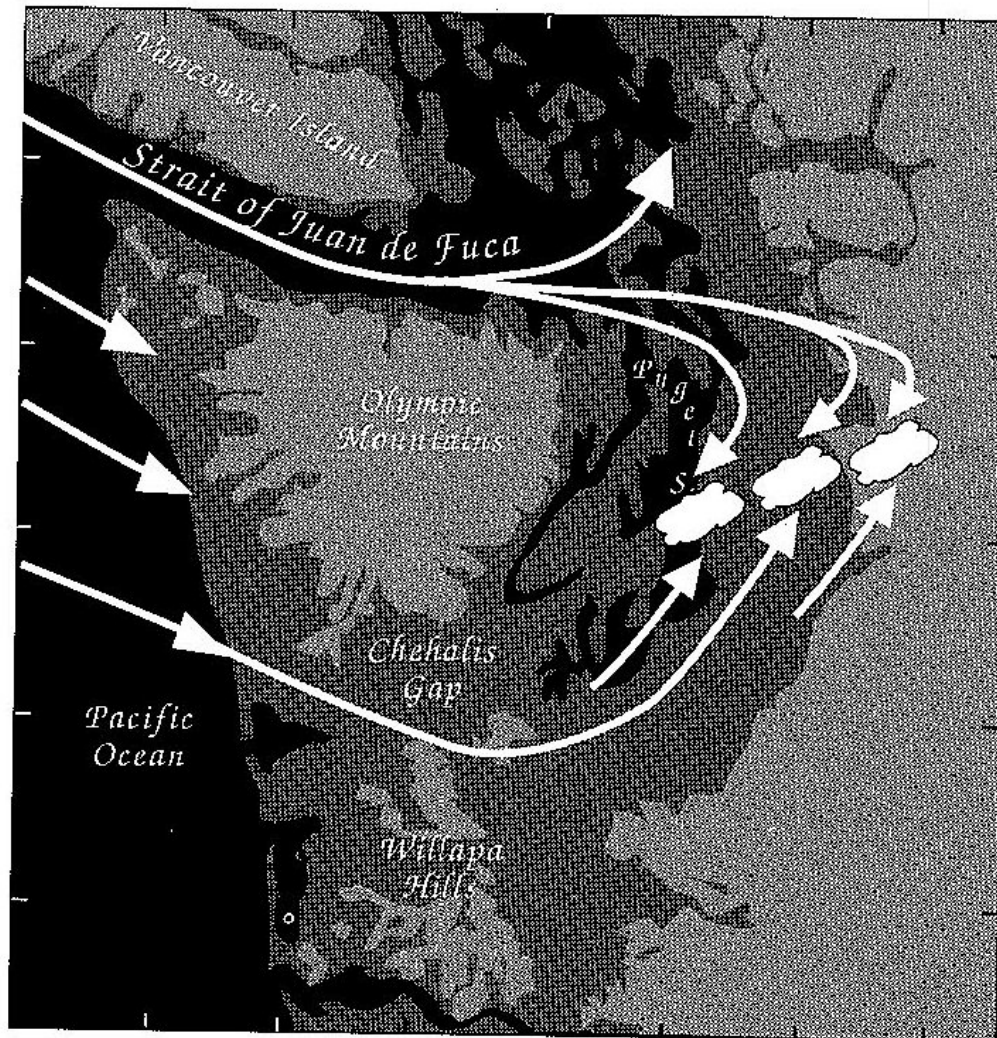
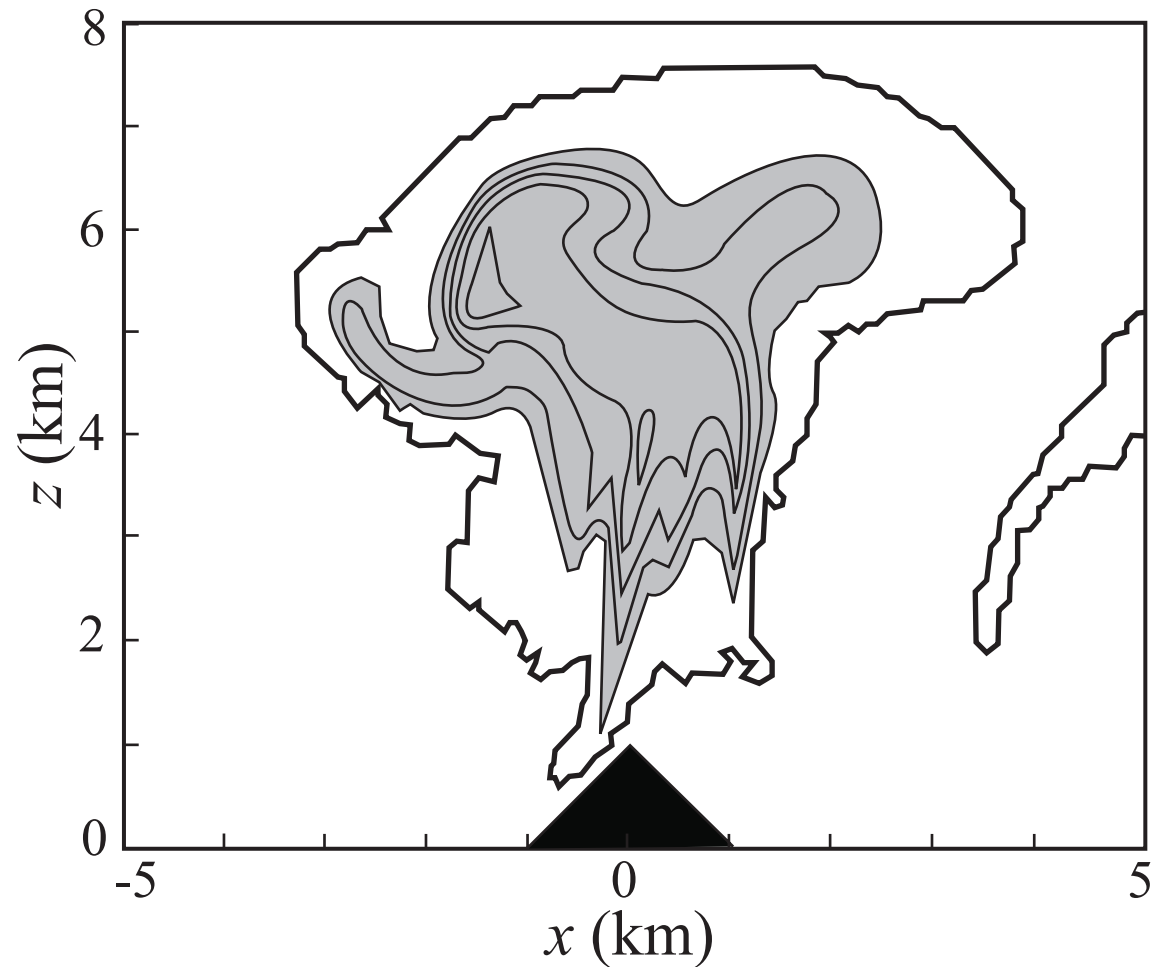


