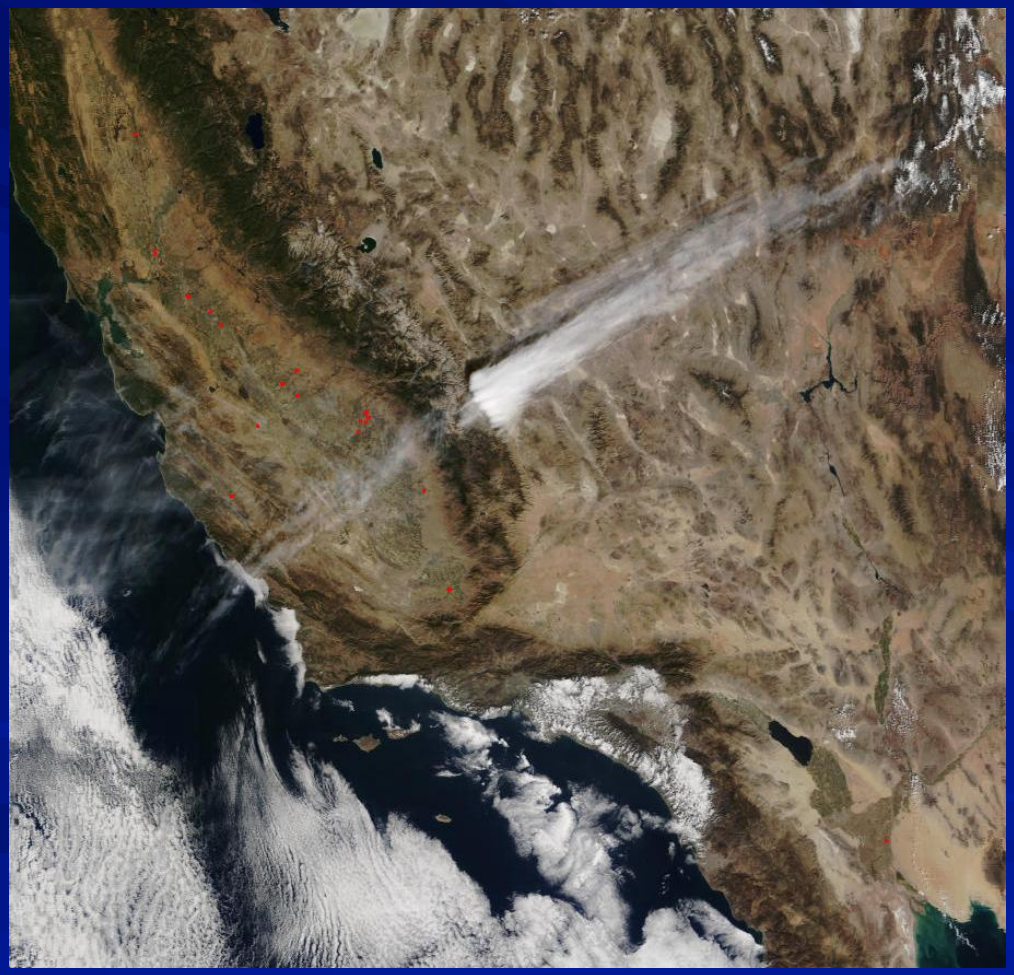
The Up-Scale Influence of Gravity-Wave Breaking



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The Current GWD Paradigm

- Determine momentum flux carried by the waves
- Determine levels of wave overturning
- Apply a decelerating force at those levels

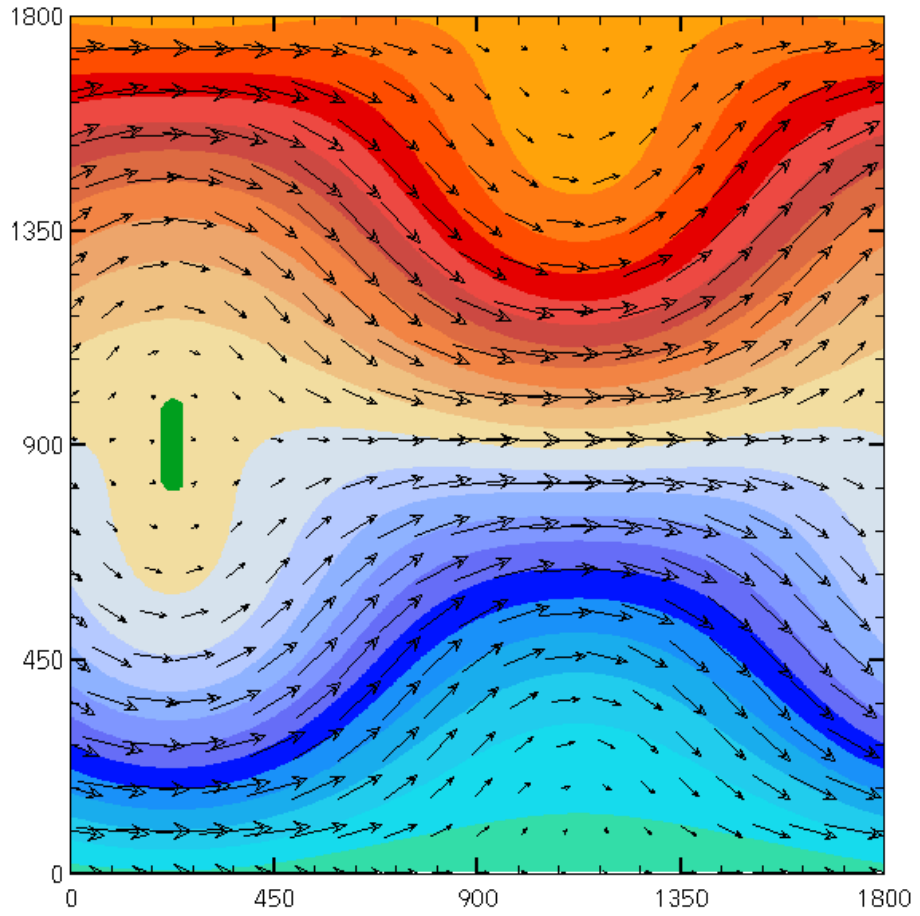
Problems with this approach

- The momentum flux parameterization is based on steady-state mountain wave theory.
- Nonlinear influences are not accurately captured
- The momentum flux divergence is not all that useful, at least at current forecast-model resolutions.
  - Horiz. resolution of ECMWF model (T1279) is about 15 km

