Effect of Latent Heating on Mesoscale Vortex Development During Extreme Precipitation: Colorado, September 2013

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- WRF simulations performed to explore the role of latent heating in mesovortex development and dominant microphysics processes involved.
- Release of latent heat had strong impact on surface flow field, leading to enhanced upslope, convection, and precipitation over Boulder, CO.
- High potential vorticity values in lower troposphere associated with positive vertical gradient in latent heating from cloud water condensation
- A 50% reduction of the latent heating contribution from cloud water condensation resulted in no mesovortex development and significant reduction in precipitation along Northern Colorado Front Range.

Background

From 9-16 September 2013, a slow-moving cut-off low in the southwestern US funneled unseasonal amounts of moisture to the Colorado Front Range, resulting in extreme precipitation and flooding. On the evening of 11 September, Boulder experienced flash flooding as a result of high rain rates accumulating over 180 mm of rain in 6 hours. From 0400-0700 UTC 12 September, a mesoscale vortex (mesovortex) was observed to travel northwestward towards Boulder. This circulation enhanced upslope flow and was associated with localized deep convection. The mesovortex originated in an area common for lee vortex formation (e.g. the Denver Cyclone), yet we hypothesize the mesovortex developed through the release of latent heat from microphysical processes.

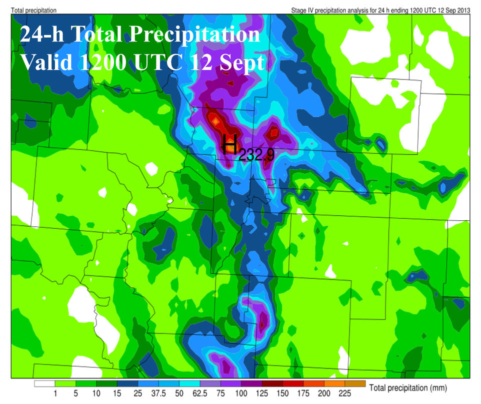

Fig. 1. NCEP Stage IV 24 hr accumulated precipitation (mm).

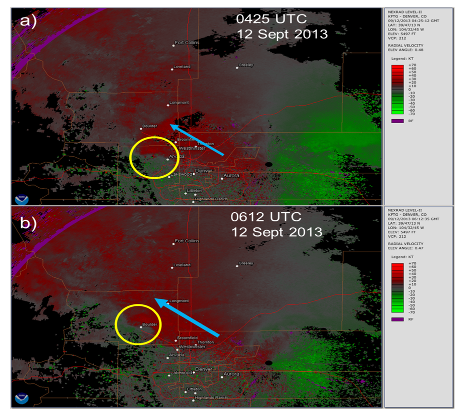

Fig. 2. Observed radial velocity from the Denver (KFTG) radar for 12 September 2013. Times shown are (a) 0425 UTC and (b) 0612 UTC.

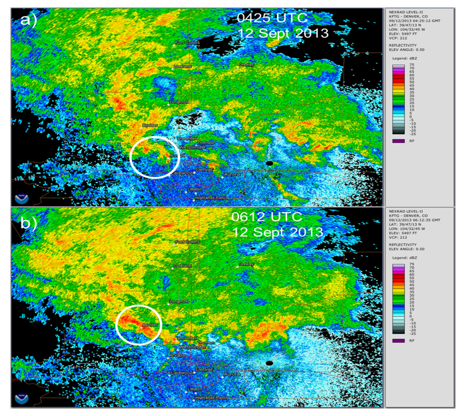

Fig. 3. Observed radar reflectivity from the Denver (KFTG) radar for 12 September 2013. Times shown are (a) 0425 UTC and (b) 0612 UTC.

Project Objectives

- Explore whether mesovortex was associated with lee vortex formation (associated with Denver Cyclone) or through dynamic feedbacks from release of latent heat
- Understand the role of latent heating to mesovortex development
- Explore dominant microphysical processes and test sensitivity of mesovortex and precipitation to strength of latent heating

Methods

Model Configuration

- Advanced Research WRF v3.3.1 (Skamarock et al. 2008)
- 60 hr forecast, initialized at 0000 UTC 11 September 2013
- Two-way nested grid, 3 domains: horizontal grid spacing (Δx) of 36km, 12km, and 4km
- 36 stretched vertical levels, 50-hPa model top
- Timesteps: 144 sec, 48 sec, and 16 sec (respectively)
- Initial and boundary (updated every 3 hrs) conditions from 0.5° NCEP GFS model

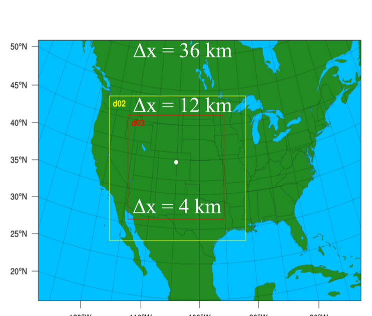

Fig. 4. WRF model domains.

