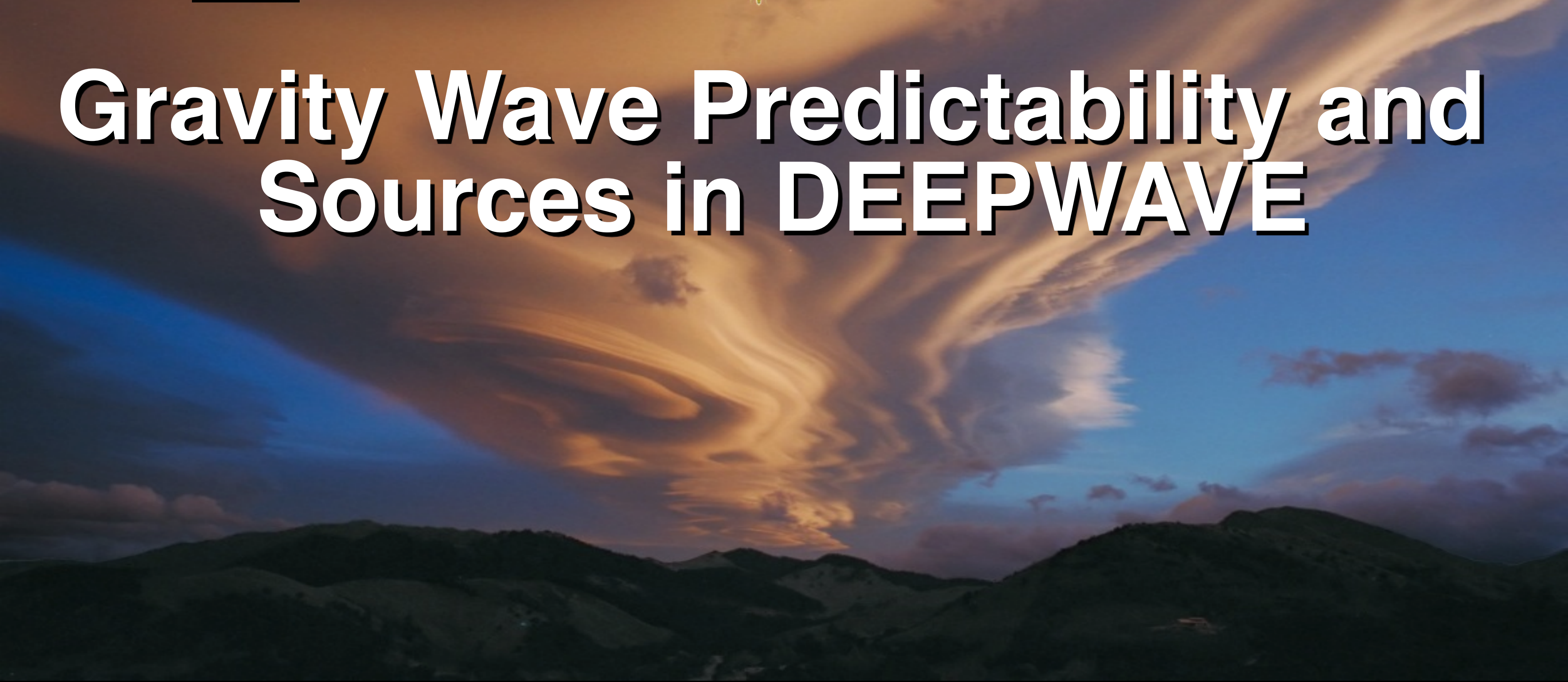
Gravity Wave Predictability and Sources in DEEPWAVE



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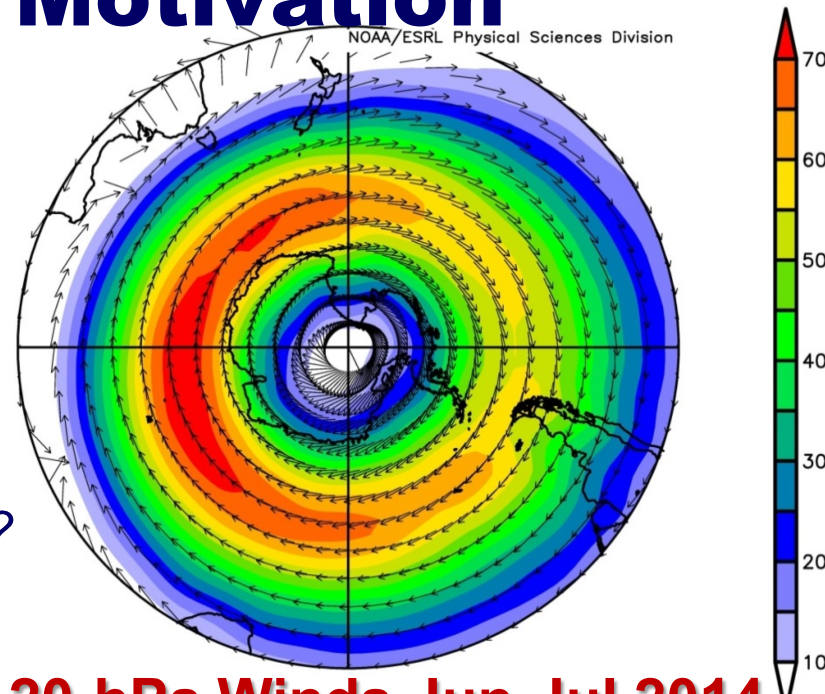
Kaituna, Masterton, New Zealand

Background and Motivation

- **Deep Gravity Wave "Hot Spots" over New Zealand & Tasmania:**
  - 26 G-V & 13 Falcon flights sampled frequent, but *episodic* gravity wave events
  - *What influences the predictability of gravity waves and deep propagation?*
  - *What are the wave source characteristics?*



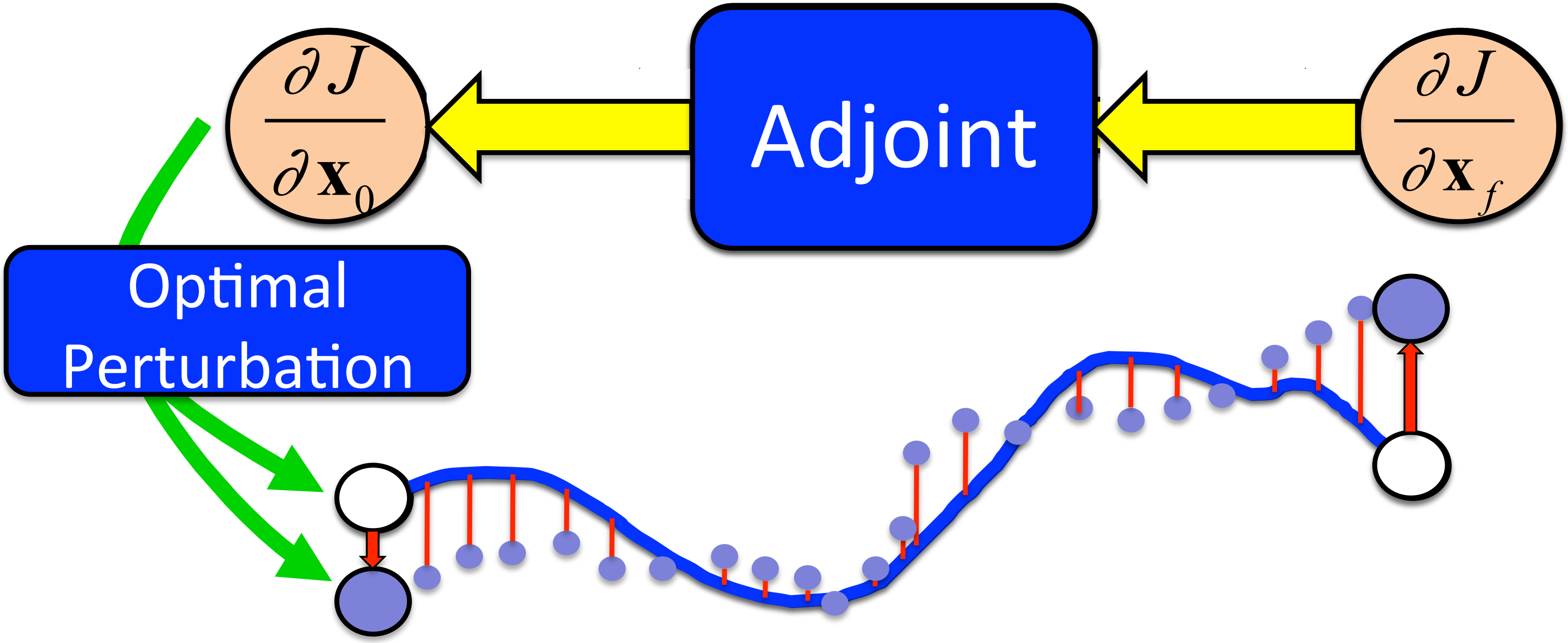
20-hPa Winds Jun-Jul 2014

- **Predictability:**
  - Nonlinear numerical models exhibit a sensitive dependence on initial state.
  - Quantify initial state sensitivity & predictability of wave launching and GWs
  - Understand implications for interpreting GW characteristics and fluxes

- **"Trailing" Gravity Waves and Sources:**
  - Frequent "trailing" gravity waves observed near the New Zealand S. Island
  - Examine role of lateral wind shear associated with SH stratospheric polar jet
  - Identify characteristics and sources of "trailing" and non-orographic waves

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 $\boldsymbol{x}_f$ backward through time.

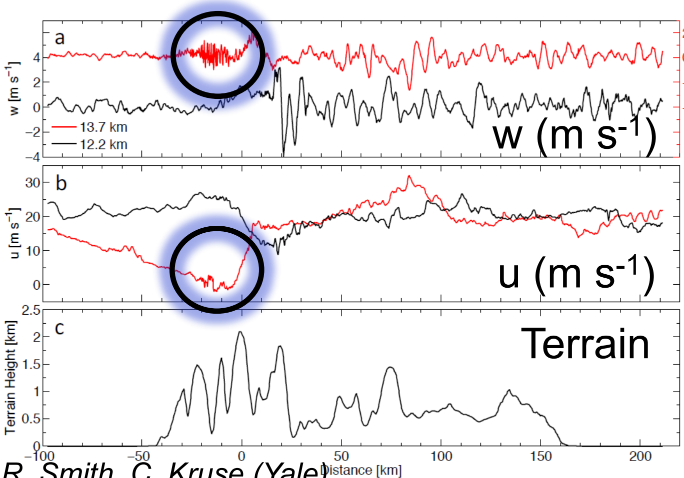
Errico (1997); Langland et al. (1995); Doyle et al. (2012; 2014)

Adapted from Brett Hoover (UW)

Predictability of Deep Propagating GWs

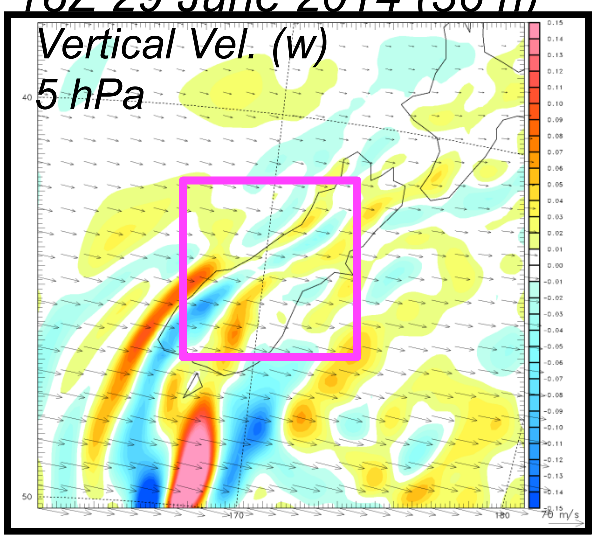
What are the predictability characteristics of deep propagating GWs?