Model Problem

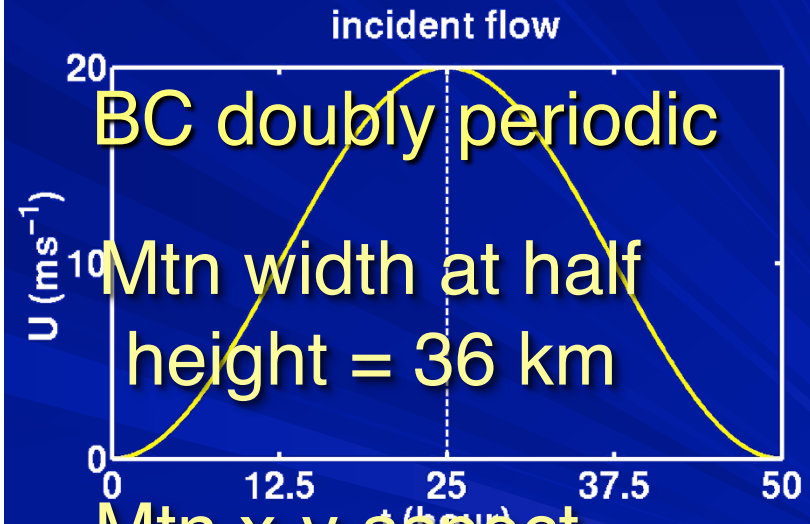
- Idealized Synoptic-Scale Flow
  - Nondivergent barotropic jet
  - Uniform stratification (constant N^2)
  - One acceleration/deceleration cycle: period τ=50 hours.
  - Initial stagnation point at the ground coincides with the location of the mountain
- Dynamics well understood without the mountain
- Mountain
  - Isolated ridge
  - Minimum $Nh_{mtn}/U = 0.75$
  - Flow is always in the steady-state wave breaking regime.

