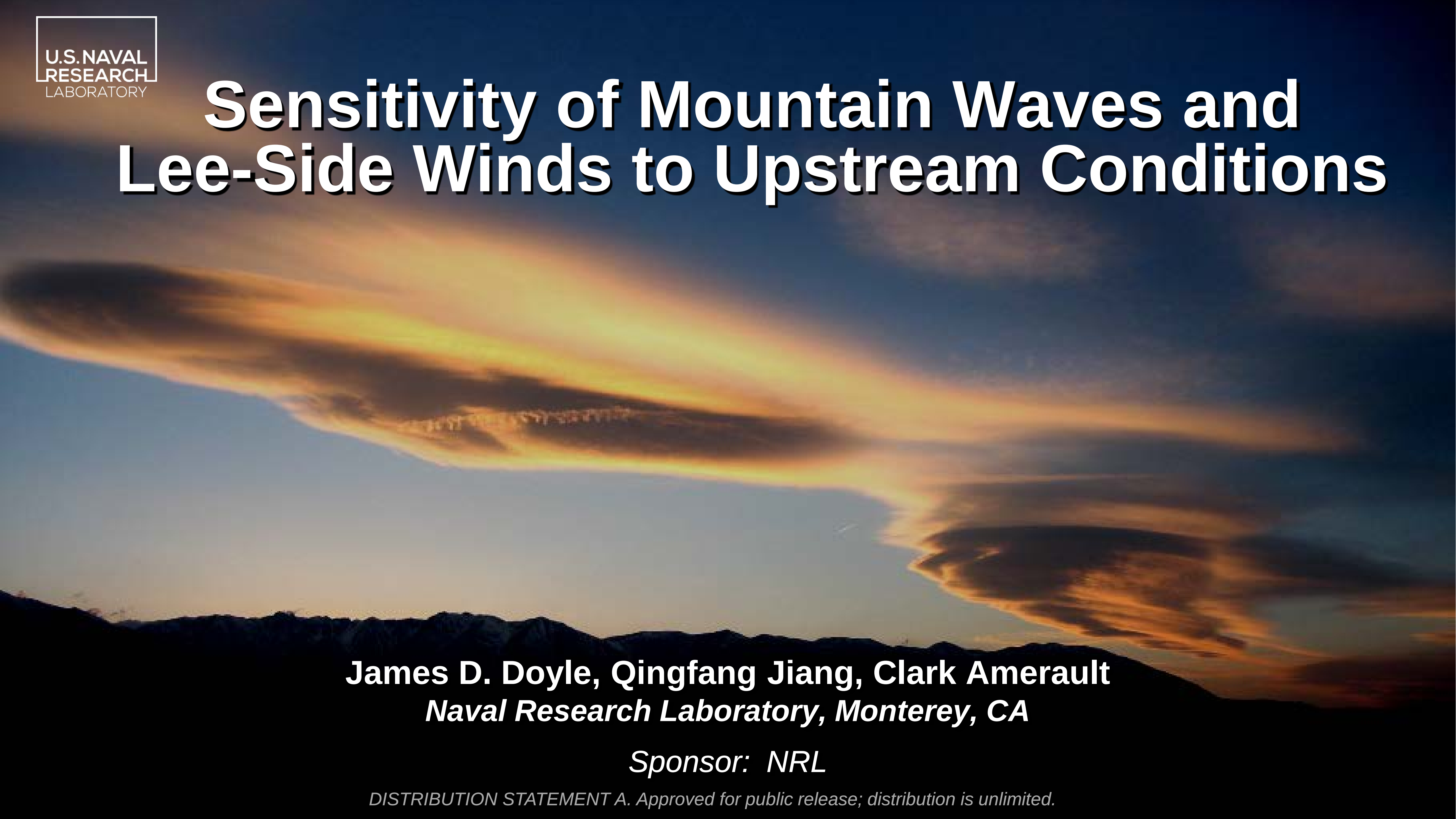

Sensitivity of Mountain Waves and Lee-Side Winds to Upstream Conditions

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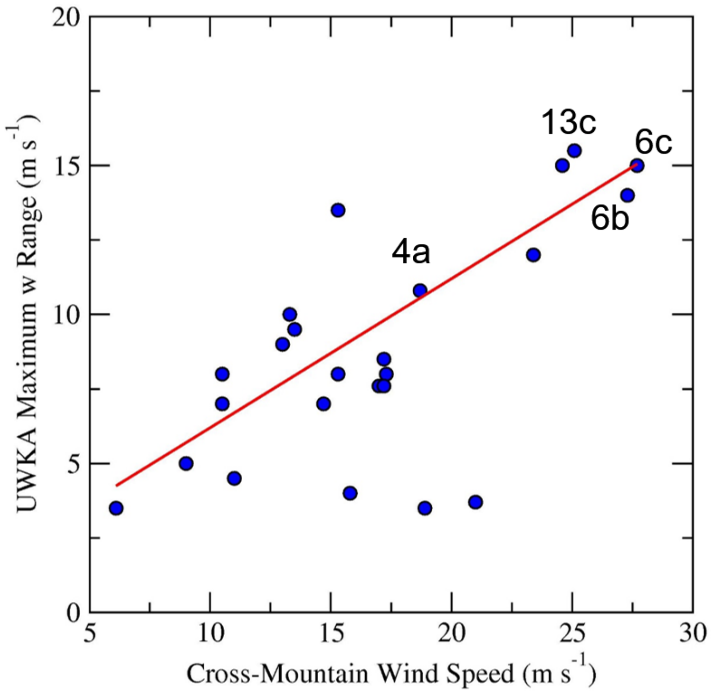
Sponsor: NRL

Background and Motivation

- **Mountain waves & lee-side winds are sensitive to upstream conditions**
  - Stability above mountain crest (Brinkman 1974; Durran 1986, 1990)
  - Wind shear and Scorer parameter layering (Klemp and Lilly 1975)
  - Wave breaking in upper troposphere lower stratosphere (Clark & Peltier 1977)
  - Boundary layer effects (Smith et al. 2006; Jiang et al. 2008)
- **Terrain-Induced Rotor Experiment (T-REX) (2006)** (Grubišic´ et al. 2008)
  - IOP 6 (25-26 March): Downslope windstorm, wave breaking
  - IOP 13 (16-17 March): Upstream layering of static-stability
- **Adjoint model is used to explore sensitivity and optimality**
  - Provides insight into the dynamics, instabilities and nonlinearity
  - Important for predictability of mountains waves and windstorms (Reinecke and Durran 2009; Doyle and Reynolds 2008; Doyle et al. 2011)
  - Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function (*J*) to changes in the initial state
  - Sensitivity of response function (*J*) at time t_n to state at t_0:

$$\frac{\partial J}{\partial \mathbf{x}(t_0)} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}(t_n)}$$

