Update on Gravity Wave Predictability, Dynamics and Sources in DEEPWAVE

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NRL-MRY DEEPWAVE Research Projects

1) **Predictability:**
   - 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.)
2) **Deep Propagating Gravity Waves and Gravity Wave Refraction:**
   - Idealized and real-data simulations of GWs and GW refraction by shear
   - RF23, RF04, RF07, RF08, RF12, RF13
3) **Gravity Wave Source Identification:**
   - Sources of “trailing” gravity waves near the New Zealand South Island
   - Sources of non-orographic gravity waves
4) **Synoptic-Scale Overview:**
   - Summarize key synoptic-scale features for GWs over the DEEPWAVE domain during June-July 2014 & interpret in a climatological perspective.

Outline

1) Predictability

2) Deep Propagating GWs and Refraction

3) Gravity Wave Sources

Summary of Predictability Missions

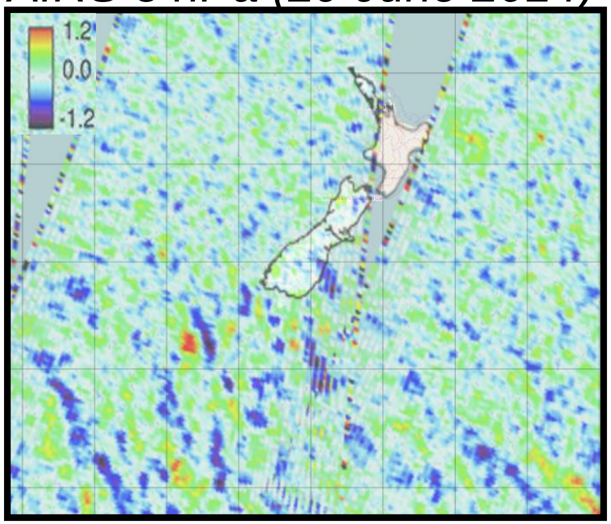
RF	IOP	Date	Flight Type	Location	Length	Comments
3	3	6/13/ 2014	Predictability	Tasman Sea	4.5 h	Sampled short wave trough, LLJ
9	8	6/24/ 2014	Predictability and SI Mountain Waves	Tasman Sea and Cook 1b	8.25 h 5 Mt. Cook transects	Sensitivity with cyclone, convection
-	-	6/25/ 2014	No flight, 3-h Hobart soundings (06Z-18Z)	Hobart, Tasmania	0	Partially sampled sensitive region.
11	9	6/28/ 2014	Predictability	Tasman Sea and Cook 1b	6 h 2 Mt. Cook transects	Sampled active convection, very strong jet.
14	9	7/01/ 2014	SI Mountain Waves with predictability dropsondes E of SI	Cook 1a and SE of SI.	0 h Transverse GW leg	Sampled frontal passage.
24	14	7/16/ 2014	S. Ocean Waves with predictability dropsondes	S. Ocean, S-SW of the SI	0 h – Flag pattern	Sampled half of sensitive region

Predictability of Deep Propagating GWs

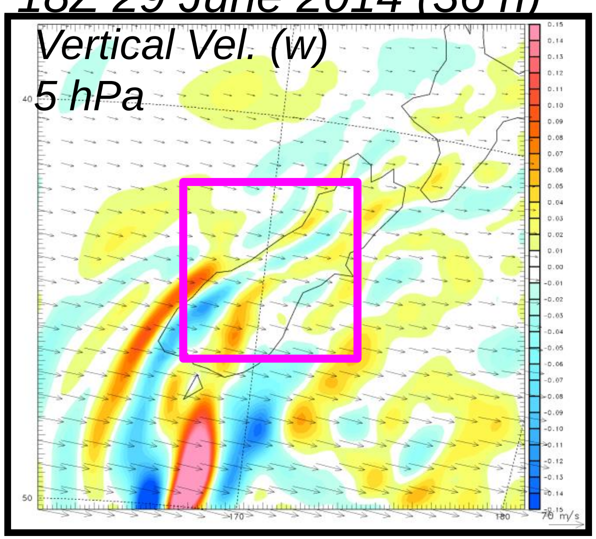
What are the predictability characteristics of deep propagating GWs?

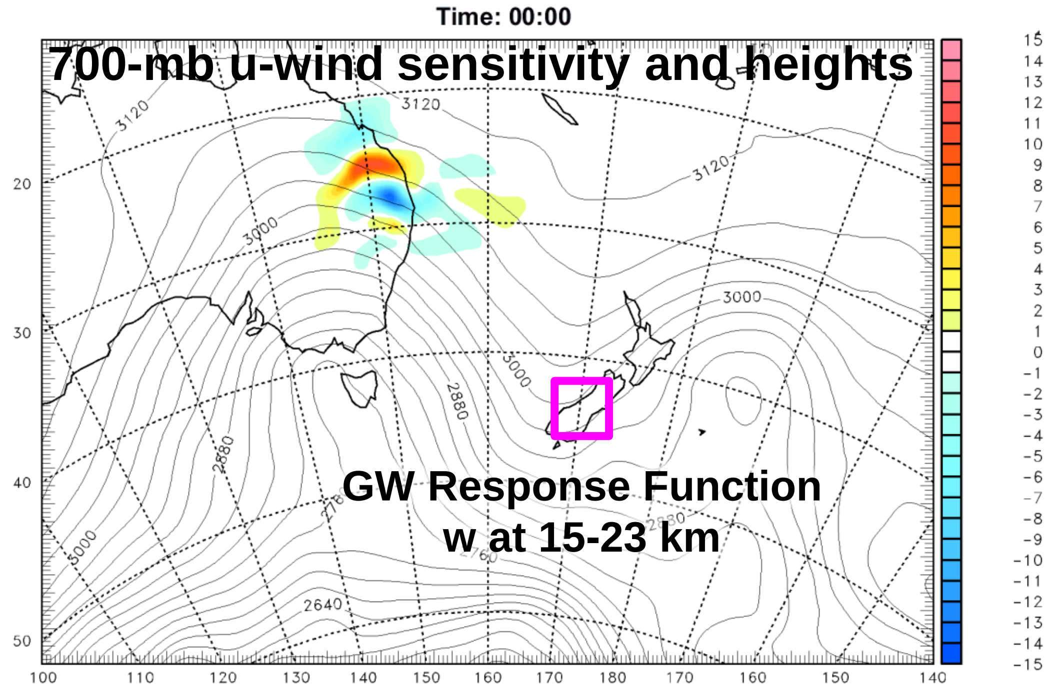
Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to changes in the initial state

AIRS 3 hPa (29 June 2014)



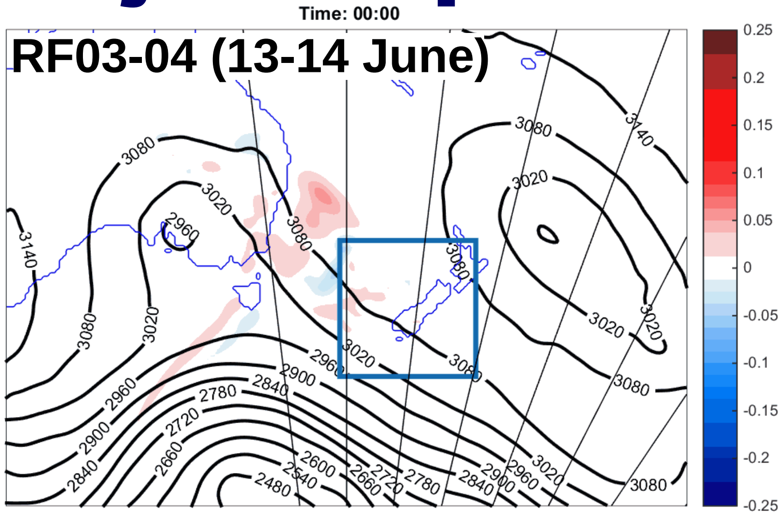
18Z 29 June 2014 (36 h)

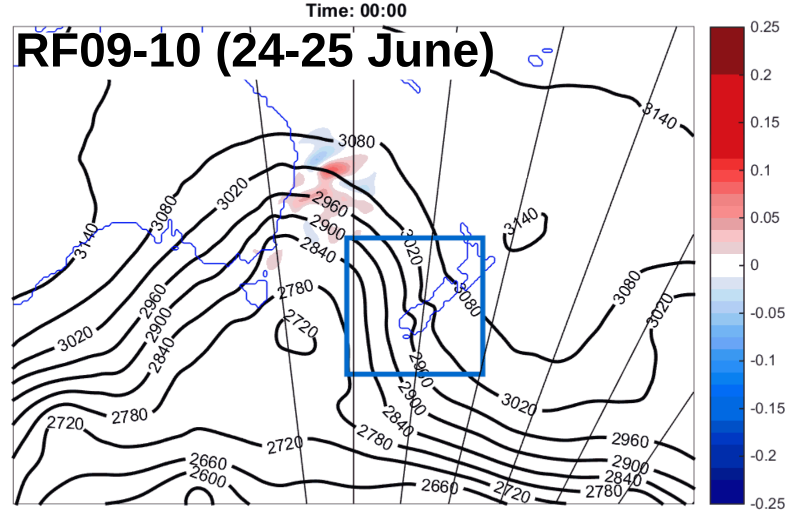


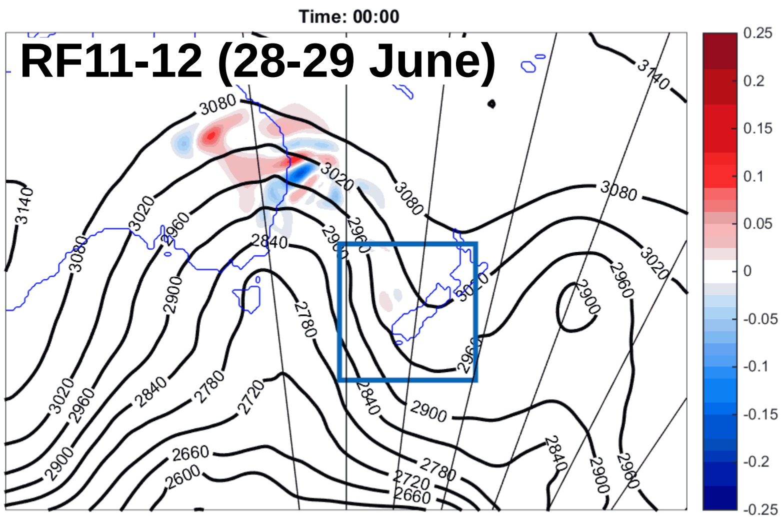


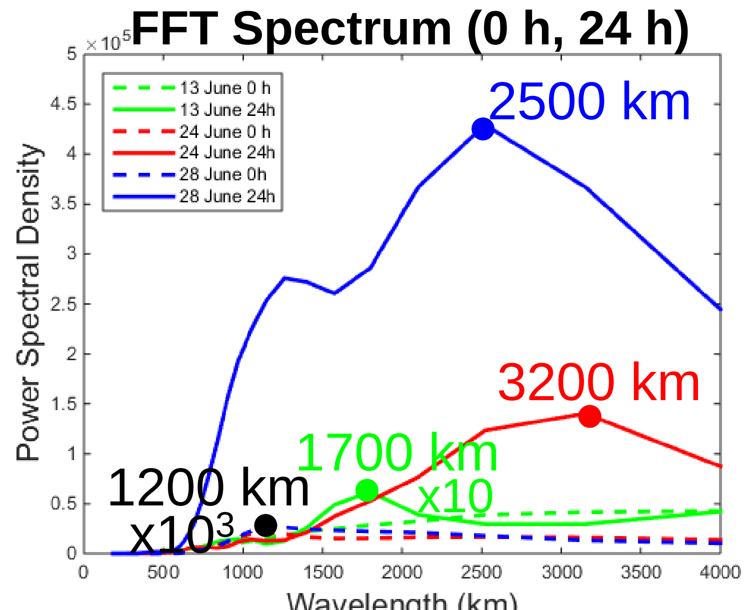
- Adjoint is used to diagnose sensitivity using a kinetic energy response function (lowest 1 km)
- Sensitivity located ~1200 km upstream near trough
- Adjoint optimal perturbations lead to strong wave propagation (refracted waves south of NZ)

