Understanding the Life Cycle of Deep Convective Storms Traversing Mountains using CACTI Observations

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How do mountains impact organized deep convective storm development and behavior?

What environments and storm-scale processes support these behaviors?

Why do we ask these questions?

Much of what we know about organized deep convective storm behavior over mountains is through

- a limited number of idealized numerical modeling studies *(Frame and Markowski 2006; Reeves and Lin 2007; Chu and Lin 2000; Letkewicz and Parker 2011; Mulholland et al. 2020)*
- observational studies that use spatially and temporally infrequent observations *(Chen et al. 1991; Letkewicz and Parker 2011)*
- a few case studies *(Tripoli and Cotton 1989a,b; Mulholland et al. 2019)*

..leaving gaps in our knowledge

CACTI Data (and Numerical Modeling) will Address these Questions

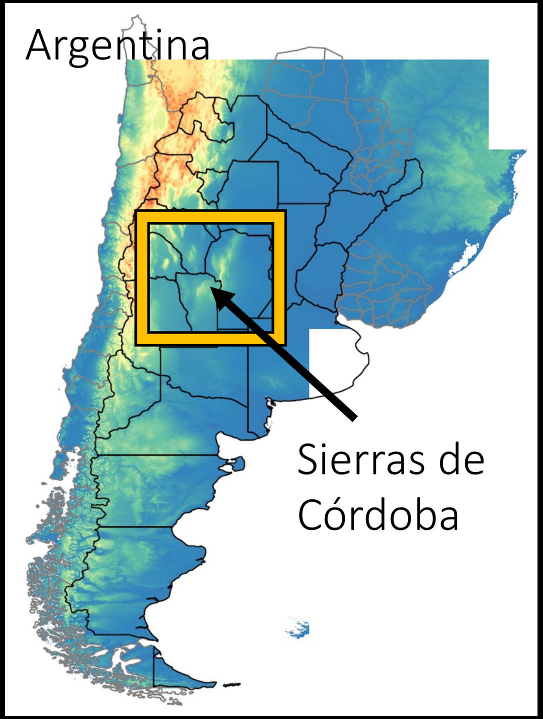
Leverage data from the Cloud, Aerosol, and Complex Terrain Interactions (CACTI; Varble et al. 2021) field campaign

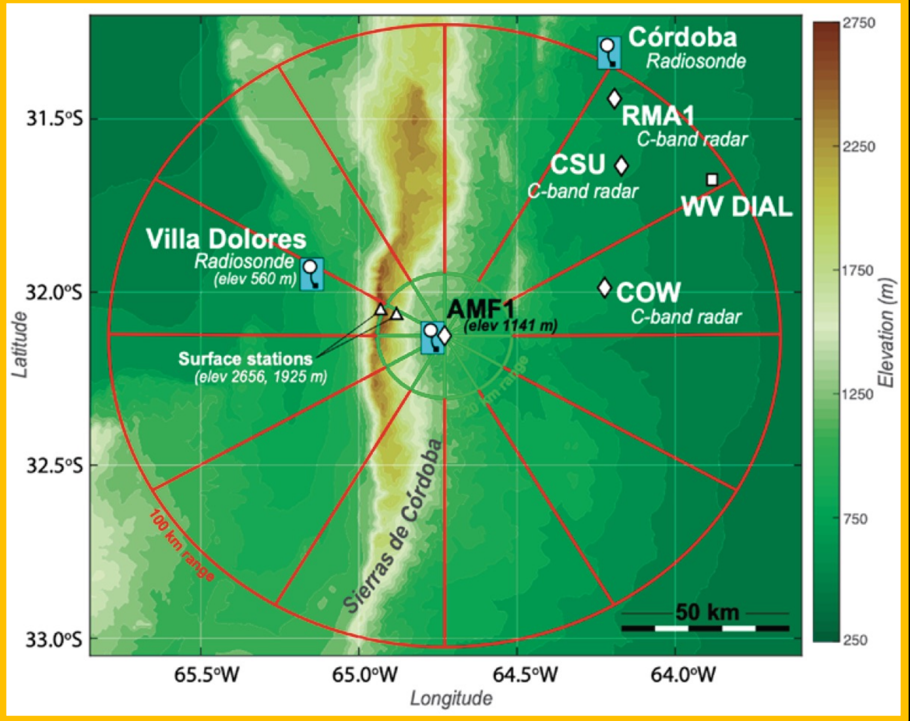
Identify/Categorize all observed organized deep convective storm cases (+null events) into different groups of storm behaviors, evaluate the supporting environments, quantify the storm-scale dynamic processes

Examples of the different flavors of storm behaviors

CACTI occurred in Argentina, near the Sierras de Córdoba mountain range

ARM Córdoba, Argentina Mobile Facility (AMF1) was continuously deployed 15 Oct 2018 – 30 Apr 2019, with a 1.5-month Intensive Observing Period from 30 Oct – 13 Dec 2018



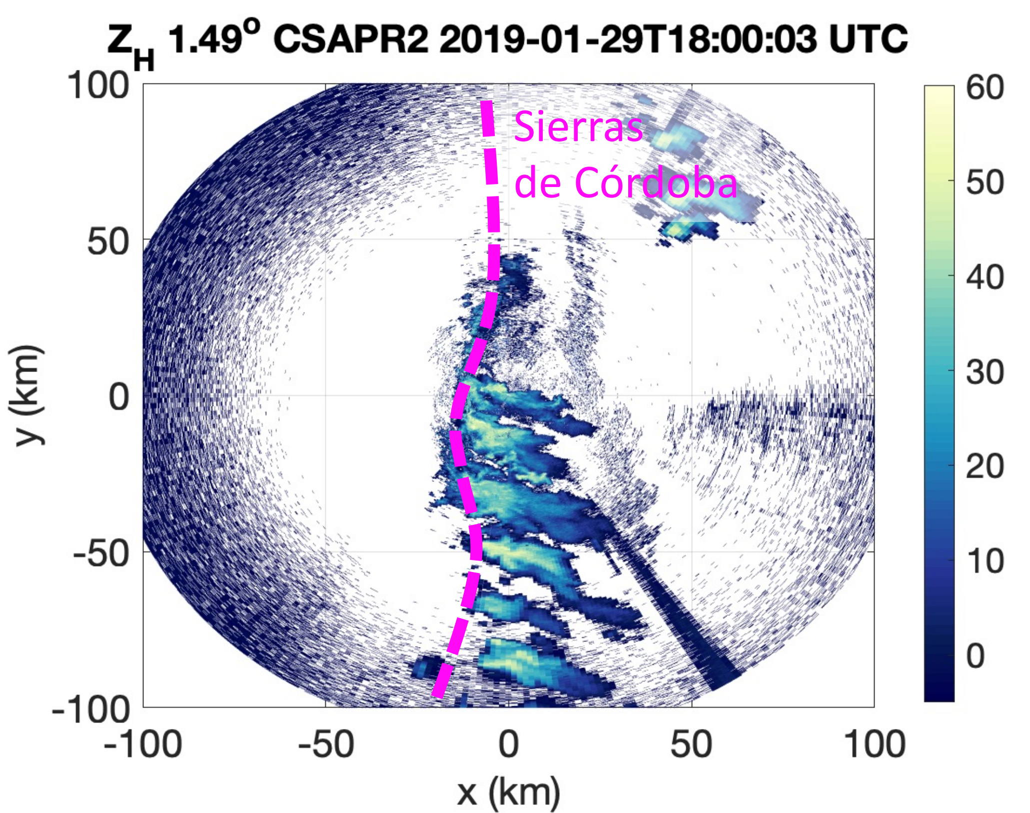


Observe many different Convective Storm Behaviors over Mountains

Deep convective cells form over mountains *(Marquis et al. 2021; Nelson et al. 2021; Feng et al. 2022; Nelson et al. 2022; Marquis et al. 2023)*

Precipitating deep convective clouds developing over Argentine mountains (photograph by Adam Varble)

CSAPR2 radar reflectivity (dBZ) plan view



Observe many different Convective Storm Behaviors over Mountains

Deep convective cells form over mountains, but then what?