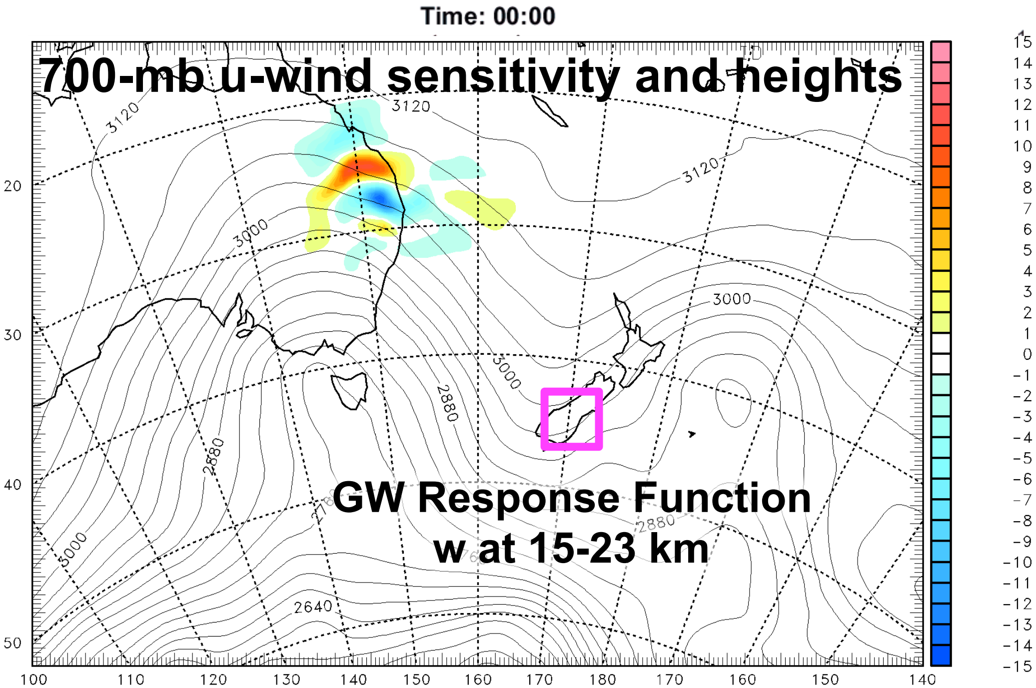
G-V Obs. (29 June 2014, RF12)



R. Smith, C. Kruse (Yale)

18Z 29 June 2014 (36 h)



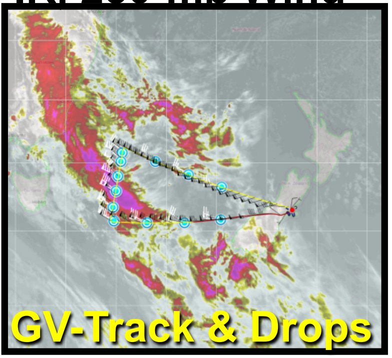


- Adjoint is used to diagnose sensitivity using a kinetic energy response function (lowest 1 km)
- Sensitivity located ~1200 km upstream near trough
- Adjoint optimal perturbations lead to strong wave propagation (refracted waves south of NZ)

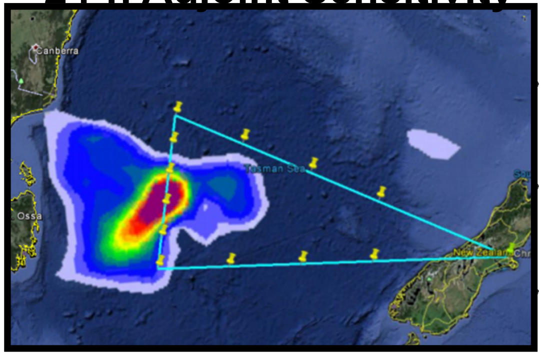
DEEPWAVE G-V Predictability Missions

RF03 (13 June)

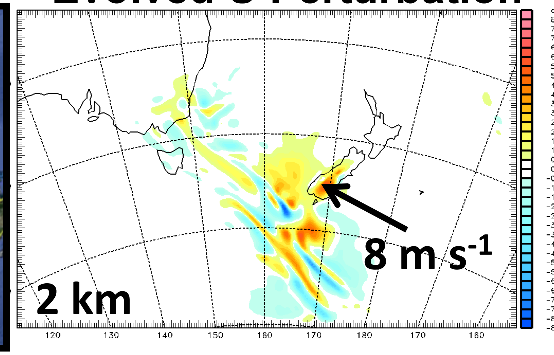
IR, 250-mb Wind



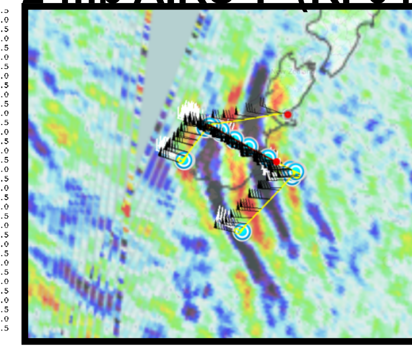
24-h Adjoint Sensitivity



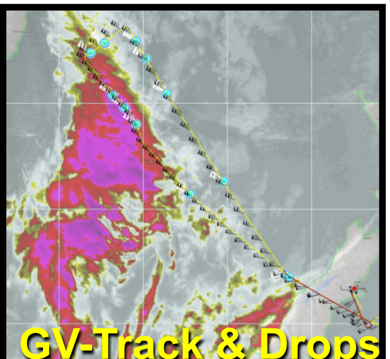
Evolved U Perturbation

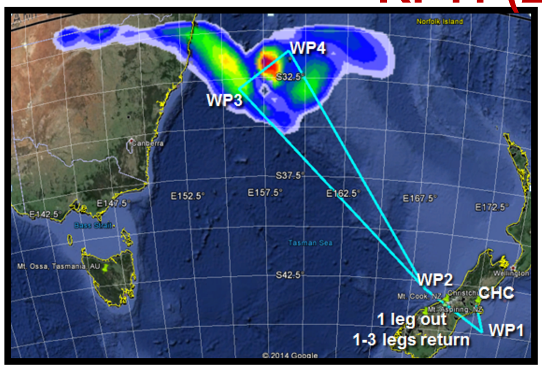


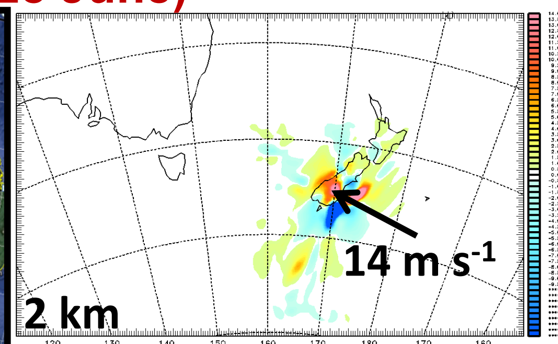
2-mb AIRS T' (RF04)



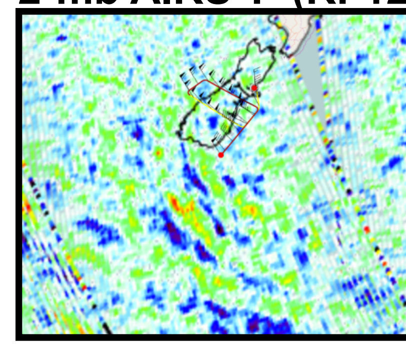
RF11 (28 June)







2-mb AIRS T' (RF12)



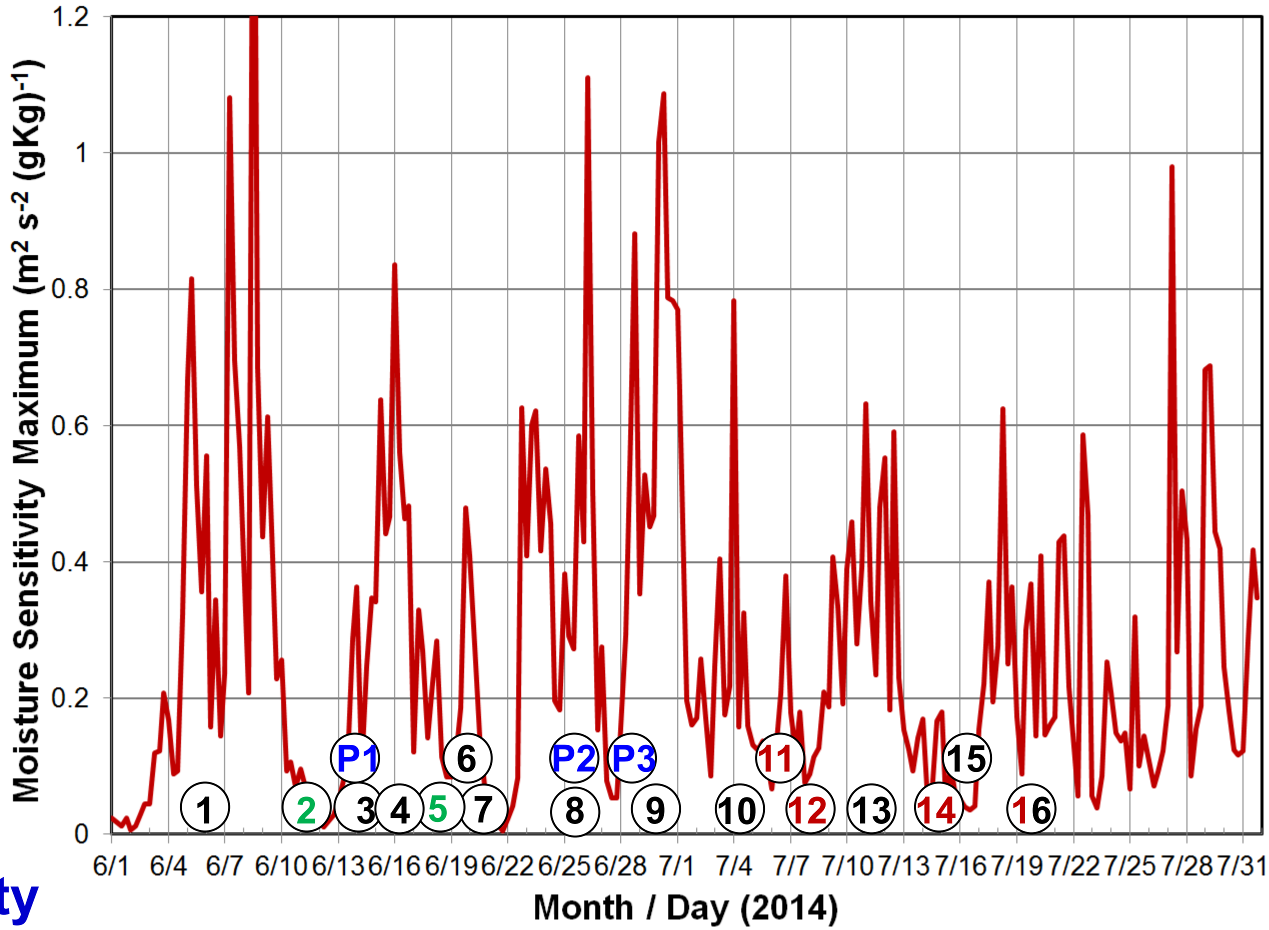
- G-V predictability flights (w/ drops) sampled initial condition sensitivity regions upstream of S. Alps prior to gravity wave events (3 flights; 6 IOPs)
- Sensitivities located in dynamically active regions (jet, front, convection).
- Evolved adjoint perturbations are large enough to impact wave launching.
- G-V gravity wave "verification" flights (following day) observed deep propagating waves and are used to quantify the predictability.