Adjoint Optimal Perturbation Growth







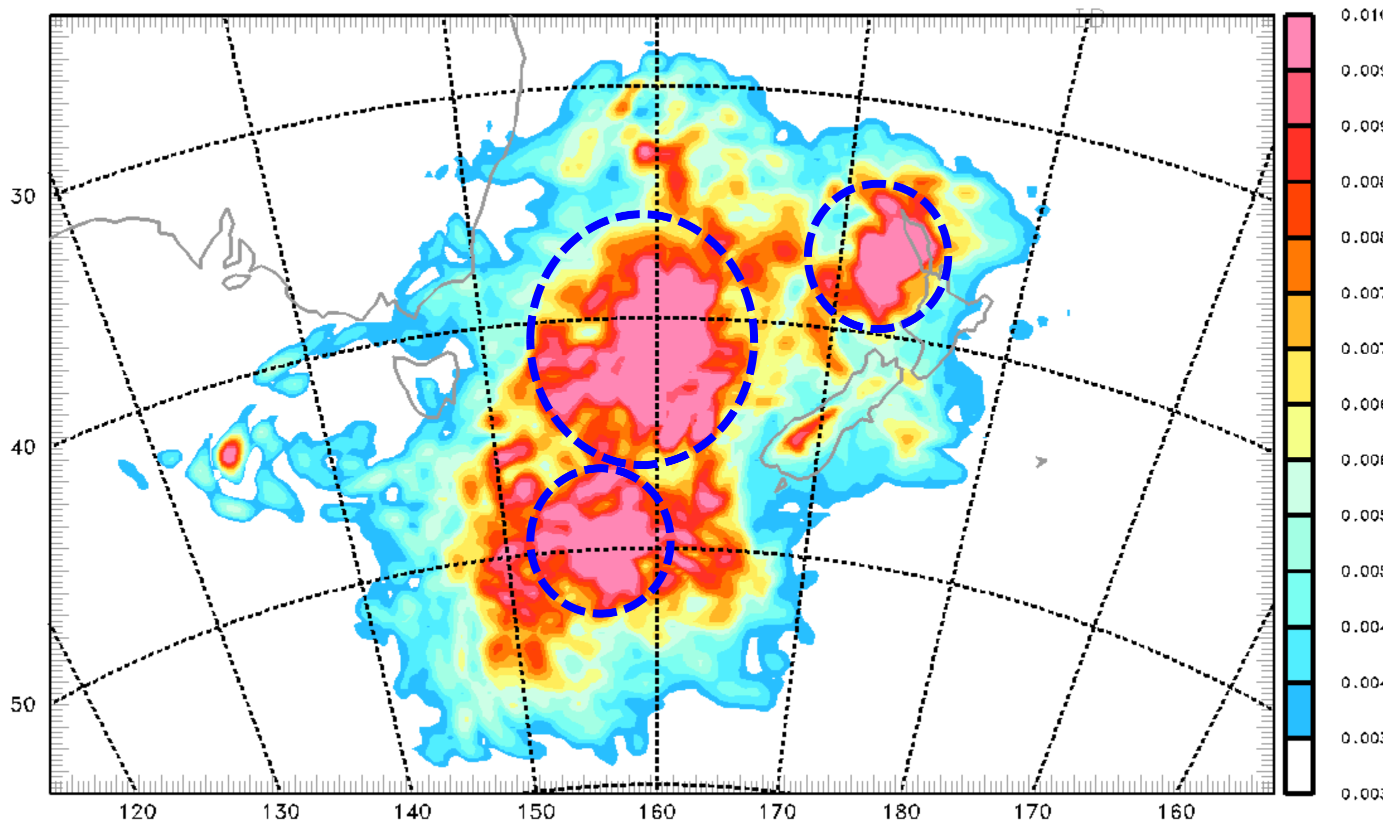


- Rapid growth for 24 & 28 June cases - slower growth for 13 June case.
- Upscale growth of optimal perturbations over 24 h.

Moist Adjoint Sensitivity

June-July 2014 Mean for $U_{1\,km}$ > 10 m s^{-1}

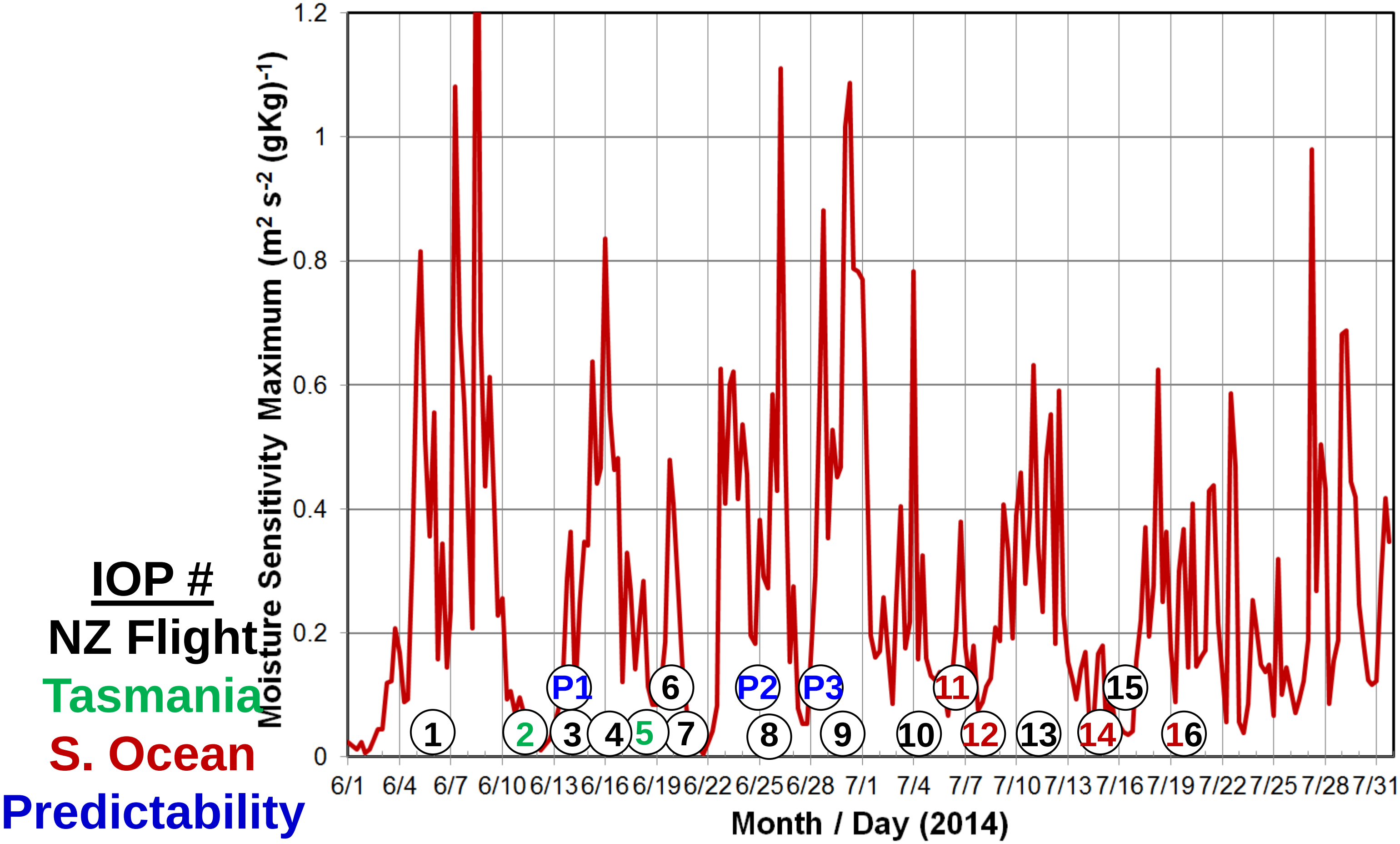
700-hPa Temperature Sensitivity (24 h)



- Mean 700-hPa flow shows a weak trough near S. Island (strong cases)
- Mean 700-hPa temperature sensitive regions are complex, with maxima to the southwest, west, north of South Island, New Zealand.

Moist Adjoint Sensitivity

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

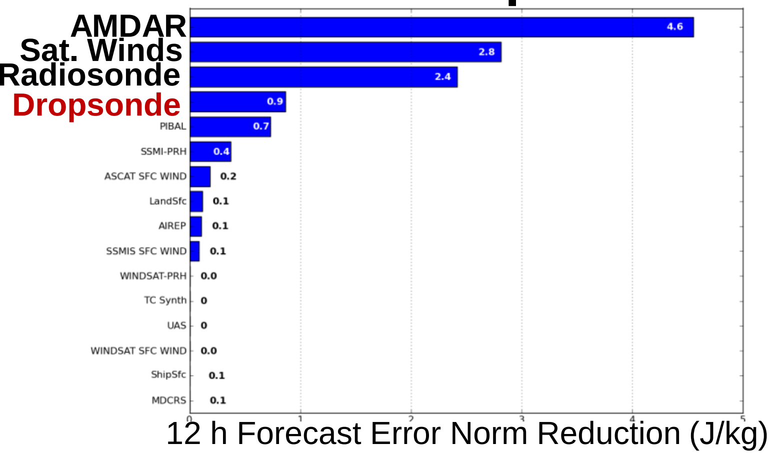


- Maximum sensitivity of the low-level wind speed over the S. Island (1 km deep response function) to the initial moisture.
- Maximima correspond to the IOP periods in general.
- Largest moisture sensitivity peaks: IOPs 1, 8, 9, lesser 4, 10, 13

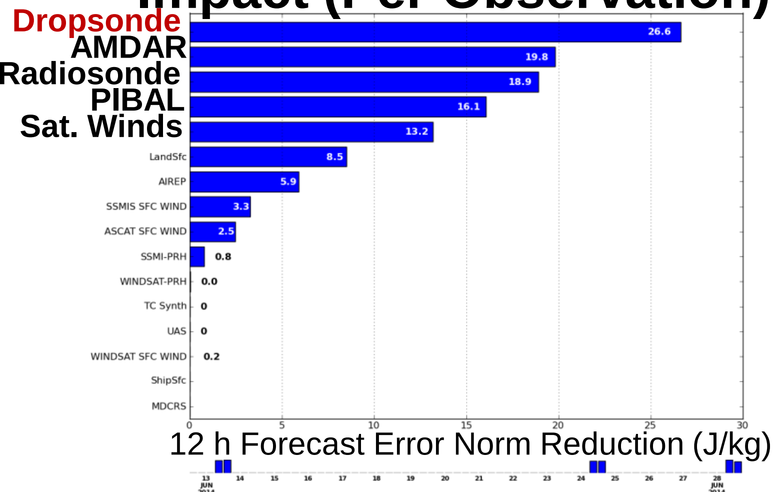
G-V Targeted Dropsonde Impact

Adjoint Observation Impact Diagnostics

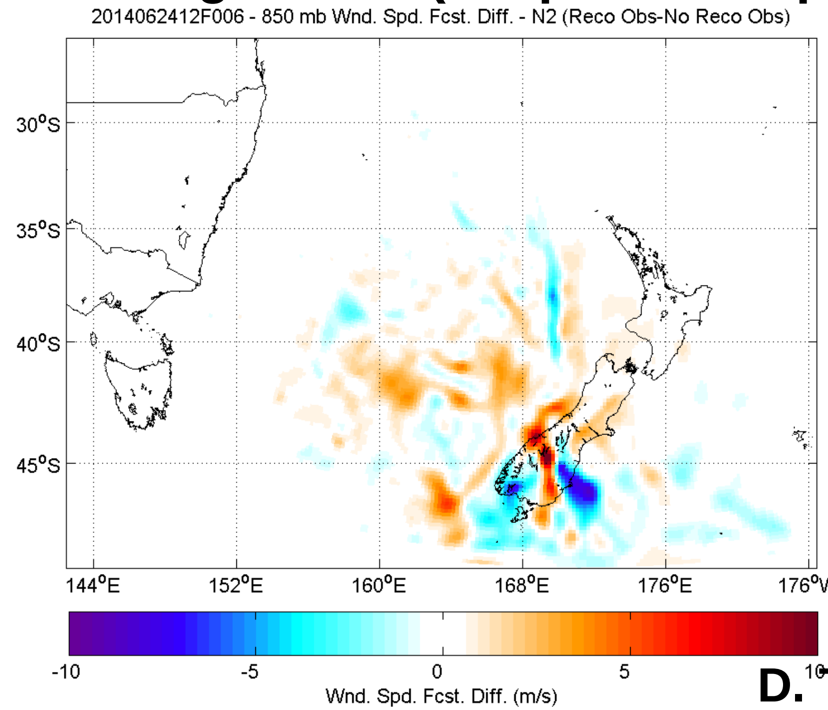
Total Impact



Impact (Per Observation)



