Dynamics of Orographic Precipitating Systems

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Chapter 14 Dynamics of Mountain-Solenoidal Circulations

[Based on Ch. 6 of *Mesoscale Dynamics* (Lin 2007)]

6.6 Dynamics of mountain-plains solenoidal circulations

- The dynamics of *mountain-plains solenoidal (MPS) circulations* is a little explored area of orographically influenced flow and weather phenomena. This is mainly due to the complicated interactions between orographic and thermal forcings.

- Taking into consideration sensible heating or cooling over elevated terrain results in a considerably more complex flow than has been considered until now. The classical view of orographically and thermally forced winds in mountains includes the slope and mountain-valley winds.

  - During the day, the mountain serves as an elevated heat source due to the sensible heat released by the mountain surface.

    In a quiescent atmosphere, this can induce mountain *upslope flow or upslope wind*, which in turn may initiate cumuli or thunderstorms over the mountain peak and produce orographic precipitation.

- At night, the opposite occurs: surface cooling produces downslope *drainage flow*.

➢ Based on observations, four stages in the development of a thermally forced circulation generated by solar heating in a mountain valley have been identified (e.g., Banta 1990):

I. Before sunrise, the nocturnal inversion layer contains drainage flow, which generally blows in a different direction from the winds above the inversion. Just prior to sunrise, this very stable layer remains adjacent to the surface;
II. After sunrise, surface sensible heating erodes the inversion layer and produces a shallow *convective boundary layer* (*CBL*) below the inversion layer and the upslope flow;
III. The shallow CBL or upslope layer deepens as the surface heating continues; and
IV. After the nocturnal inversion layer disappears during the afternoon, a deep, well-mixed CBL is created.

Linear theories described in Sections 6.1 and 6.2 have been applied to study the combined effects of orographic and thermal forcing for mesoscale mountain flow (e.g., Raymond 1972; Smith and Lin 1982). Numerical modeling studies of the combined orographical and thermal forcing have been explored as early as the 1960's (e.g., Orville 1964, 1968). More sophisticated numerical models with a variety of initial conditions have been adopted in the more recent studies of mountain-plains solenoidal circulations. The results given by these models have been verified by conventional observations as well as field experiments (e.g. Tripoli and Cotton 1989; Wolyn and McKee 1994).

➢ Figure 6.26 shows a conceptual model for the daytime evolution of the MPS circulation.

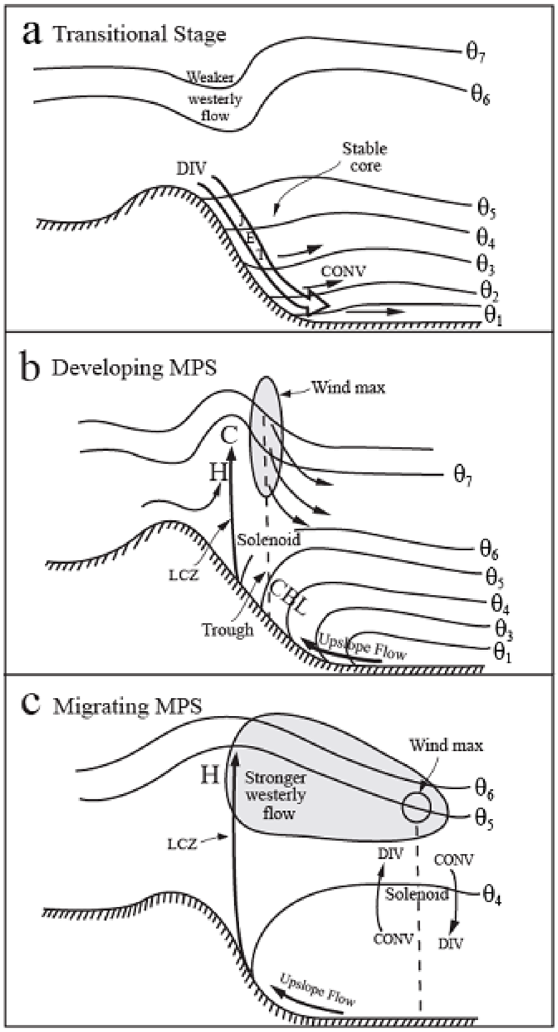

Fig. 6.26: Conceptual model of the daytime evolution of the mountain-plains solenoidal (MPS) circulation east of a mesoscale mountain under conditions of clear skies, steady-state synoptic-scale situation, and light basic westerly wind (e.g., 5 ms^{-1}). Three primary stages may be identified: (a) transition stage, (b) developing MPS stage, and (c) migrating MPS stage. Symbols DIV, CONV, JET, C, H, CBL, and LCZ denote divergence, convergence, katabatic jetlike flow, cold core, higher pressure, convective boundaru layer, and leeside convergence zone, respectively. Regions of wind maximum are shaded. Solid lines are the isentropes. (Adpated after Wolyn and McKee 1994)

The circulation primarily includes:

- Transitional stage
- Developing mountain-plain solenoidal (MPS) stage
- Migrating MPS stage.

