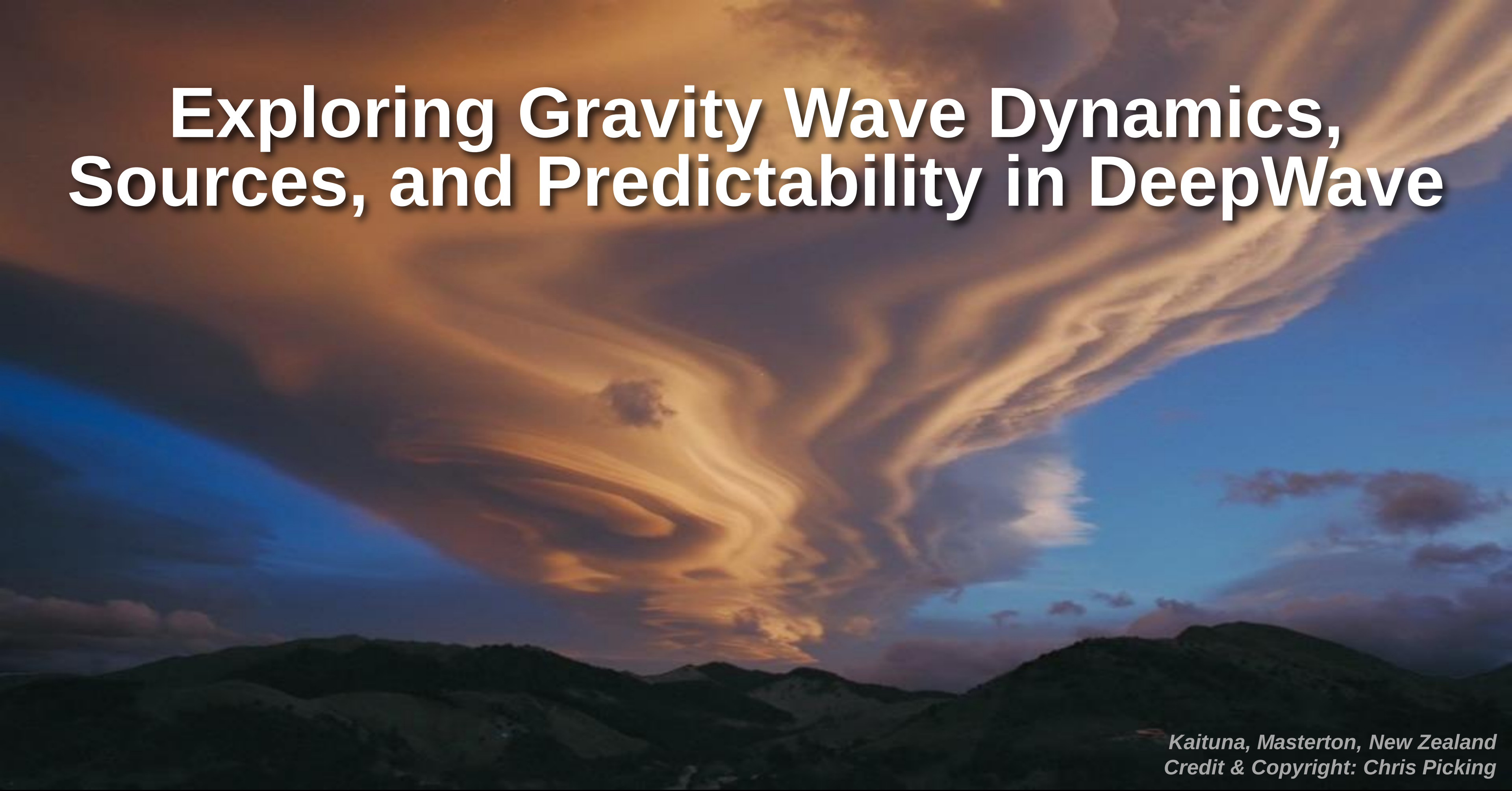
Exploring Gravity Wave Dynamics, Sources, and Predictability in DeepWave



Kaituna, Masterton, New Zealand
Credit & Copyright: Chris Picking

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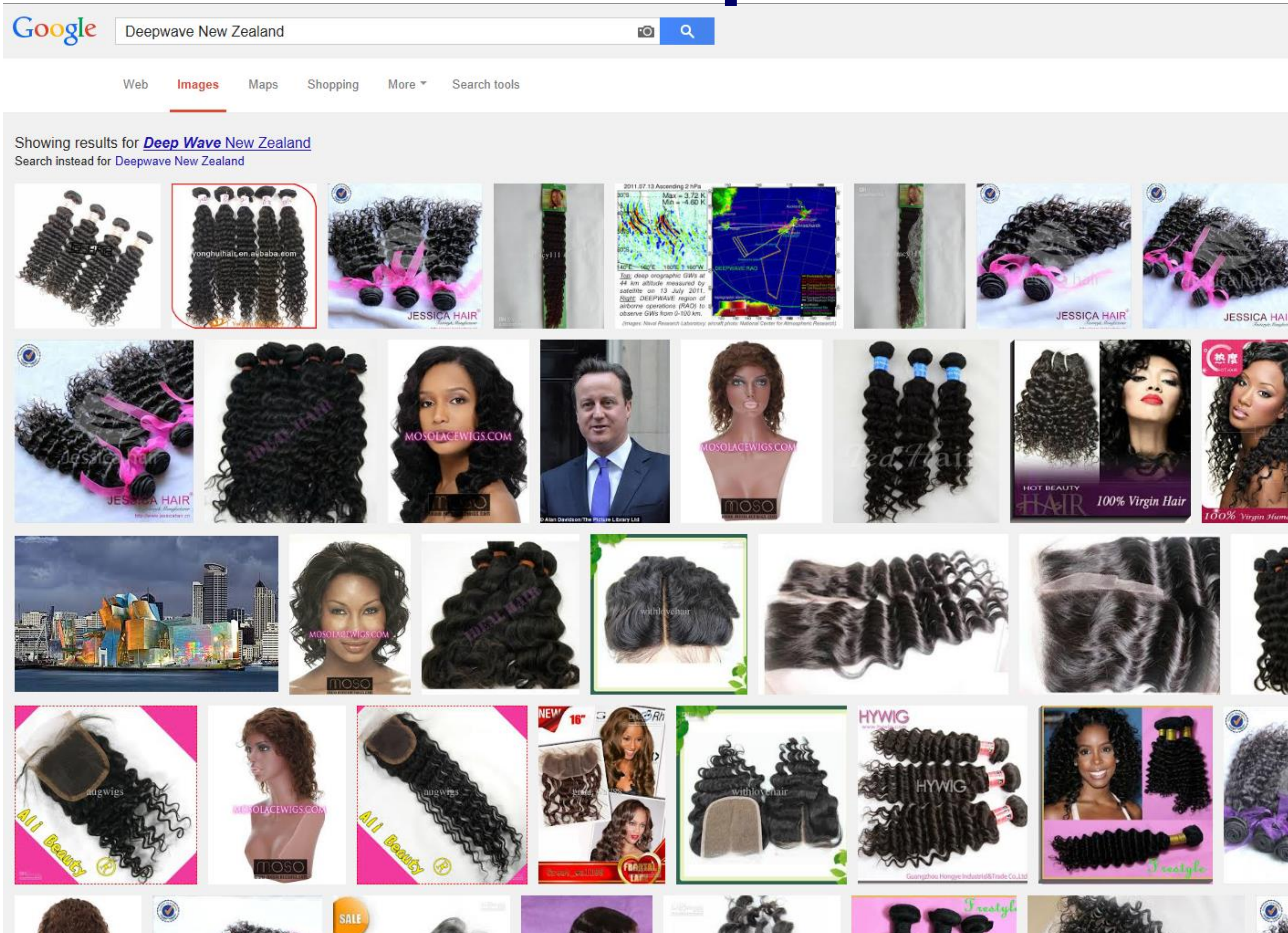
Acknowledgements: NSF, NRL, NCAR, DeepWave Team

Outline

- Introduction
- Climatological Perspective
- Modeling of Gravity Wave Dynamics
- Predictability
- Gravity Wave Sources

What is DeepWave?



NRL-Monterey DeepWave Objectives

Dynamics, Sources, Predictability

- **NRL-MRY DeepWave Objectives:**
  - **Dynamics:**
    - **Influence of horizontal and vertical shear on gravity waves**
    - **Characterizing gravity wave sources (mountains, jet stream, convection etc.)**
    - **Tropopause effects (stability jump and shear)**
    - **Gravity wave characteristics (momentum flux, energy flux, launching conditions)**
  - **Modeling Issues:**
    - **Gravity wave drag parameterizations (especially non-local parameterizations)**
    - **Verification of explicit gravity wave simulations (and breaking)**
  - **Predictability:**
    - **Quantify initial condition sensitivity and predictability of wave launching and deep propagating gravity waves using ensemble and adjoint approaches**
    - **Links between stratospheric gravity wave predictability and tropospheric storms**
- **Facilities**
  - NCAR GV: in situ, dropwindsondes (data assim., predict.), remote sensing
  - DLR Falcon: in situ, wind lidar
  - ISS: characterization of upstream conditions (predictability)
  - Satellite observations (e.g., AIRS), conventional radiosondes, surface obs

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- Predictability of Gravity Waves
- Gravity Wave Sources

Questions

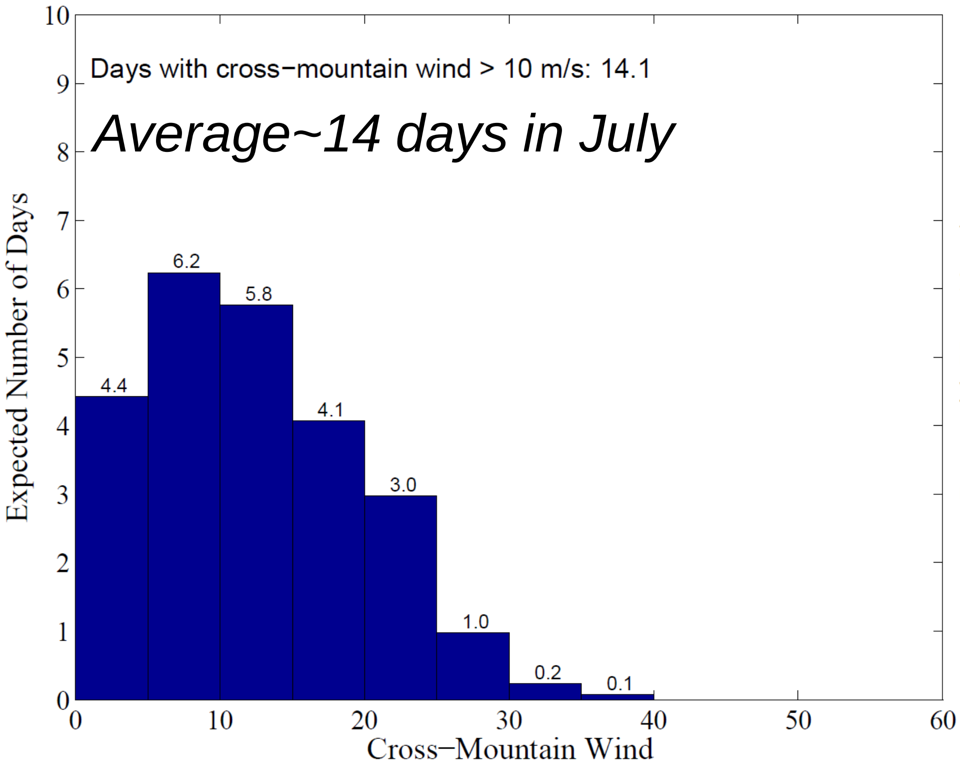
- What is the frequency of moderate and strong wave launching events over the New Zealand Alps
- What are the mean wave launching conditions?
- How frequent is turbulence over NZ?

Deep GW Propagation over New Zealand

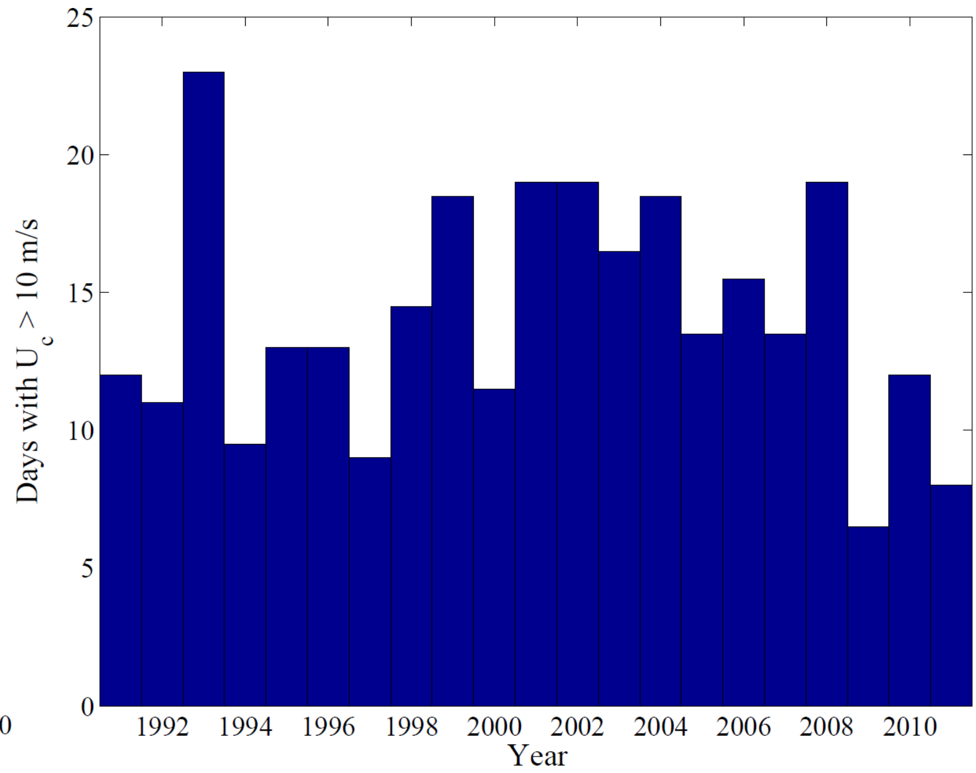
ECMWF Interim Reanalysis (July 1991-2011)

Moderate Wave Launching Conditions (U_c>10 m s^{-1})

