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Impact of Upstream Winds and Stability on Rotors

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Mesoscale Symposium Session 11 - Gravity Waves, Turbulence, and Orographic Processes

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Motivation and Background

- Our objective is to explore the sensitivity of the downslope windstorm and rotors to the upstream winds and stability for the Marshall Fire (CO, 2021).
  How predictable are downslope windstorms and rotors?

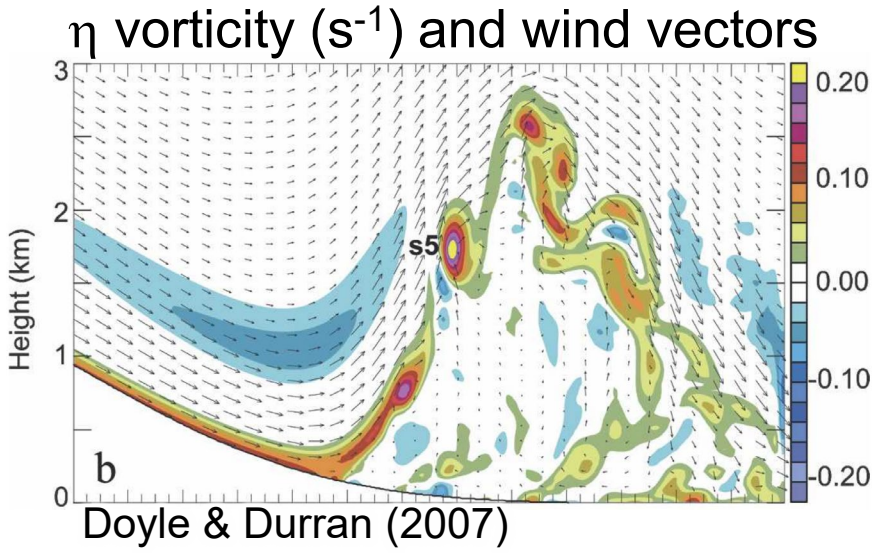
- Mountain waves and downslope windstorms are sensitive to upstream conditions
  - Stability above mountain crest (Brinkman 1974; Durran 1986, 1990)
  - Wind shear & Scorer parameter layering (Klemp and Lilly 1975)
  - Wave breaking in UTLS (Clark & Peltier 1977)
  - Boundary layer effects (Smith et al. 2006; Jiang et al. 2008)

- Rotors form in the lee of mountains when a vortex sheet, generated by shear in the PBL, ascends into the lee wave and breaks down into sub-rotor vortices and turbulence

- Examine the predictability of the:

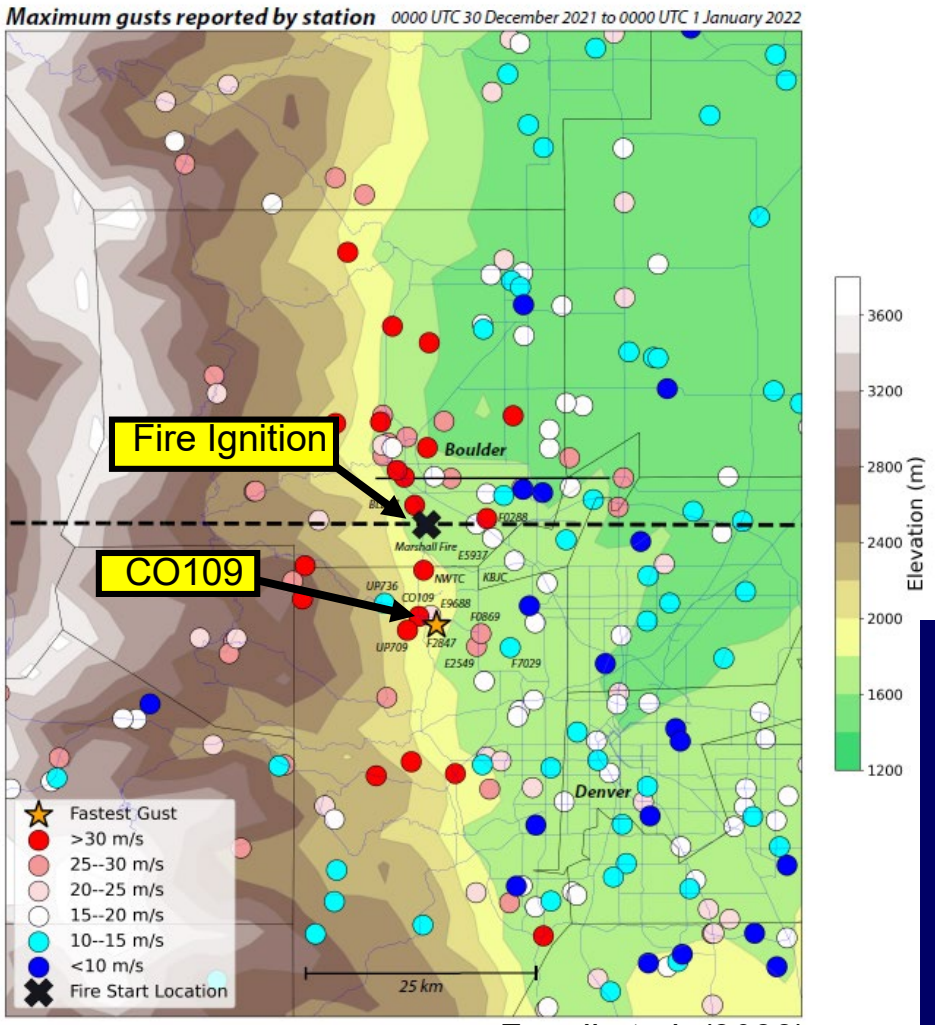
  i) Downslope windstorm using an adjoint

  ii) Rotors using large eddy simulation (LES)