Parameterizations	
Cumulus (for d01 and d02)	Grell-Devenyi 3 (G3)
Shortwave; Longwave Radiation	Dudhia; RRTM
Land surface	Noah
Microphysics	Thompson
Boundary layer	YSU

Experimental Setup

1. Latent Heating Experiments

Initial Model Simulations

Forecast Time	Latent Heating (LH)			
11 Sept 00-18 UTC	ON	OFF	ON	OFF
11 Sept 18 UTC – 13 Sept 12 UTC	ON	OFF	OFF	ON

CONTROL (LH_ON): Make sure main features of event are well represented before experimenting

LH_OFF: Test if LH had any effect on vortex development (initial testing)

LHON_LHOFF: Test if precipitation on prior day has impact on the vortex development on Sept 12th

LHOFF_LHON: Test if precipitation on Sept 12th has impact on vortex development that same day

2. Sensitivity to Latent Heating Strength

- Hypothesis: Any process that could reduce the energy released from cloud water (CW) condensation would effect shape of heating profile near the surface leading to weakening of vertical gradient in LH and less potential vorticity (PV) generation (i.e. mesovortex development)
- Experiment: Directly reduce the LH contribution from CW condensation by 50% (after 1800 UTC 11 Sept.; LHON_LHHALF)
  – by simply adjusting physical parameter describing the energy released per unit mass of vapor converted to liquid (leaving the rate of mass condensation unaffected)

$$\frac{d(PV)}{dt} \approx (\zeta + f)\frac{d\dot{\theta}}{dz}$$

Results

1. Latent Heating Experiments

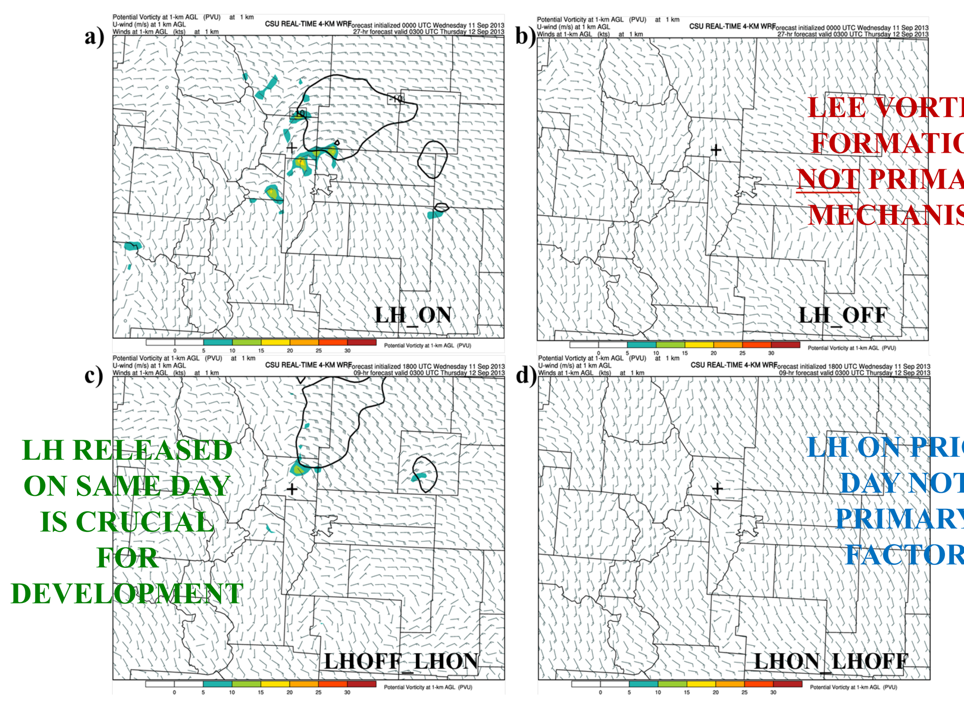

Fig. 5. WRF simulations of potential vorticity (10-5 s-1, color), u-wind (m/s, solid black line), and wind barbs (kts) at 1-km AGL at 0300 UTC 11 September 2013. (a) LH_ON (control), (b) LHON_LHOFF, (c) LHOFF_LHON, and (d) LH_OFF simulations. U-wind contour interval is 5 m/s, starting at -10 m/s.

