Update on Gravity Wave Predictability, Dynamics and Sources in DEEPWAVE

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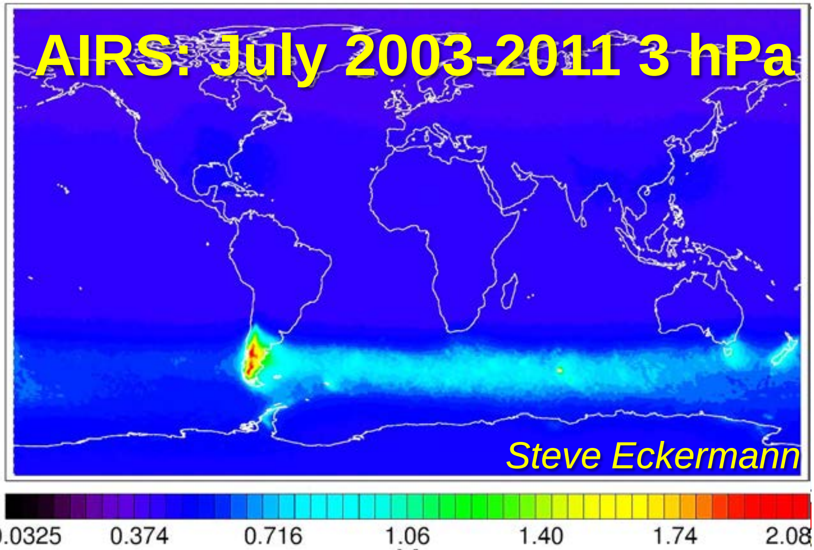
NRL-MRY DEEPWAVE Research Projects

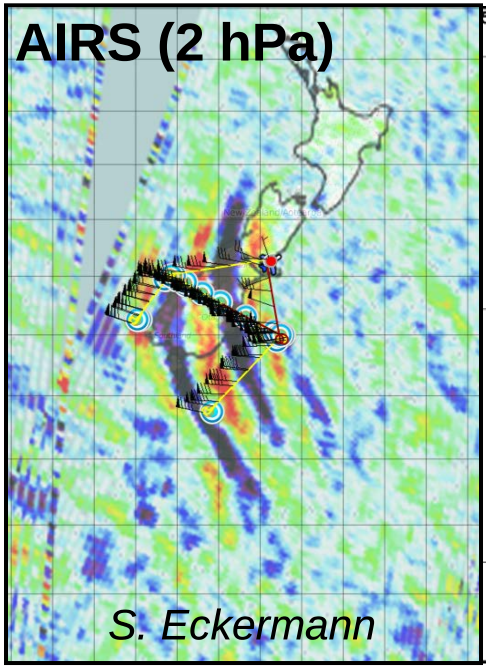
1) **Gravity Wave Source Identification (manuscript spring 2017):**
   - Sources of "trailing" gravity waves near the New Zealand South Island
   - Sources of non-orographic gravity waves
2) **Predictability (manuscript winter 2017):**
   - Quantify initial state sensitivity & predictability of wave launching and GWs
   - Adjoint-based tools (RF3, RF9, RF11, RF14, RF24)
   - Dropsonde impact on forecast skill
   - Meteorology of sensitive regions (dropsondes, MTP etc.)
3) **Trailing Gravity Waves (2 manuscripts):**
   - Idealized and real-data simulations of GWs and GW refraction by shear
   - Real data: RF23, RF04, RF07, RF08, RF12, RF13 (Qingfang's talk)
4) **Boundary Layer Impact on Deep GWs (Just starting):**
   - Impact of the boundary layer on stratospheric waves in DEEPWAVE
   - Preliminary results so far (sensitivity to PBL mixing length)
5) **Synoptic Overview (Led by Sonja.Gisinger)**

Background and Motivation

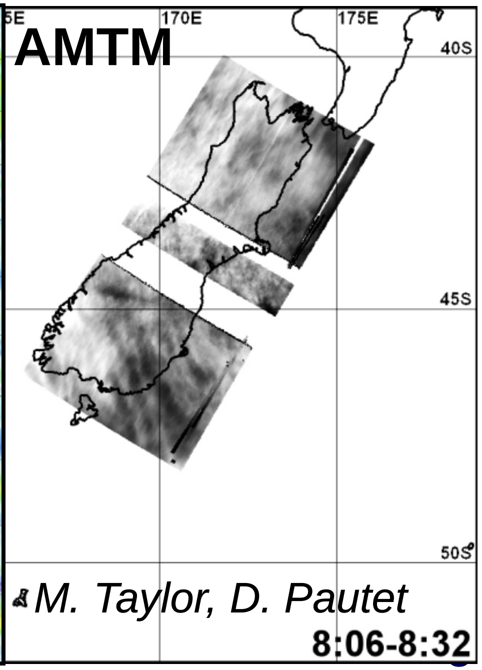
- **During DEEPWAVE, G-V & Falcon sampled gravity wave "Hot Spots"**
  - Orographic waves generated by NZ Alps, Tasmania and sub-Antarctic islands
- **Non-orographic gravity wave belt**
  - Sources from jets, fronts, precipitation?
- **"Trailing" gravity waves**
  - Source(s) from orography?



RF04



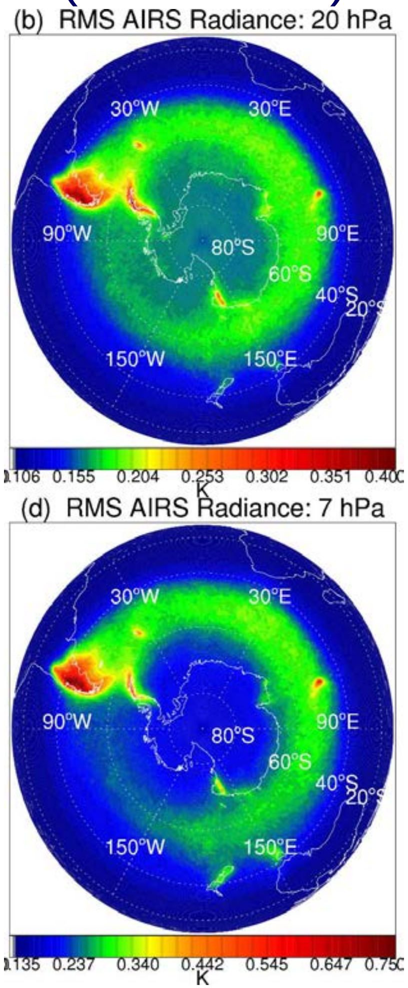
RF05



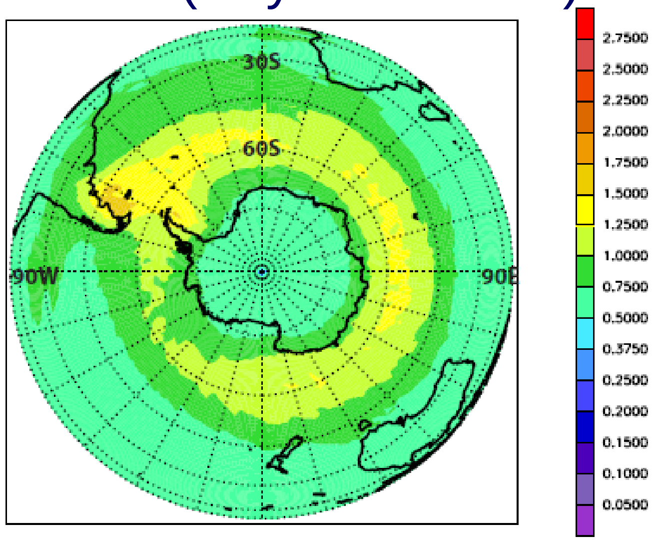
- **What are sources and characteristics of "trailing" gravity waves?**
- **What are the key source characteristics of non-orographic gravity waves during DEEPWAVE?**

