Microscale and mesoscale modeling of extreme convective rainfall in mountainous terrain

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Overview

- Focus placed on extreme **convective** precipitation at **sub-daily** time scales
  - Rules out long-lived stratiform precipitation events (e.g., west-coast atmospheric rivers)

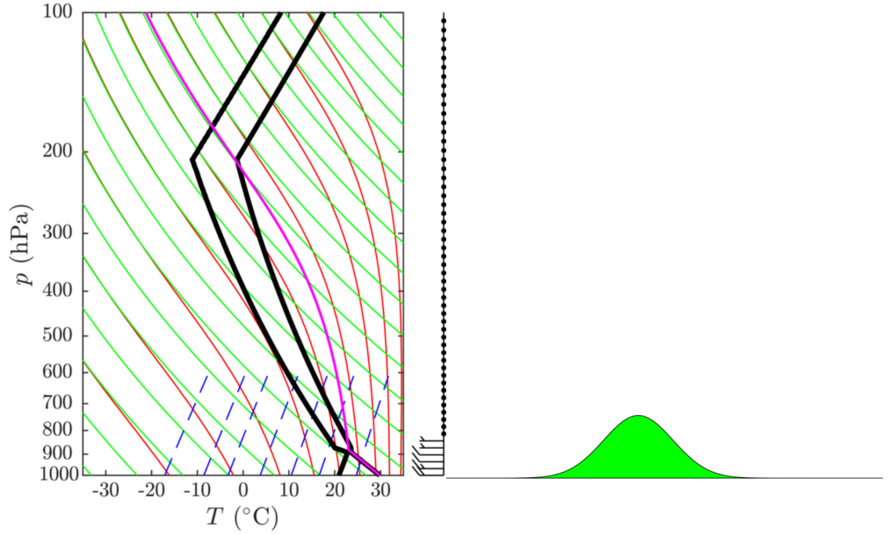
- Physical considerations
  - Synoptic requirements
  - Mesoscale mechanisms anchoring/training storm cells

- Modelling challenges
  - Resolution considerations
  - Sensitive parameterized processes

Synoptic requirements

- From Lin et al. (2001)
  - Moist low-level jet impinging on terrain
  - Conditional/potential instability: necessary for DCI, but amounts vary greatly across events
  - Steep terrain?

- Other factors
  - Low-level inversion: may inhibit upstream convection (Big Thompson). Also, promotes valley channeling and more focused uplift regions
  - Vertical shear: reverse shear is favorable for heavy precipitation (Miglietta and Rotunno, 2014)

