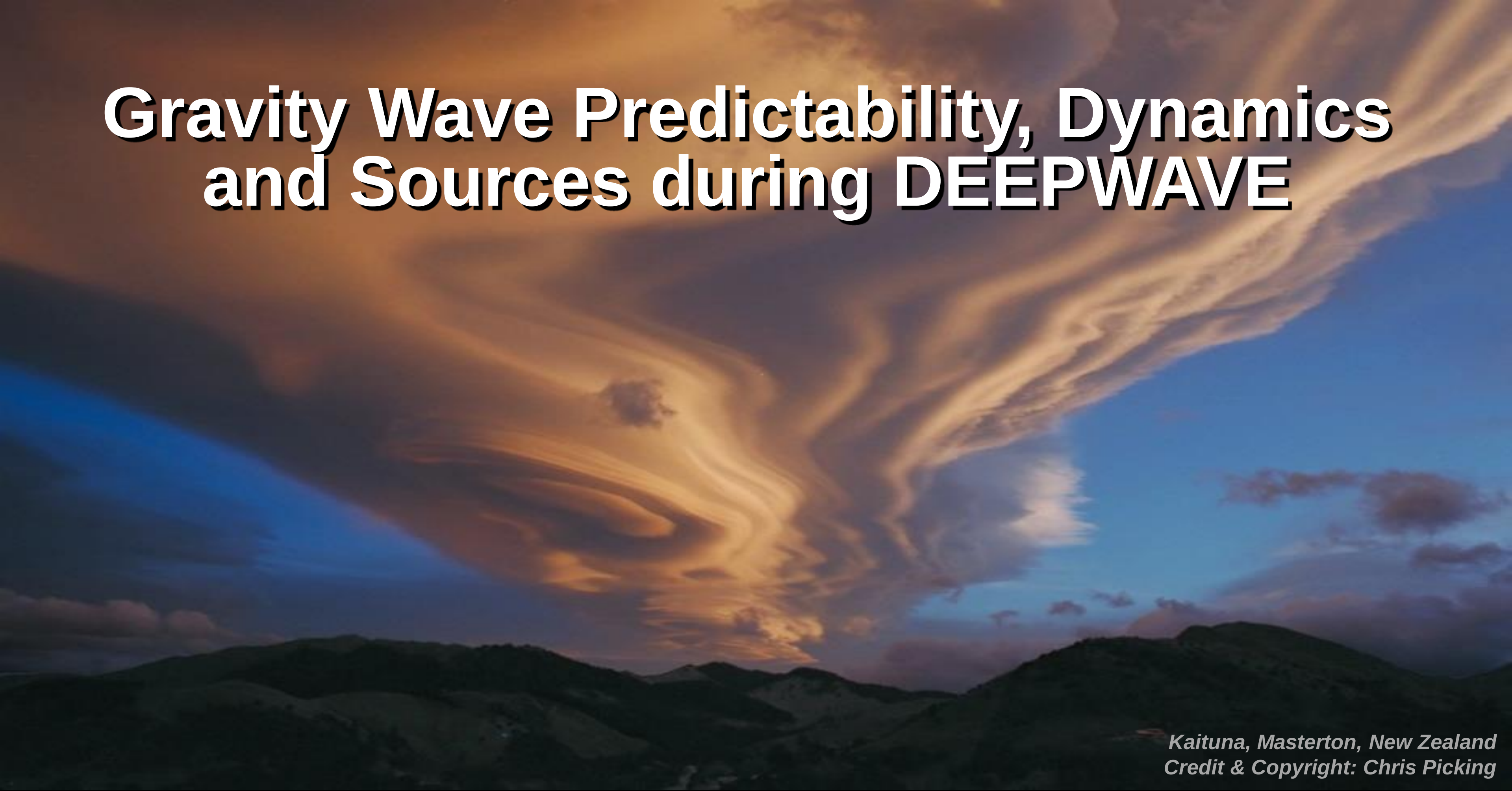
Gravity Wave Predictability, Dynamics and Sources during DEEPWAVE



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

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Acknowledgements: NSF, NRL, NCAR, DeepWave Team

NRL-Monterey DEEPWAVE Objectives

Predictability, Dynamics and Sources of Deep Gravity Waves

- **Summary of our (very) preliminary results and plans**
- **Predictability (J. Doyle, A. Reinecke):**
  - Quantify initial condition sensitivity and predictability of wave launching and deep propagating gravity waves
  - Links between stratospheric GW predictability and tropospheric storms
  - Quantify the uncertainty in wave predictions, fluxes etc.
- **Dynamics (J. Doyle, Q. Jiang, A. Reinecke):**
  - Deep propagating gravity waves induced by islands (RF23)
  - Trailing wave dynamics
  - Stochastic nature of gravity waves (particularly fluxes)
- **Gravity Wave Sources (J. Doyle, Q. Jiang):**
  - Sources of “trailing” gravity waves
  - Sources of non-orographic gravity waves

Summary of Predictability Missions

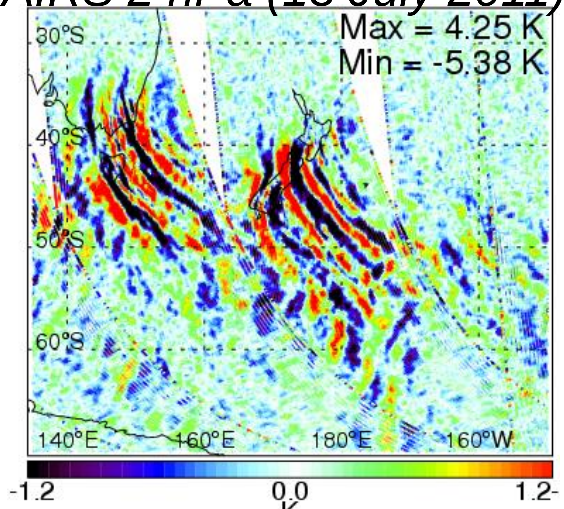
RF	IOP	Date	Flight Type	Location	Length	Comments	Grade
3	3	6/13/ 2014	Predictability	Tasman Sea	4.5 h	Sampled short wave trough, LLJ	A
9	8	6/24/ 2014	Predictability and SI Mountain Waves	Tasman Sea and Cook 1b	8.25 h 5 Cook transects	Sensitivity with cyclone, convection	A
-	-	6/25/ 2014	No flight, 3-h Hobart soundings (06Z-18Z)	Hobart, Tasmania	0	Partially sampled sensitive region.	C
11	9	6/28/ 2014	Predictability	Tasman Sea and Cook 1b	6 h 2 Cook transects	Sampled active convection, very strong jet.	A
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.	C
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	B

Predictability of Deep Propagating GWs

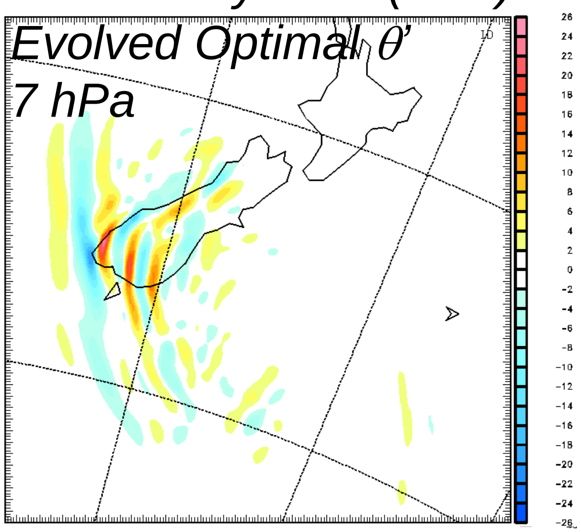
What are the predictability characteristics of deep propagating GWs?

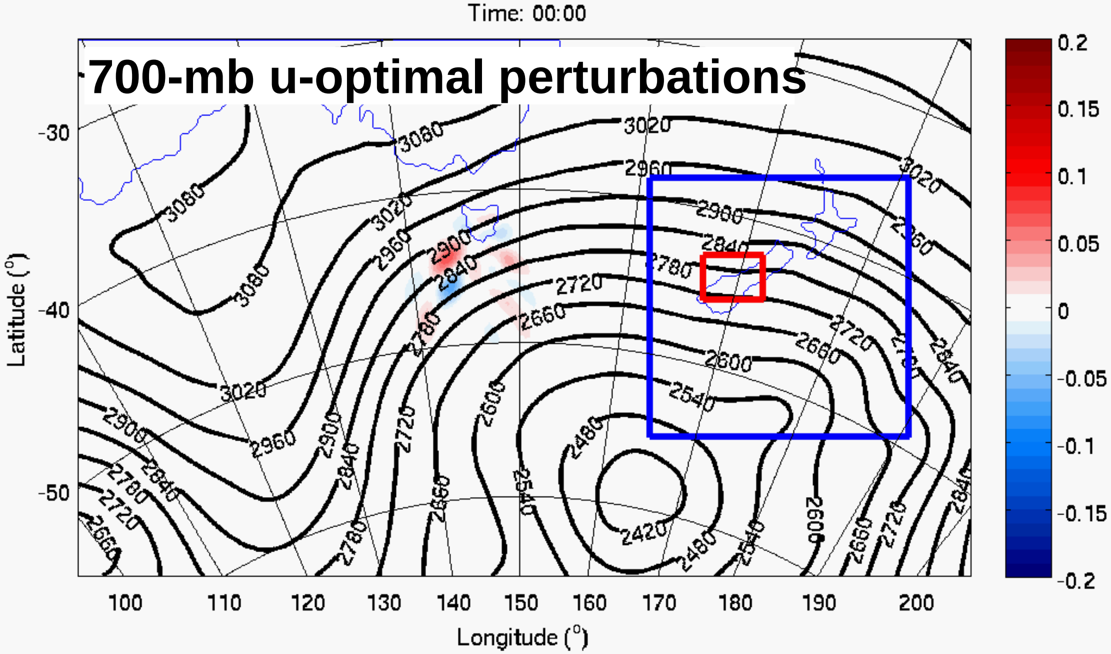
Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to changes in the initial state

AIRS 2 hPa (13 July 2011)



12Z 13 July 2011 (24 h)

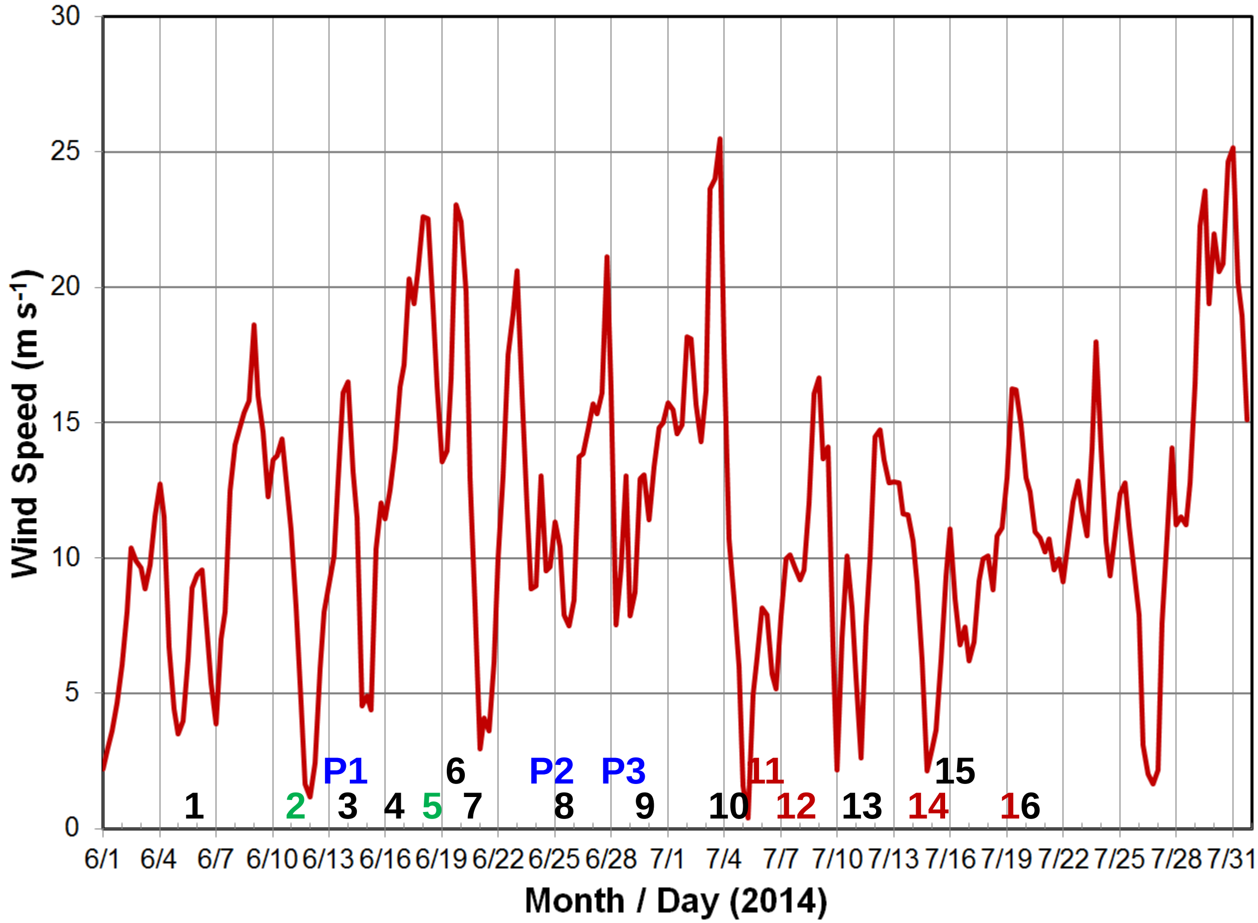




- Adjoint is used to diagnose sensitivity using a kinetic energy response function (lowest 1 km)
- Sensitivity located ~1200 km upstream near trough
- Adjoint optimal perturbations lead to strong wave propagation (refracted waves south of NZ)