Figure 12.31 Triggering of convection in the lee of the Olympic Mountains under conditions of the Puget Sound Convergence Zone of Washington State. Streamlines represent surface winds. (Adapted from Mass, 1981. Reproduced with permission from the American Meteorological Society.)

Combined thermal and orographic forcing

- During the day, a mountain serves as an elevated heat source due to the sensible heat released by the mountain surface.
- In a quiescent atmosphere, this may induce upslope winds, which in turn may initiate cumuli or thunderstorms over the mountain peak and produce orographic precipitation.
- The cumulus could be advected to lee side of the mountain and produce precipitation over the lee slope if the ambient wind is strong enough.
- This type of orographic cumuli, as well as that induced by orographic lifting alone, has been observed by photogrammetry, instrumented airplanes in the 1950's, and by radars since 1960's.
- The understanding of the dynamics of these thermally and orographically forced cumuli and their associated precipitation has been advanced significantly by numerical modeling simulations since 1970's.
- The next figure shows an example of an orographic rainstorm simulated by an early cloud model.
- Besides sensible heating, cooling over the mountain slope at night may influence the airflow and the formation of clouds and precipitation.



A rainstorm simulated by an early cloud model. The rainstorm is initiated by a combined orographic and thermal forcing. The cloud boundary is depicted by solid curves and the rainwater content exceeding 1 g kg^{-1} is shaded. The vertical domain of the model extends to 10 km (Adapted after Orville and Sloan 1970)