Distribution of Cross Mtn. Winds
Invercargill, New Zealand



Frequency of 700 hPa U_c>10 m s^{-1}
Invercargill, New Zealand

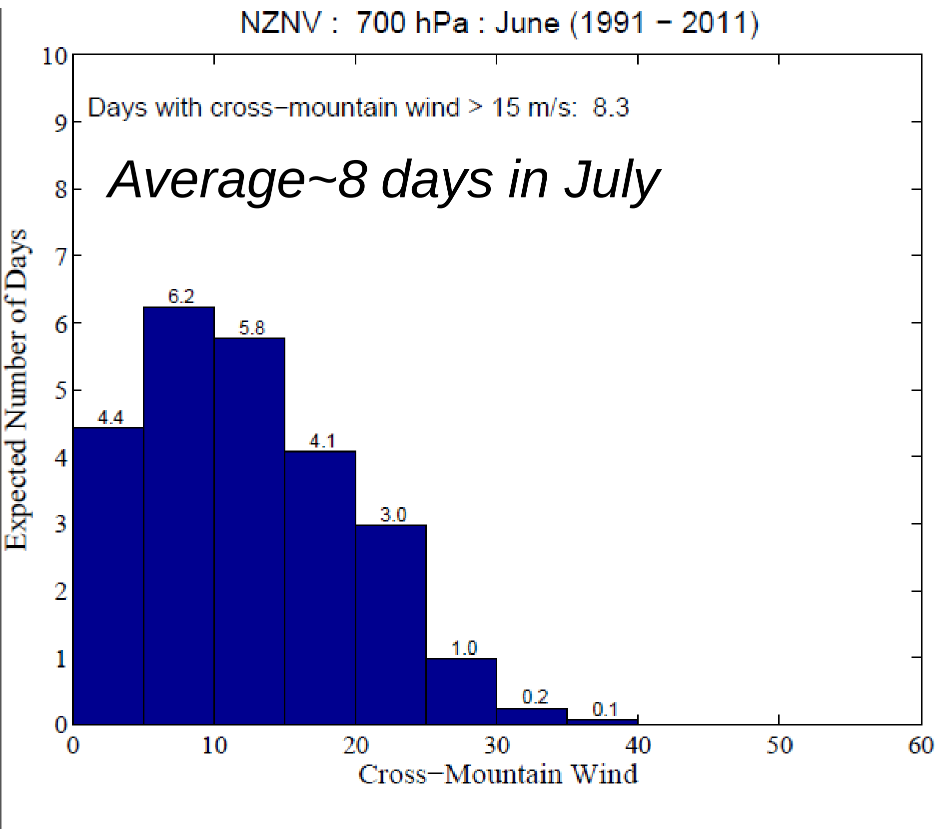


Moderate wave launching conditions (U_c>10 m s^{-1}) are quite common, with approximately 14 days/July expected (every other day could be an IOP).

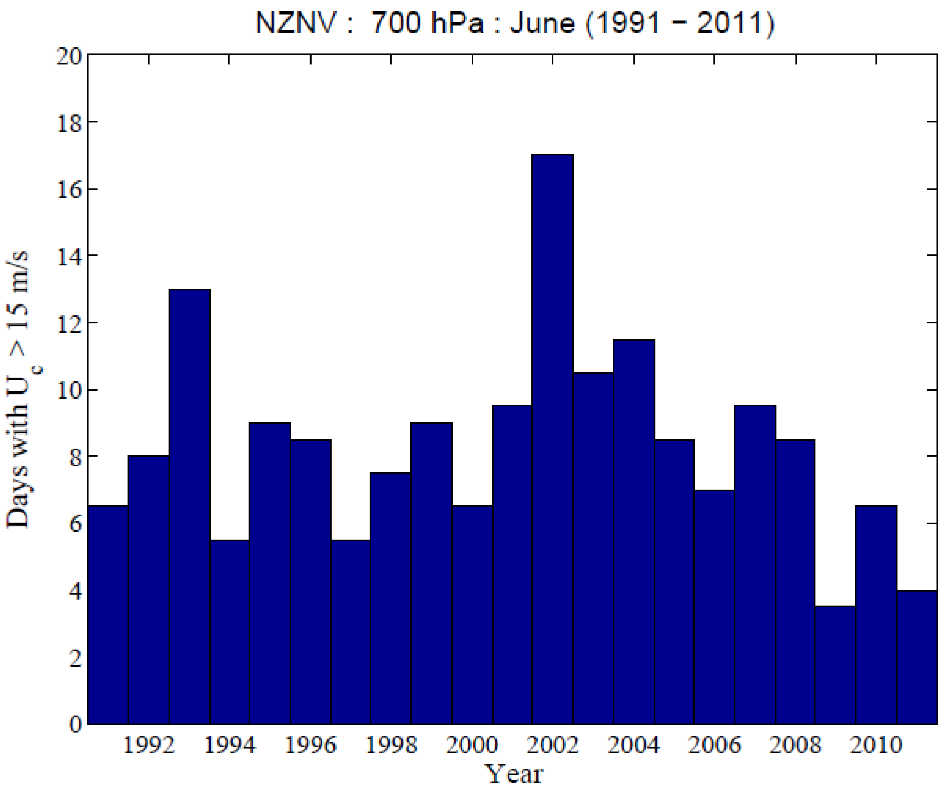
Deep GW Propagation over New Zealand

ECMWF Interim Reanalysis (July 1991-2011)
Strong Wave Launching Conditions (U_c>15 m s^{-1})

Distribution of Cross Mtn. Winds Invercargill, New Zealand



Frequency of 700 hPa U_c>15 m s^{-1} Invercargill, New Zealand

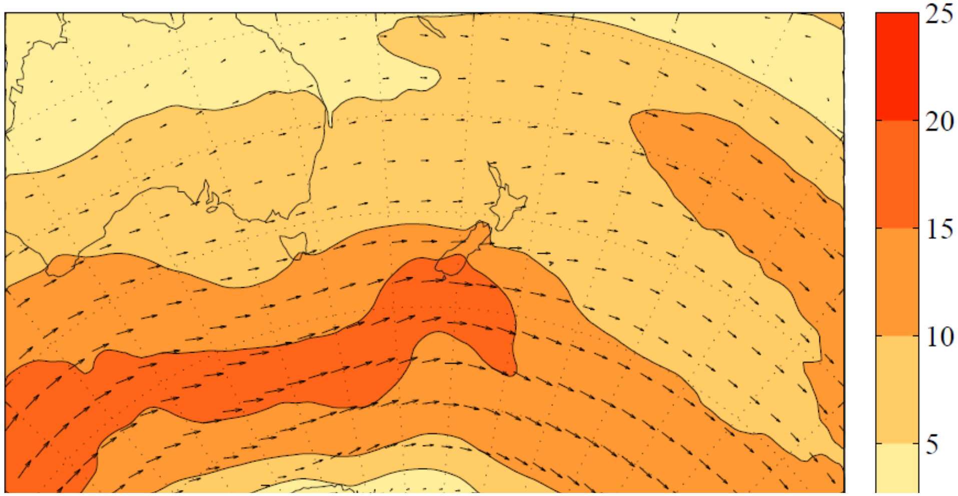


Strong wave launching (U_c>15 m s^{-1}) conditions are quite common, with approximately 8 days/July expected for intense events.

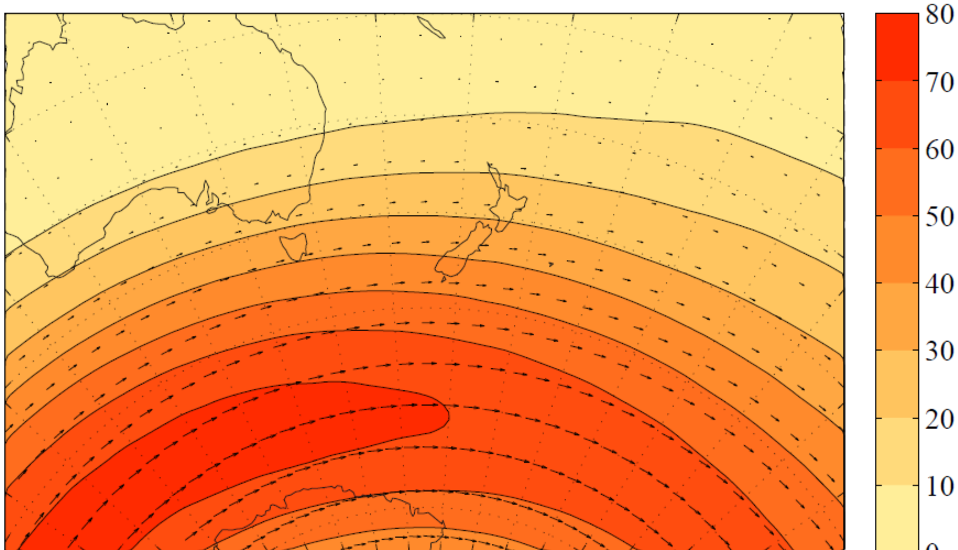
Deep GW Propagation over New Zealand

ERA Reanalysis (June-July 1991-2011): Event Composite

June−July 700 hPa composite wind speed
Given that NZNV 700−hPa U > 10 m/s



June−July 10 hPa composite wind speed
NZNV 700−hPa U > 10 m/s

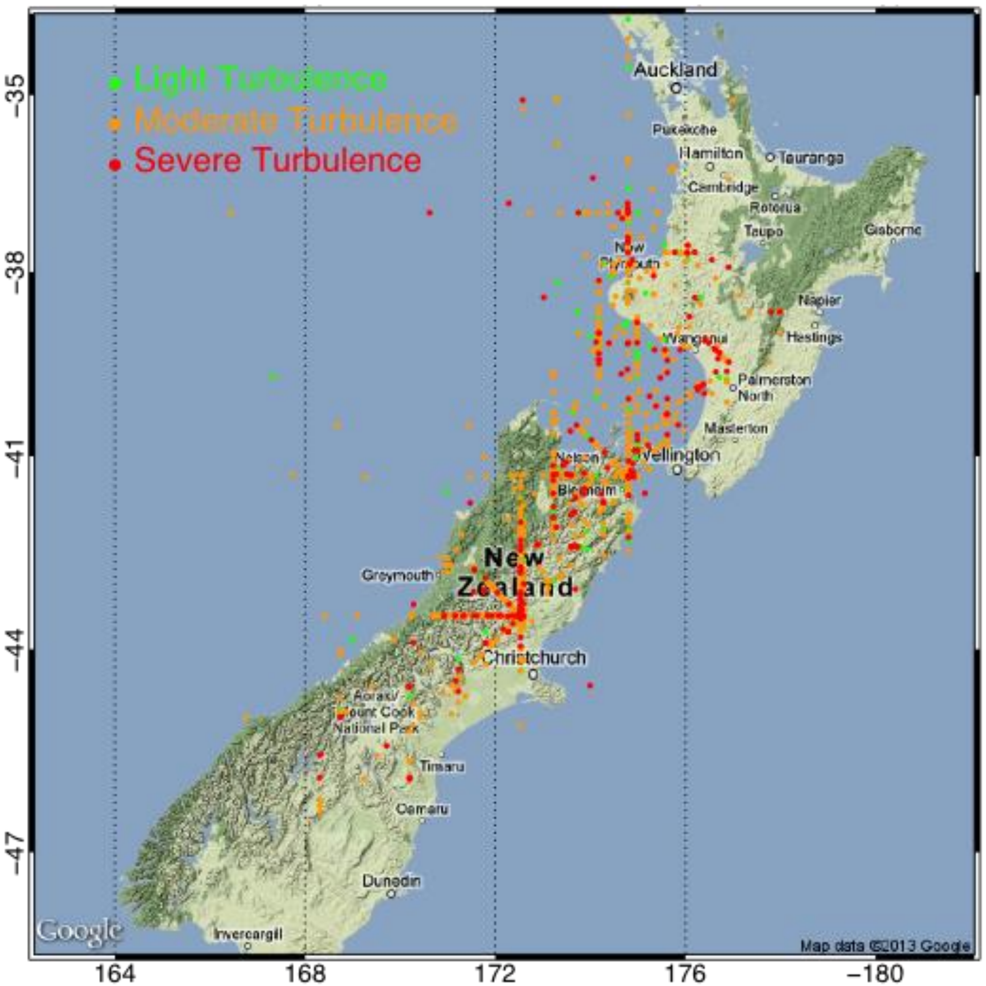


Wave launching conditions (U_c>10 m s^{-1}) composite show:

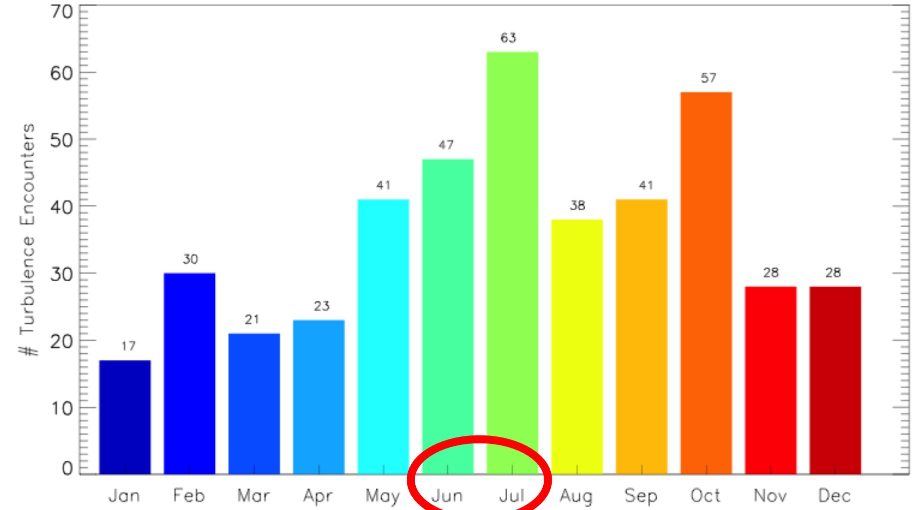
- Strong 700-hPa low-level jet.
- Strong westerlies aloft up through 10 hPa to allow deep propagation.
- Wind speed gradient at 10 hPa near S. Island; possibility of critical level filtering in some events if winds are weaker aloft.