- Cells decay over the mountains
- Cells move away from mountains
- Cells merge and grow upscale into a large quasi-linearly organized deep convective storm (mesoscale convective system; MCS)

Precipitating deep convective clouds developing over Argentine mountains (photograph by Adam Varble)

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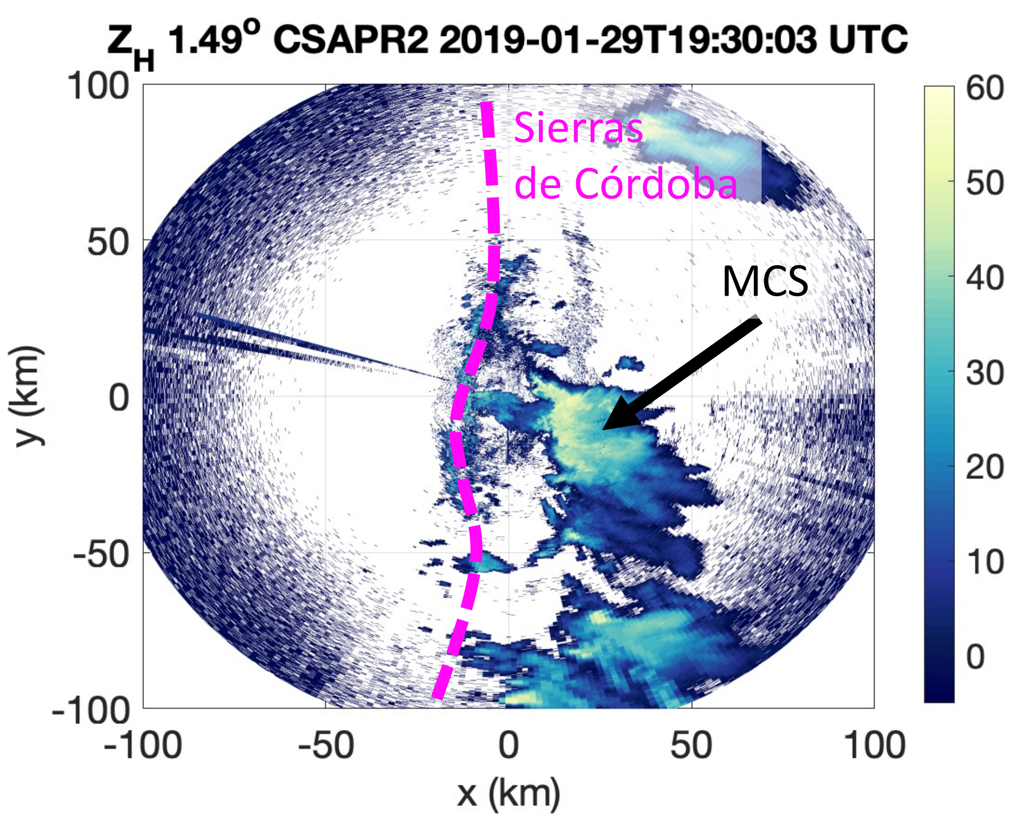
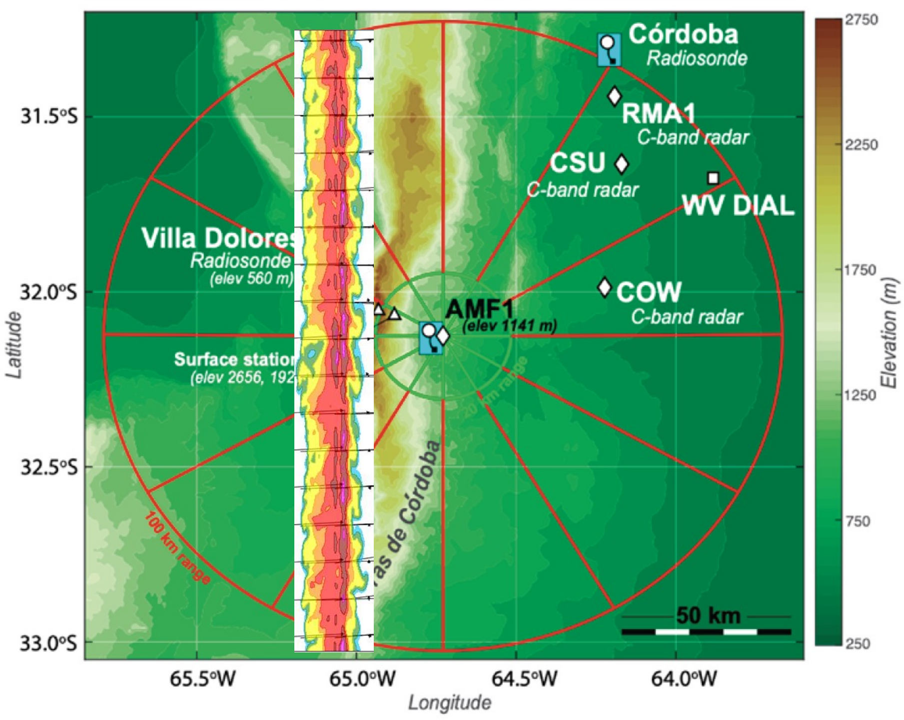


Mature MCS moves from West to East and encounters Mountains

MCS develops upwind of the mountains and moves toward them, but then what?

- Storm is blocked by the mountains and decays, unable to cross the ridge



idealized depiction of organized storm approaching the Sierras de Córdoba from the west

What can cause this behavior?

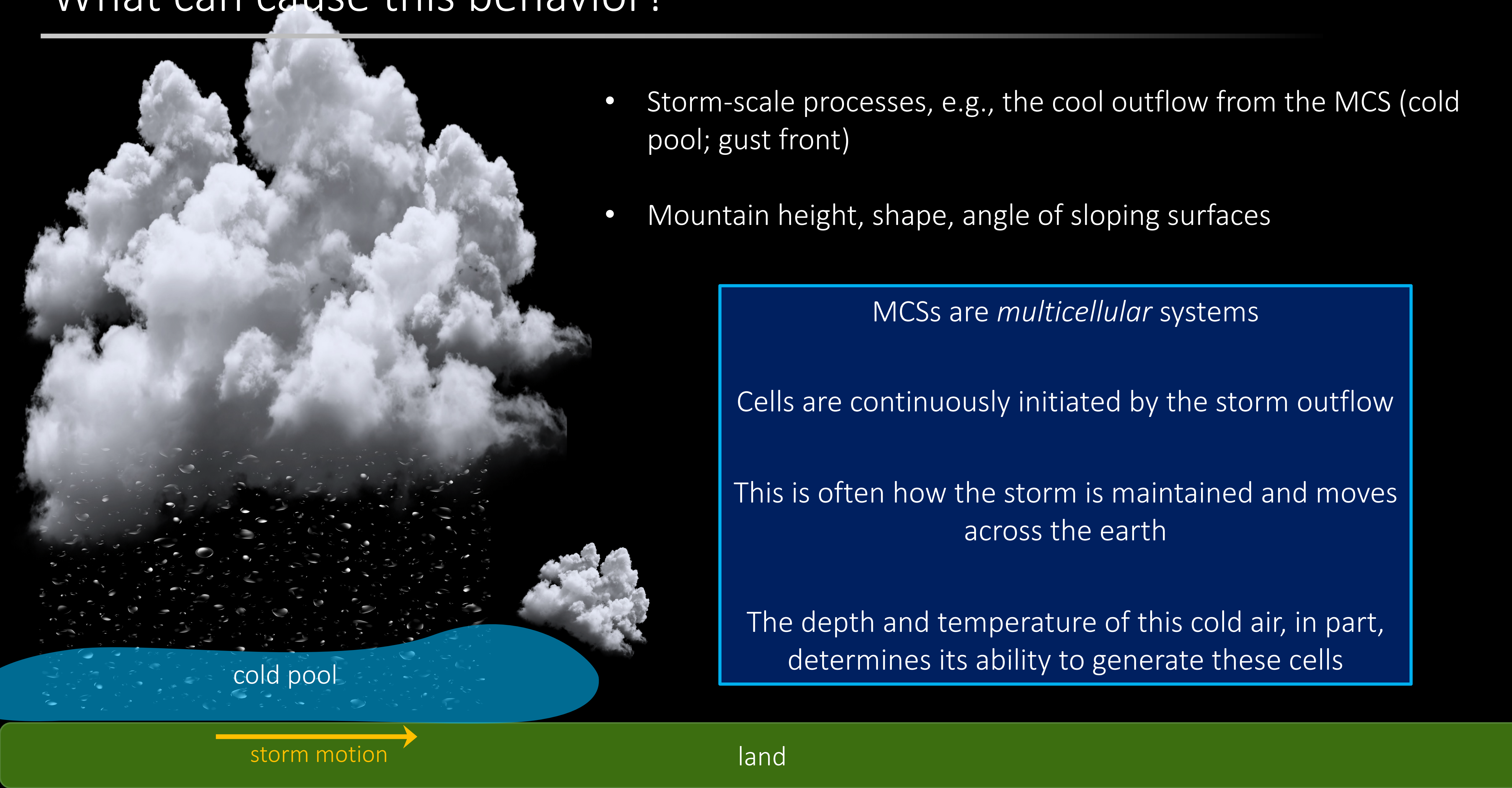
- Storm-scale processes, e.g., the cool outflow from the MCS (cold pool; gust front)
- Mountain height, shape, angle of sloping surfaces