Moist Adjoint Sensitivity

June-July 2014 Moisture Sensitivity Maximum ($m^2\ s^{-1}\ (g\ Kg)^{-1}$)

IOP #

NZ Flight
Tasmania
S. Ocean
Predictability

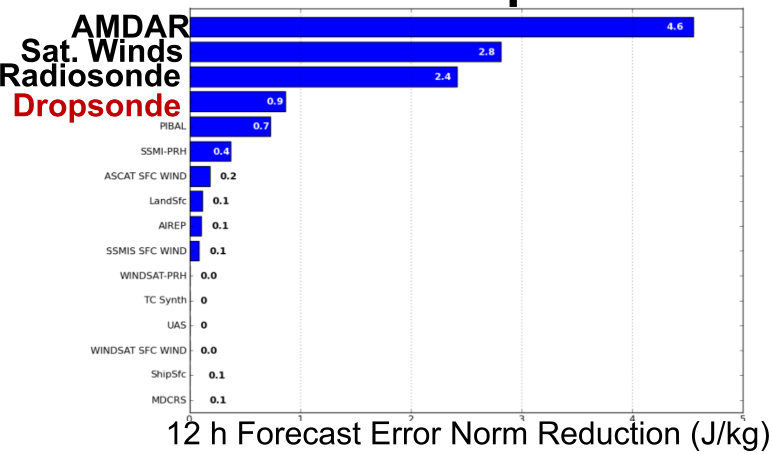


- Maximum sensitivity of the low-level wind speed (GW launching) over the S. Alps (1 km deep response function) to the initial moisture.
- Maxima correspond to the IOP periods in general.
- Largest moisture sensitivity peaks: IOPs 1, 8, 9, lesser 4, 10, 13

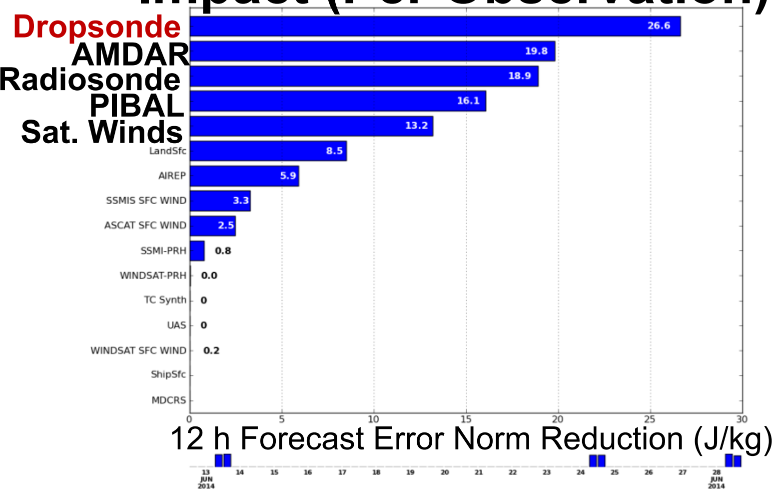
G-V Targeted Dropsonde Impact

Adjoint Forecast Sensitivity to Observation Diagnostics

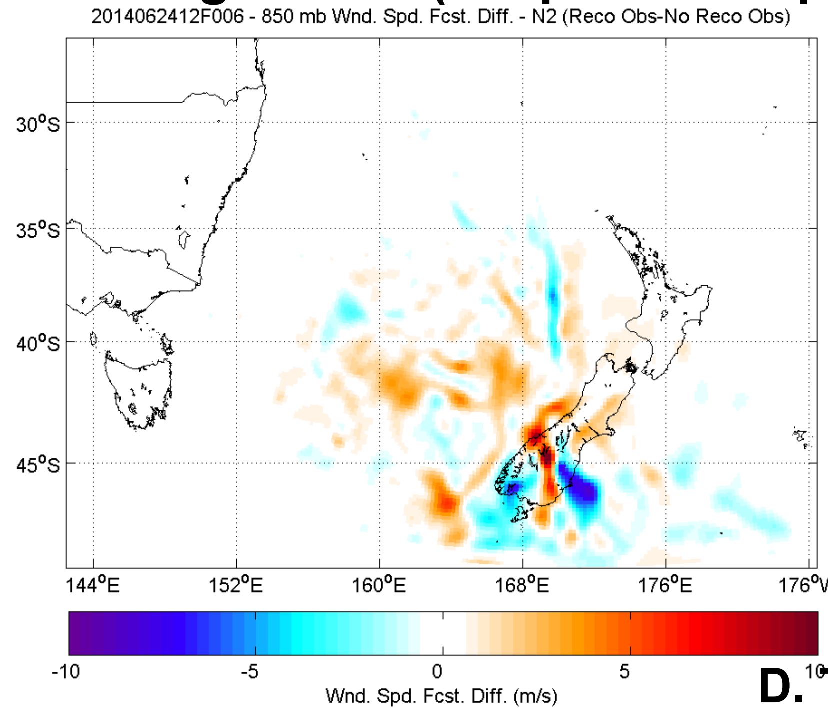
Total Impact



Impact (Per Observation)



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



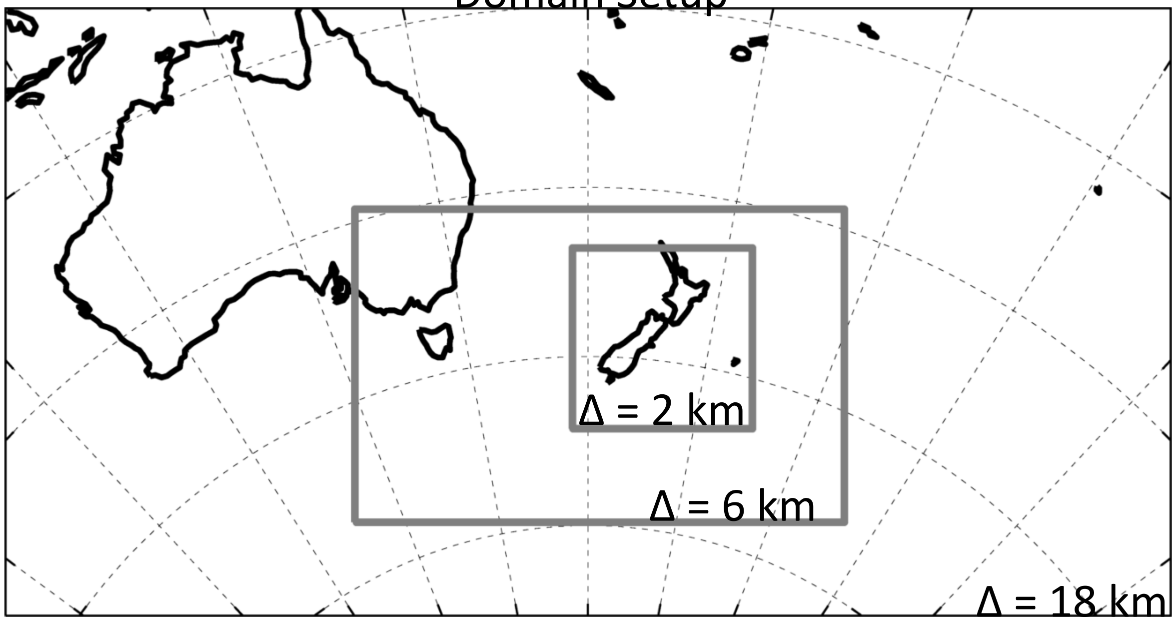
D. Tyndall

- 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.

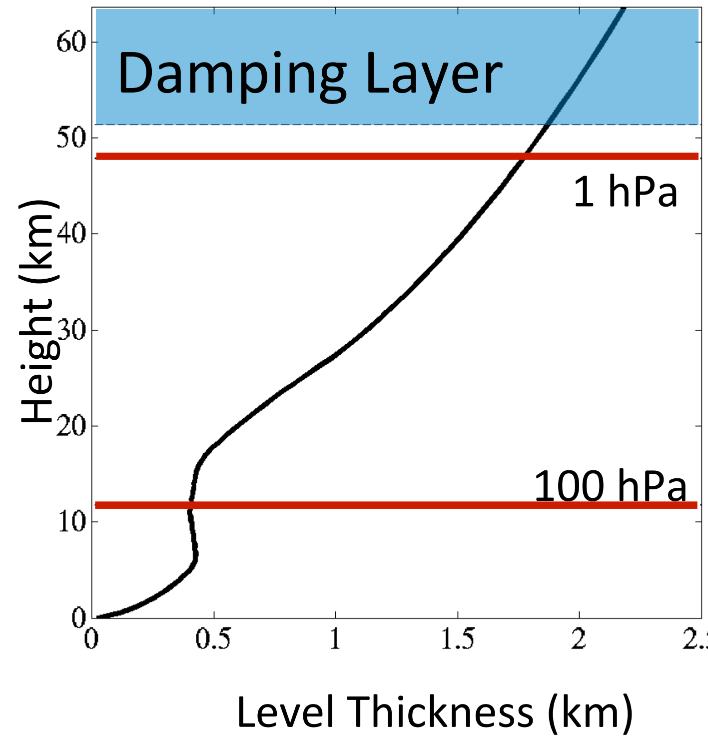
COAMPS Ensemble

Configuration

Domain Setup



Vertical Grid



Alex Reinecke

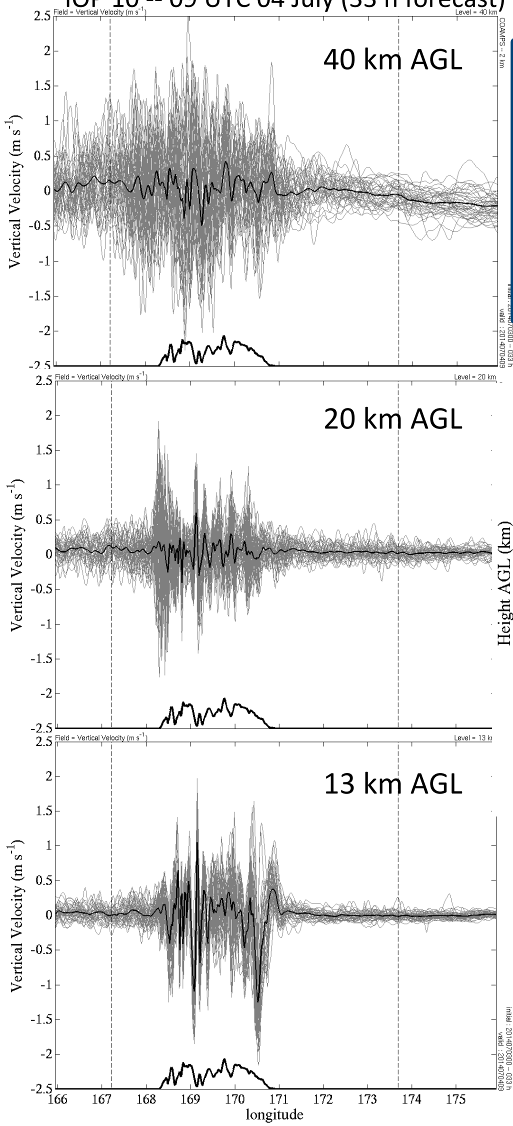
- 40 members: IC/BC's perturbations from global Ensemble Transform
- Ensemble mean IC/BC interpolated from a NAVGEM analysis
- 93 vertical levels: 38 levels below 10 km, 61 levels below 20 km
- Ensemble runs of w and MFx for 14 June and 04 July

COAMPS Ensemble

Ensemble Gravity Wave Forecasts

IOP 10

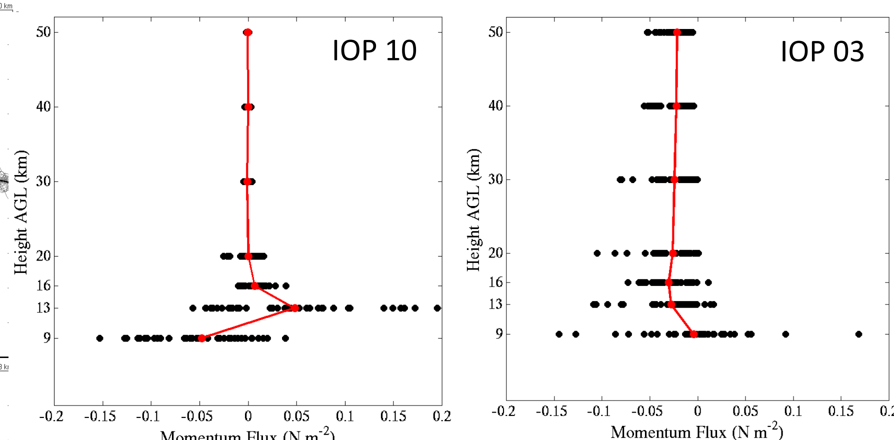
IOP 10 -- 09 UTC 04 July (33 h forecast)



IOP 10

- 13 km: low spread, relatively large amplitude
- 40 km: small wave amplitude growth for individual members, large spread in phase
- Little zonal momentum flx aloft, little spread
- Uncertainty in deep layer of decreasing Mfx

Zonal Momentum Flux

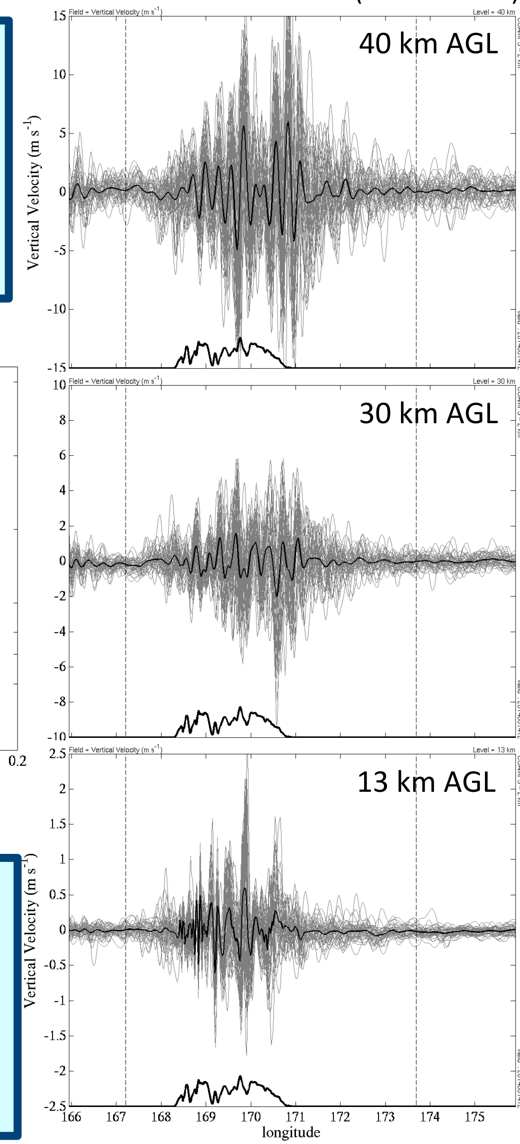


IOP 03

- 13 km: Weak wave, some phase uncertainty
- 40 km: Wave grows with height, large phase and amplitude uncertainty near stratopause
- Large uncertainty in zonal momentum flux through depth of the stratosphere