DeepWave Region and Turbulence

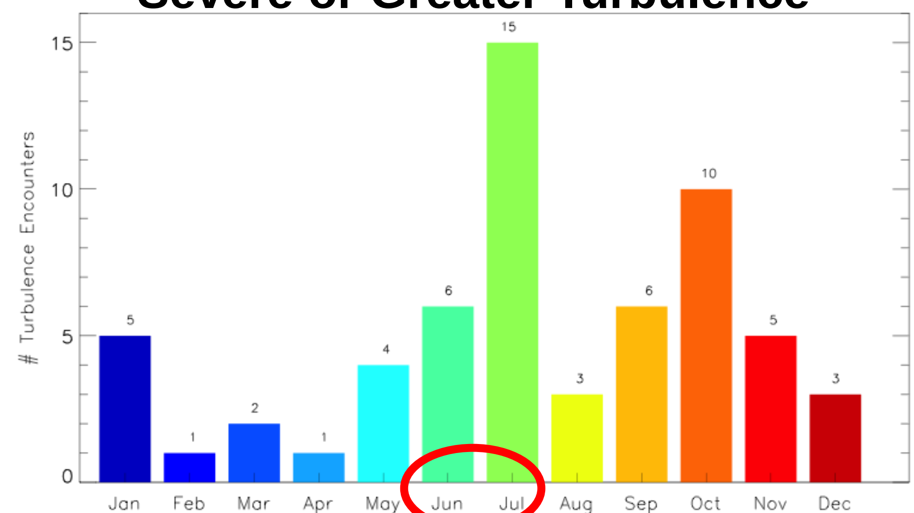
Distribution of PIREPS



Moderate or Greater Turbulence



Severe or Greater Turbulence



MoG and SoG turbulence encounters occur most frequently in July (DeepWave field campaign), with a second maximum in spring.

Courtesy of NZ MetService, Todd Lane, Steve Eckermann, Kate Zawdie

Outline

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- Predictability of Gravity Waves
- Gravity Wave Sources

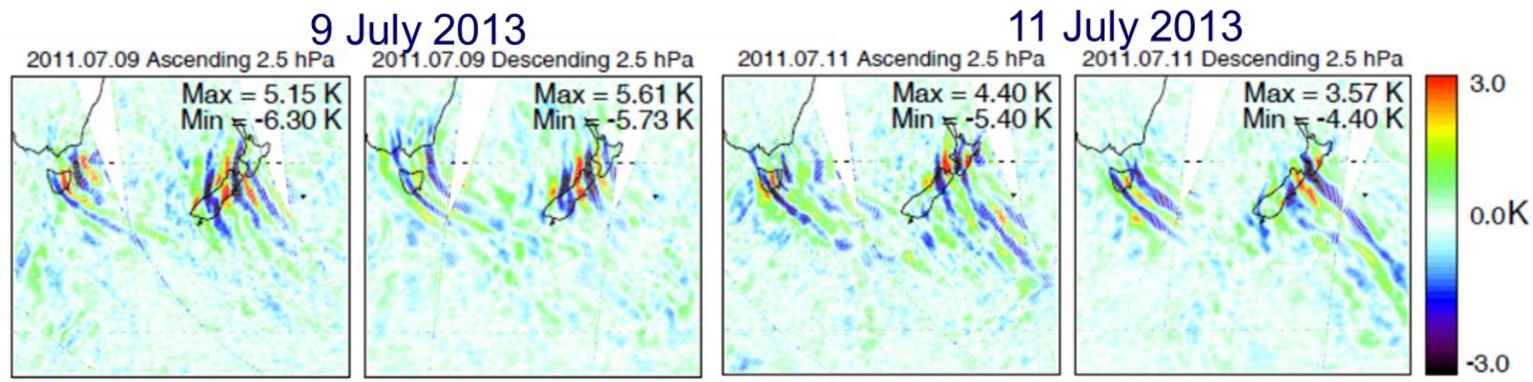
Questions

- What are the characteristics of tropospheric and stratospheric gravity waves? What are the scales?
- How does horizontal shear impact stratospheric gravity waves?

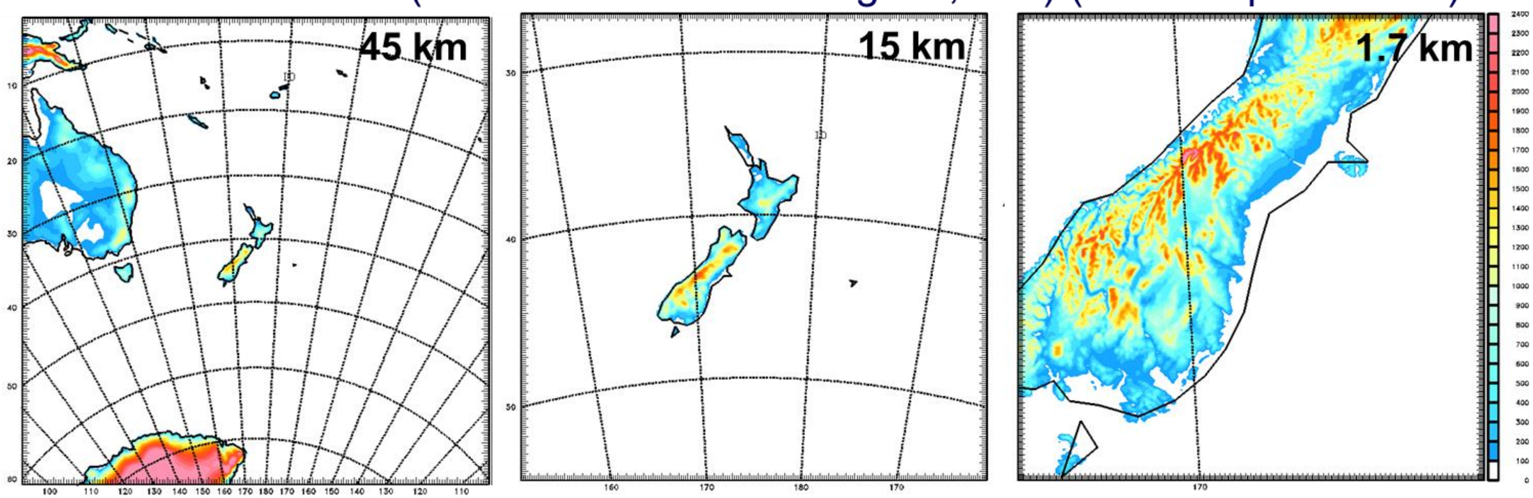
COAMPS Case Study of a NZ GW Event

Exploration of the Impact of Horizontal Resolution

AIRS Radiances at 2.5 hPa (~40 km)

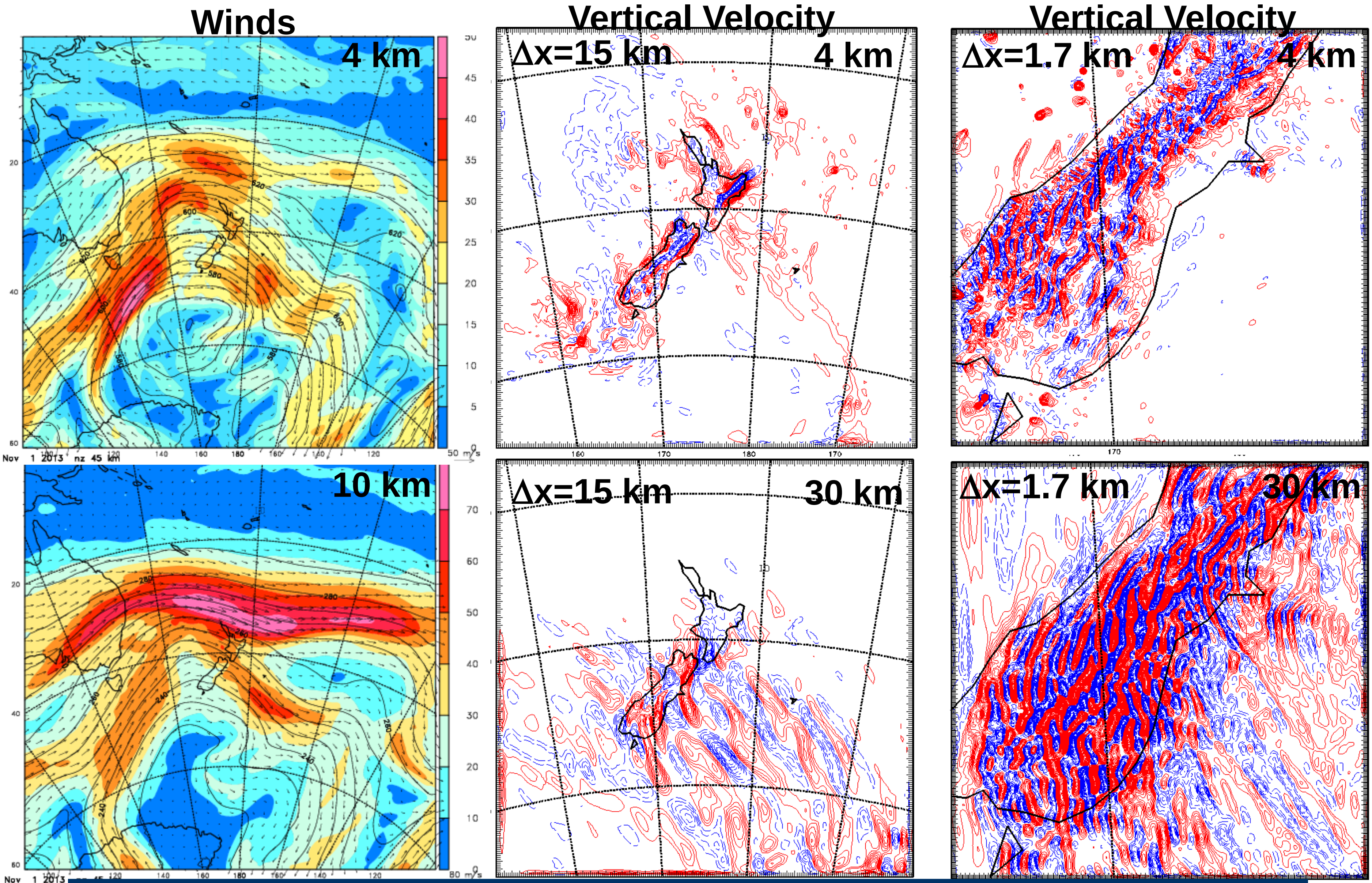


COAMPS Terrain (45/15/5/1.7 km nested grids, 80L) (Model top at 45 km)



- Navy's nonhydrostatic model, COAMPS, is used to examine the sensitivity of gravity wave characteristics to horizontal resolution
- Event is from an active period July 9-11, 2011, as diagnosed from AIRS

COAMPS Case Study of a NZ GW Event

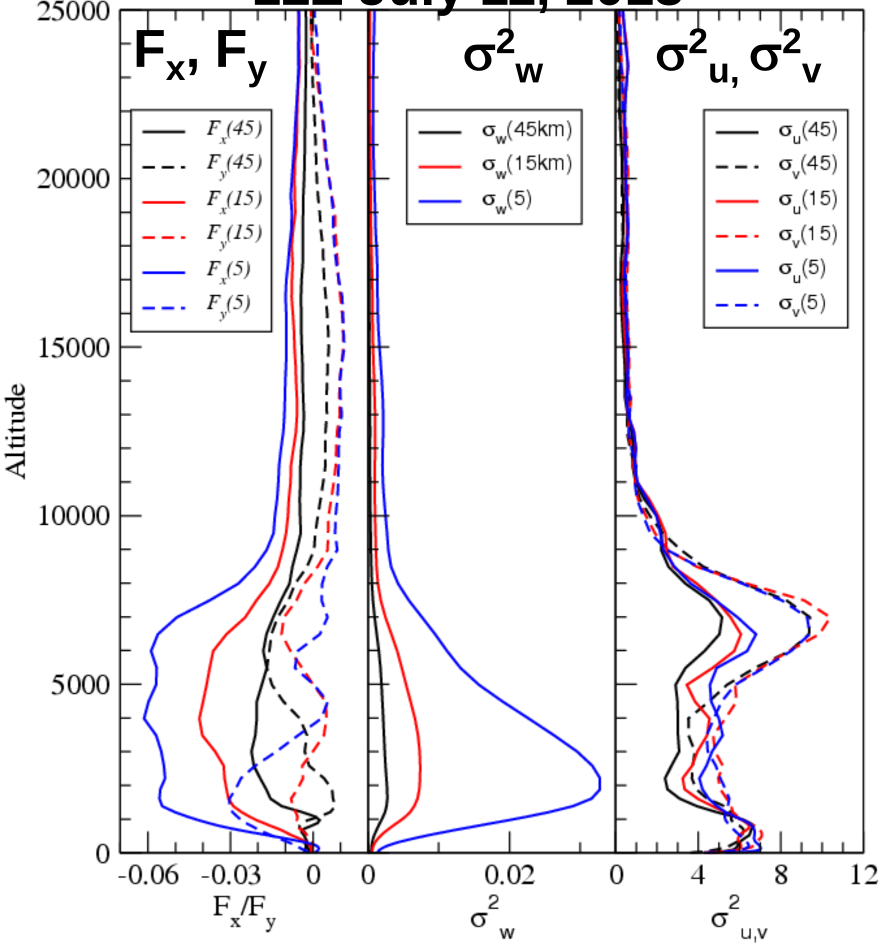


Higher resolution exhibits smaller-scale waves, although the broad characteristics are similar between resolutions (e.g., refraction aloft).