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

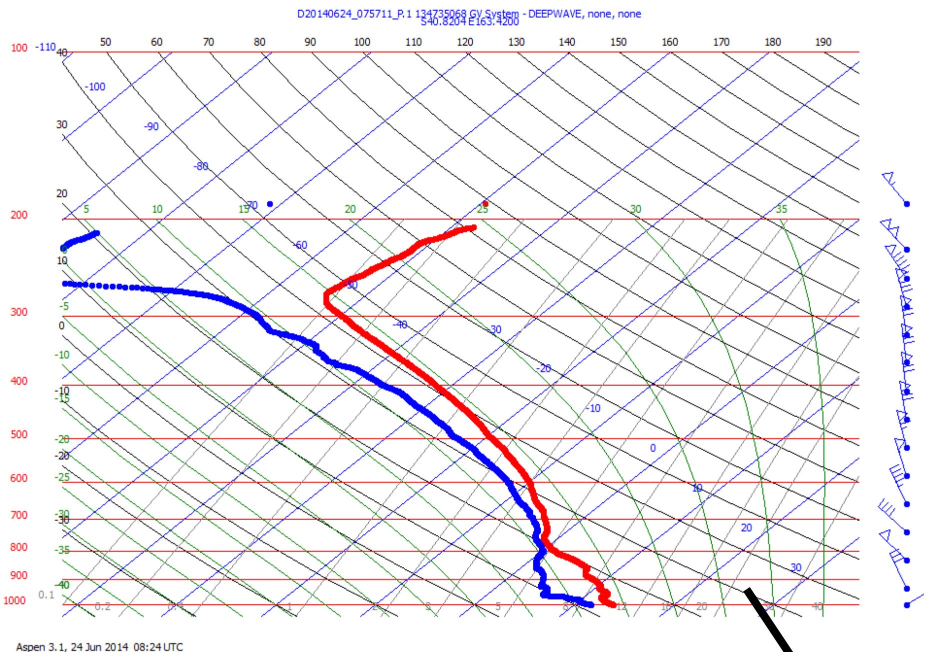


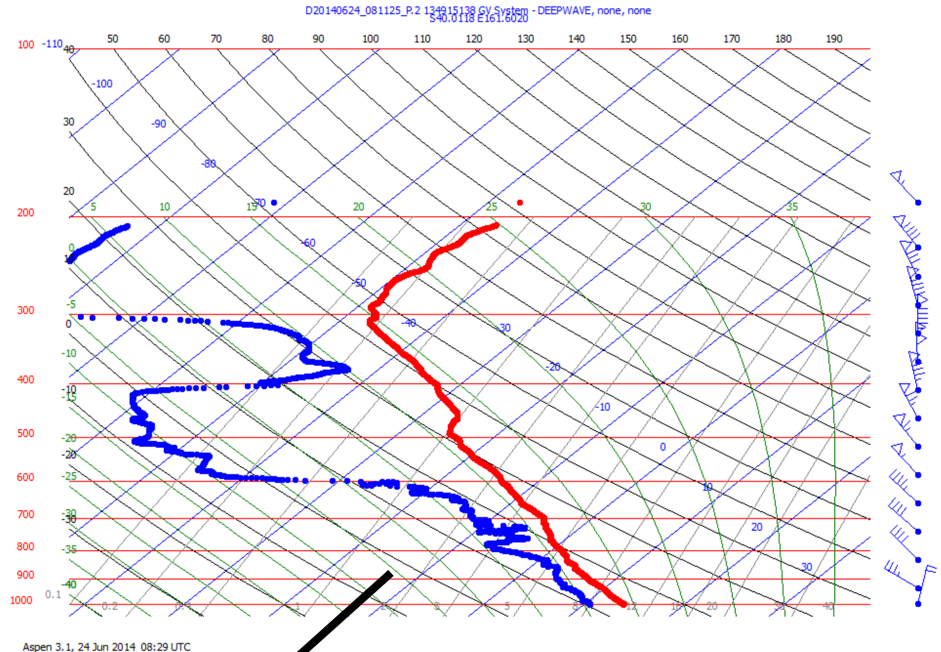
D. Tyndall

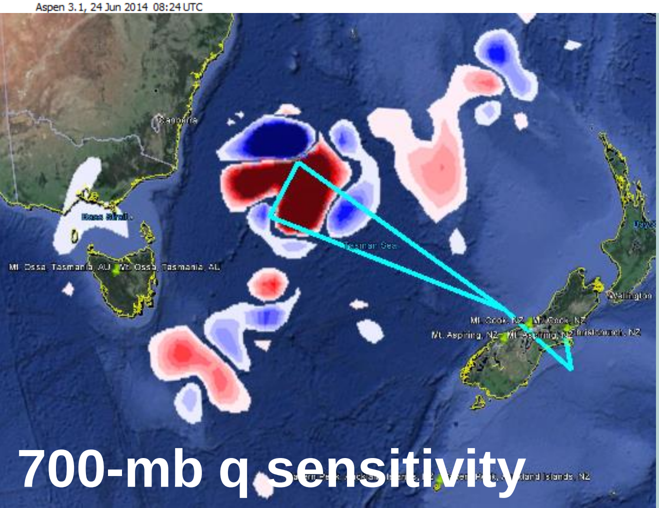
- Adjoint (model/DA) observation impact on 12-h forecasts for the 3 predictability flights.
- Targeted dropsondes have the largest impact on a per observation basis, and 4th largest impact overall.
- Forecasts with dropsondes assimilated in 4D-Var differ greatly in wave launching.

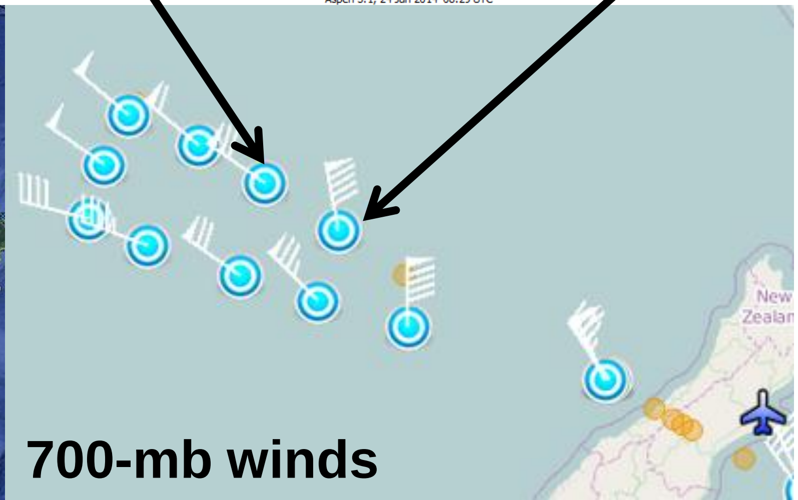
Adjoint Sensitivity

Meteorology of the Sensitive Regions: RF09





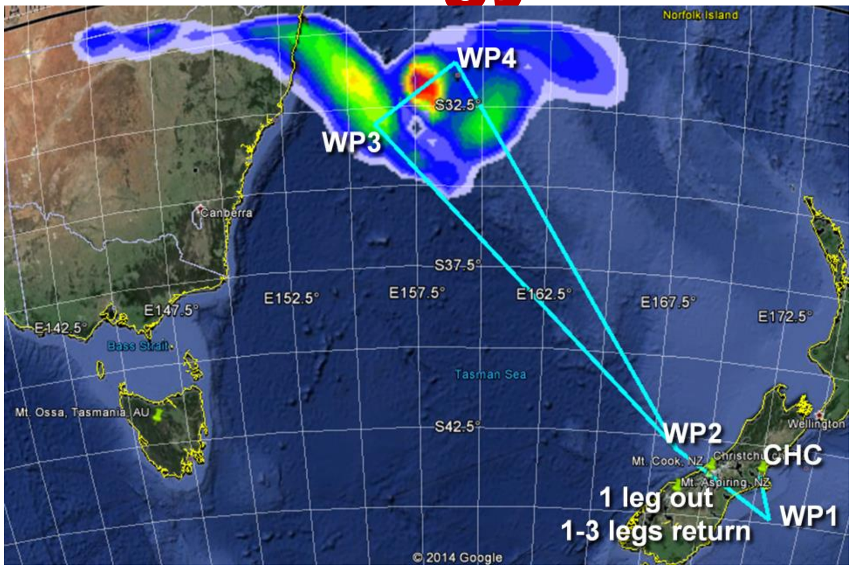


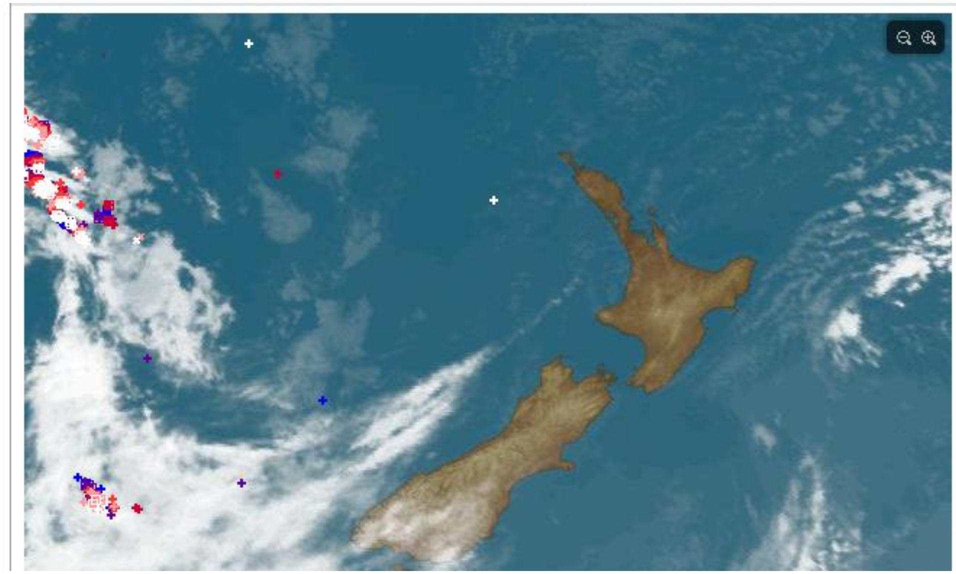


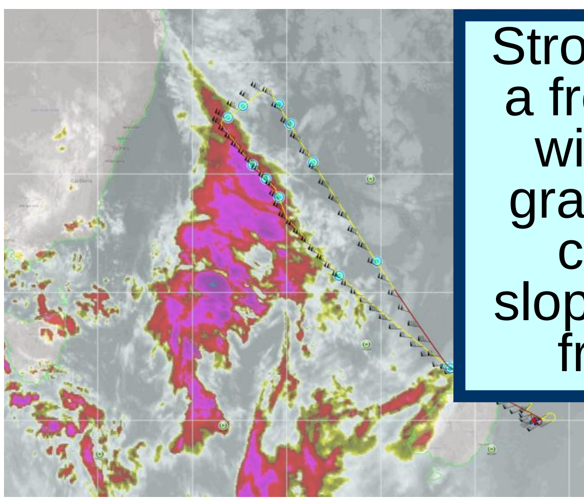
Large differences in the moisture over short distance