MCSs are *multicellular* systems

Cells are continuously initiated by the storm outflow

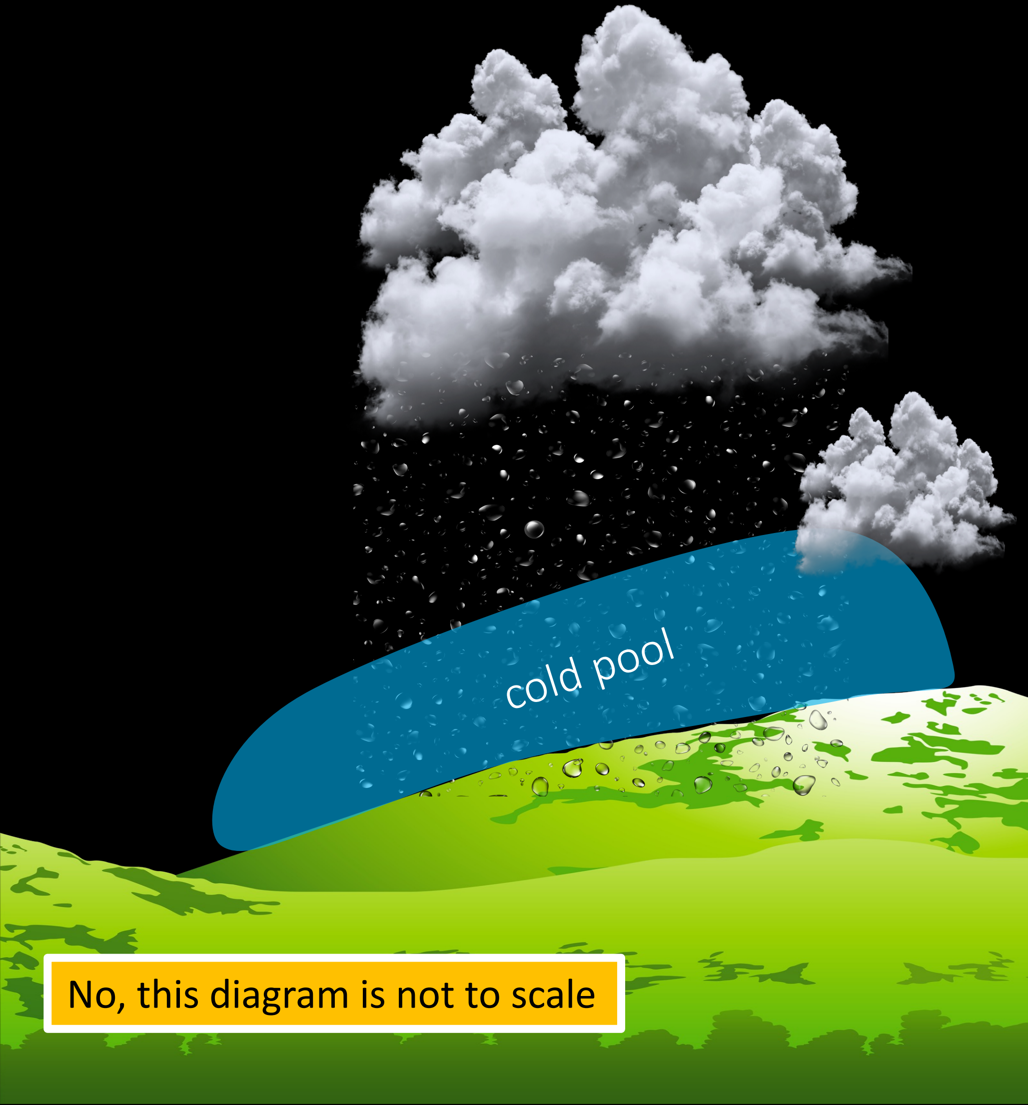
This is often how the storm is maintained and moves across the earth

The depth and temperature of this cold air, in part, determines its ability to generate these cells



Sloping Mountain Surfaces Modify the Cold Pool

Cold pool depth and temperature change as it moves up and down mountain slopes



As storms ascend a mountain, cold pools deepen and cool due to gravitational deceleration and orographic lift supporting rain

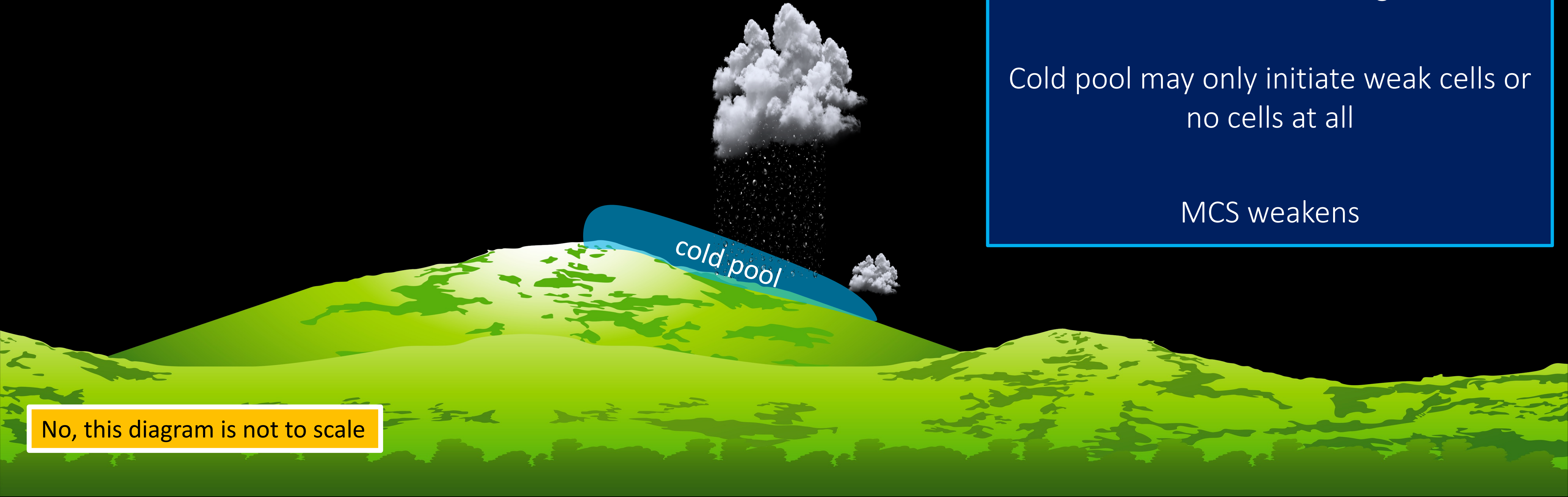
Cells are more easily initiated by this deep cold pool

