Gravity Wave Launching, Sources and Predictability

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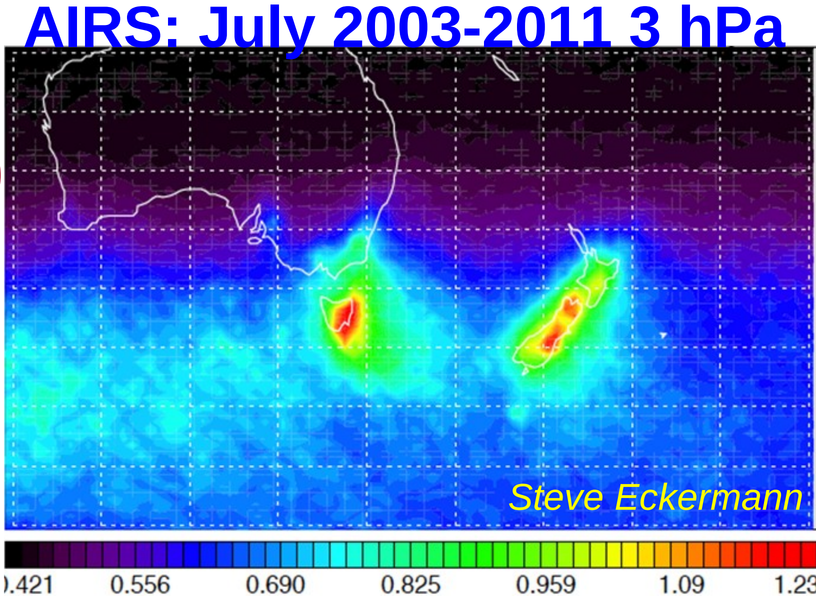
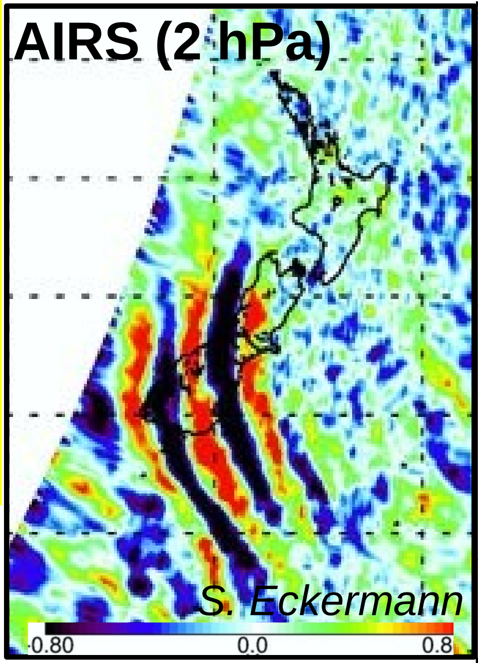
Background and Motivation

- **Gravity wave *Hot Spots* sampled in DEEPWAVE (aircraft;ground-based)**
- **“Trailing” gravity waves observed**
  - Extend or trail downstream from orography
  - Typically observed at ~5 hPa and above
  - Waves oriented at a significant angle to ridge crest along wind

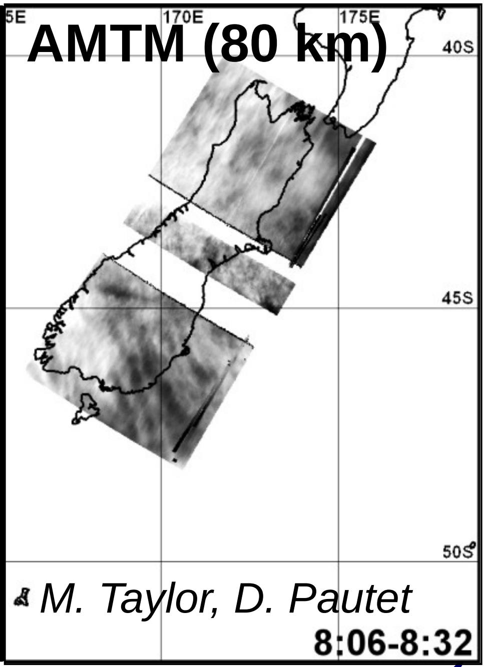


- Why do these gravity waves “trail” downstream?
- What are the key characteristics and sources of trailing gravity waves?
- What influences the predictability of gravity waves?

RF04

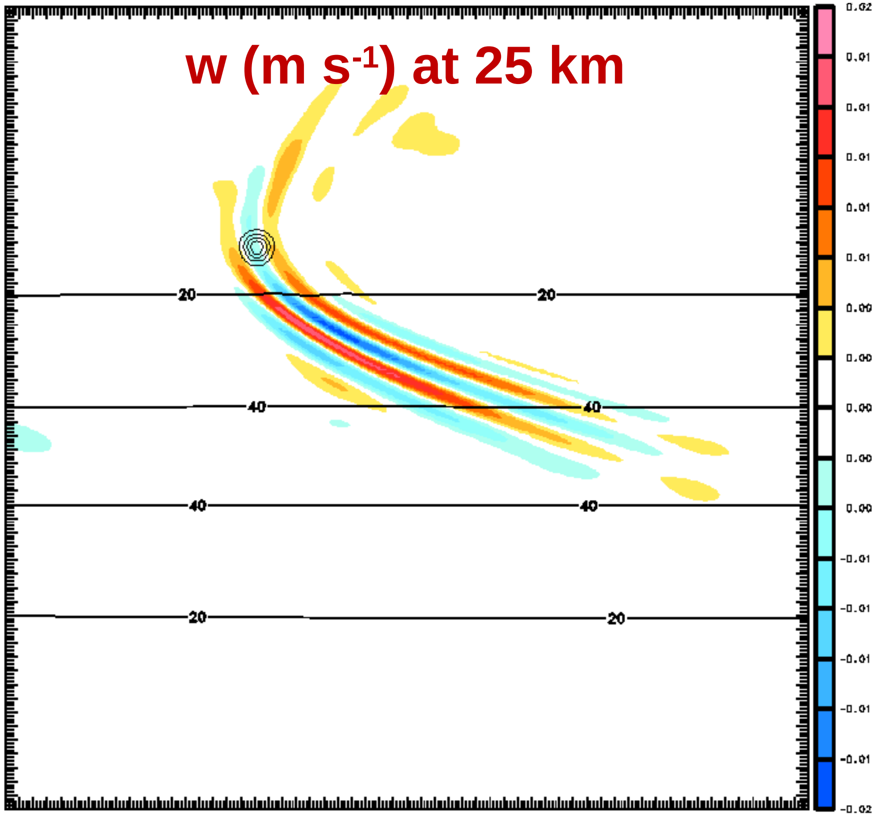


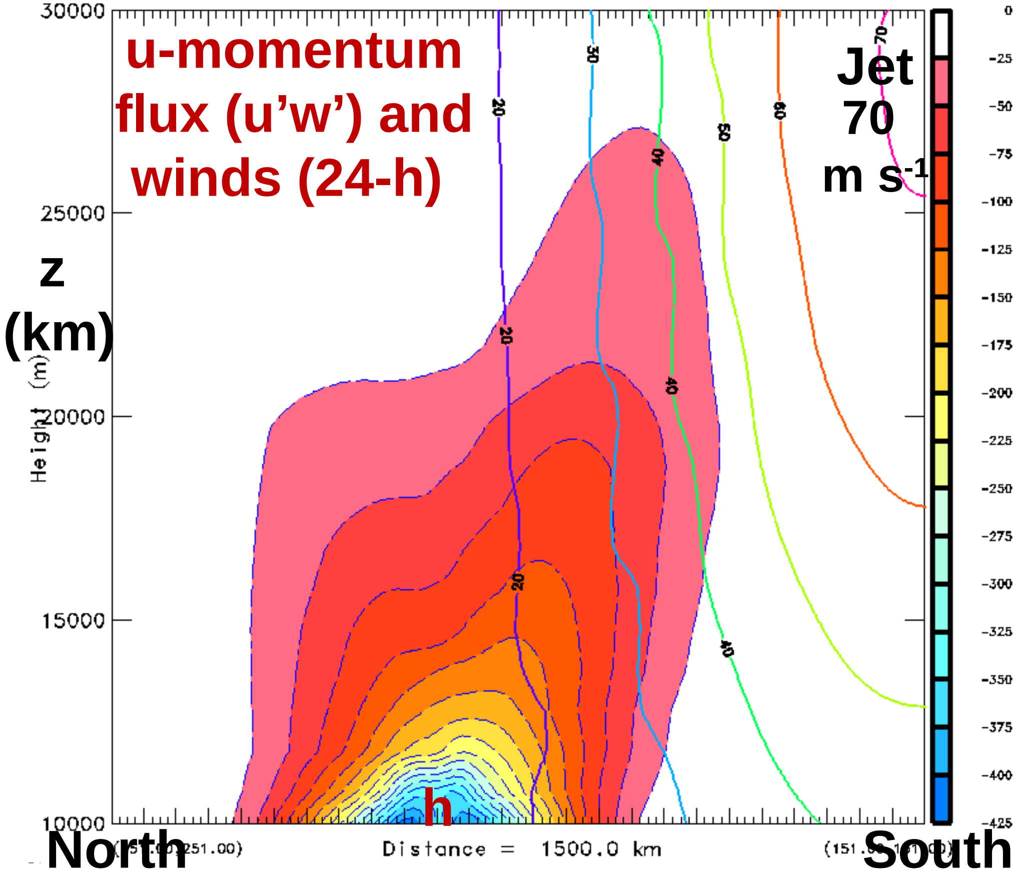
RF05



Gravity Waves in Sheared Flow

Idealized Shear Experiments



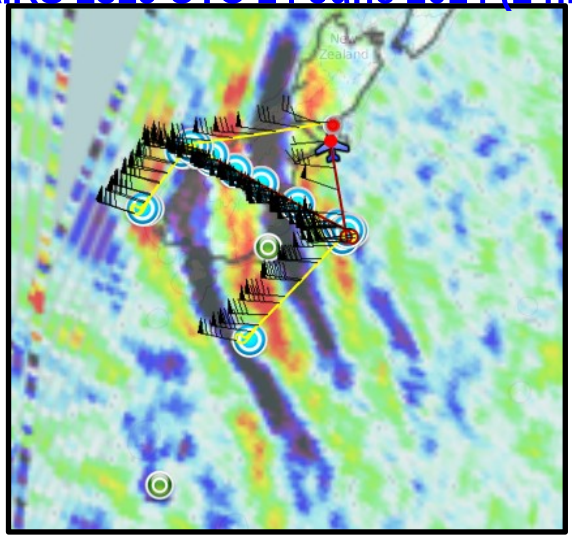


- High wind speeds imply a large component of wind normal to horizontal wavevector (& intrinsic horizontal group velocity), which allows advection of wave energy normal to wavevector (parallel to phase lines) (see Blumen and Dietze 1981, Dunkerton 1984, Sato et al. 2009, Vosper 2015)
- Zonal momentum flux in the stratosphere shows refraction due to shear.