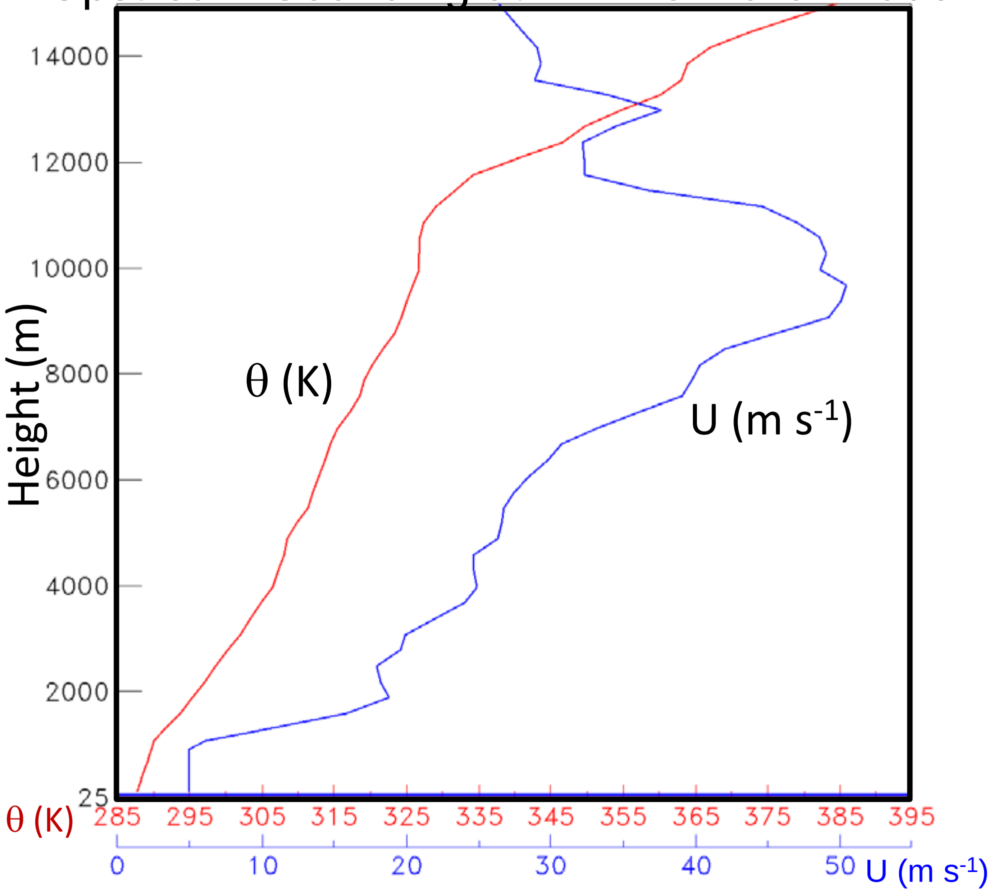
Cross-Mountain Flow and Wave Amplitude (T-REX)



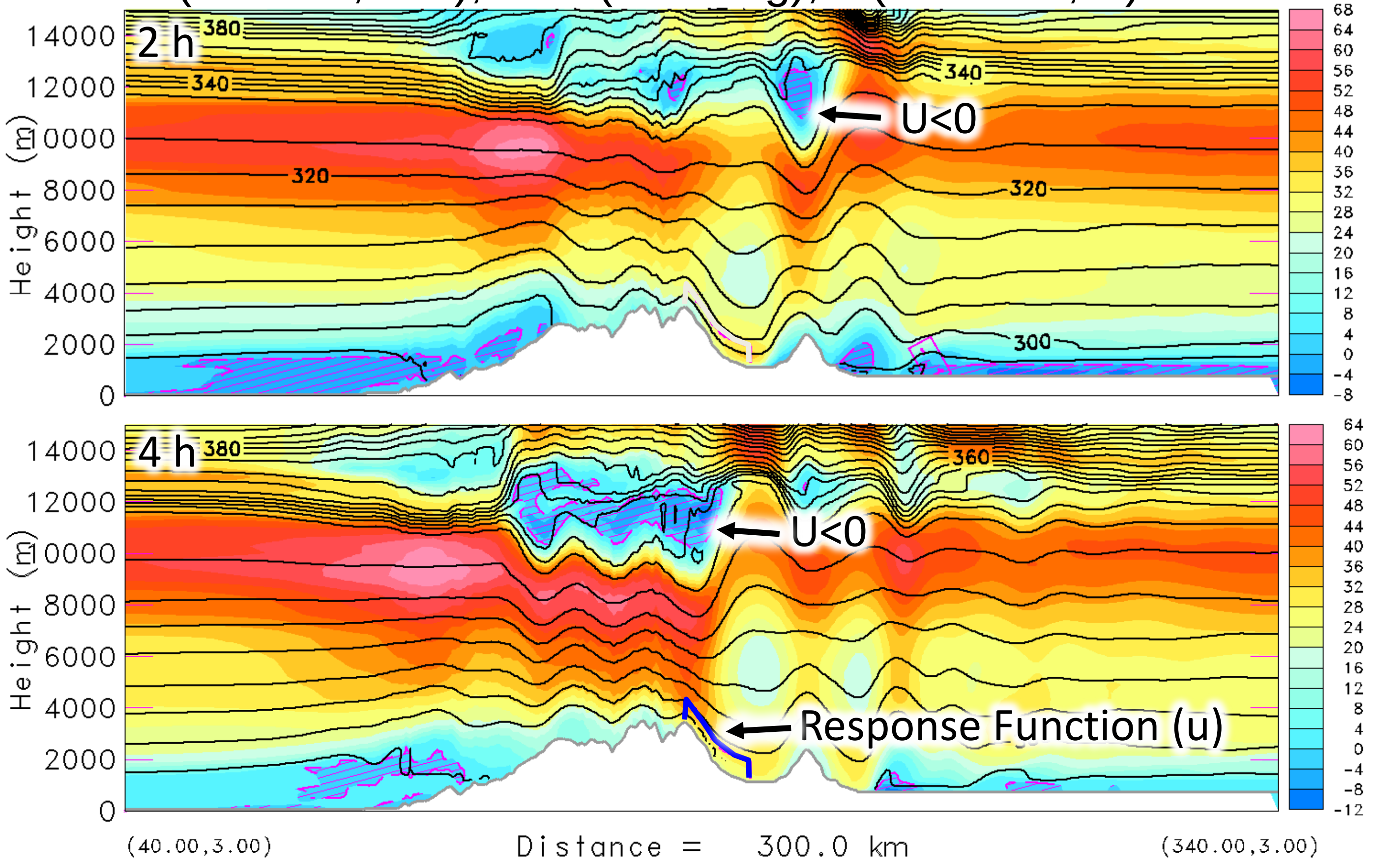
T-REX IOP6 Mountain Waves and Windstorm

2D Dry COAMPS (Δx=1 km, 95L) (Adjoint 2-4h)