Predictability of Deep Propagating GWs

June - July 2014 Wind Speed Over New Zealand at 1 km



IOP #

NZ Flight

Tasmania

S. Ocean

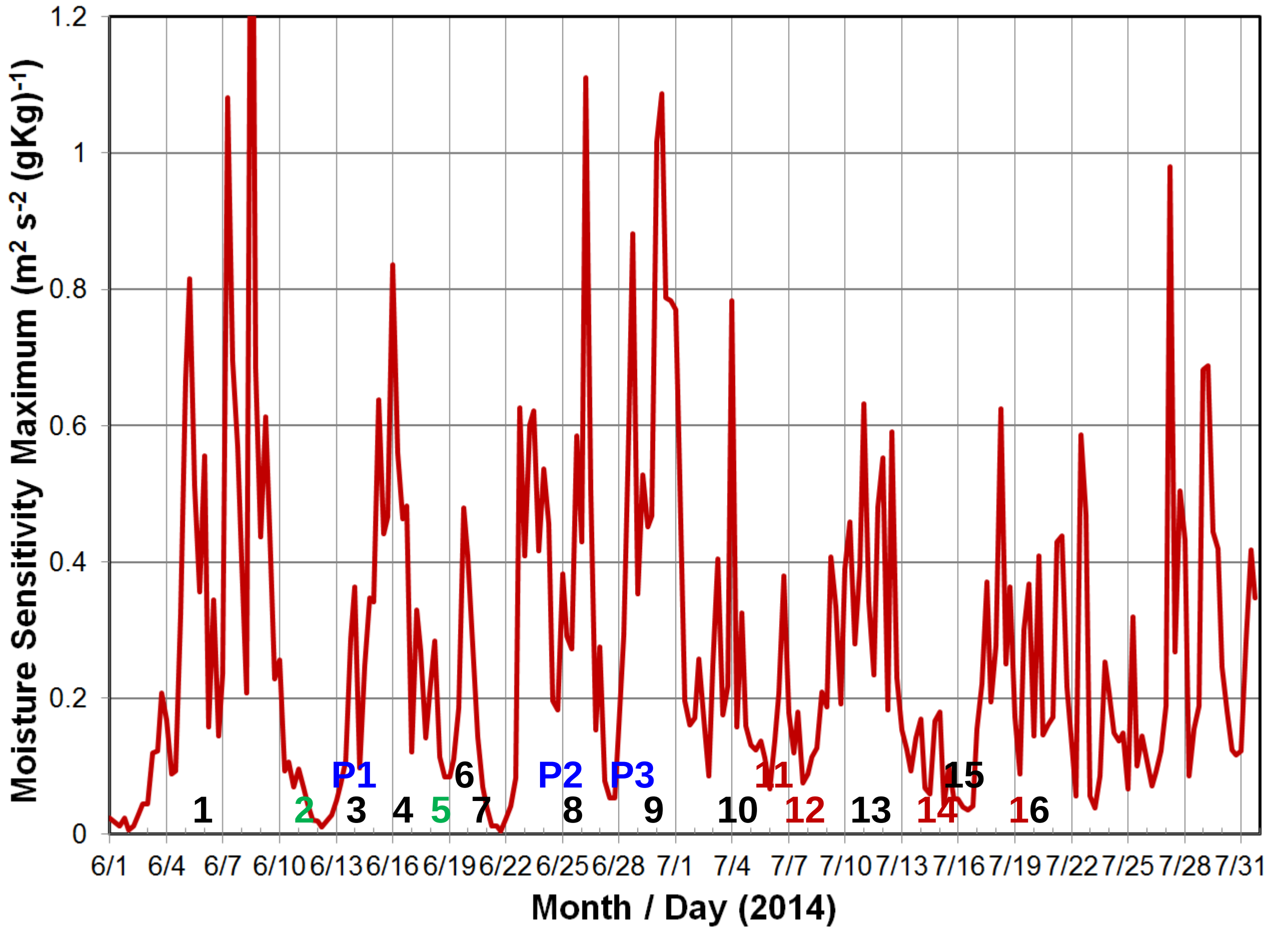
Predict.

- COAMPS adjoint: 25-km resolution, 24-h sensitivity, forecasts every 6h
- Mean wind speed at 1 km above surface shows active periods in June, quiescent after 4 July (S. Ocean flights) and then stronger flow after the end of the program.

Predictability of Deep Propagating GWs

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

IOP #
NZ Flight
Tasmania
S. Ocean
Predict.

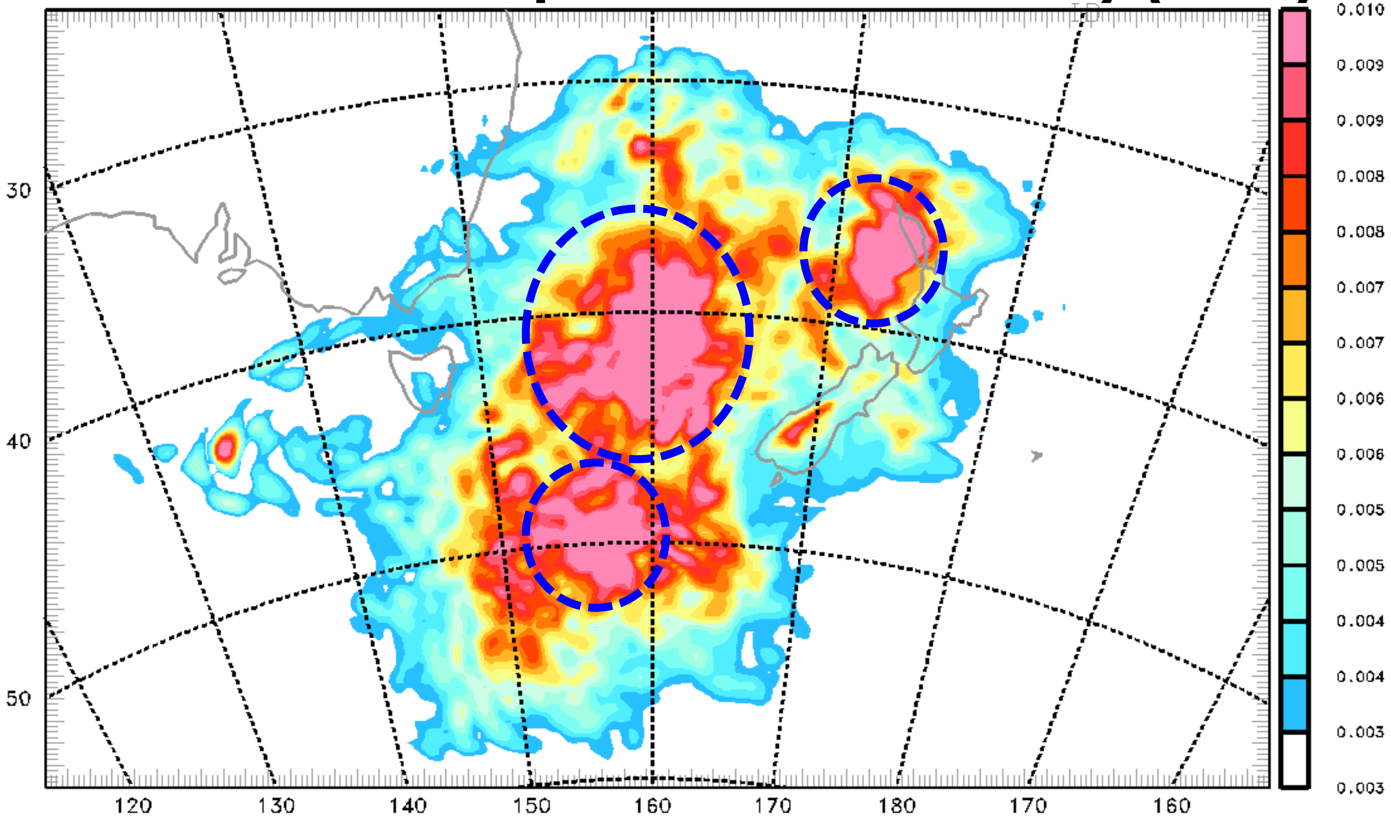


- Maximum sensitivity of the low-level wind speed over the S. Island (1 km deep response function) to the initial moisture.
- Maximima correspond to the IOP periods in general.
- Largest zonal sensitivity peaks: IOPs 8, 9, lesser 1, 4, 13

Predictability of Deep Propagating GWs

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

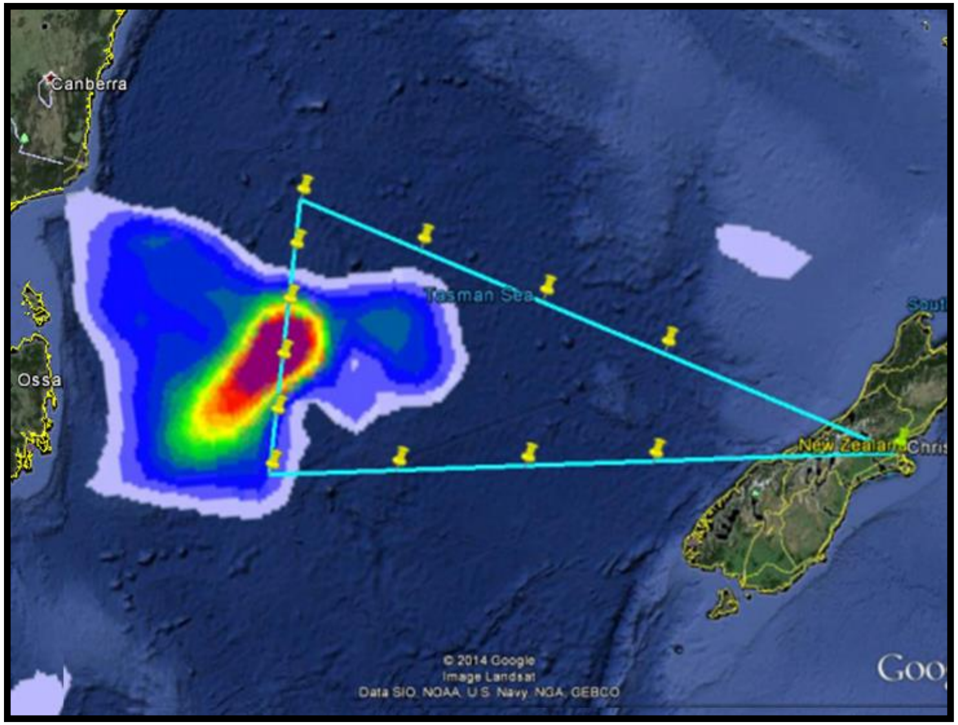
700-hPa Wind Speed and Heights (24h)
700-hPa Temperature Sensitivity (24 h)



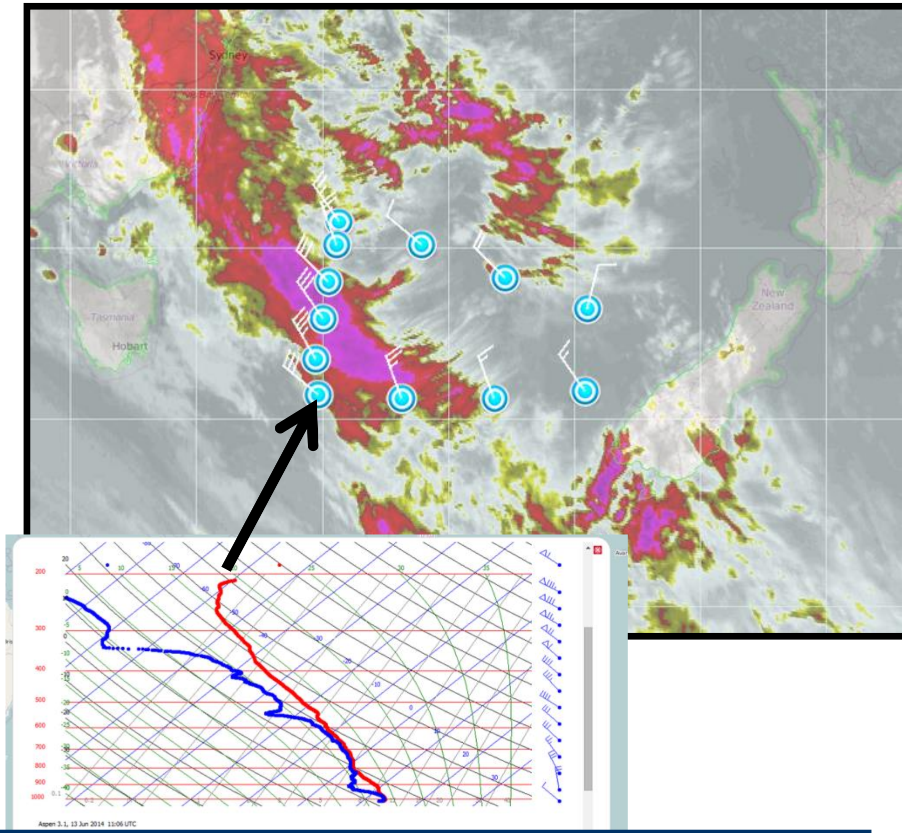
- Mean 700-hPa flow shows a weak trough near S. Island (strong cases)
- Mean 700-hPa temperature sensitivity maxima more complex, with maximum to the southwest and north of the South Island New Zealand.