Adjoint Sensitivity

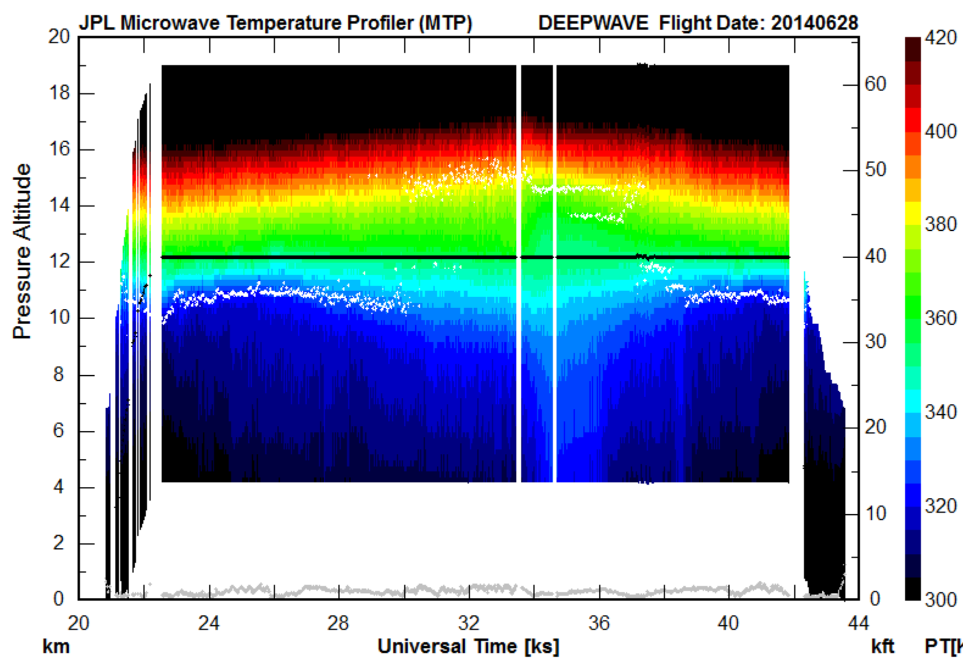
Meteorology of the Sensitive Regions: RF11





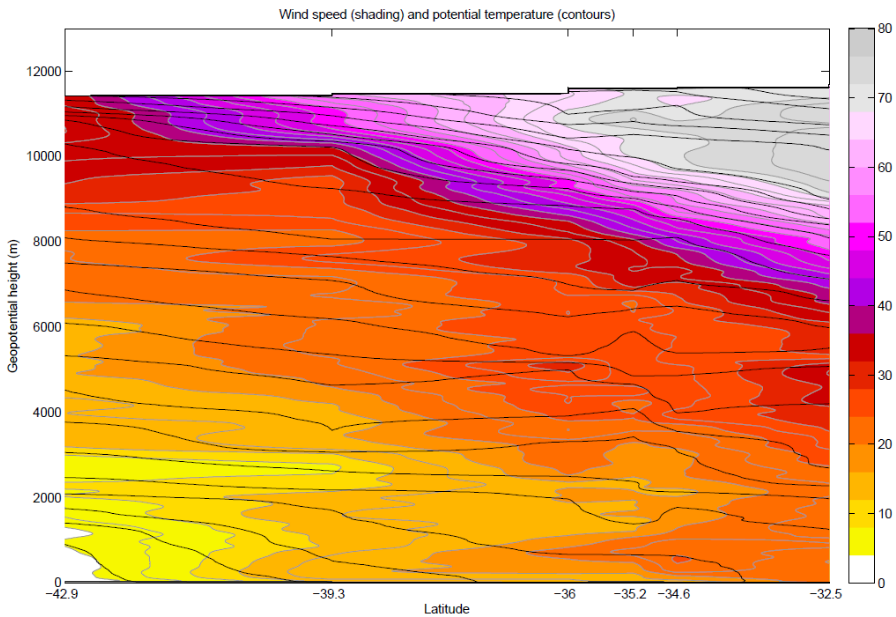


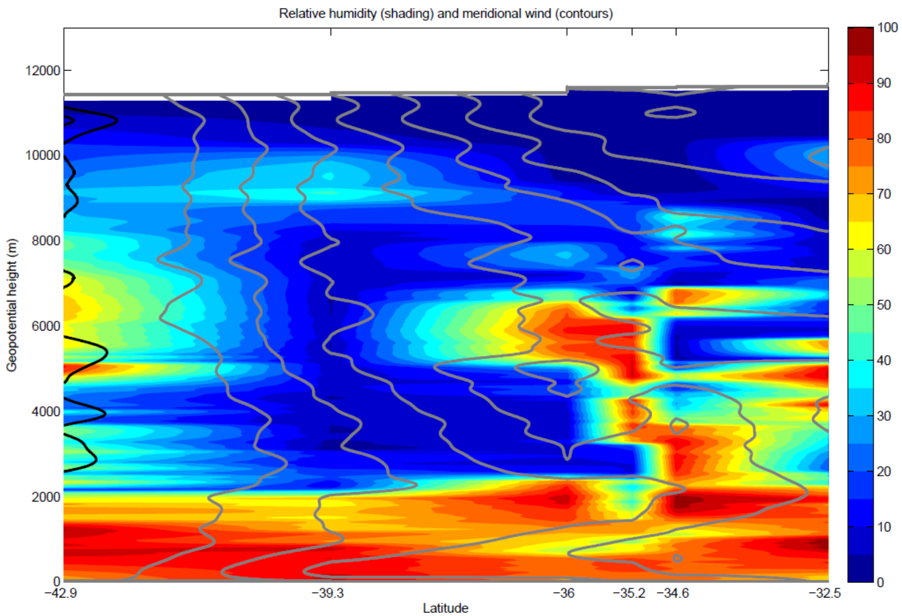
Strong jet, above a frontal system with moisture gradients, deep convection, sloping mid-level front (MTP)



Adjoint Sensitivity

Meteorology of the Sensitive Regions: RF11

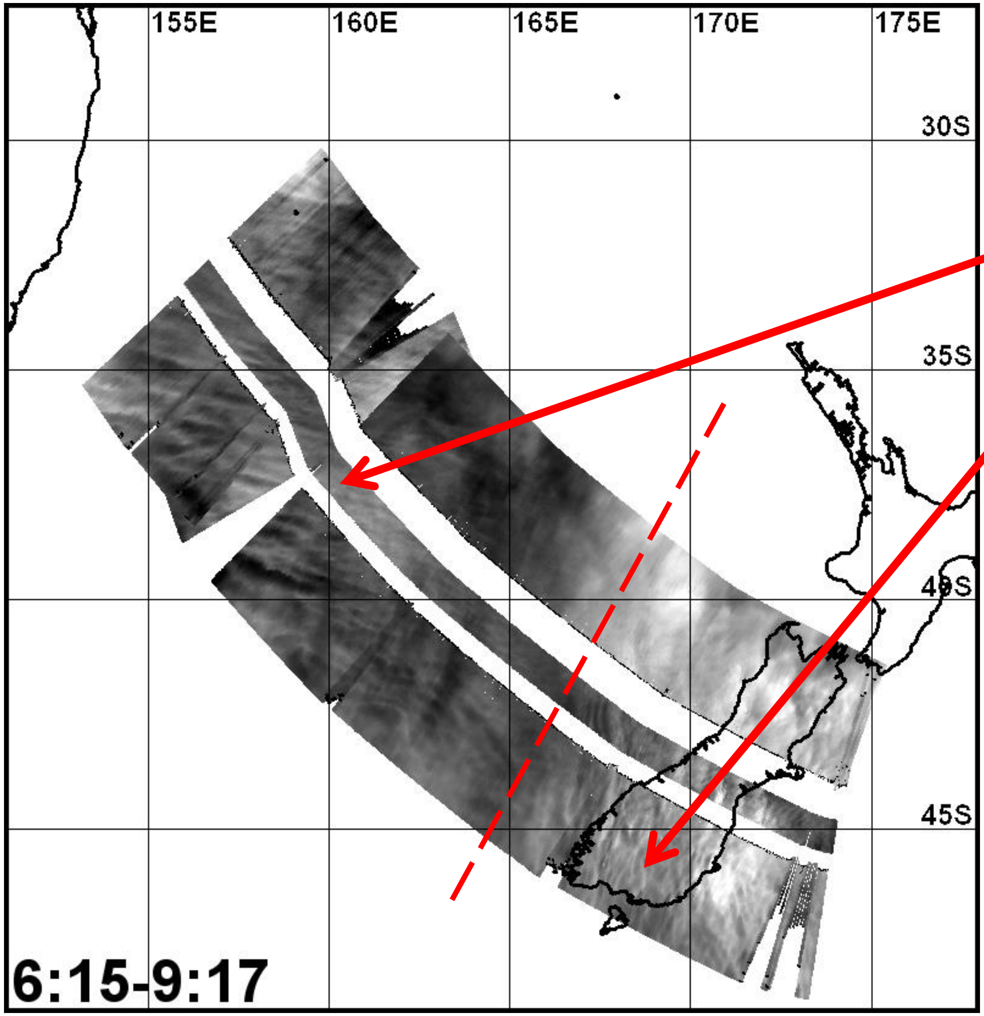




Dropsondes show sloping frontal region, strong upper-level and low-level coupled jets and evidence of convection.

Comparison of Over Land and Open Ocean Regions of Gravity Waves

DEEPWAVE RF11 28 June



- Two Different Source Regions
  - Tasman Sea
  - South Island, NZ
- Extensive regions of gravity waves excited by non-orographic (convection and/or jet) and orographic forcing.

Mike Taylor, Dominique Pautet (USU Group)

Outline

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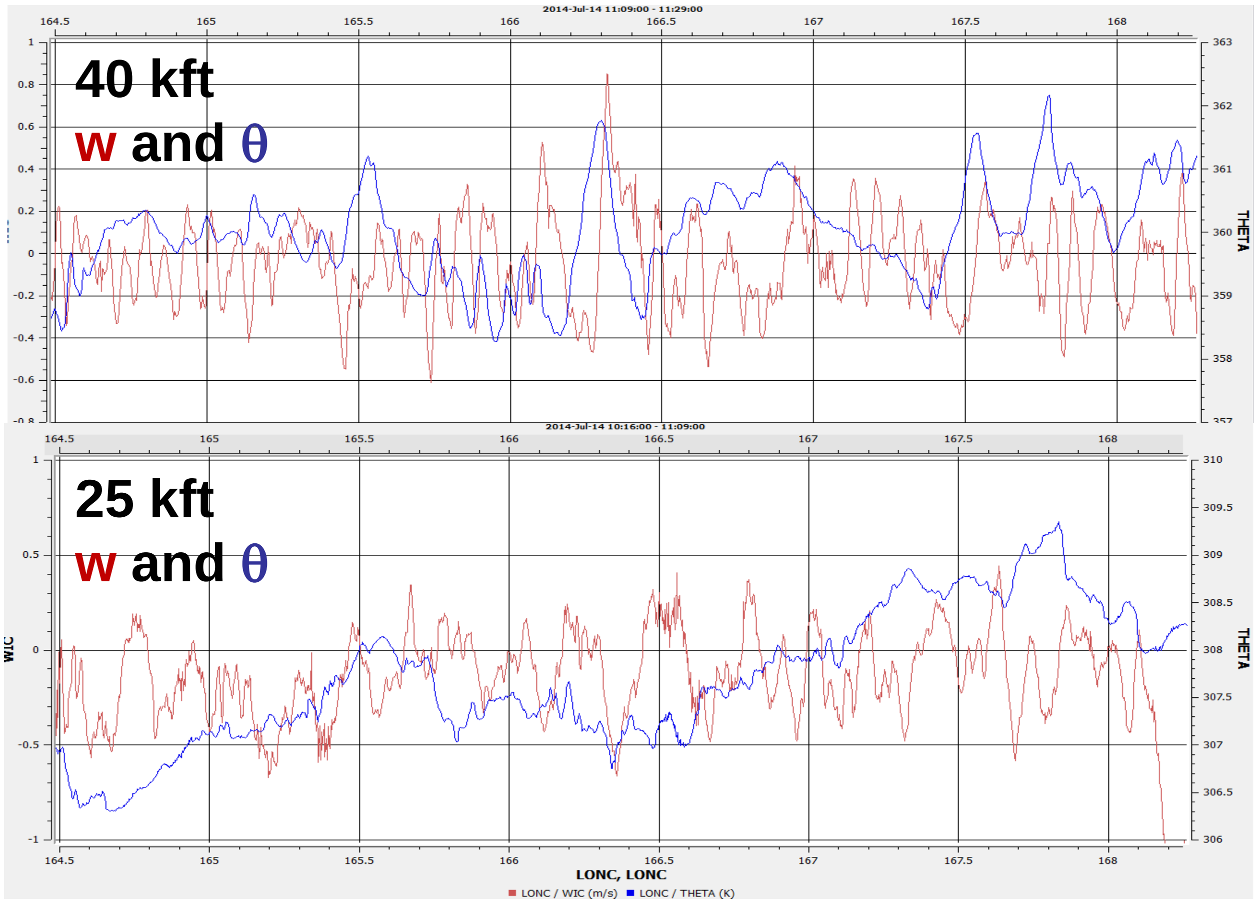
3) Gravity Wave Sources