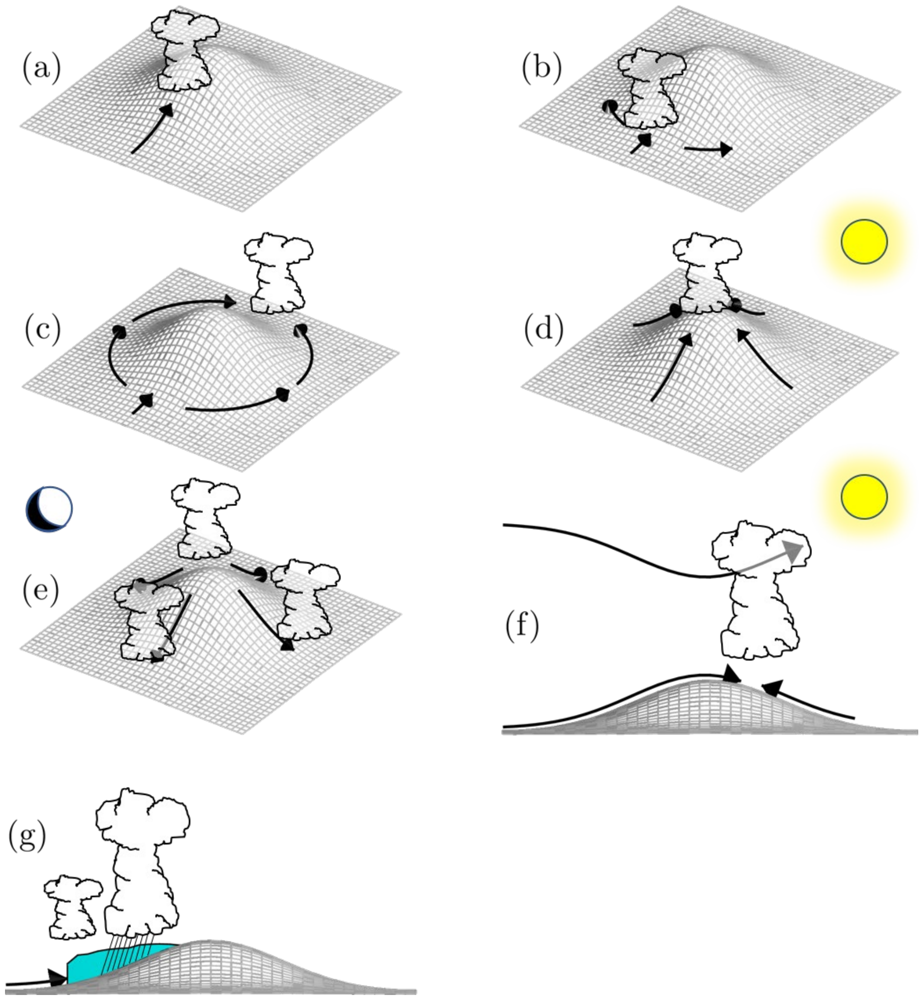


Mesoscale orographic convection mechanisms

- Mechanical, thermal, or some combination thereof

- How does picture change over more realistic terrain with multiscale ridge—valley systems?
    - How important are terrain variations on scales of 1-10 km?

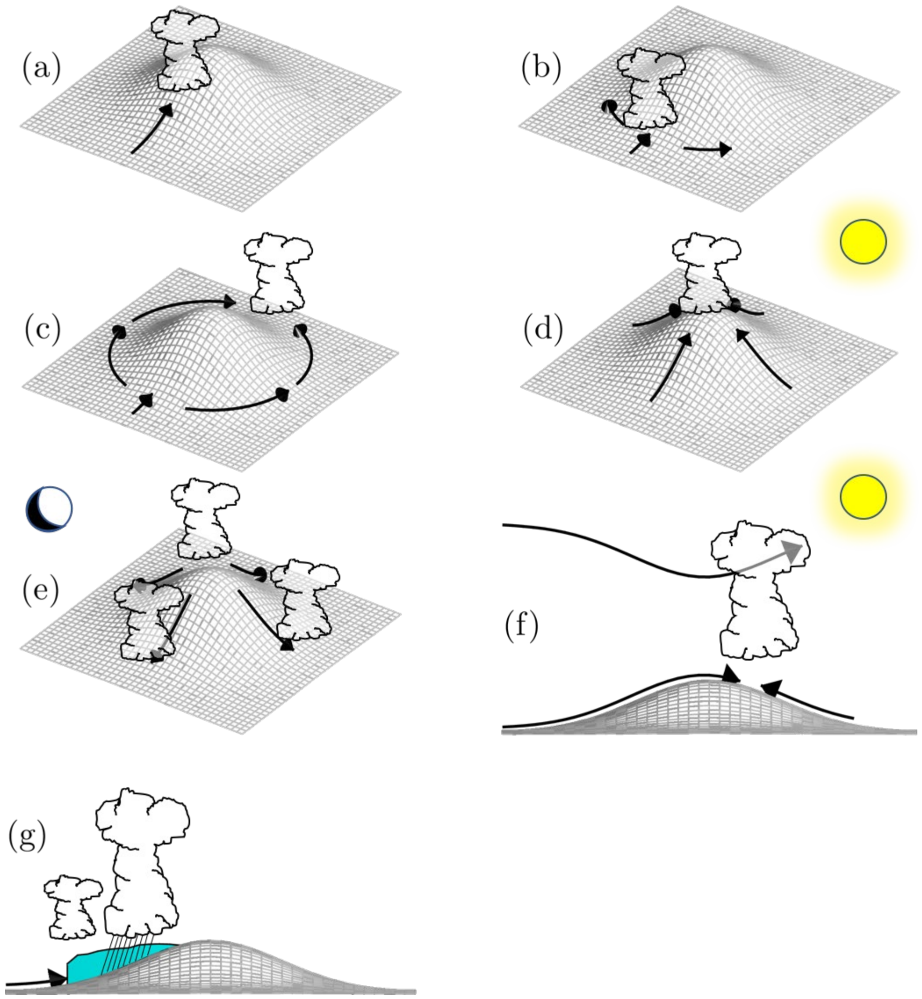
Kirshbaum et al. (2018)



Extremes: mechanical or thermal?