RF03 (IOP 3 Predictability Flight 1)

Optimal Pert. at 12 UTC 13 June



Satellite IR 1000 UTC 13 June

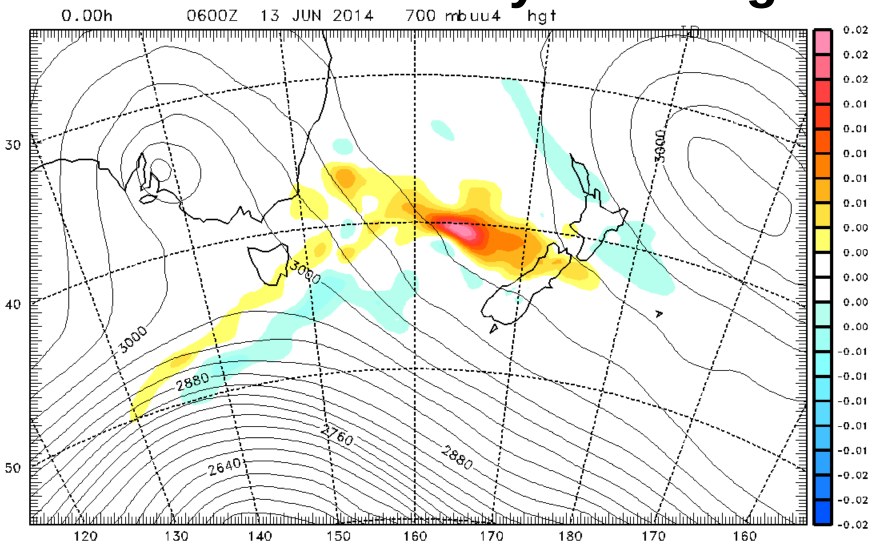


- Sampled initial condition sensitivity region upstream of the S. Alps prior to a GW event that was observed in RF04 (strong wave event).
- Sensitivity maximum located near shortwave at 700 and 500 mb. Enhanced cloud shield and low-level jet in sensitive region.
- Dropsondes indicated shallow convection with moist layer
- Targeted dropsondes successfully observed this feature well

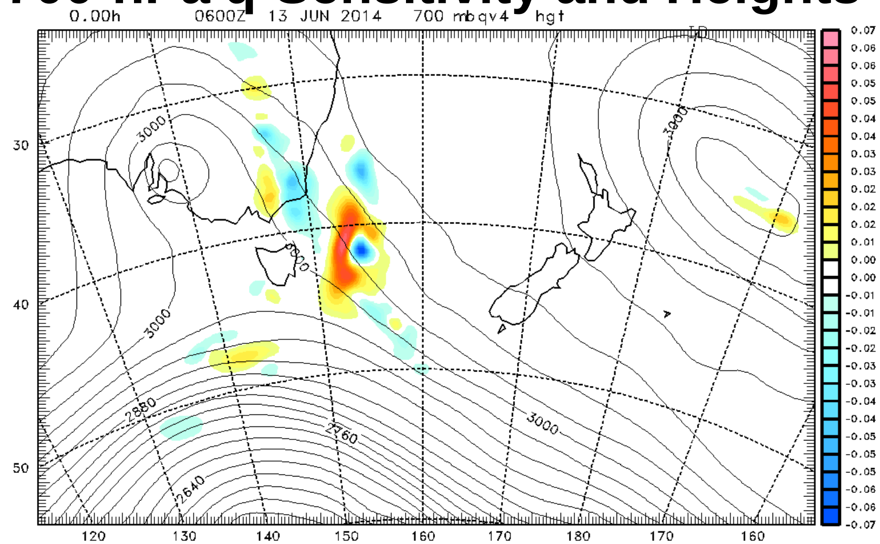
RF03 (IOP 3 Predictability Flight 1)

Initial Condition Sensitivity 0600 UTC 13 June

700-hPa U-Sensitivity and Heights



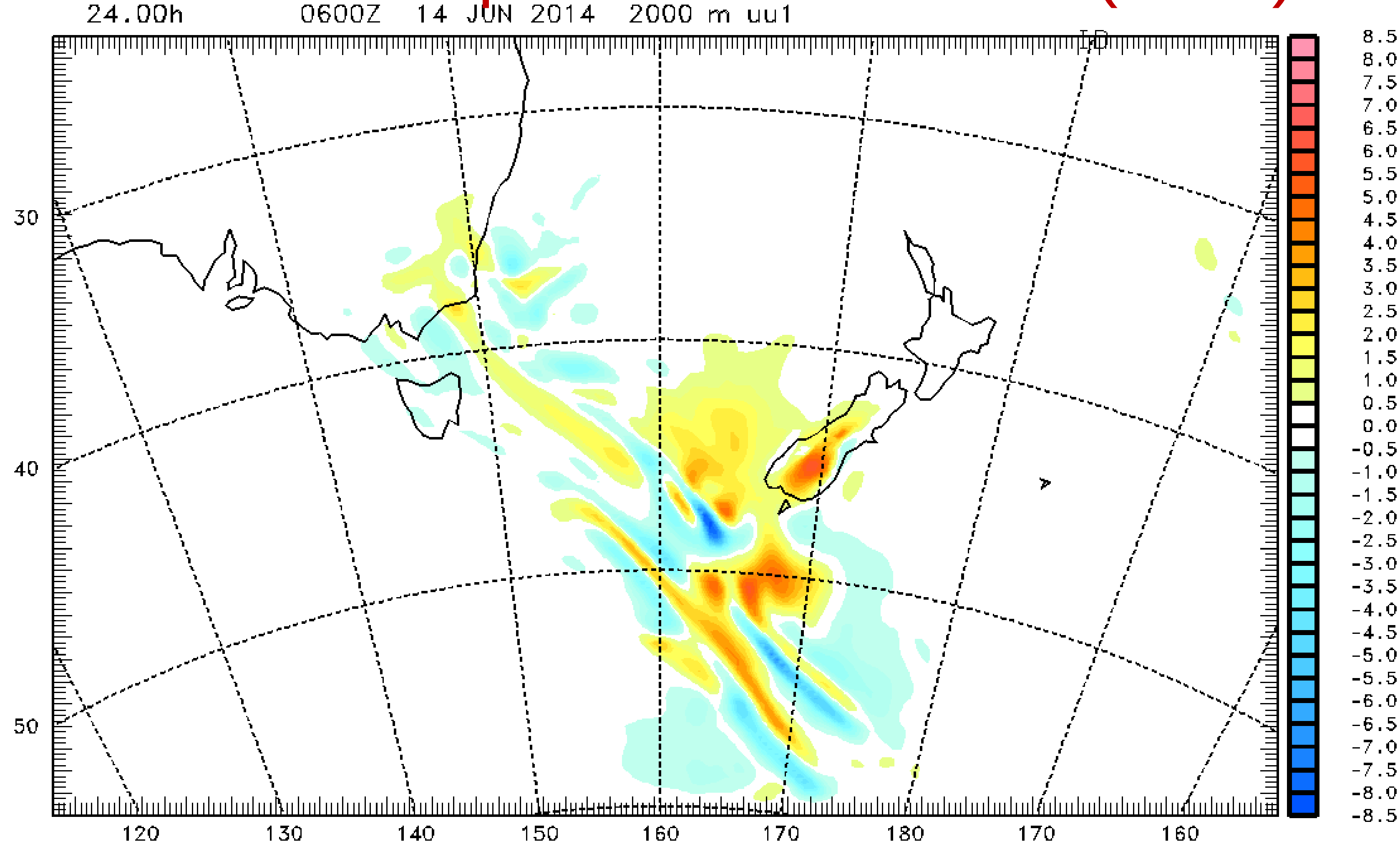
700-hPa q-Sensitivity and Heights



- U- and q-sensitivity highlight different mesoscale features.
- Maximum q-sensitivity near LLJ and cloud shield along leading edge of 700-hPa trough.
- Greater sensitivity to the initial moisture than zonal wind speed.
- Increase in the initial moisture near cloud shield leads to stronger cross mountain flow (and wave launching).

RF03 (IOP 3 Predictability Flight 1)

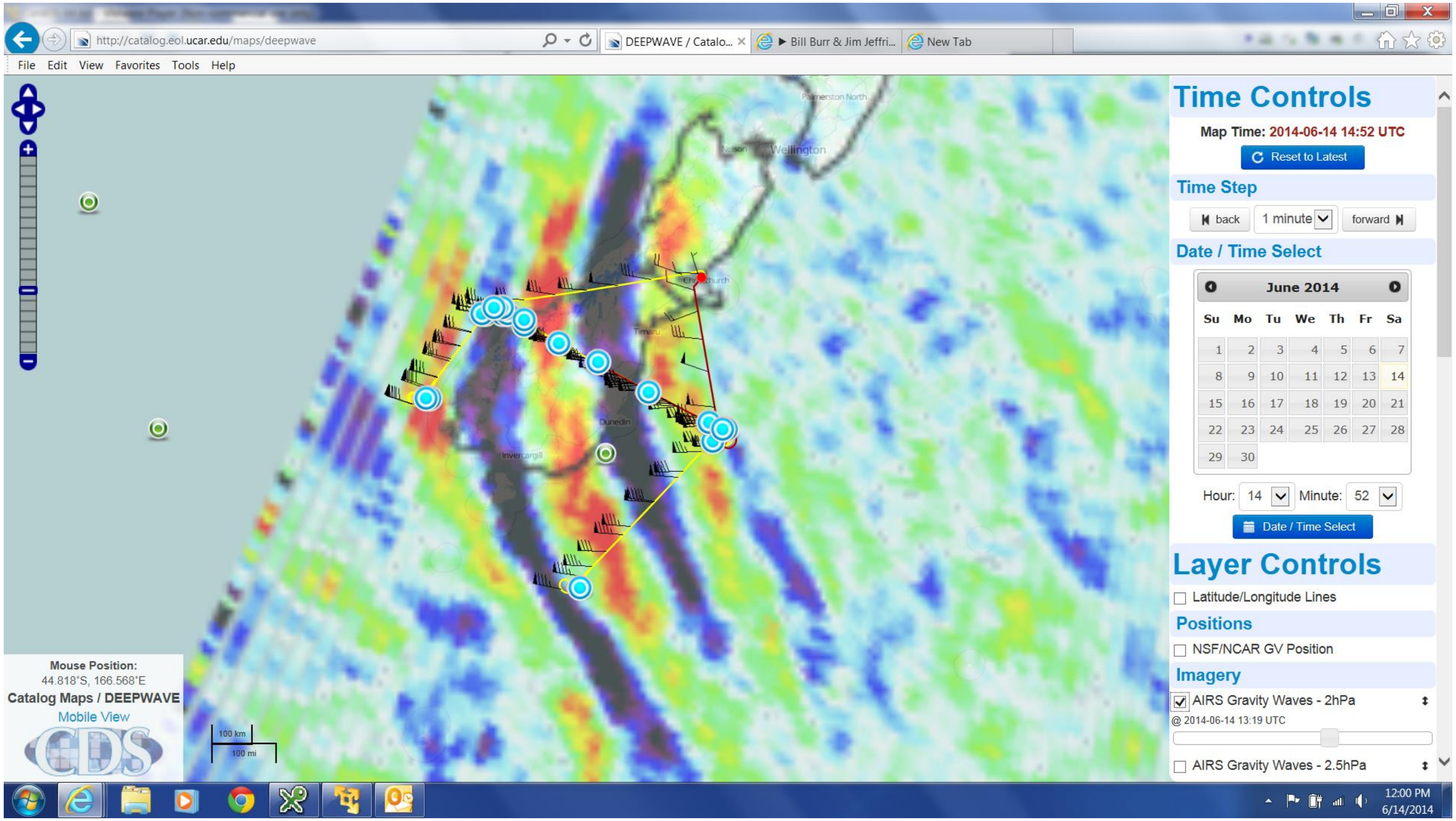
Evolved Optimal Perturbation (2 km)



- Evolved optimal perturbations exhibit growth from 0.5 to ~9 m s^{-1} over 24 h
- Initial errors that project on to sensitive regions should lead to errors in GW launching.