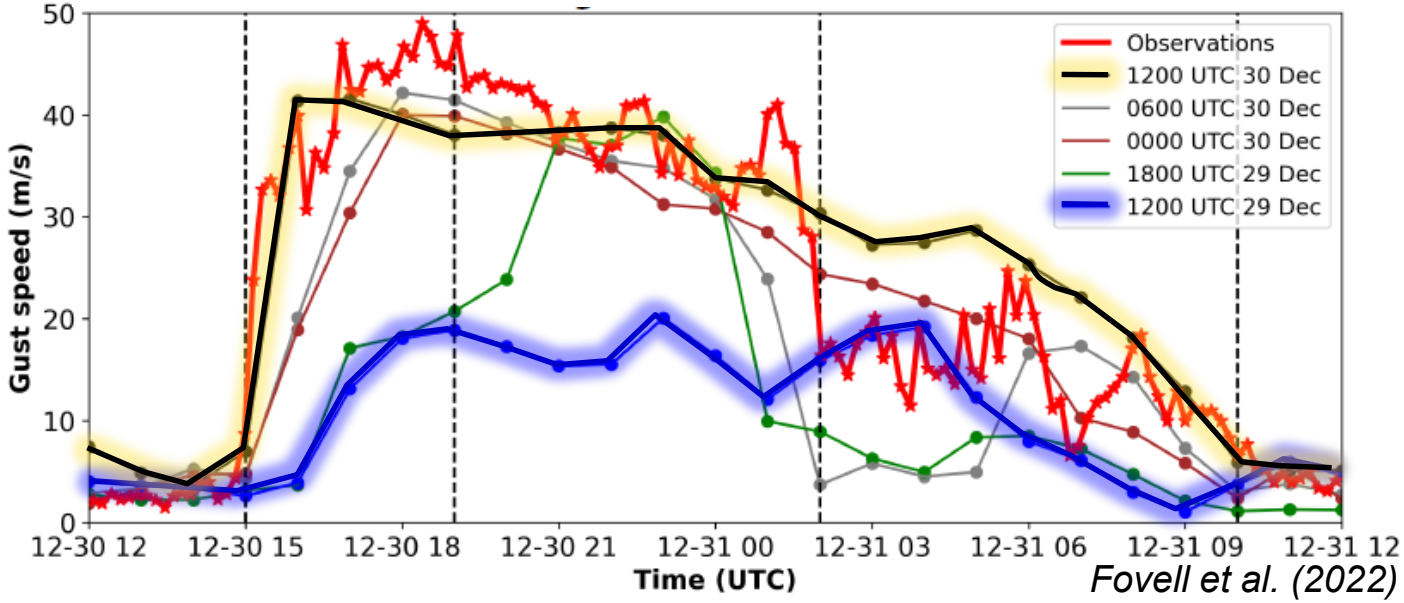
Marshall Fire 30 December 2021

Max Gusts (00Z 30 Dec – 00Z 1 Jan)



Fovell et al. (2022)

Observed and HRRR Forecast Gusts at Station CO109



Fovell et al. (2022)

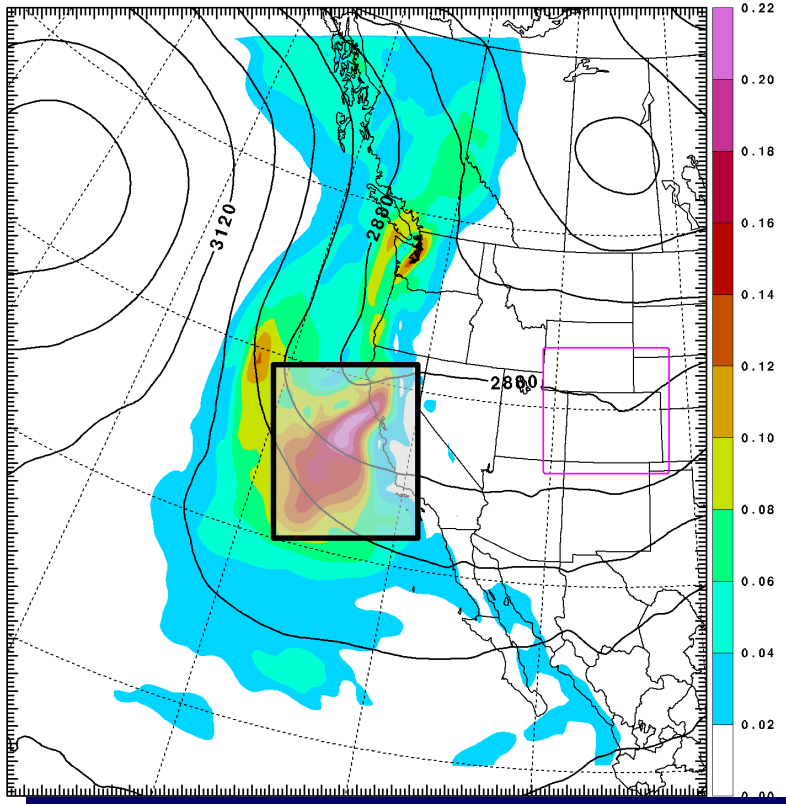
- Marshall Fire (30 December 2021) was the most costly wildfire in Colorado history destroying more than 1000 homes (Juliano et al. 2023)
- Observations show a rapid onset of high winds with gusts >50 m s^{-1} along the eastern foothills of the Rockies
- High-resolution operational models (e.g., HRRR) beyond a few hours lead time performed poorly
- COAMPS adjoint is used to identify regions of initial condition sensitivity related to the poor downslope windstorm forecasts

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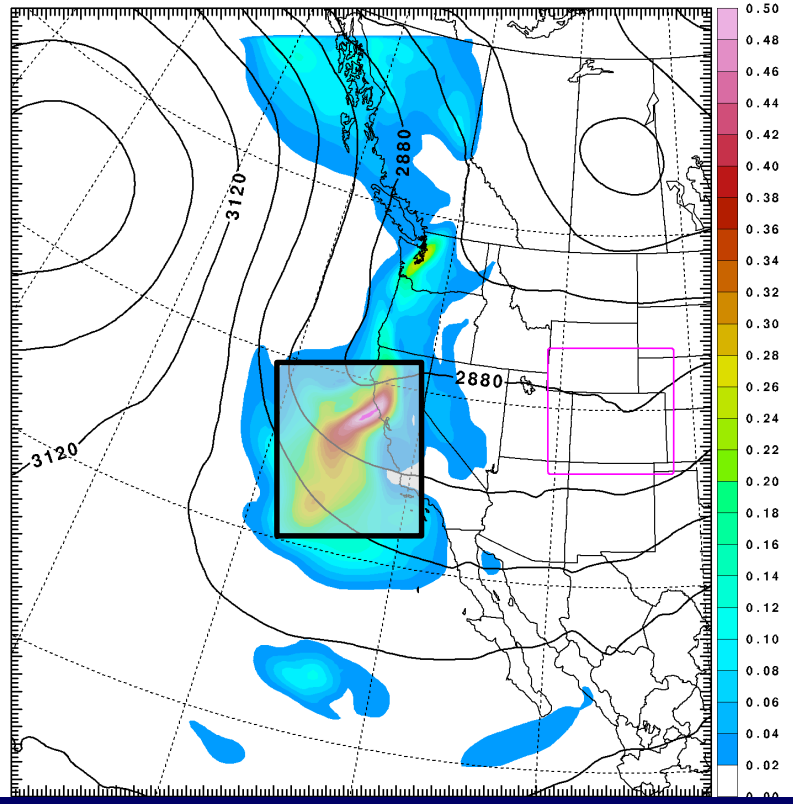
Adjoint Perturbations