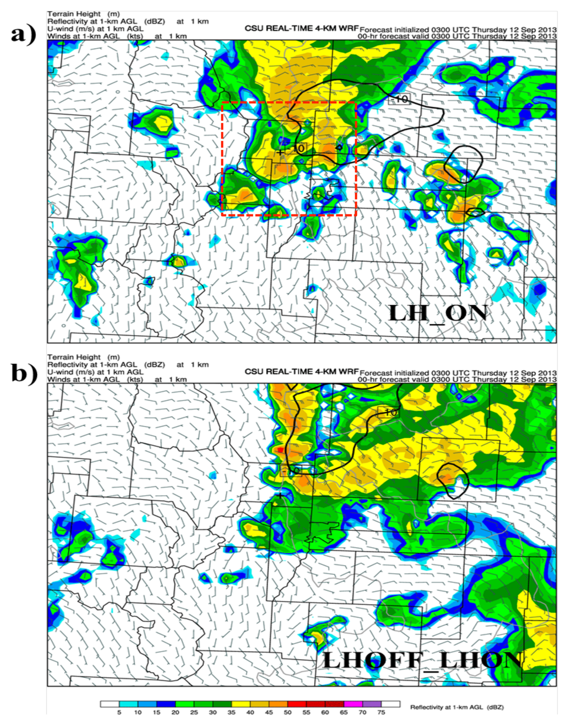

Fig. 6. Radar reflectivity (dBZ; color filled), negative u-wind (m/s, solid black contour), and wind barbs (kts) all at 1km AGL for 0300 UTC September 12. (a) Control (LH_ON) and (b) LHOFF_LHON simulations. U-wind contour interval is 5 m/s, starting at -10 m/s. Dashed red square denotes domain where horizontal averaging was performed, corresponding to Fig. 7 and 8.

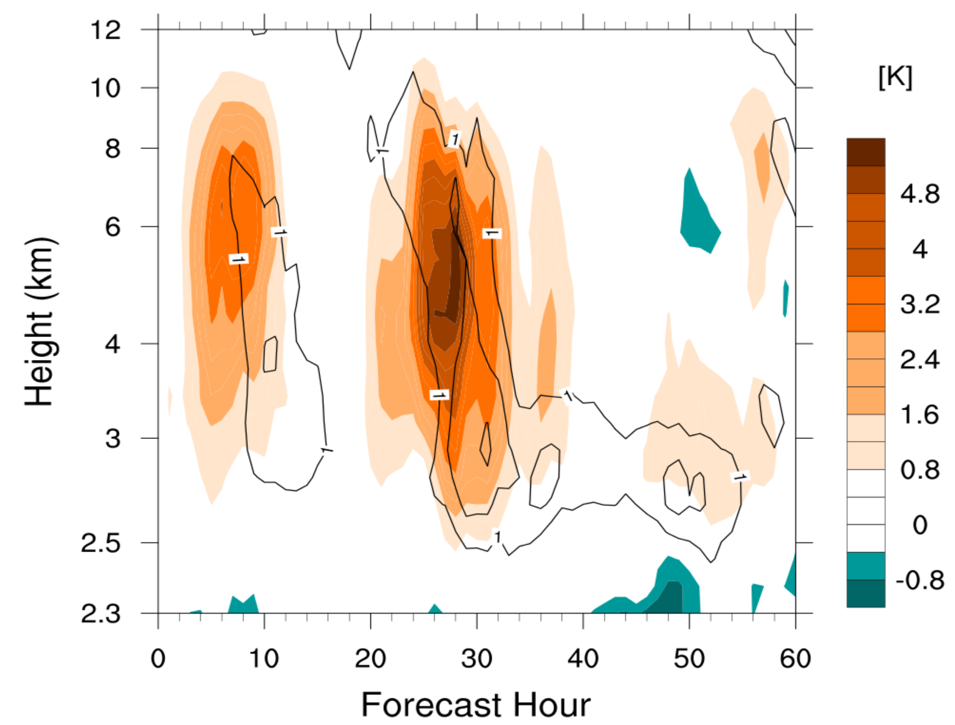

Fig. 7. Time-height plot of domain-averaged accumulated microphysics heating (K; color-fill) and potential vorticity (PVU; black contours) for every forecast hour starting at 0000 UTC September 11. Potential vorticity contour interval is 0.5 PVU from 1 to 2 PVU. The vertical axis is geopotential height (km MSL). Averaged domain shown in Fig. 6a by dashed red square.

