Sensitivities of orographic precipitation to terrain geometry in idealized simulations

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1. Introduction and motivation

The dimensions of a mountain (height, length, width) can strongly influence the flow response and associated orographic precipitation. In this study, we consider variations to the

- Non-dimensional mountain height ($\hat{H}$)
- Horizontal aspect ratio (β)

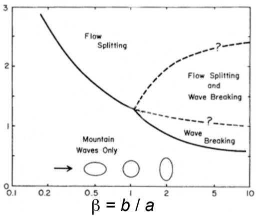
for different terrain shapes, where

- $\hat{H} = N h / U$, N is the Brunt-Vaisalla Frequency
  , h is the mountain height
  , U is the impinging wind speed
- $\beta = b / a$, b is the mountain length
  , a is the mountain width

FLOW REGIME DIAGRAM

The flow regime diagram by Smith (1989) illustrates how changes to $\hat{H}$ and β can modify the orographic response of an impinging flow. It identifies the critical values of $\hat{H}$ for the onset of wave breaking and flow splitting with respect to β.

A flow regime transition can significantly change the amount and distribution of orographic precipitation, dictating the transition from flow-over the obstacle (mountain waves / wave breaking) to flow-around the obstacle (flow-splitting).



A regime diagram for hydrostatic flow over a mountain, adapted from Smith (1989).

Moisture is important. Smith's (1989) regime diagram is derived for a dry flow. The addition of moisture can reduce flow stability in saturated regions and increase the critical-$\hat{H}$ for regime transition via release of latent heat.

Terrain shape is important. A study by Jiang (2006) showed a concave ridge reduces the critical-$\hat{H}$ compared to a straight ridge due to stronger flow deceleration.

AIM: **Changes in the flow response has important implications for precipitation. How do variations to $\hat{H}$ and β influence the orographic flow response and associated precipitation for a straight and a concave ridge?**

2. Experimental Design

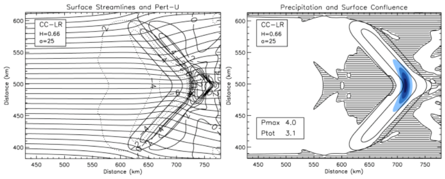
An idealized three-dimensional model (WRF V3.1.1) is initialized with a sounding representative of a pre-frontal NW flow that produced heavy precipitation in the Australian Alps.

The single sounding has:
- unidirectional wind profile (along x-axis) of 20 m s^{-1}
- average low-level stability of N ≈ 0.012 s^{-2}
- stable to parcel ascent
- average upstream relative humidity of 75 %
- freezing level at 2.1 km

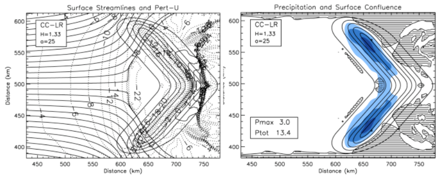
Experimental constants			Sensitivity to $\hat{H}$			Sensitivity to a		
Expt	b	α	$\hat{H}$	h_m	N	**Expt**	a	β
ST-SR	50 km	0	0.66	1.025 km	0.013	Narrow	12.5 km	8.0
ST-LR	100 km	0	0.8	1.28 km	0.0125	Control	25 km	4.0
CC-SR	50 km	45°	1.0	1.65 km	0.0121	Wide	50 km	2.0
CC-LR	100 km	45°	1.33	2.25 km	0.0118			
			2.0	3.4 km	0.0117			

3. Results

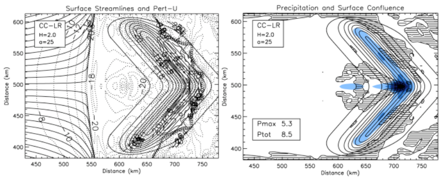
FLOW CONFLUENCE AND PRECIPITATION



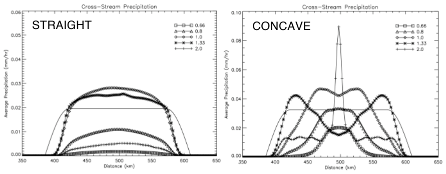
- The forward-reaching arms of a concave ridge can induce a region of flow confluence near the vertex (the hatched region) when the flow is unblocked (mountain waves).
- This is characteristic of and fundamental to the precipitation enhancing funneling mechanism (Jiang 2006).