Vertically Integrated Adjoint Perturbation Magnitude and 700-hPa Heights Valid at 1200 UTC 29 Dec. (0 h)

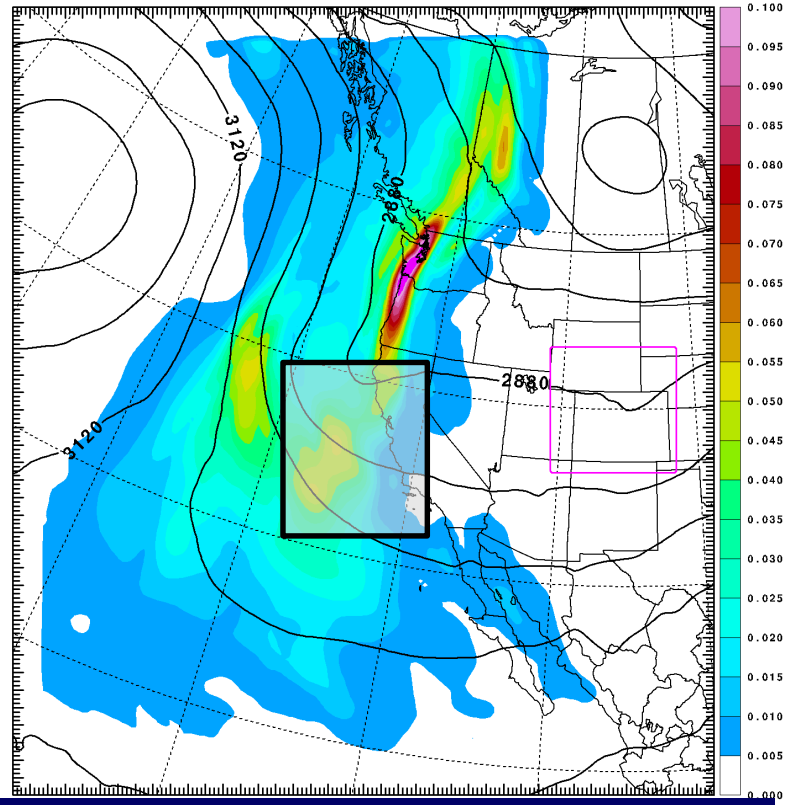
θ Perturbations



Water Vapor Perturbations



V-Wind Perturbations

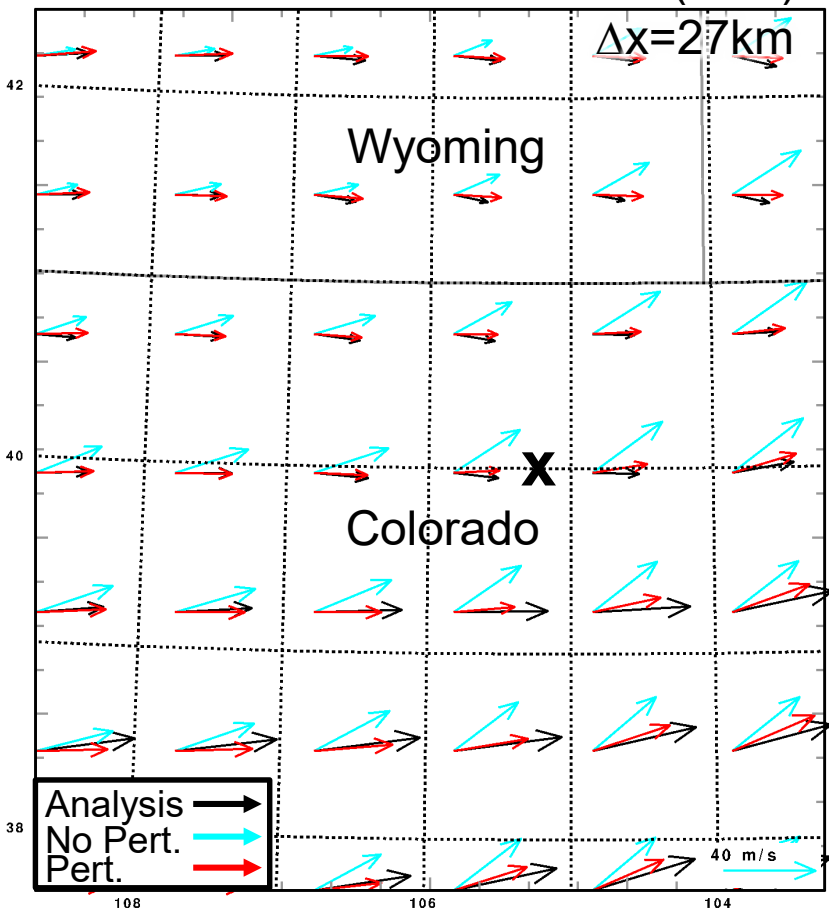


- COAMPS adjoint (27-km mesh similar resolution as operational DA systems), is used to iteratively minimize the forecast pressure error (using the GFS analysis as truth) over CO & WY
- Perturbations are located near a shortwave trough on the West Coast and is spatially widespread, similar to other studies (e.g., Durran et al. 2013; Lloveras et al. 2023; 2025), although local maxima are present
- Two experiments (Δx=1 km): 1) full perturbations, 2) no perturbations in box, rescaling perturbations outside box such that the difference total energy (DTE) is the same