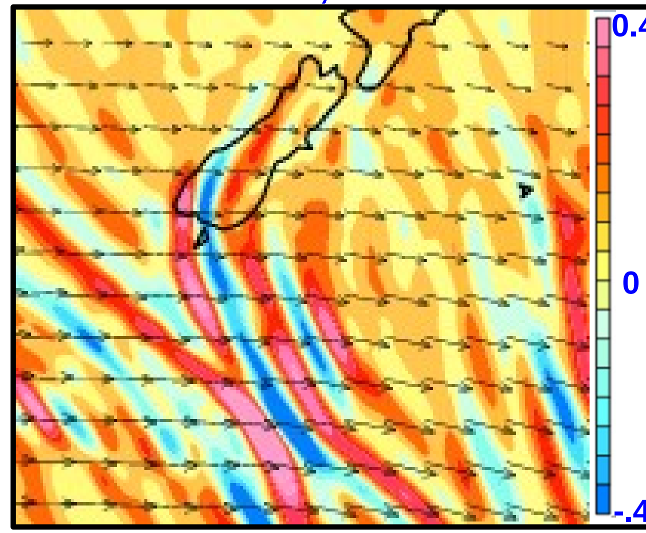
Trailing Waves during DEEPWAVE

IOP 3

AIRS 1319 UTC 14 June 2014 (2 hPa)

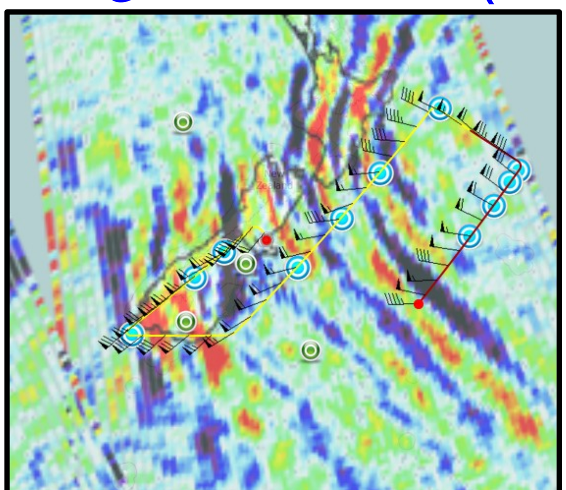


w 30km 1200 UTC, 14 June 2014

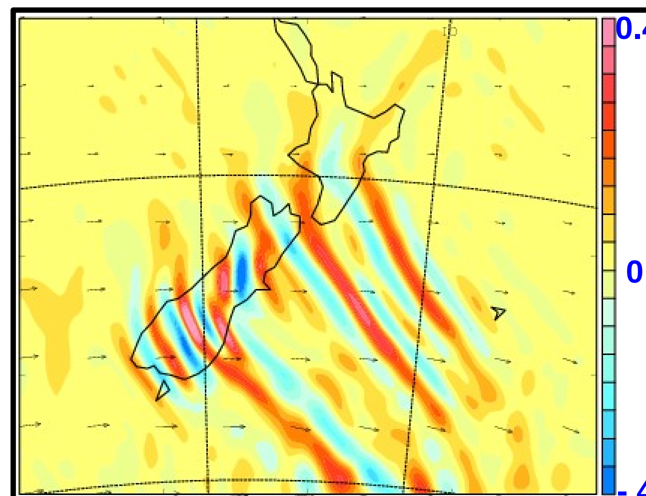


IOP 6

AIRS @ 0230 UTC 19 June (2 hPa)

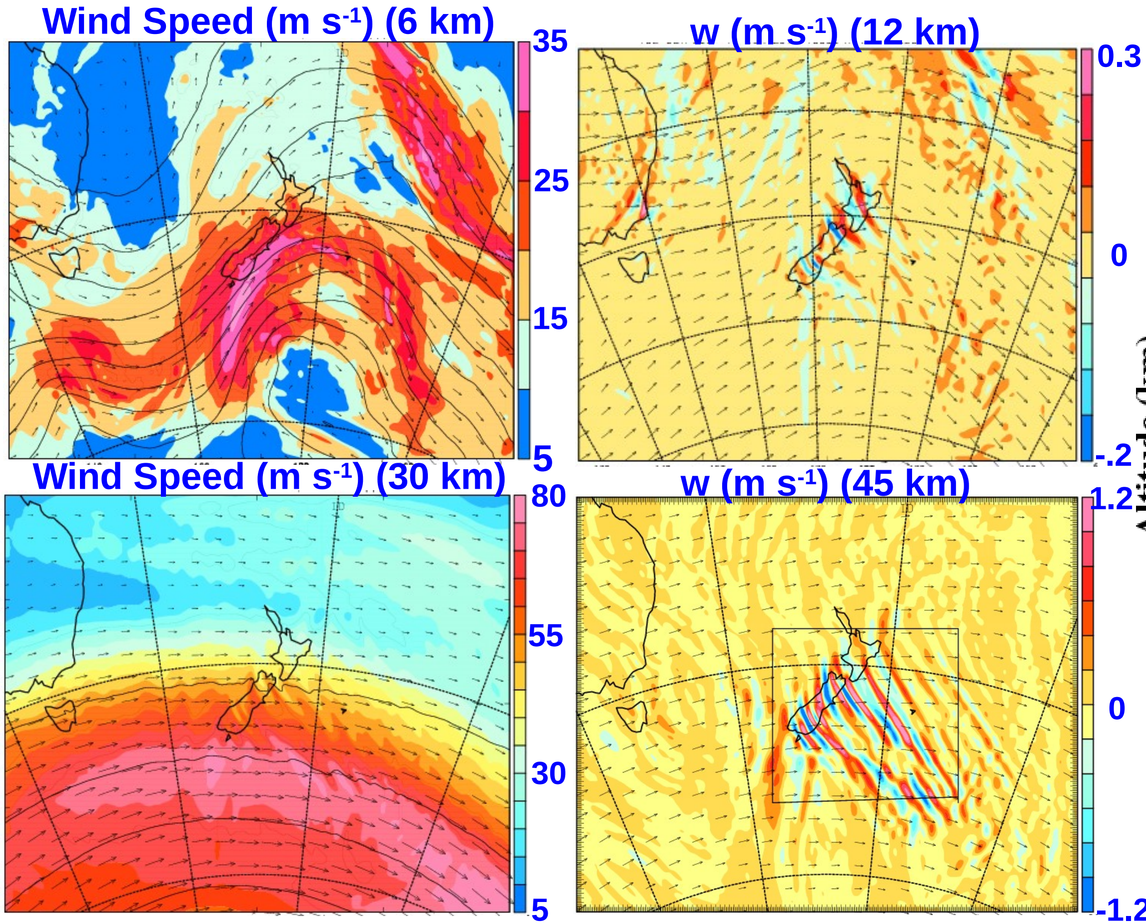


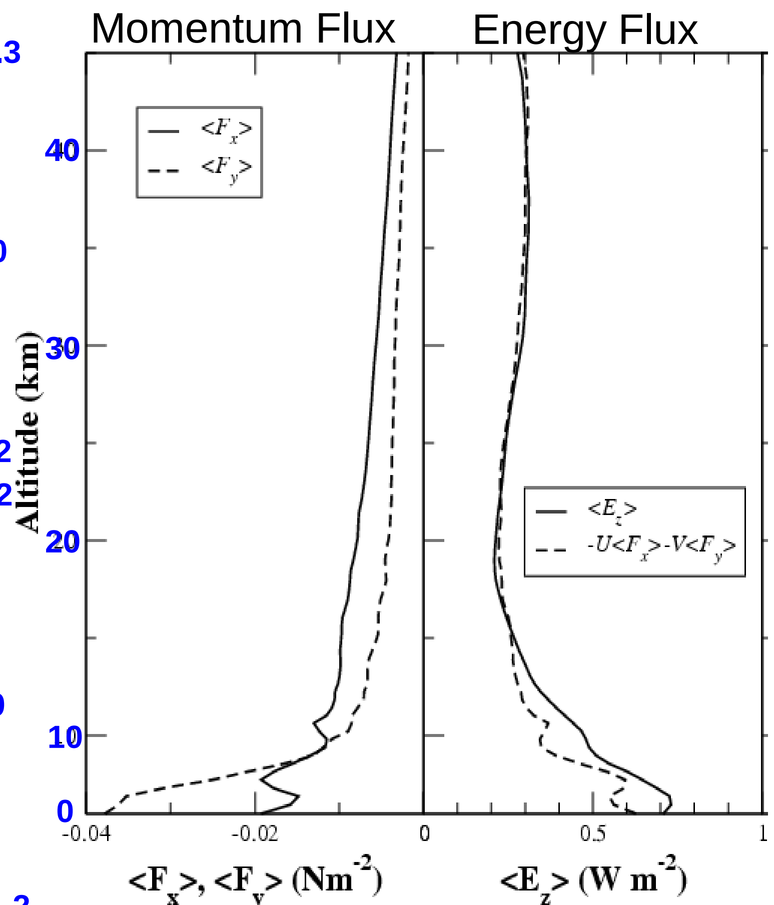
w 30 km 0200 UTC, 19 June 2014



- AIRS observed trailing waves from South Island during several DEEPWAVE IOPs
- COAMPS simulations captured salient characteristics of the observed TW