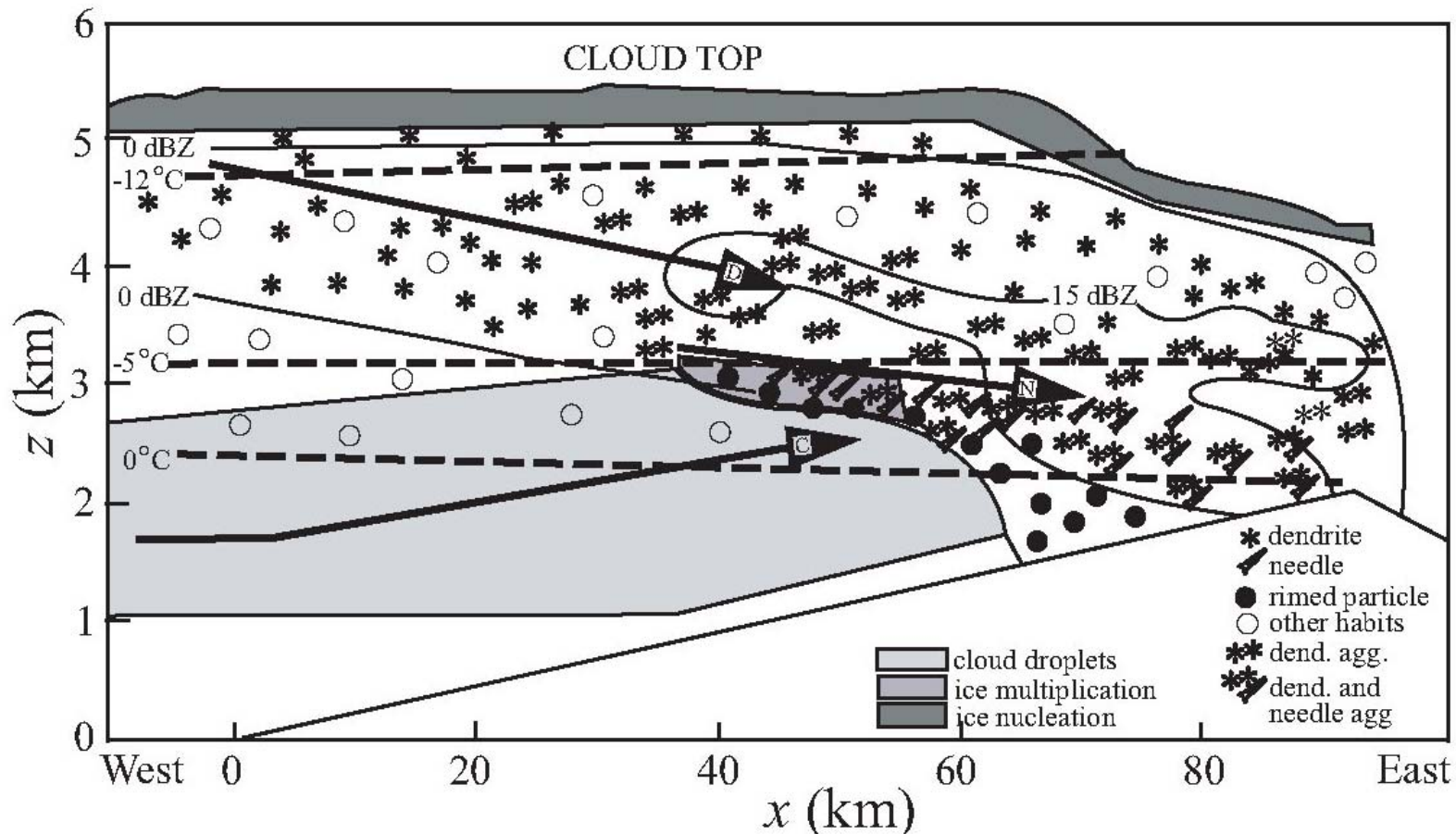
Seeder-feeder mechanism

- Over small hills, there is a remarkably strong dependence of rainfall with height for stratus rain, although topography does not seem to have much effect on convective showers.
- The stable ascent mechanism could not explain the heavy orographic rainfall observed over such small hills, and the phenomenon was then explained by the *seeder-feeder mechanism* (Bergeron 1949).
- Based on this mechanism, cloud droplets in the low-level (feeder) clouds formed by orographic lifting over small hills could be washed out by raindrops or snow from the midlevel (seeder) clouds through coalescence or aggregation process, respectively. In some cases, the feeder clouds may contain ice particles.
- The seeder-feeder mechanism can significantly enhance the rainfall over the small hills, which could not be produced by the feeder clouds alone, which has been applied to explain the rainfall over the Welsh Hills (Browning et al. 1974), where the seeder clouds were associated with potentially unstable air during the passage of a wintertime warm sector.
- Note that the “classic” seeder-feeder mechanism of Bergeron (1949) yields rain over cloud-covered hills that would not otherwise exist without the presence of the seeder particles. However, many cases of orographic precipitation represent enhancements of pre-existing disturbances that produce rainfall prior to their interaction with topography.
- The seeder-feeder process may also combine with other processes that independently yield raindrops at low levels.

Dynamical-microphysical interaction mechanism

Microphysical processes may interact with dynamical processes induced by orography to enhance precipitation in various ways, such as

- (a) increase of vertical transport of water vapor, hydrometeors;
- (b) enhancing the accretion processes, such as coalescence between water (rain or cloud water) drops, aggregation between ice particles and riming between ice particles and water droplets, through the reduction of the lifting condensation level over the mountain surface;
- (c) changes in microphysical pathway in the production of precipitation;