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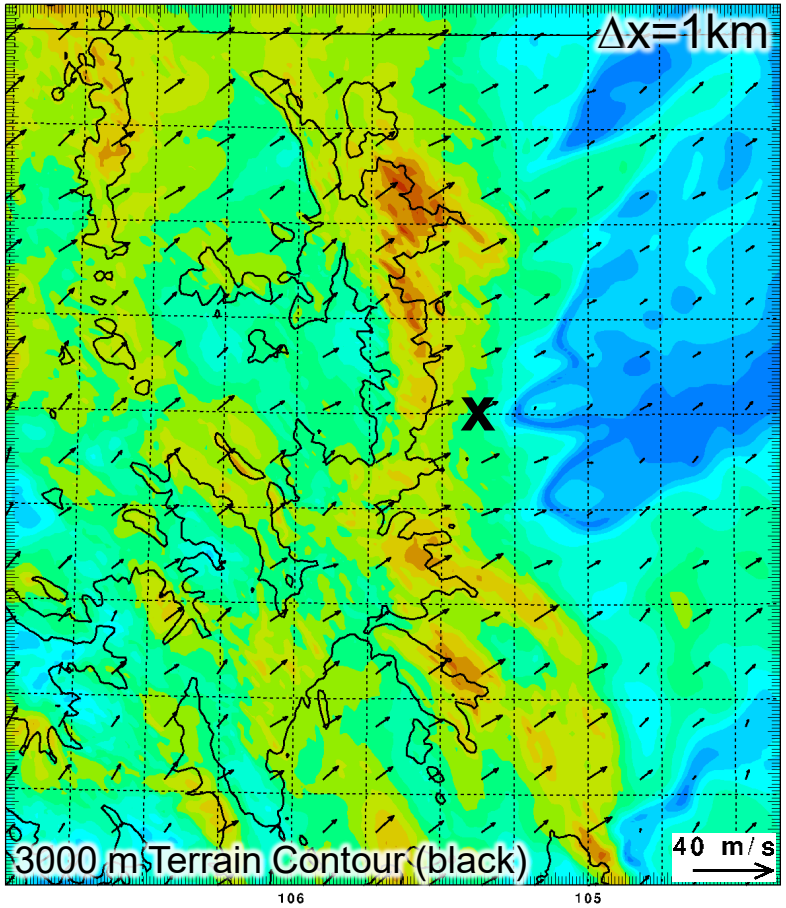
Impact of Adjoint Perturbations

400-hPa Wind Vectors (m s^{-1})
Valid at 1800 UTC 30 Dec. (30 h)

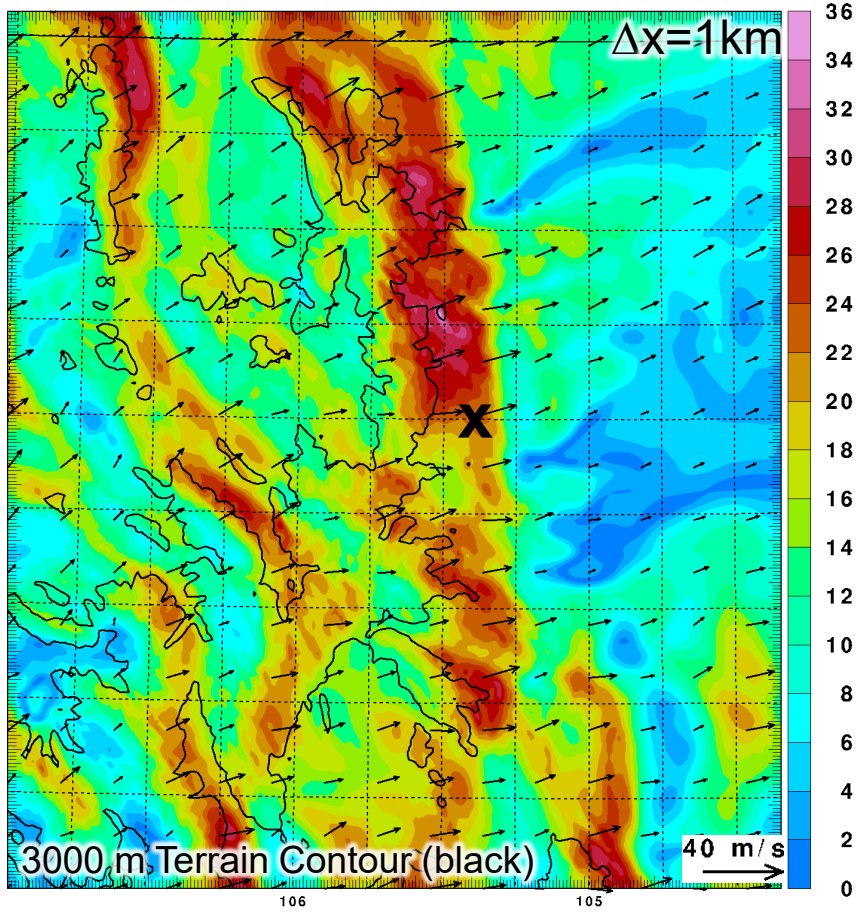


10-m Wind Speed (shading, m s^{-1}); Valid at 2100 UTC 30 Dec. (33 h)

