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Essential Ingredients for Heavy Orographic Rainfall and their Potential Application for Prediction

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1. Introduction

By examining several heavy orographic rainfall events in the US, several authors (e.g. Maddox et al. 1978; Pontrelli et al. 1999) found some common synoptic and mesoscale environments: (1) a low-level jet (LLJ) with high θe impinging on the mountain, (2) a deep shortwave trough propagating towards the mountain, and (3) an upper-tropospheric pressure ridge to slow the movement of convective system. Note that a high value of CAPE is not consistently observed for these events. In this study, we examine these conditions in heavy orographic rainfall events in Alps.

2. Synoptic and mesoscale environments conducive to heavy orographic rainfall in Alps

In analyzing some heavy orographic precipitation events which have occurred over the southern Alps (e.g., the Vaison-la-Romaine event, the Brig and South Ticino, and the Piedmont) during the fall season, Massacand et al. (1998) found that all of these events were accompanied by a deep, narrow, and elongated upper-tropospheric filament of extruded stratospheric air, which extended in a meridianally-oriented (north-south) direction from the British isles to the western Mediterranean. In each case, the filament of stratospheric air translated relatively slowly eastward, and the storm event ensued as the filament's forward flank approached the Alpine ridge. They proposed that these high PV streamers act as a precursor and tend to: (i) enhance the southerly flow component toward the Alps, (ii) reduce the static stability beneath the upper-level PV anomaly and (iii) trigger ascent on the PV streamer's forward flank to generate or enhance convection. The ascent induced by the forward (eastern) flank of the upper-level trough or PV streamer may coincide with the low-level orographically induced upward motion to trigger vigorous convection.

In investigating heavy orographic rain over the southern Alps, Buzzi and Foschini (2000) found that the following large and mesoscale flow features are important: (1) The flow at low levels maintains a southerly direction over the western Mediterranean, with pronounced confluence over the western Alps, between the post-frontal southwesterly flow and the pre-frontal southeasterly flow located more to the east. (2) There exists an 850 hPa pre-frontal LLJ which serves as a "warm conveyor belt" that flows directly towards western Alps. (3) There exists a deep upper-tropospheric trough approaching the Alps. (4) There exists a quasi-stationary pressure ridge in the upper-troposphere, located to the east, associated with an anticyclone over Eastern Europe.

It appears that the high PV streamers found by Massacand et al. (1998) are related to the deep shortwave trough found in Buzzi et al.'s studies (e.g. 2000). In addition, if one inspects Massacand et al.'s figures closely, it can be seen that there also exists a quasi-stationary pressure ridge to the east of the high-PV streamer in all cases, which was not emphasized in their paper. The low-level jets which occurred just before the onset of the heavy orographic rainfall events were partially associated with the approaching deep shortwave troughs. In other words, the approaching deep shortwave trough not only provides the upper-level divergence for additional upward motion over the upsloping topography on its forward (eastern) flank, but it also strengthens the LLJ and helps bring the deep layer of conditionally unstable air from the Mediterranean Sea to interact with the Alpine mountains to produce diffluence and outflow aloft. Similar to US events, high values of CAPE are not consistently observed in Alpine heavy orographic rainfall events. One particular flow feature associated with the majority of Alpine heavy orographic rainfall events is that convection often starts in the concave region south of Alps, such as the Lago Maggiore and Ticino regions (Buzzi and Foschini 2000). This confluent flow tends to enhance the low-level upward motion induced by the upslope, which in turn triggers the convection.

Figure 1 shows the accumulated 12-h rainfall ending at 00UTC and 12UTC 20 September 1999 during the MAP IOP2 heavy orographic rainfall event. The rainfall accumulated during the whole event (13UTC 19 September 1999 to 01UTC 21 September 1999) in the Lago Maggiore region ranges from 100 to 300 mm (Fig. 1). The rainfall region during the 12-h period ending at 00UTC 20 September (Fig. 1) extended from the Gulf of

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Genoa to the Lago Maggiore region, with the heaviest precipitation focused in the Lago Maggiore area. The maximum 12-h rainfall amount reaches 130 mm. This heavy rainfall area was associated with the impinging trough (not shown), which brought in from the Ligurian Sea air of high moisture content. Similar to the previously discussed historical events, the upper-level pressure ridge located to the east of the approaching deep shortwave trough is quasi-stationary (not shown). It can be seen clearly from Fig. 1 that the rainfall started in the Lago Maggiore region (Fig. 1a), which is located in the concave topography region of the southern slopes of the European Alps (see 500m contour in Fig. 2b). During the next 12-h period ending 12UTC 20 September, the heavy rainfall encompassed the entire southern slopes of the Alps, where the maximum rainfall amount reached a value higher than 130 mm (Fig. 1).