Gravity Wave Sources

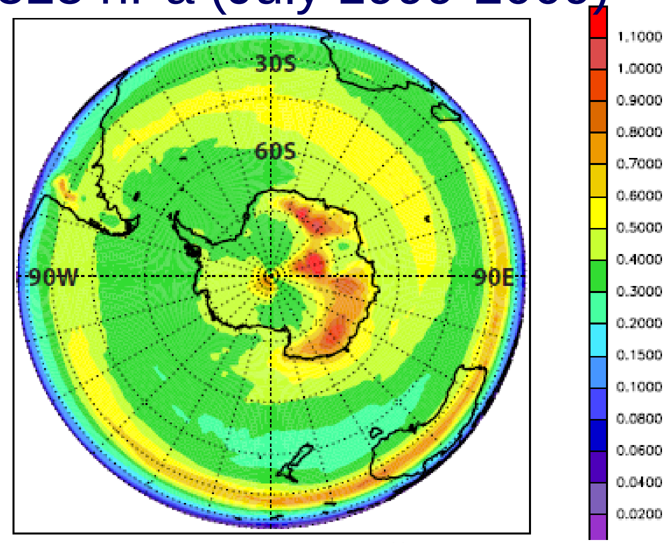
AIRS Radiances (2003-2011)



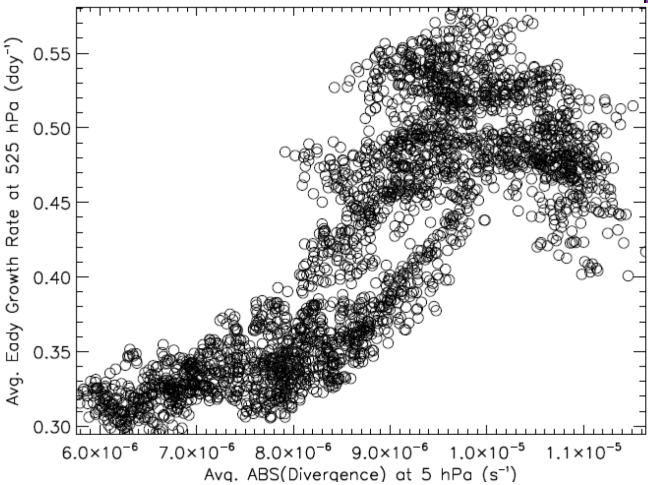
ERA divergence (10^{-5} s^{-1}) 5 hPa (July 1999-2009)



ERA Eady growth rate (day^{-1}) 525 hPa (July 1999-2009)



Correlation of the July average 5-hPa divergence with 525-hPa Eady growth rate (50-60°S)

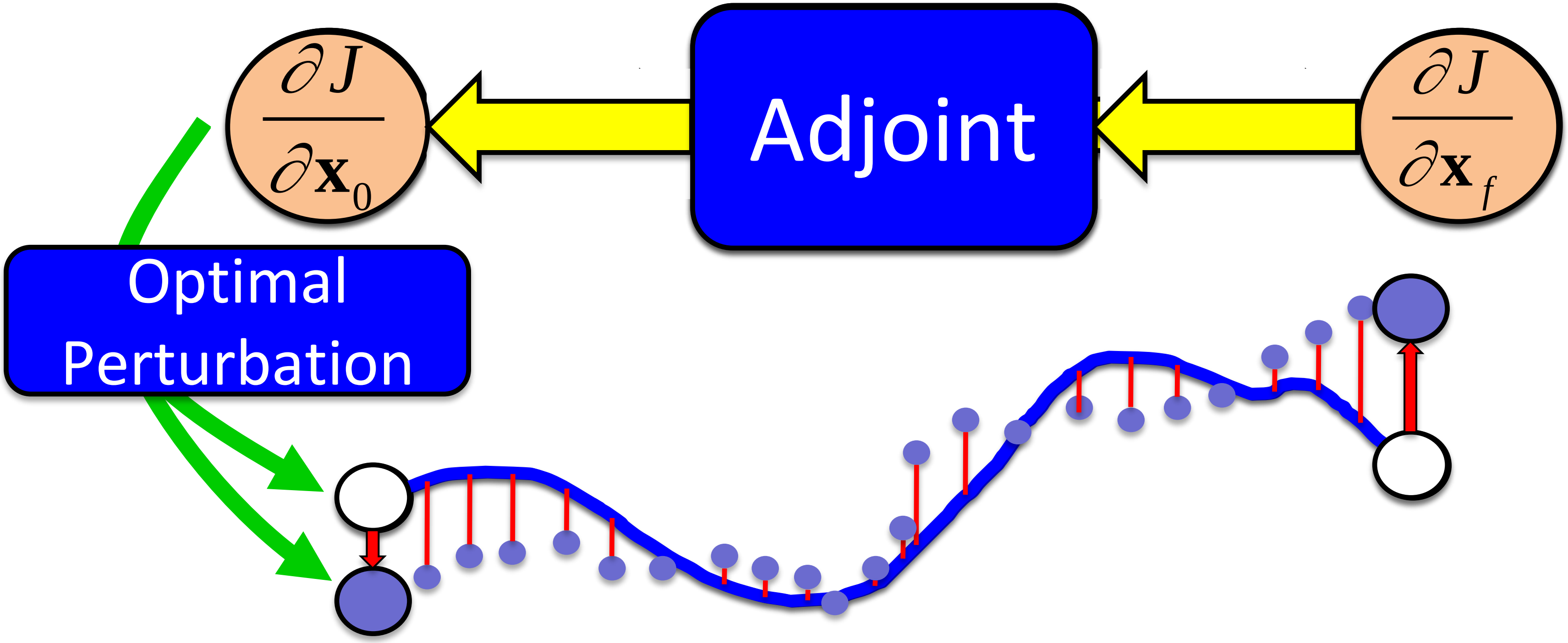


Hendricks et al. 2014 (JAS)

Eady growth rate and divergence (ECMWF reanalysis) correlation points to possible spontaneous GW emission sources from jets and baroclinic waves.