Upstream Sounding at 21Z 25 March 2006



U (color fill, m/s), U<0 (hatching), θ (contours, K)

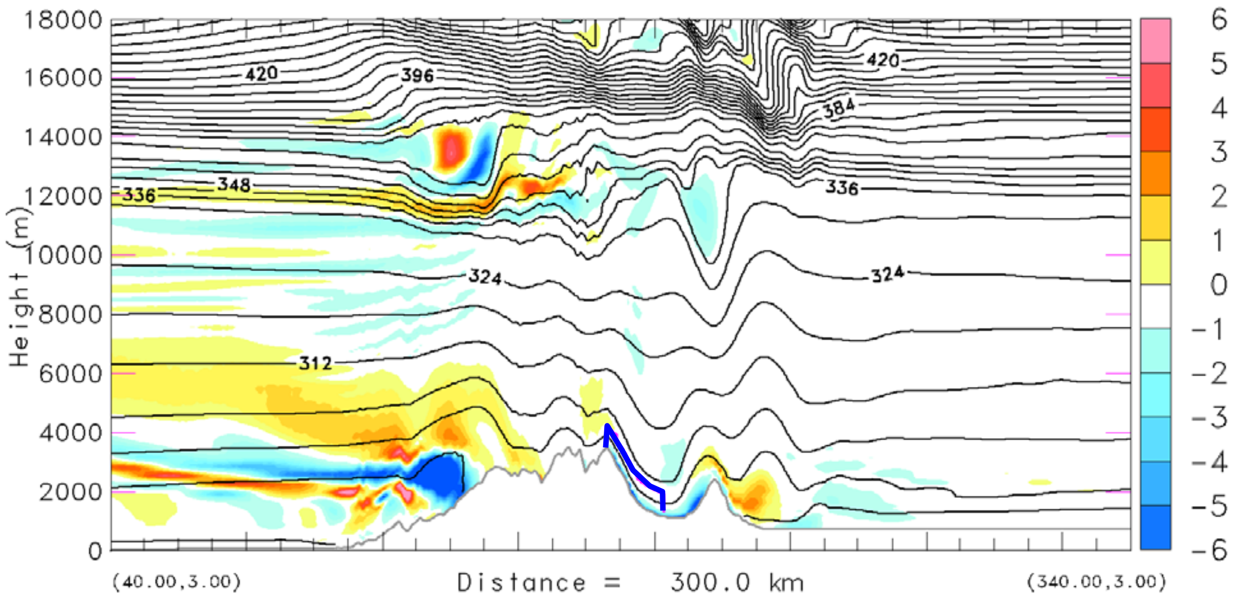


- Upstream sounding used to initialize 2D COAMPS (dry) with surface friction (NH/U~2.5-3.0)
- Strong downslope winds (~25 ms^{-1}) and wave breaking in the lower stratosphere at 4-h time
- Response function is the u-wind along the lee slopes in the lowest 725 m (lowest 9 levels)

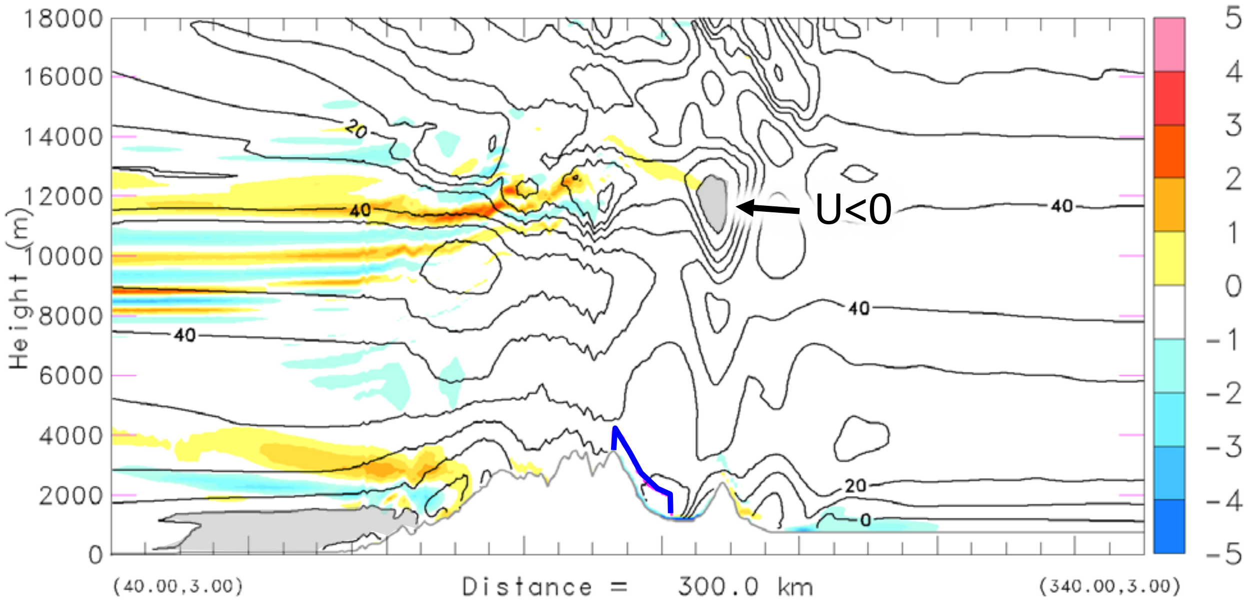
T-REX IOP6 Mountain Waves and Windstorm

2D Dry COAMPS (Δx=1 km, 95L) (Adjoint 2-4h)

θ Sensitivity (∂J/∂θ), θ (contours, K) (2h)



U-Wind Sensitivity (∂J/∂u), u (contours, m s^{-1}) (2h)