Initial Condition Ingredients



$\overline{U} = 10 \text{ ms}^{-1}$

$0 \leq U \leq 20 \text{ ms}^{-1}$



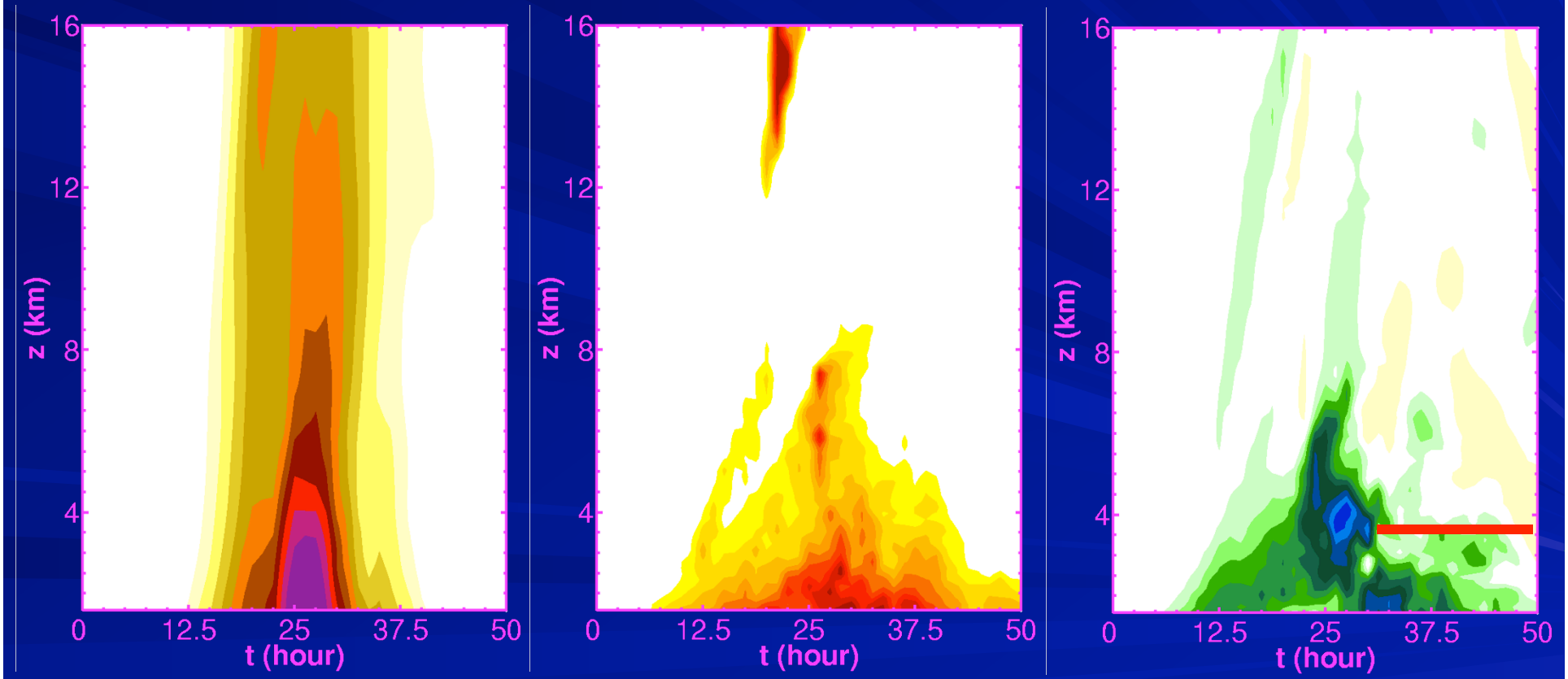
BC doubly periodic

Mtn width at half height = 36 km

Mtn x-y aspect ratio = 5

Forcing for the Domain-Averaged Zonal Flow

$-\overline{uw}$ K $-\partial\overline{uw}/\partial z$

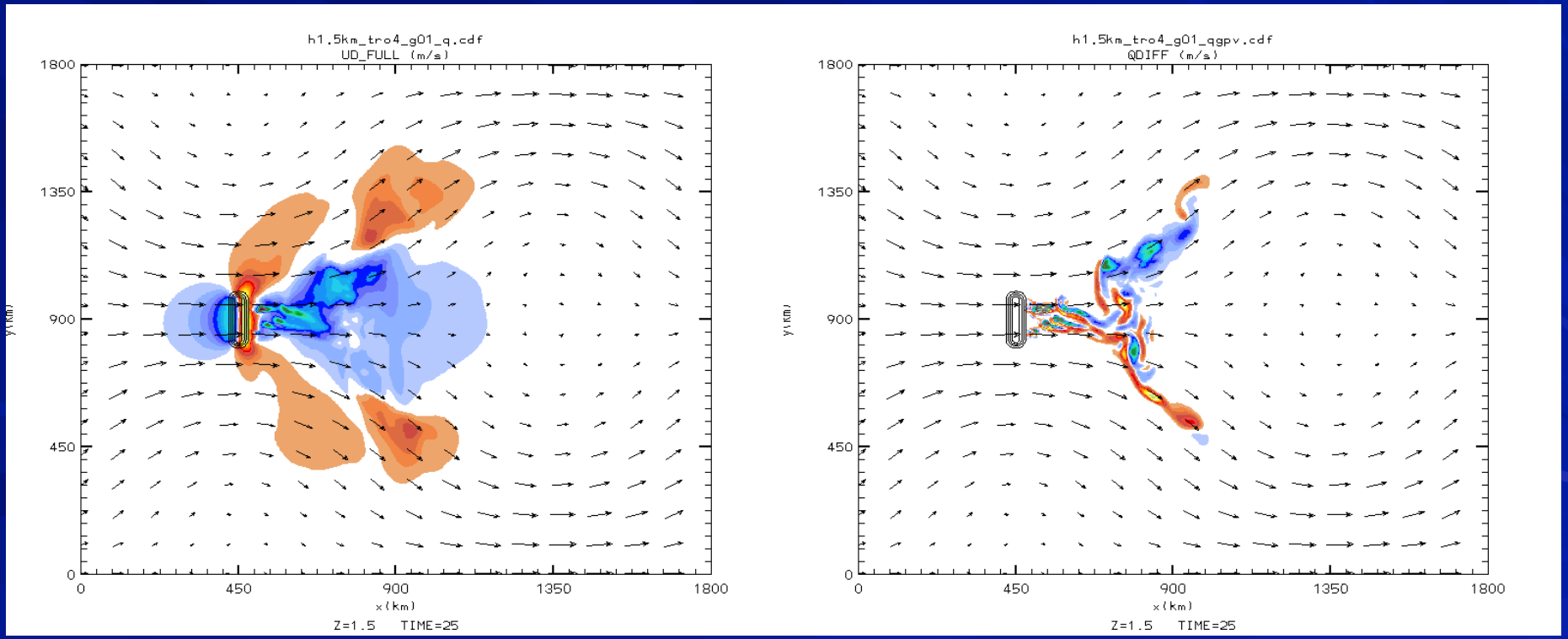


Perturbations Induced by Mountain

t = 25 hours z = 1.5 km (mtn top)

u'

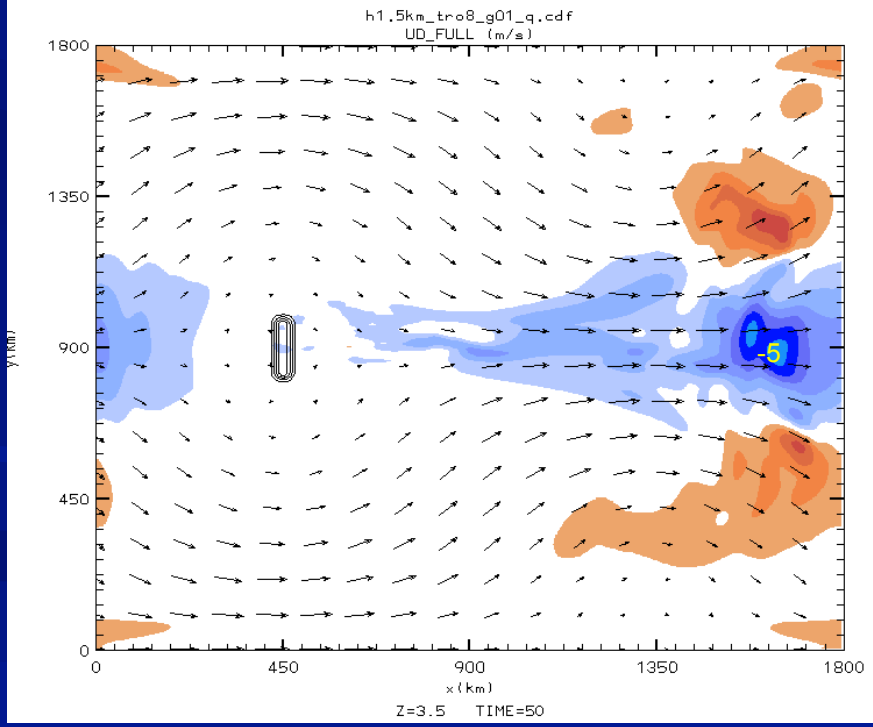
q' (Ertel PV)