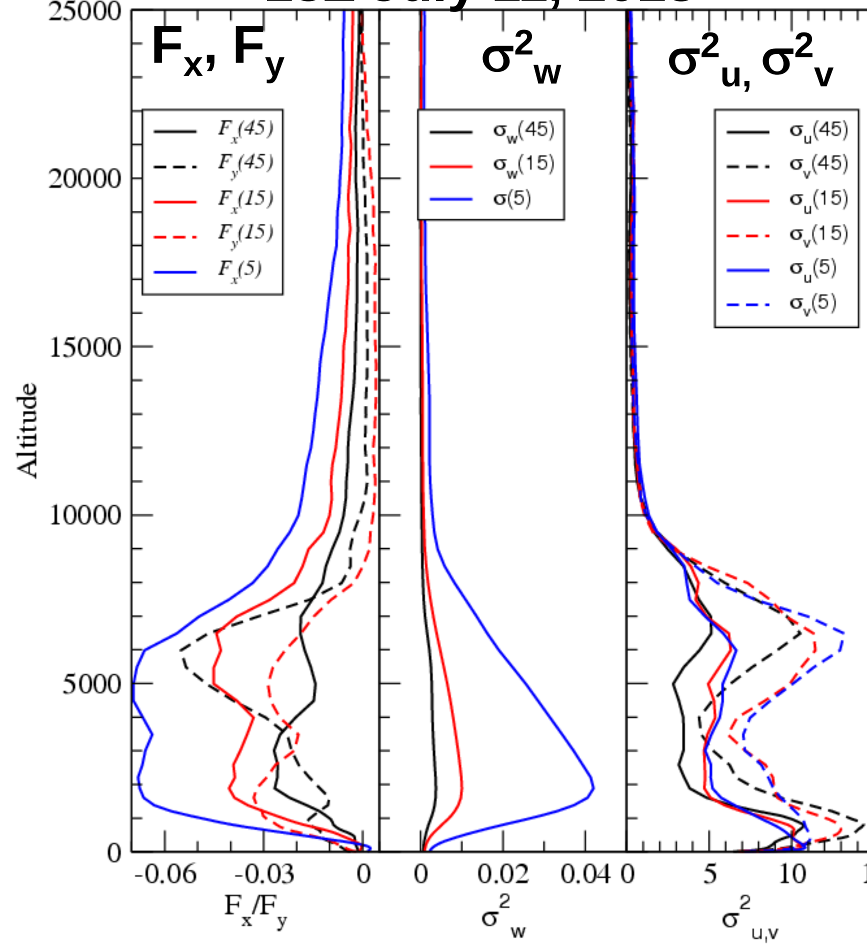
COAMPS Case Study of a NZ GW Event

Wave Momentum Flux Diagnostics (45, 15, 5 km meshes)

12Z July 11, 2013



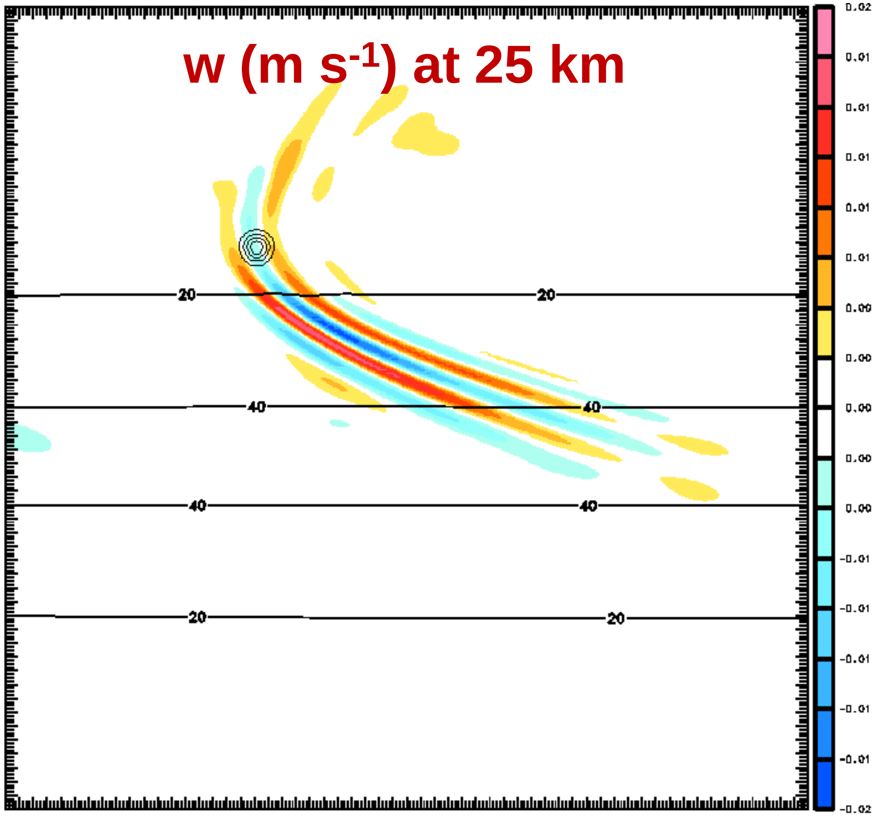
18Z July 11, 2013

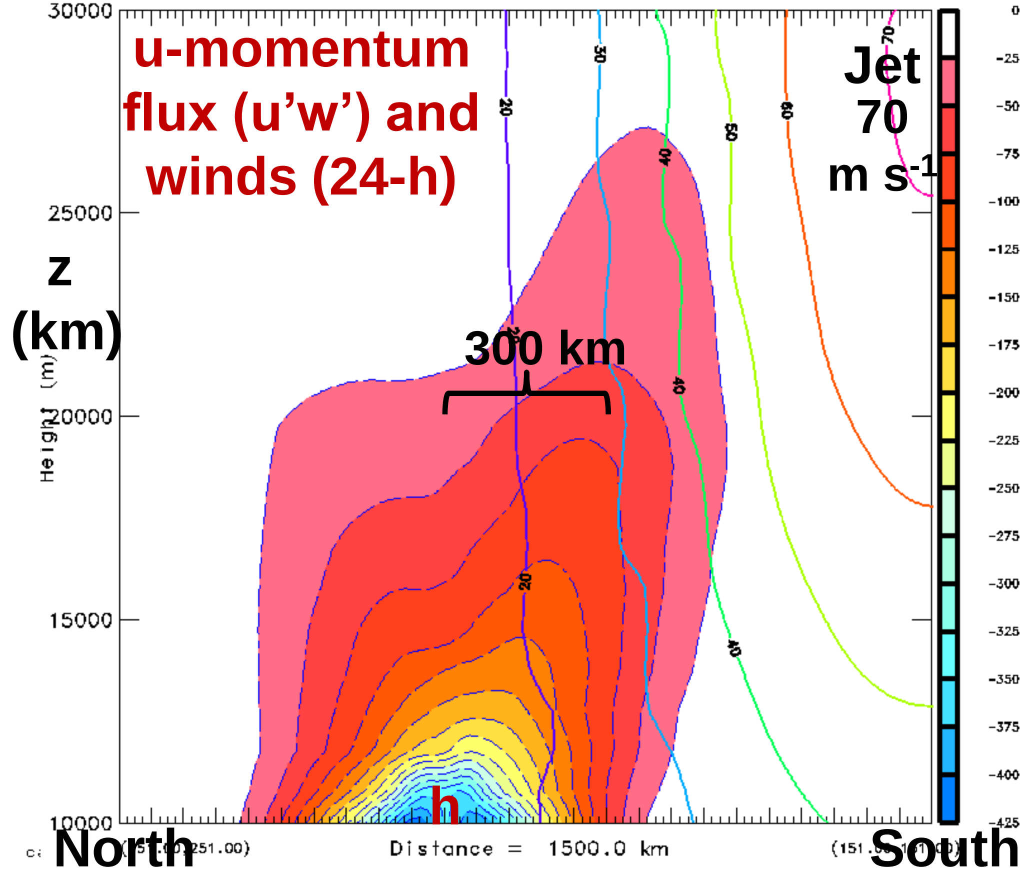


- Wave momentum flux, wind variances computed for difference grids.
- Vertical velocity variance (σ^2_w) is highest on the highest resolution grid.
- Wave momentum flux on 5 and 15 km grids converge in stratosphere.

Gravity Waves in Sheared Flow

Idealized Shear Experiments



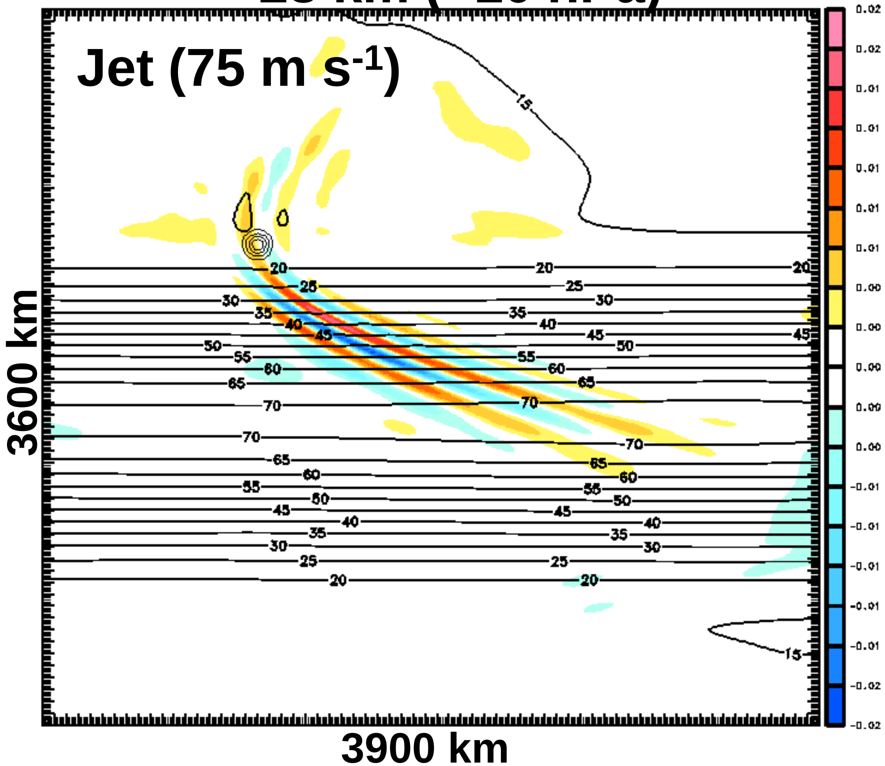


- Role of horizontal shear often is not considered in GW studies.
- Idealized simulations of gravity waves in balanced shear (Δx=15 km)
- Flow over Gaussian hill (north of jet) leads to vertically propagating waves that are refracted by the horizontal shear in the stratosphere.
- Zonal momentum flux in the stratosphere shows refraction due to shear.

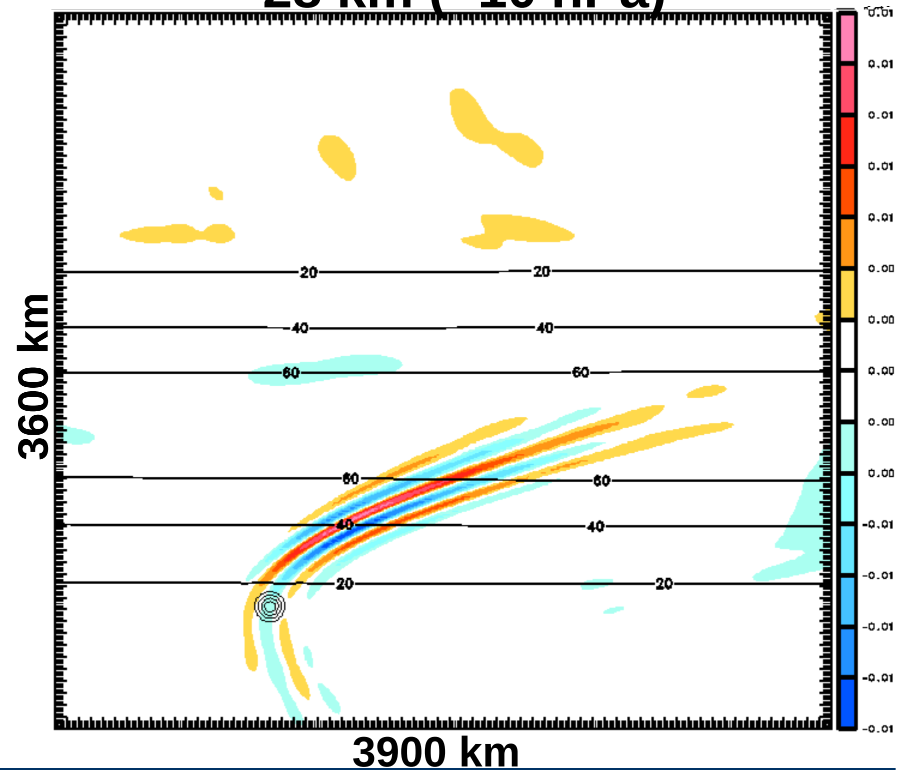
Gravity Waves in Sheared Flow

Idealized Shear Experiments

Vertical Velocity
28 km (~10 hPa)



Vertical Velocity (65 m s^{-1} Jet)
28 km (~10 hPa)



- 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.

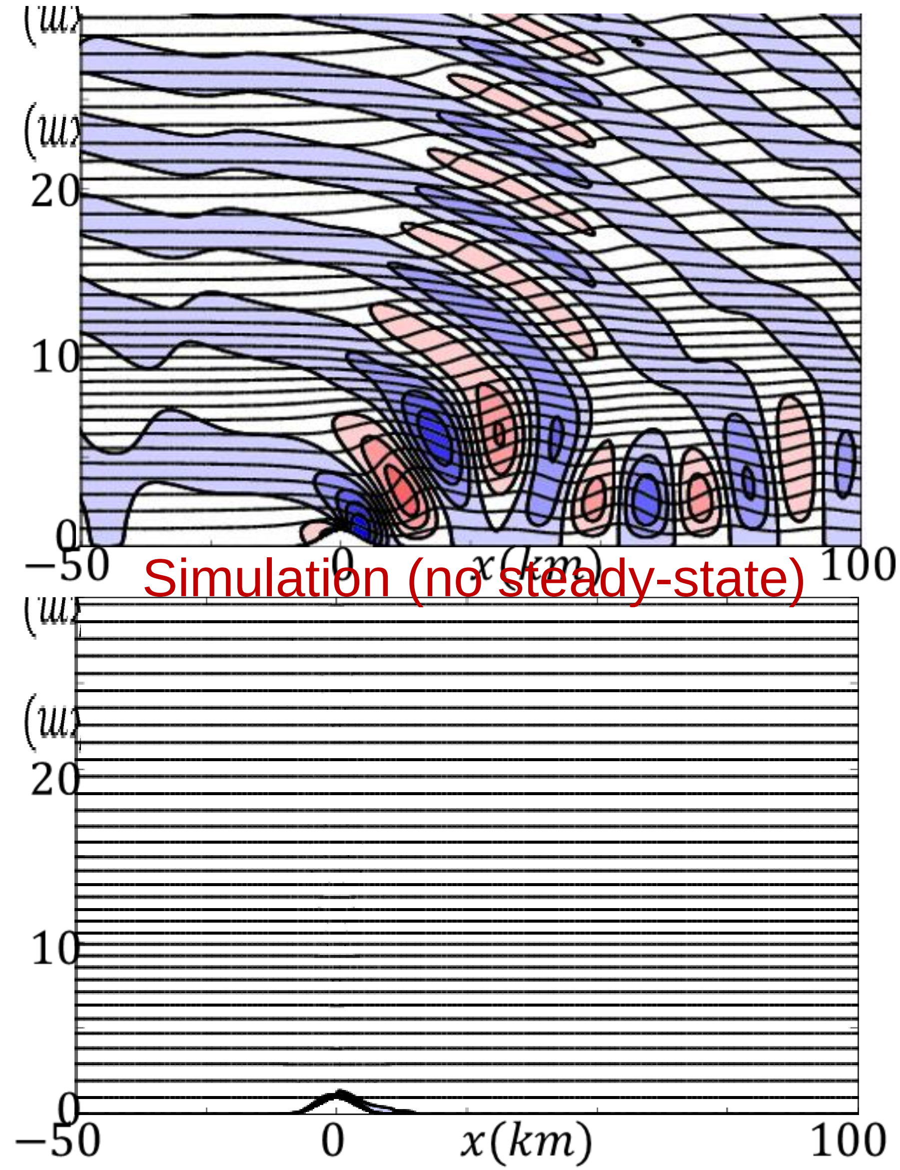
Nonlinear Theory and Resonant Instability

Idealized Experiments

Fast growing resonant instability occurs in conditions similar to the S. Hemisphere stratosphere.