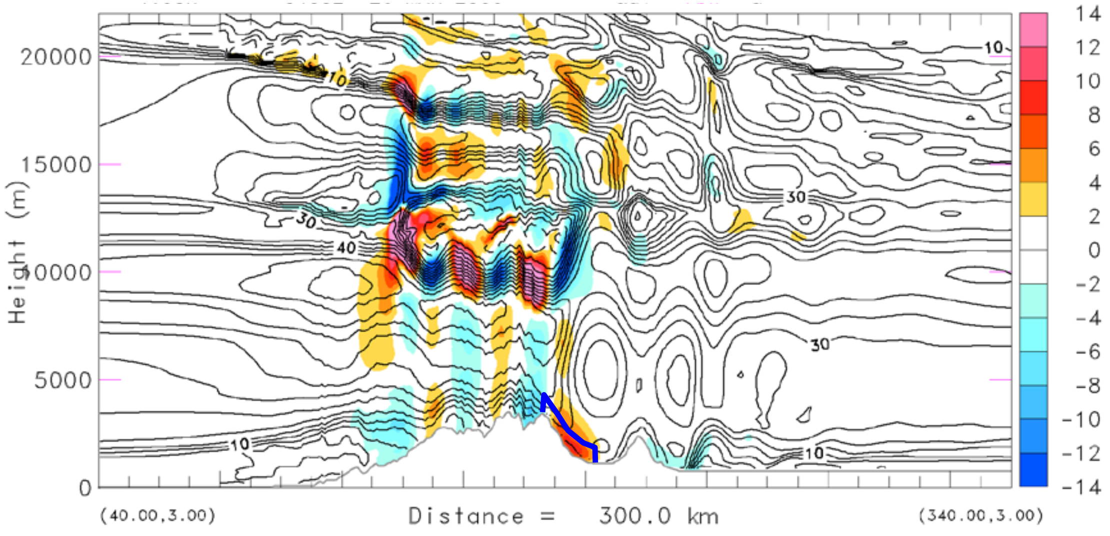


- Low-level Sensitivity
  - Increased stability upstream and forward shear leads to stronger downslope winds
  - 1°C warming upstream at ridge crest leads to a ~50% larger increase in downslope winds than a 1 m s^{-1} wind speed increase
  - Strong sensitivity within the PBL upstream along the slopes and downstream
- Upper-level Sensitivity
  - Wave breaking region in upper troposphere and lower stratosphere (UTLS) (shear / stability)

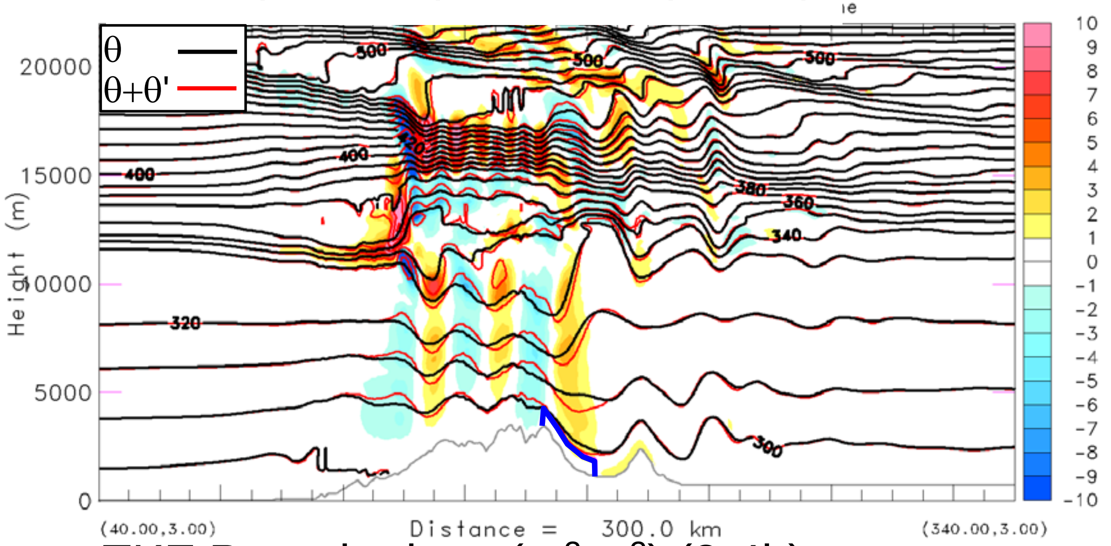
T-REX IOP6 Mountain Waves and Windstorm

Evolved Optimal Perturbations (2-4h) [2D Simulation]

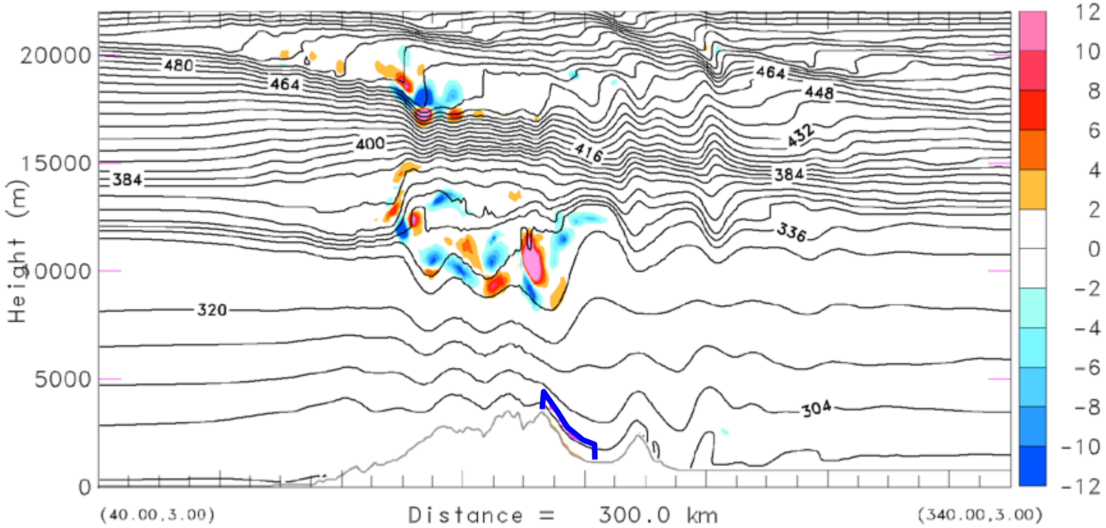
U' (color, m s^{-1}) (2-4h)
U Wind NLM (black, m s^{-1})



θ' (m s^{-1}) (2-4h)
θ NLM (black, K) and θ+θ' (red, K)



TKE Perturbations (m^2 s^{-2}) (2-4h)