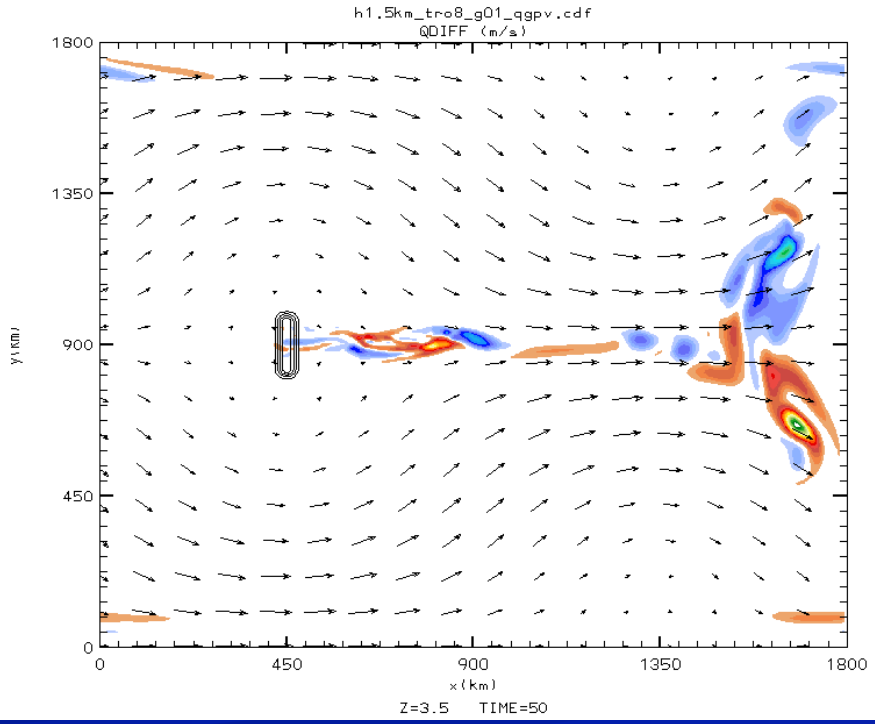
Perturbations Induced by Mountain

t = 50 hours z = 3.5 km (max forcing)

u'



q'



PV dynamics

Near the mountain, PV anomalies are generated through diabatic processes.

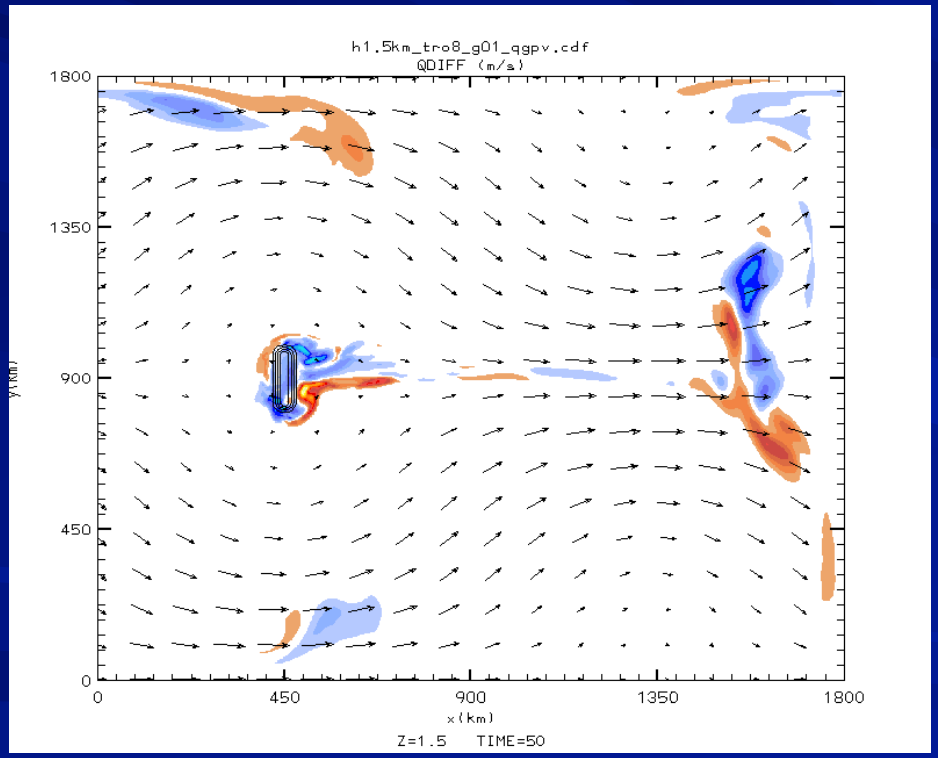
$$\frac{Dq}{Dt} = \vec{\omega} \cdot \nabla \dot{\theta} + (\nabla \times \mathbf{F}) \cdot \nabla \theta$$