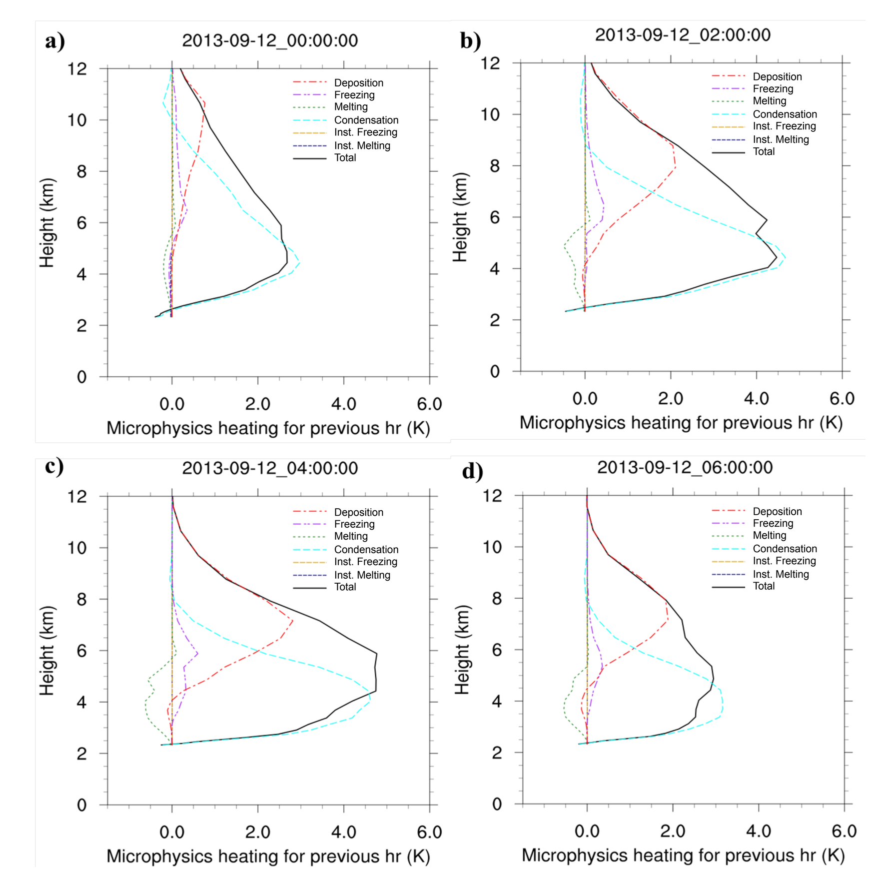

Fig. 8. Vertical profiles of domain-averaged hourly accumulated microphysics heating (K) for each "bulk" microphysics term. The profiles are for 12 September 2013 at (a) 0000 UTC, (b) 0200 UTC, (c) 0400 UTC, and (d) 0600 UTC. Averaged domain shown in Fig. 6a by dashed red square.