No Perturbations



Perturbations

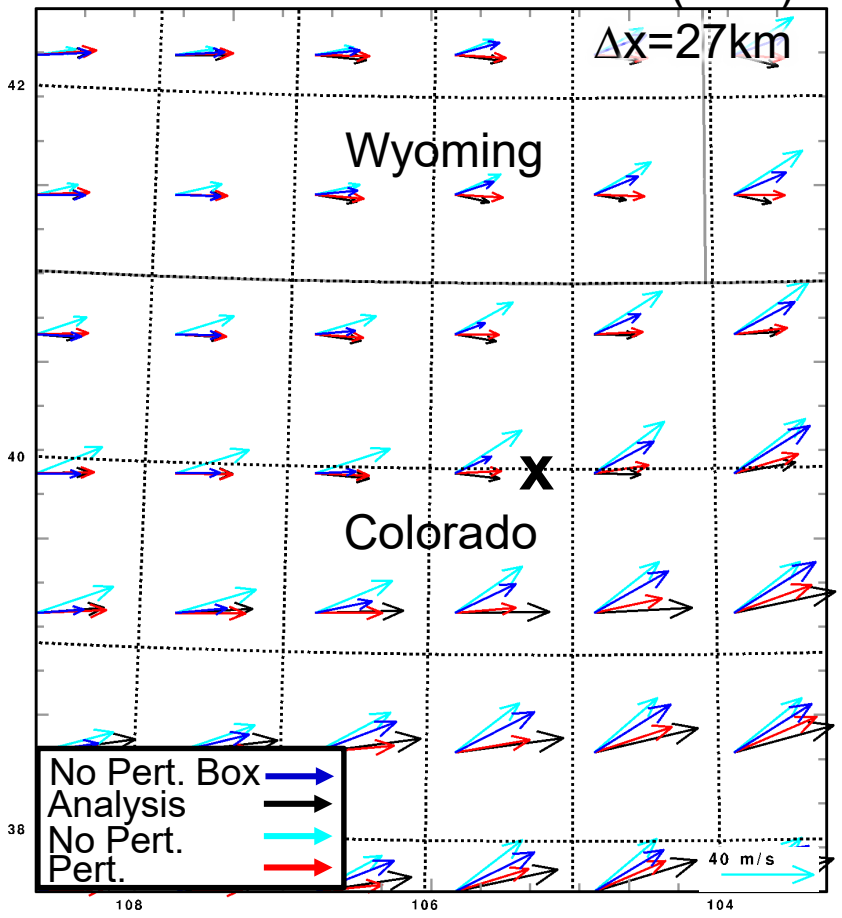


- Perturbations (~2 K / g kg^{-1} / m s^{-1}) shift the jet farther south (as in Fovell et al. 2022) with a more zonal direction
- Perturbations in a high-resolution run (Δx=1 km) (initialized at 12Z 29 Dec.) greatly improve forecasted windstorm

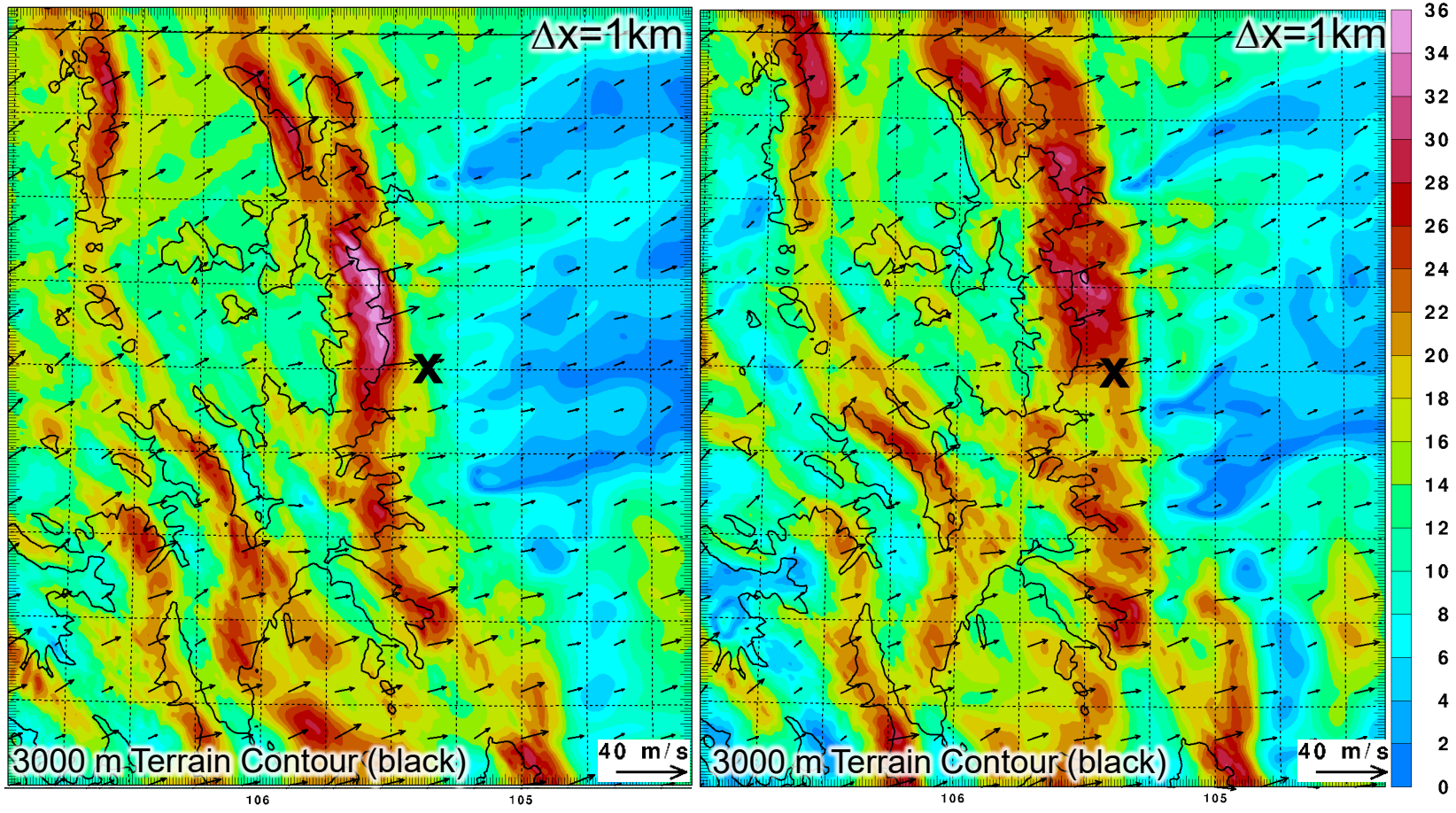
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Impact of Adjoint Perturbations

400-hPa Wind Vectors (m s^{-1})
Valid at 1800 UTC 30 Dec. (30 h)



10-m Wind Speed (shading, m s^{-1}); Valid at 2100 UTC 30 Dec. (33 h)



Perturbations withheld in the box and rescaled (equivalent DTE)

- Wind direction in the jet has a more southwesterly direction relative to the full perturbation run and analysis
- Highest winds remain along the slopes, although a significant improvement over the no perturbation run

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Rotors during the Marshall Fire