Adjoint Model

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



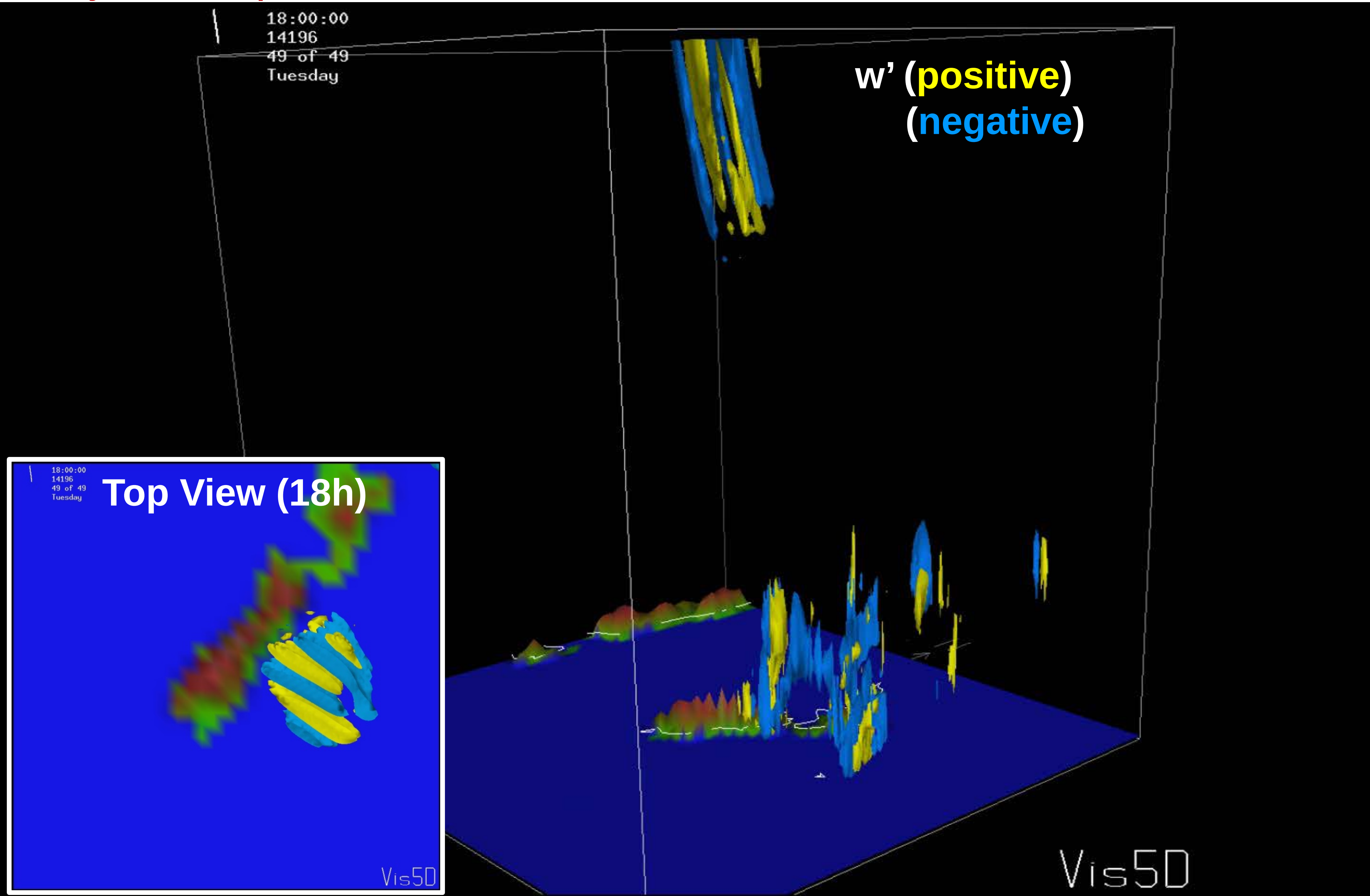
Adjoint is the transpose of the TLM, and evolves the gradient of a response function (J) with respect to $\boldsymbol{x_f}$ backward through time.

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

Adapted from Brett Hoover (UW)

Adjoint Model Example

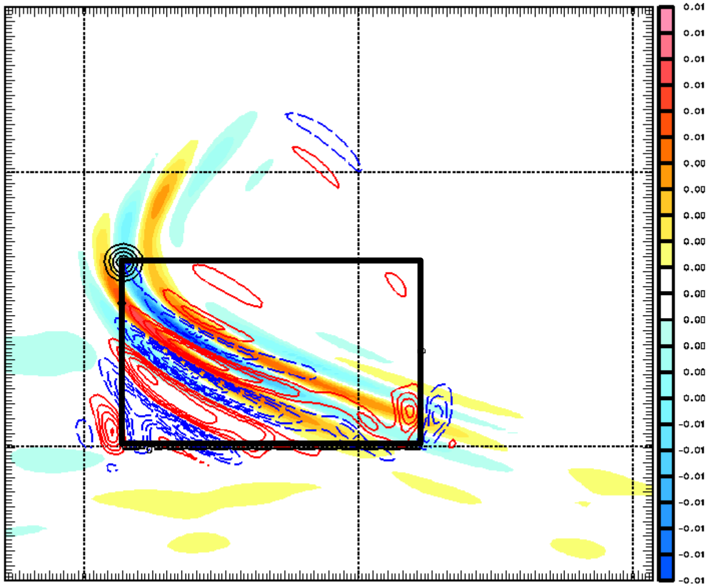
Adjoint Optimal w Perturbation: 18Z-06Z 14 Jun 2014