The impinging deep shortwave trough helped induce the southerly low-level jet, which reached a maximum value of about 12.5 ms^{-1} at Milan, Italy. CAPE values calculated from the Milan soundings were very small (149 J kg^{-1} and 201 J kg^{-1} at 00UTC and 12UTC 20 September, respectively). As also found in previous studies of historical flash flooding events over the southern Alps, the low-level jet is very moist, which has a tongue of high moisture with water vapor mixing ratio (q_v) covering northern Italy and the Lago Maggiore region. This high moisture tongue was increasing during the heavy rainfall period for the next 12 h.

In summary, similar to the US cases, the synoptic and mesoscale environments conducive to heavy orographic rainfall in the European Alps are: (1) a conditionally or potentially unstable airstream impinging on the mountains, (2) a very moist LLJ, (3) steep mountains to help release instability, (4) an upper-tropospheric deep shortwave trough or high-PV (potential vorticity) anomaly approaching the threat area (which helps to enhance low-level upward motion), and (5) an upper-tropospheric quasi-stationary high pressure ridge to force the convective system to be quasi-stationary or slow it's forward progress over the threat area. In addition, the low-level confluent flow plays an important role in helping to trigger the convection in the Alpine cases. For the MAP IOP-2 case, a tongue of high moisture extended into the threat area. In the next section, we will examine whether or not these conditions are essential for producing heavy orographic rainfall in East Asia.

In examining 3 heavy orographic rain events associated with tropical depressions approaching Taiwan and Japan, we found the following common synoptic and mesoscale features are essential for producing heavy orographic rainfall associated with a tropical storm or depression in Taiwan and Japan: (1) A steep mountain helps to release instability. (2) A tropical storm or depression helps enhance the low-level jet (LLJ). (3) The LLJ is highly conditionally (i.e. high CAPE) and potentially unstable. (4) A quasi-stationary synoptic system, such as a typhoon in Taiwanese cases or a stationary front in Japanese cases, acts to impede or slow the movement of the convective system over the mountains.

3. Some essential ingredients for producing heavy orographic rainfall

Based on Doswell et al. (1996), the total precipitation produced is determined by

$$P = E(wq)L_s / c_s \,, \qquad (1)$$

where *E* is the precipitation efficiency, *wq* the vertical moisture flux, *Ls* and c_s the horizontal scale and propagation speed of the convective system, respectively. For flow over a mountain range, the upward vertical motion may be estimated by

$$w = w_{oro} + w_{env} = \boldsymbol{V_H} \cdot \nabla h + w_{env} \,, \qquad (2)$$

where w_{env} is the environmentally-induced vertical motion, *h(x,y)* is the mountain geometry and $\boldsymbol{V_H}$ is the horizontal wind. The environmentally-forced upward vertical motion (w_{env}) is determined by the transient synoptic setting, such as the divergence associated with an approaching deep shortwave trough. Combining Eqs. (1) and (2) gives

$$P = E\left[\boldsymbol{V_H} \cdot \nabla h + w_{env}\right] q\, L_s / c_s \,. \qquad (3)$$

Doswell et al. (1998) has used a form similar to $\boldsymbol{V_H} \cdot \nabla h$ to diagnose three episodes of heavy rainfall in the western Mediterranean. Therefore, Eq. (3) indicates that a heavy orographic rainfall requires significant contributions from any combination of the following essential ingredients: (1) An incoming flow with high efficiency, (2) an intense low-level jet, (3) steep orography, (4) favorable (e.g. concave) mountain geometry and a confluent flow field, (5) strong environmentally-forced *w*, (6) a high moisture flow upstream, (7) the presence of a large, pre-existing convective system, (8) impeded movement of the convective system, and (9) a conditionally or potentially unstable low-level flow. Ingredient (9) is required for a deep convective system, which is often the case for heavy orographic rainfall events.