- Extreme events are likely dominated by mechanical forcing, not thermal forcing
- Why? Thermally forced convection is moisture-limited
  - Thermal circulations carry moisture uphill, but they are typically shallow (~1/2 CBL depth)
  - Moist air mixes with dry air aloft en route to crest
- Mechanical forcing, in contrast, can carry a much deeper moist layer uphill
  - Layer mixes with itself en route to crest

Kirshbaum et al. (2018)

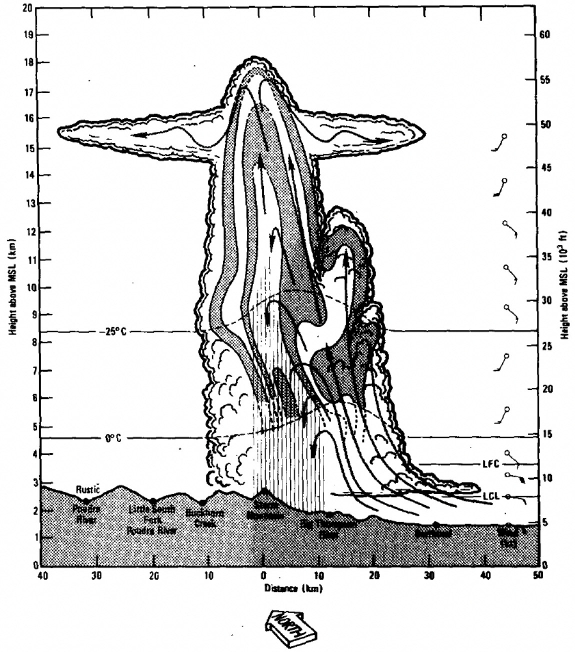


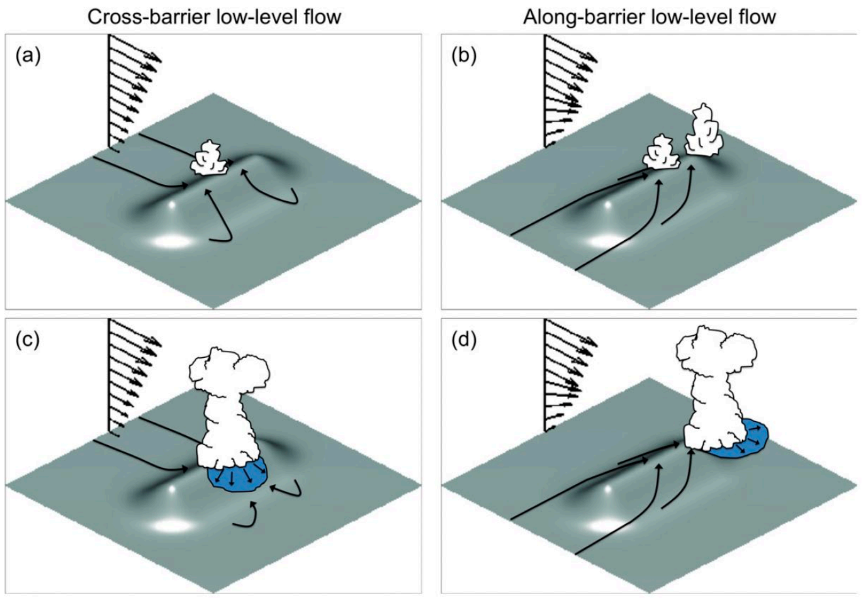
Storm duration

- Extreme precipitation requires storms to remain stationary or to repeatedly traverse the same locations
  - Requires separation between storm inflow and outflow (cold pool)

- Achieving the separation
  - Deep moist layer and orographic ascent may saturate flow over deep layer, inhibiting cold pool formation (Smethport?)
  - Impinging low-level jet may arrest upstream cold-pool propagation (Big Thompson?)
  - Ridgeline-parallel low-level flow can shift cold pools into lee (Soderholm et al. 2014)

Caraceña et al. (1978)