Deep Propagating Gravity Waves Over Auckland and Macquarie Islands (RF23)

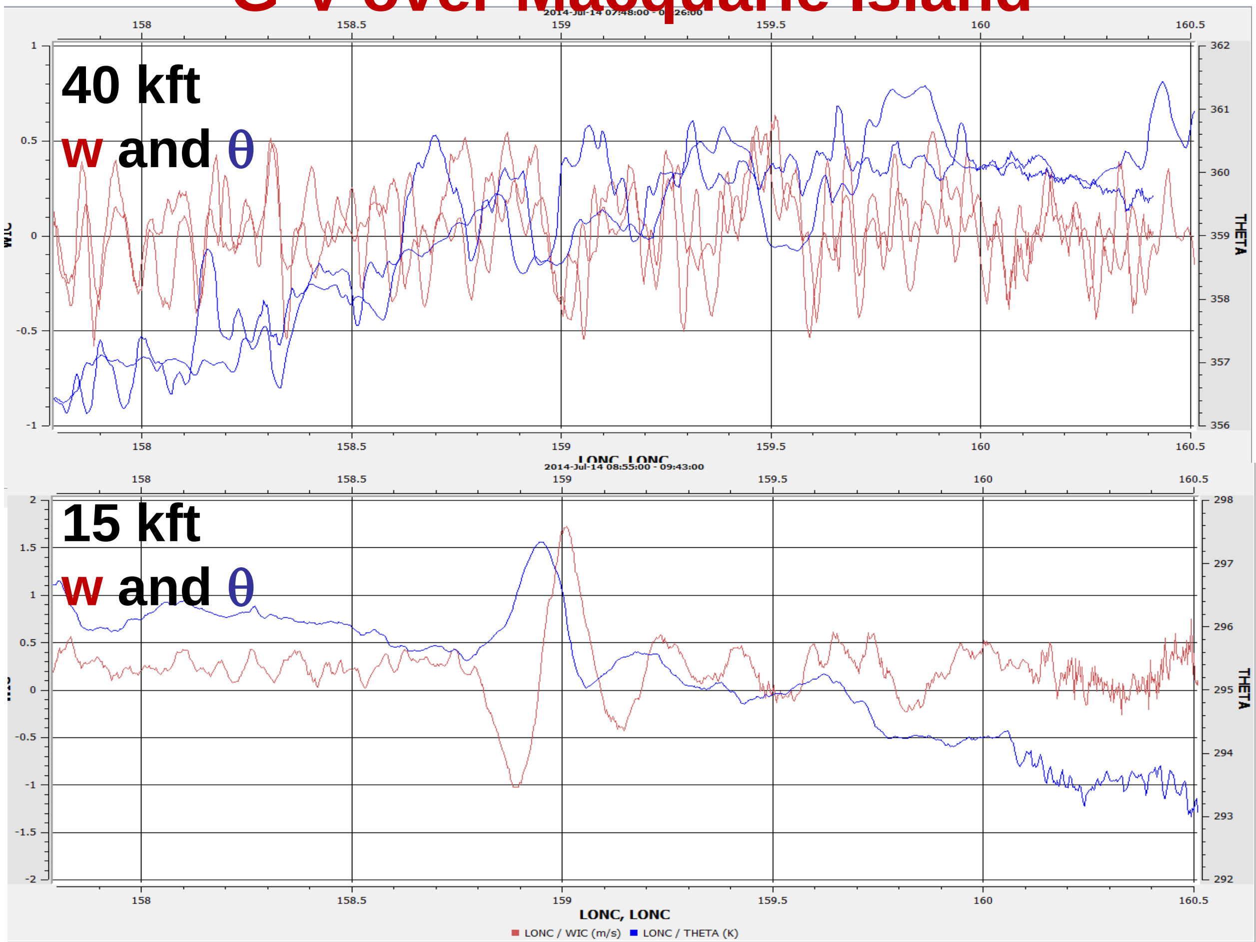
G-V over Auckland Islands



•G-V showed small amplitude wave over AI at 40kft, not as clear at 25 kft.

Deep Propagating Gravity Waves Over Auckland and Macquarie Islands (RF23)

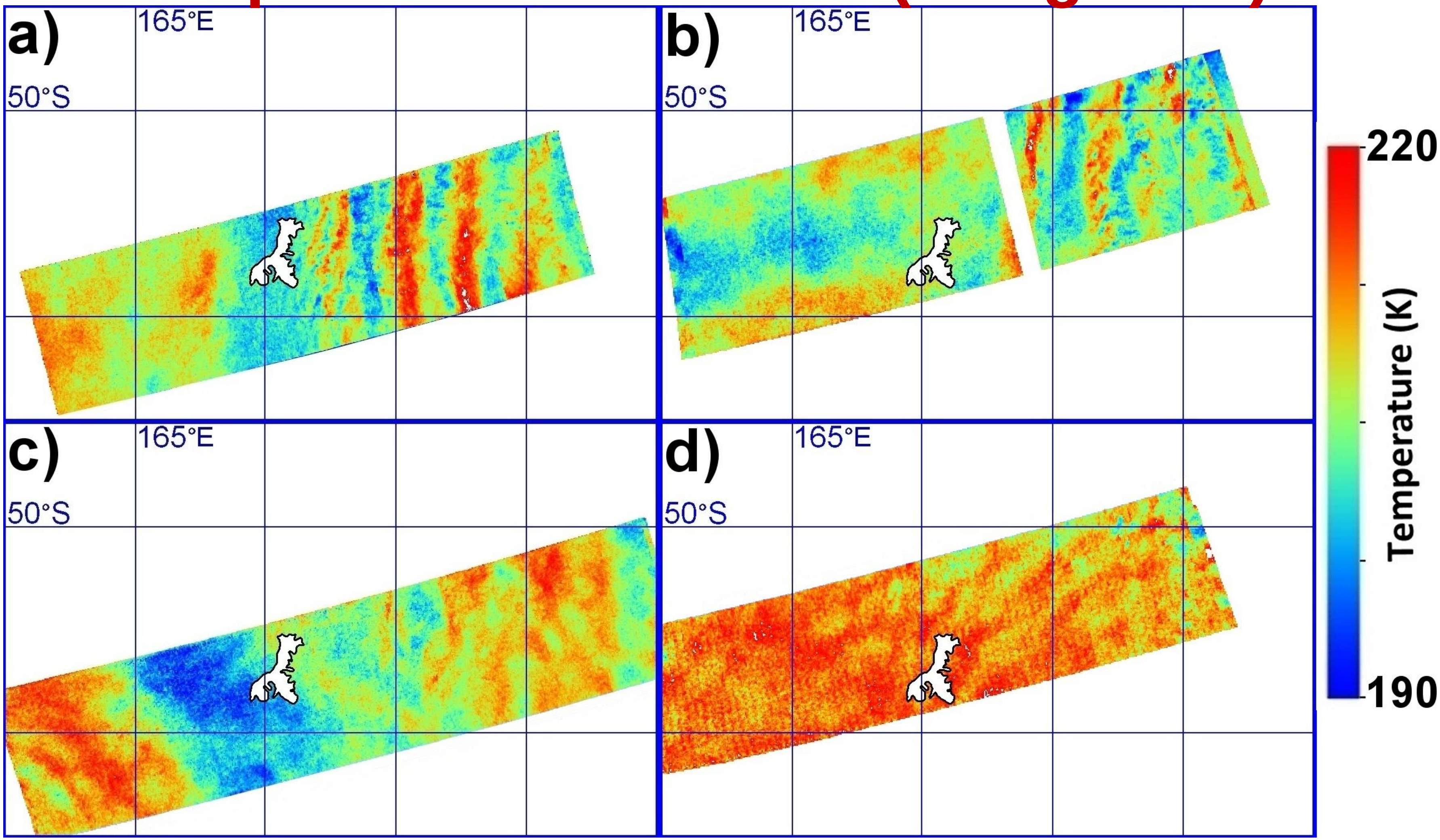
G-V over Macquarie Island



- Over Macquarie, the small amplitude waves at 15 kft do not seem to be apparent at the 40 kft level.
- The Macquarie terrain is likely too narrow to support deep propagation.

Deep Propagating Gravity Waves Over Auckland Island (RF23)

Temperature Retrievals (Keograms)



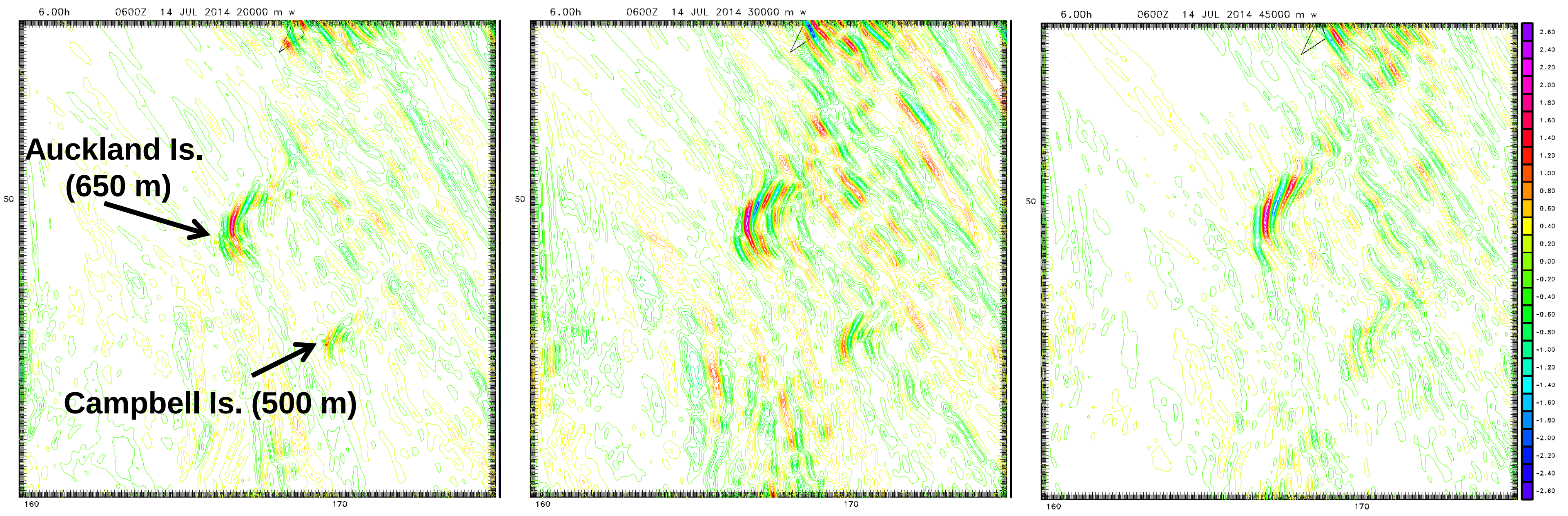
Dominique Pautet, Mike Taylor (USU Group)