It appears that the common synoptic and mesoscale conditions conducive to heavy orographic rainfall over US, Alpine, Taiwan, and Japan mountains belong to a subset of the above listed essential ingredients. Although a high CAPE is not consistently observed for US and Alpine heavy orographic rainfall events, this remains to be investigated. For Alpine heavy oro-graphic rainfall events, which often start in a concave region (such as the Ticino and Lago Maggiore regions), mesoscale vertical motion may be produced if there exists incoming confluent flow as indicated by ingredient (4).

In Table 1, we have provided rough estimates for some of the essential ingredients apparently responsible for producing heavy orographic rain in the US, the European Alps, and East Asia. These include the low-level wind (*U*), mountain slope ($\partial h / \partial x$), water vapor mixing ratio (*q*), and CAPE. Note that w_{env} is difficult to estimate without fine-resolution data, so that we just denote whether or not there is an approaching synoptic scale system (such as a deep shortwave trough), which is able to enhance the low-level upward vertical motion. It is also difficult to estimate the horizontal scale of the convective system and its propagation speed (c_s). Thus, as a first attempt, we only provide estimates for *U*, $\partial h / \partial x$, and *q* and compare them with the maximum observed rainfall rate. For Alpine events, the index is > 4.7 (except for the South Ticino case). Therefore, this proposed index may help provide additionally valuable information for helping to predict the occurrence of upstream heavy orographic rainfall events. For the Taiwanese and Japanese cases, it has a relatively high value (e.g. > 6) and the proposed index is roughly proportional to the observed maximum rainfall rates. For US events, it appears that the index has a lower value, but is still >2.7. With w_{env} included, the index should be able to reach a higher value (comparable to those estimated for the Taiwanese and Japanese cases).

Fig. 2 shows a distribution of a more complete index, such as $(\boldsymbol{V_H} \cdot \nabla h)\, q$, for MAP IOP2 by using triply nested MM5 simulated results. A similar index has also been used by Doswell et al. (1998). The horizontal resolution is 5 km and the predicted fields are valid at 12UTC 20 September 1999, which is within the heaviest rainfall period. From the figure, it can be seen that the horizontal distribution of the proposed index (Fig. 2a) compares fairly well with observed 12 h rainfall (Fig. 1) and model predicted rainfall distribution (Fig. 2b).

4. Concluding Remarks

Similar to US events, the following common features are also observed in the European and East Asian cases: (1) a conditionally or potentially unstable airstream impinging on the mountains, (2) the presence of a very moist LLJ, (3) the presence of steep orography to help release instability, and (4) the presence of a quasi-stationary synoptic scale system is required to impede or slow the progress of the orographically-forced convective system over the threat area. A deep short-wave trough or positive potential vorticity (PV) anomaly is found to approach the threat area in both the US and Alpine cases, but is absent in the East Asian cases. On the other hand, high values of CAPE are observed in the East Asian cases, but are not consistently observed in either the US or Alpine cases. The quasi-stationary synoptic system can be different in different regions, but plays similar role as to retard or impede the convective system. In both the Alpine and Taiwanese cases, convection often starts in a concave region of the mountain, which induces confluent flow and enhances the upward vertical motion.

Based on an ingredient argument, we found that heavy orographic rainfall requires significant contributions from any combination of some essential ingredients. The common synoptic and mesoscale environmental environments conducive to heavy orographic rainfall events observed in the US, Europe, and East Asia appear to belong to this set of essential ingredients. In addition, these essential ingredients are also used to help explain the synoptic and mesoscale environments observed in some heavy orographic rainfall events occurred in China, New Zealand, and India.

We also proposed an index $U(\partial h / \partial x) q$ to help predict the occurrence of heavy orographic rainfall. This quantity appears to be promising. By applying a more complete form, such as $(\boldsymbol{V_H} \cdot \nabla h)\, q$, to MAP IOP2 event, we found the distribution of the index value compares well with the rainfall data predicted by a mesoscale model.

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Table 1: An estimate of the contributions from some ingredients