The transitional stage occurs when the sun rises. The most pronounced feature of the transition stage is the katabatic jetlike flow down the east side of the mountain (Fig. 6.26a).

The slowing of the nocturnal jet on the eastern plains produces a convergence that lifts the cold air, thus creating a *stable core* that is shallower farther east of the barrier. This nocturnal katabatic flow weakens as it is affected by the surface heating, and is replaced by a mesoscale solenoidal circulation 3-4 h after sunrise (Fig. 6.26b).

A shallow convective boundary layer (CBL) is produced below the inversion layer and an upslope flow is produced by the horizontal pressure gradient force toward the slope in response to the buoyancy associated with the surface sensible heating. The main upward motion of the solenoidal circulation occurs in a narrow zone over the eastern slope of the mountain, and is called the *leeside convergence zone* (LCZ). The LCZ lifts the air into the ambient air above, creating the cold core (denoted by "C" in Fig. 6.26b).
A strong sinking motion occurs to the east of the cold core, creating a pressure trough in which the center of the solenoid is located. The horizontal pressure gradient associated with the cold core and the trough to the east produces a horizontal wind speed maximum. A broad region of sinking motion is located to the east of the solenoid center.

At the later time of this stage, the sinking and horizontal warm-air advection immediately east of the solenoid center is able to warm the air enough to create a negative pressure gradient in the stable core above the CBL.

The final stage of the mountain-plains solenoidal circulation is characterized by the eastward migration (Fig. 6.26c). Convergence (divergence) near the height of the wind maximum region and divergence (convergence) near the surface tend to produce sinking motion ahead (behind) the horizontal wind maximum located beneath the leading edge of the cold core.

The solenoid center is located in a pressure trough beneath the eastward-moving leading edge of the cold core, while the LCZ remains anchored over the lee slopes. Only the migrating MPS may be defined as a disturbance, and as thus can significantly affect the atmosphere on the plains located east of the system during the daytime circulations. The CBL grows explosively and the depth of the upslope flow increases when the solenoid passes a location.

The MPS has been shown to be responsible for producing a strong updraft, which in turn generated the dominant wave of the second episode of gravity waves observed on 11-12 July 1981 during the Cooperative Convective Precipitation Experiment (Koch et al. 2001). A gravity wave was generated as the updraft impinged upon a stratified shear layer above the deep, well-mixed boundary layer developed by strong sensible heating over the Absaroka Mountains. Explosive convection developed directly over the remnant gravity wave as an eastward-propagating density current, produced by a rainband generated within the MPS leeside convergence zone, merged with a westward-propagating density current in eastern Montana. The complicated interactions of differing sensible heat contributions from complex terrain, gravity waves, and convection indicate the need for increasingly detailed observations and theories to verify existing MPS hypotheses and gravity wave generation.

Appendix 6.1: Laplace transform

If a function *f*(*t*) is defined in the interval $0 \le t < \infty$, where t and f(t) are real, then the function $\hat{f}(s)$, defined by the *Laplace integral*

$$\hat{f}(s) = \mathcal{L}(f(t)) = \int_0^\infty f(t)e^{-st}dt, \qquad \text{(A6.1.1)}$$

where *s* is a complex number. The transformation of *f*(*t*) into $\hat{f}(s)$ is called the *Laplace transform*, which is often used to solve differential equations involving time. The first step is to apply (A6.1.1) to transform the differential equation into the Laplace space. The second is to find the solution for the unknown function $\hat{f}(s)$ in the Laplace space. The third step is to invert $\hat{f}(s)$ back to the physical space *f*(*t*), i.e., to take the *inverse Laplace transform*. The actual inverse Laplace transform involves the contour integration in the complex plane, but in practice it is often performed by applying some known properties of Laplace transform, such as the linear property,

$$\mathcal{L}(af(t) + bg(t)) = a\hat{f}(s) + b\hat{g}(s). \qquad \text{(A6.1.2)}$$

Some basic properties of Laplace transform and inverse Laplace transform can be found in Hildebrand (1976), among other mathematical textbooks.

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