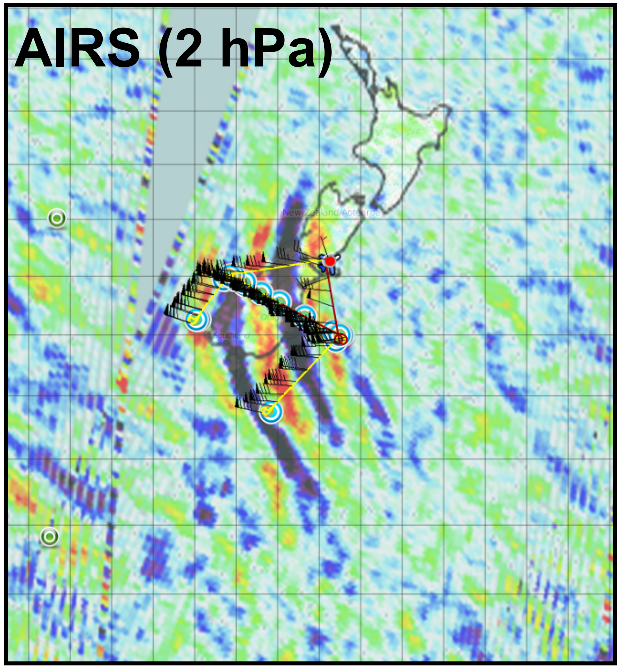
IOP 03

IOP 03 -- 12 UTC 14 June (48 h forecast)

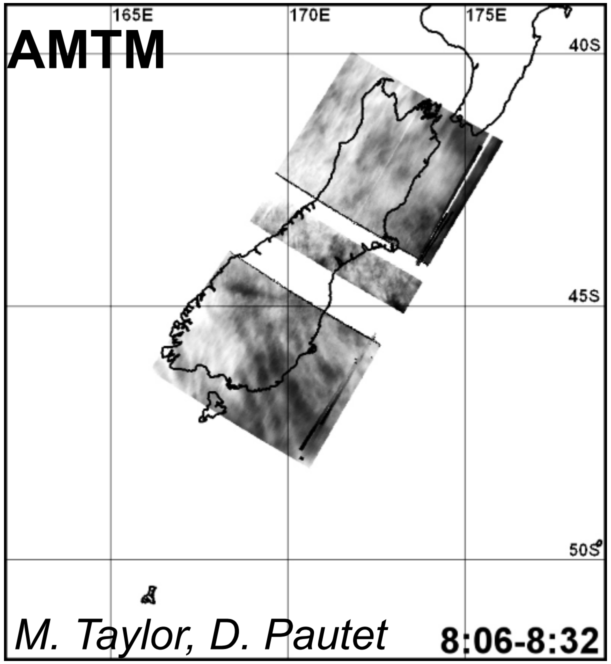


“Trailing” Gravity Waves during DEEPWAVE

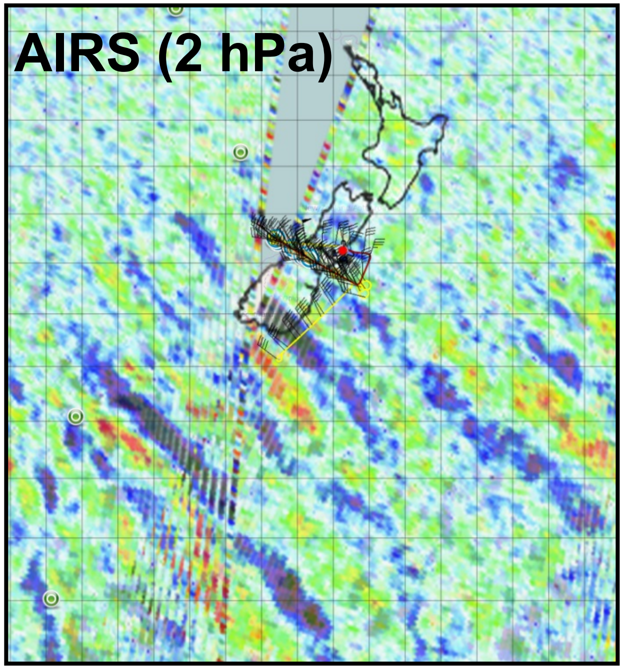
RF04



RF05



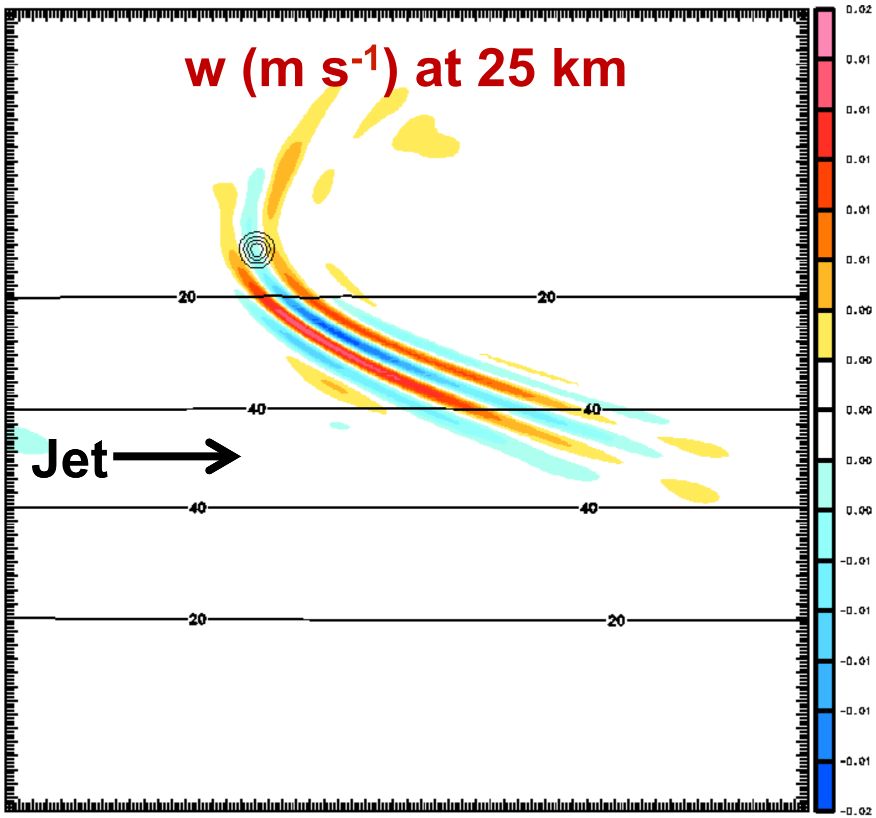
RF18

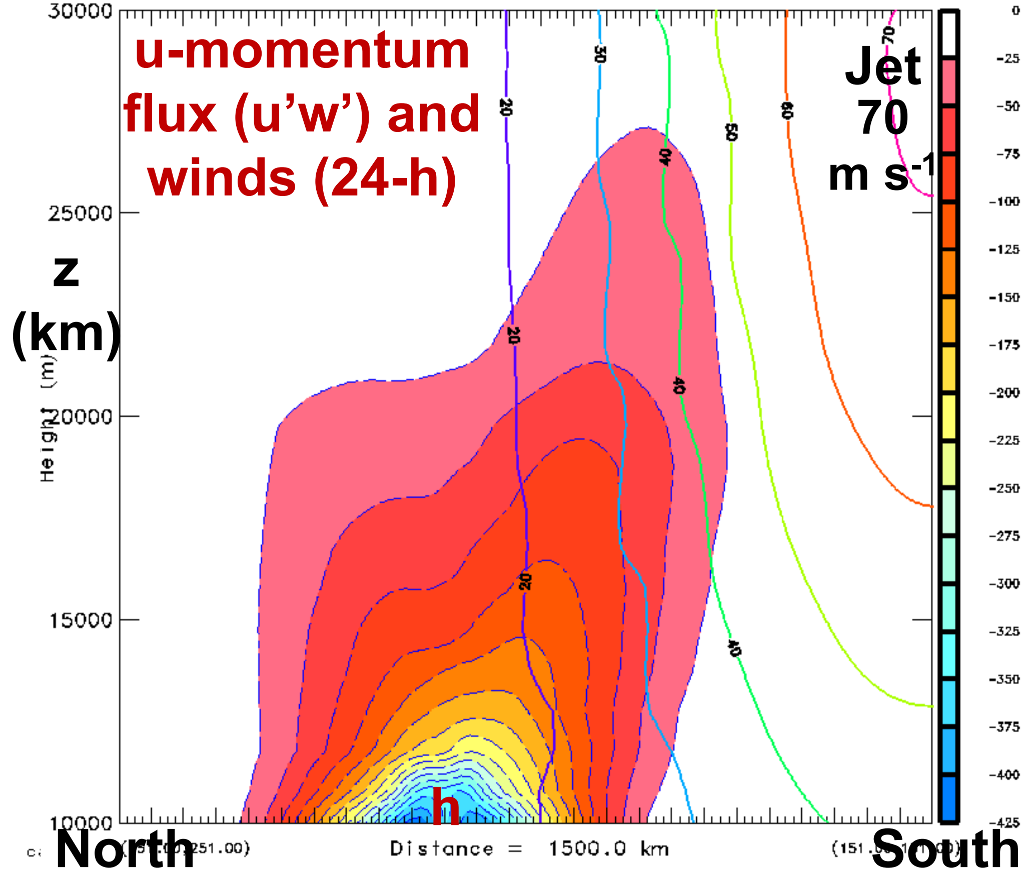


Frequent cases during DEEPWAVE of observations of “trailing” gravity waves oriented nearly normal to the terrain ridge.