- Weak forward shear was found to be most unstable situation.
- In this case the unstable mode has an e-doubling period <1 hour.
- Energy rapidly propagates into the stratosphere and downstream in the form of trapped waves.
- Deepwave observations may provide evidence of this instability

(Viner, Epifanio, Doyle, JCP, 2013)



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Questions

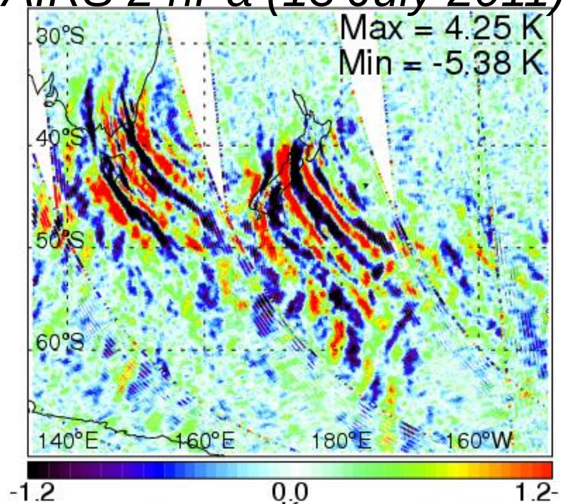
- What is the multi-scale predictability of deep propagating gravity waves?
- How does tropospheric predictability impact the upper atmosphere?
- Can targeted observing be effectively used to improve the prediction of GWs?

Predictability of Deep Propagating GWs

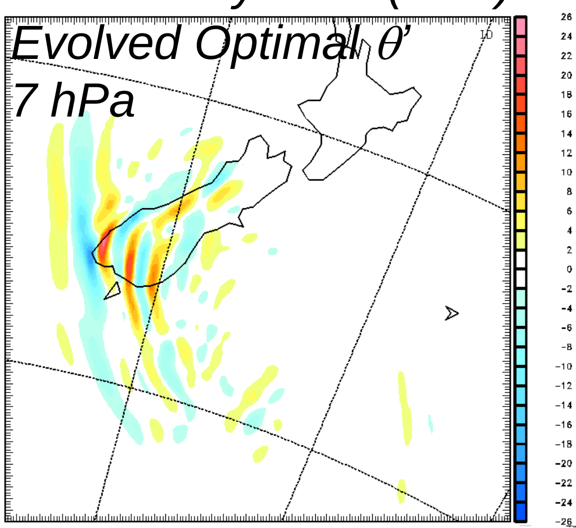
What are the predictability characteristics of deep propagating GWs?

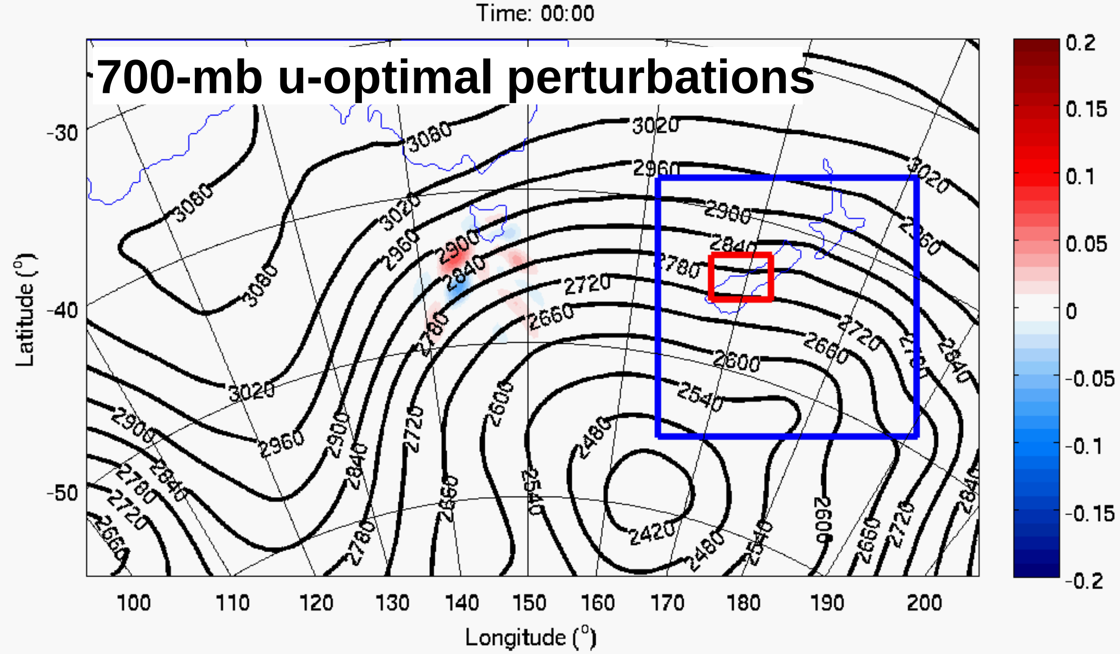
Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to changes in the initial state

AIRS 2 hPa (13 July 2011)



12Z 13 July 2011 (24 h)

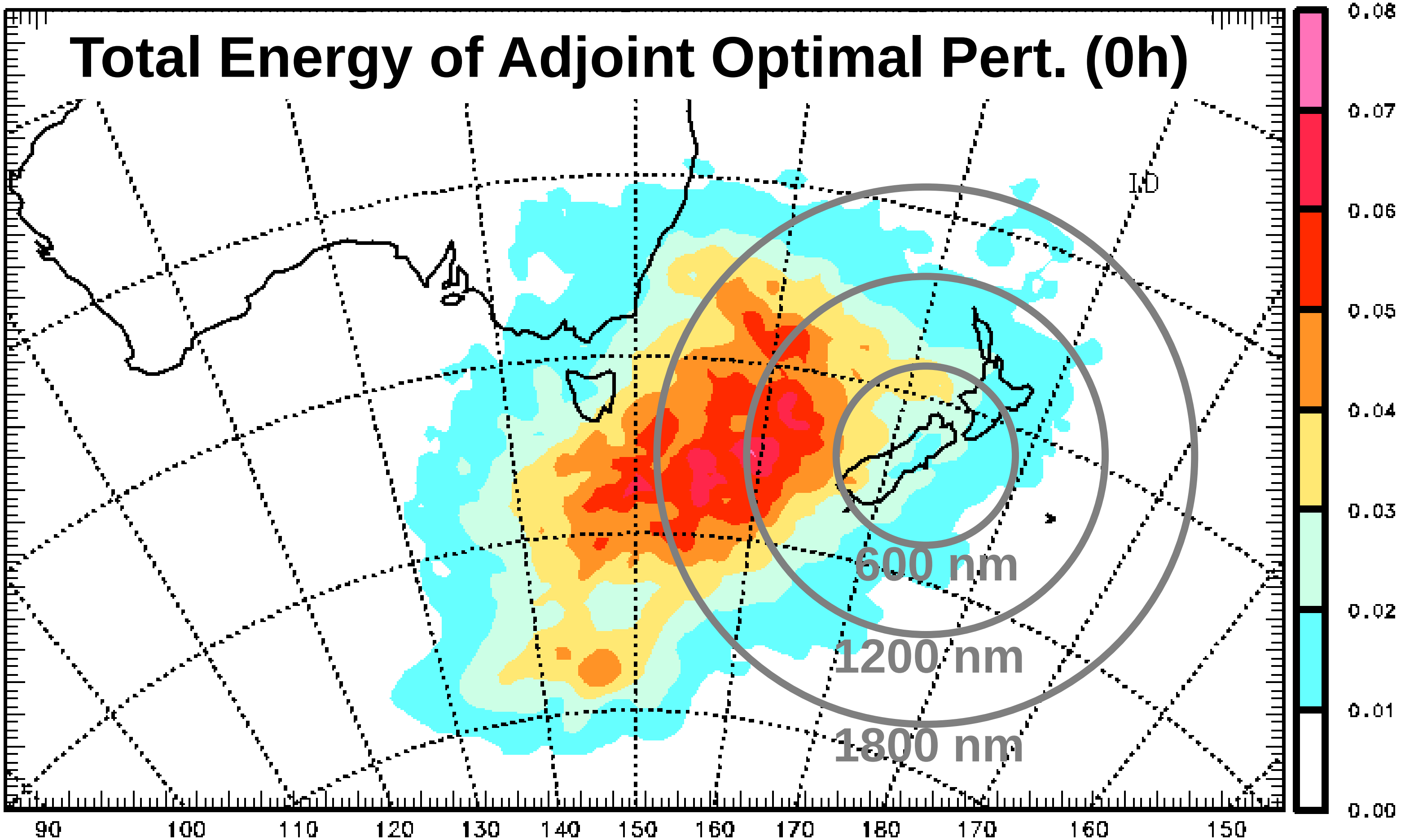




- Adjoint is used to diagnose sensitivity using a kinetic energy response function (lowest 1 km)
- Sensitivity located ~1200 km upstream (in coarse mesh over 24 h) near 700 hPa shortwave.
- Adjoint optimal perturbations lead to strong wave propagation (refracted waves south of NZ)

Predictability of Deep Propagating GWs

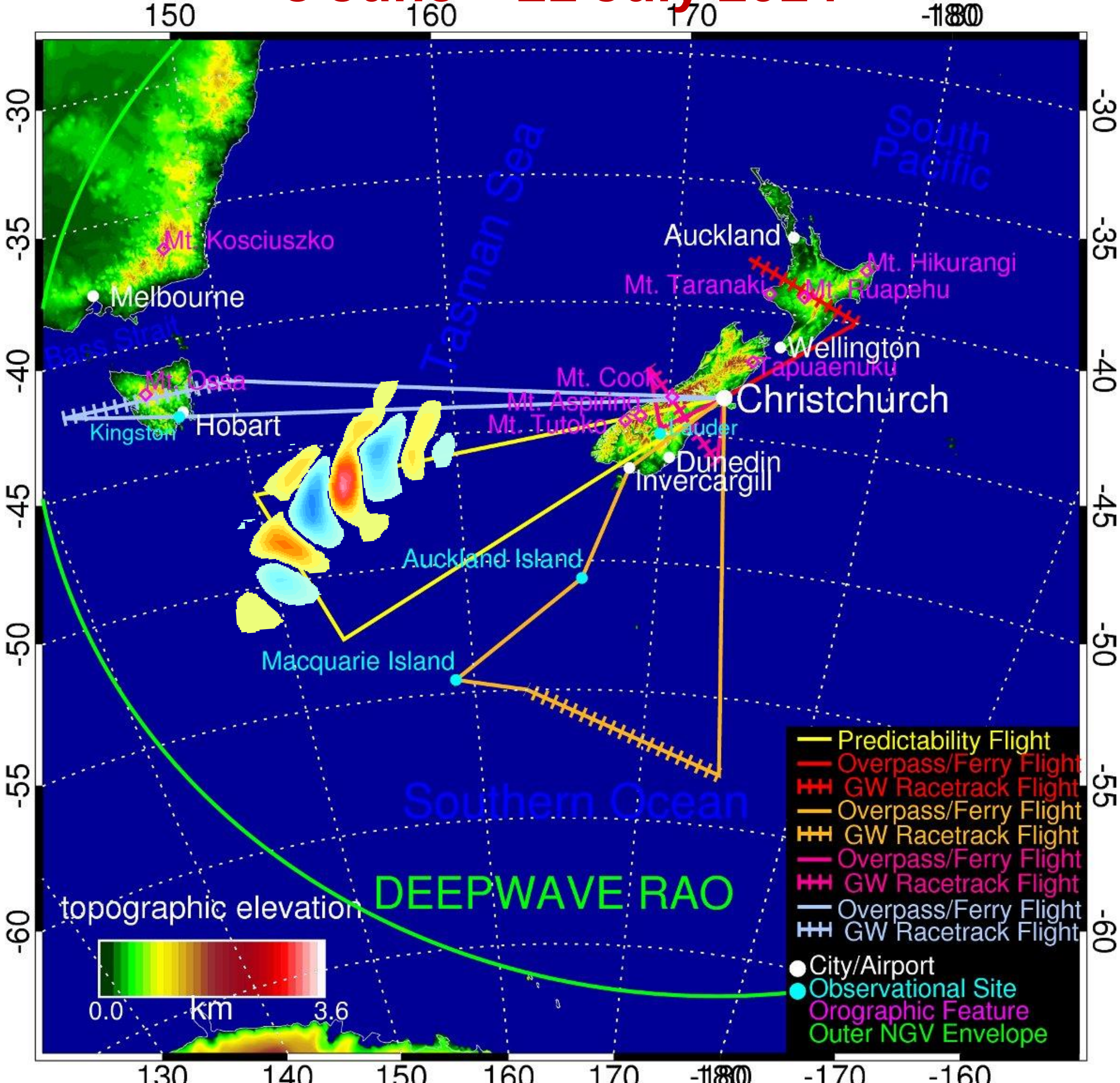
June-July 2010-2011 <u>Mean</u> for $U_{700\ hPa} > 10\ m\ s^{-1}$



Mean 700-hPa sensitivity is location over the Tasman Sea to the west of New Zealand and very accessible for G-V (dropsondes) and Falcon (wind lidar) to perform targeted observing.