Deep Propagating Gravity Waves Over Auckland and Macquarie Islands (RF23)

COAMPS Simulations of Auckland Is Gravity Waves

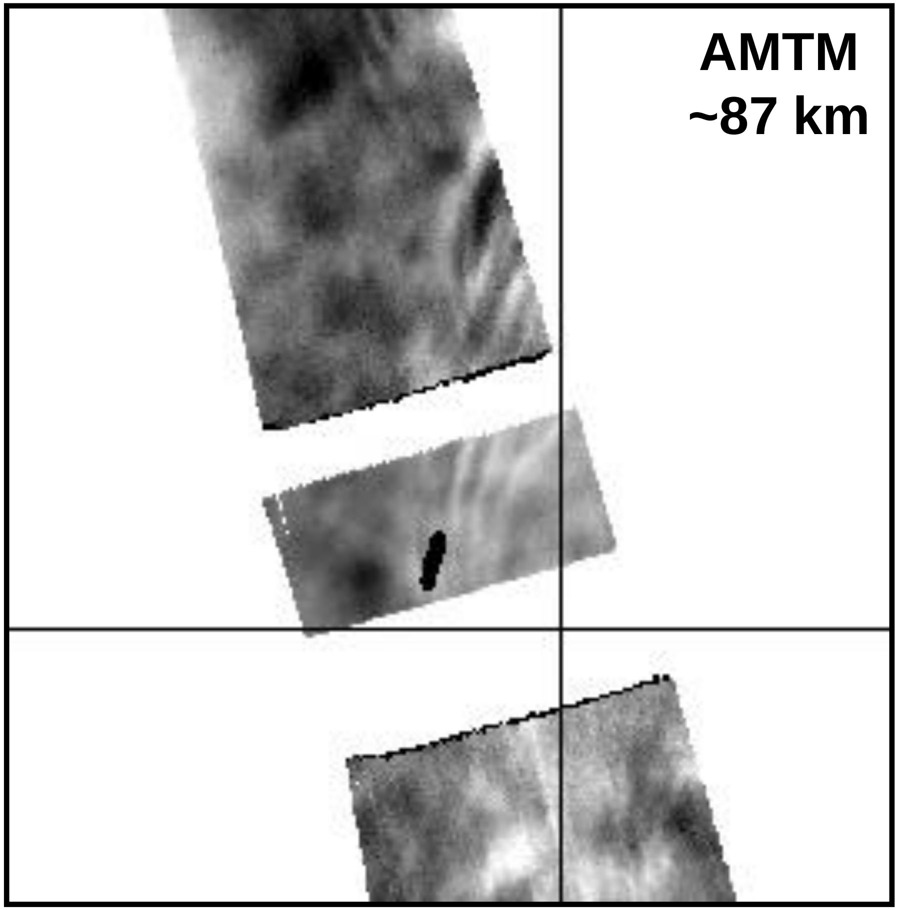
- 1.7 km resolution nest, 86 vertical levels
- Model top: 58 km

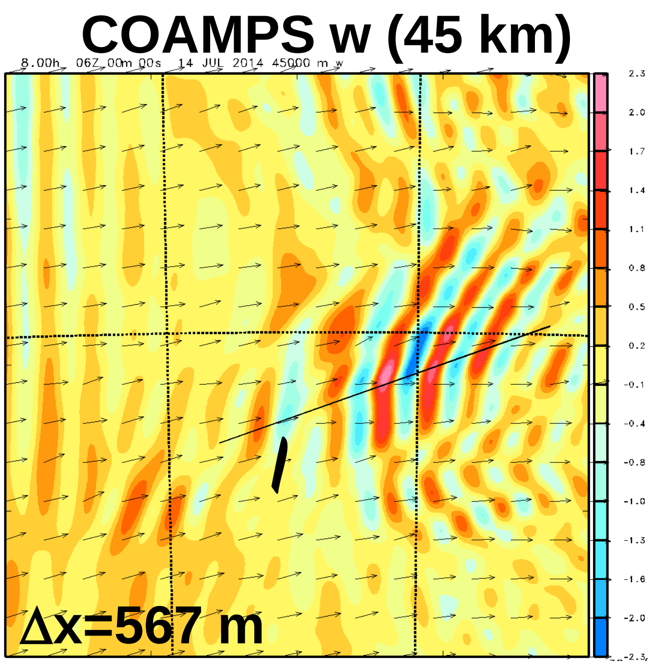
w at 20 km **w at 30 km** **w at 45 km**

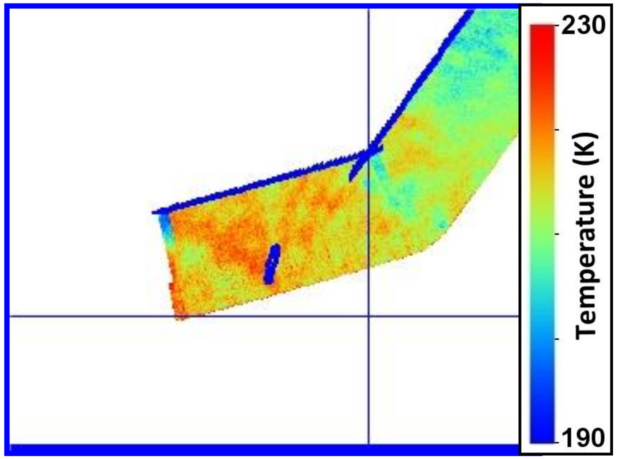


Mountain waves generated by Auckland Is. Penetrate to high altitudes (45 km and above), while mountain waves excited by Campbell Is. do not.

Deep Propagating Gravity Waves Over Macquarie Island (RF23)







Macquarie Island (h=410m)

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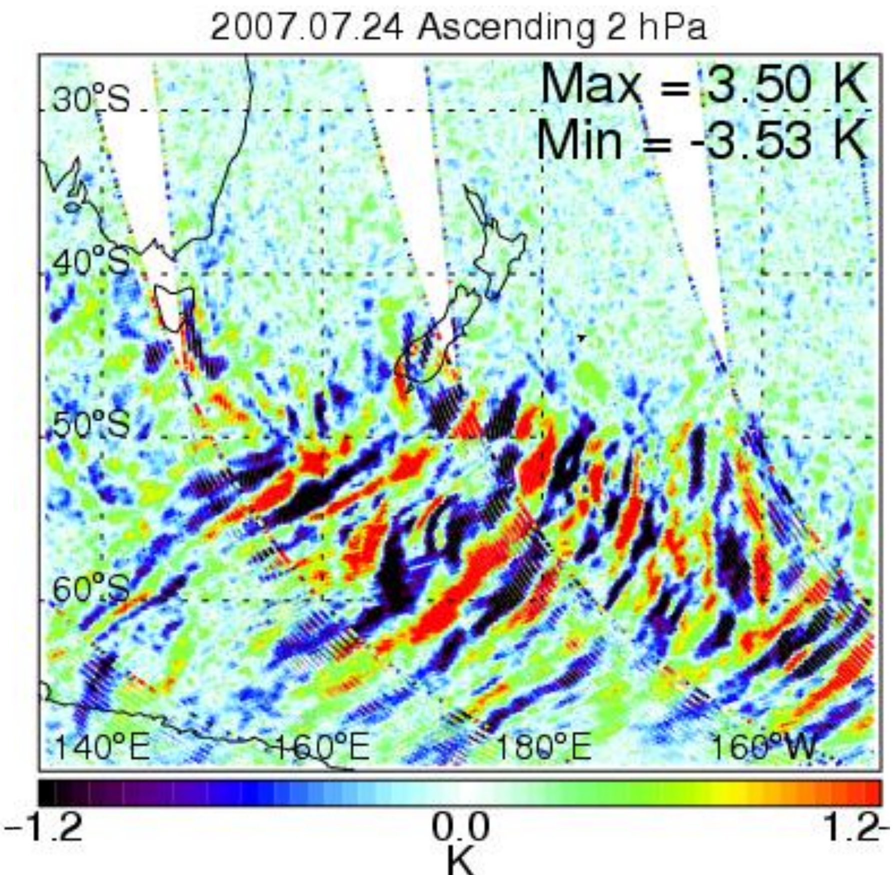
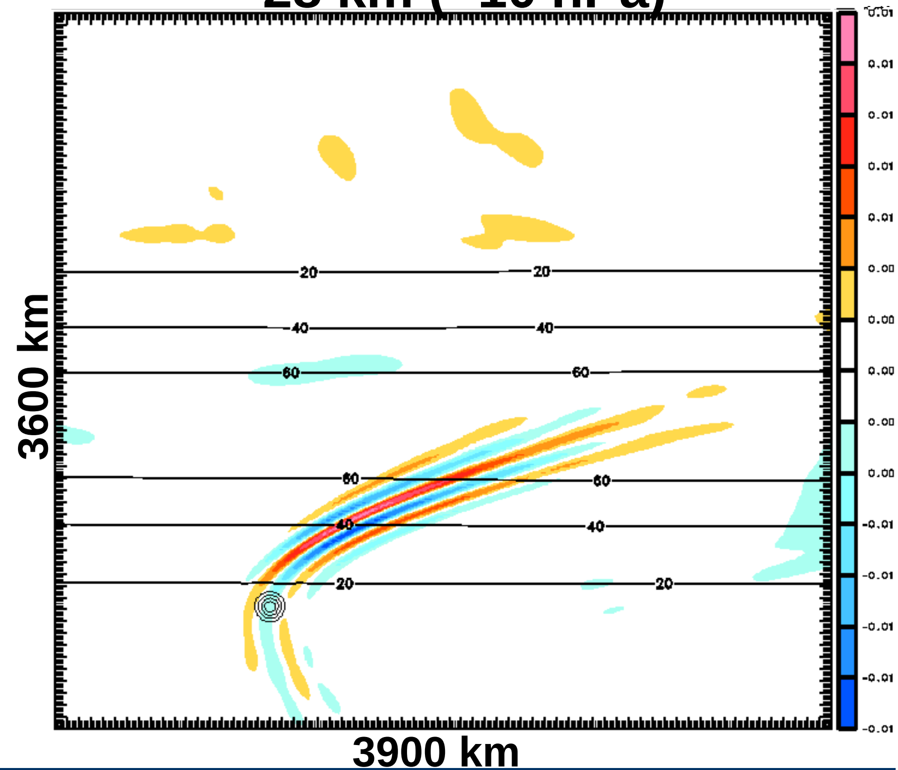
Gravity Waves in Sheared Flow