2. Sensitivity to Latent Heating Strength

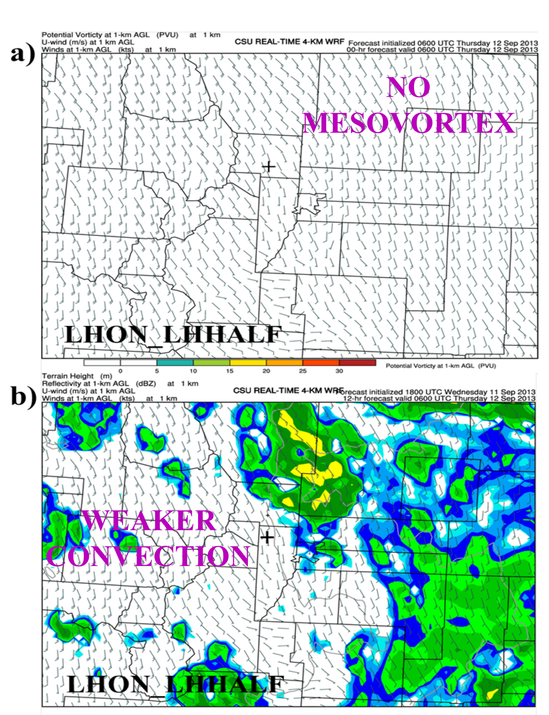

Fig. 9. (a) Potential vorticity (same as Fig. 5) and (b) radar reflectivity (dBZ) for 0600 UTC 12 September for the LHON_LHHALF experiment.

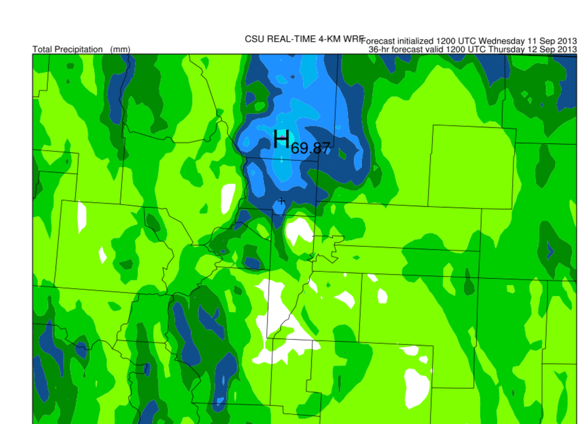

Fig. 10. WRF 24-hr accumulated precipitation for LHON_LHHALF (mm) valid at 1200 UTC 12 September.

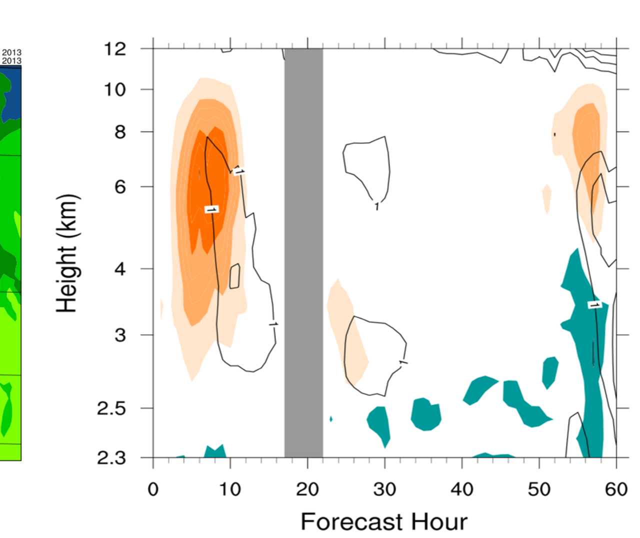

Fig. 11. Time-height plot of accumulated microphysics heating and PV (same as Fig. 7) for LHON_LHHALF.

Conclusions

1. Latent Heating Experiments

- Turning off LH resulted in no mesovortex
  – Suggests LH release and *not* lee vortex formation (not a Denver Cyclone) was responsible for development
- LH released just before and during event played larger role than that on prior day
- LH had strong effect on surface flow field
  – Low-level jet enhanced in response to upward motions caused by LH, leading to enhanced upslope, which enhanced convection and surface precipitation
- 12 Sept heating profiles had convective characteristics
  – A convective environment is more favorable for producing a circulation near the surface caused by a positive vertical gradient in LH inducing a positive PV anomaly
  – High values of PV were found near the surface associated with strong, positive vertical gradient in LH located in the lower troposphere

2. Sensitivity to Latent Heating Strength

- Cloud water condensation was dominant process responsible for positive vertical gradient in LH
  – Lack of high rain evaporation near the surface helped keep gradient strong
- Reducing the LH contribution from cloud water condensation by 50% (after 1800 UTC 11 Sept.)
  – This degree of reduction resulted in no mesovortex development and significant reduction in precipitation along northern Front Range

Simulations and sensitivity studies suggest that the mesovortex was indeed responsible for the increased rain rates observed on 12 Sept. over Boulder, CO. The mesovortex was more akin to a mesoscale convective vortex (MCV) than to the Denver Cyclone.

Acknowledgements

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