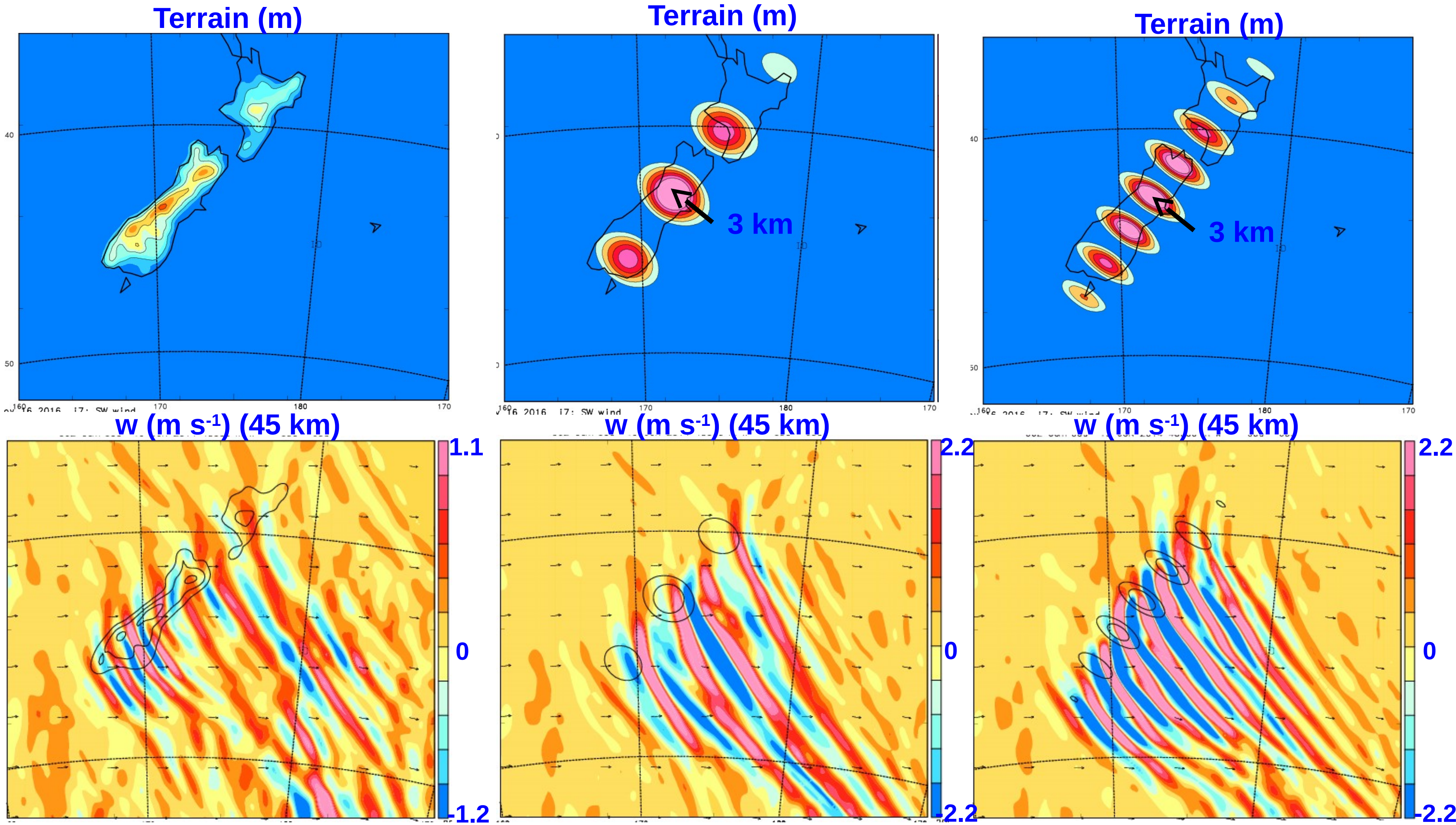
Trailing Waves during IOP 6





- In UTLS, MWs are nearly left-right symmetric with respect to the southwesterly jet.
- Asymmetric trailing waves develop in the stratosphere
- TWs carry negative (positive) zonal momentum (energy) flux, consistent with Eliassen-Palm theorem.

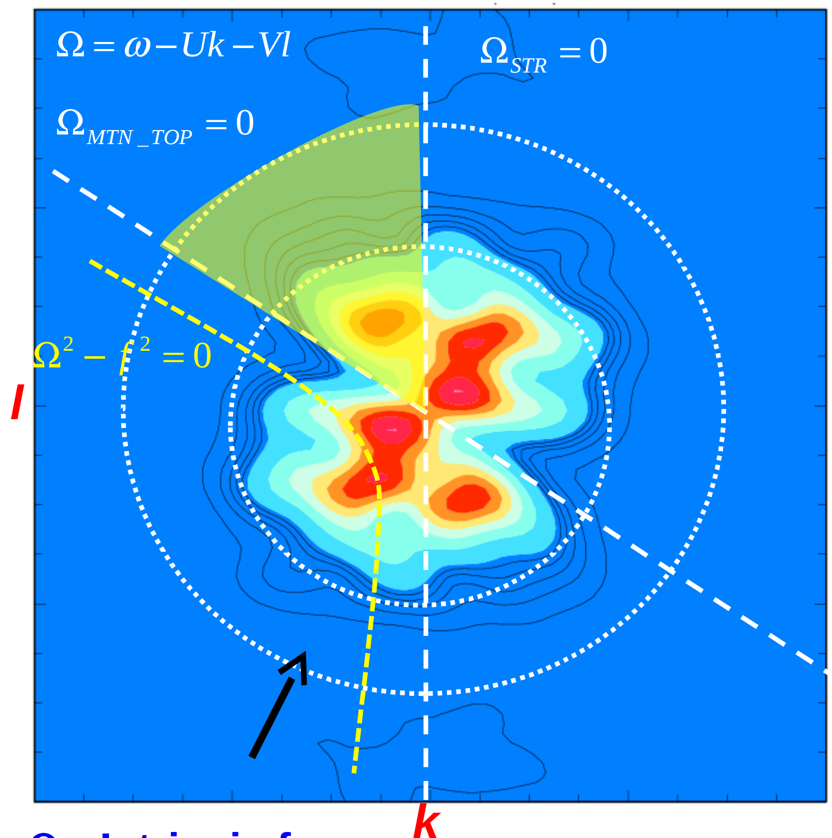
Sensitivity to the Terrain



- TWs are orographically generated steady waves
- TW characteristics are determined by individual peaks rather than main ridge
- Narrower peaks generate TW beams with shorter wavelengths

Wave Sources and Ray Tracing

Power spectra of w at the mountain height level

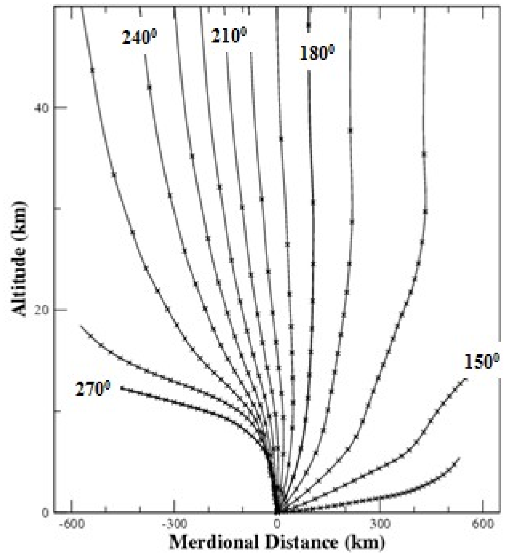


Ω : Intrinsic frequency

Ω_{MTN_TOP}=0 : Ω-critical level at mtn. height level

Ω_{STR} =0 : Ω-critical level lower stratosphere

Ω^2-f^2 =0: Jones critical level

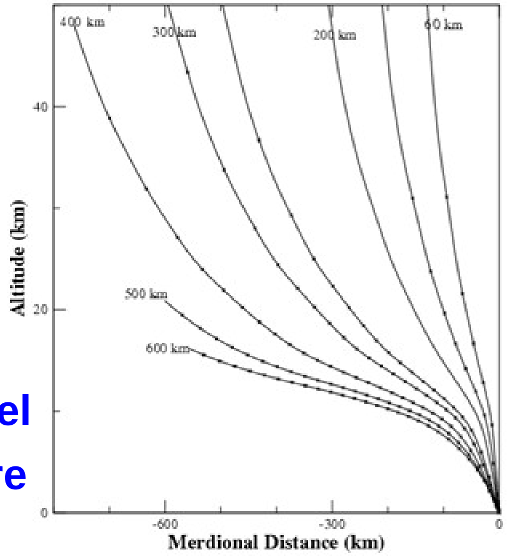


- **Ray-path in y-z plane for waves with initial wave numbers:**

$$(k,l) = Ke^{i\theta}$$

where K=2π/200km^{-1}

- **Wave vector angle θ increases 140⁰ (2nd quadrature) to 270⁰ .**



- **Ray-path in y-z plane for waves with initial wave numbers:**

$$(k,l) = Ke^{i\theta}$$

where θ =240⁰; K=2π/λ

- **λ ~60-600km**

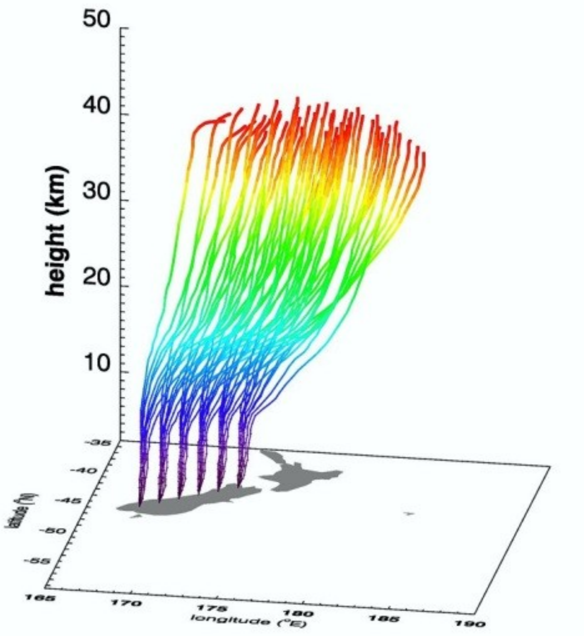
Key factors that regulate TW characteristics: Terrain spectra; low-level winds; directional shear; Jones critical level; meridional wind shear