- When $\hat{H}$ increases and flow splitting is induced, the impinging flow is deflected away from the vertex and passes over the ridge arms.
- This diminishes the flow confluence zone between the ridge arms.
- The deflection of flow away from the vertex changes the distribution of precipitation from a single precipitation maximum to a dual-precipitation maxima.



- When $\hat{H}$ is sufficiently large, flow reversal develops on the windward slope.
- Flow-reversal can initiate a secondary circulation on the windward slope, where incoming flow converges with the reverse-downslope flow. This generates updrafts detached from the surface.
- The forward-reaching arms of the concave ridge funnel the reverse downslope flow toward the vertex, enhancing the secondary circulation and expanding the flow confluence zone.
- The precipitation maximum returns to the vertex, flanked by two, small local precipitation maxima near the ridge ends.

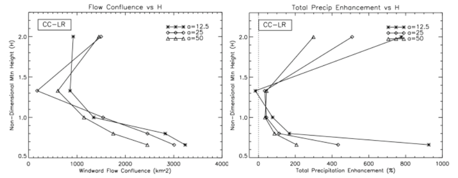


- The average cross-stream precipitation illustrates how variations to $\hat{H}$ influence precipitation differently for the straight ridge and the concave ridge.
- When the flow is unblocked, precipitation increases for both the straight and concave ridge.
- The onset of flow-splitting (blocked flow) reduces precipitation substantially for the straight ridge, whereas precipitation is redistributed for the concave ridge.
- Precipitation for the concave ridge is more sensitive to changes in $\hat{H}$, especially when the ridge is long and narrow (large β).

3. Results (cont.)

PRECIPITATION ENHANCEMENT

- The concave ridge generates more precipitation than the corresponding straight ridge in almost all cases.
- The enhancement of precipitation by the concave ridge relative to the straight ridge is closely tied to flow confluence.
- The flow confluence zone shrinks as $\hat{H}$ increases, although it redevelops with the onset of flow reversal (LEFT FIG).
- The strength of the precipitation enhancement has a similar relationship to $\hat{H}$ (RIGHT FIG).

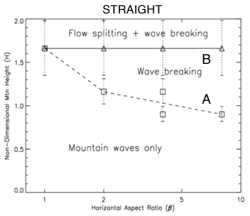


- The largest precipitation enhancement occurs when the flow is very unblocked (i.e., $\hat{H}$ is small).
- It was believed that the concave ridge would not enhance precipitation relative to the straight ridge when the flow was blocked, however the funneling of the reverse-downslope flow (which strengthens the secondary circulation above the windward slope) facilitates an enhancement of precipitation.

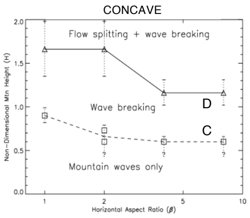
FLOW REGIME DIAGRAM

- A flow regime diagram is constructed for the straight and concave ridge using results from all simulations.

- The regime diagram for the straight ridge shows good qualitative agreement with Smith's (1989) regime diagram.
- Curves A and B are 30-40% higher in this study because of moisture effects (the release of latent heat when saturation occurs aids flow over the ridge).



- The concave ridge reduces the critical-$\hat{H}$ for regime transition (consistent with Jiang, 2006), hence curves C and D are lower than for the straight ridge.
- Lower bound of curve C when β > 2?
- Where do curves C and D intersect?



4. Summary

Examination of variations to the height, length and width of two relatively simple terrain geometries has illustrated the sensitivity of precipitation to flow-regime transitions and the influence of terrain shape.

A surprising result was the re-strengthening of the precipitation enhancing funneling mechanism near the vertex of the concave ridge when $\hat{H}$ was sufficiently large to induce flow reversal. The resultant pattern of precipitation was substantially different to that shown in previous studies.

For further details see Watson and Lane (2012, *J. Atmos. Sci*, **69**, 1208-1231).