RF04 (IOP 3 Verification Flight)

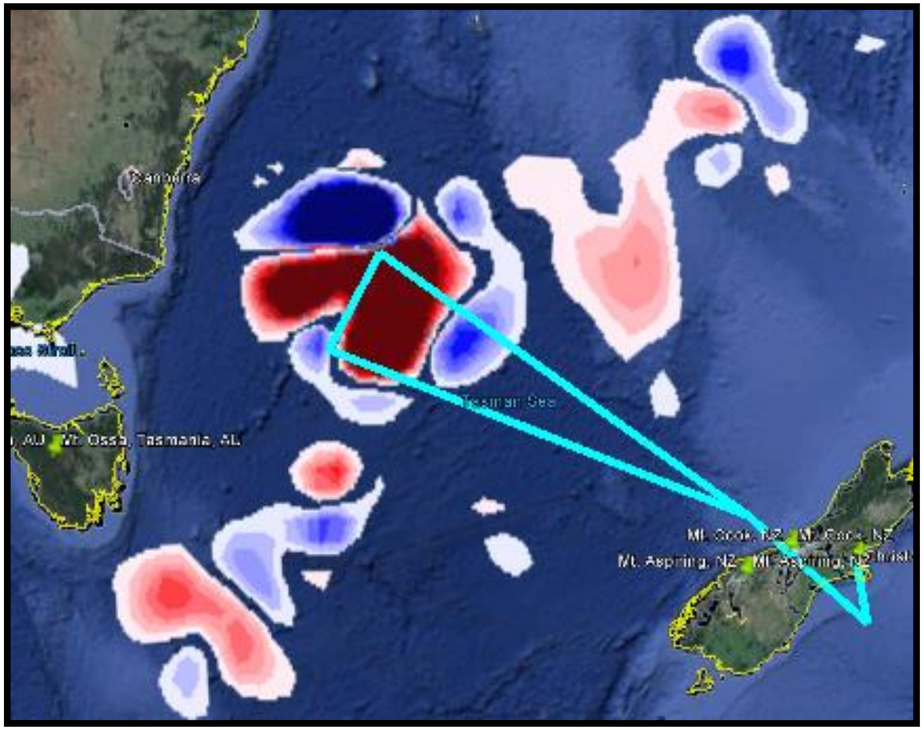
Observations of Deep Gravity Waves



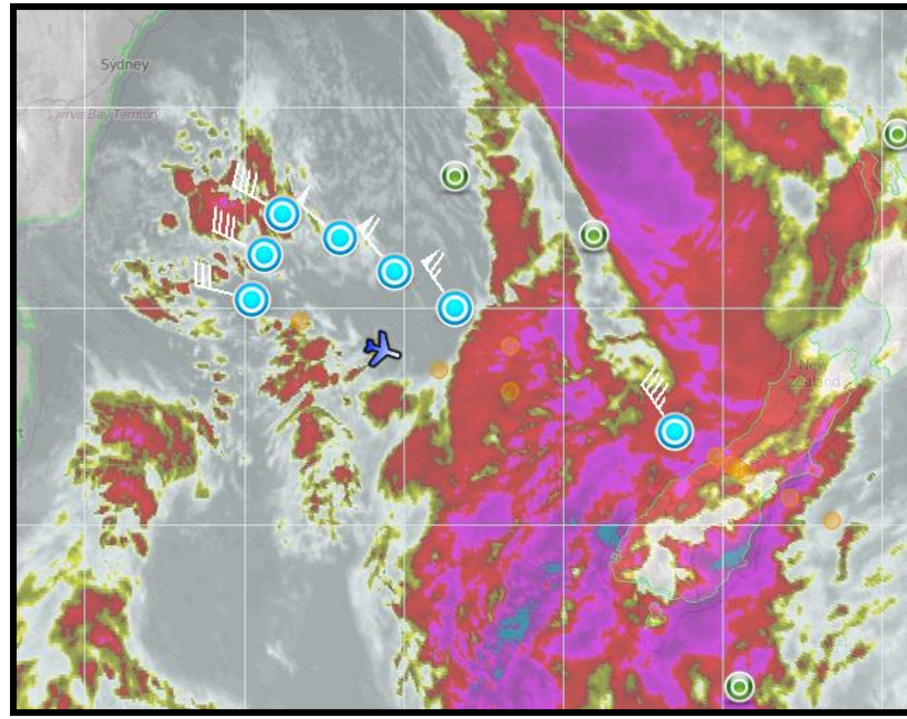
- Companion “verification flight” on 14 June was conducted (RF04).
- Questions remain regarding the degree to which the gravity wave forecasts for 14 June are improved through the assimilation of the additional dropsondes.

RF09 (IOP 8, Predictability Flight 2)

700-mb Moisture Sensitivity
12 UTC 24 June



Satellite IR and Dropsonde Winds
12 UTC 24 June

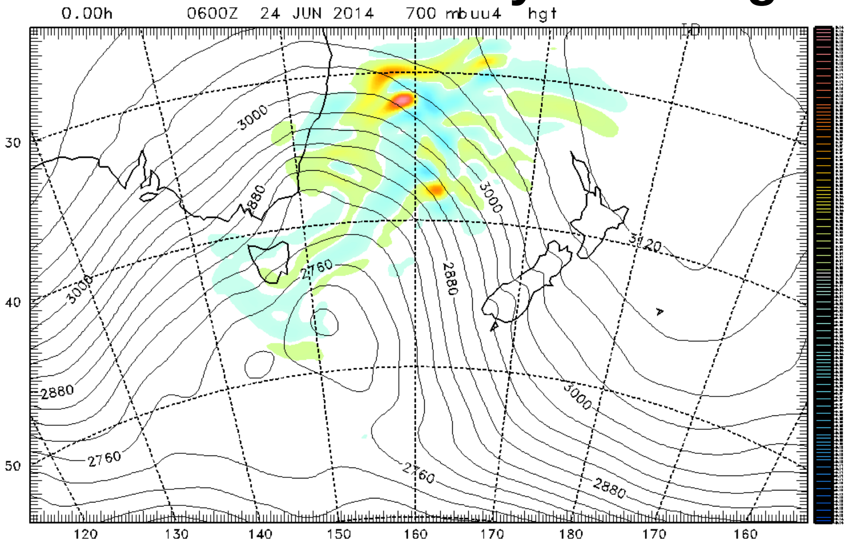


- Sampled a region of adjoint sensitivity upstream of the Southern Alps prior to a gravity wave event.
- Sensitivity in a dynamically active region of convection and lightning that impacted the SI and generated GWs observed in RF10.
- Sensitivity near region of strong horizontal shear at 400 hPa.

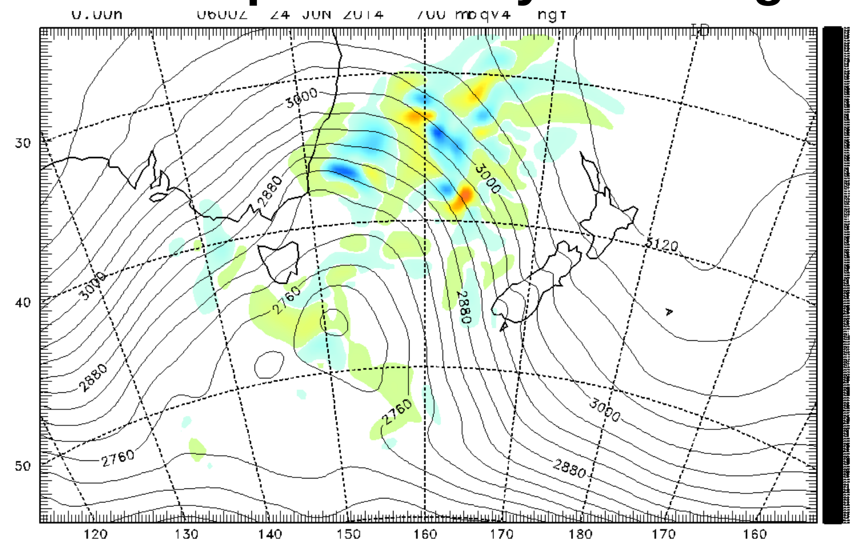
RF09 (IOP 8 Predictability Flight 2)

Initial Condition Sensitivity 0600 UTC 24 June

700-hPa U-Sensitivity and Heights



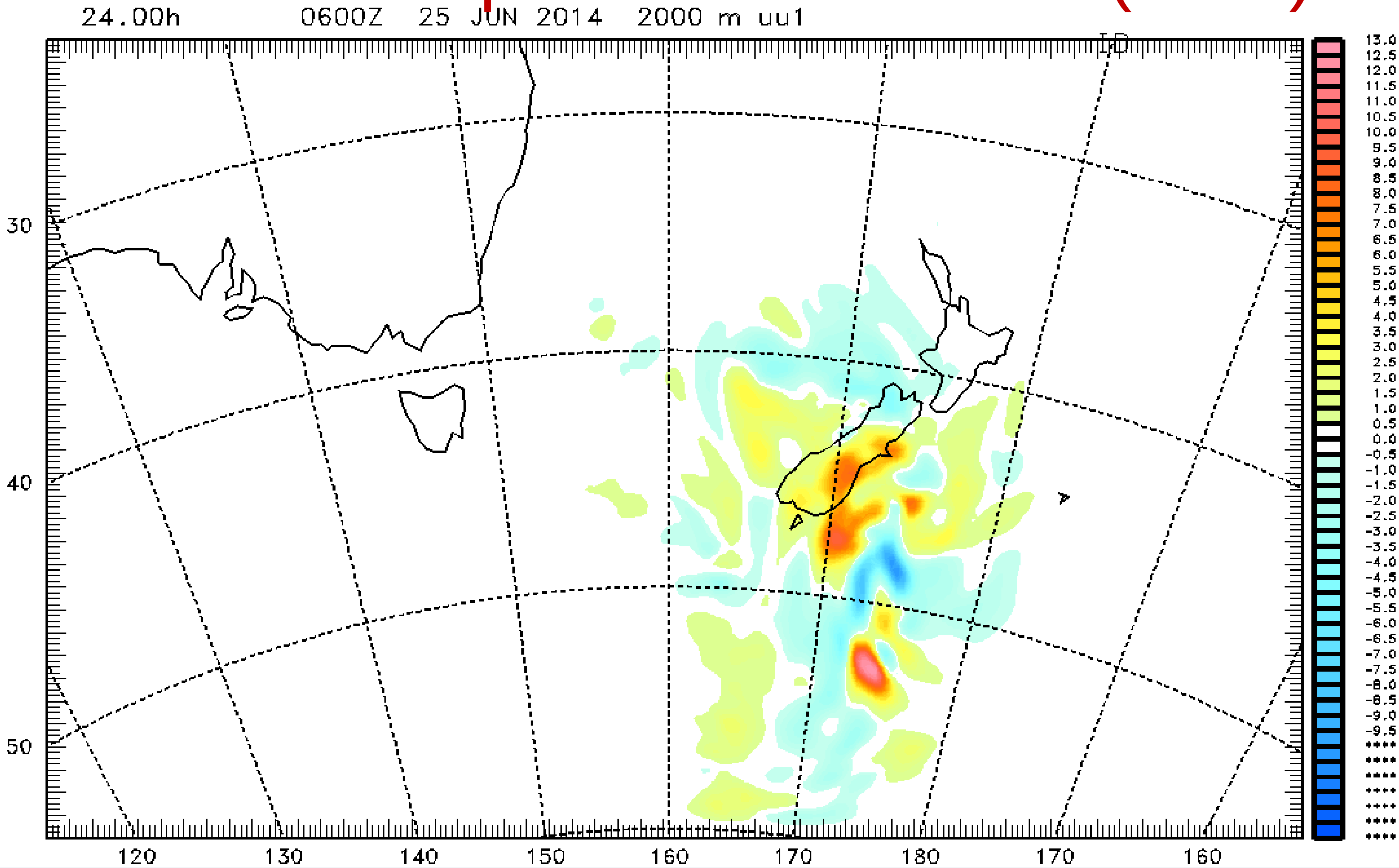
700-hPa q-Sensitivity and Heights



- U- and q-sensitivity near LLJ and convective region along leading edge of 700-hPa trough.
- Greater sensitivity to the initial moisture than zonal wind speed.
- Sensitivity more complex than IOP 3, with more spotty regions consistent with convectively unstable regions.