MCS intensifies

No, this diagram is not to scale

Sloping Mountain Surfaces Modify the Cold Pool

Cold pool depth and temperature change as it moves up and down mountain slopes



As storms descend a mountain, cold pools become shallower and warmer due to gravitational acceleration and adiabatic warming

Cold pool may only initiate weak cells or no cells at all

MCS weakens

No, this diagram is not to scale

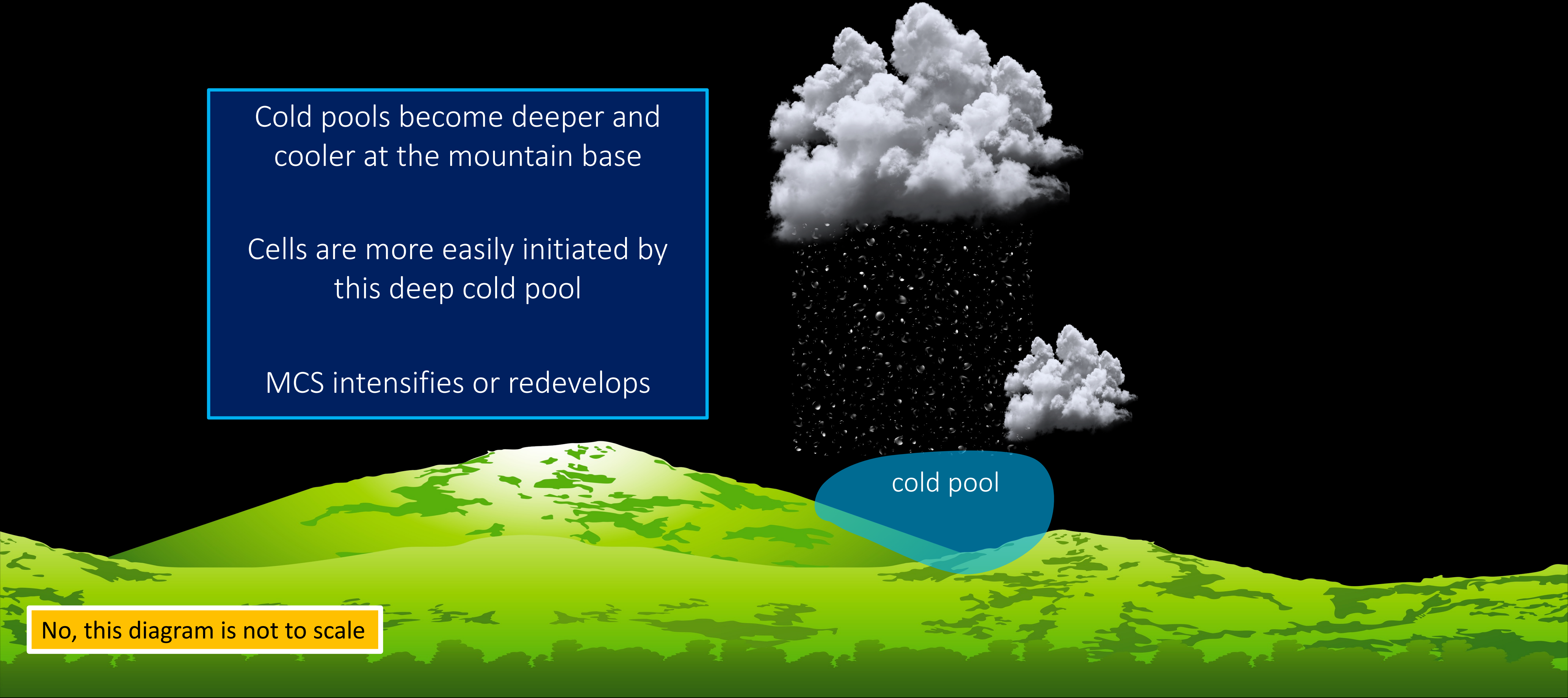
Sloping Mountain Surfaces Modify the Cold Pool

Cold pool depth and temperature change as it moves up and down mountain slopes

Cold pools become deeper and cooler at the mountain base

Cells are more easily initiated by this deep cold pool

MCS intensifies or redevelops



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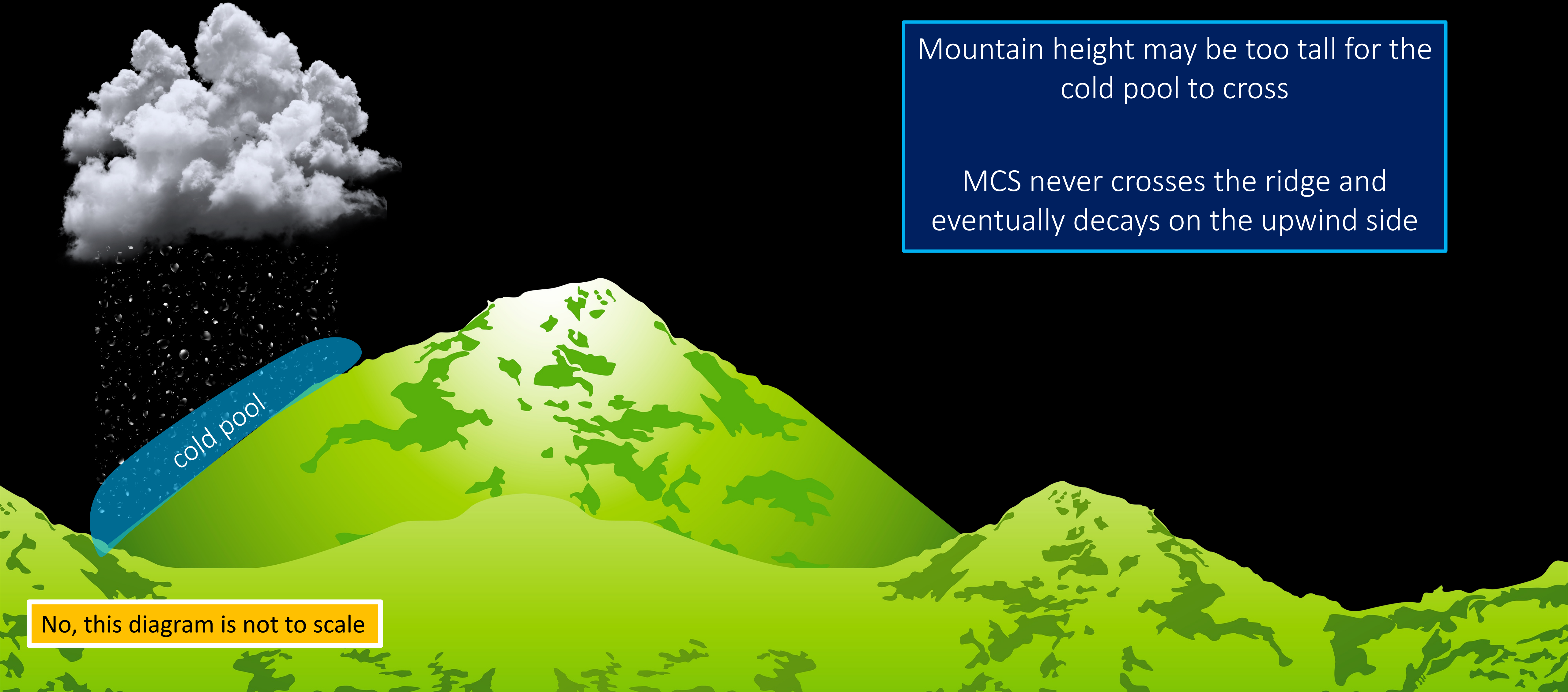
Mountains can Completely Block Storm Outflow