GROGRAT 3-D Ray Paths

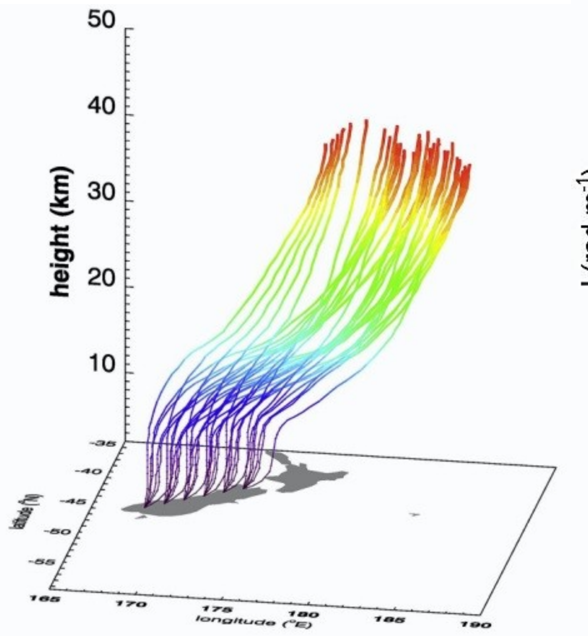
19 June 2014 0000 UTC

Launch Azimuths 225°, 235°, 245°, Height=2 km

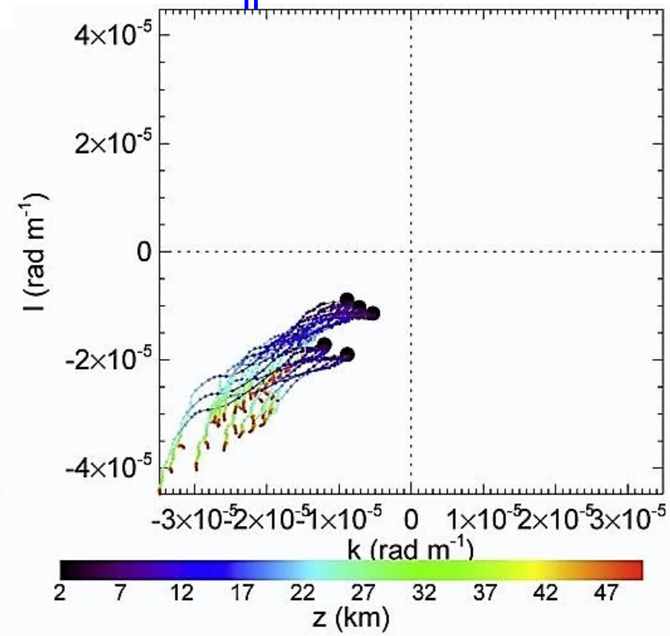
λ_h=100, 150 & 200 km



λ_h=300 & 500 km



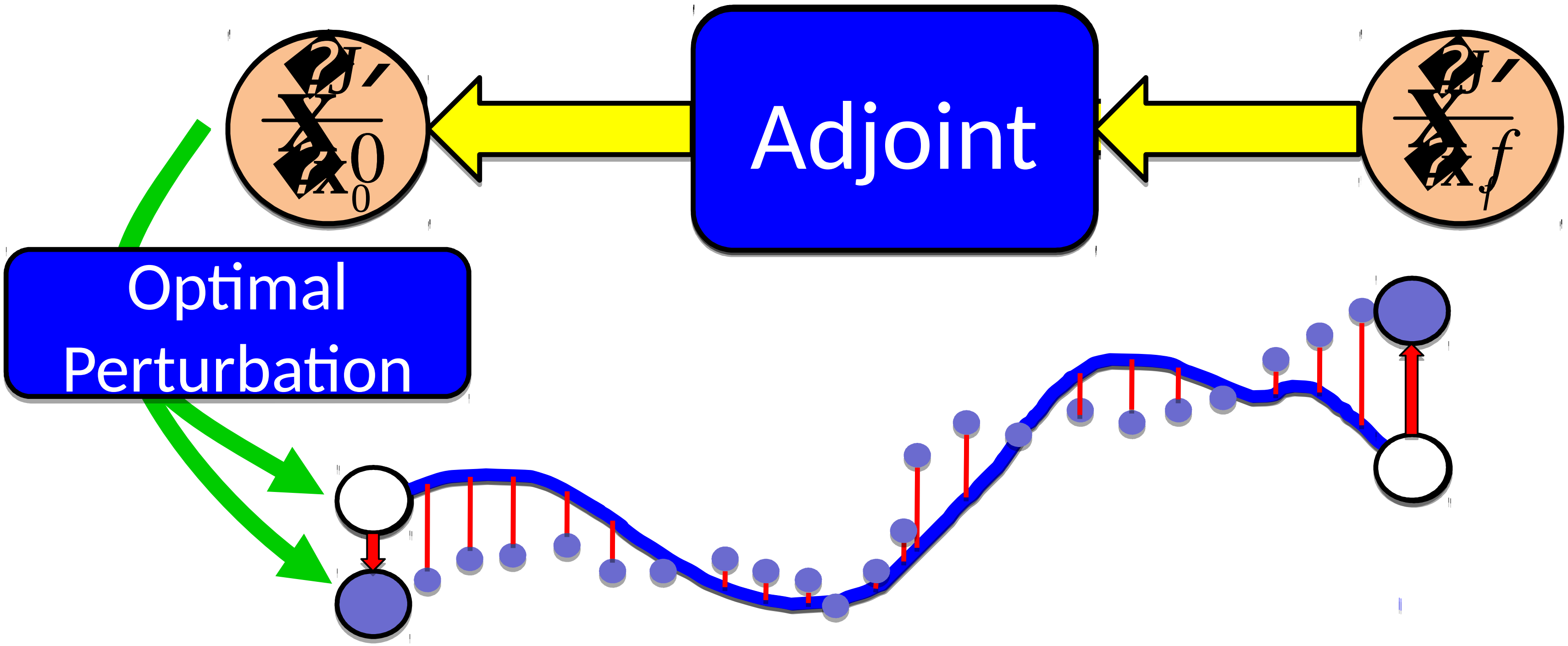
λ_h=300 & 500 km



- 3D Ray paths using profiles from NAVGEM reanalyses (Eckermann et al.)
- Waves propagate vertically in troposphere and then to the SE in stratosphere
- Ray paths influenced by directional shear with height that leads to an imbalance between the wave intrinsic group velocity and wind speeds across phase fronts, in addition to the advection of groups across phase fronts
- Meridional and zonal shear important for refraction and in concert reduce the wavelengths; but phase lines remain linear downstream (1000-2000 km to SE)

Adjoint Model

$$\frac{\partial J}{\partial \mathbf{x}_0} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}_f}$$



Adjoint is the transpose of the TLM, and evolves the gradient of a response function (*J*) with respect to x_f backward through time.

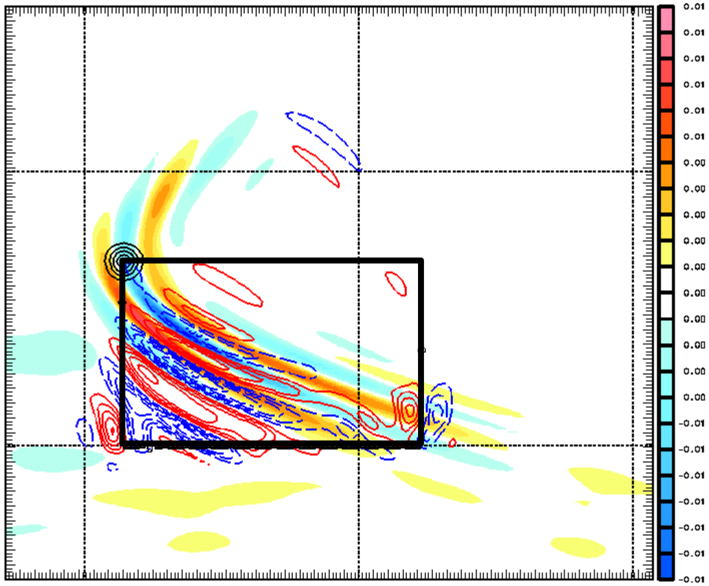
Errico (1997); Langland et al. (1995); Doyle et al. (2012; 2014)

Adapted from Brett Hoover (UW)

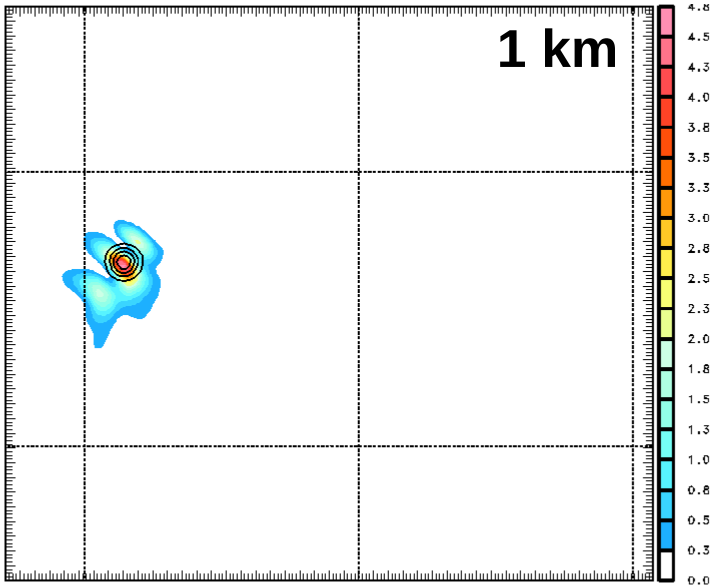
Gravity Wave Source Identification

Adjoint Experiments (Idealized 65 m s^{-1} Jet)