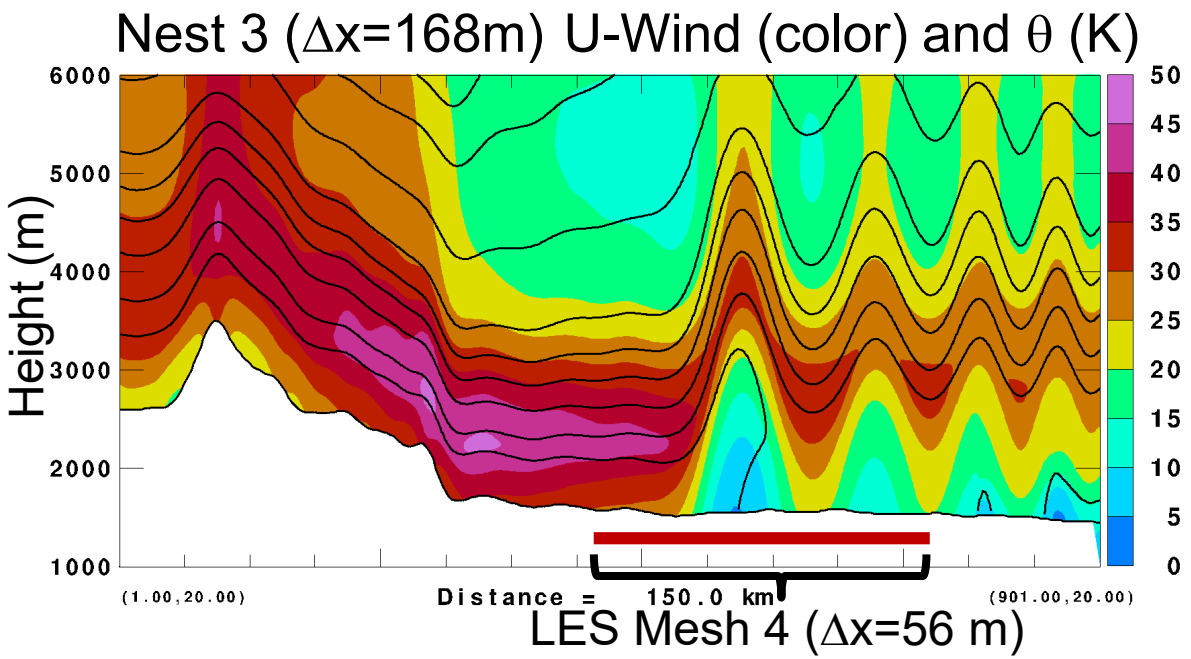


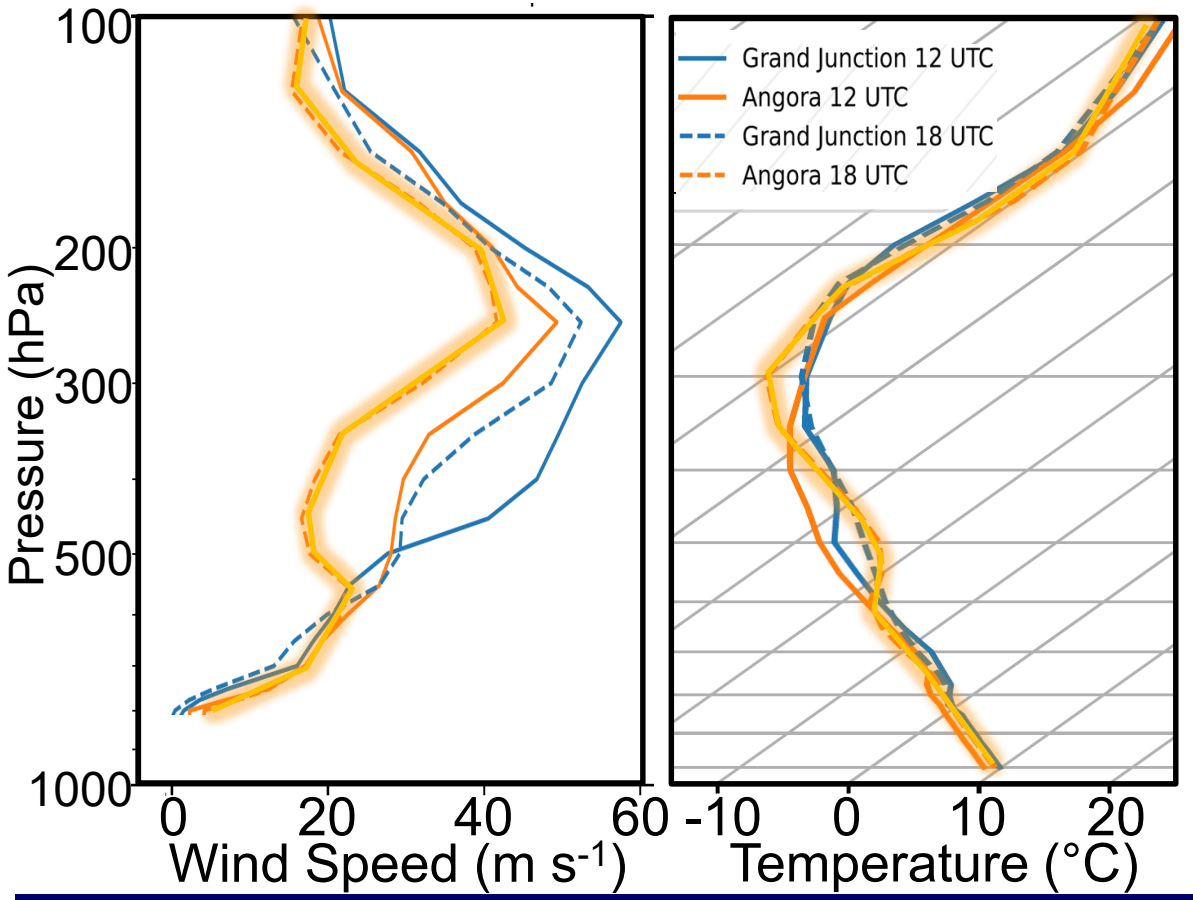
Courtesy of National Weather Service – Boulder, CO

Surface observations and videos are consistent with the presence of lee waves and rotors, with gusty E/SE winds in the area of the fire