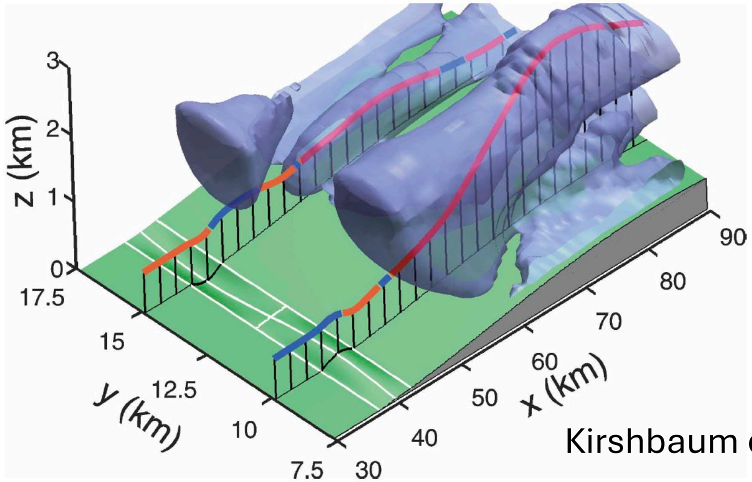




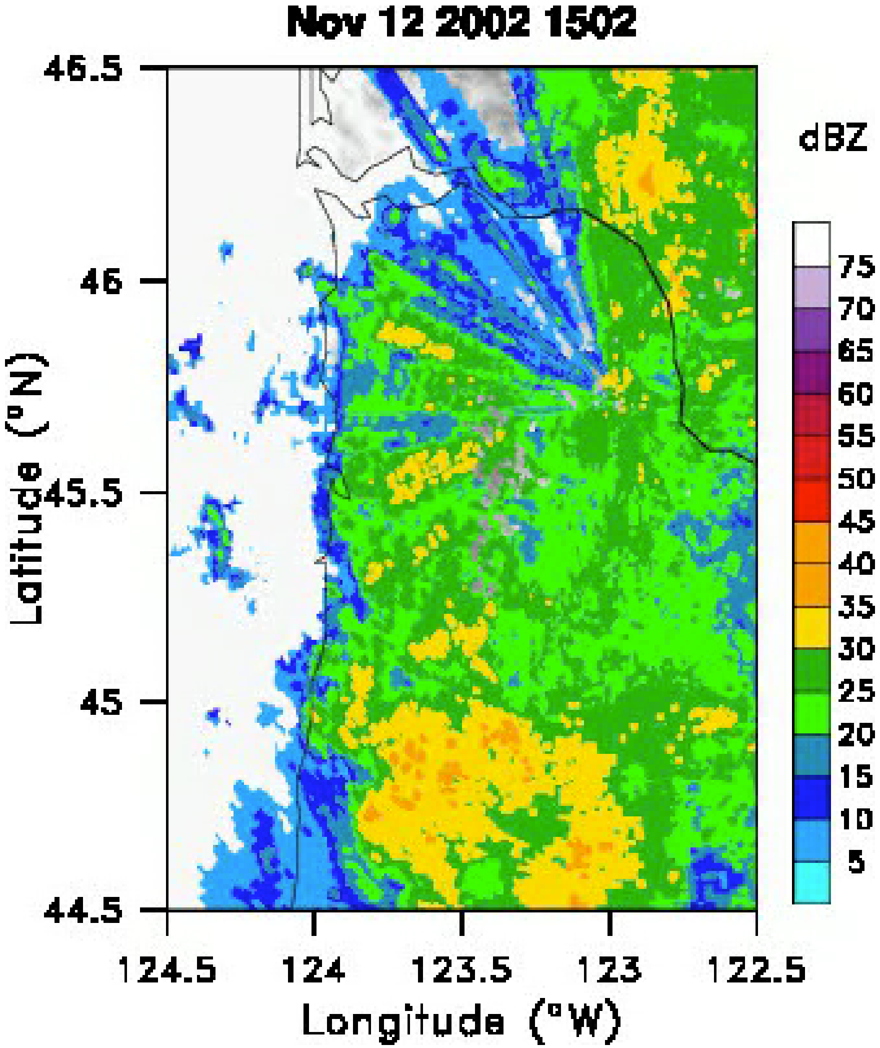
Soderholm et al. (2014)

Some anchoring mechanisms

- Lee-wave initiation of bands over small-scale peaks on mesoscale ridge (Kirshbaum et al., 2007)
  - Observed in cold season, but may extend to warm-season deep convection