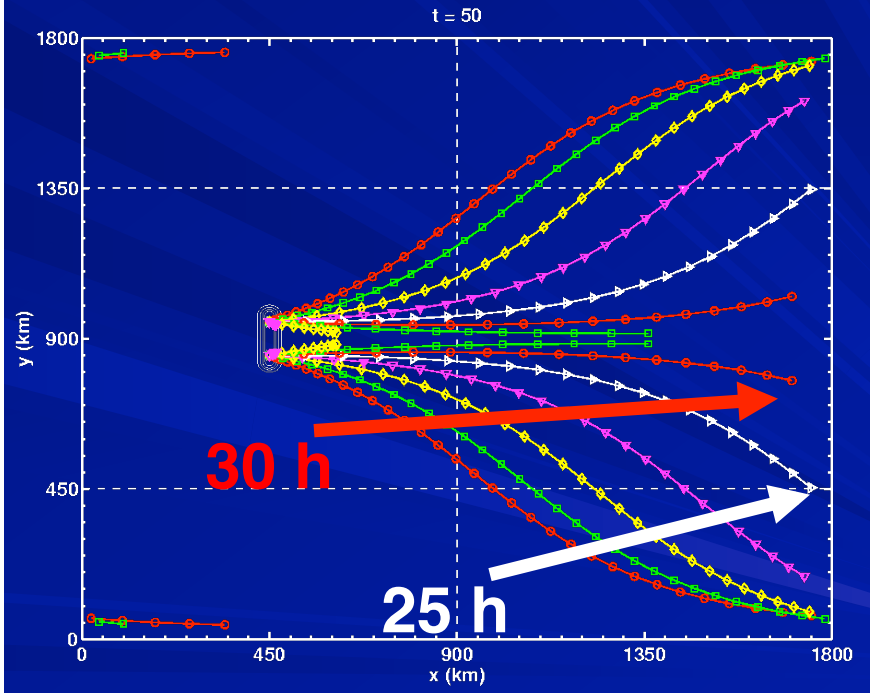
Away from the mountain, the trajectory of PV anomalies is mainly determined by the background large-scale flow,

$$\frac{Dq'}{Dt} \approx \left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} + V \frac{\partial}{\partial y} \right) q' \approx 0$$

PV location predicted by trajectory calculation at t = 50 hours.

q'





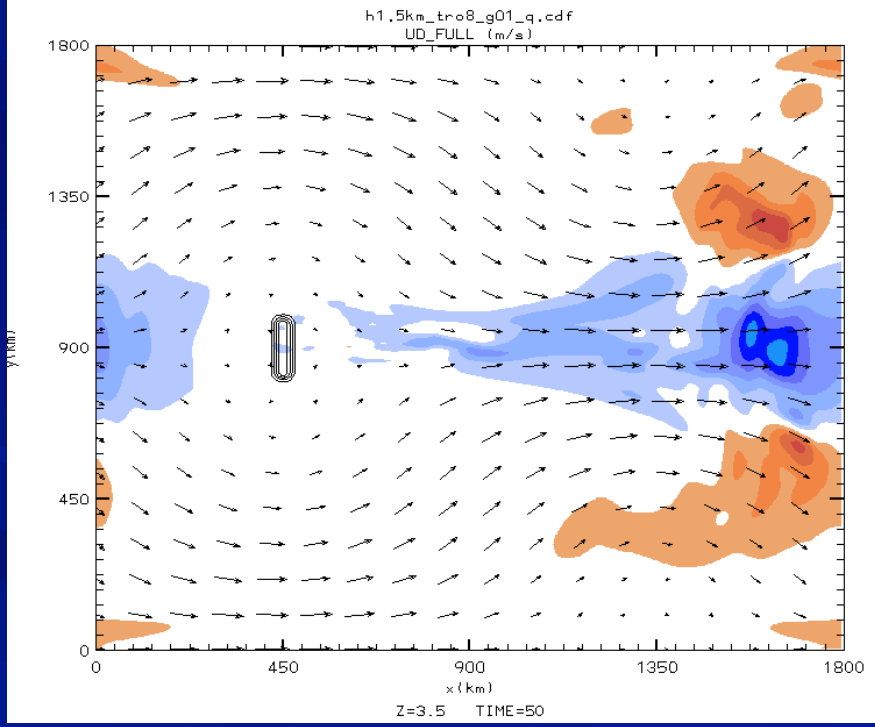
Are the perturbations balanced by hour 50?

Ertel PV difference is inverted using geostrophic balance as the balance constraint.

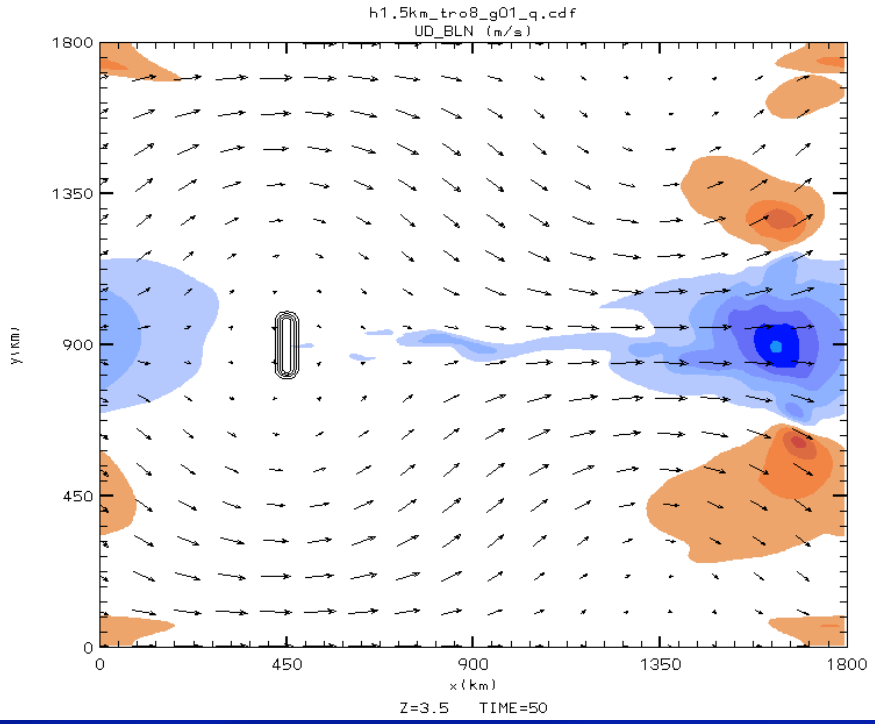
u perturbation vs balanced u’

t = 50 hours z = 3.5 km

u'