Evolved Vertical Velocity (15-24h)
20 km (~10 hPa)



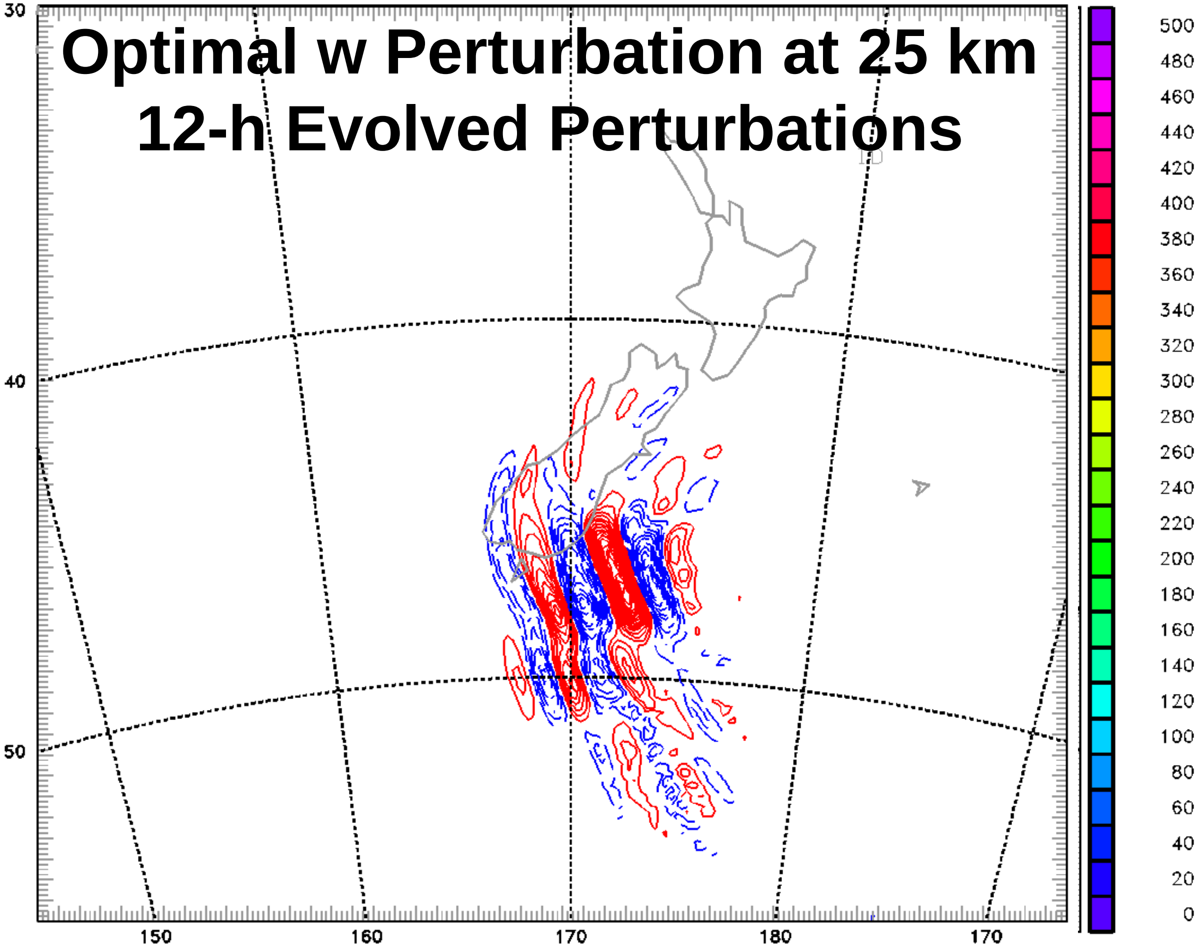
Adjoint Sensitivity (15 h)
Kinetic Energy



- Idealized simulations with balanced jet and 100 m high hill
- Adjoint is used to diagnose the the orographic source (9 h integration)
- Response function is the vertical velocity at 20-25 km in “box”
- Adjoint optimal perturbations propagate from terrain and project on to the arced “trailing” wave phase lines within the “box”

Gravity Wave Source Identification

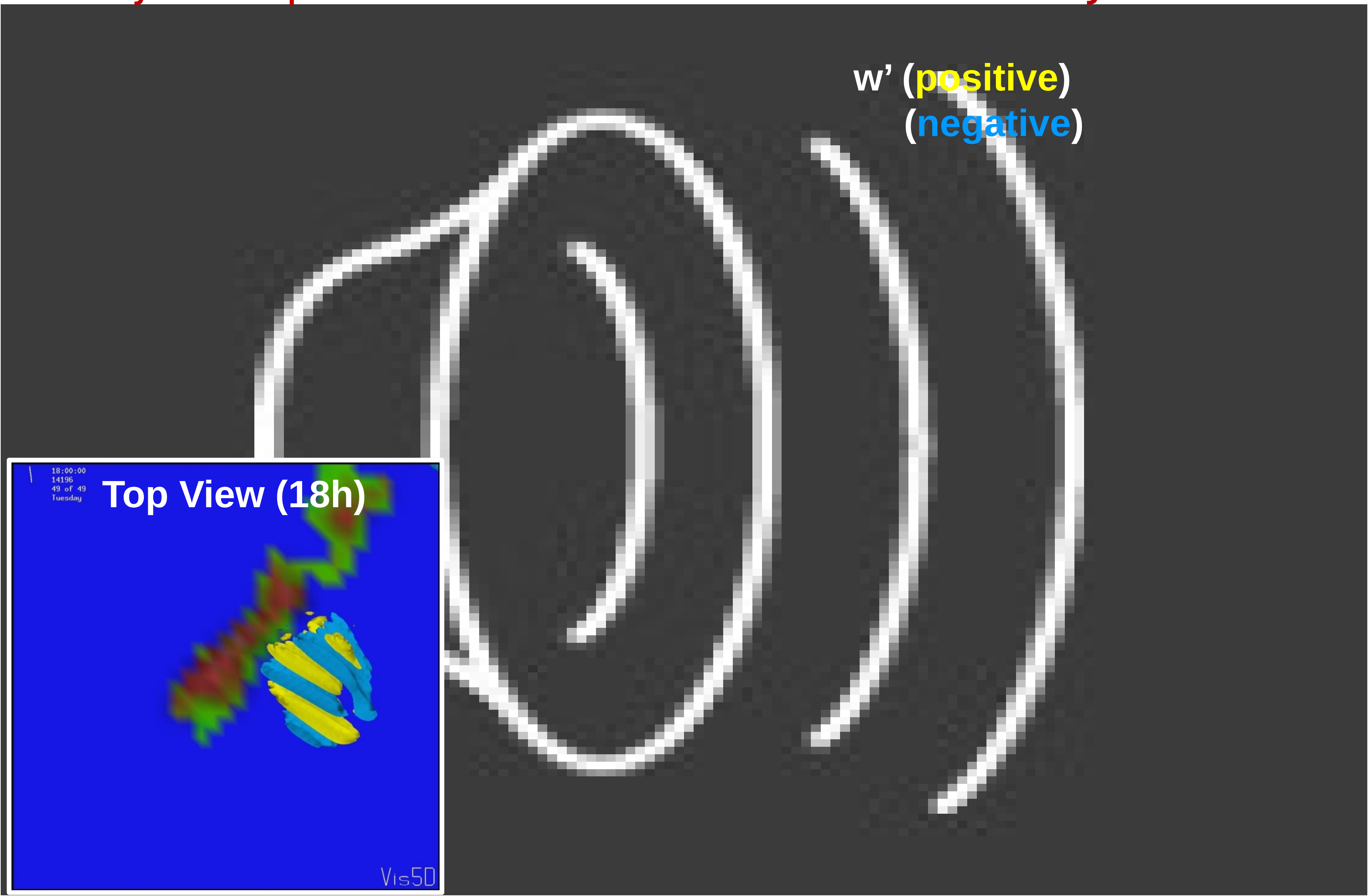
Trailing Waves in IOP 3 (RF04)



- Adjoint identifies most sensitive portion of the S. Alps for wave launching
- Trailing waves located to south of NZ are launched from S. Alps peaks