Idealized Shear Experiments



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



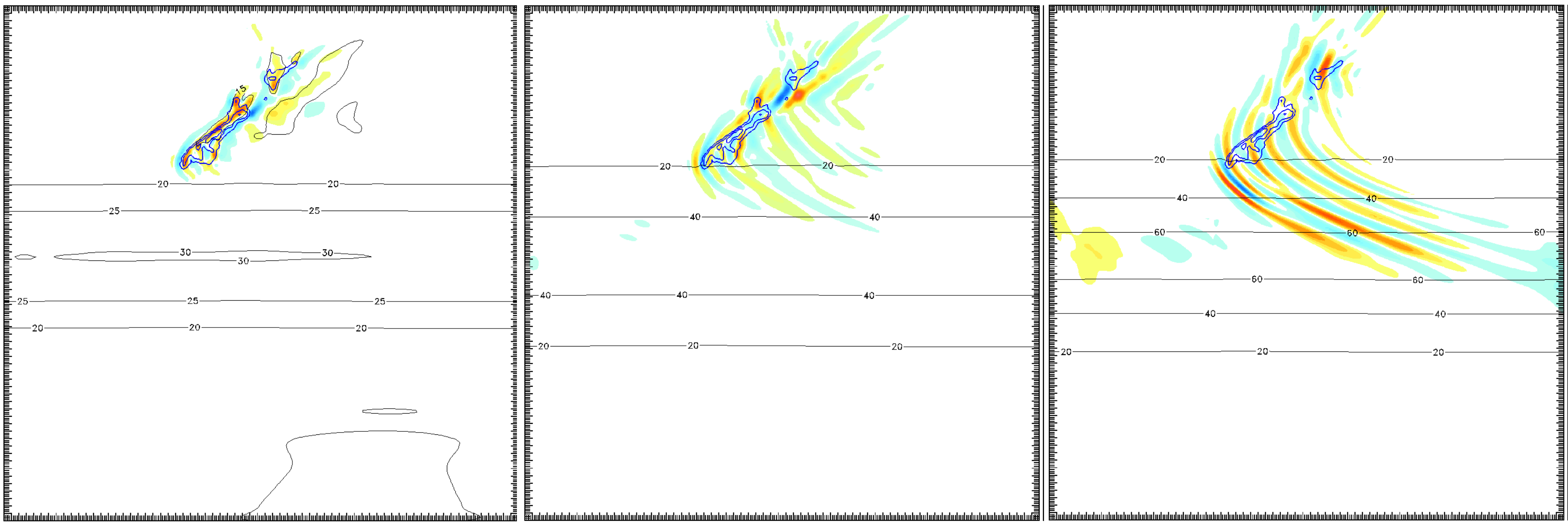
- Stronger shear leads to greater wave refraction and further propagation of the wave energy into the jet and downstream.
- Marked asymmetries are apparent in the waves due to the refraction into the jet and absorption at directional critical lines.
- None of these effects are included in wave drag parameterizations.

Gravity Waves in Sheared Flow

Idealized Shear Experiments with New Zealand Terrain

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

5 km **12 km** **25 km**



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

Outline

1) Predictability

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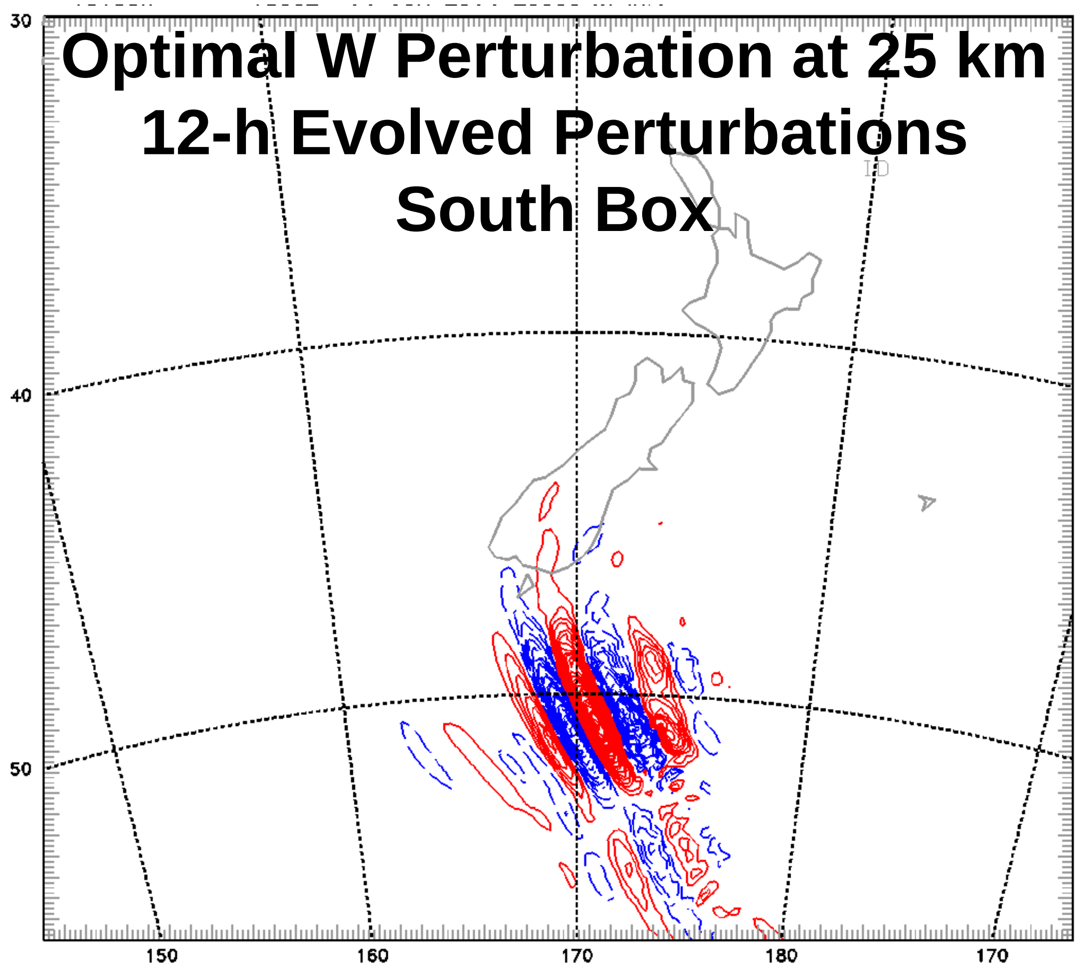
3) Gravity Wave Sources

Gravity Wave Source Identification

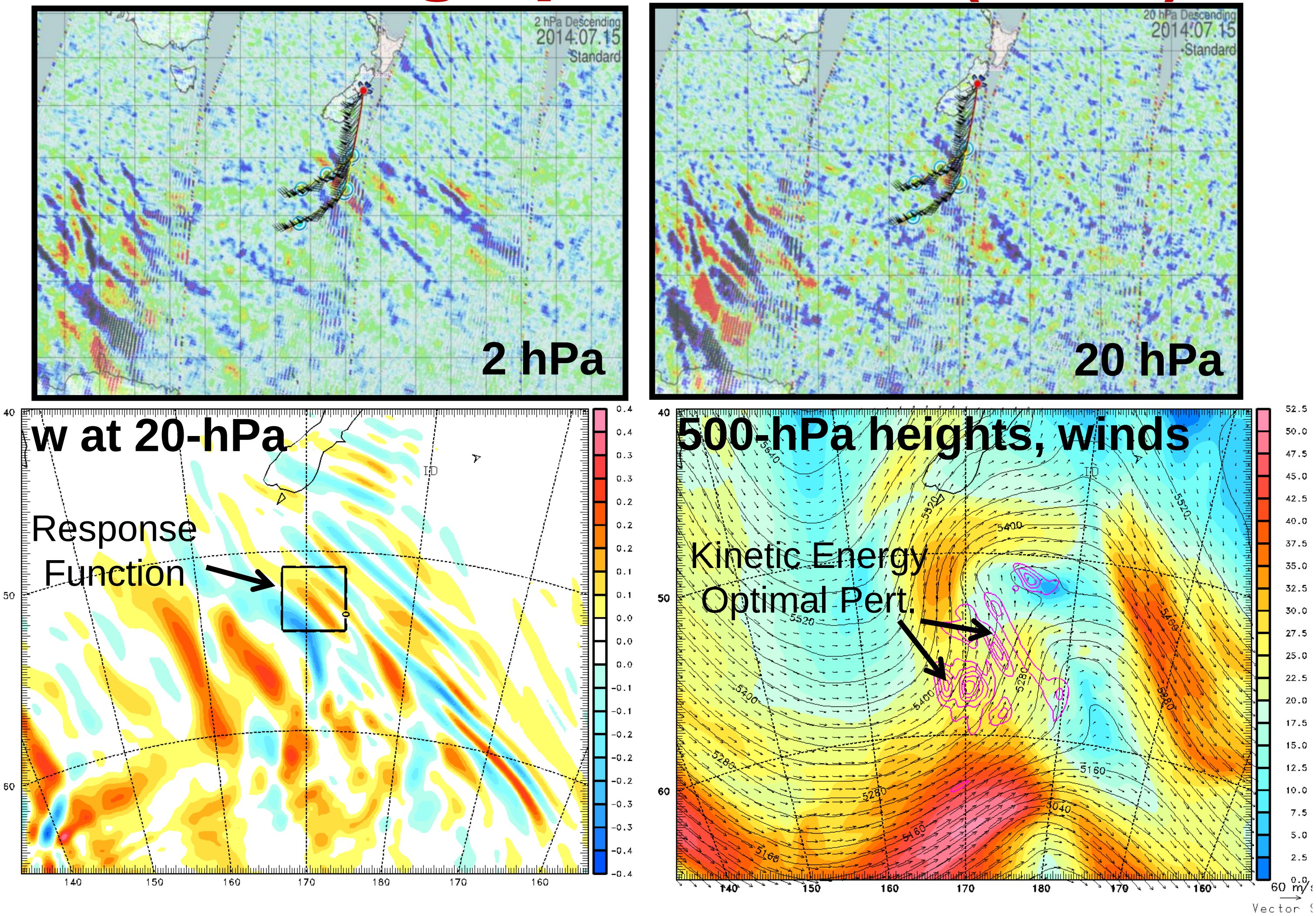
Trailing Waves in IOP 3 (RF04)



- 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 (RF24)



- Adjoint identifies left exit region of mid-tropospheric jet as possible source
- Waves may also be excited by decelerations in high-amplitude pattern.

Summary

- **Predictability:**
  - ➢ Overview of adjoint results and linking sensitivity with weather
    - Need to incorporate dropsondes and MTP into analysis of sensitivity
  - ➢ Observation impact and data denial experiments using 4D-Var
    - Assimilate latest dropsonde dataset, compare waves between model and obs
  - ➢ Sensitive regions (GW seeds) linked to strong meteorological forcing

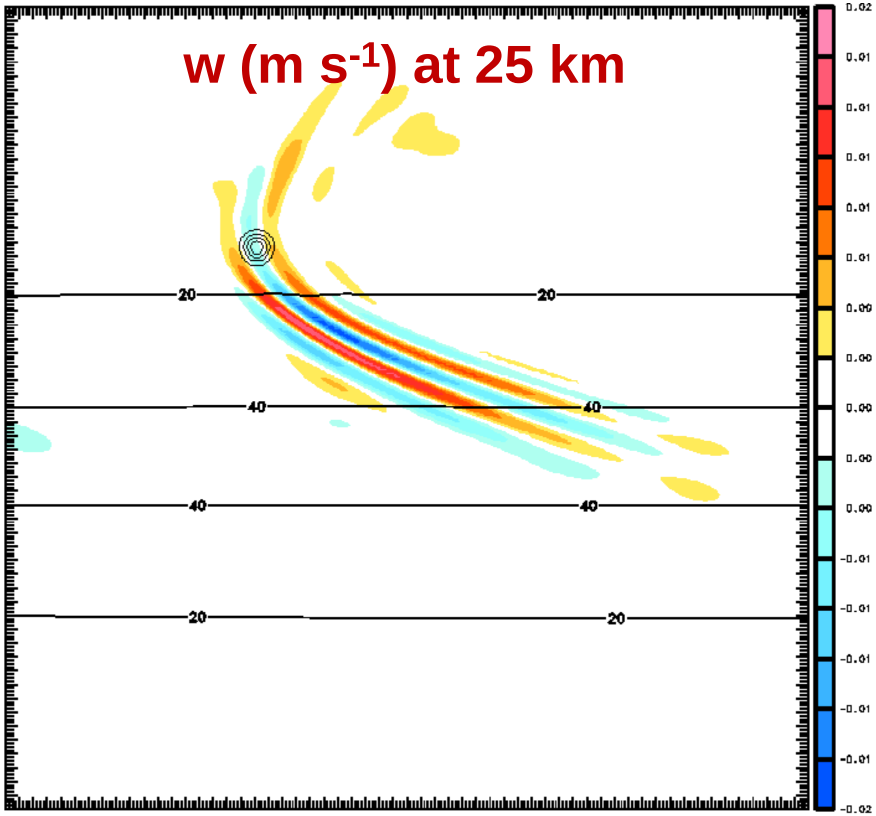
- **Deep Propagating Gravity Waves and Gravity Wave Refraction:**
  - ➢ Idealized gravity waves in lateral shear
  - ➢ RF23 study: 95 km top, compare w/G-V, AMTM, lidars, linear models