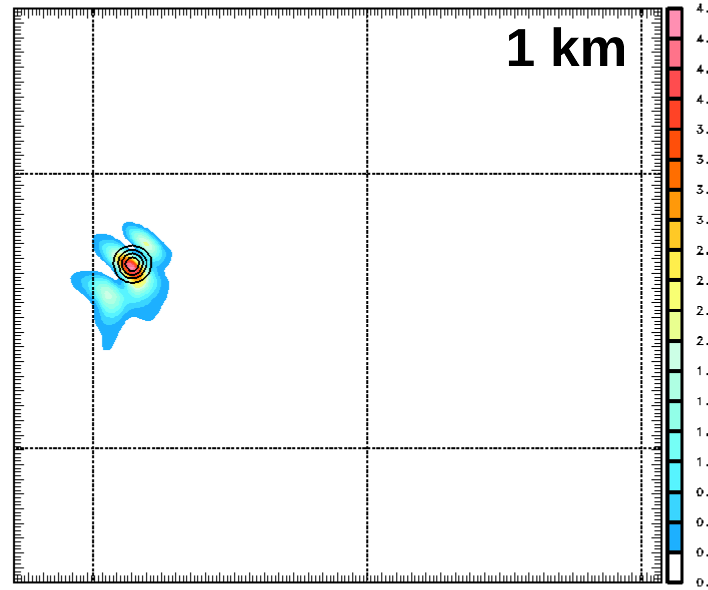
Gravity Wave Source Identification

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

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



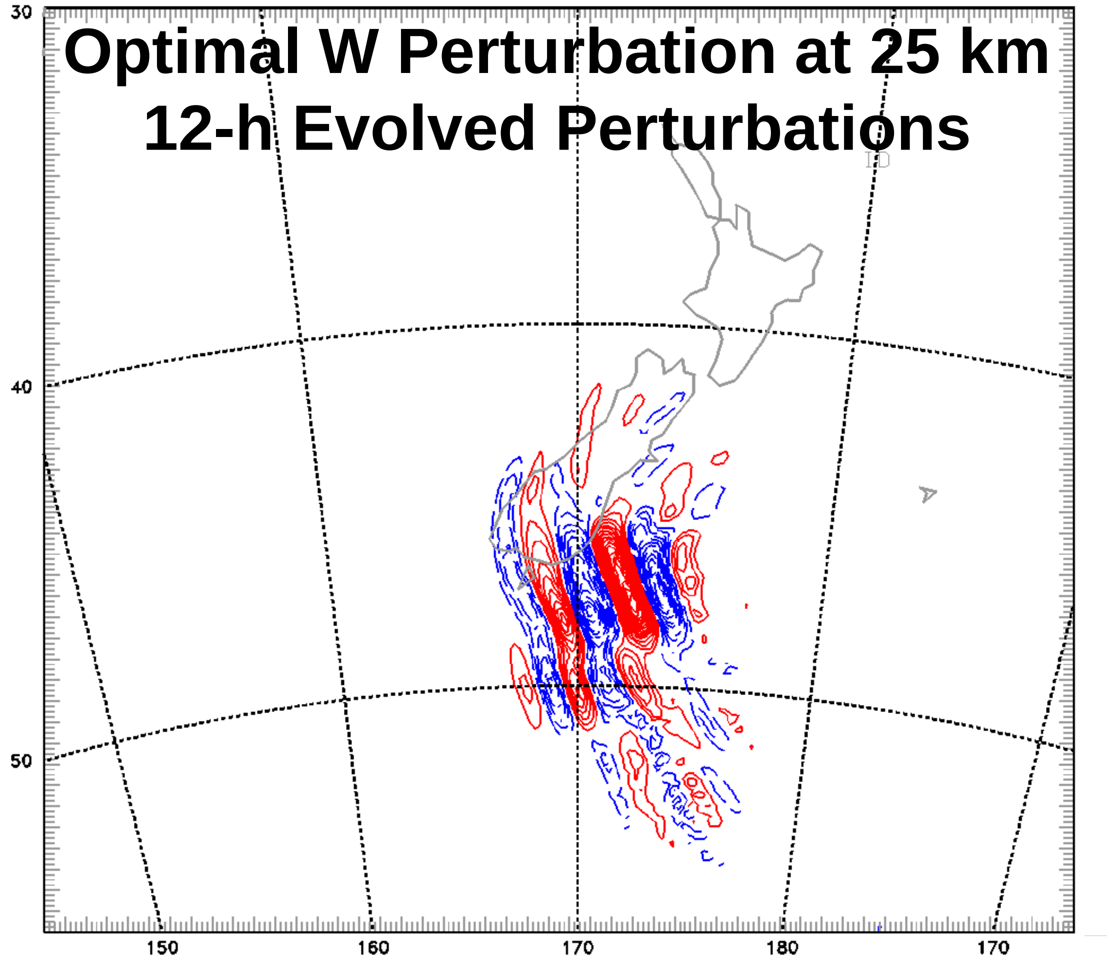
Adjoint Sensitivity (15 h)
Kinetic Energy



- 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)

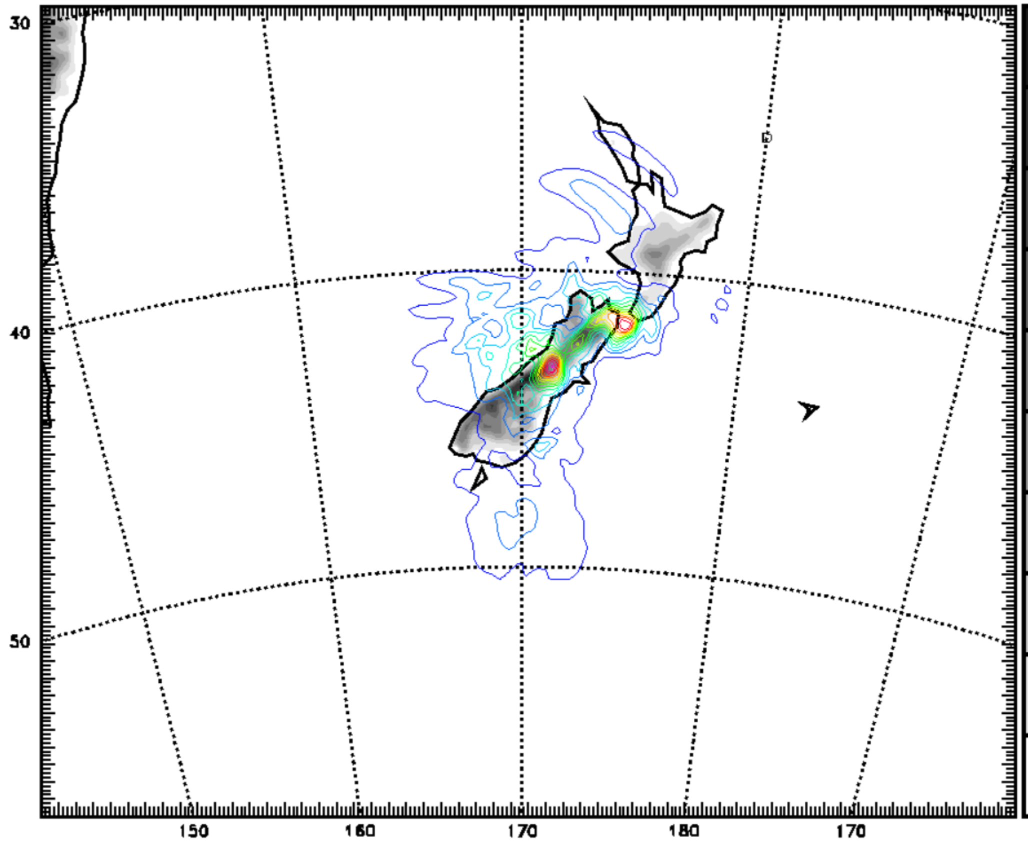


- Adjoint identifies most sensitive portion of the Alps for wave launching
- Trailing waves located to S of NZ are launched from S. Alps (south of Cook)
- Excitation of waves by non-orographic sources for detached trailing GWs

Gravity Wave Source Identification

Trailing Waves in IOP 6 (RF07)

COAMPS Adjoint (KE); 0000 UTC 19 June (12 h)

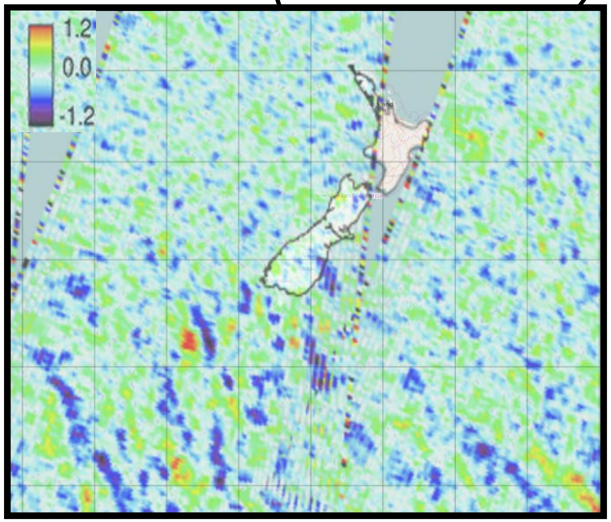


- Adjoint identifies most sensitive portion of the S. Alps for wave launching
- Trailing waves located to S of NZ are launched from S. Alps (south of Cook).