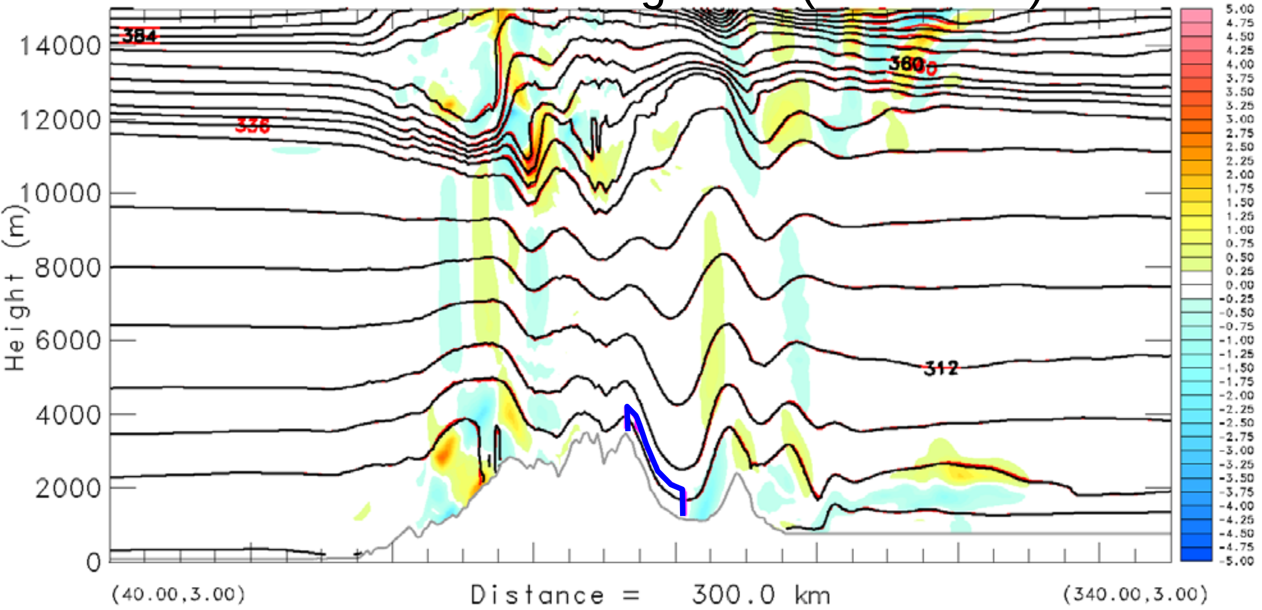
- Optimal perturbations (max. 1 m s^{-1}, 1 K)
- Perturbations:
  - Enhanced downslope winds ~10 m s^{-1}
  - Increased wave breaking in UTLS
  - Wave amplitudes increased, especially above lee slopes
- Resonant wave amplification

Nonlinearity

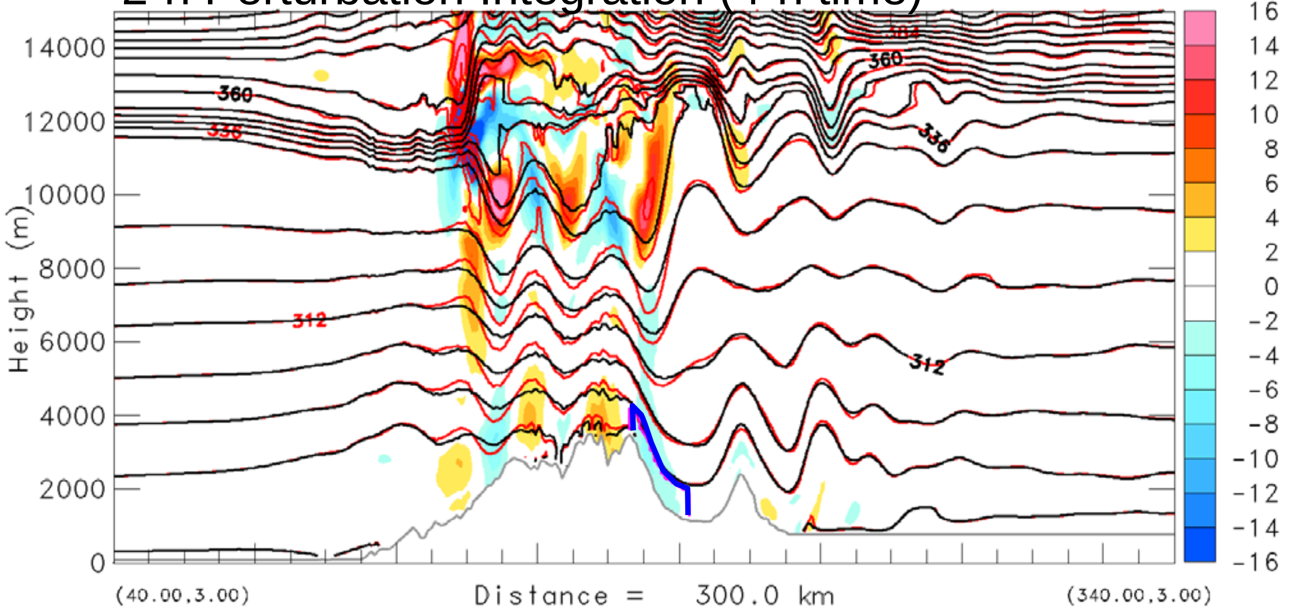
Evolved Optimal U-Wind (m s^{-1}) Perturbations (2-4h) [2D Simulation]

U(NL)-U(TL) (color, m s^{-1}); Potential Temperature (NL black, TL red)

30 min. Perturbation Integration (2.5-h time)



2-h Perturbation Integration (4-h time)



- Perturbations evolved in nonlinear (NL) and tangent linear (TL) models
- Nonlinear growth in the stratosphere, above topography and along lee slopes
- TLM lee-side u-wind 9 m s^{-1} vs 6 m s^{-1} in NLM at final time; maximum in NLM farther down lee slope
- Evolved perturbation correlations in NLM/TLM are 0.92 (box) /0.65 (domain); TLM/adjoint are accurate