Gravity Waves in Sheared Flow

Idealized Shear Experiments

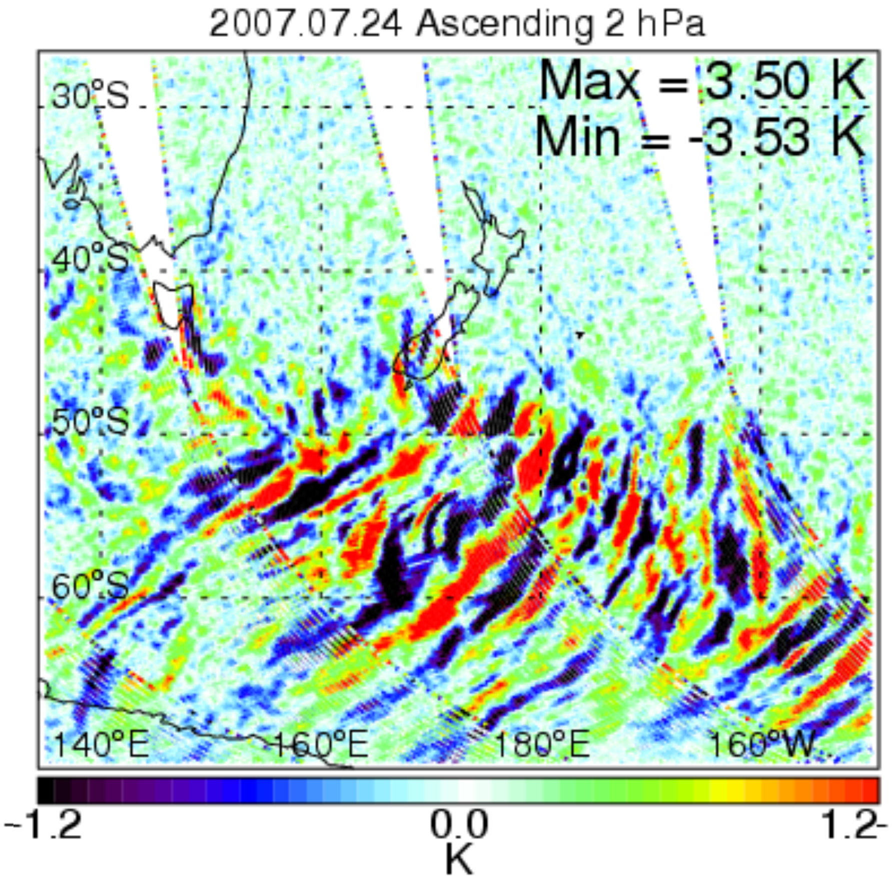


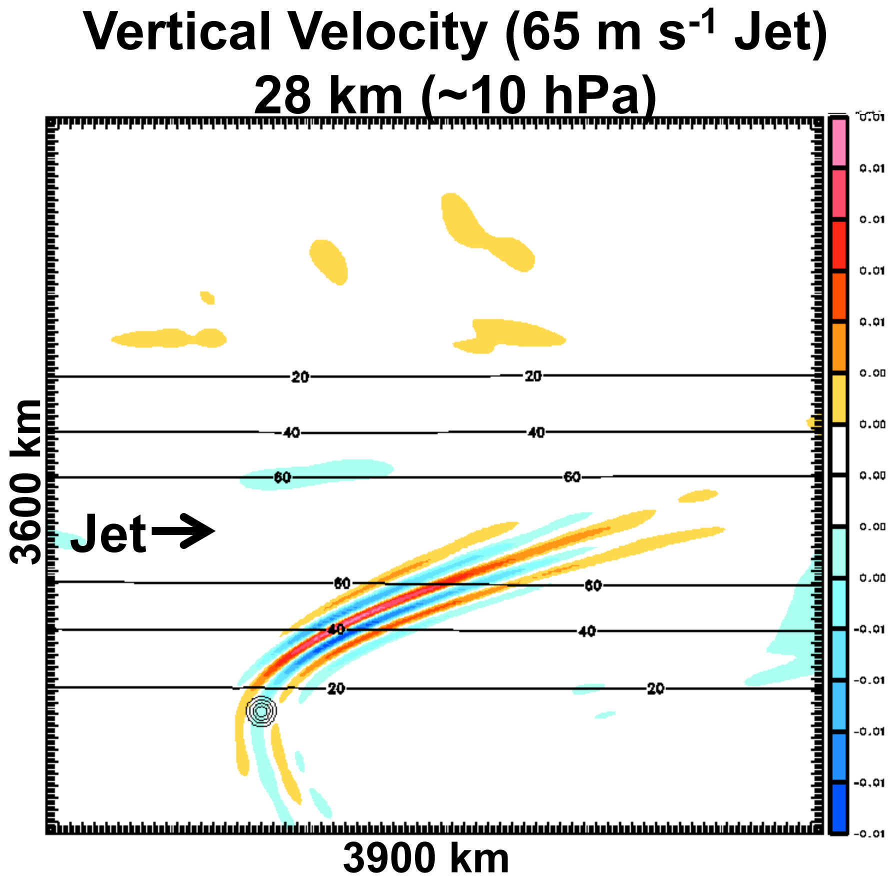


- High wind speeds imply a large component of wind normal to horizontal wavevector (and intrinsic horizontal group velocity), which allows advection of wave energy perpendicular to wavevector (parallel to phase lines) (see Dunkerton 1984, Sato et al. 2009, Vosper 2015)
- Zonal momentum flux in the stratosphere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

Gravity Waves in Sheared Flow

Idealized Shear Experiments



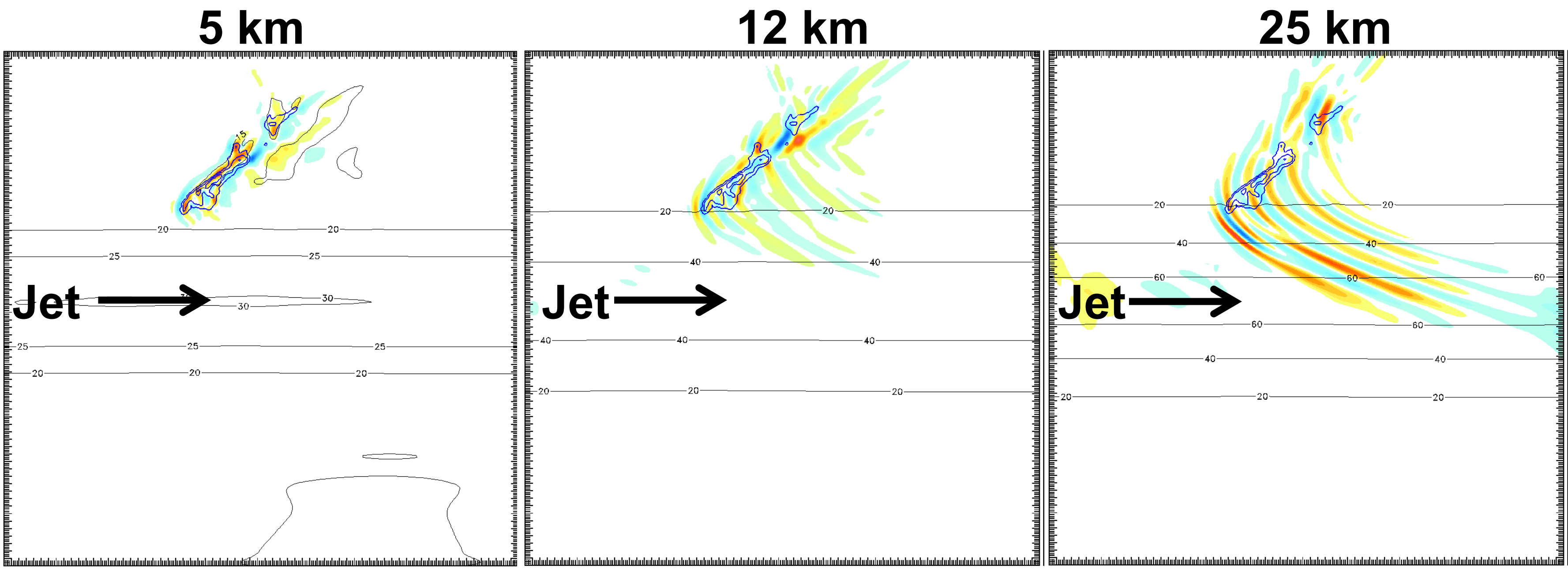


- Stronger shear leads to greater wave refraction and further propagation of the wave energy into the jet and downstream
- Marked asymmetries are apparent in the waves due to the refraction into the jet and absorption at directional critical lines

Gravity Waves in Sheared Flow

Idealized Shear Experiments with New Zealand Terrain

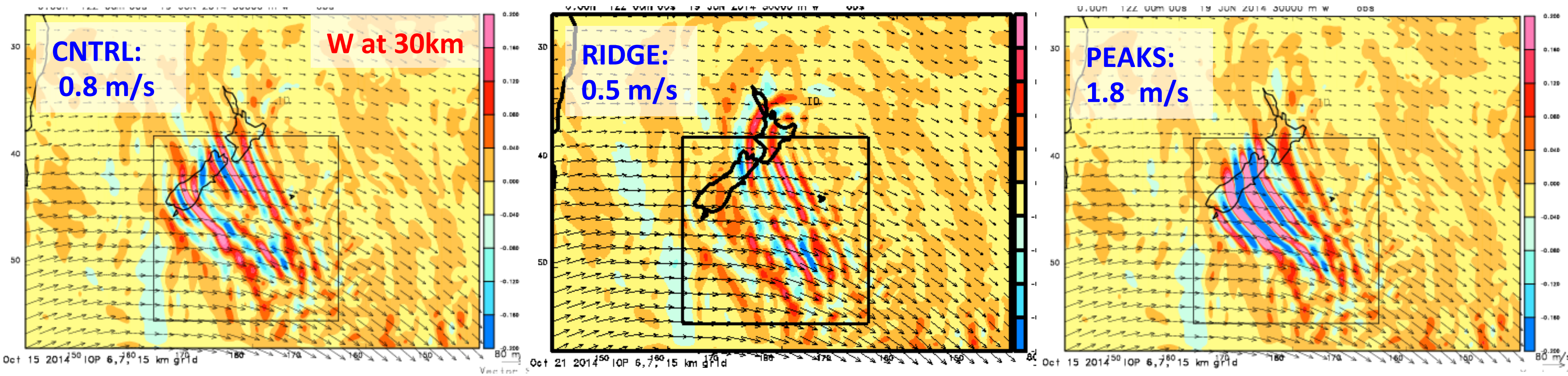
Vertical Velocity (70 m s^{-1} Jet)



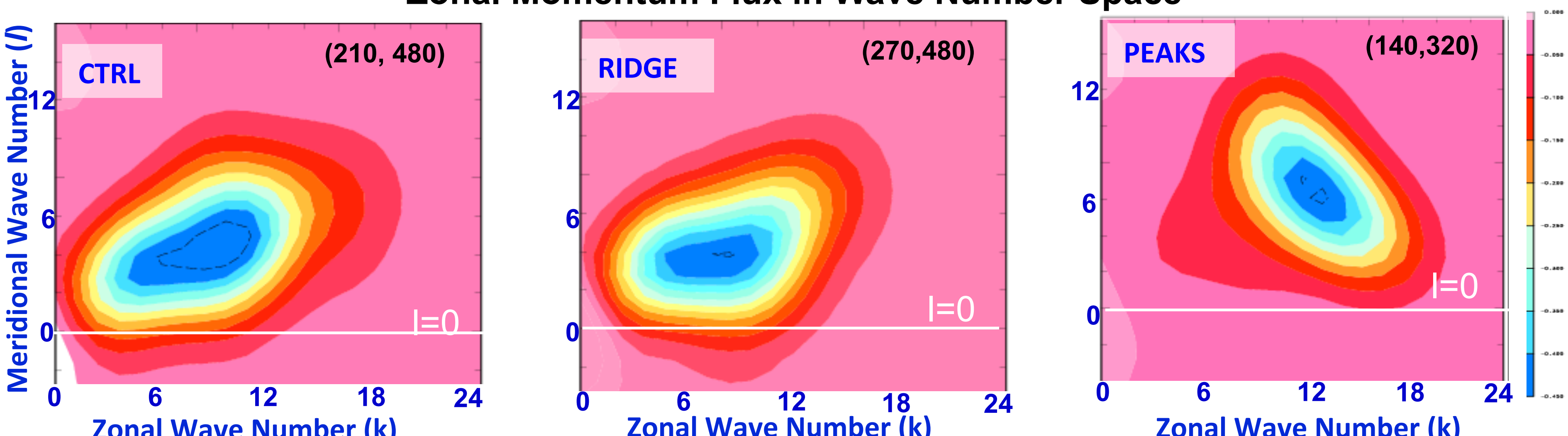
New Zealand terrain launches gravity waves that are refracted by the shear in a similar manner to the idealized hill.

Sensitivity of TWs to Topography

CNTRL: Real Terrain | **RIDGE: a smooth ridge with h_m = 3 km** | **PEAKS: Multiple (4) peaks along ridge**



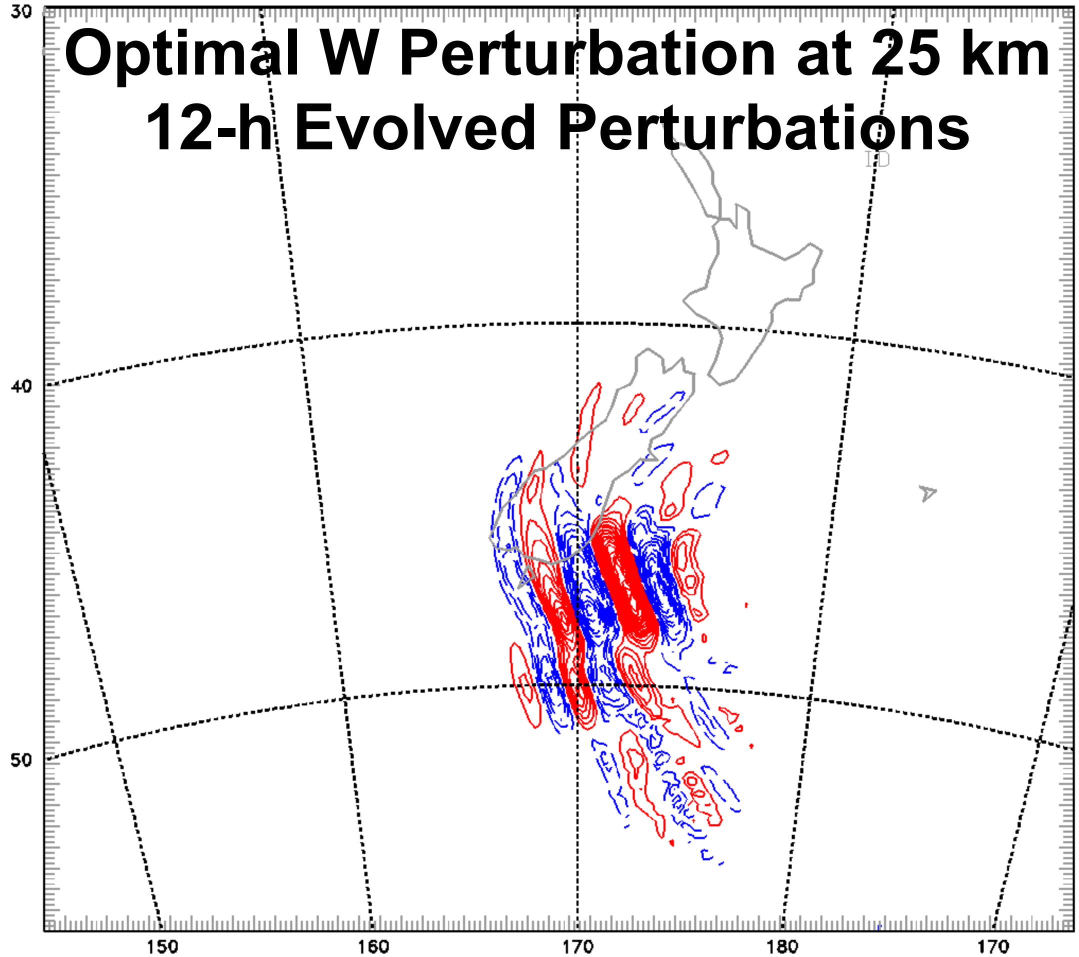
Zonal Momentum Flux in Wave Number Space