Mountain height may be too tall for the cold pool to cross

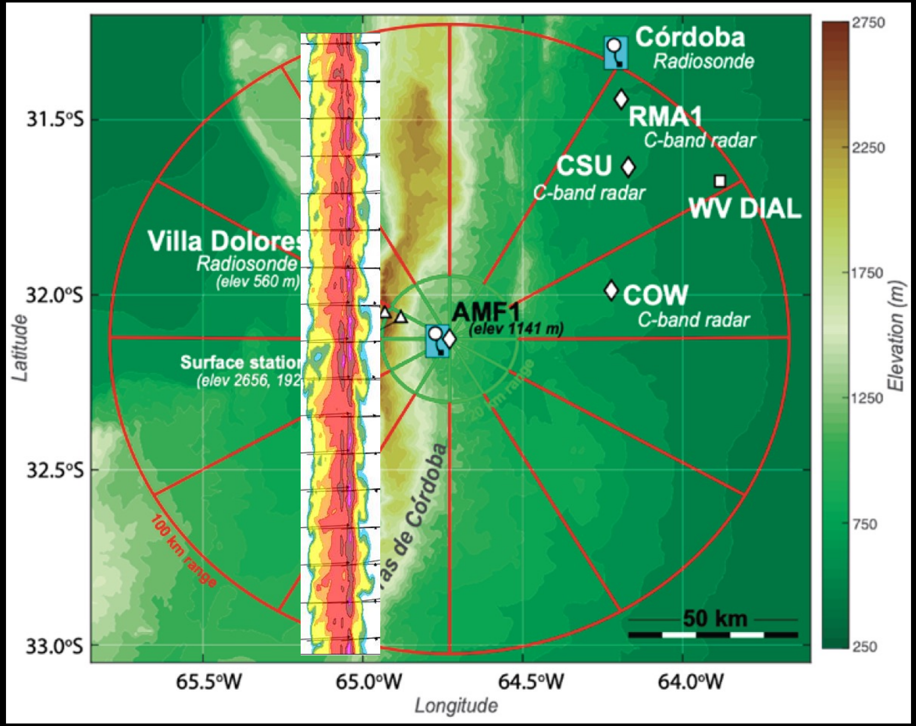
MCS never crosses the ridge and eventually decays on the upwind side

No, this diagram is not to scale

Mature MCS moves from West to East and encounters Mountains

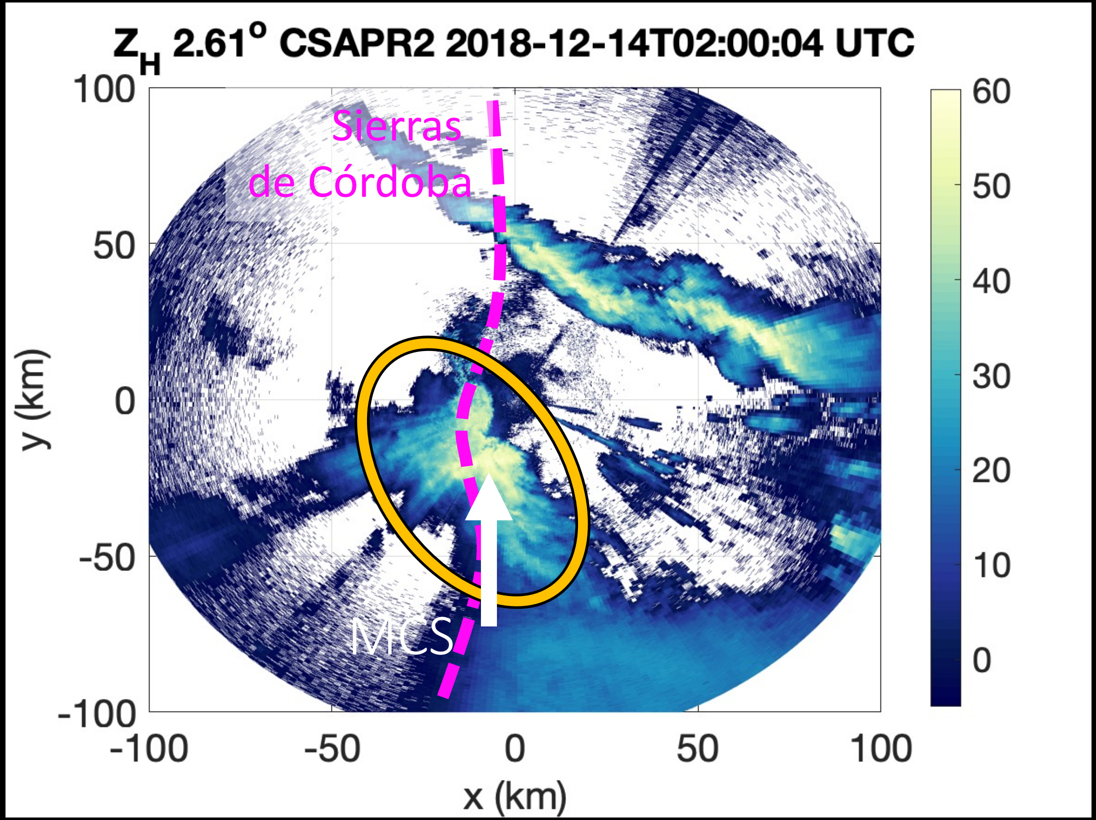
MCS develops upwind of the mountains and moves toward them, but then what?

- Storm is blocked by the mountains and decays, unable to cross the ridge
- Storm moves over the mountain unaffected



idealized depiction of organized storm approaching the Sierras de Córdoba from the west

CSAPR2 radar reflectivity (dBZ) plan view



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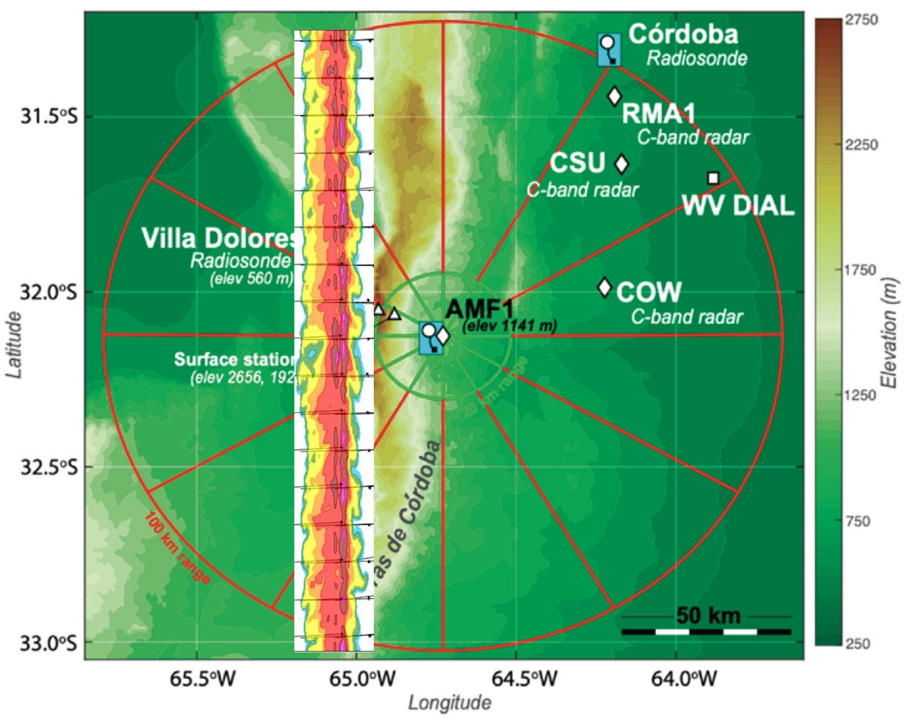