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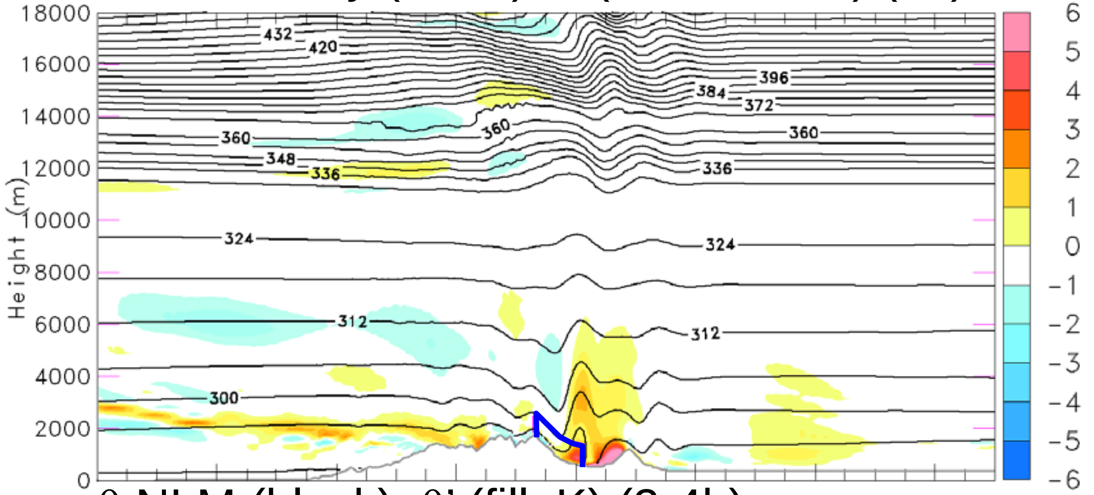
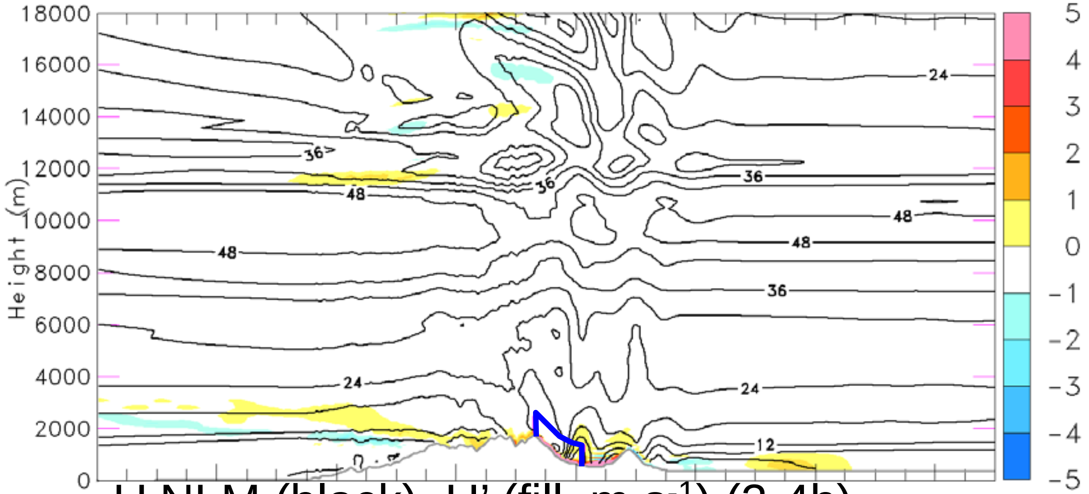
T-REX IOP6 Mountain Waves and Windstorm

Sensitivity Experiment: Reduced Terrain Height (50%) [2D Simulation]

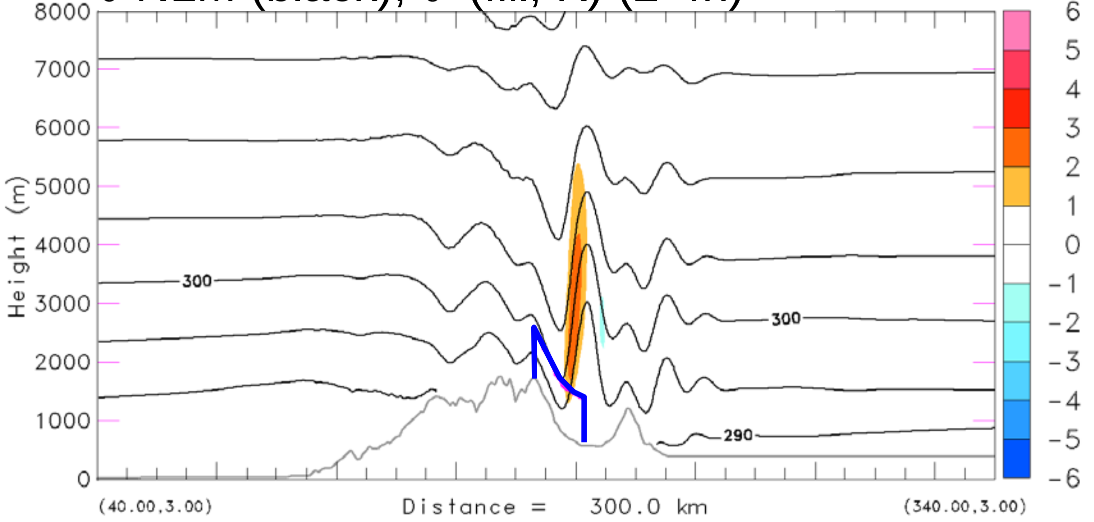
θ Sensitivity (∂**J**/∂θ), θ (contours, K) (2h)



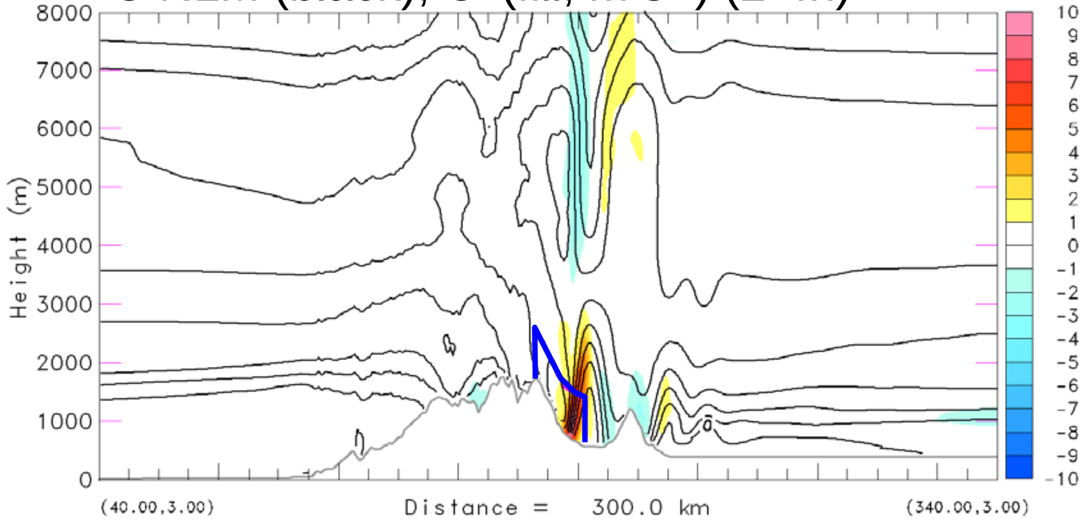
U-Wind Sensitivity (∂**J**/∂**u**), u (contours, m s^{-1}) (2h)



θ NLM (black), θ' (fill, K) (2-4h)



U NLM (black), U' (fill, m s^{-1}) (2-4h)