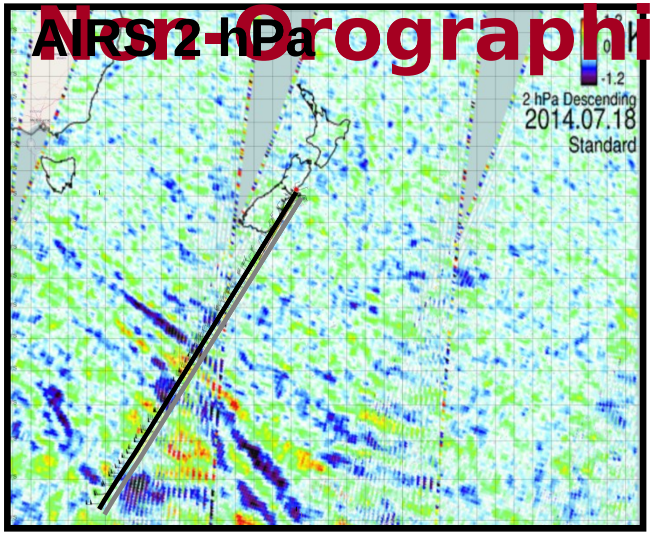
Adjoint Model Example

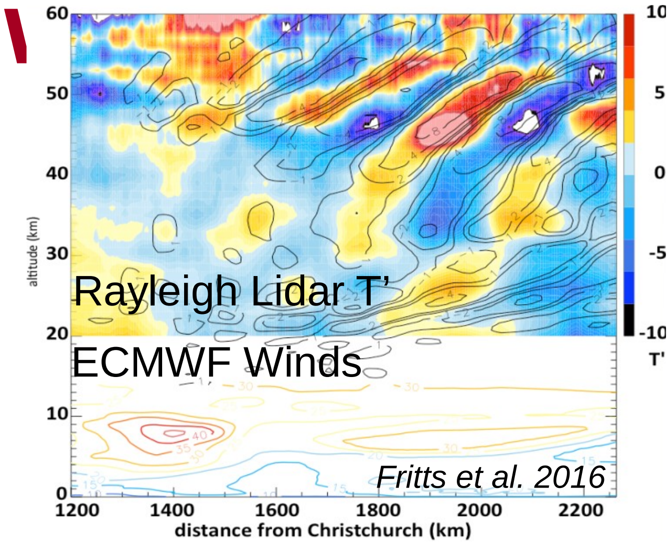
Adjoint Optimal w Perturbation: 18Z-06Z 14 Jun 2014



Gravity Wave Source Identification

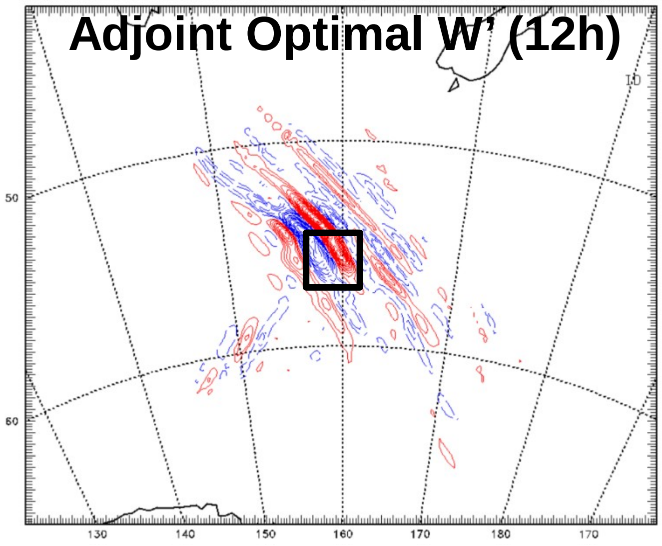
Non-Orographic \

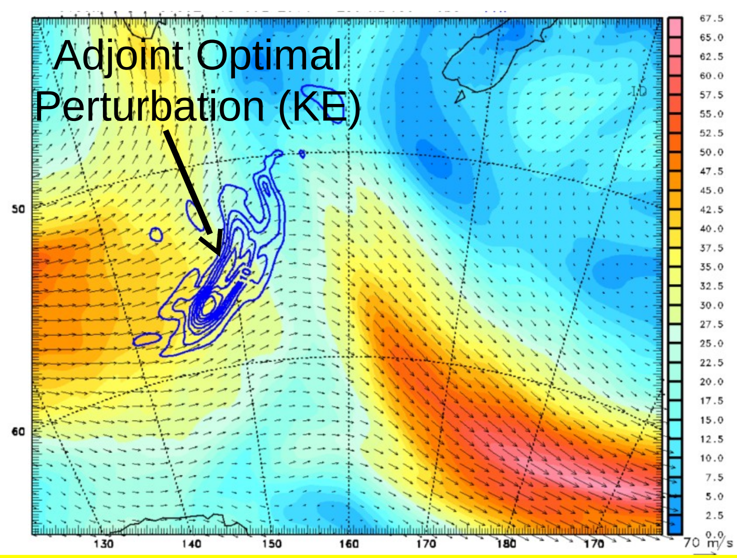




20-hPa Vertical Velocity

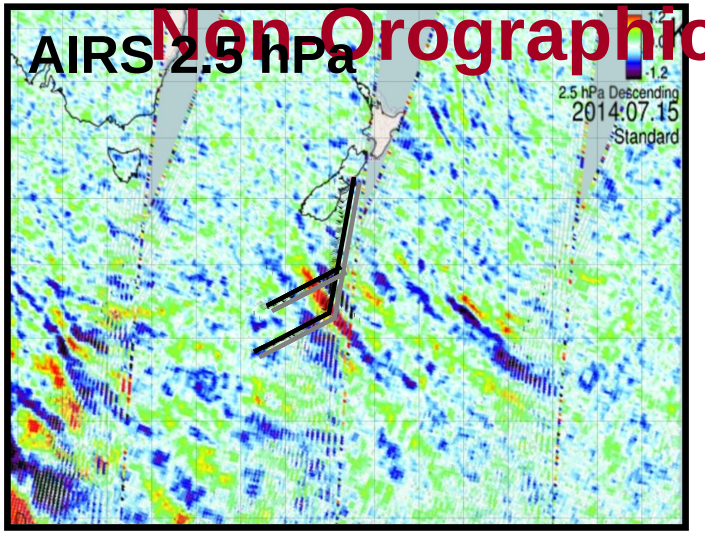
250-hPa Winds

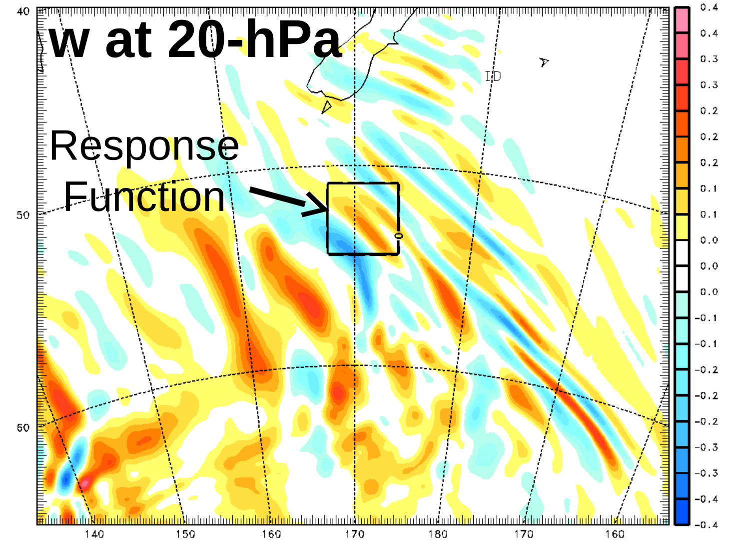




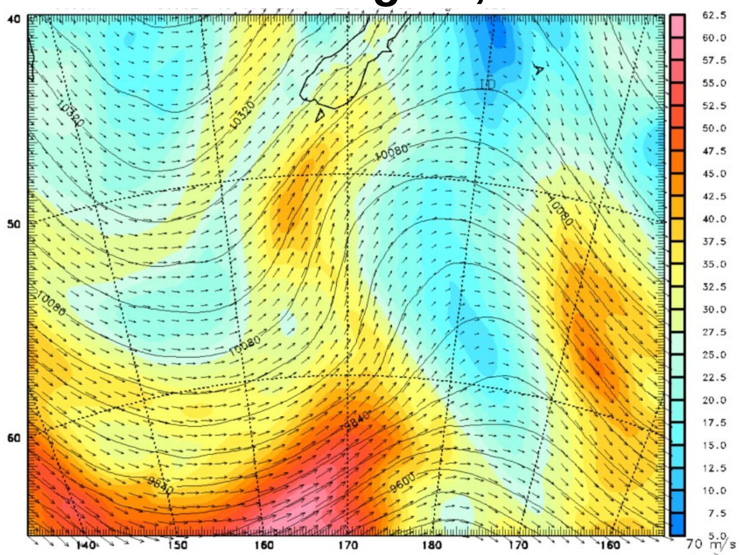
- Adjoint identifies exit region of jet as likely source
- GWs excited by decelerations in high-amplitude pattern.

Gravity Wave Source Identification

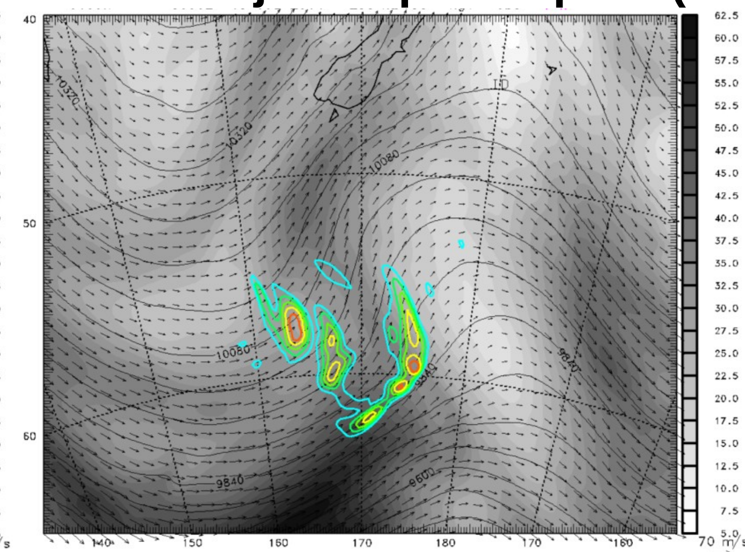




250-hPa heights, winds



250-hPa adjoint optimal pert. (KE)