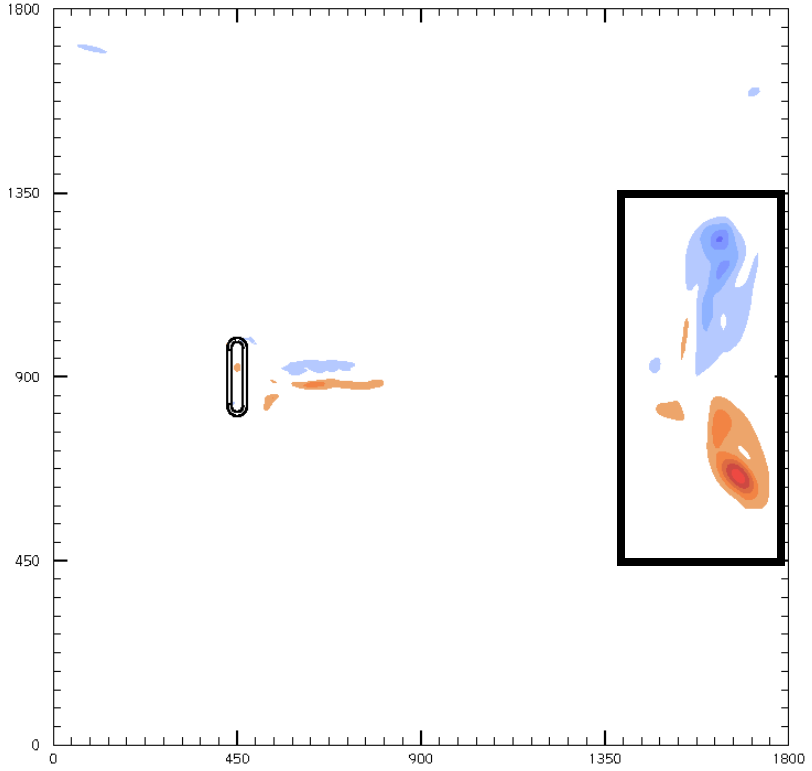


u'_b

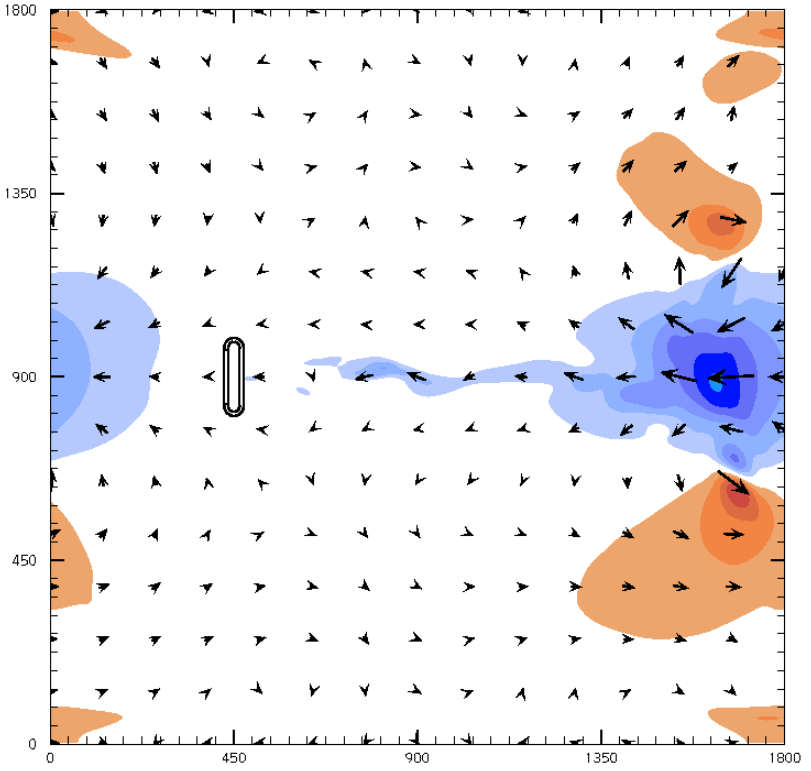


Piecewise PV inversion

$q', z = 1.5 \sim 6$ km



$(u_b', v_b'), z = 3.5$ km



Response Is Mostly Balanced

But

… the Balanced Response Makes No Contribution to the Domain Average!

$$f u_b' = -\frac{\partial \psi'}{\partial y} \qquad f v_b' = \frac{\partial \psi'}{\partial x}$$

$$\overline{u_b'} = \overline{v_b'} = 0$$

Suggests there is tremendous latitude in the design of GWD schemes.

Different distributions of q have no influence on domain-averaged flow tendencies.

Does a “perfect” GWD parameterization recover the spatial response?