RF09 (IOP 8 Predictability Flight 2)

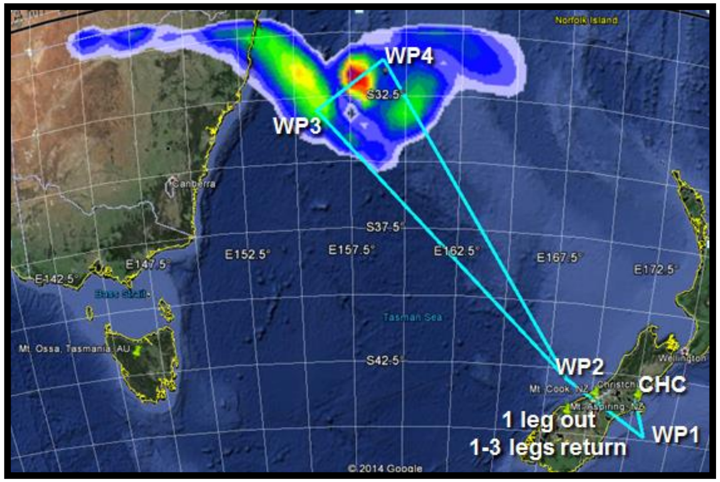
Evolved Optimal Perturbation (2 km)



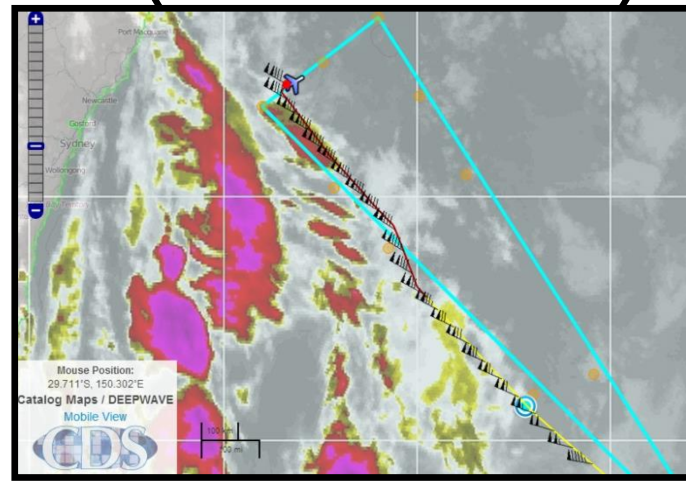
- Evolved optimal perturbations exhibit growth from 0.5 to ~15 m s^{-1} over 24 h
- Initial errors that project on to sensitive regions should lead to errors in GW launching.

RF11 (IOP 9, Predictability Flight 3)

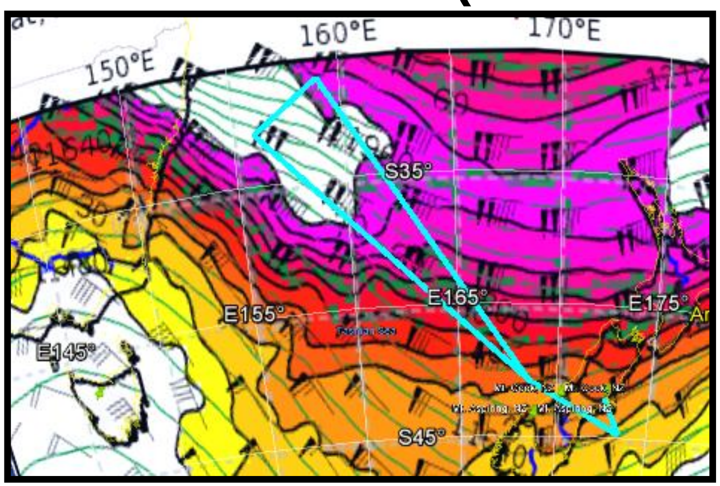
Optimal Pert. (12 UTC 28 June)



IR (0832 UTC 28 June)



ECMWF 200-hPa Winds (12 UTC 28 June)



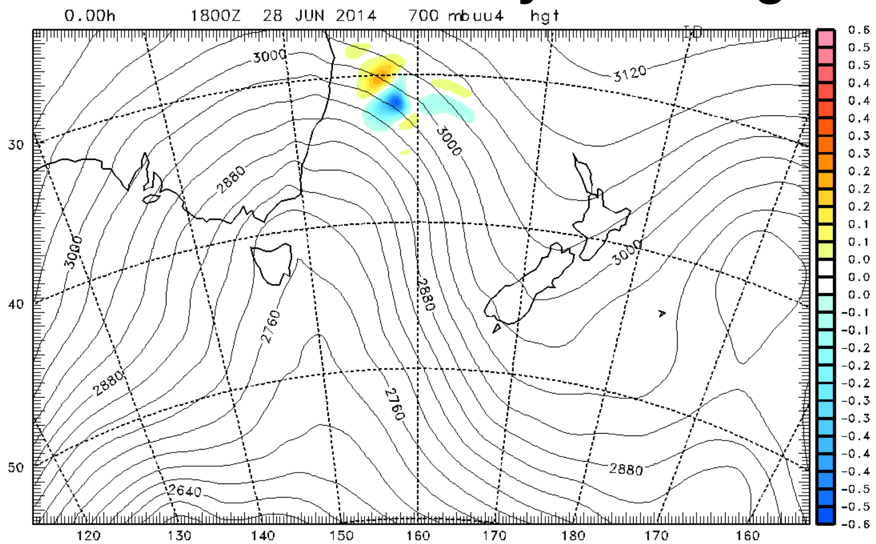
AMTM (0642Z 28 June)

- Sampled a region of adjoint sensitivity in the northern Tasman Sea upstream of the Southern Alps prior to a gravity wave event (RF12).
- Sensitivity at exit of 75 m s^{-1} jet, within convection region; MTM active.

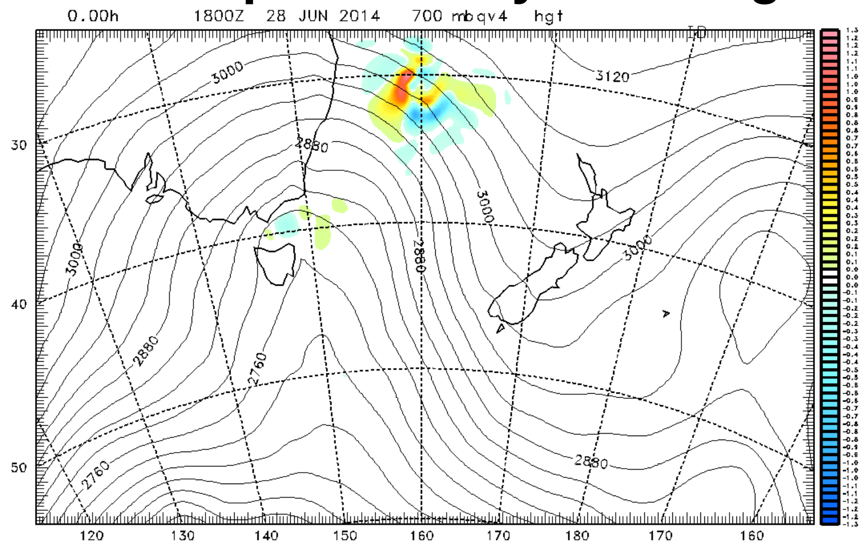
RF11 (IOP 9 Predictability Flight 3)

Initial Condition Sensitivity 1800 UTC 28 June

700-hPa U-Sensitivity and Heights



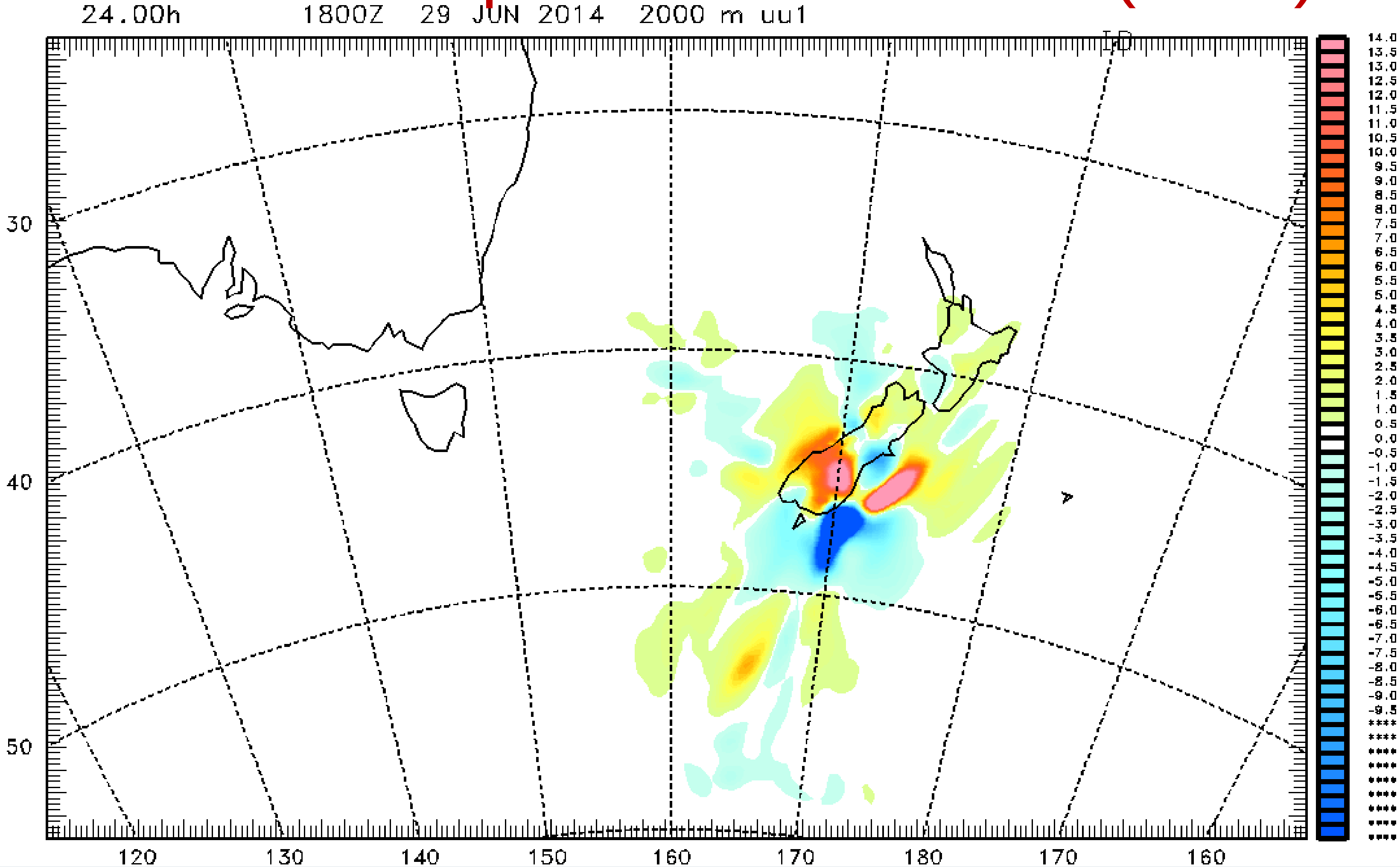
700-hPa q-Sensitivity and Heights



- U- and q-sensitivity near LLJ, upper-level jet (75 m s^{-1}) and deep convective region along leading edge of 700-hPa trough.
- Slightly greater sensitivity to the initial moisture than wind speed.
- Sensitivity more coherent than IOP 8.