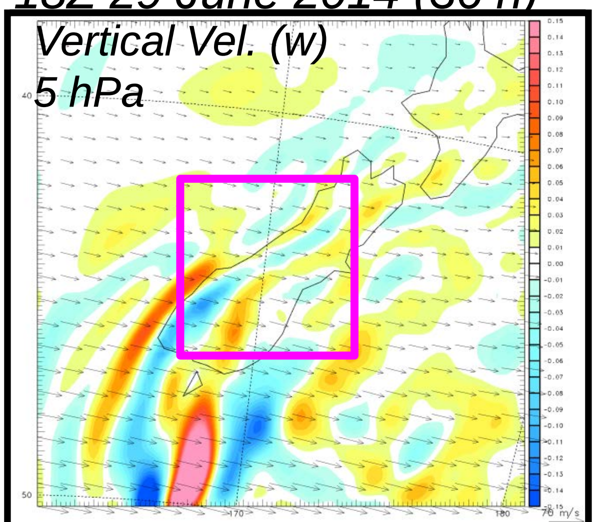
Predictability of Deep Propagating GWs

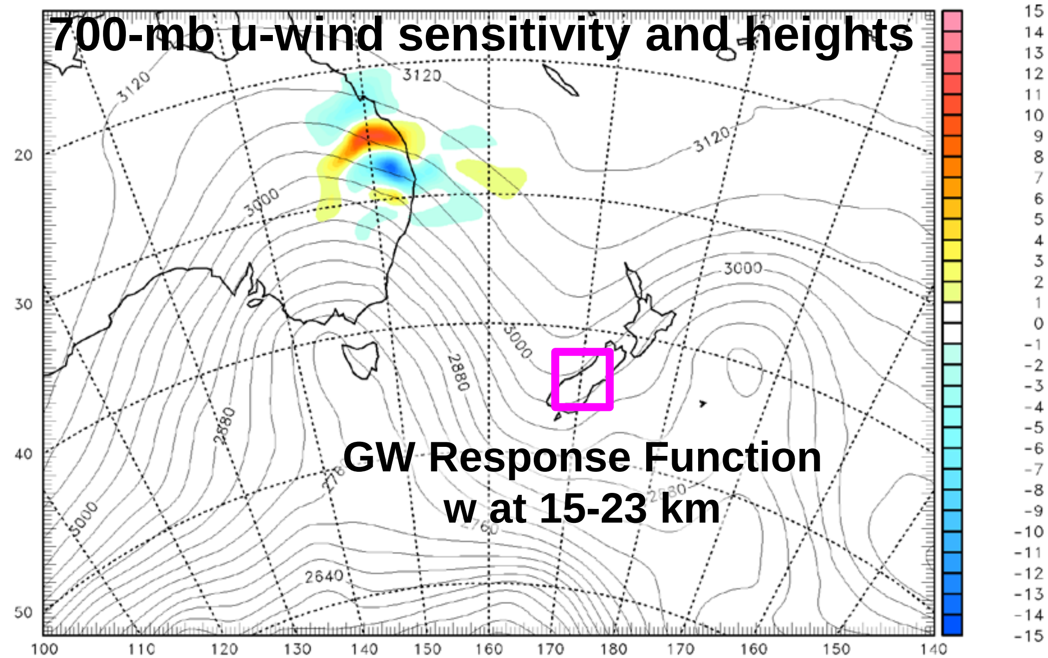
What are the predictability characteristics of deep propagating GWs?

AIRS 3 hPa (29 June 2014)



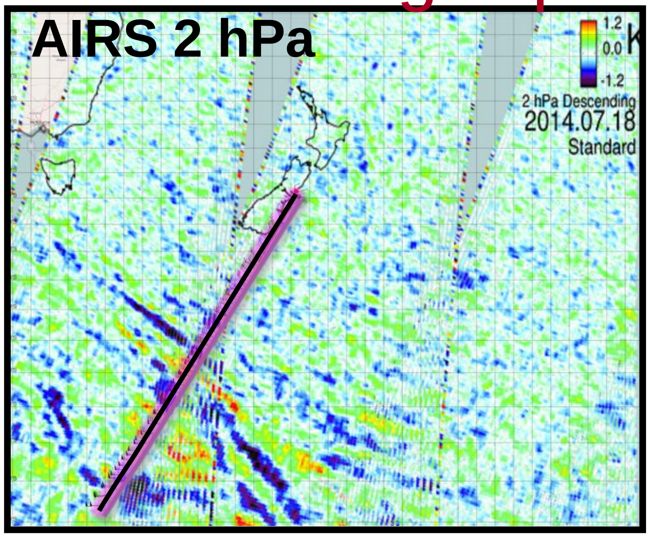
18Z 29 June 2014 (36 h)

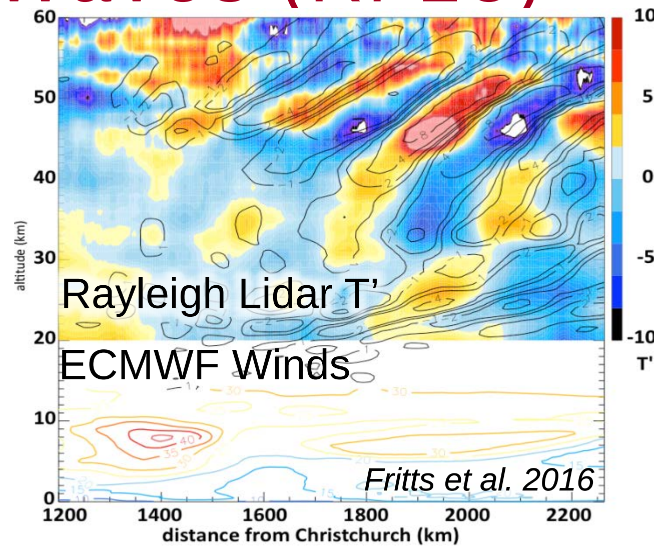




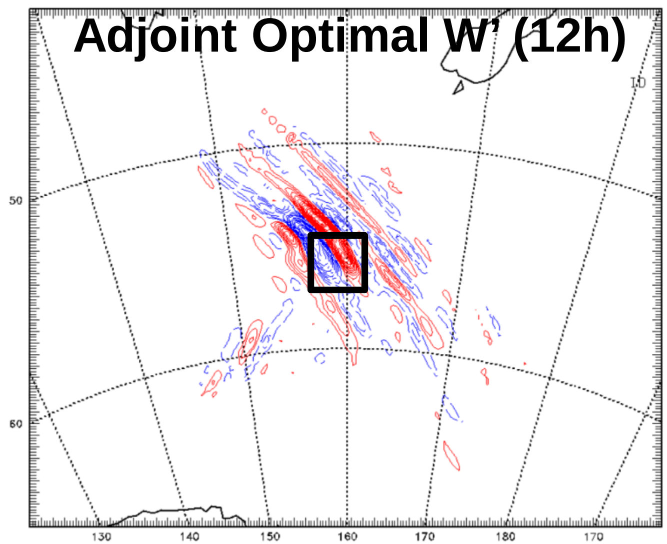
- Adjoint is used to diagnose sensitivity using a kinetic energy response function (lowest 1 km)
- Sensitivity located ~1200 km upstream near trough
- Adjoint optimal perturbations lead to strong wave propagation (refracted waves south of NZ)

Gravity Wave Source Identification
Non-Orographic Waves (RF25)