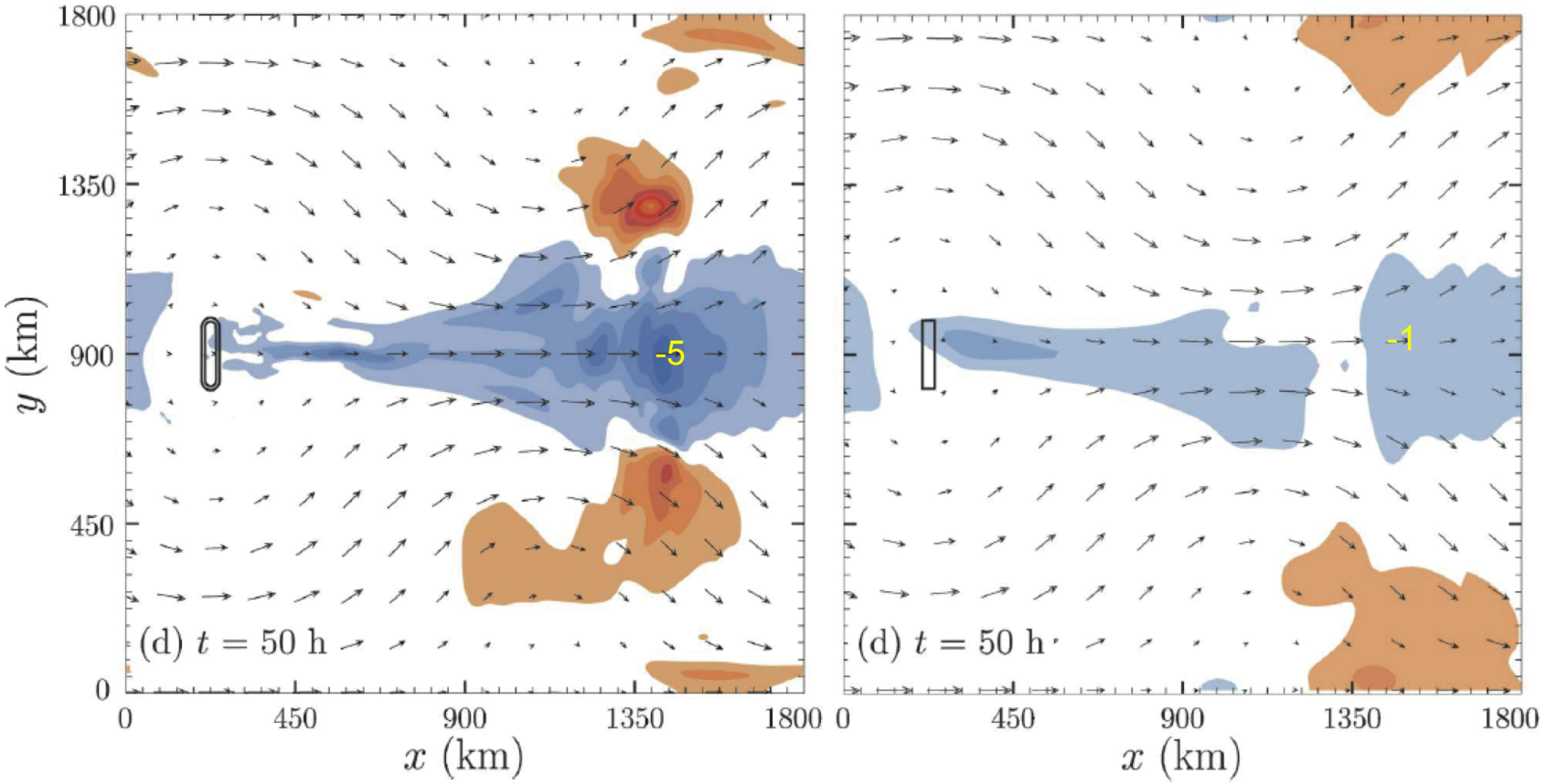
- GWD parameterizations estimate the vertical profile of the momentum flux (hard to do).
- These fluxes are known exactly from our simulations.
- Let’s put the correct momentum-flux profile into a simulation without a mountain.

u' GWD Parameterization Experiment

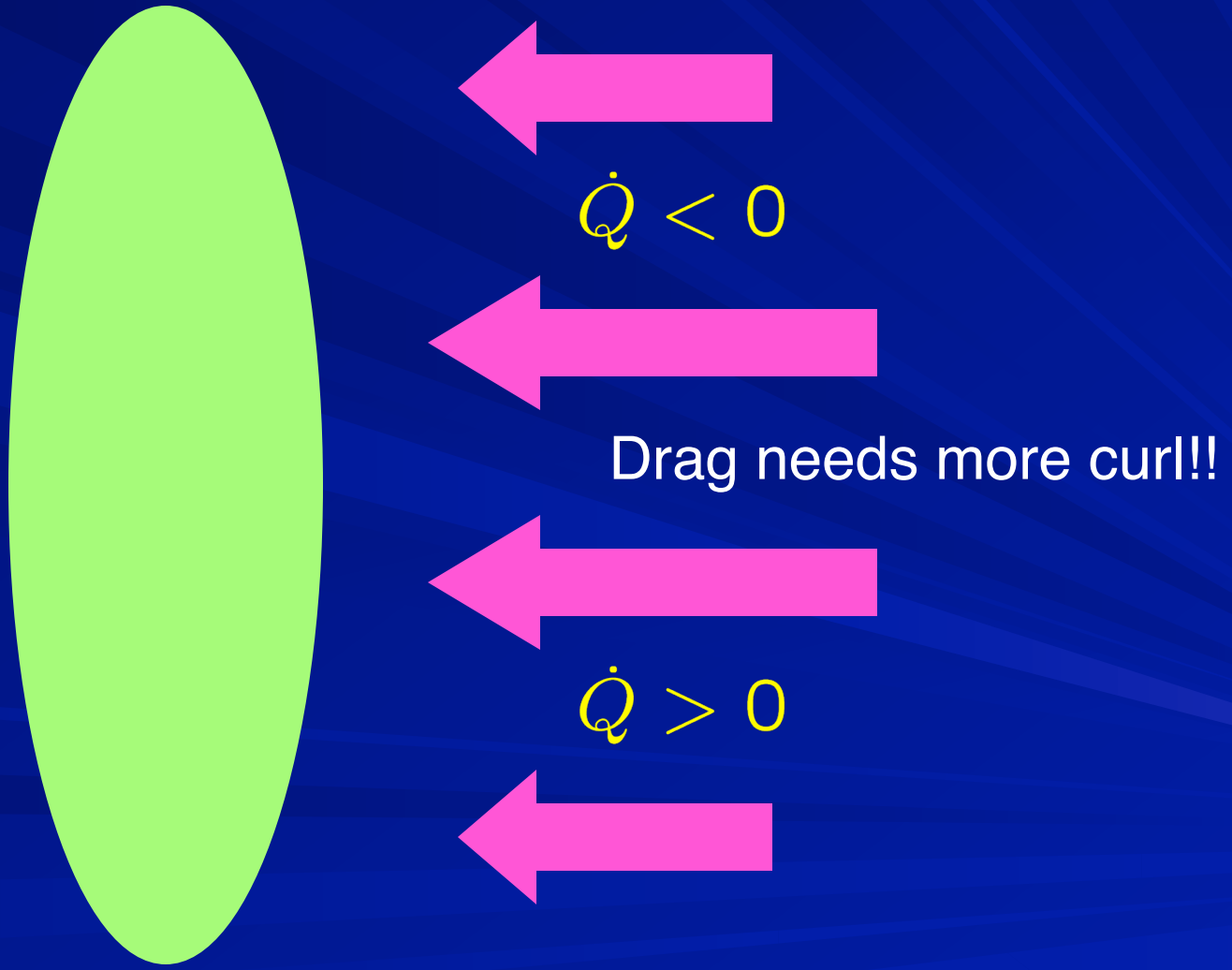
Drag applied in a 2x10 gridpoint area; t = 50 hours, z = 3.0 km