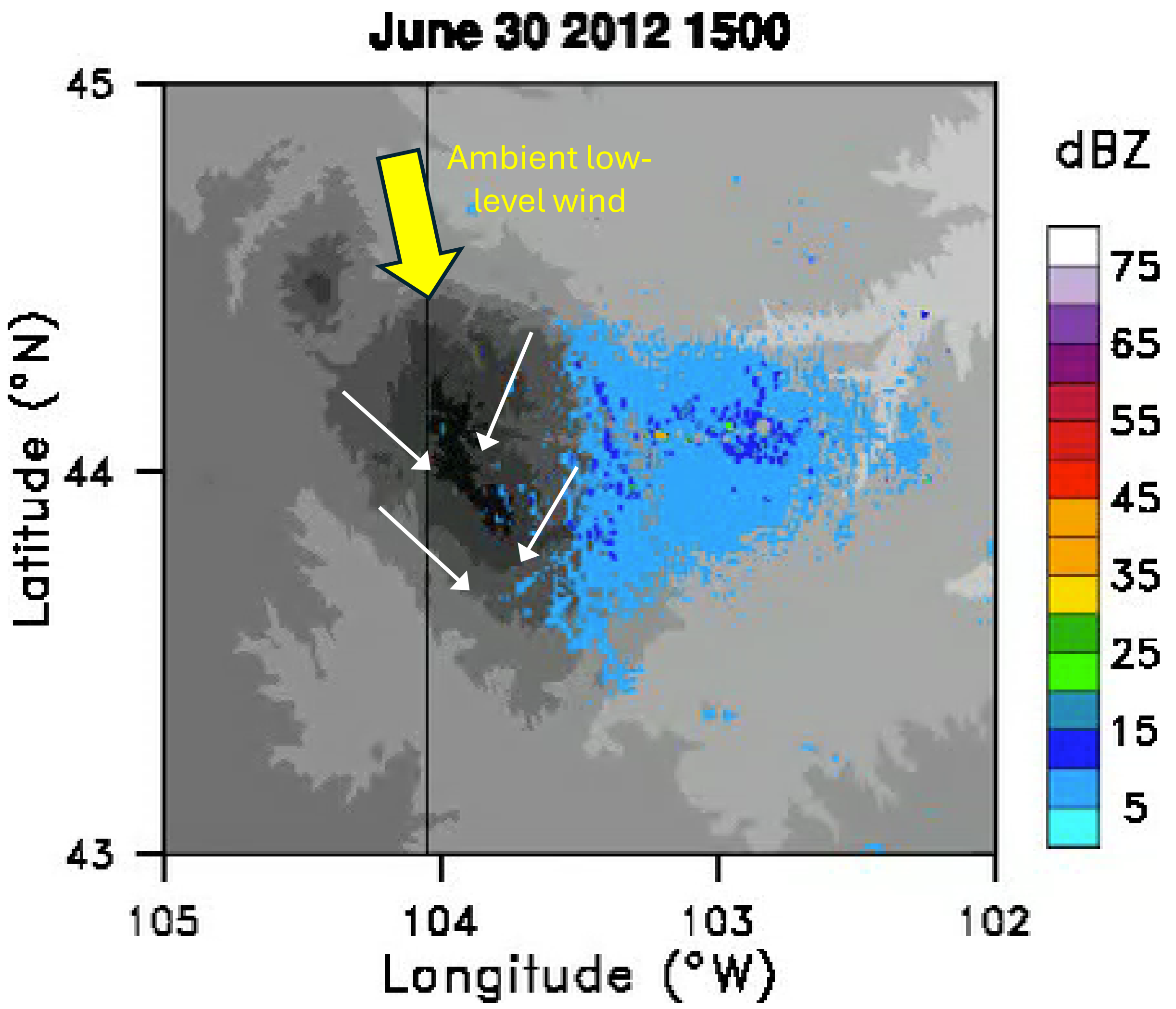


Kirshbaum et al. (2007)



Some anchoring mechanisms

- Along-ridge low-level winds separate inflow from outflow (Soderholm et al. 2014)
    - Thermally driven upslope flow converges along ridge axis
    - Storms and attendant cold pools develop on lee side
- Black Hills case (June 30, 2012)
    - 88 mm radar-derived rain in 90 min
    - N low-level flow; W flow aloft



Some anchoring mechanisms

- Miglietta and Rotunno (2014)
  - Reverse-sheared cross-barrier wind profile can hold cold pool at bay
  - Low-level impinging jet at surface; weak cross-barrier winds aloft

- Other benefits of reverse shear
  - RKW theory (Rotunno et al. 1988): supports more upright updrafts along gust front
  - Inhibits mountain-wave vertical propagation—no wave downdrafts aloft
  - May also favor storm rotation

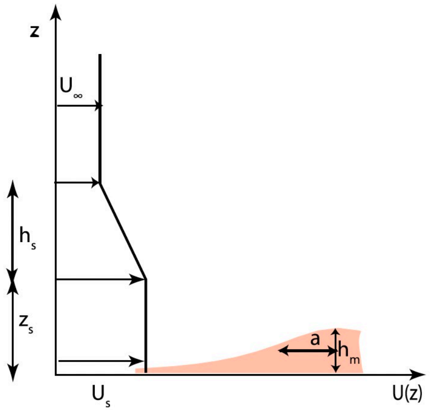


FIG. 1. Parameters varied in the experiments.