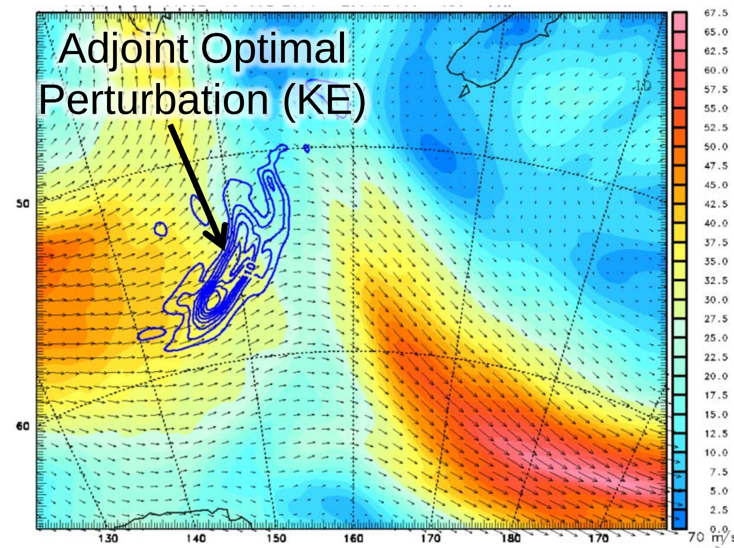




20-hPa Vertical Velocity



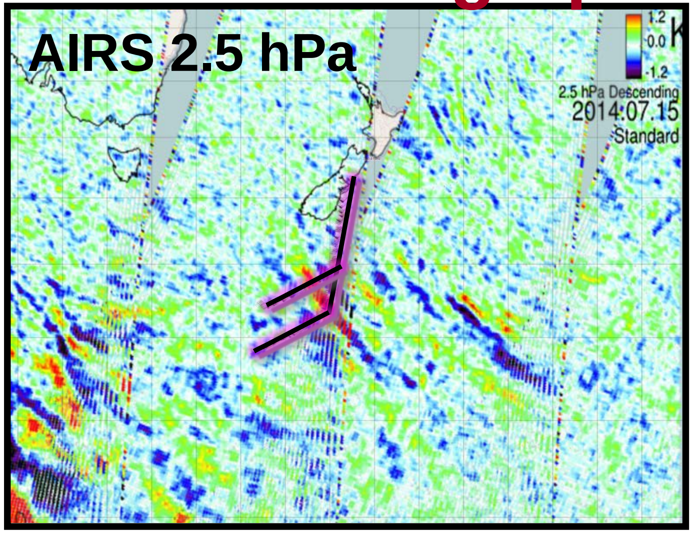
250-hPa Winds

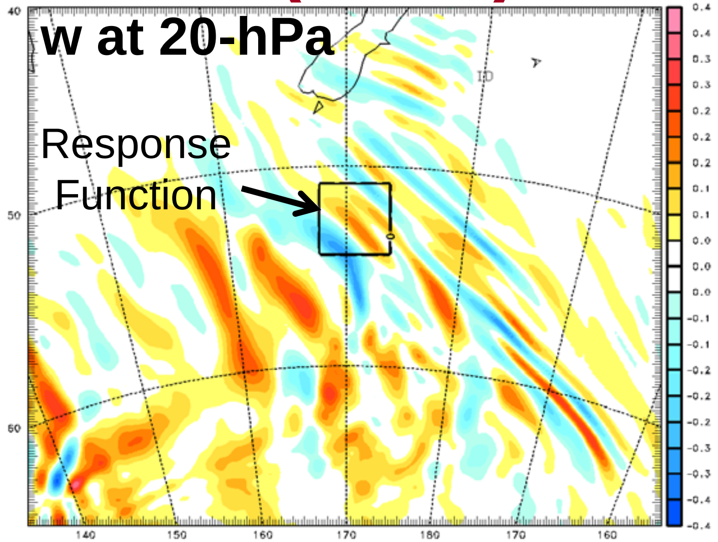


- Adjoint identifies exit region of jet as likely source
- GWs excited by decelerations in high-amplitude pattern.

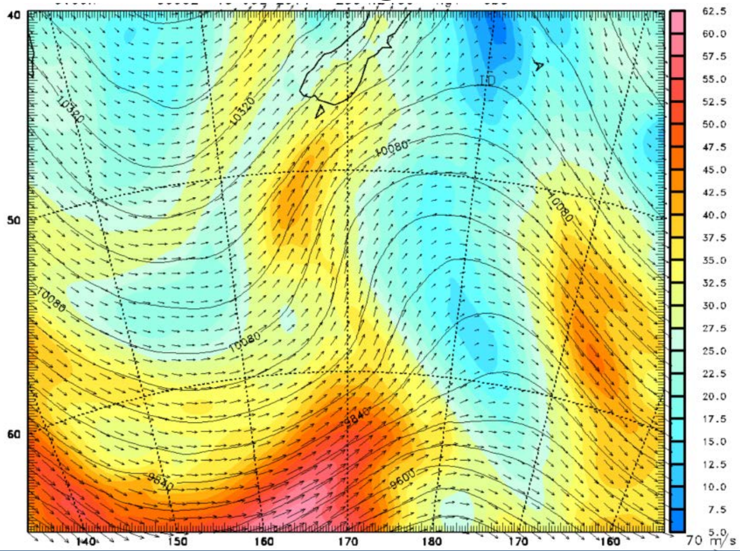
Gravity Wave Source Identification

Non-Orographic Waves (RF24)

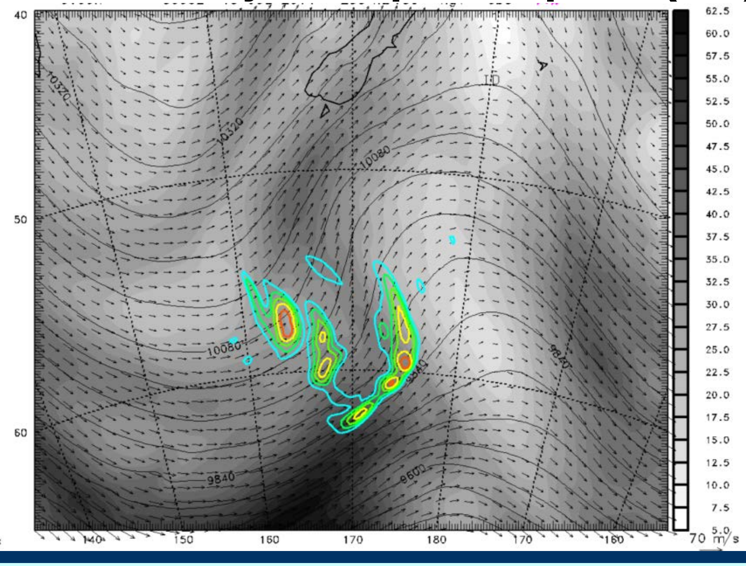




250-hPa heights, winds



250-hPa adjoint optimal pert. (KE)