DeepWave Field Campaign

5 June – 21 July 2014



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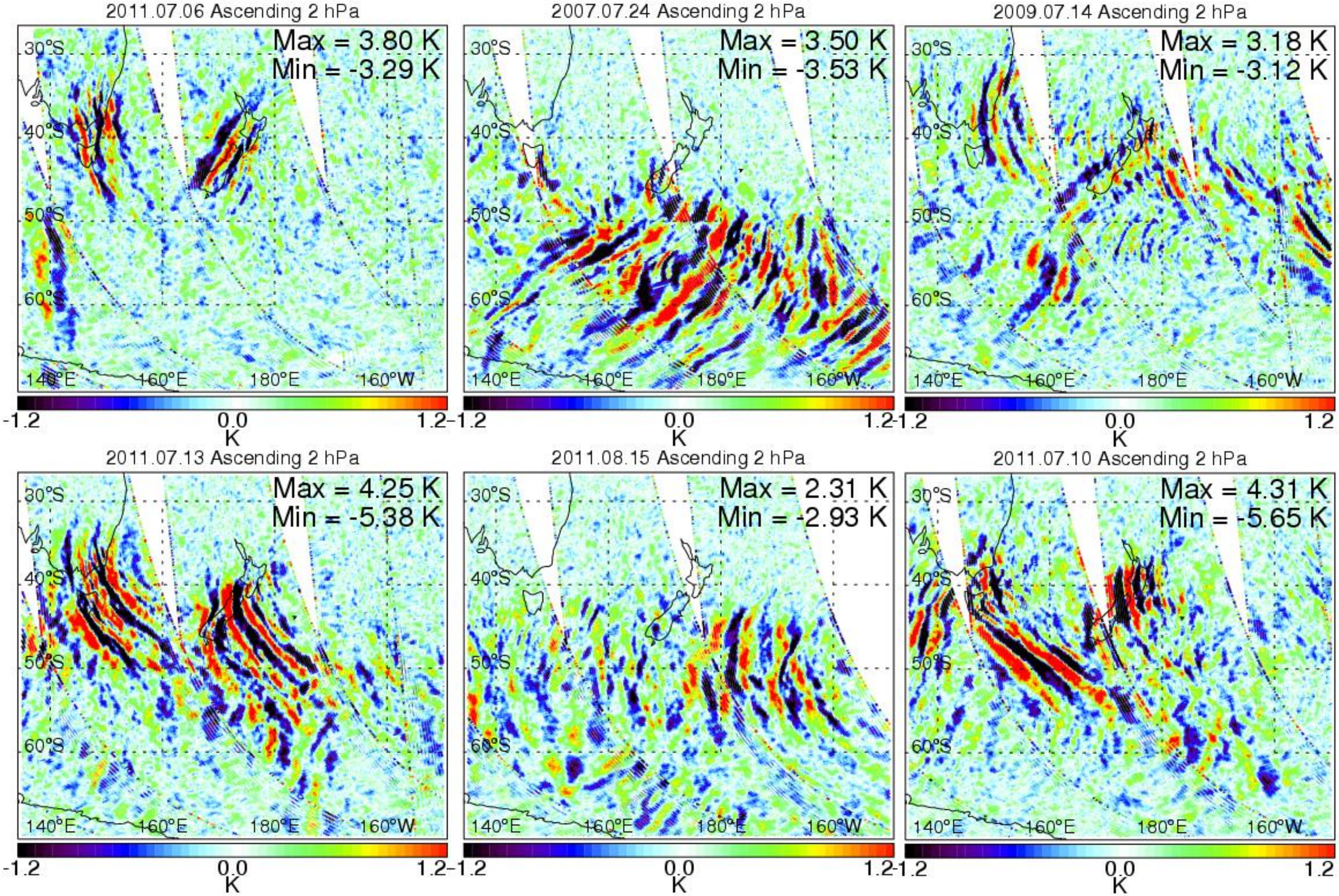
- What are the dominant sources of stratospheric GWs over NZ, S. Ocean?
- How can gravity wave sources be identified in real world situations?

Gravity Wave Sources
New Zealand & Southern Oceans

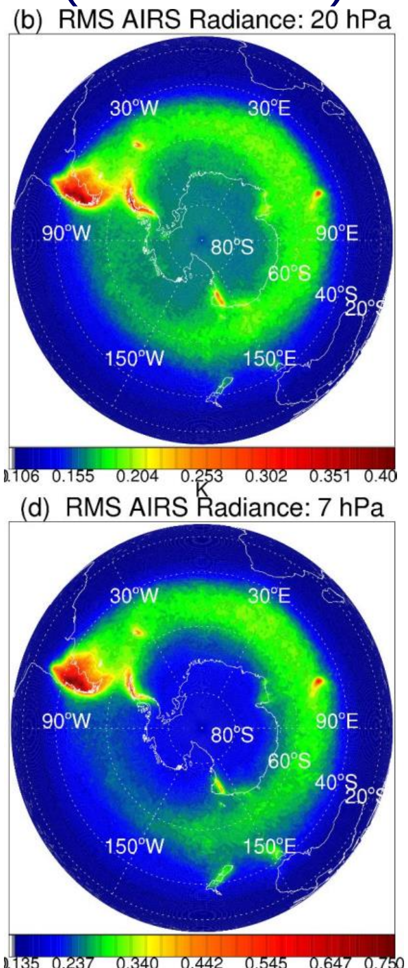
Examples from AIRS Radiances

Mountain Waves | **Non-Orographic GWs** | **Multiple Sources?**

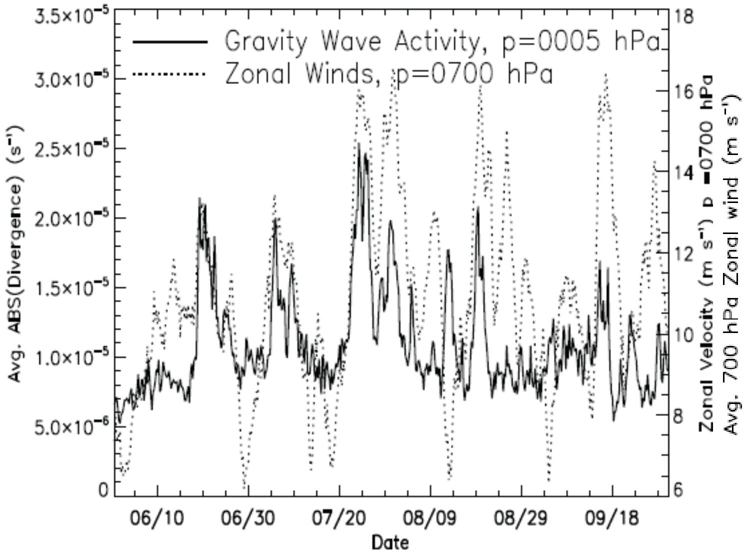


Gravity Wave Sources

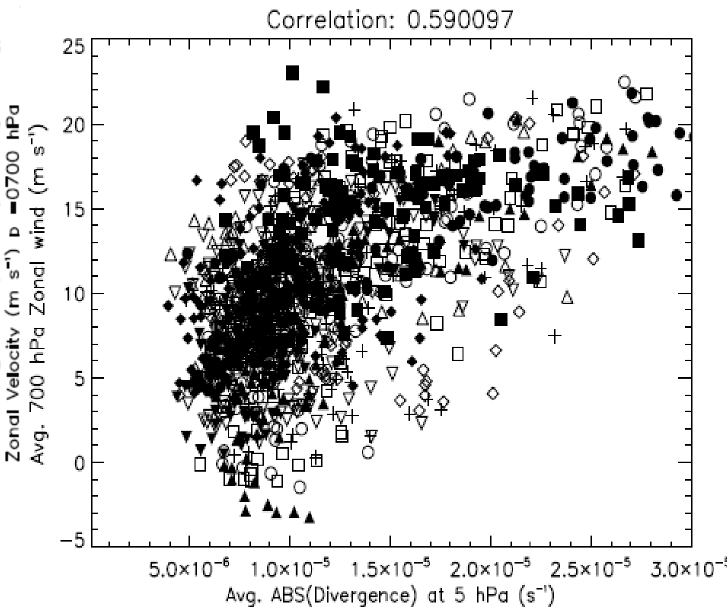
AIRS Radiances (2003-2011)



ECMWF Reanalysis: 700-hPa Winds and 5-hPa divergence (Jun-Sep 1999) Averaged Over S. Andes



ECMWF Reanalysis: 700-hPa Winds and 5-hPa divergence (Jun 1999-2009) Averaged Over S. Andes

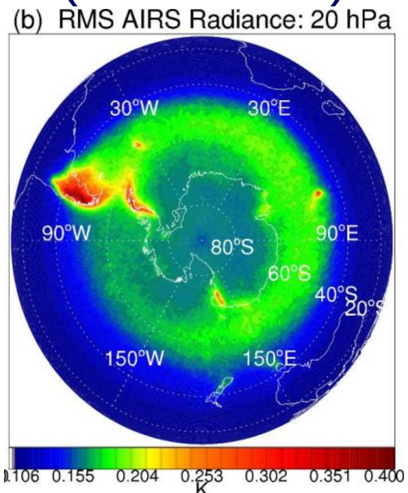


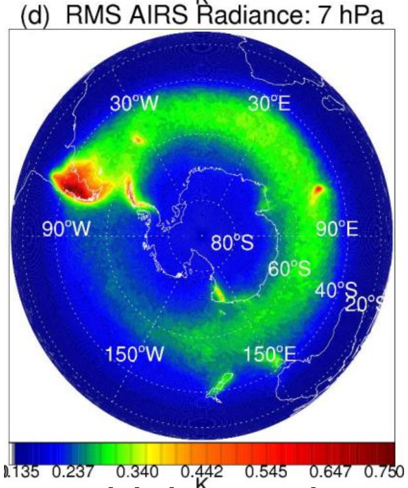
Hendricks et al. 2014 (JAS, in review)

- AIRS stratospheric GW climatology shows numerous maxima near orography (e.g., S. Andes, islands, New Zealand etc.)
- Stratospheric GWs near orography are highly correlated with terrain-forced wave launching

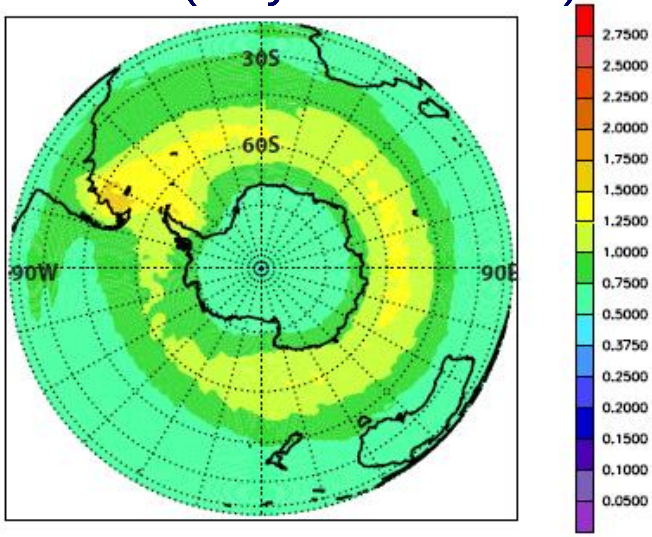
Gravity Wave Sources

AIRS Radiances (2003-2011)

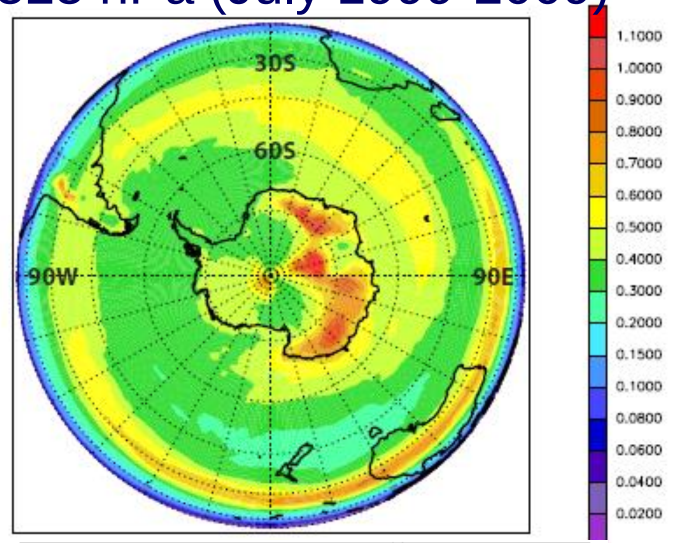




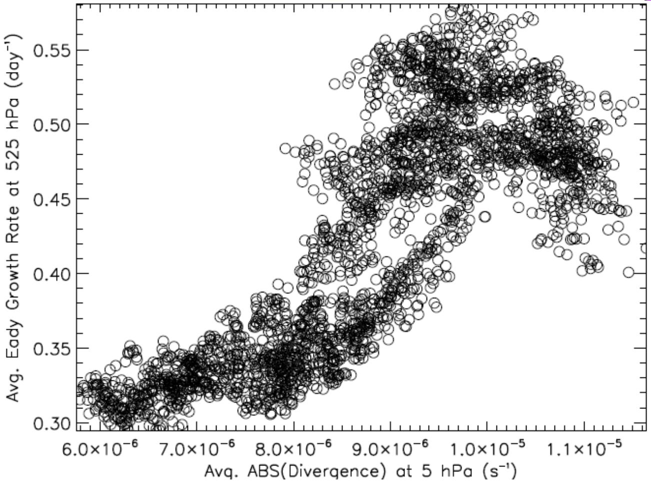
ERA divergence (10^{-5} s^{-1}) 5 hPa (July 1999-2009)



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)



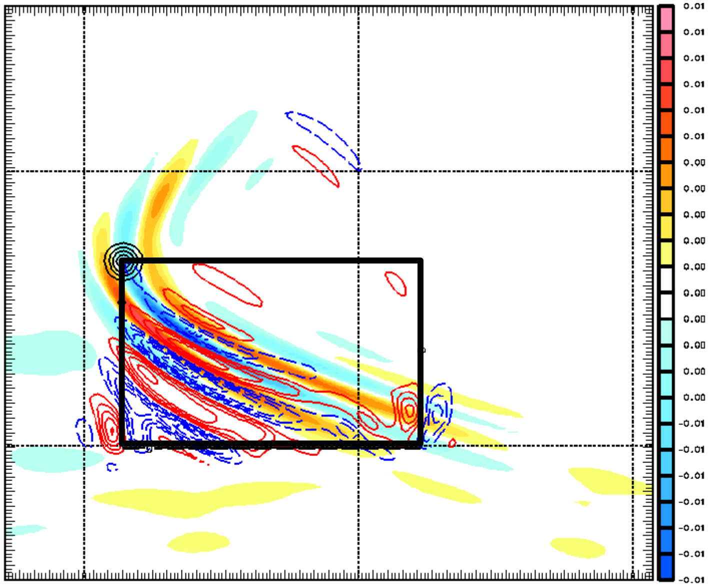
Hendricks et al. 2014 (JAS, in review)

- Eady growth rate and divergence (ECMWF reanalysis) correlation points to possible spontaneous GW emission sources from jets and baroclinic waves.
- What are the dominant sources that contribute to stratospheric GW activity?