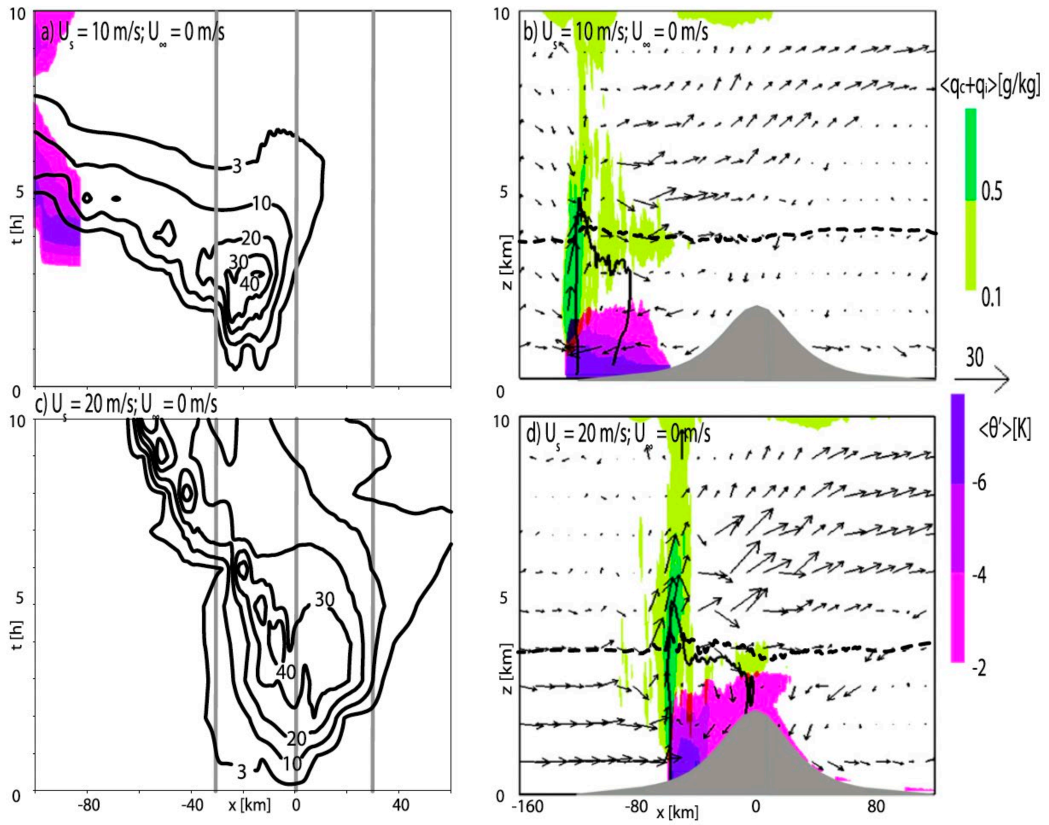


FIG. 3. Zero-wind-aloft cases: as in Fig. 2, but for (a),(b) expt A.3 ($U_s = 10\,\mathrm{m\,s^{-1}}$, $U_\infty = 0\,\mathrm{m\,s^{-1}}$) and (c),(d) expt A.14 ($U_s = 20\,\mathrm{m\,s^{-1}}$, $U_\infty = 0\,\mathrm{m\,s^{-1}}$). The vertical cross sections are shown, respectively, at $t = 6$ h (expt A.3) and at the final integration time $t = 10$ h (expt A.14).

What is the specific role of orography in these events?

- As a cell enhancer (Smethport?)
  - Dominant mechanisms are nonorographic and may be understood from conventional synoptic—mesoscale analyses
  - Orography primarily serves to wring more precipitation out of cells

- As a cell initiator (Big Thompson, Madison County)
  - Cells initiate where strong ascent and adequate moisture content coincide
  - Cells either remain stationary or repeatedly form and translate along common path
  - Inflow—outflow separation critical

Convection-permitting climate modelling for PMP

- Positives
  - Can resolve meso-β (20-200 km) processes responsible for extreme precipitation
  - Storm cells and mesoscale terrain explicitly represented
  - Climate-scale PMP estimation sidesteps predictability challenges of short-to-medium-range NWP

- Challenges
  - Lack meso-γ (2-20 km) terrain variations that may anchor and fuel the convection
  - Grid spacing within deep-convection “gray zone” O(1-10 km): storms explicit but only partially resolved
  - Reliance on uncertain subgrid parameterizations

What grid spacing is needed to capture these events?