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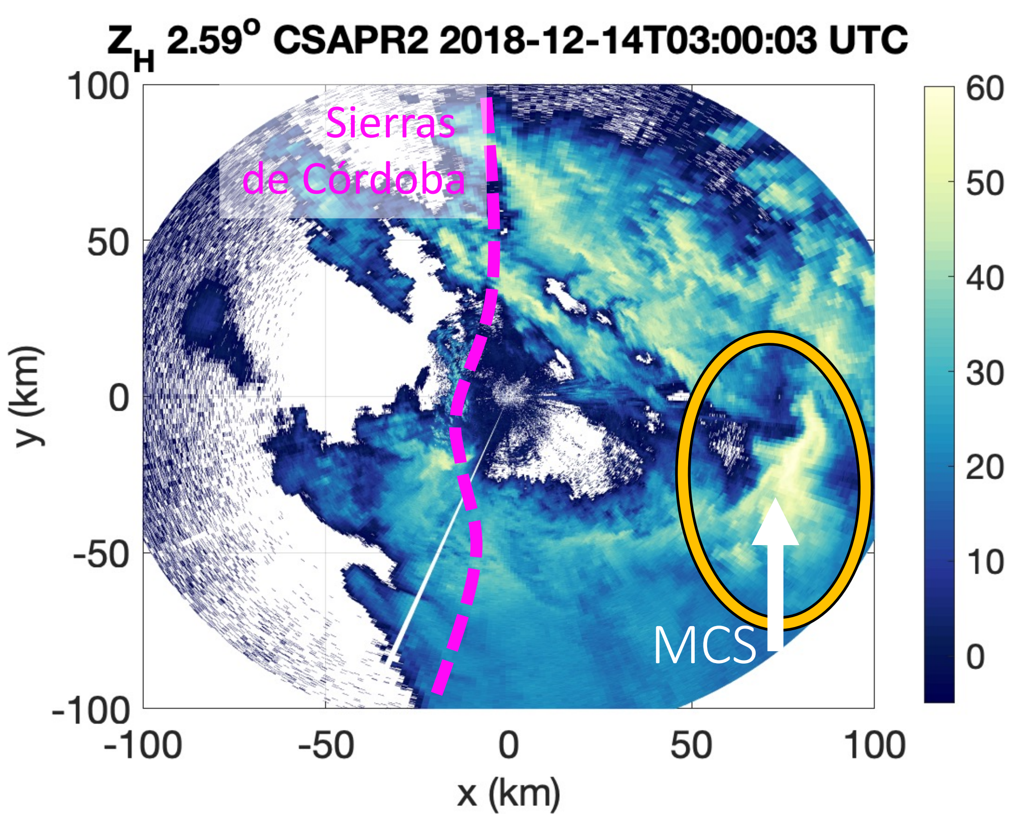

Mature MCS moves from West to East and encounters Mountains

MCS develops upwind of the mountains and moves toward them, but then what?

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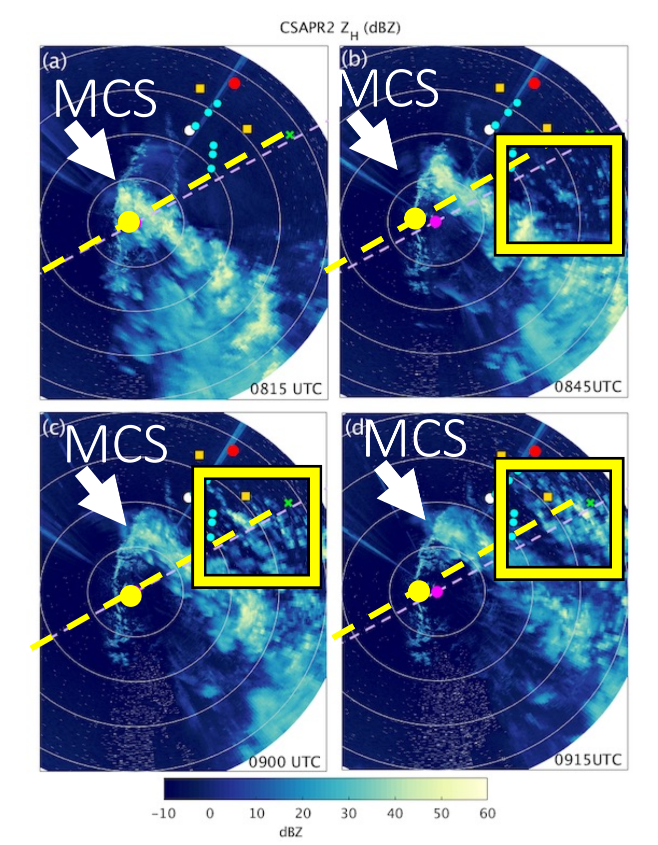
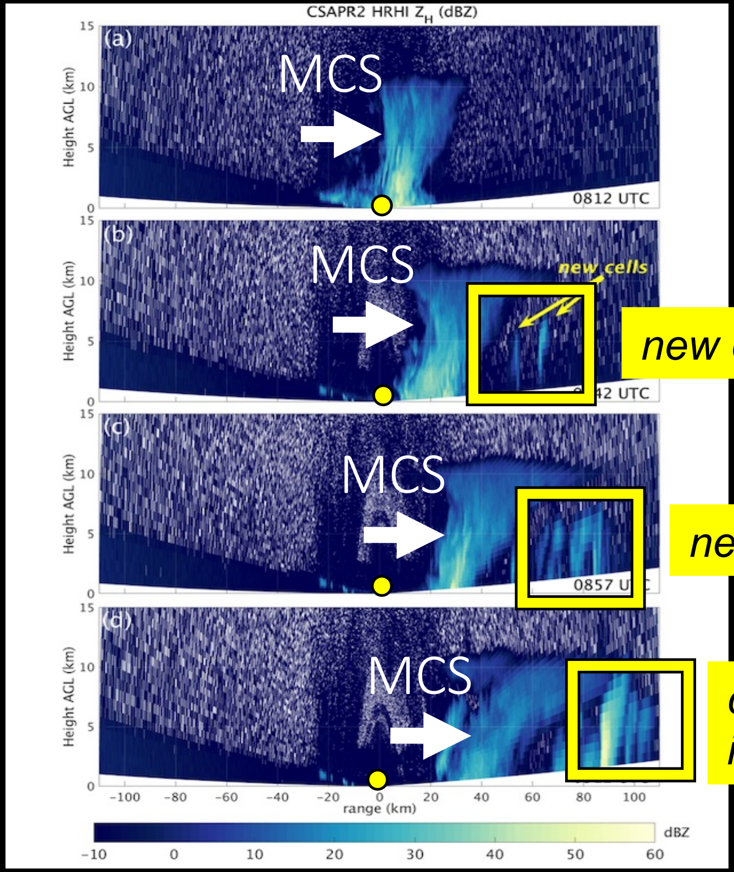
- Storm moves over the mountain unaffected
- Storm "jumps" forward (discrete propagation)

CSAPR2 radar reflectivity (dBZ) plan view



60° azimuth along which the hemispheric RHI scan was taken

CSAPR2 radar reflectivity (dBZ) cross section



new cells

new cells

cells grow upscale into a new MCS

cells form 20-30 km ahead of the MCS (well away from the storm outflow)