RF11 (IOP 9 Predictability Flight 3)

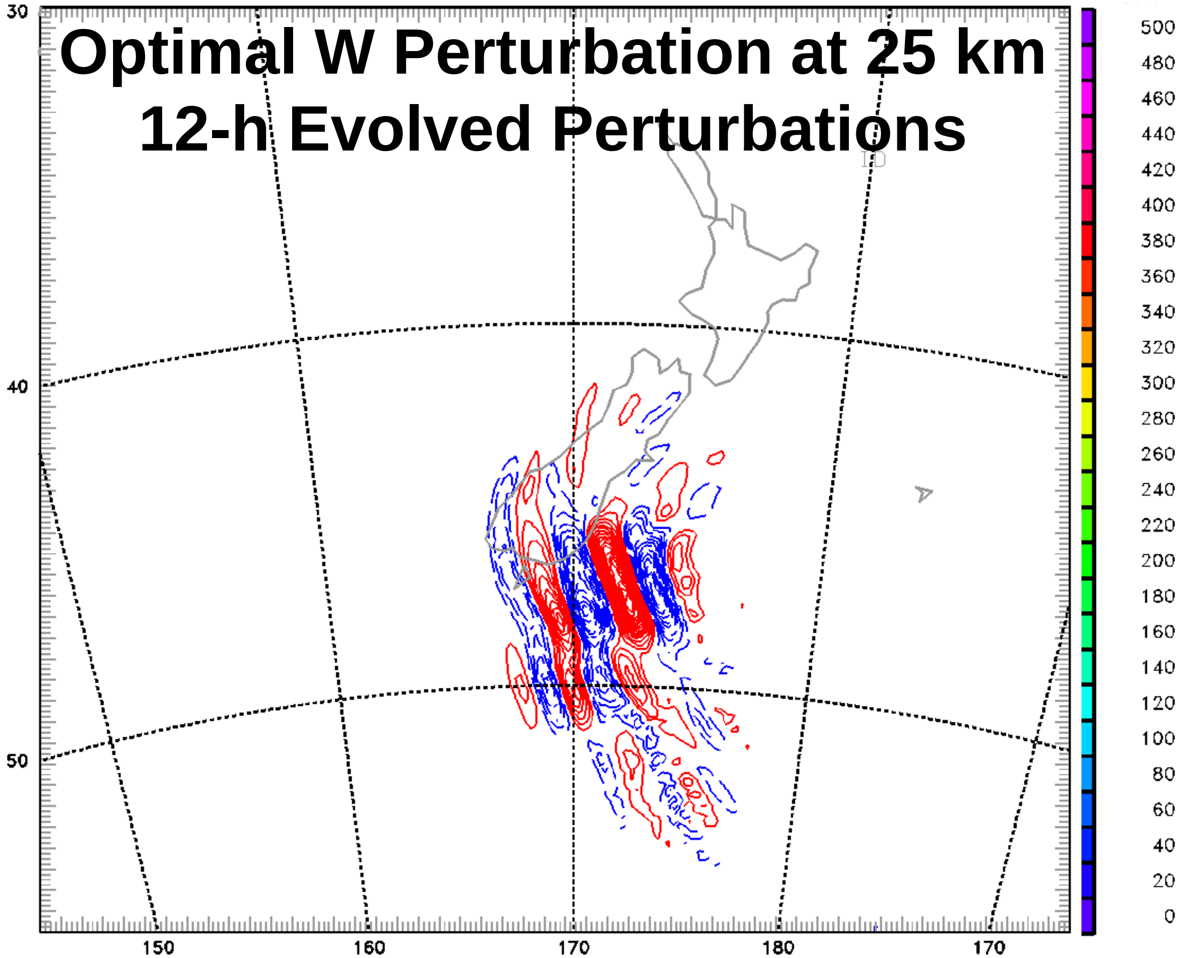
Evolved Optimal Perturbation (2 km)



- Evolved optimal perturbations exhibit growth from 0.5 to ~18 m s^{-1} over 24 h
- Growth over South Island greater than other 2 IOPs.
- Propagation speed of perturbations is very fast (~2000 km / 24 h).

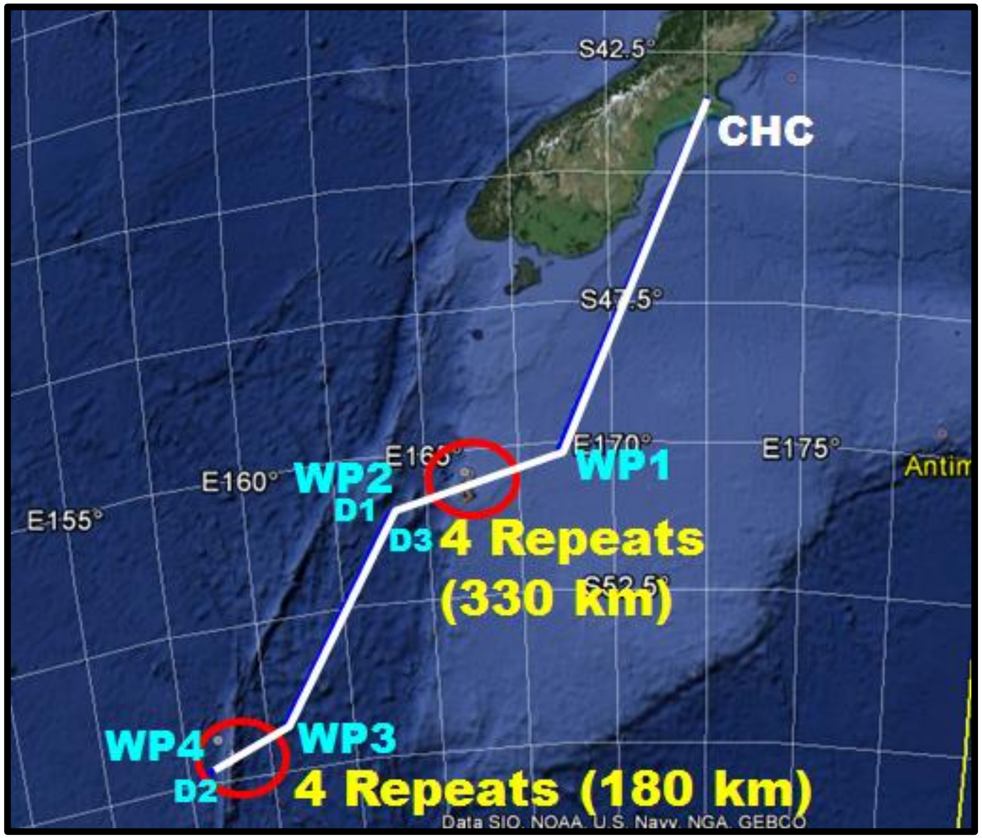
Gravity Wave Source Identification

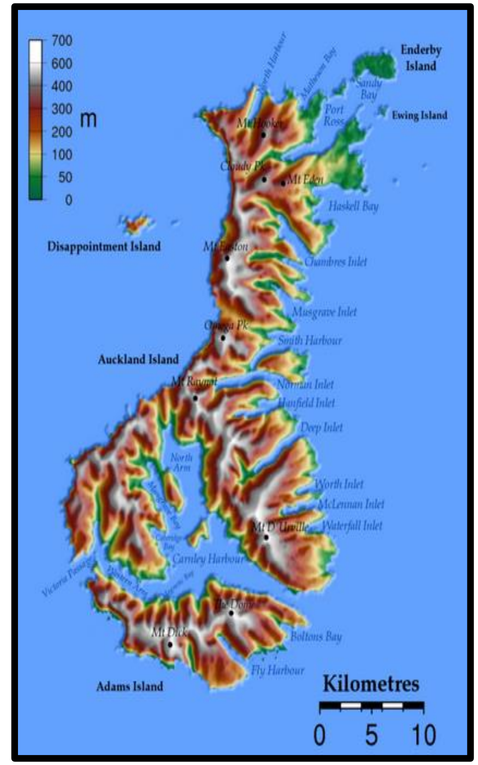
Trailing Waves in IOP 3

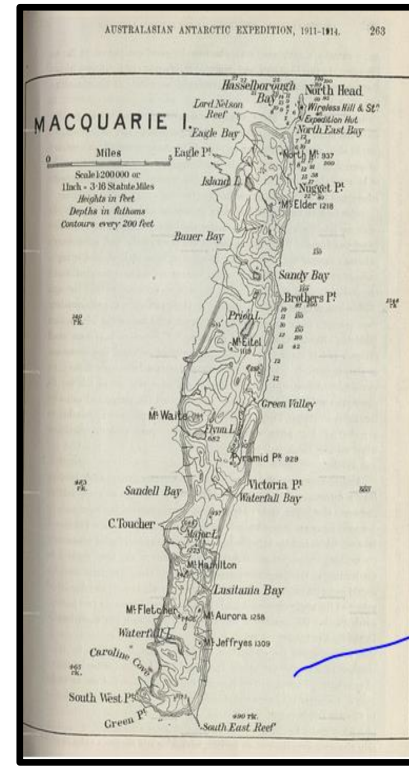


- Adjoint identifies most sensitive portion of the Alps for wave launching.
- Trailing waves located to S of NZ are launched from S. Alps (south of Cook).

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



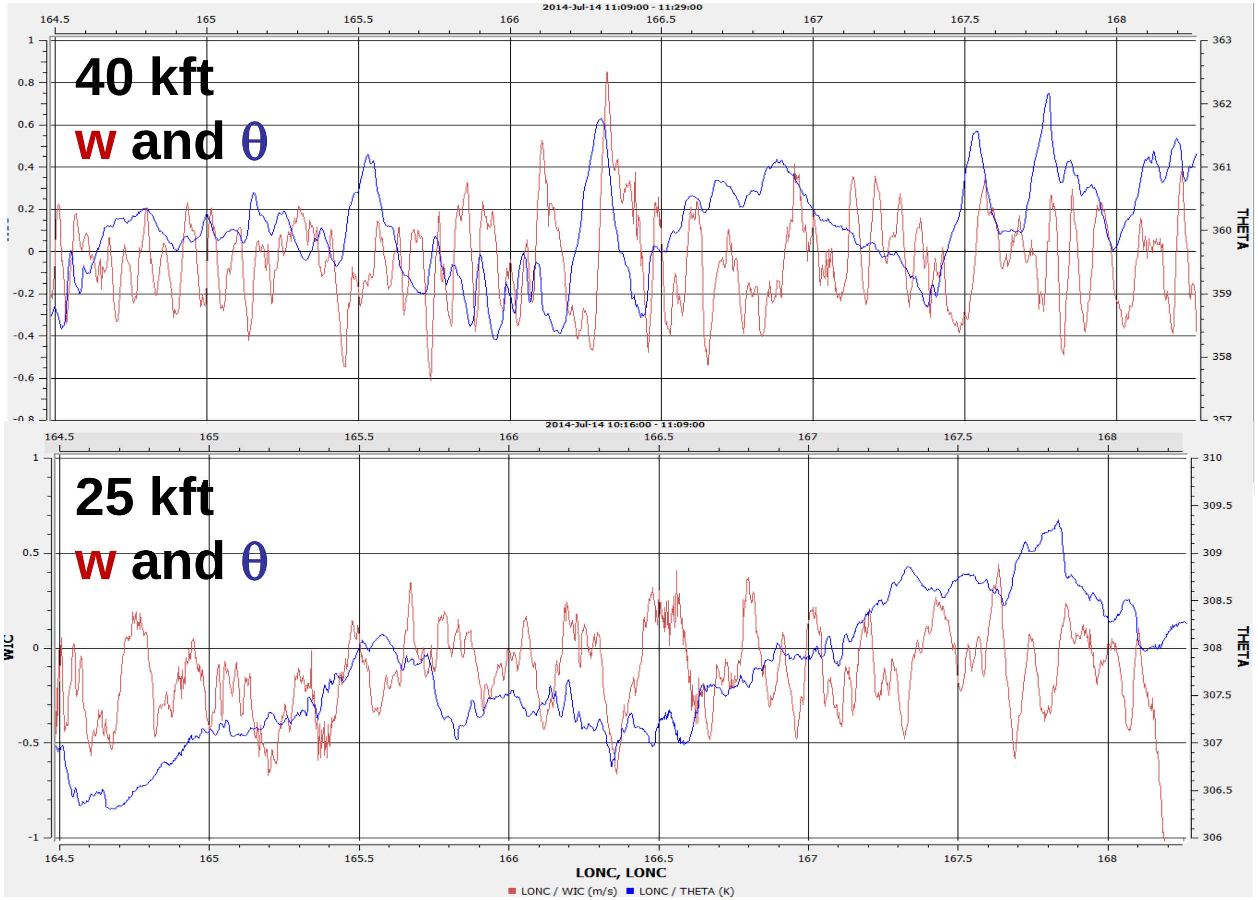




- RF23 (IOP 14) sampled deep propagating gravity waves over Macquarie and Auckland Islands at multiple levels.
- Dropsondes indicated > 20 m s^{-1} flow upstream of the islands.