Wavelength, wave strength, and momentum fluxes are sensitive to topography, suggestive that nature of the terrain is closely linked to the trailing gravity waves characteristics in stratosphere

Gravity Wave Source Identification

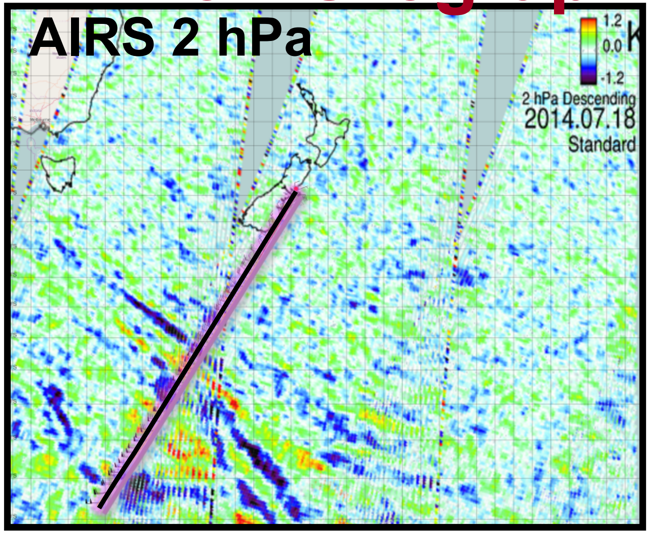
Trailing Waves in IOP 3 (RF04)

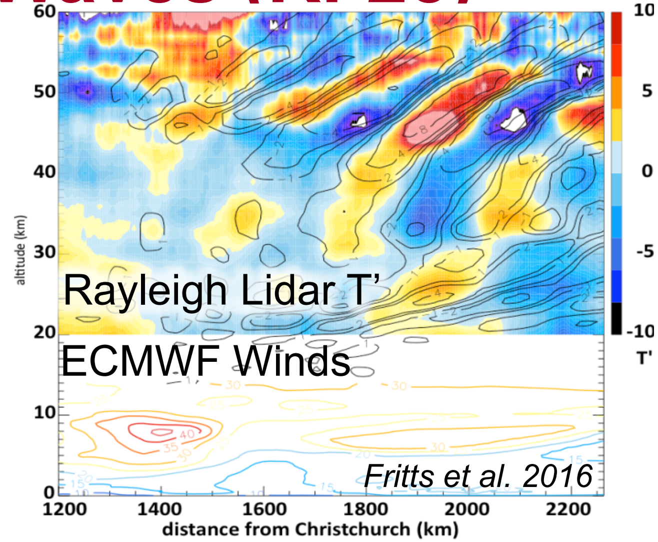


- Adjoint identifies most sensitive portion of the Alps for wave launching
- Trailing waves located to S of NZ are launched from S. Alps (south of Cook)
- Excitation of waves by non-orographic sources for detached trailing GWs

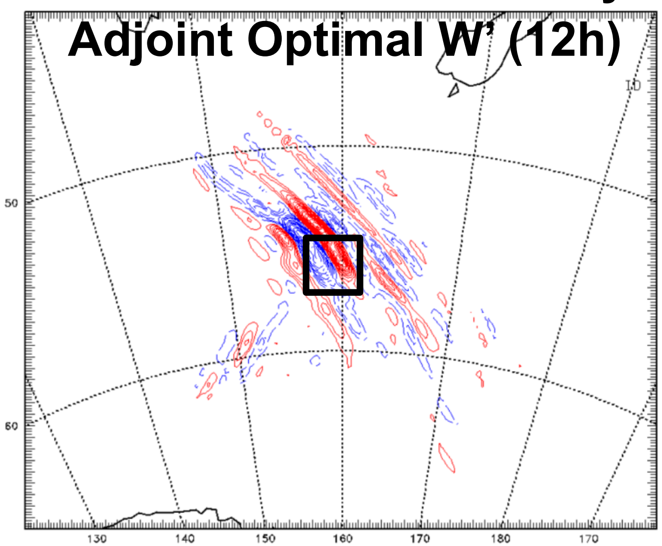
Gravity Wave Source Identification

Non-Orographic Waves (RF25)

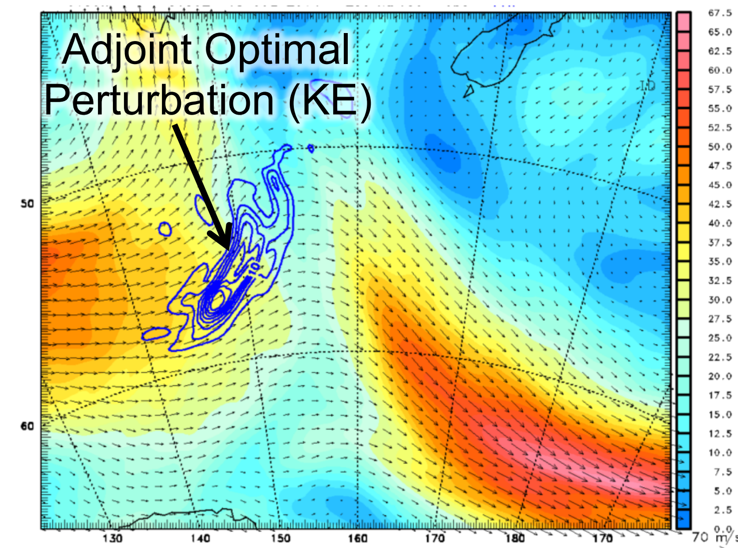




20-hPa Vertical Velocity



250-hPa Winds

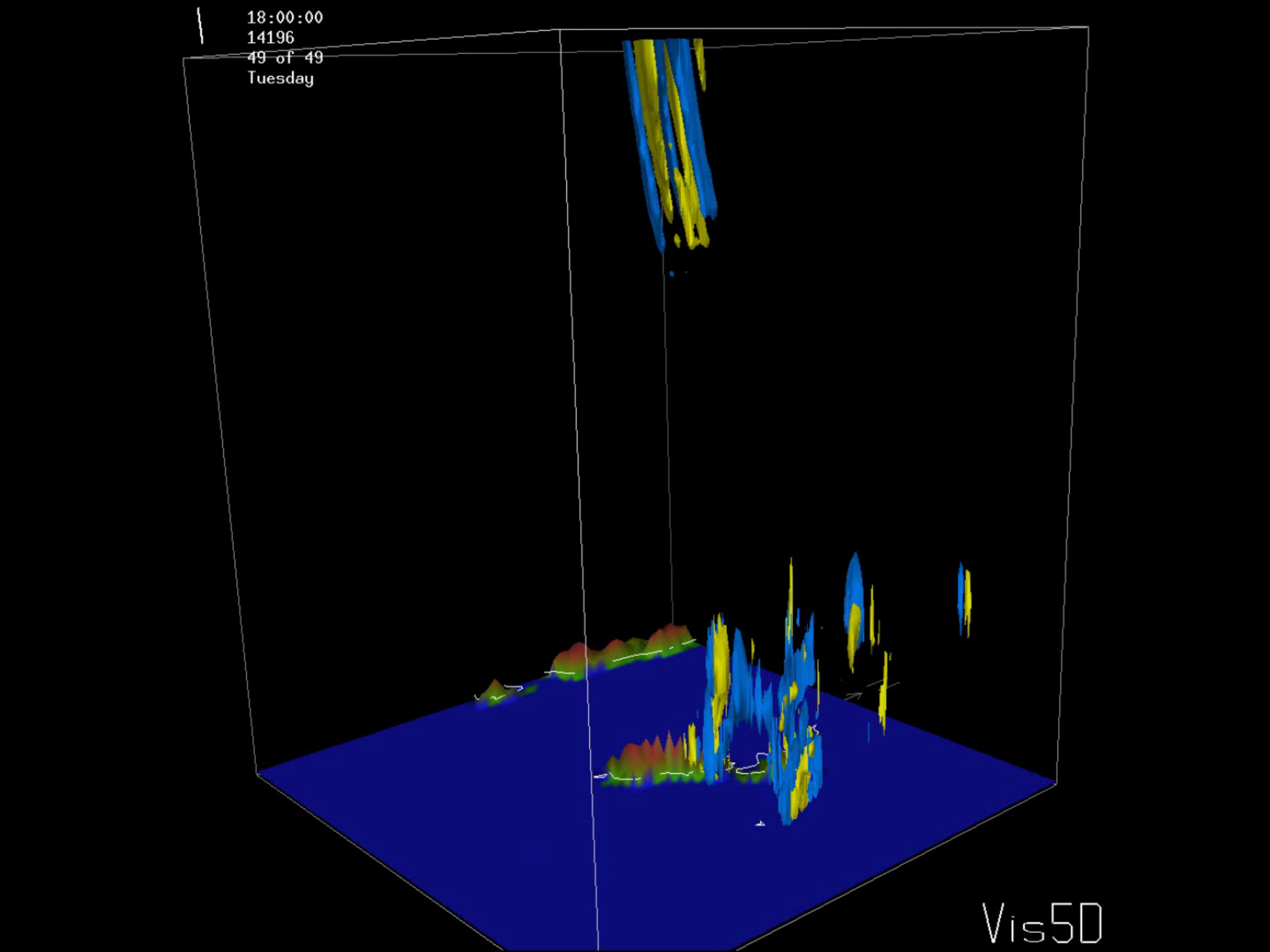


- Adjoint identifies exit region of jet as a possible source (in at least 2 cases)
- GWs excited by non-linear imbalance in the high-amplitude pattern

Summary and Conclusions

- **Gravity Wave Predictability**
  - Sensitive regions (*particularly moisture*) are in physically meaningful locations important for wave launching: troughs, jets, and convection
  - DEEPWAVE dropsondes have a large positive impact on gravity wave launching and impacts the explicit prediction of gravity waves
  - Ensembles highlight large uncertainties in the prediction of mountain wave characteristics and momentum flux