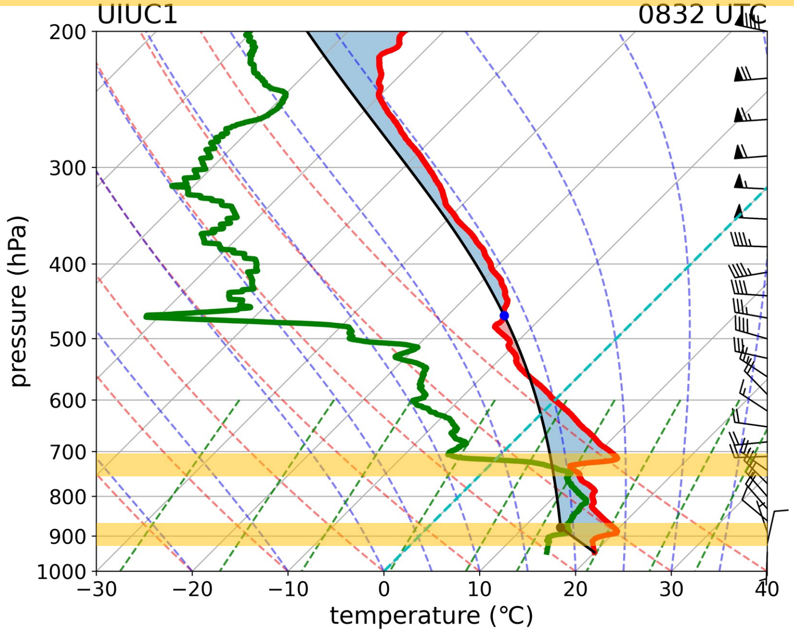
Lombardo and Kumjian (2022)

What can cause this behavior?

The environment

- Temperature/moisture profile (vertical stability) and wind profile (vertical wind shear)
- Synoptic- and meso-scale features (low pressure systems, troughs, fronts, boundaries) are important too, just not for this event

two stable layers & wind shear were critical for discrete propagation to occur



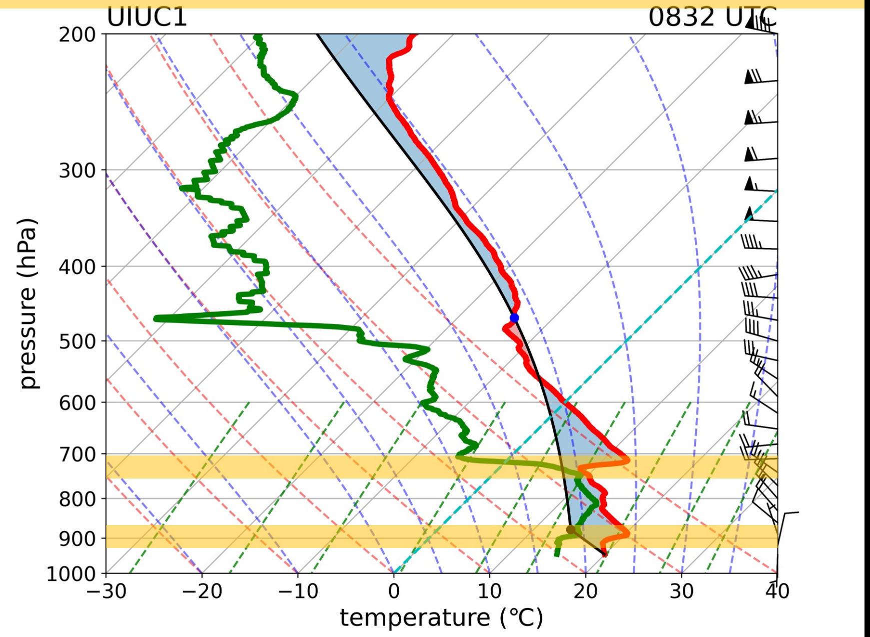
preconvective environment from CACTI discrete propagation event

Environment Supported a Bore & Low-level Gravity Waves

Bore and trailing gravity waves initiated cells ahead of main MCS and cool outflow, cells grew upscale into the new MCS ("jump")

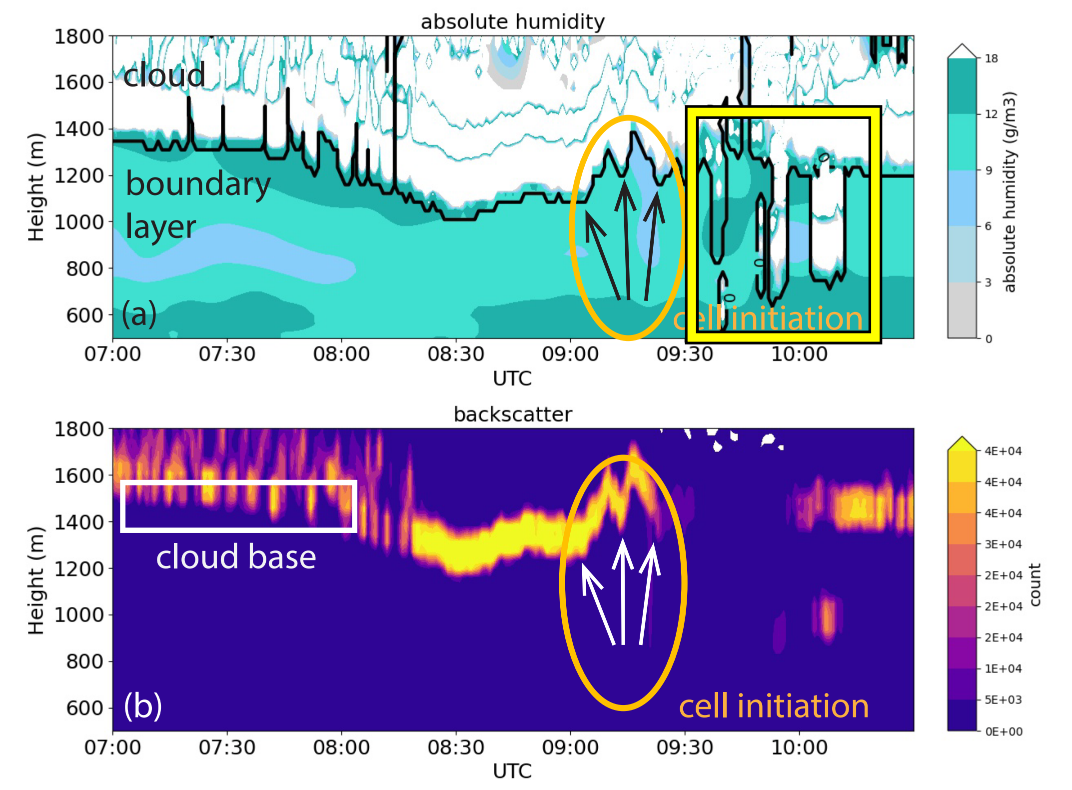
Observed perturbations in cloud base height during bore/wave passage just prior to cell formation