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

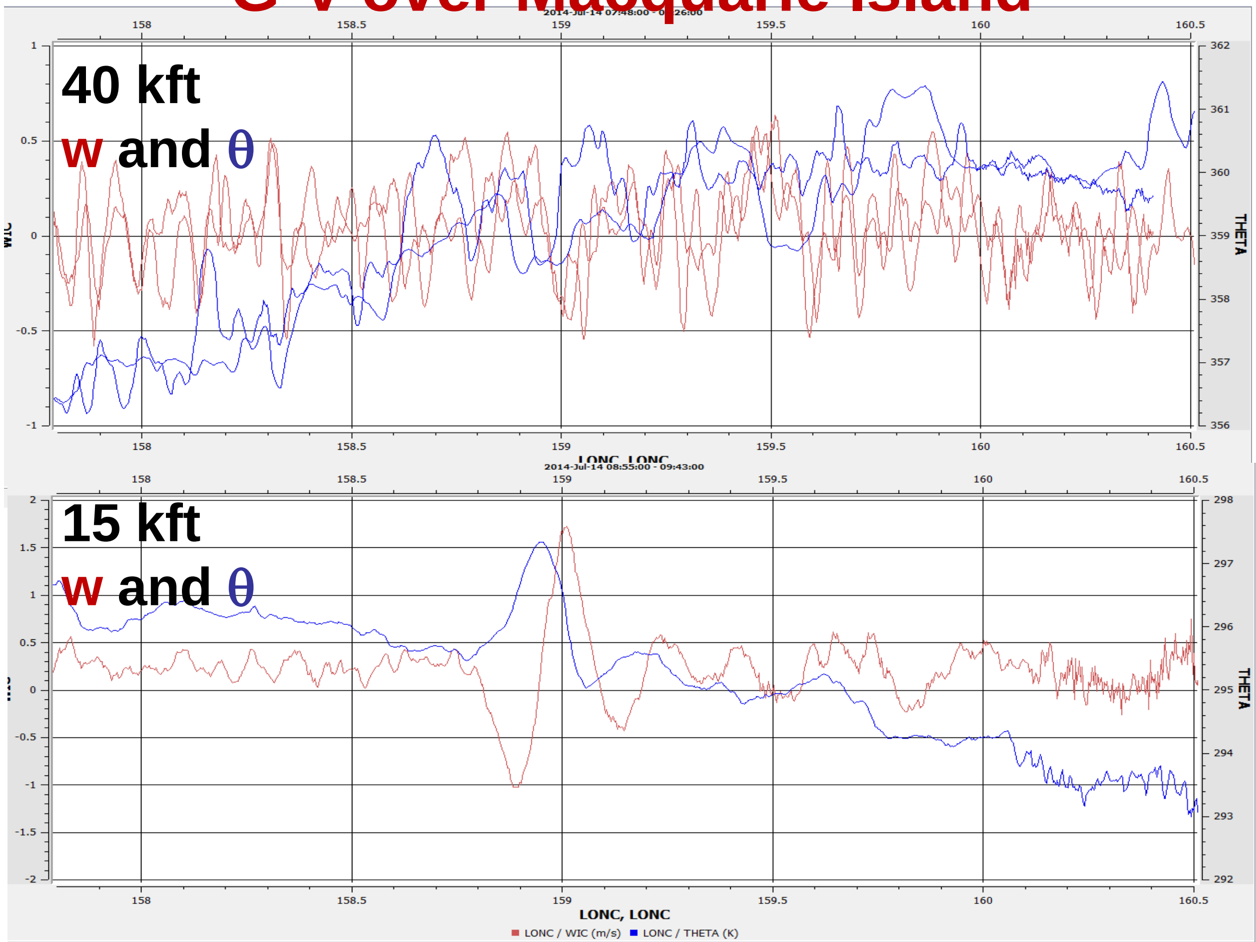
G-V over Auckland Islands



- 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)

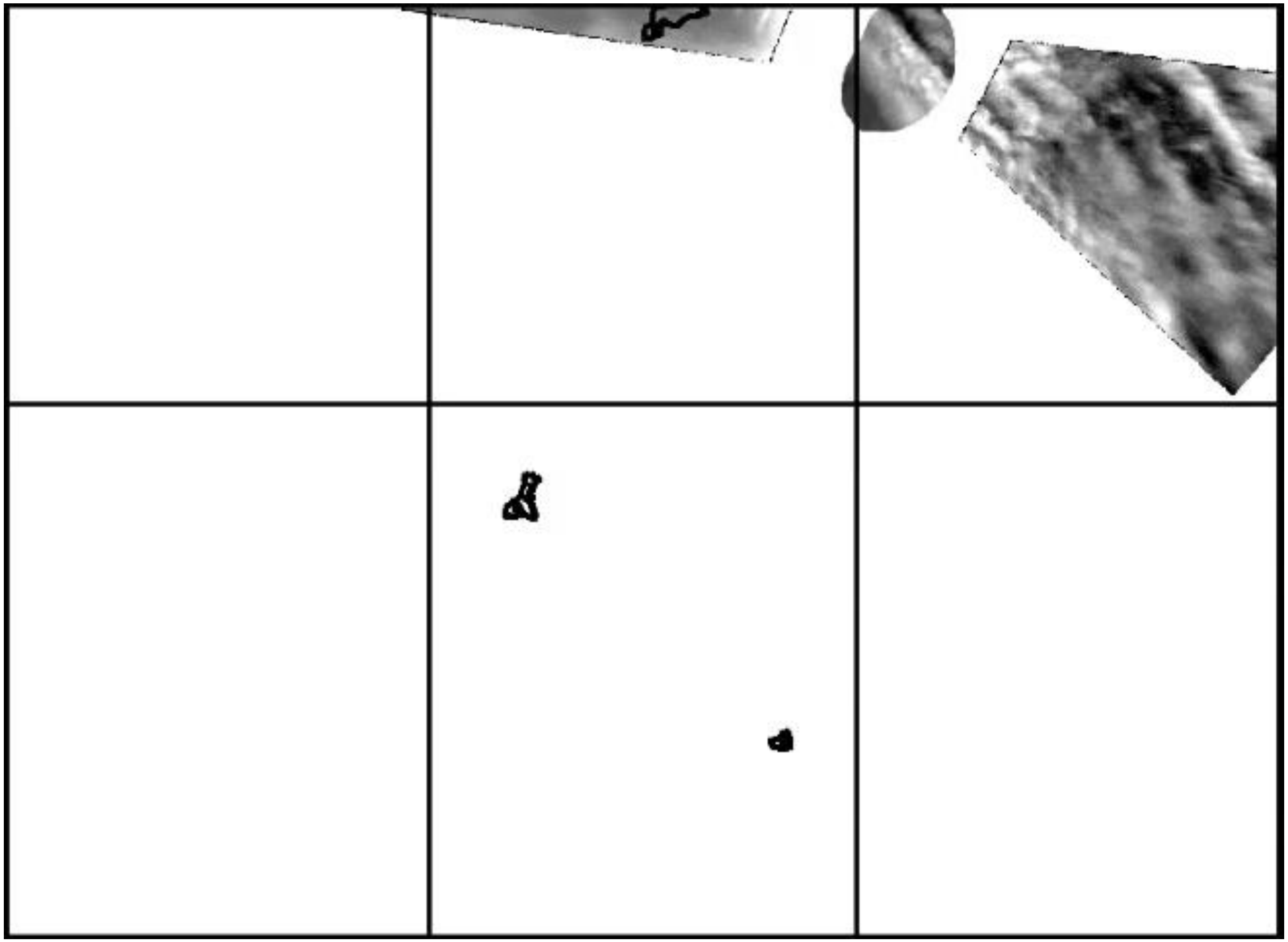
G-V over Macquarie Island



- 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.

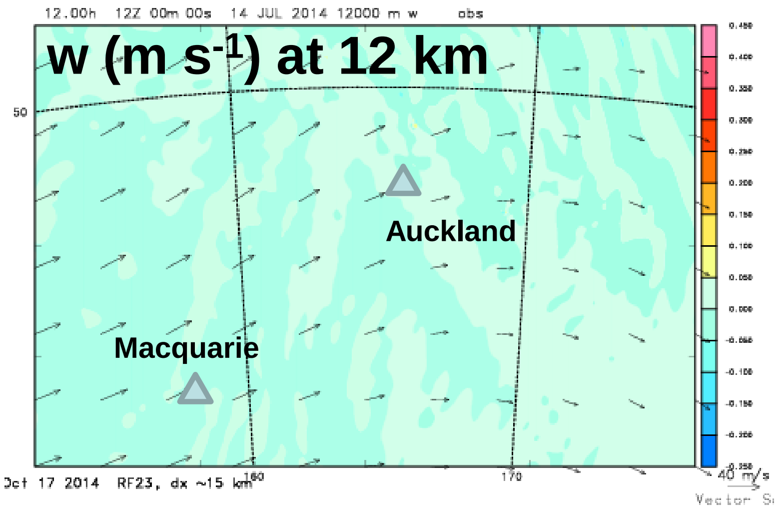
Deep Propagating Gravity Waves Over Auckland and Macquarie Islands (RF23)

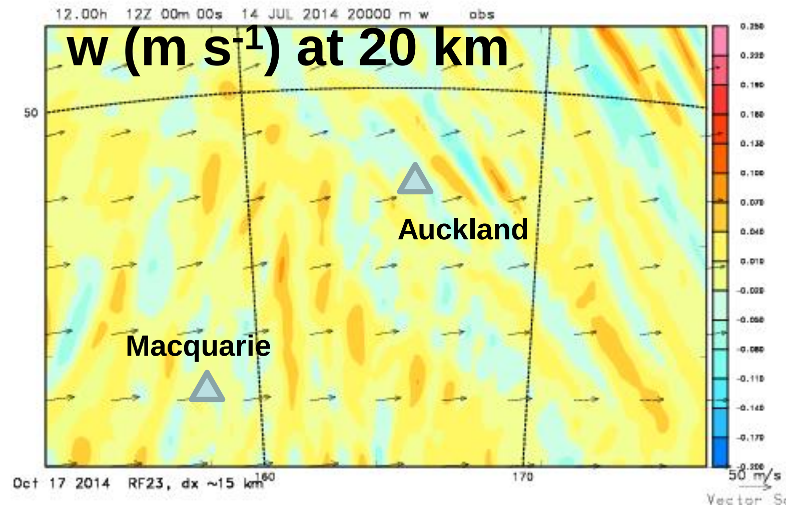
MTM Observations

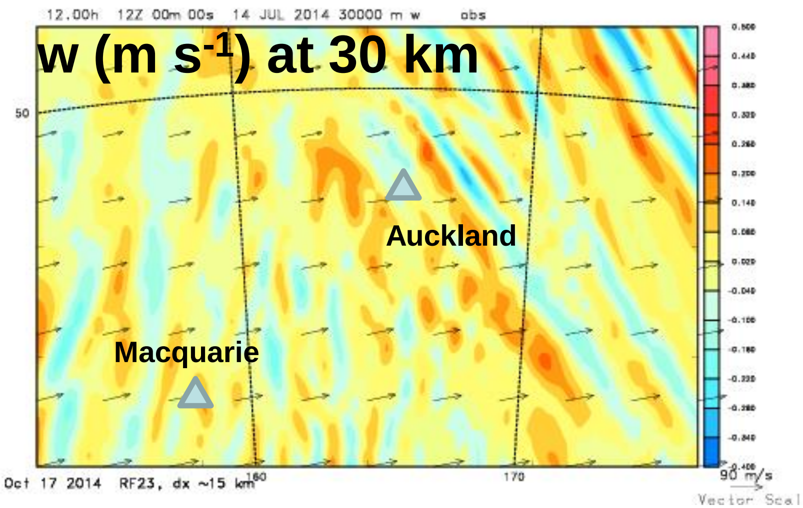


Deep Propagating Gravity Waves Over Auckland and Macquarie Islands (RF23)

COAMPS (Δx=5 km) Simulation (Control)