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LES Experimental Design





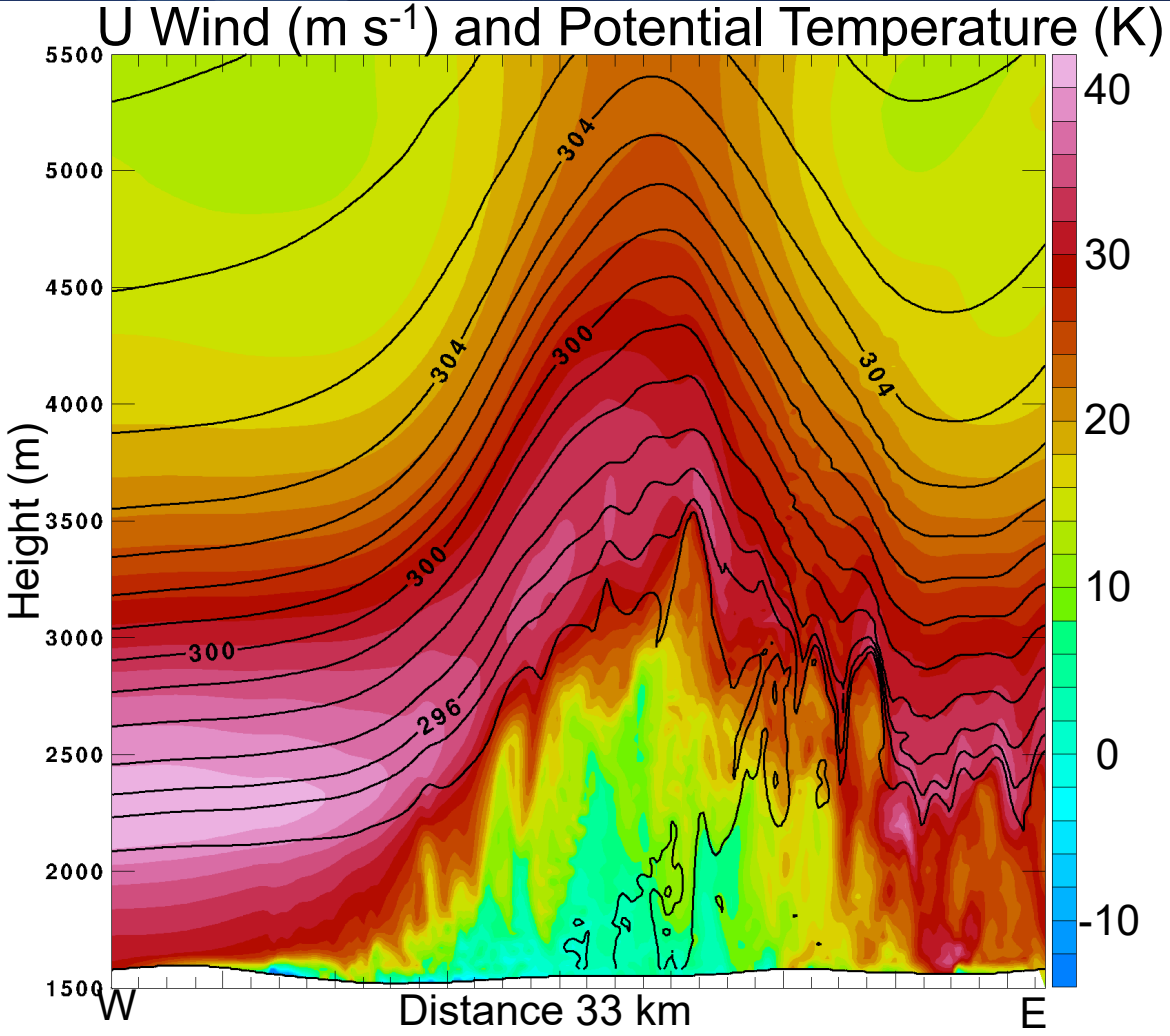
LES Setup

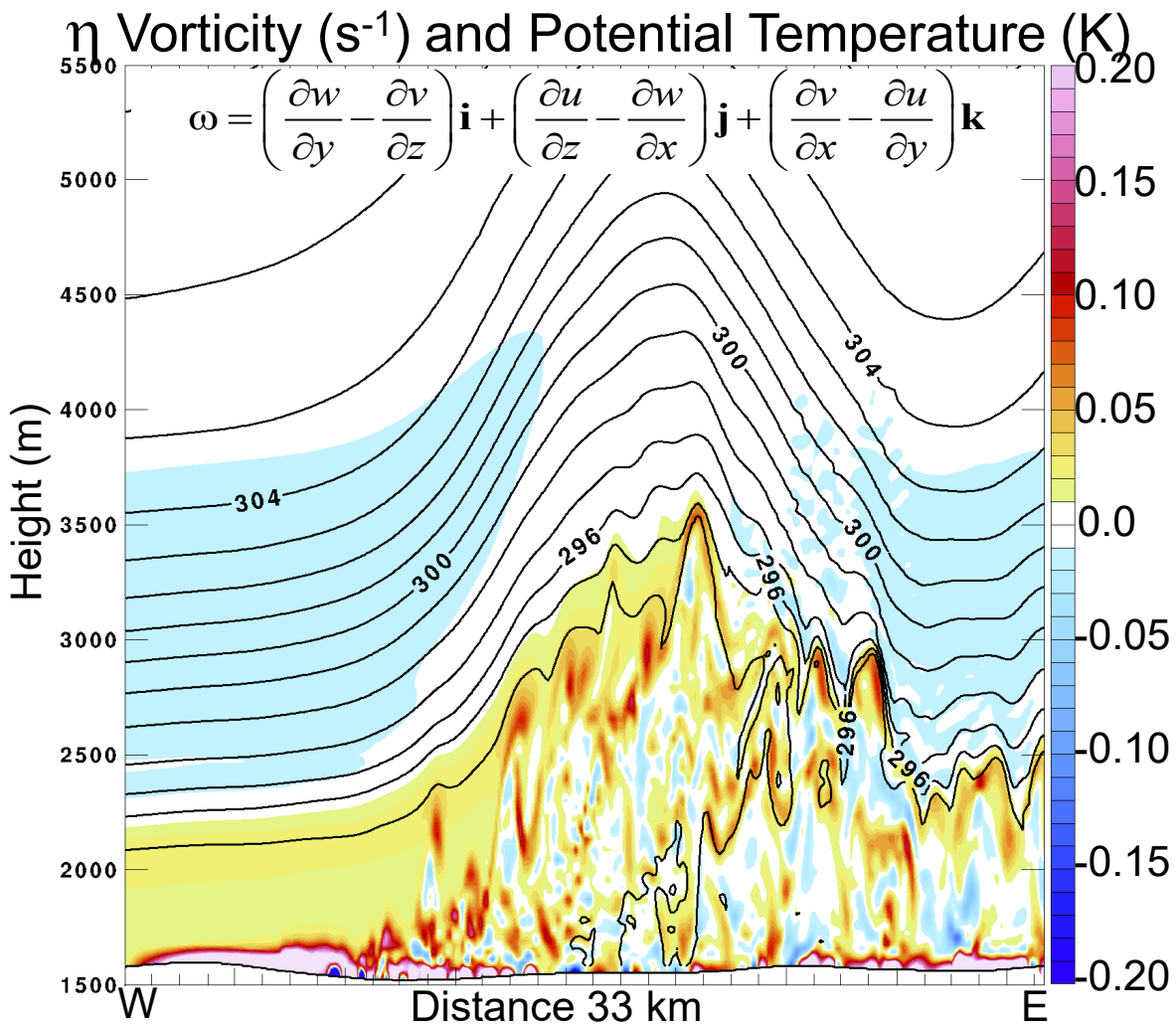
- 4 meshes with Δx=56 m on mesh 4 (50.1 km x 6 km)
- N-S periodic boundaries
- Real terrain along E-W section, uniform terrain in N-S
- No slip lower boundary
- Mesh 4 located over the foothills east of the ridge