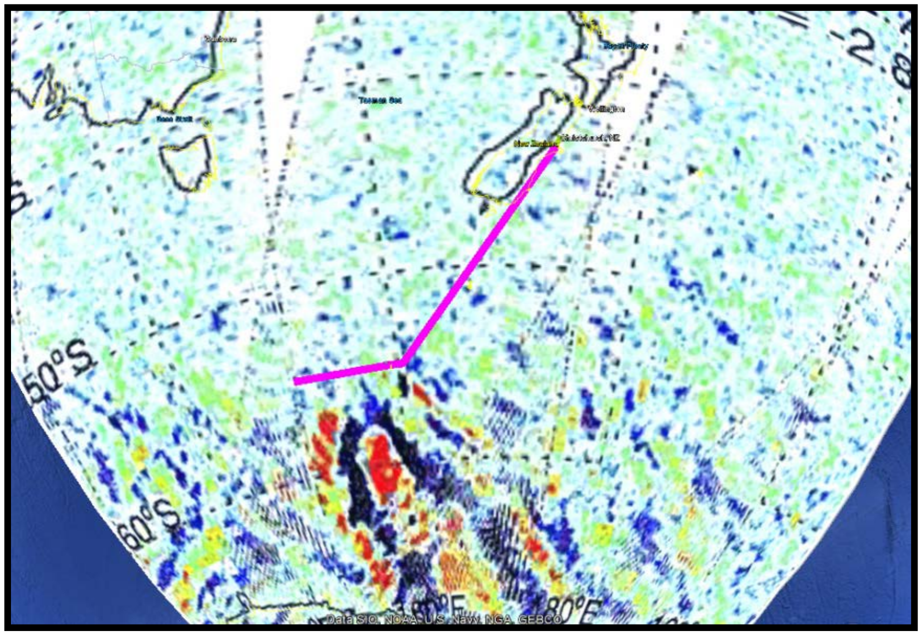
- Adjoint identifies left exit region of jet as possible source
- GWs excited by decelerations in high-amplitude pattern.

Gravity Wave Source Identification

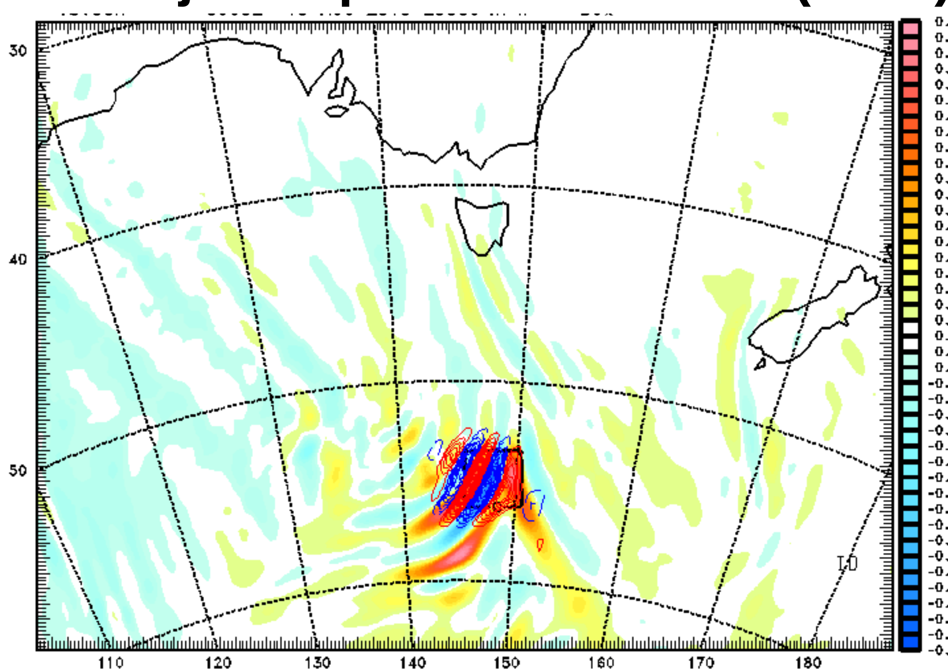
Non-Orographic Waves

pre-DEEPWAVE case; 14-15 August 2013

AIRS 4 hPa



18-h w at 25 km (m s^{-1})
18-h adjoint optimal w at 25 km (m s^{-1})



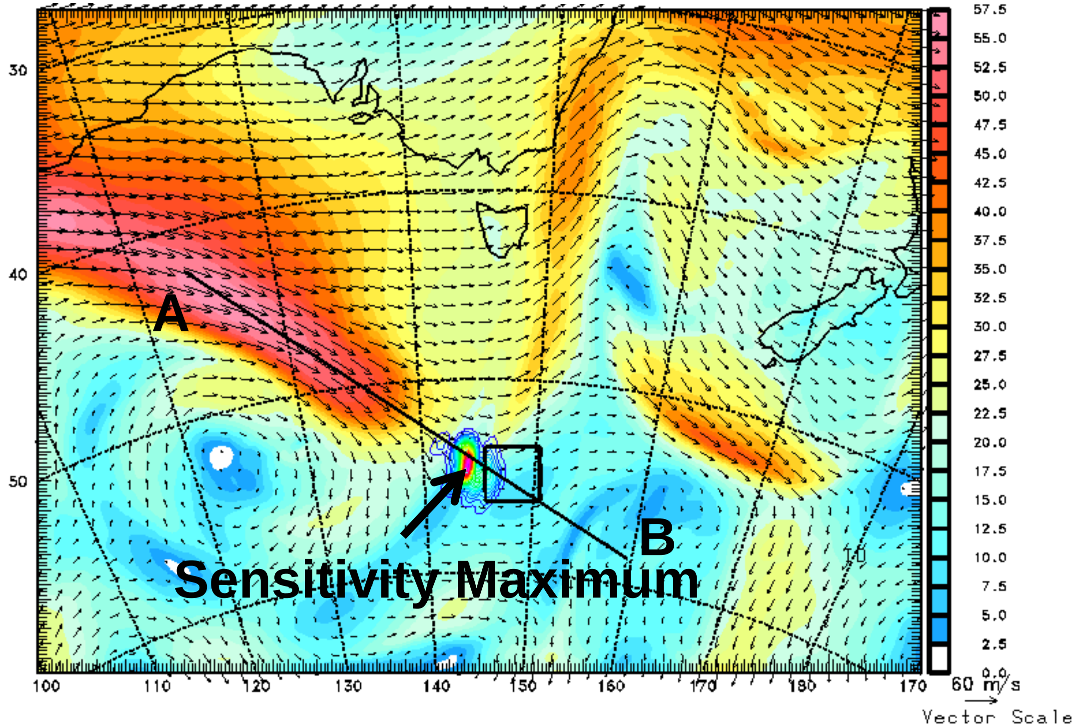
- Gravity waves observed by AIRS located well to the south of New Zealand and in a region with no topography.
- Adjoint optimal perturbation project on to the gravity wave packet generated by the exit region of the jet and precipitation processes.