Can subdivide based on the role of orography

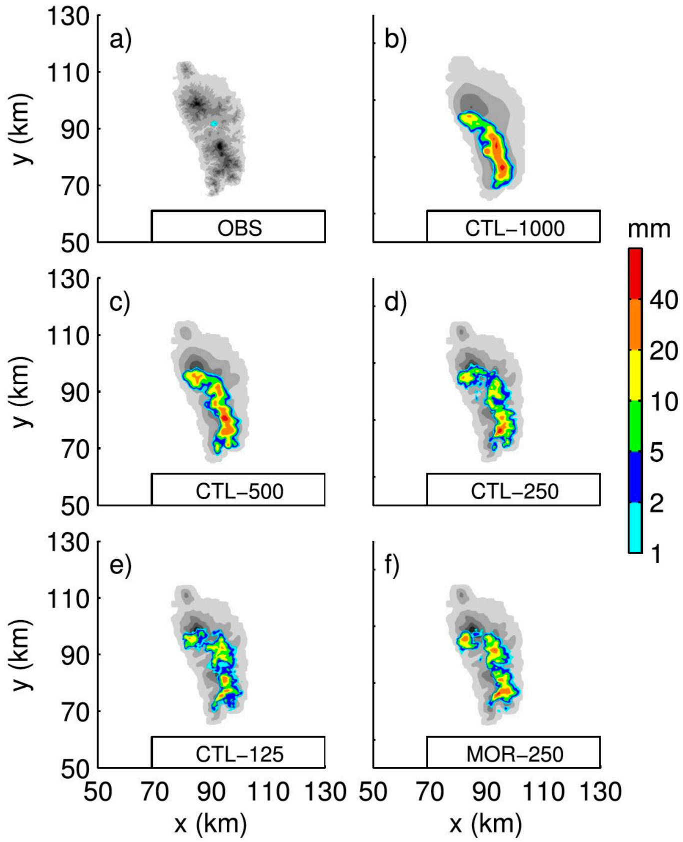
- As a cell enhancer (Smethport?)
  - O(1-4 km): Need to explicitly represent storm cells and mesoscale terrain

- As a cell initiator (Big Thompson, Madison County)
  - O(100 m-1 km) to resolve meso-γ orography and subcloud circulations leading to DCI, shallow-to-congestus cumuli and their preconditioning

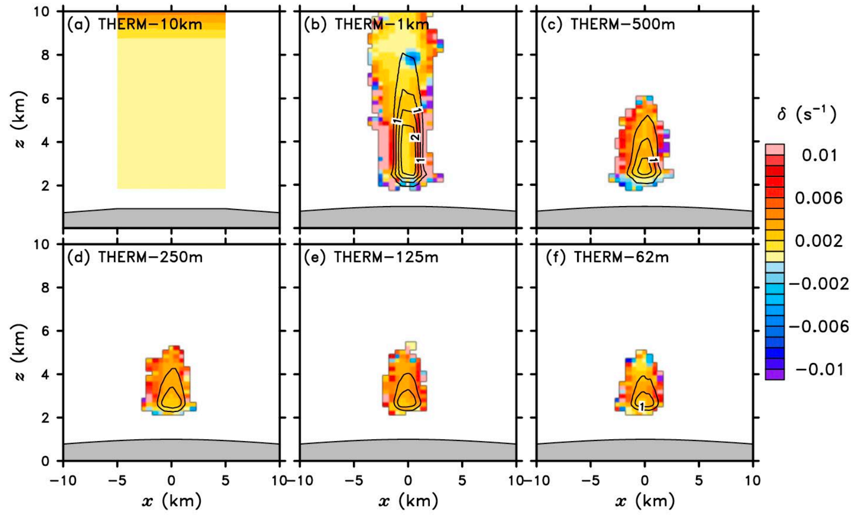
Parameterization problems

- Microphysics
  - Overdoes convective warm-rain precipitation
- Turbulence
  - Schemes designed for LES, not CPMs
  - Result: underestimated cloud dilution and detrainment
  - Clouds grow too deep, too fast

Wang and Kirshbaum (2015)



Kirshbaum (2020)