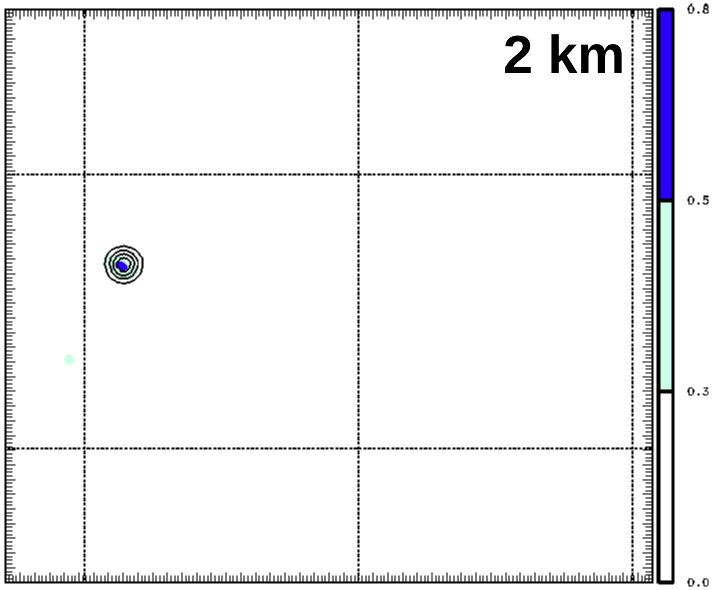
Gravity Wave Source Identification

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

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



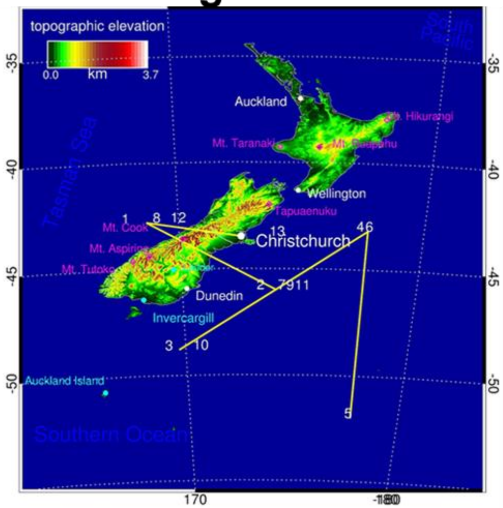
Adjoint Sensitivity (15 h)
Kinetic Energy



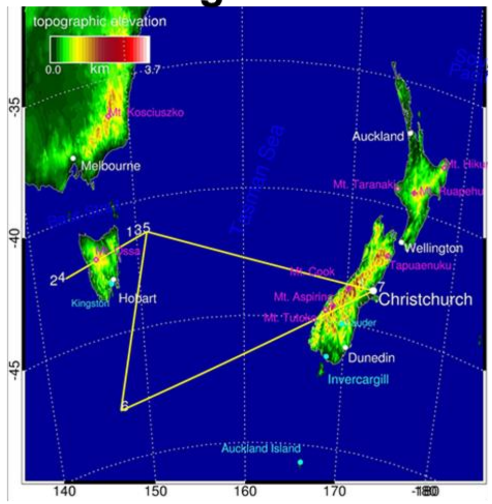
- Idealized simulations with balanced jet and 100 m high hill
- Adjoint is used to diagnose the most sensitive regions in the initial conditions as a proxy for the wave source (9 h integration).
- Adjoint identifies the terrain at surface as the “source”.
- Response function is the vertical velocity at 20-25 km in “box”.
- Adjoint optimal perturbations propagate from terrain and project on to the curved wave phase lines within the “box”.

Gravity Wave Sources Real Data Cases

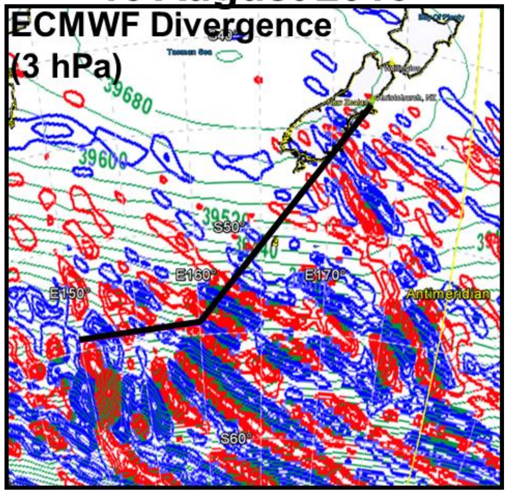
New Zealand Flight
8 August 2013



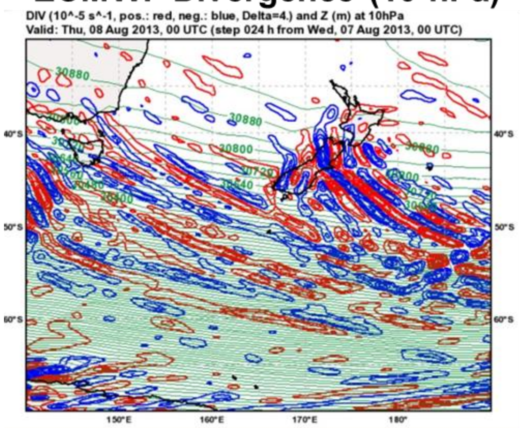
Tasmania Flight
10 August 2013



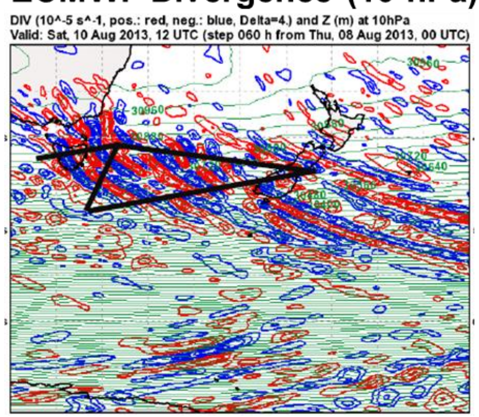
S. Ocean Flight
15 August 2013



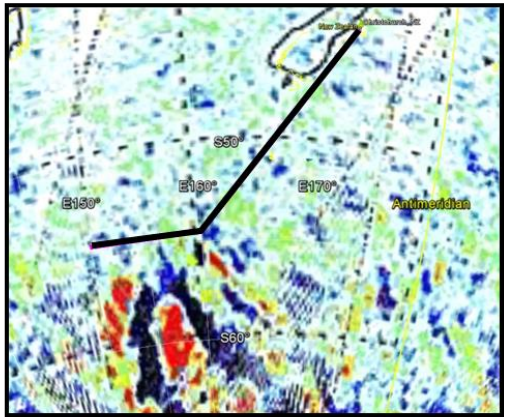
ECMWF Divergence (10 hPa)



ECMWF Divergence (10 hPa)



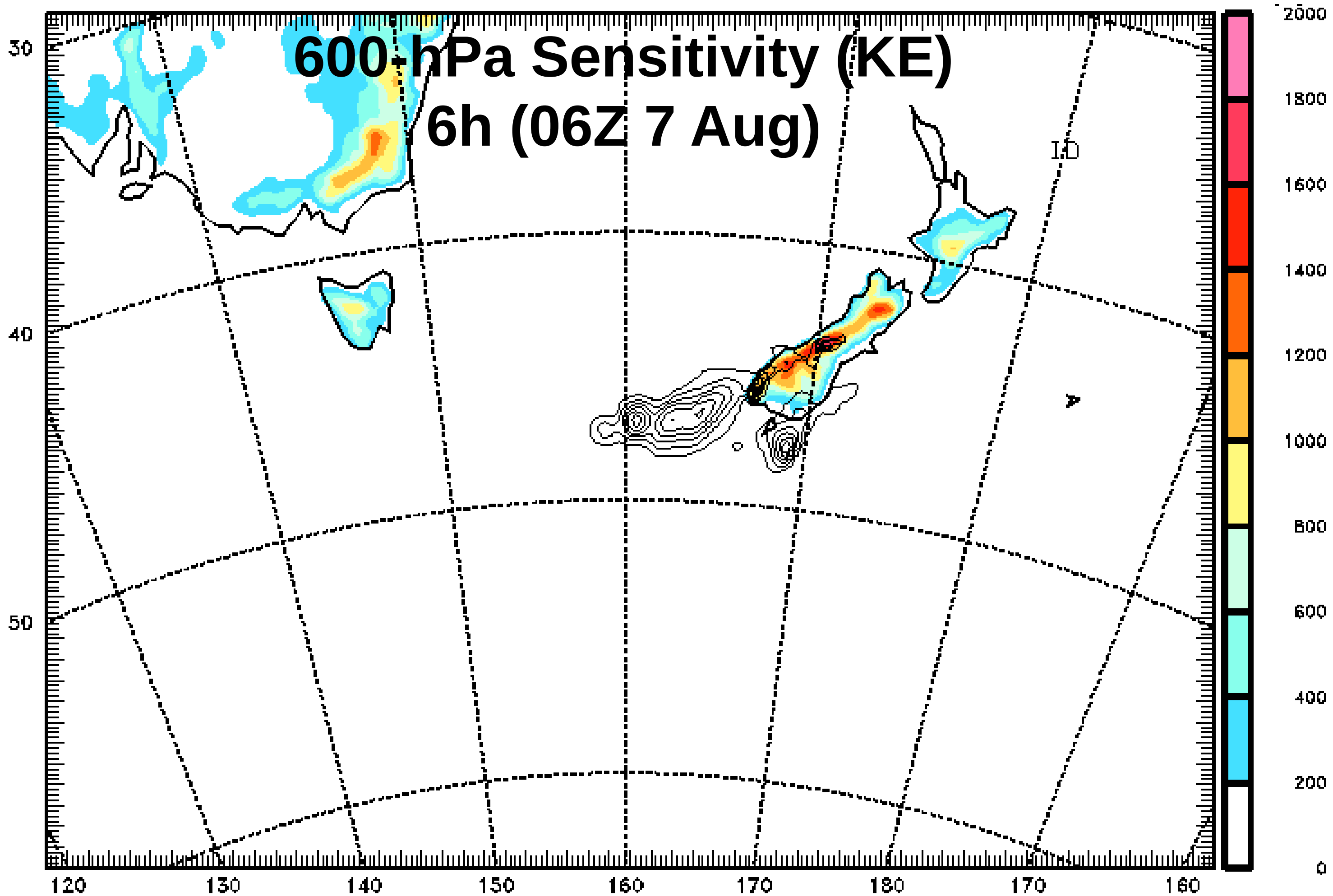
AIRS Radiances (3 hPa)



- Dry run exercise (5-15 August 2013) examples examined, with a focus on 8 August (New Zealand GWs) and 15 August (S. Ocean GWs) cases.
- What are the gravity wave sources and characteristics?

Gravity Wave Source Identification

Orographic Wave Case (7-8 August 2013)

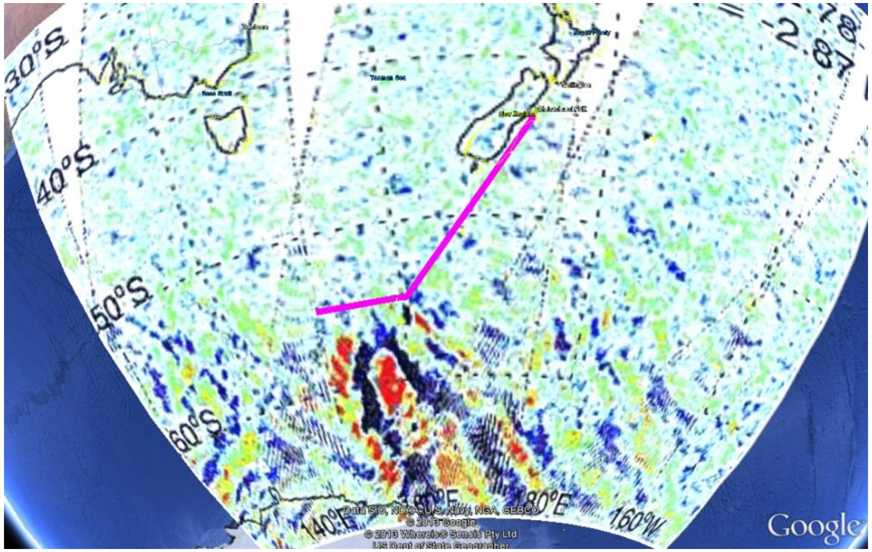


- Adjoint identifies most sensitive portion of the Alps for wave launching.
- Bands located to SE of NZ are linked with GW launching from the N. Alps.
- Bands located to S of NZ are linked with S. Alps and nonorographic forcing?