two stable layers & wind shear were critical for discrete propagation to occur



preconvective environment from CACTI discrete propagation event

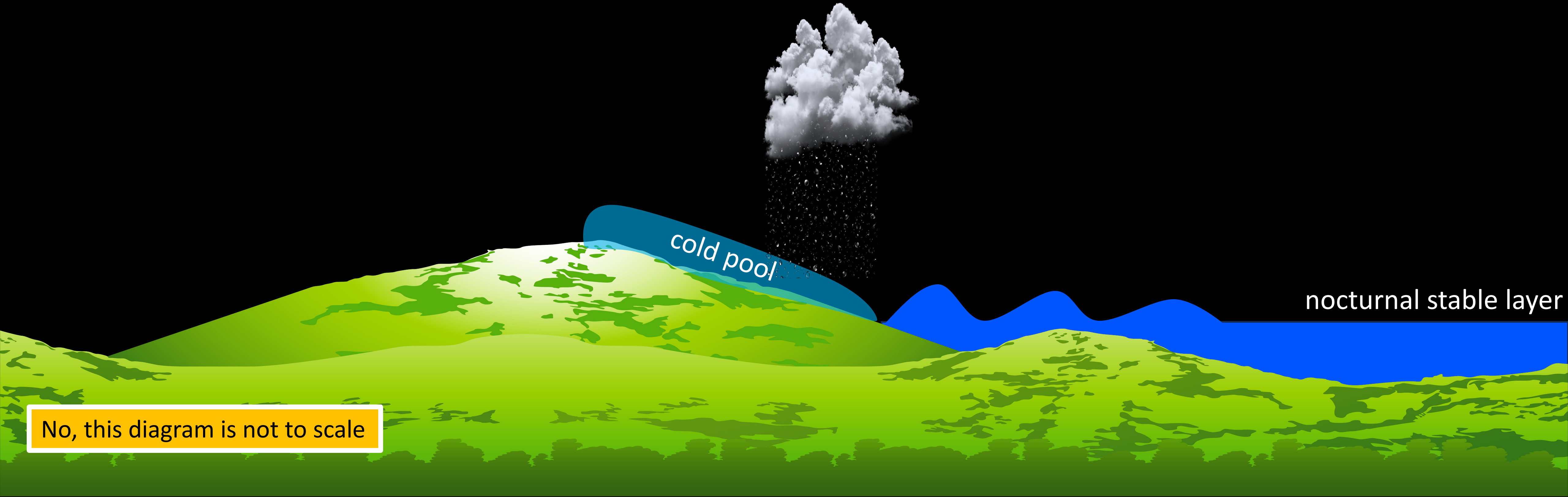
timeseries of water vapor micropulse differential absorption lidar (DIAL) from CACTI discrete propagation event



Waves Formed as Cold Pool Perturbed Nighttime Stable Layer

MCS cold outflow (partially) moved over the ridge and perturbed a nocturnal stable layer in the mountain lee

Bore/waves formed, environment supported and maintained their existence



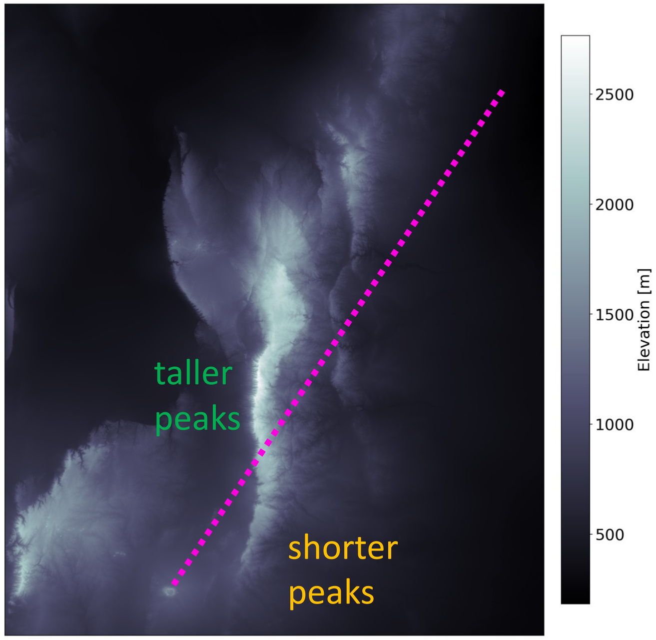
No, this diagram is not to scale

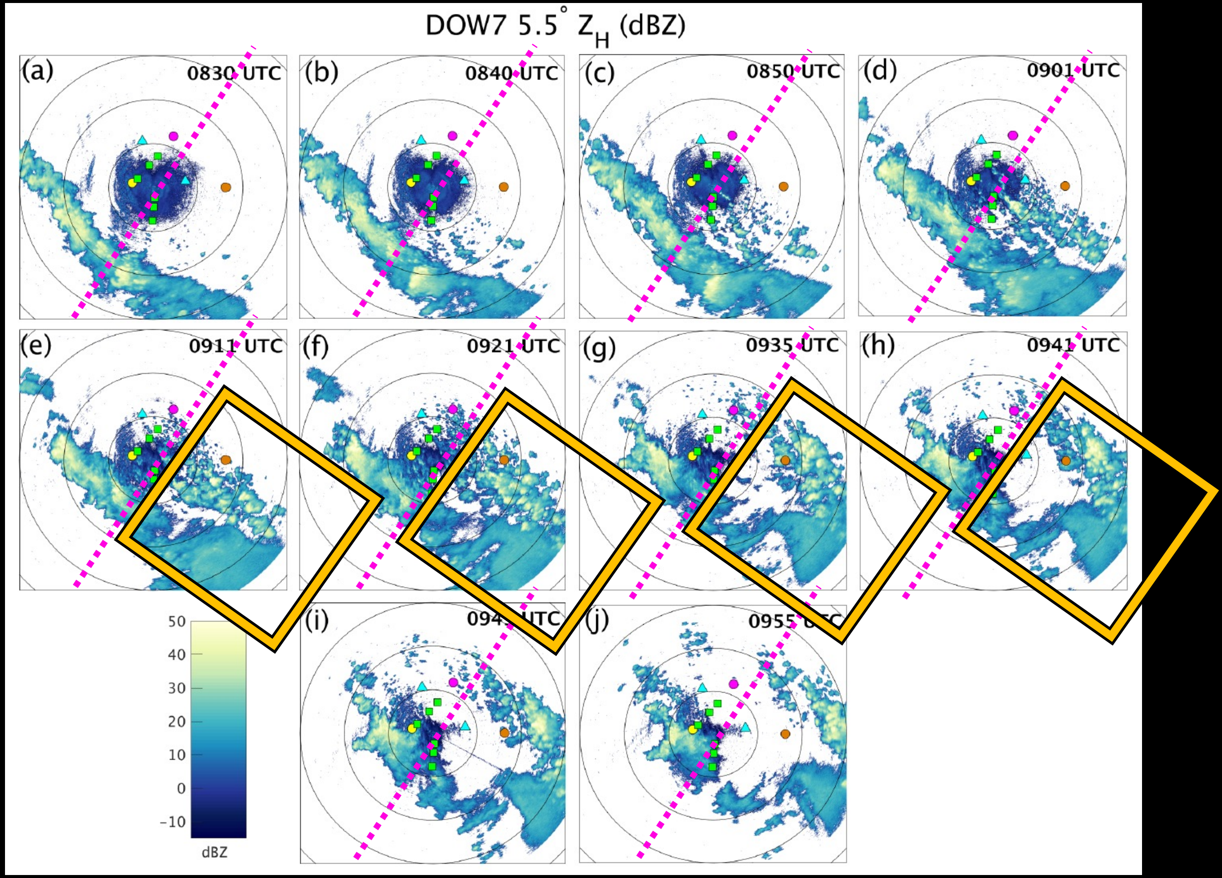
Discrete Propagation Impacted by Variations in Mountain Height

Taller peaks blocked the cold pool, which was necessary for the bore/wave formation (cold pool collided with nocturnal stable layer in lee), preventing wave generation in the northern lee

Only the southern portion of the storm propagated discretely, while the northern portion decayed over the mountains

Sierras de Córdoba are taller on the northern end than the southern end





Summary

Organized deep convective storm (MCS) behavior is impacted by mountainous landscapes

The environment, cold pool characteristics (in part, determined by the environment), and the mountain characteristics are all influential on storm development and evolution

CACTI data allows us to identify/categorize a variety of observed evolutions, and quantify the environments that support the observed behaviors

CACTI case studies allow us to evaluate the storm scale dynamic processes (e.g., bore/gravity wave formation)

Future idealized storm-scale numerical modeling work will

- evaluate the relative role of the environment vs. cold pool storm dynamics
- diagnose the impact of mountain structure on storm behavior
- identify the numerical model grid spacings necessary to represent anticipated storm behavior

Thank you!

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