- (d) interception of hydrometeors by a mountain surface at a higher level than that without a mountain;
- (e) changes in the horizontal advection scale of air motion compared to the time scale for microphysical process may change the precipitation distribution over the mountain surface;
- (f) changes in precipitation efficiency;
- (g) enhanced evaporation over the downslope with the addition of adiabatic warming; and
- (h) unsteadiness of small-scale orographic precipitation via turbulent motion. In fact, the seeder-feeder mechanism may also be viewed as a special case of this dynamical-microphysical interaction mechanism.



A conceptual model of the microphysical processes occurring in the orographic cloud and precipitation system, based on the observations of an orographic cloud and precipitation system over the Sierra Nevada on 12 February 1986 during the Sierra Cooperative Pilot Project (SCPP). Two intersection zones of hydrometeor species over the upslope can be seen: $(x, z) = (40-60 \text{ km}, 3 \text{ km})$ and $(70-90 \text{ km}, 2-3 \text{ km})$. Cloud droplet (C), needle (N), and dendritic particle (D) trajectories in the plane of the cross section are indicated by arrows. Radar-echo contours (solid) and isotherms (dashed) are also shown. (Adapted after Rauber 1992)

In this example, two intersection zones of hydrometeor species over the upslope during this event can be seen. One region is located over the middle upslope (about $x = 40$ to 60 km) at about $z = 3$ km, where large cloud droplets rise from the cloud base and interact with the snow dendrites descending from the cloud top. The cloud droplet and snow dendrite interaction leads to secondary ice production from rime splintering and the formation of graupel.

The other region is located near the mountain top (about $x = 70$ to 90 km) in the layer of $z = 2$ to 3 km. In this region, there is enhanced dendritic aggregate production as the ice crystals created by secondary ice production interact with the falling snow crystals.

This conceptual model demonstrates how the cloud microphysical processes are influenced by the orography.