exact Δ=2 km

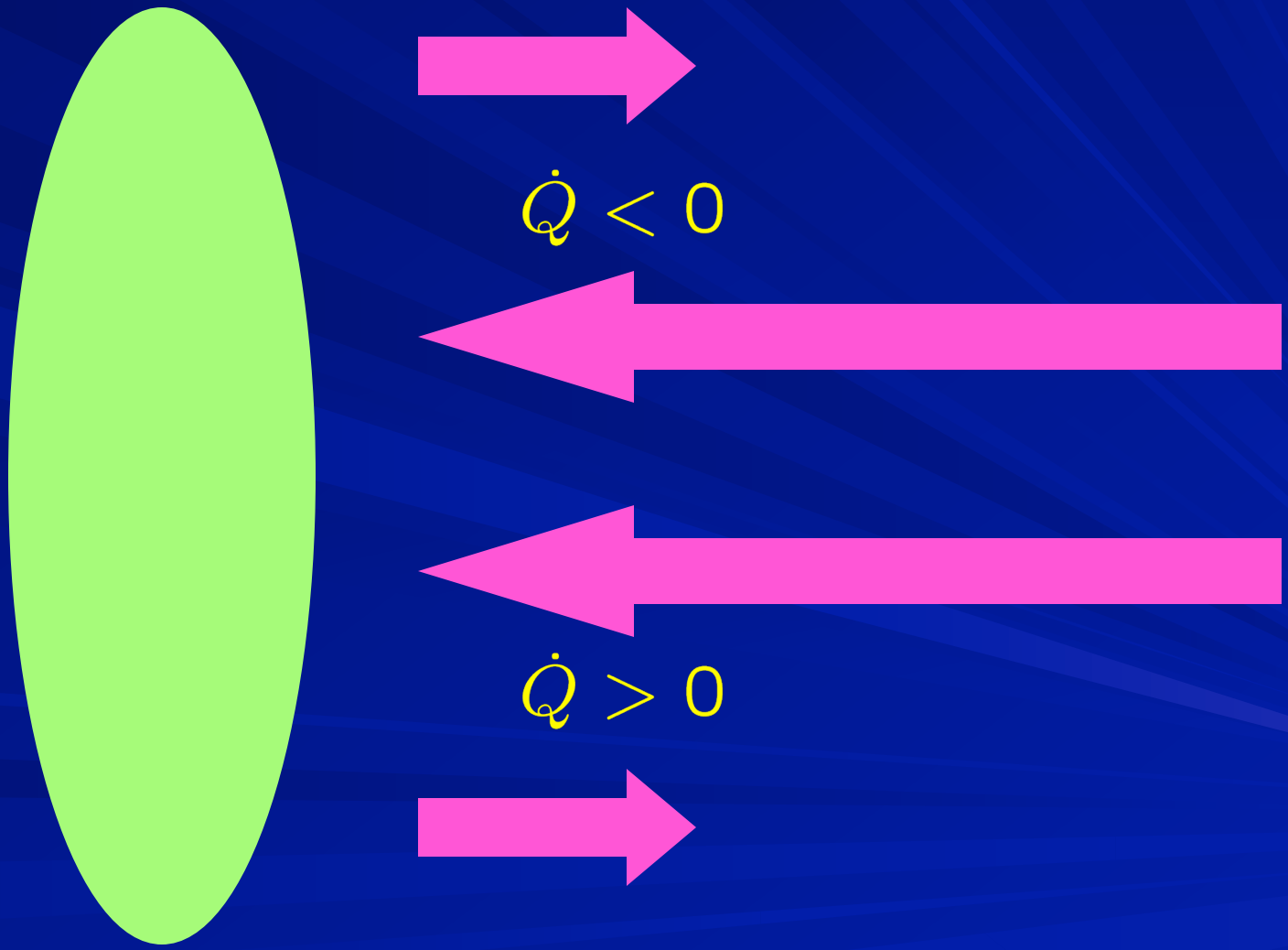
param Δ=18 km



Problem with GWD parameterization



More Curl, but Same Domain Averaged Drag



Summary

- Decelerated flow is produced at leading edge of jet, with patches of flow acceleration north and south of it.
- Small-scale PV anomalies are initially generated by wave breaking, but QGPV inversion ultimately recovers most of the spatially varying response.
- The balanced response makes no contribution to the domain-averaged drag.
- The “perfect” GWD parameterization fails to reproduce the spatial structure of the large-scale response.
- Need to parameterize terrain-induced PV perturbations to correctly capture the spatial structure of the response?

References

- Chen, C.-C., G.J. Hakim, and D.R. Durran 2007: Transient Mountain Waves and Their Interaction with Large Scales. *J. Atmos. Sci.,* **64**, 2378-2400

- Chen, C.-C., D.R. Durran and G.J. Hakim, 2005: Mountain-wave momentum flux in an evolving synoptic-scale flow. *J. Atmos. Sci.,* **62,** 3213-3231