Gravity Wave Source Identification

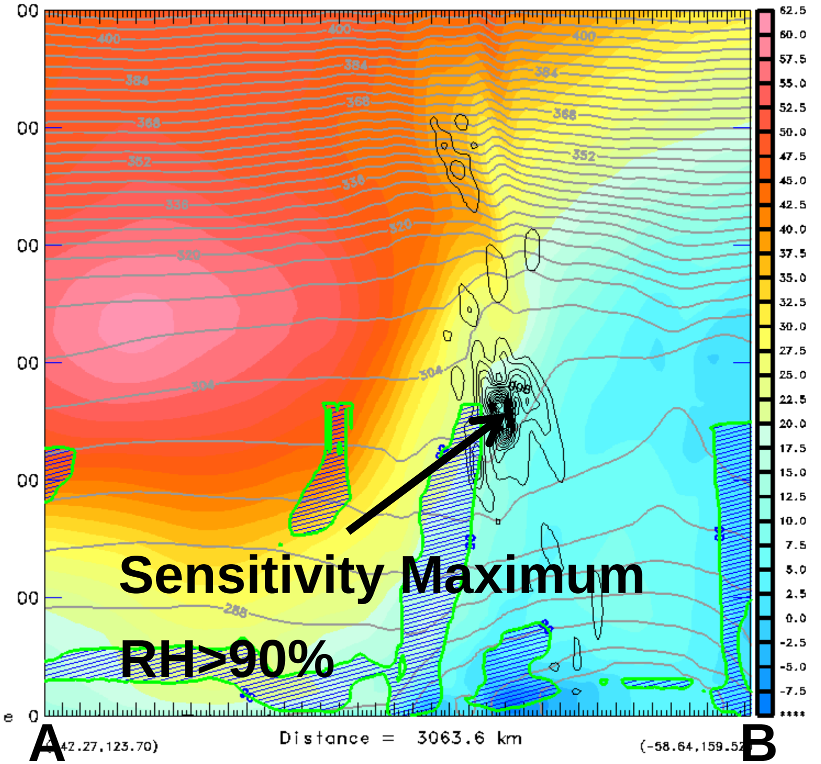
Non-Orographic Waves

pre-DEEPWAVE case; 14-15 August 2013

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



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



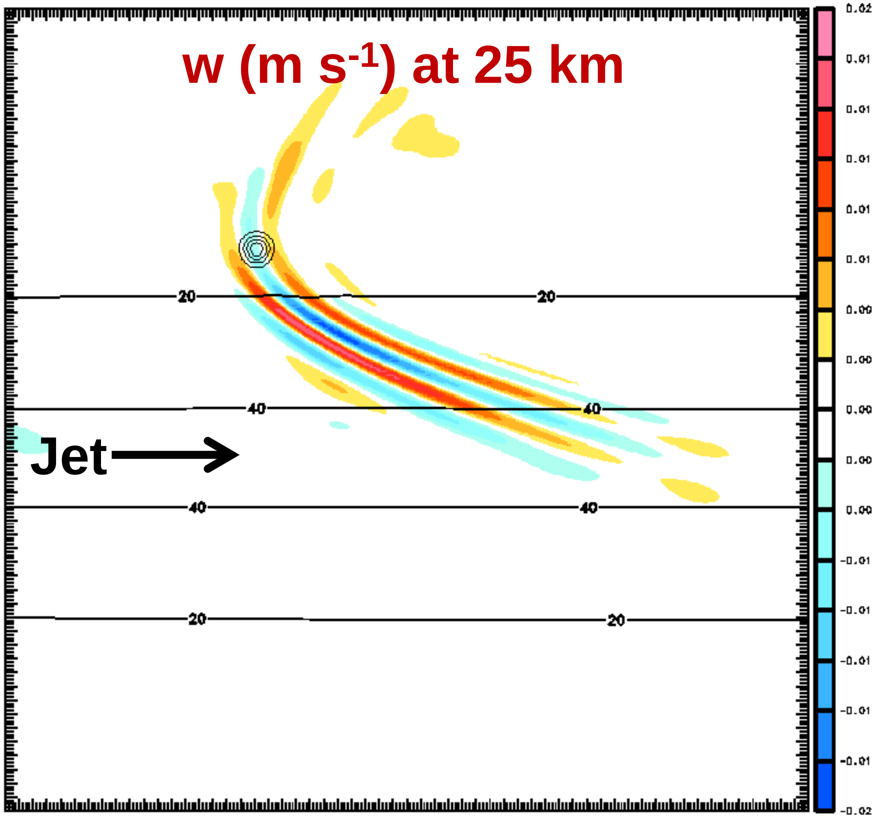
Sensitivity maximum is locations upstream of the response function near the exit region of a very strong jet and near 7 km near the top of a region of saturated rising motion (e.g., grid scale precipitation).

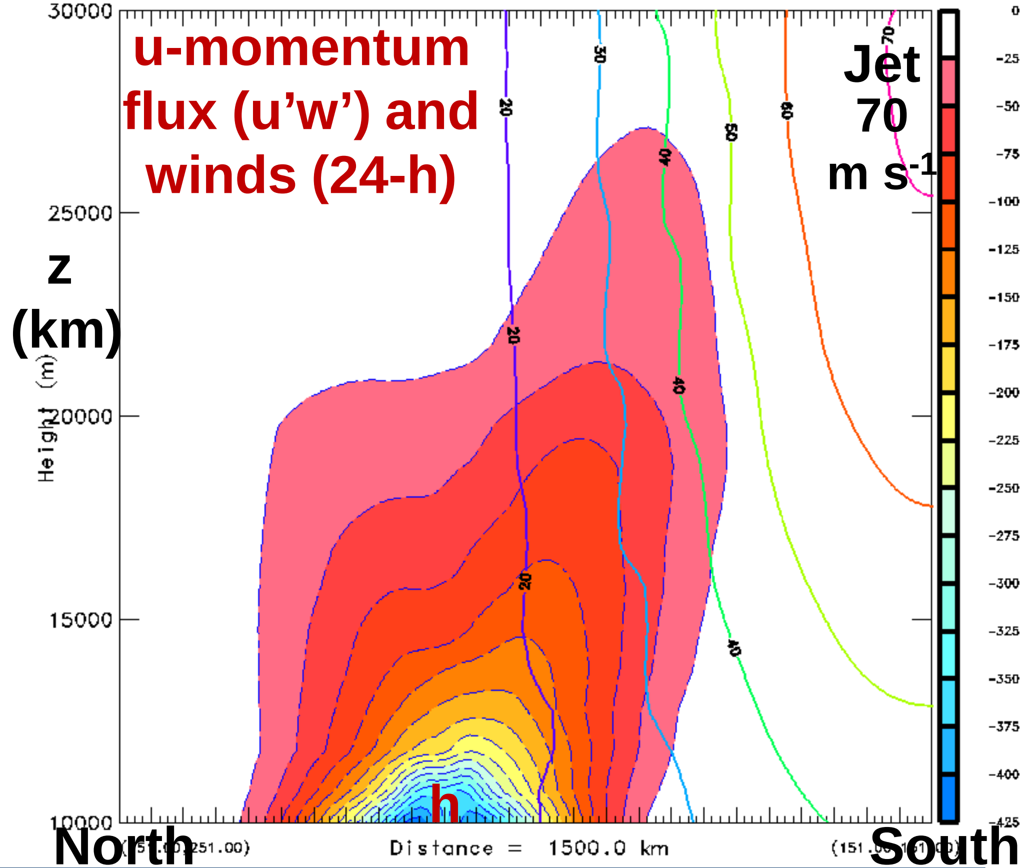
Summary

- **Adjoint is used to identify gravity wave sources**
  - Utilizes time dependent non-linear trajectory
  - Includes key physics (moisture, key diabatic processes, boundary layer)
- **New Zealand “Trailing” Gravity Wave Sources**
  - Generated by S. Island Alps ridge and high peaks (Cook, Aspiring…)
  - Gravity wave refracted due to lateral shear from the SH polar jet
- **Non-Orographic Gravity Wave Sources**
  - Sources associated with jet exit regions, fronts and precipitation
  - Non-orographic gravity waves propagate to high altitudes as observed during DEEPWAVE

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