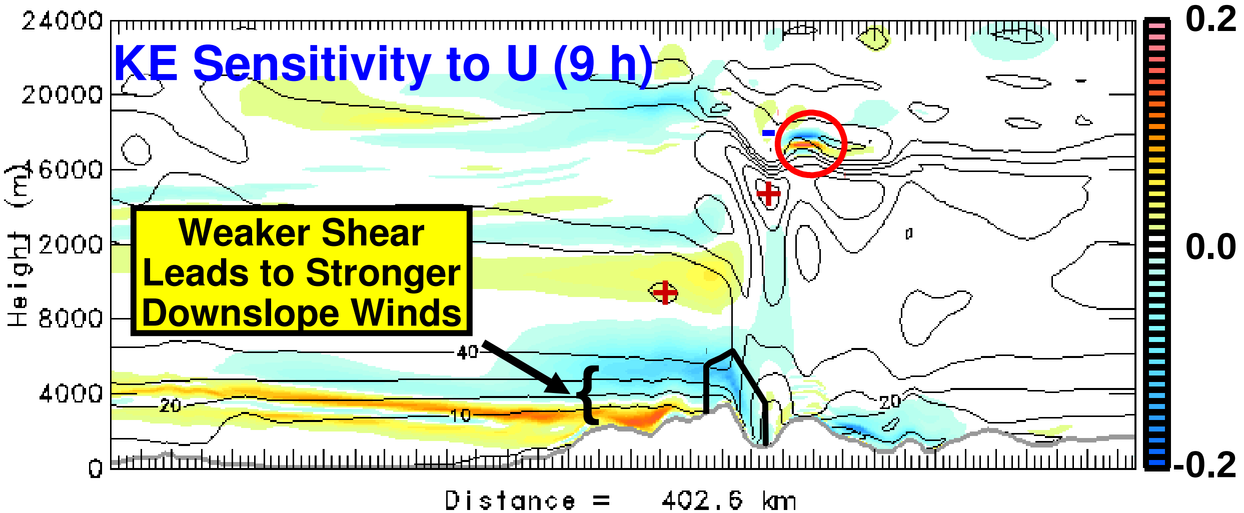


- Adjoint identifies left exit region of jet as possible source
- GWs excited by decelerations in high-amplitude pattern.

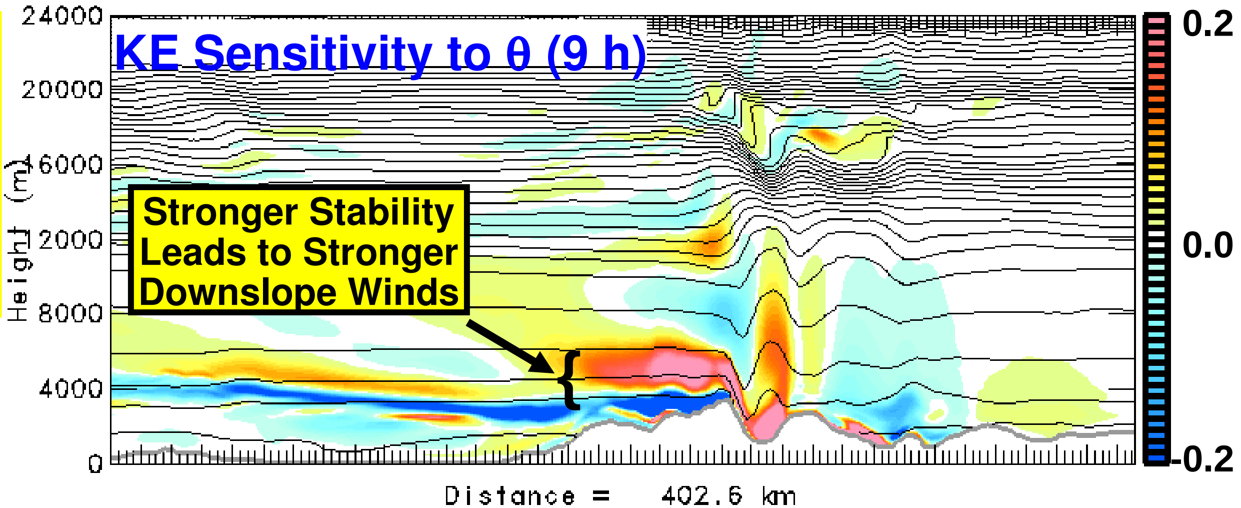
Predictability of Downslope Winds

T-REX IOP-13 Mountain Wave (Δx=3 km)

Sensitivity to Crest Level Shear and Shear Aloft (Wave Breaking)



Sensitivity to Stability at Crest Level, Within Valley, Aloft in Waves

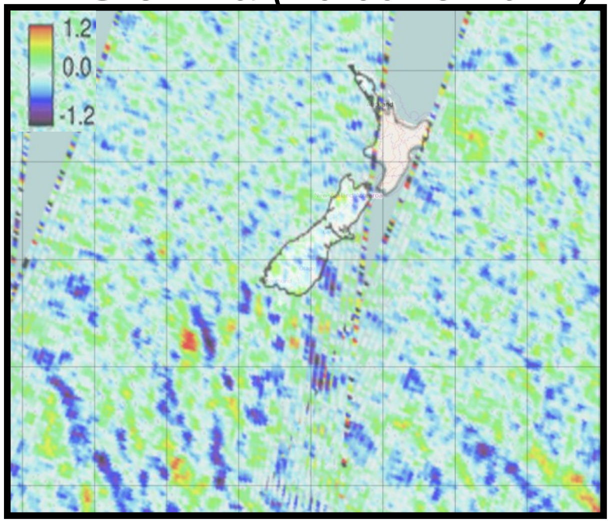


Predictability of Deep Propagating GWs

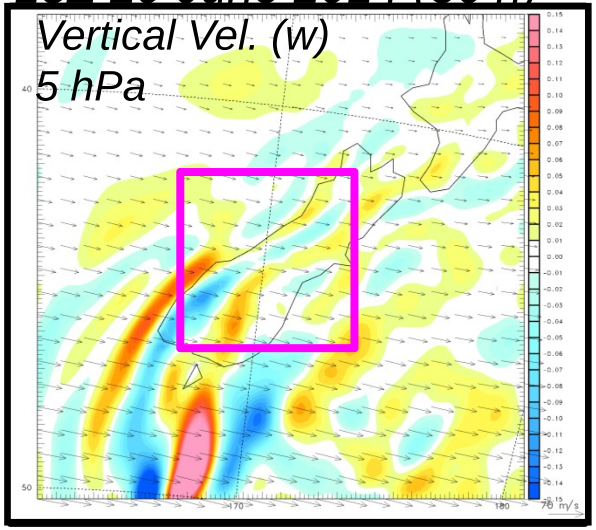
What are the predictability characteristics of deep propagating GWs?

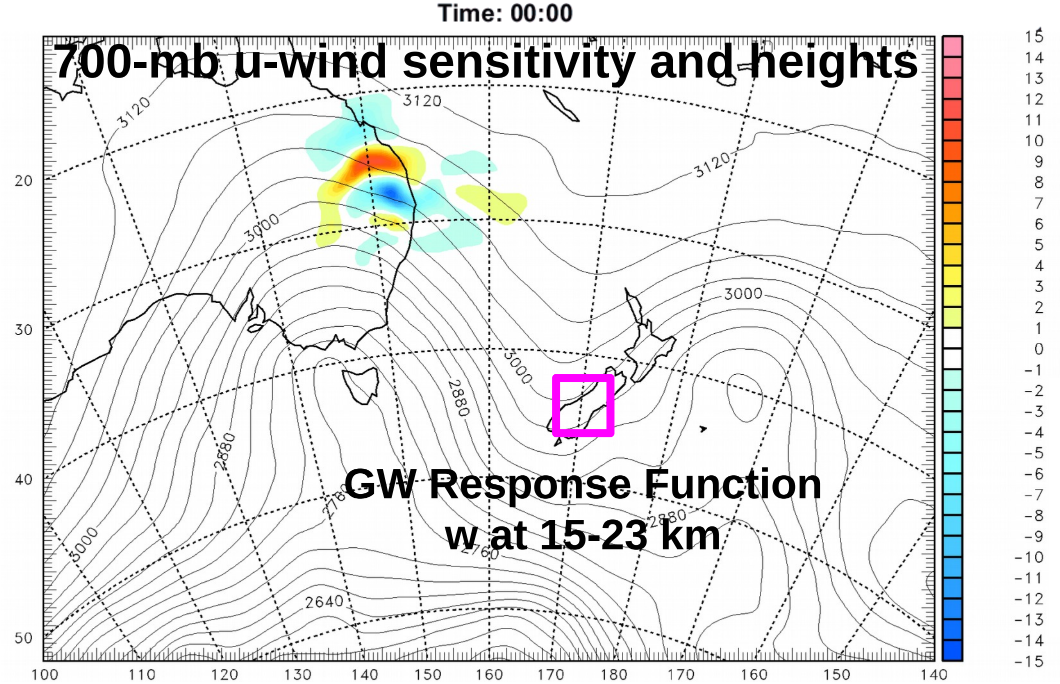
Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to changes in the initial state

AIRS 3 hPa (29 June 2014)



18Z 29 June 2014 (36 h)



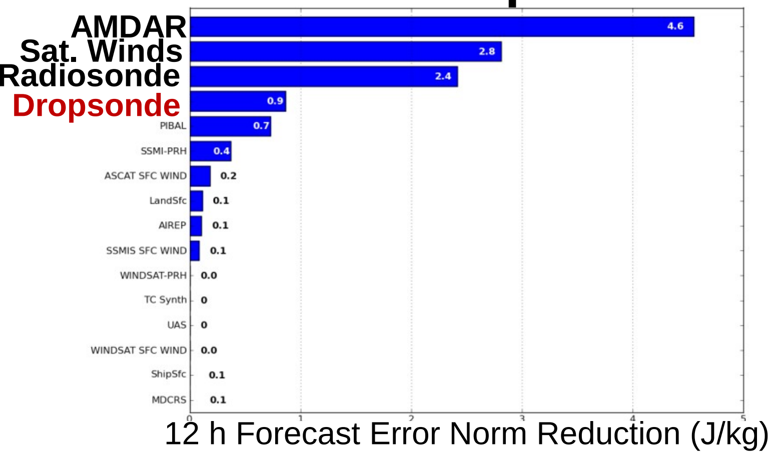


- Adjoint is used to diagnose sensitivity using a kinetic energy response function (lowest 1 km)
- Sensitivity located ~1200 km upstream near trough
- Adjoint optimal perturbations lead to strong wave propagation (refracted waves south of NZ)