- All 4 meshes are initialized horizontally uniform using the 1800 UTC ERA5 Angora profile upstream of fire
- Grand Junction sounding does not support trapped lee waves or rotors

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Large Eddy Simulation
3.5 h on mesh 4 (Δx=56m)





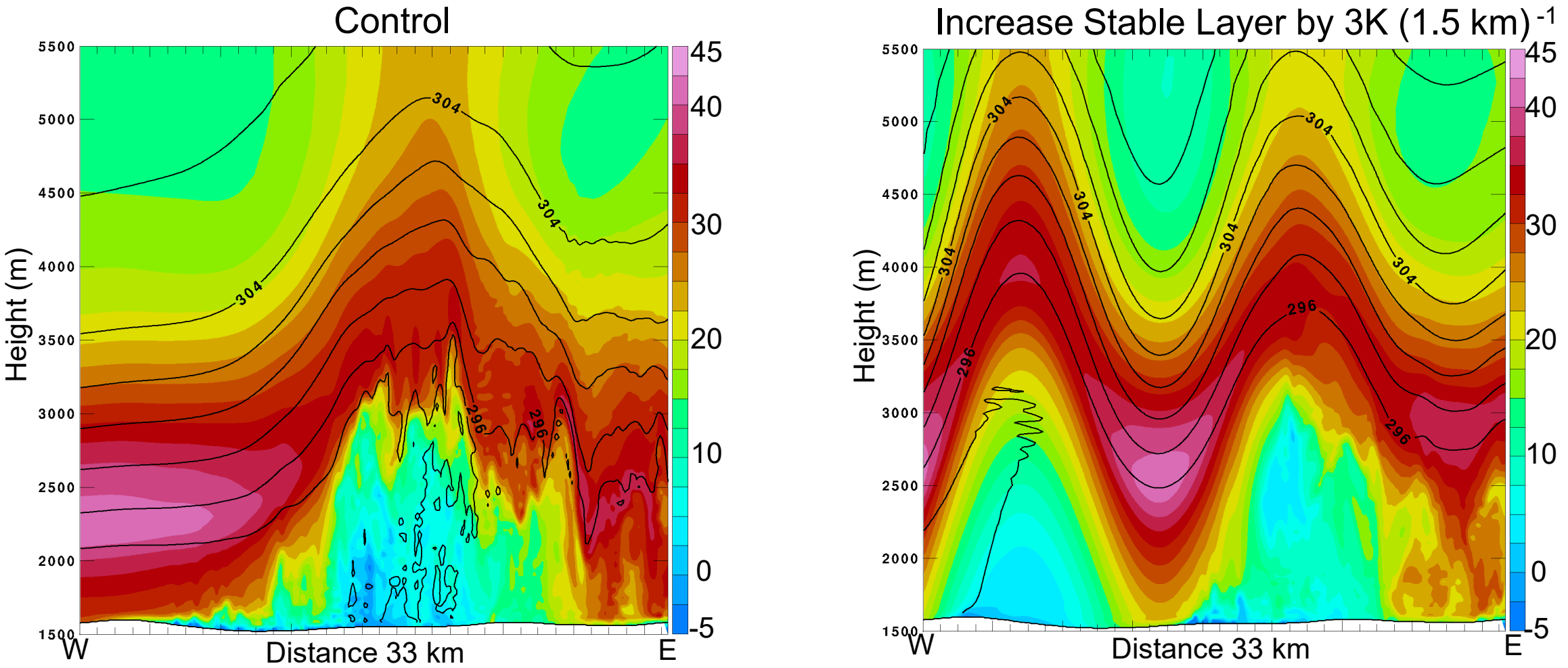
- Mechanical shear in the PBL results in a horizontal vorticity sheet that is lifted vertically into the lee wave at the separation point, and breaks down into sub-rotor vortices ($\eta > 0.15$ s^{-1}) and surface wind gusts (> 35 m s^{-1})
- Strong wind gusts occur in the vortex sheet separation and re-attachment zones and near sub-rotors

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Sensitivity to Upstream Stability

4 h on mesh 4 (Δx=56m)

U Wind (m s^{-1}) and Potential Temperature (K)



Increasing the stratification in the inversion increases the wave amplitude, decreases the wavelength, and the high winds and rotors move ~20 km upstream closer to the mountain slopes

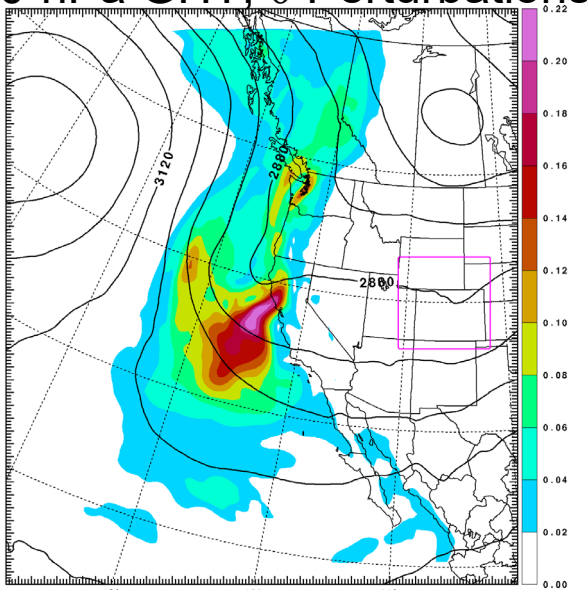
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Summary

Short-term forecasts of the downslope winds during the Marshall Fire are very sensitive to the upstream conditions over the E. Pacific

- High-resolution models failed to predict the windstorm even 24h in advance
- Addition of small amplitude adjoint perturbations in the upstream trough greatly improves the forecast windstorm, underscoring the limited predictability

700-hPa GHT; θ Perturbations



Rotors are sensitive to upstream low-level stability and winds

- LES indicates the presence of rotors (consistent with observations), sub-rotor vortices, and extreme wind gusts, which are sensitive to small changes in the upstream stability (and vertical wind shear)
- This limited predictability has important implications for fire weather forecasting

η Vorticity (s^{-1}) and θ (K)