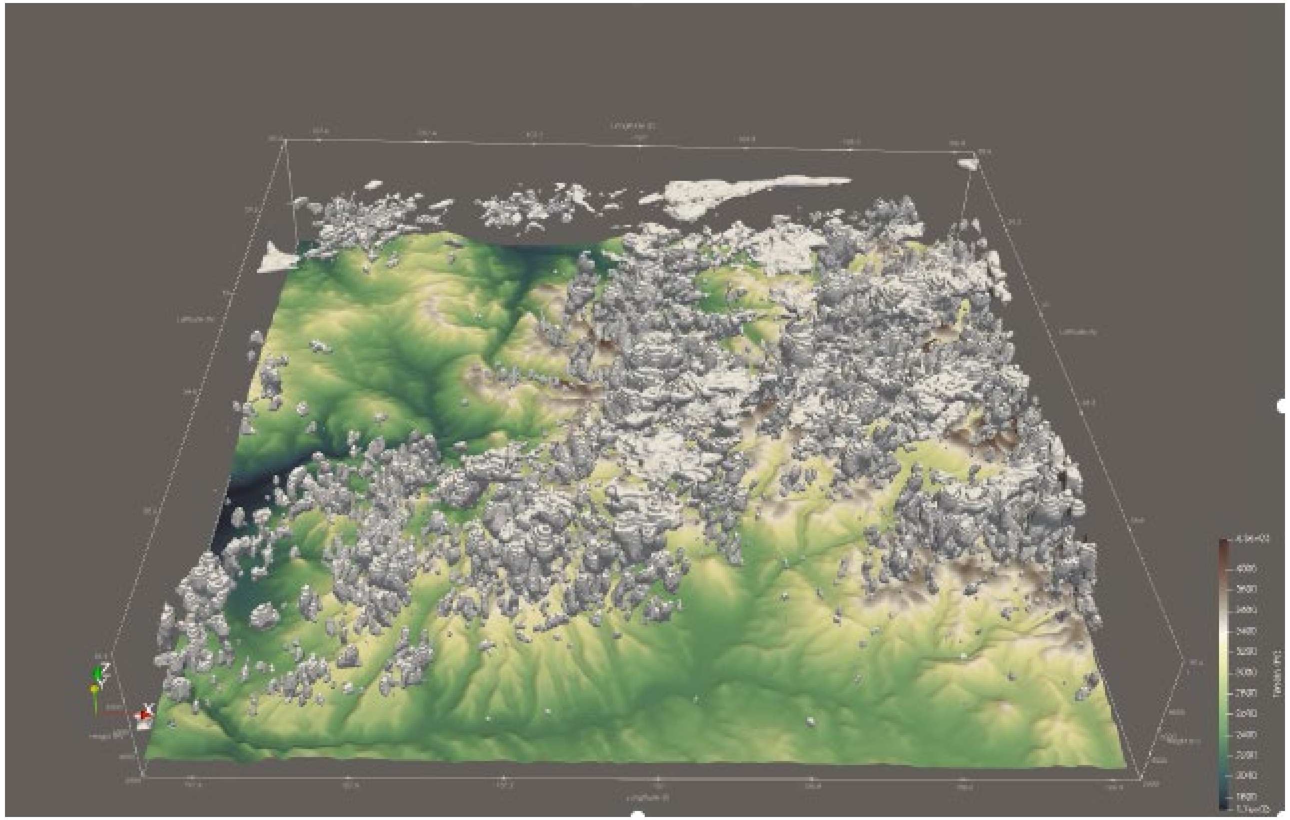


How can LES help?

- Largely overcomes the turbulence, terrain resolution problems
  - Microphysics still a concern

- Can use on a case-by-case basis to evaluate fidelity of CPM approach
  - Run both NWP and LES in ensemble mode
  - How do LES and CPM compare to each other, and to observations, in recent extreme (and null) cases?

WRF 111-m LES of thermally forced convection during SAIL (courtesy Jialin Liu, McGill)



Summary

- Extreme orographic convection events share certain synoptic characteristics, but role of orography, and storm-anchoring mechanisms, may differ

- Climate-scale CPMs are a sound approach to PMP estimation, but…
  - Substantial errors in storm development and precipitation should be expected due to parametric uncertainty and marginal terrain/storm resolution
  - PMP estimates may have large (factor of 50%) uncertainties

- LES can help to critically evaluate and refine approach
  - Simulate recent extreme cases and non-extreme cases that present similar environmental conditions
  - Can strengthen confidence in CPM approach and/or pinpoint critical model biases