- **Gravity Wave Sources**
  - Evidence of GW refraction due to lateral shear from the SH polar jet, explains the existence of “trailing” gravity waves in the lee of New Zealand
  - Implications for momentum fluxes and GW drag parameterizations
  - Preliminary adjoint results show non-orographic GWs generated in jet exit and along fronts in moist convection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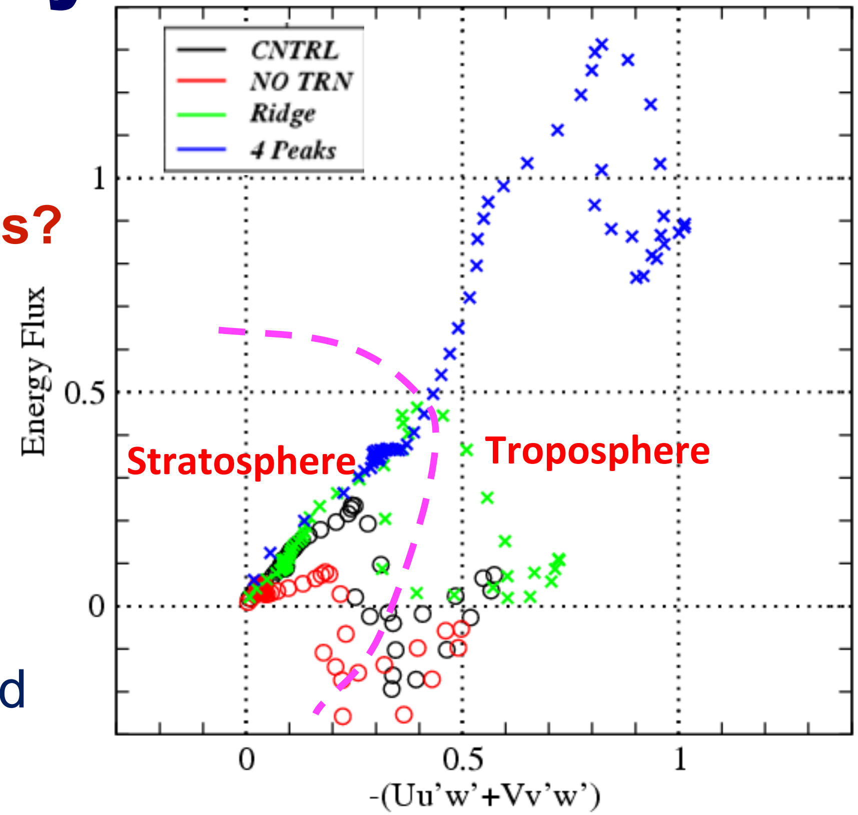
Trailing Gravity Waves

- **Trailing Wave source?**
  - GW Launching by Topography
- **What determines the TW characteristics?**
  - Topography
  - Vertical and lateral wind shear
- **How does shear impact the GWs?**
  - Vertical directional shear filters out shorter waves
  - The left branch of waves are dissipated or refracted due to lateral shear
- **Why are TWs present in stratosphere?**
  - TWs in stratosphere are more apparent due to shear filtering
  - Development of TWs may require wave refraction due to strong lateral shear



According to Eliassen-Palm Theorem: For linear stationary waves, the wave energy flux is related to momentum flux as

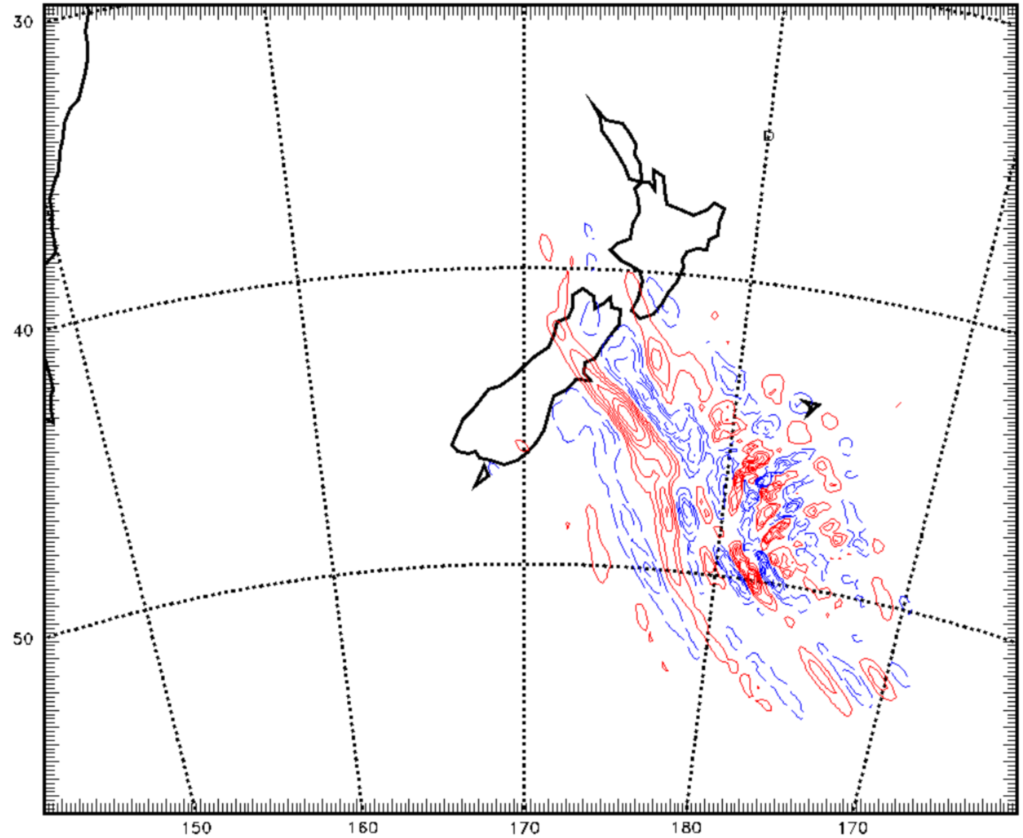
$$\overline{p'w'}/\overline{\rho}(z) = -\left[U\overline{u'w'} + V\overline{v'w'}\right]$$

- Wave energy flux is much reduced from troposphere to stratosphere
- In stratosphere, TWs are consistent with EP theorem.

Gravity Wave Source Identification

Trailing Waves in IOP 6 (RF07)

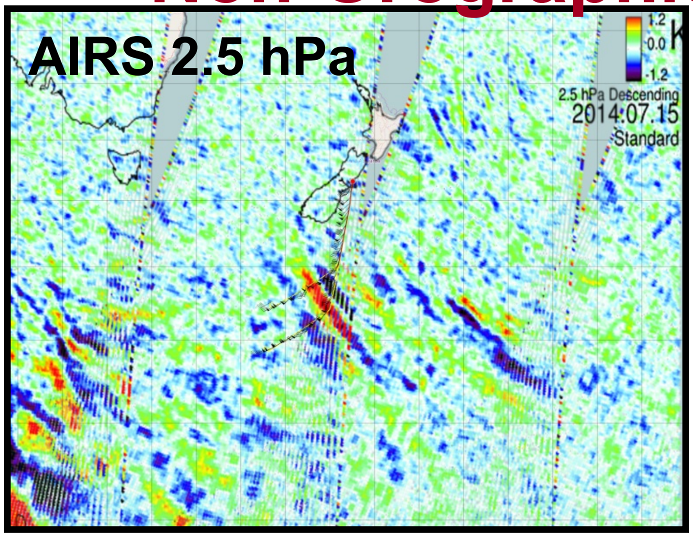
COAMPS Adjoint Optimal Perturbation w (15 hPa); 1800 UTC 19 June (12 h)

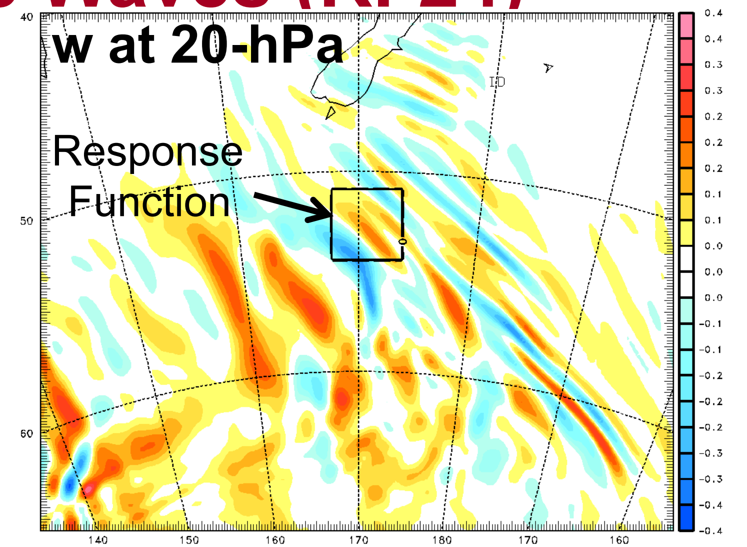


- Adjoint identifies most sensitive portion of the S. Alps for wave launching
- Trailing waves located to S of NZ are launched from S. Alps (south of Cook).

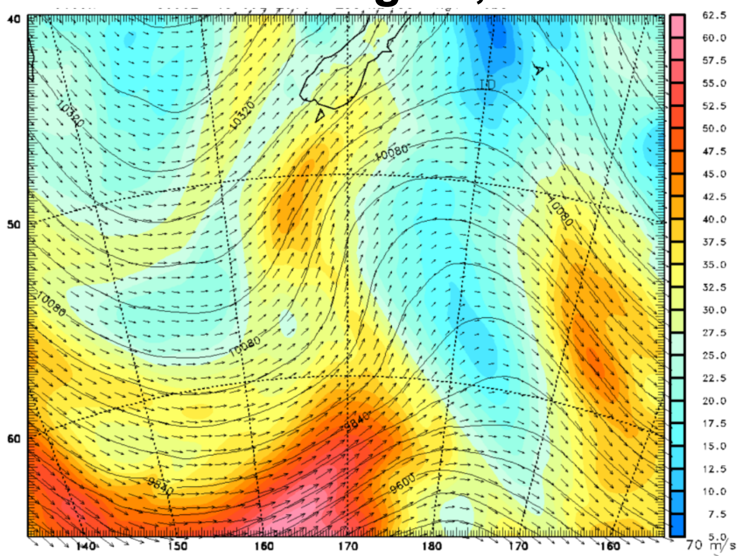
Gravity Wave Source Identification

Non-Orographic Waves (RF24)

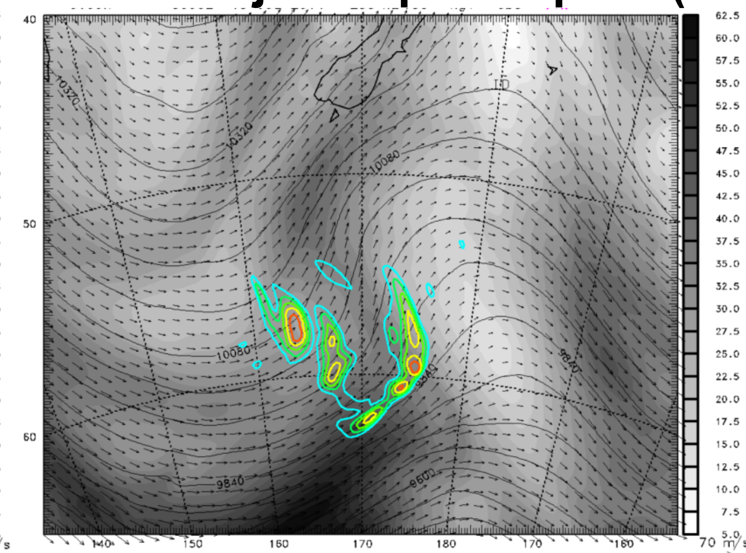




250-hPa heights, winds



250-hPa adjoint optimal pert. (KE)

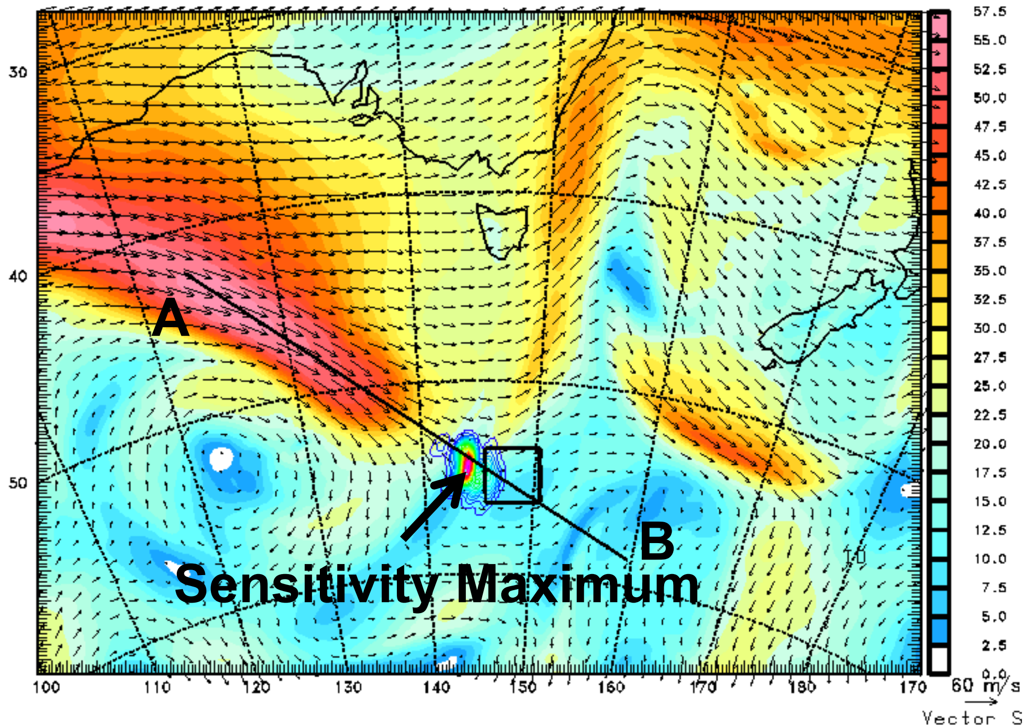


- Adjoint identifies left exit region of jet as possible source
- GWs excited by decelerations in high-amplitude pattern.