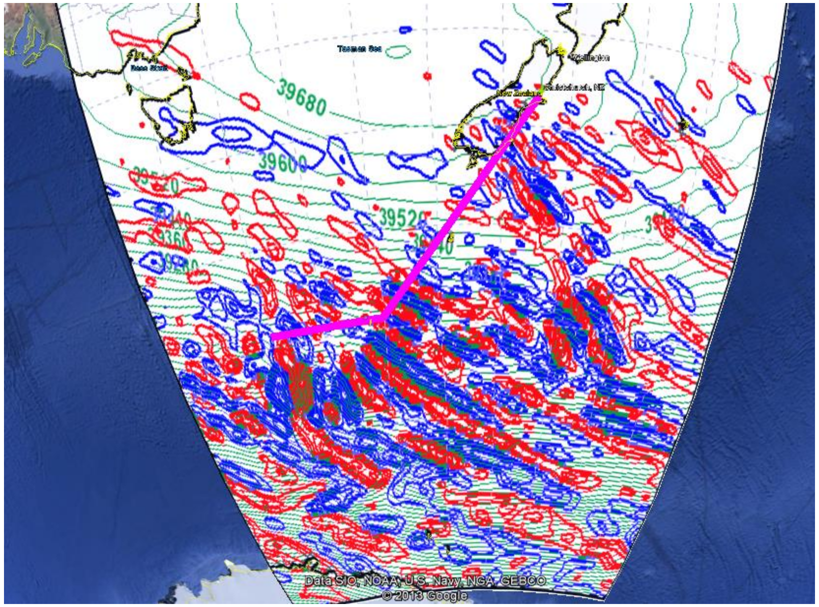
Gravity Wave Source Identification

Non-Orographic Gravity Wave Case (14-15 August 2013)

AIRS (3 mb)



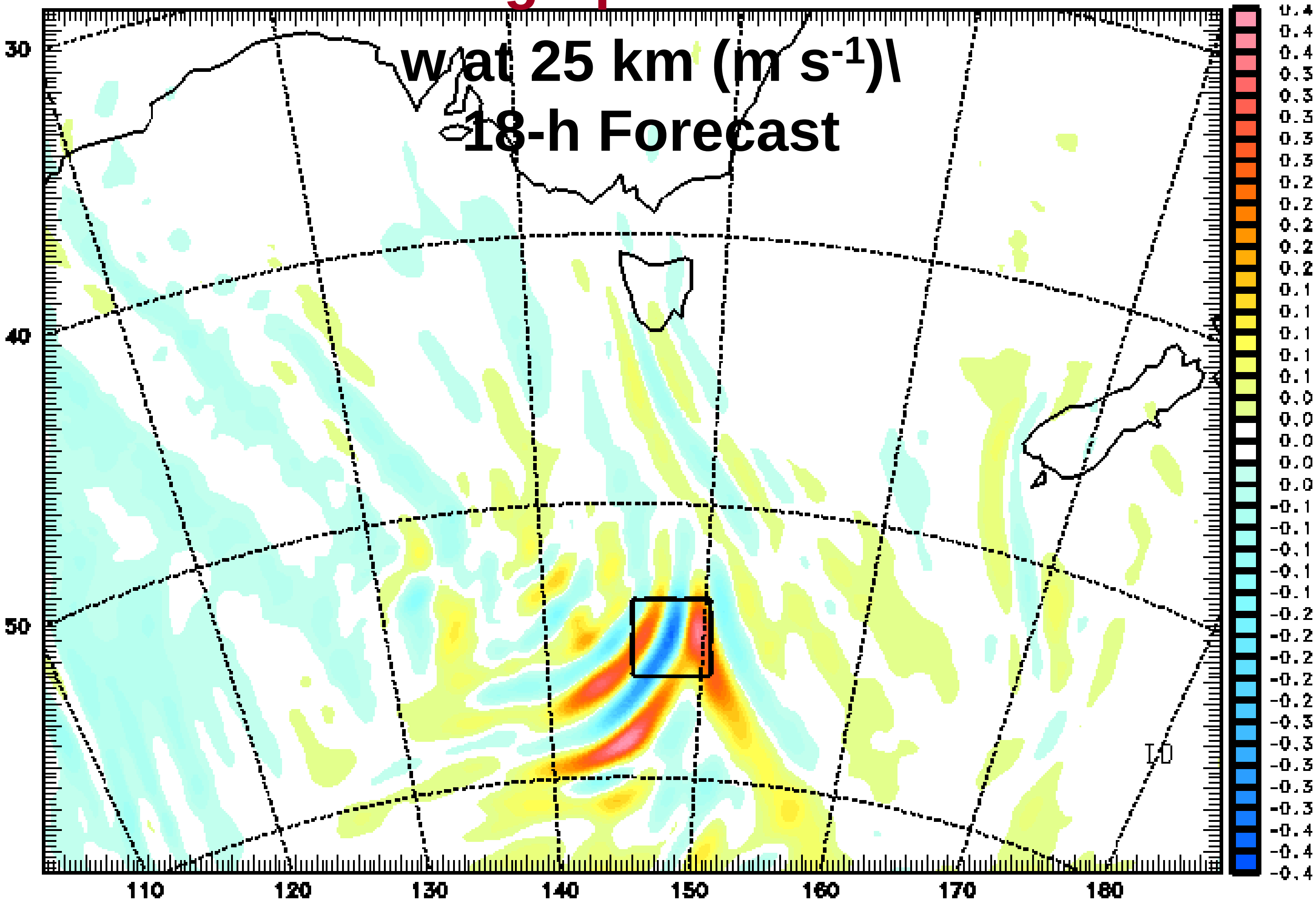
ECMWF Divergence (3 mb)



- Focus on a possible non-orographic gravity wave case from the DeepWave dry run on 14-15 August 2013.
- Gravity waves observed by AIRS located well to the south of New Zealand and in a region with no topography.

Gravity Wave Source Identification

Non-Orographic Wave Case

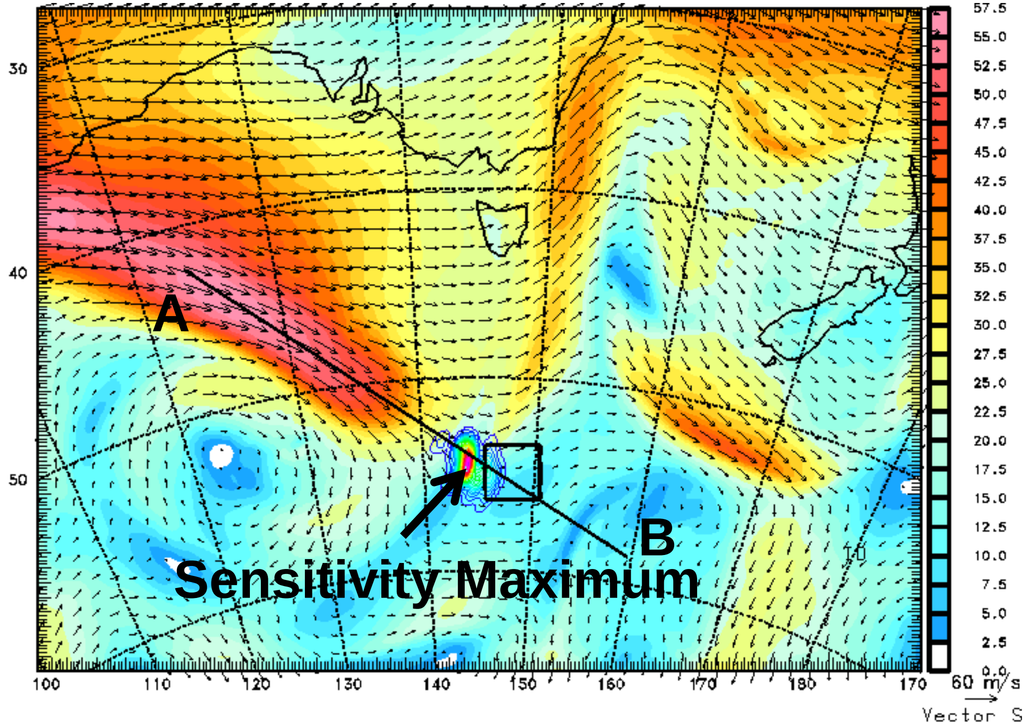


COAMPS model appears to capture the characteristics of the stratospheric gravity waves fairly well.

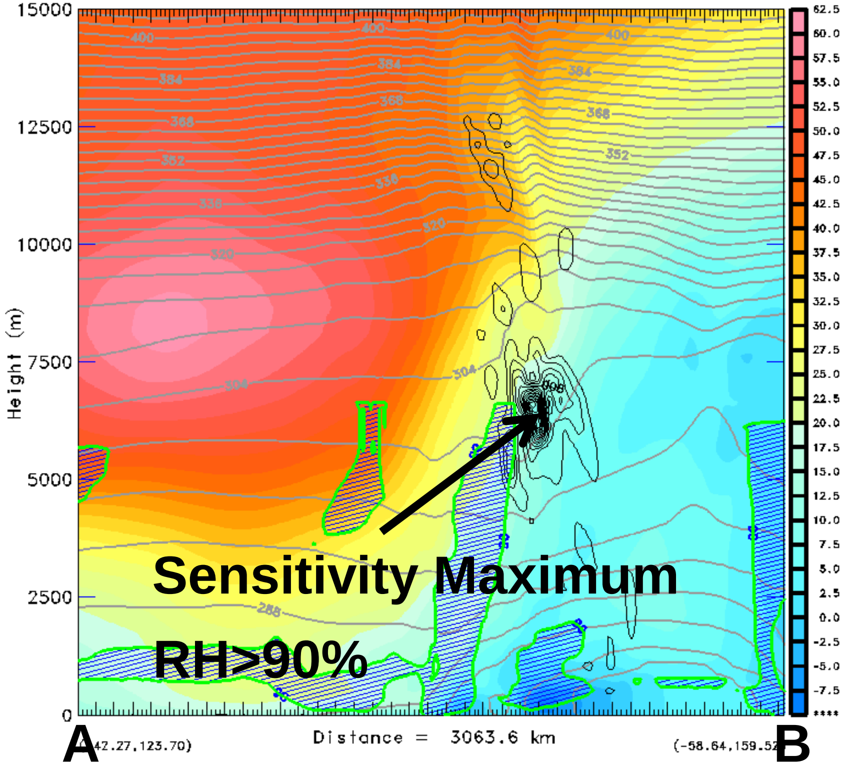
Gravity Wave Source Identification

Non-Orographic Wave Case

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



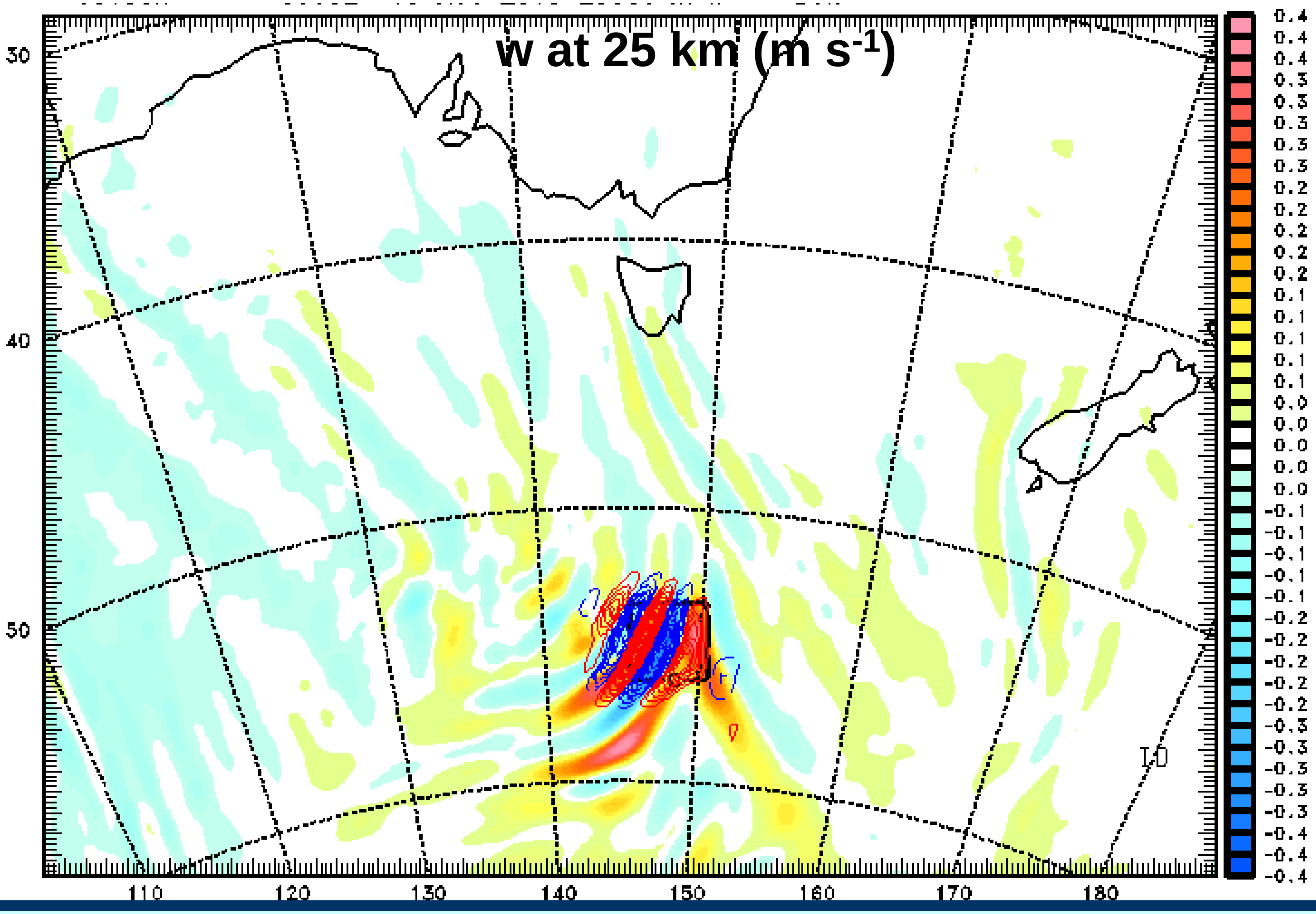
Along section wind speed (m s^{-1})
Optimal Perturbation KE (6 h)



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.

Summary and Future Research Directions

- **Gravity wave dynamics and numerical modeling**
  - Role of horizontal shear and impact on stratospheric gravity waves
  - Characteristics of stratospheric and upper-level waves, wave breaking
  - Opportunity to observe resonant instabilities associated with nonlinearity
  - Gravity wave drag parameterization and nonlocal nature of drag
- **Gravity wave predictability**
  - Multi-scale predictability of deep propagating gravity waves
  - Links between tropospheric predictability and the upper atmosphere
  - Can targeted observing be used to improve the prediction of GWs?
- **Sources of stratospheric GWs**
  - Terrain-forcing, spontaneous GW emission from baroclinic waves & jets
- **Opportunities for collaboration on modeling issues, dynamics, predictability, GW sources**
  - Multi-model intercomparisons