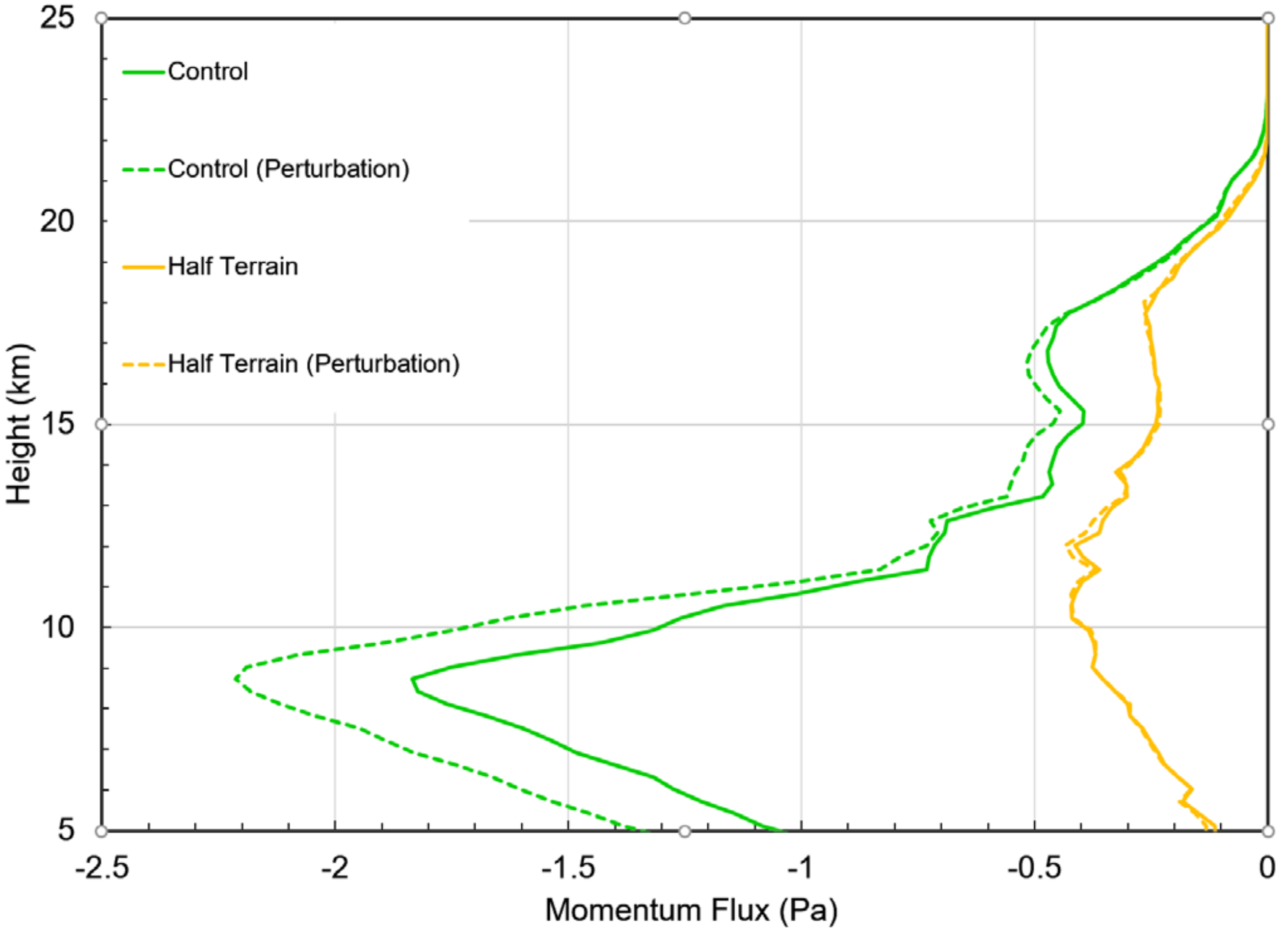


- Sensitivity: Upstream (increased stability, increased shear); downstream (PBL, lee wave)
- Evolved perturbations increase lee wave amplitude, and lee side winds (~9 m s^{-1})

Momentum Flux

Zonal Momentum Flux for Control and Sensitivity Test

$$M_x = \rho \int_{-\infty}^{\infty} u'w' \, dx$$

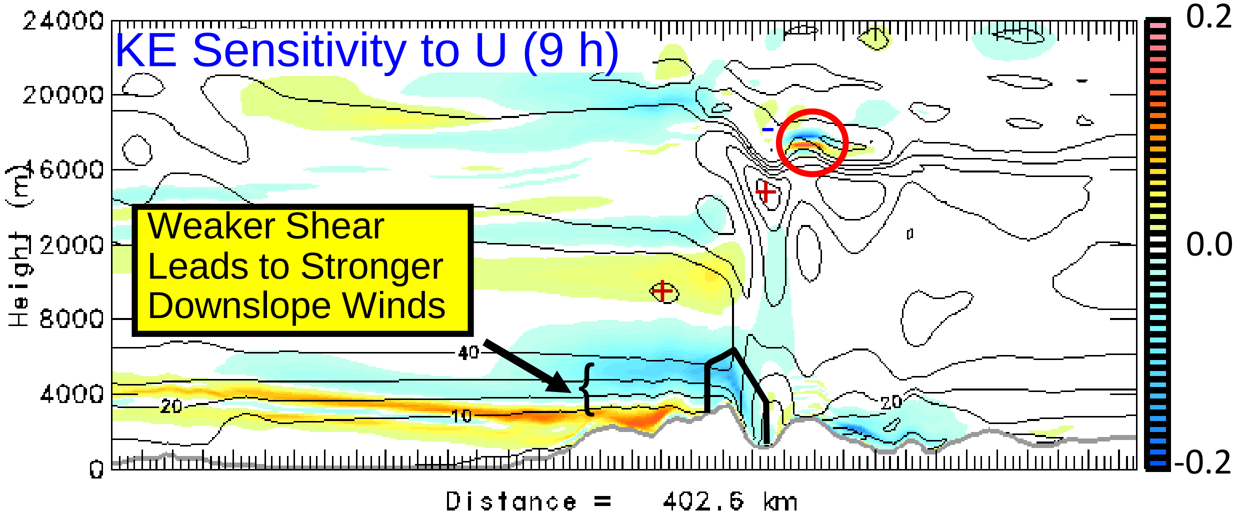


- Drag increases strongly with the adjoint perturbations, consistent with the increase in downslope winds.
- High sensitivity of drag to upstream environment is closely tied to wave breaking in the UTLS.
- Momentum flux is less sensitive to the adjoint perturbations in the non-breaking regime (reduced terrain)