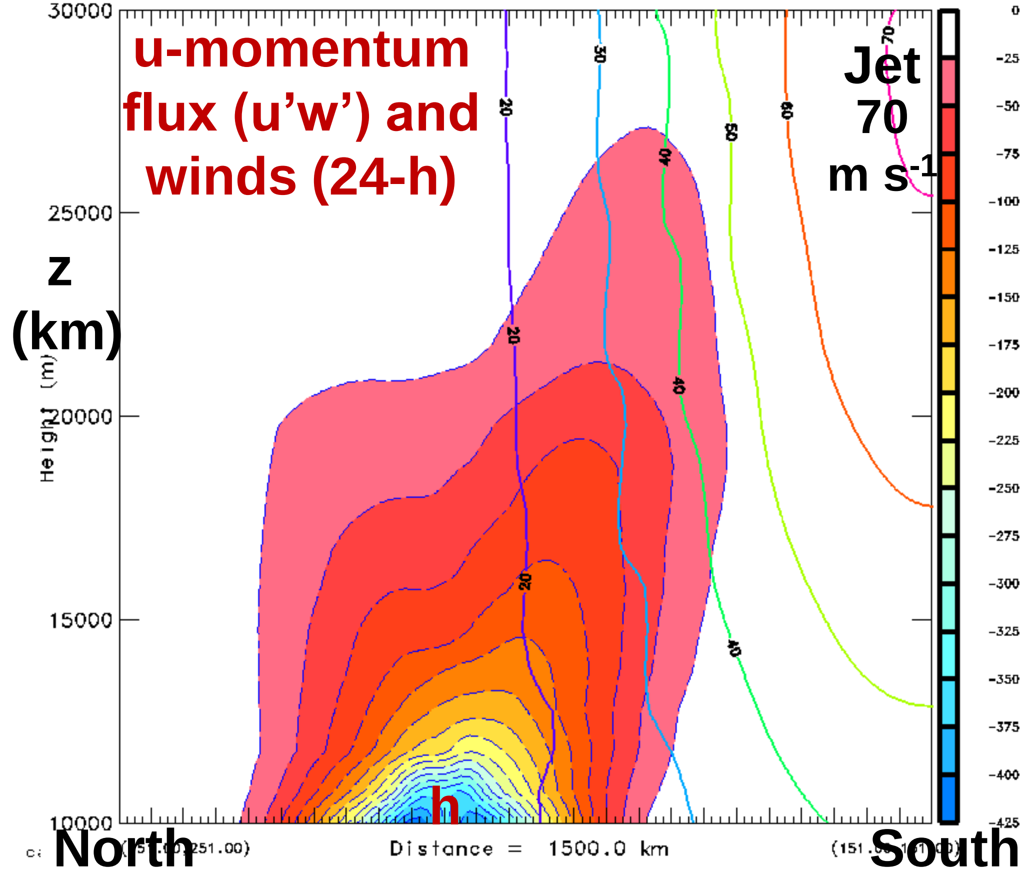
- **Gravity Wave Source Identification:**
  - ➢ Demonstration of technique, comparison with linear ray tracing (Steve?)

- **Synoptic-Scale Overview (w/ DLR):**
  - ➢ Summarize key synoptic-scale features for GWs over the DEEPWAVE domain during June-July 2014 & interpret in a climatological perspective.
    - Collaborate with DLR and others…

Gravity Waves in Sheared Flow

Idealized Shear Experiments

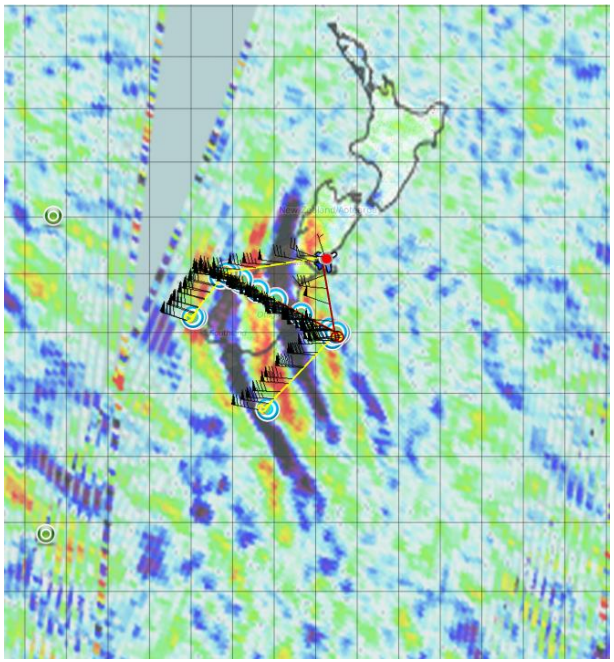




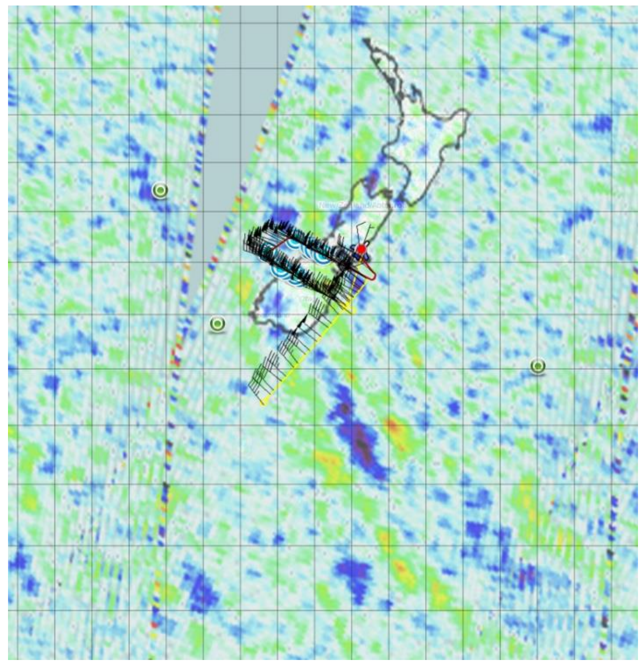
- Role of horizontal shear potentially a key issue for DEEPWAVE.
- Idealized simulations of gravity waves in balanced shear (Δx=15 km)
- Flow over Gaussian hill (north of jet) leads to vertically propagating waves that are refracted by the horizontal shear in the stratosphere.
- Zonal momentum flux in the stratosphere shows refraction due to shear.

Deep Propagating Gravity Waves and Wave Refraction due to Shear

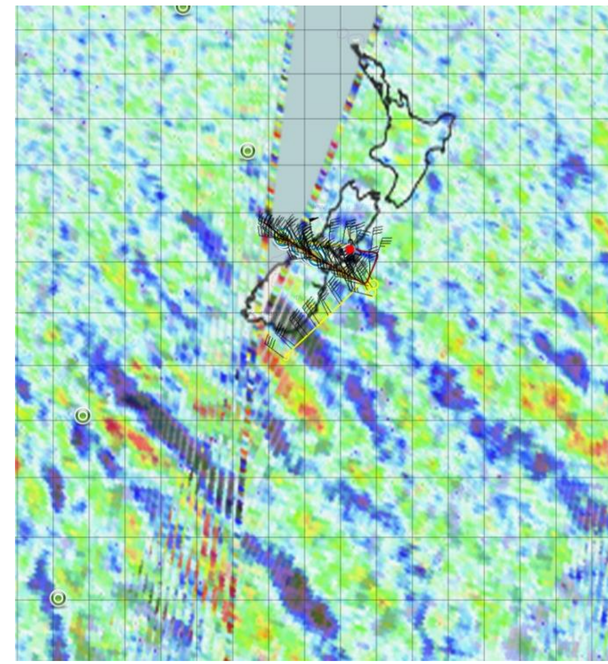
RF4



RF13

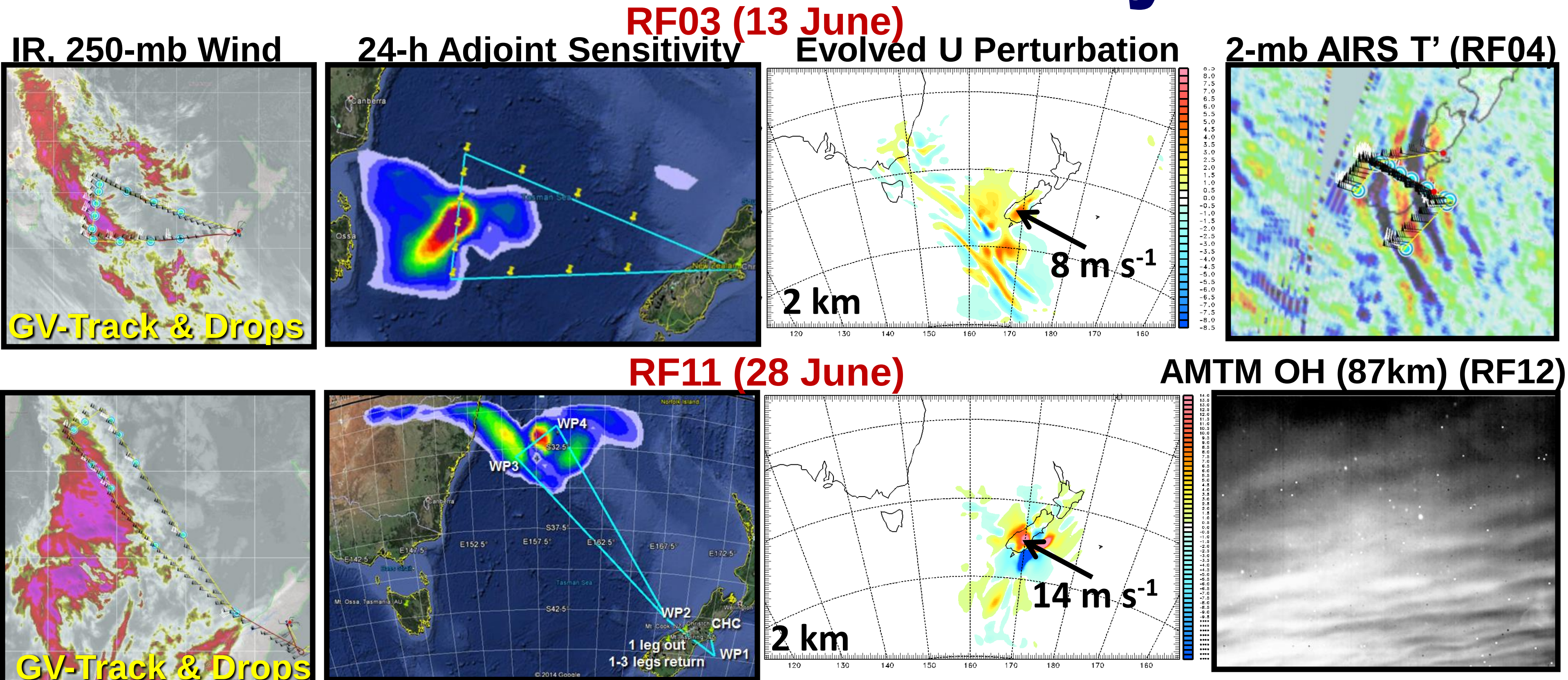


RF18



- Several cases during DEEPWAVE of G-V measurements beneath trailing waves.

DEEPWAVE G-V Predictability Missions



- G-V predictability flights (w/ drops) sampled initial condition sensitivity regions upstream of the S. Alps prior to gravity wave (GW) events (3 flights)
- 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 will be used to quantify the predictability relationship between lower and upper levels of the atmosphere.