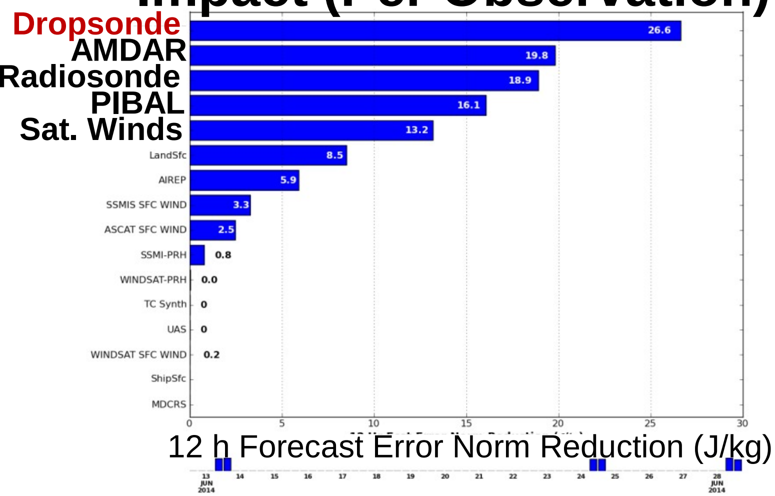
G-V Targeted Dropsonde Impact

Adjoint Observation Impact Diagnostics

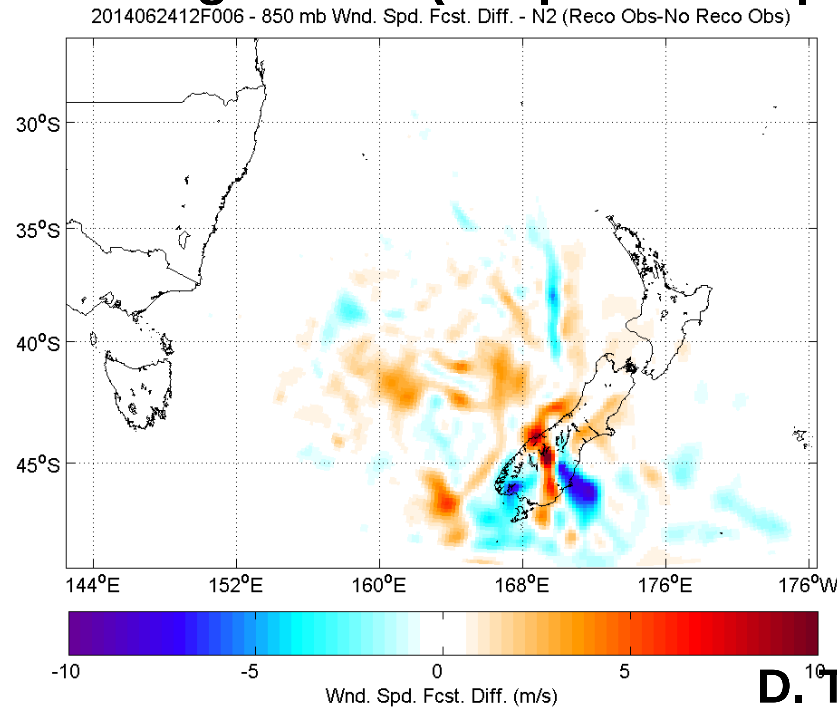
Total Impact



Impact (Per Observation)



Impact using 4D-Var (Drops-No Drops, 6h)



D. Tyndall

- Adjoint (model/DA) observation impact on 12-h forecasts for the 3 predictability flights.
- Targeted dropsondes have the largest impact on a per observation basis, and 4th largest impact overall.
- Forecasts with dropsondes assimilated in 4D-Var differ greatly in wave launching.

Summary

- Stratospheric gravity waves observed during DEEPWAVE that “trail” downstream from the New Zealand terrain
- High wind speeds in SH polar jet imply a large component of wind normal to horizontal wavevector (& horizontal group velocity), which allows downstream advection of wave energy normal to wavevector
- Trailing wave characteristics are determined by: terrain spectra; low-level winds; wind speed and directional shear; Jones critical level
- Adjoint is used to identify gravity wave sources
  - Utilizes time dependent non-linear trajectory & includes key physics
- Non-Orographic Gravity Wave Sources
  - Sources associated with jet exit regions, fronts and precipitation
- Ongoing research:

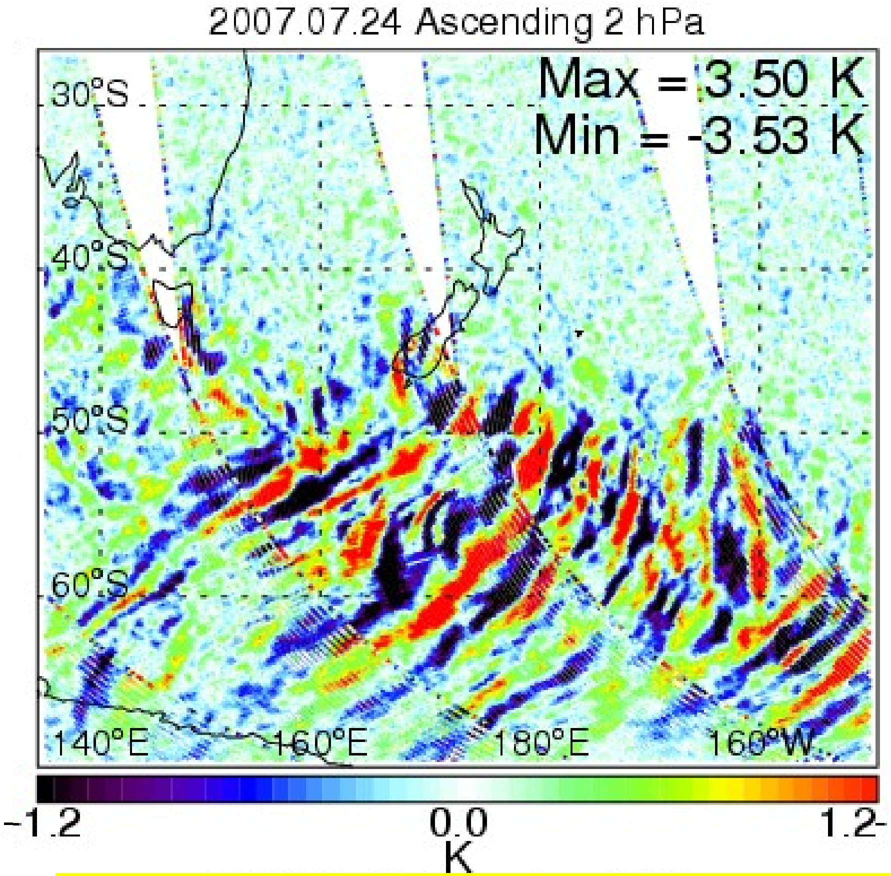
  i) DEEPWAVE trailing waves; ii) Idealized modeling of TWs

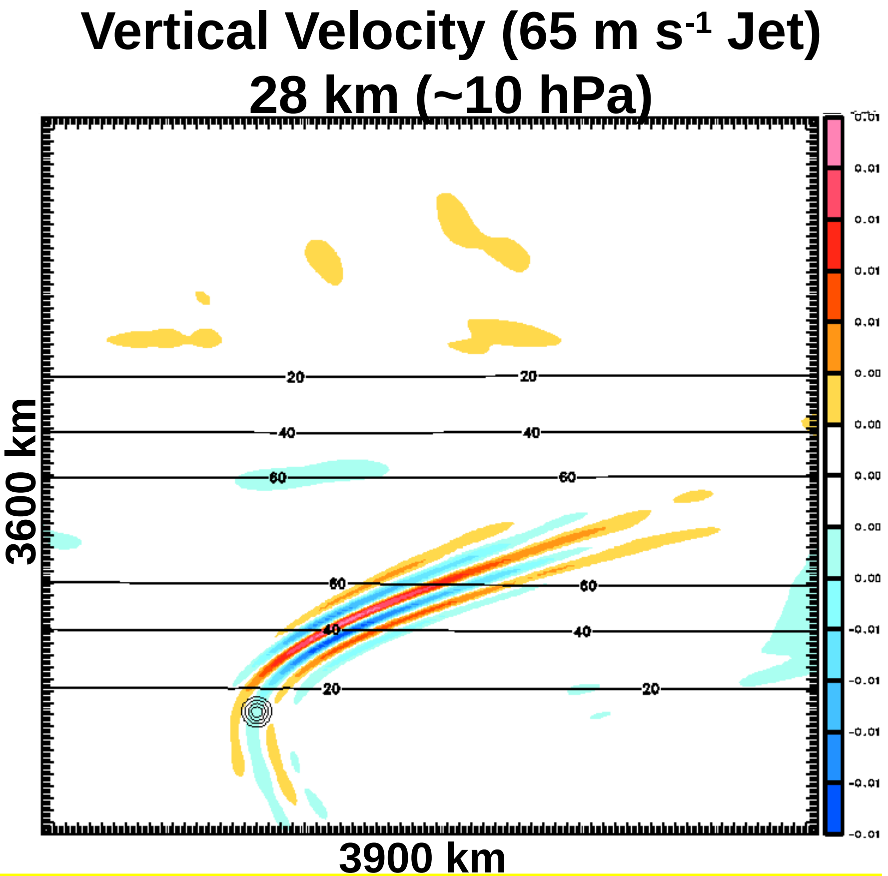
  iii) Adjoint GW ray tracing; iv) predictability;

  v) high-top (100 km) COAMPS cases

Gravity Waves in Sheared Flow

Idealized Shear Experiments





- Stronger shear leads to greater wave refraction and further propagation of the wave energy into the jet and downstream.
- Marked asymmetries are apparent in the waves due to the refraction into the jet and absorption at directional critical lines.
- None of these effects are included in wave drag parameterizations.