Event	***U*** (m/s)	**Mtn Slope** ($\partial h/\partial x$)	**q** (g/kg)	**Index** [$U(\partial h/\partial x)q$]	w_{env}	**Max. Rainfall Rate**	**CAPE** (J/kg)
Vaison-la Romaine	15(20)	0.027	15 (12)	6.1+	trough	300 mm/d	2662 (383)
Piedmont	13	0.033	11	4.7+	trough	250 mm/d	212
South Ticino	10	0.033	9.3	3.1+	trough	260 mm/d (130 mm/6h)	383
Lago Maggiore IOP2)	12.5	0.033	11.5	4.7+	trough	300 mm/36h	90
Big Thompson	12.5	0.025	16	5.0+*	trough	915 mm/d (305 mm/4h)	2526
Rapid City	12.5	0.020	13.5	3.4+	trough	1143 mm/d (381 mm/4h)	------ (<2180)
Ft. Collins	10	0.021	13	2.7+	trough	519 mm/d (259 mm/6h)	628
Madison County	12.5	0.025	16	5.0+	trough	600 mm/d	286
Taiwan-1999	10.0	0.033	21	6.9	No	200 mm/d	2099
Taiwan-1959	17.5	0.033	22	12.7	No	500 mm/d	2406
Japan	17.5	0.020	19	6.7	No	150 mm/d	1149

* The symbol "+" indicates that the index may be higher with the addition of w_{env} associated with an approaching synoptic system.

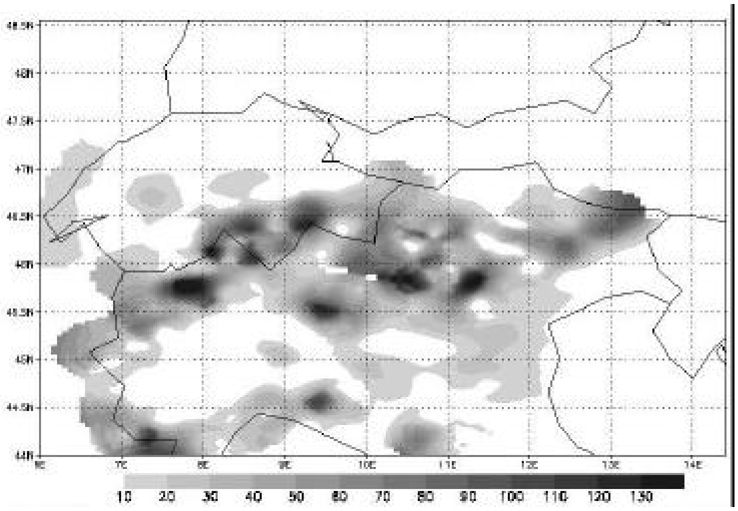
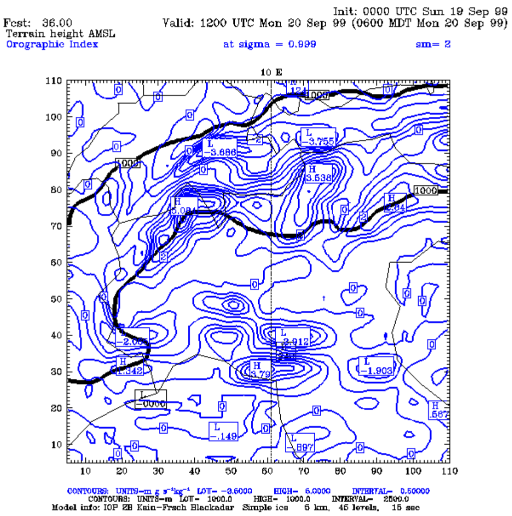


Fig. 1: Observed 12-h rainfall accumulations ending at 12UTC 20 September 1999 for the MAP IOP-2 heavy rainfall event.



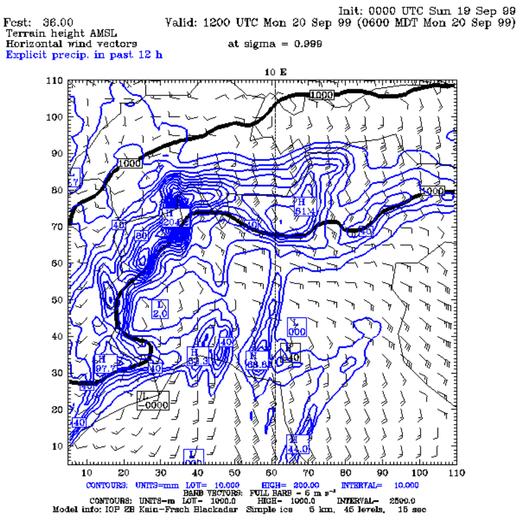


Fig. 2: (a) Orographic moisture flux index, $(\boldsymbol{V}_H \cdot \nabla \mathrm{h})\,\mathrm{q}$, calculated from a 5-km resolution MM5 simulation results, and (b) MM5 model predicted rainfall. Both are valid at 12UTC 20 September 1999. The 500 m terrain contour is also depicted in panel