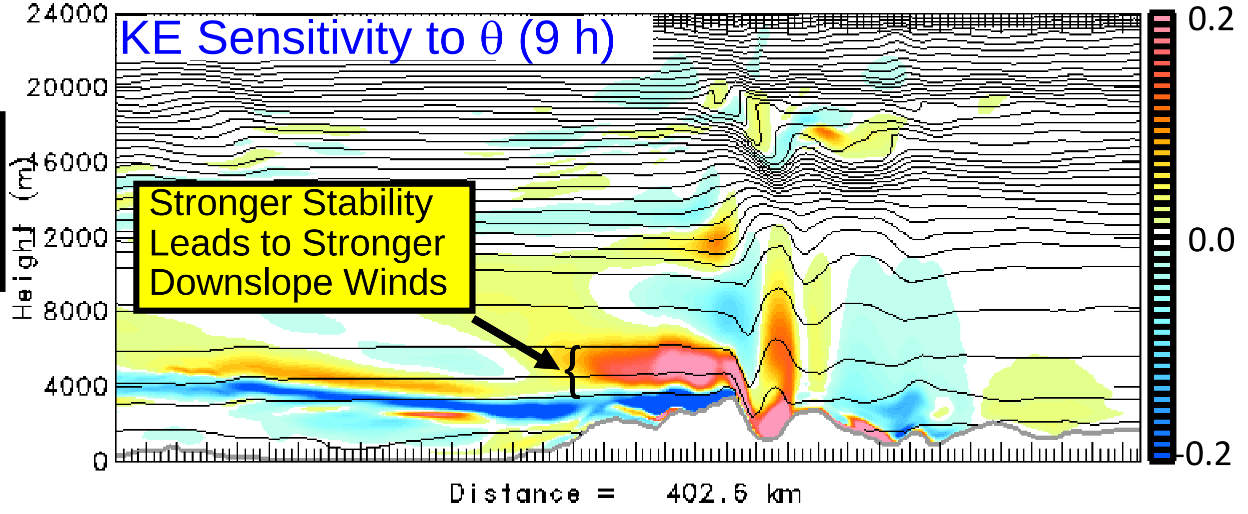
T-REX IOP13 Mountain Waves

3D Nested COAMPS (Δx=3 km) (Adjoint 9-12h)

Sensitivity to crest level shear and UTLS region

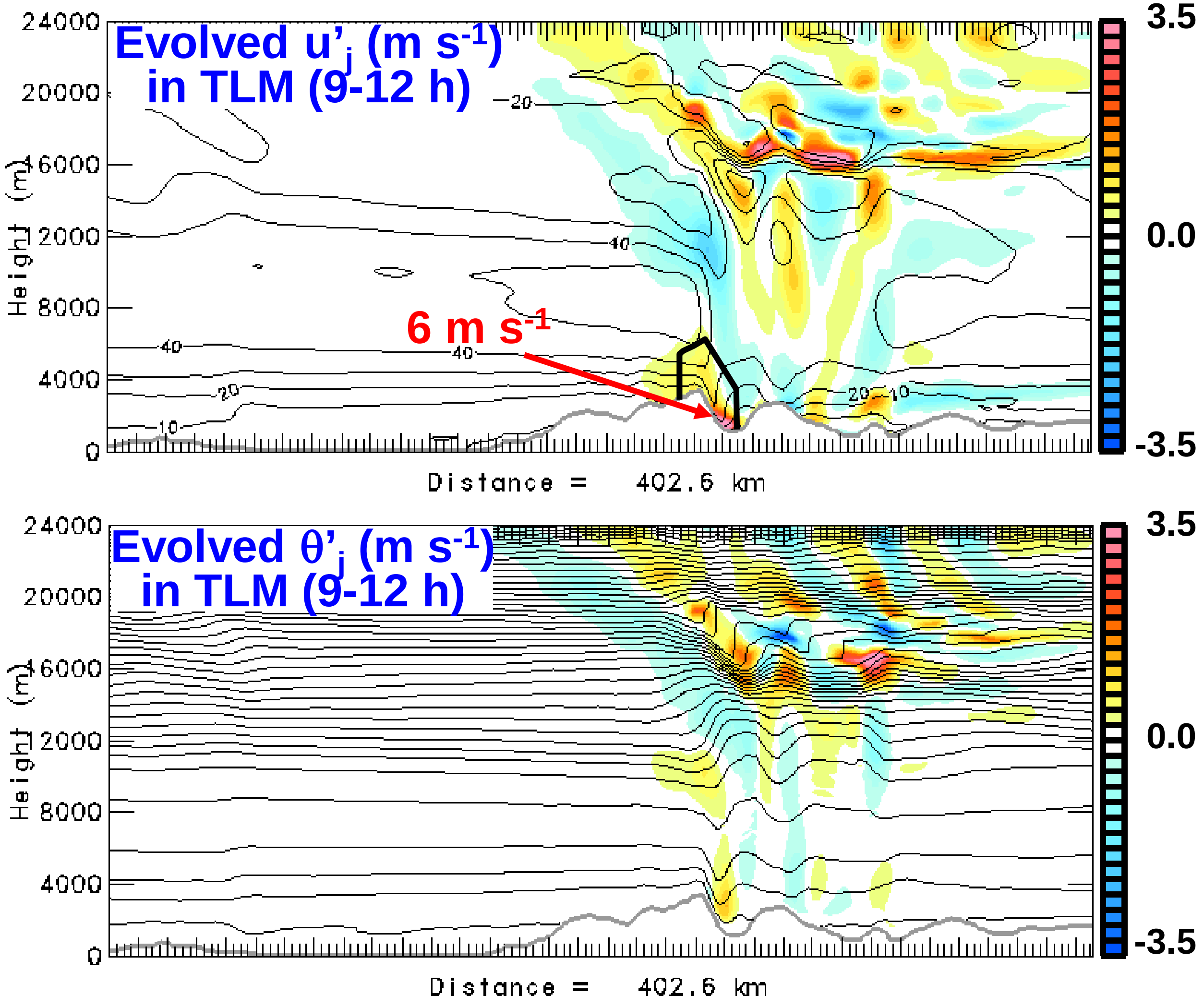


Sensitivity to stability at crest level, within valley, aloft in waves



T-REX IOP13 Mountain Waves

3D Nested COAMPS (Δx=3 km) (Adjoint 9-12h)



Large u' and θ' Growth Along Lee Slopes and in UTLS Waves

Conclusions

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- Simulations and adjoint sensitivity of T-REX IOPs 6 and 13 highlight:
  - –Increasing stratification upstream is more efficient than increasing upstream winds to enhance downslope winds in the lee of the Sierra
  - –Importance of wave breaking in the UTLS and nonlinearity
- Boundary layer sensitivity:
  - –Sensitivity to temperature and winds along upstream slopes, and BL top
  - –Downstream sensitivity in the valley beneath lee wave crests
- Predictability implications:
  - –Importance of observing the upstream stratification, winds (to a less degree), and UTLS (associated with wave breaking)
  - –Downstream boundary layer environment beneath lee waves