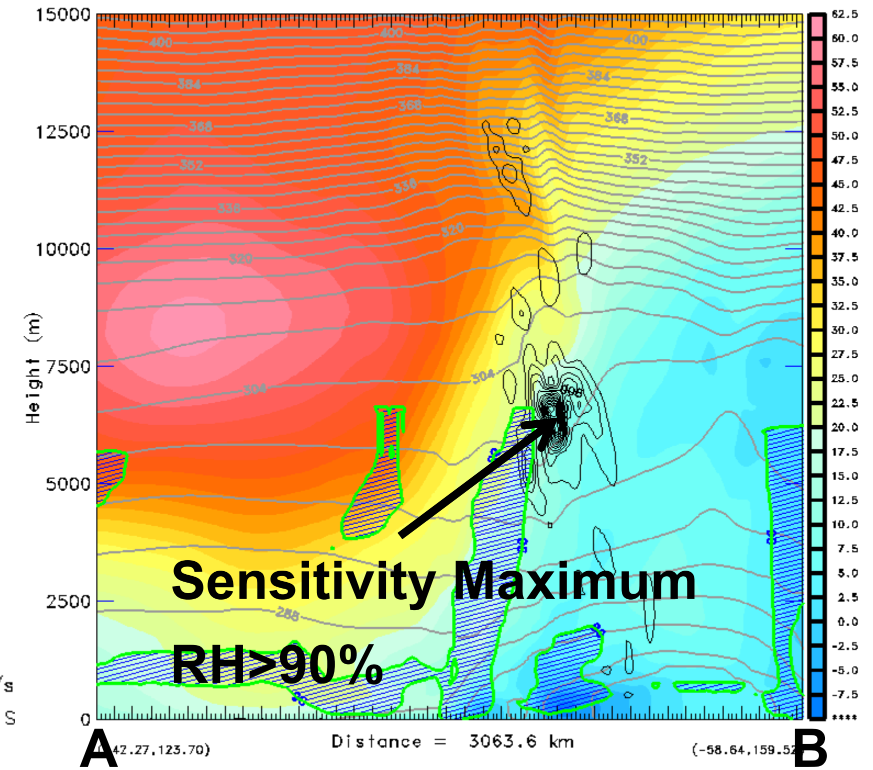
Gravity Wave Source Identification

Non-Orographic Wave Case

400 hPa wind speed (m s^{-1})
Optimal Perturbation KE (6 h)



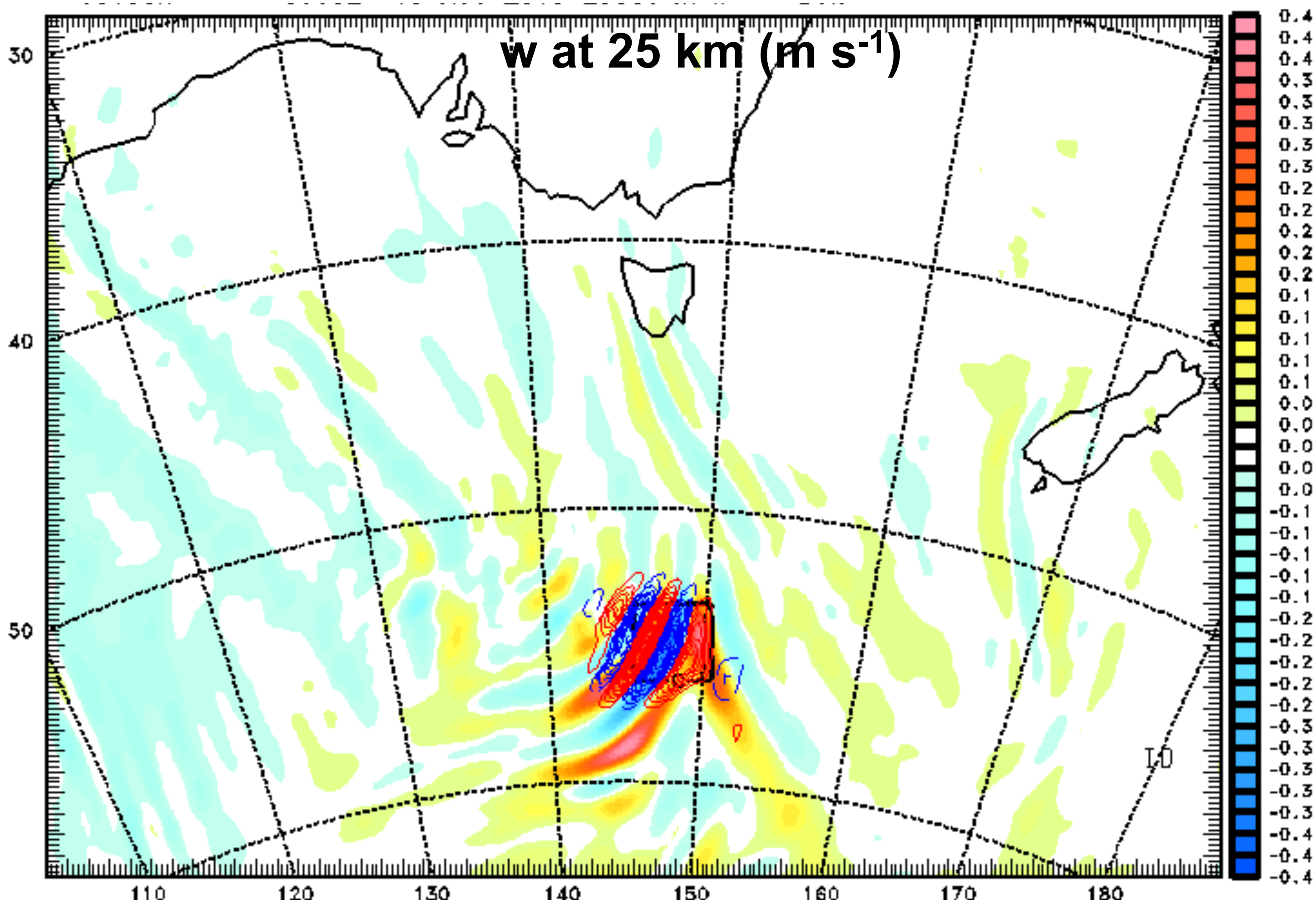
Along section wind speed (m s^{-1})
Optimal Perturbation KE (6 h)



Sensitivity maximum is locations upstream of the response function near the exit region of a very strong jet and near 7 km near the top of a region of saturated rising motion (e.g., grid scale precipitation).

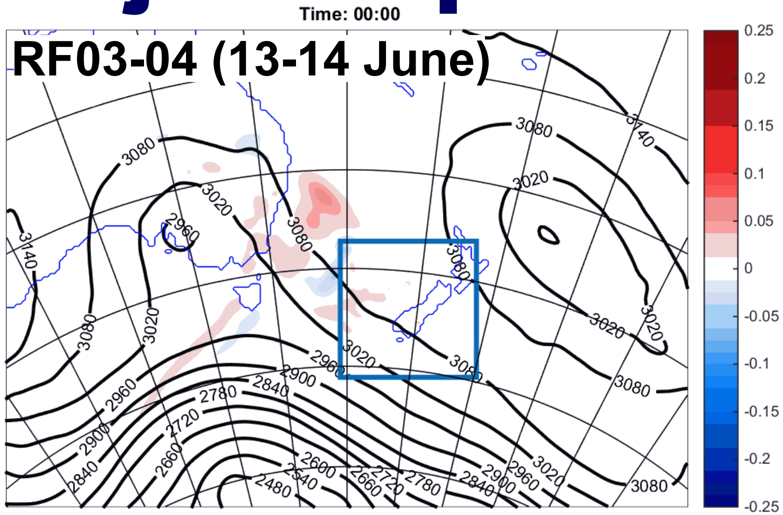
Gravity Wave Source Identification

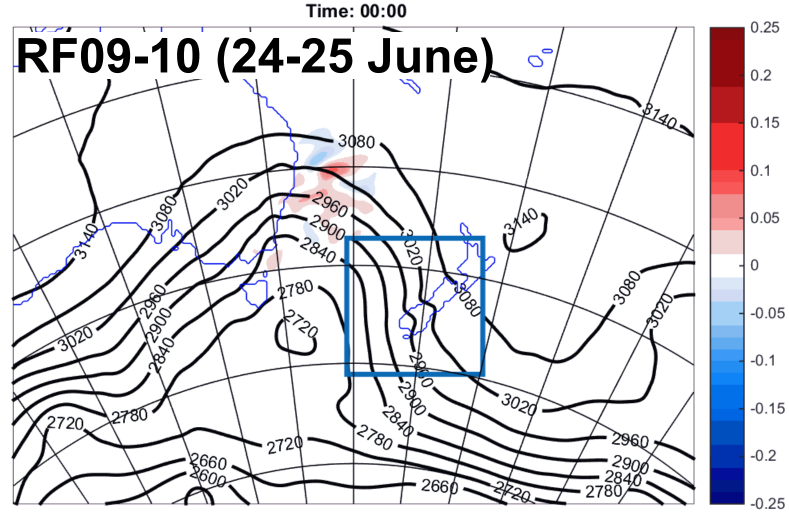
Non-Orographic Wave Case

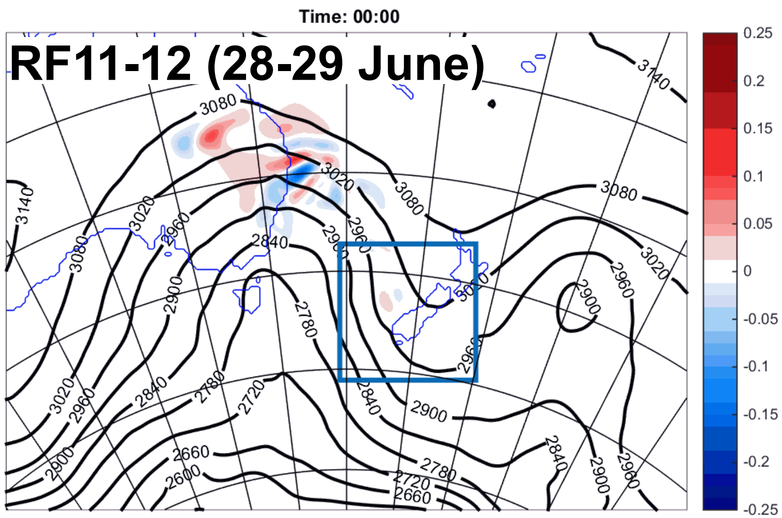


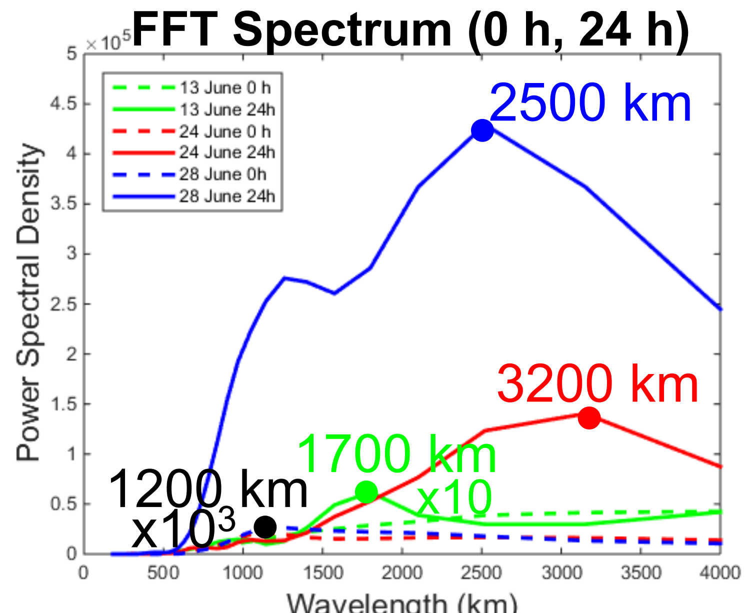
Adjoint optimal perturbation project on to the gravity wave packet generated by the exit region of the jet and precipitation processes, demonstrating the physical significance of the adjoint sensitivity.

Adjoint Optimal Perturbation Growth









- Rapid growth for 24 & 28 June cases - slower growth for 13 June case.
- Growth most rapid at medium (synoptic) scales.