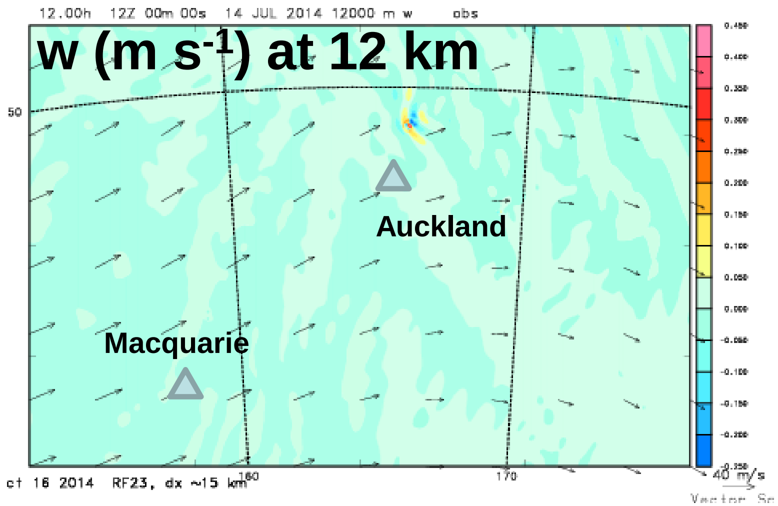


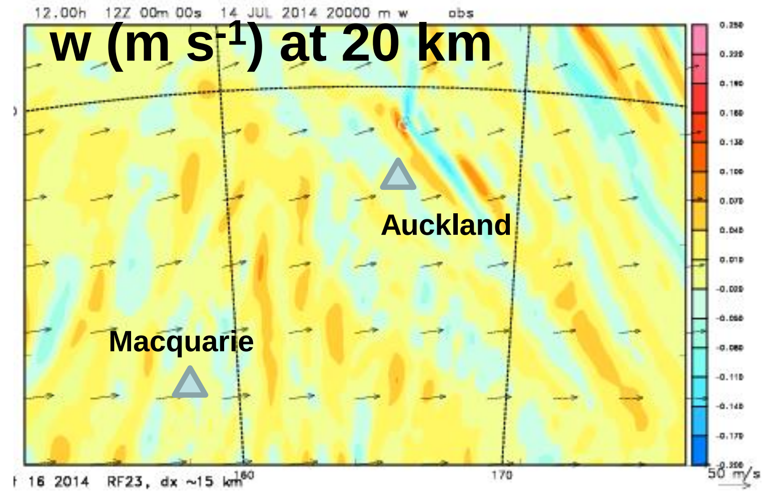


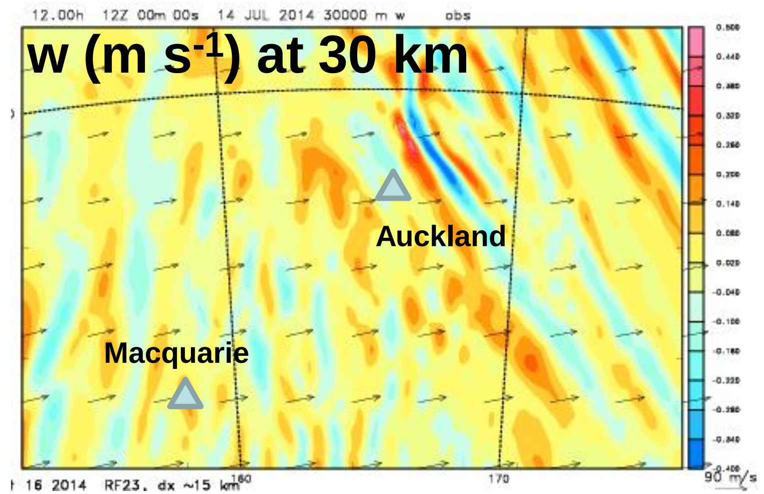
- COAMPS (60 km top) used with 3 nests and 5 km horizontal resolution (601x451)
- Control run shows weak waves at 30 km and above.

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

COAMPS (Δx=5 km) Simulation (4X Terrain)







- COAMPS (60 km top) used with 3 nests and 5 km horizontal resolution (601x451)
- Enhanced terrain run shows more well-defined waves.
- Motivates the need for higher resolution simulations (500 m?)
- Linear model simulations appear to be promising also.

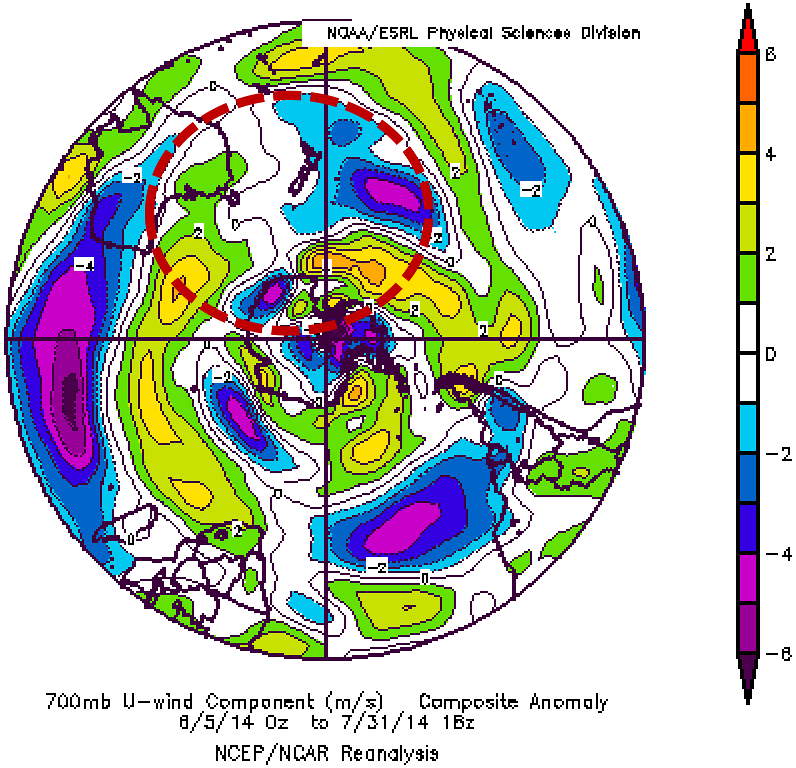
Summary and Future Directions

- **Predictability**
  - Sensitive regions were in physically meaningful locations near: i) troughs, ii) jet streaks, iii) convection. What are the implications?
  - Sensitive regions appear to be the "seeds" for GWs & their characteristics
  - Data denial studies are underway to assess the impact of sonds on GWs.
  - Links between tropospheric predictability and the upper atmosphere?
- **Dynamics – GWs excited by S. Ocean islands**
  - Auckland Is. supports deep GW propagation, Macquarie may excite more nonhydrostatic GWs because of the narrow terrain.
  - Higher resolution (500 m) simulations will be conducted to resolve terrain fully.
- **Sources of stratospheric GWs**
  - GWs from terrain, jets, convection…
  - Adjoint can help identify GW sources
- **Collaboration welcomed with observing and modeling teams.**

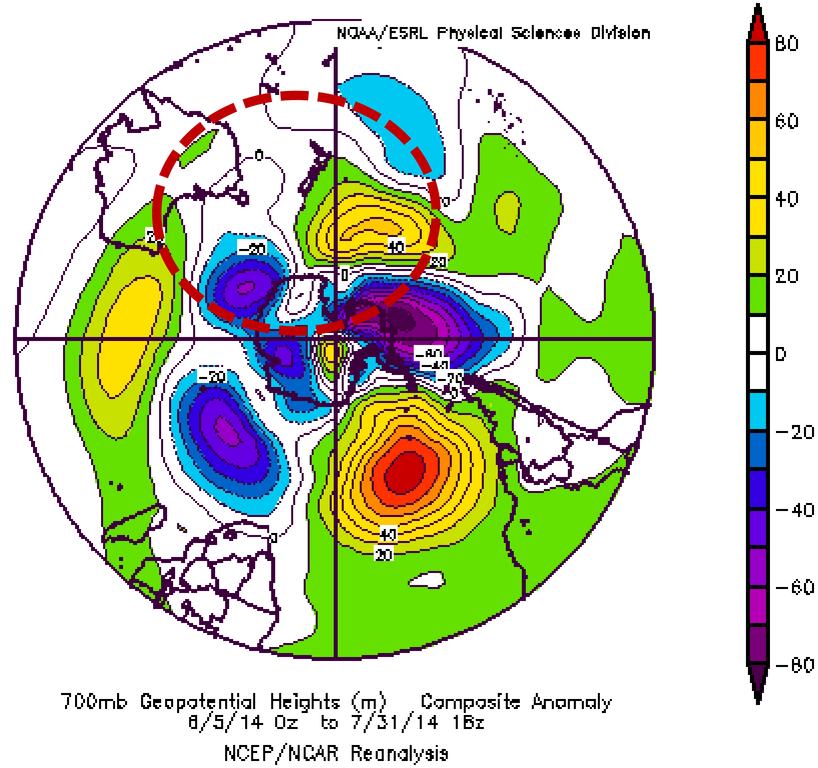
Large-Scale Flow During DEEPWAVE

NCEP/NCAR Reanalysis Anomaly
700-hPa

Zonal Wind Anomaly



Geopotential Height Anomaly

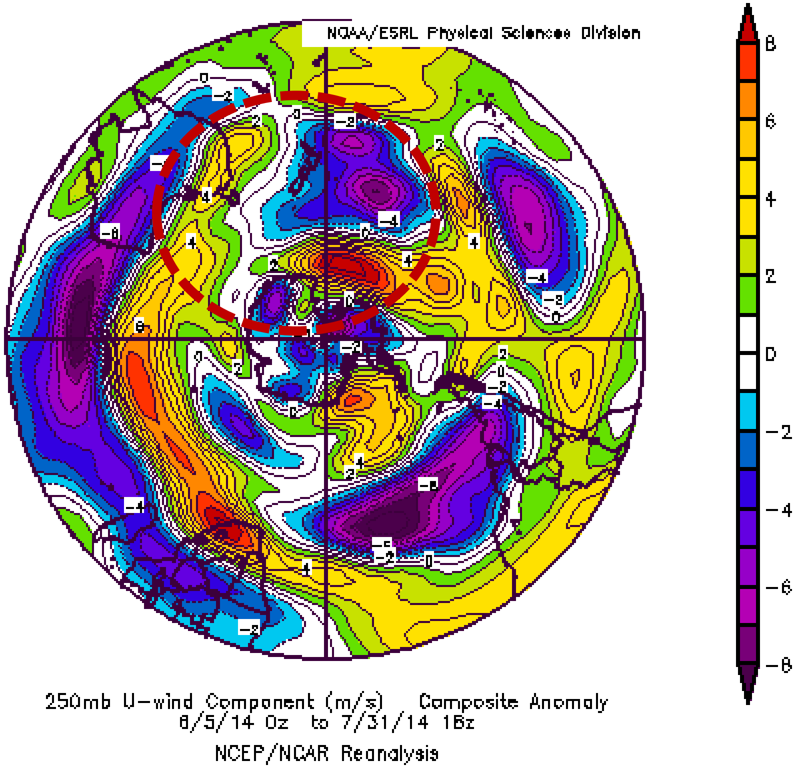


- Strong tropospheric ridge to SE of New Zealand
- Weaker westerly flow than average over New Zealand extending to east

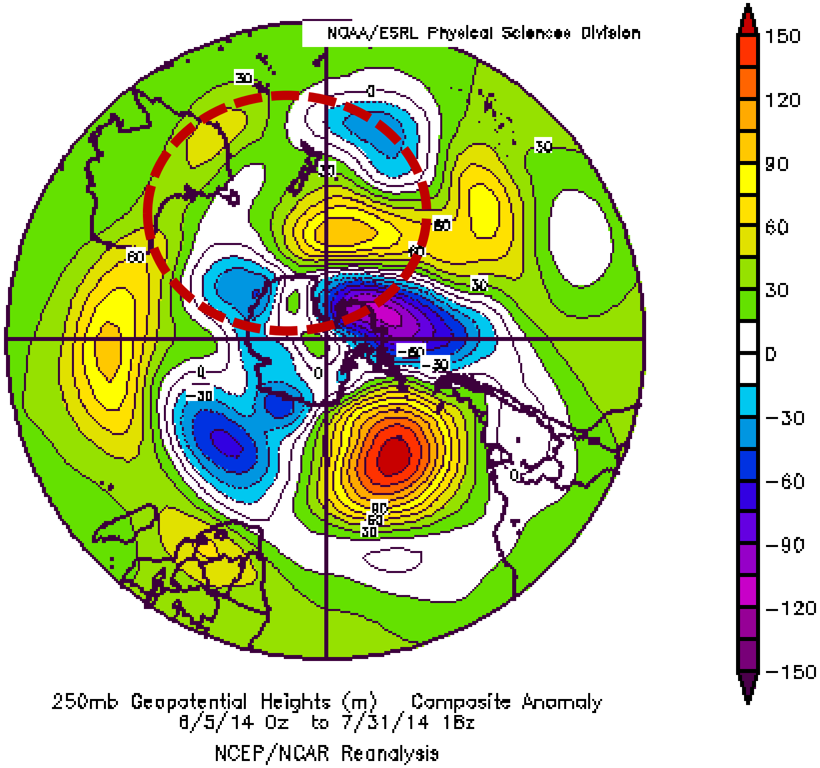
Large-Scale Flow During DEEPWAVE

NCEP/NCAR Reanalysis Anomaly
250-hPa

Zonal Wind Anomaly



Geopotential Height Anomaly

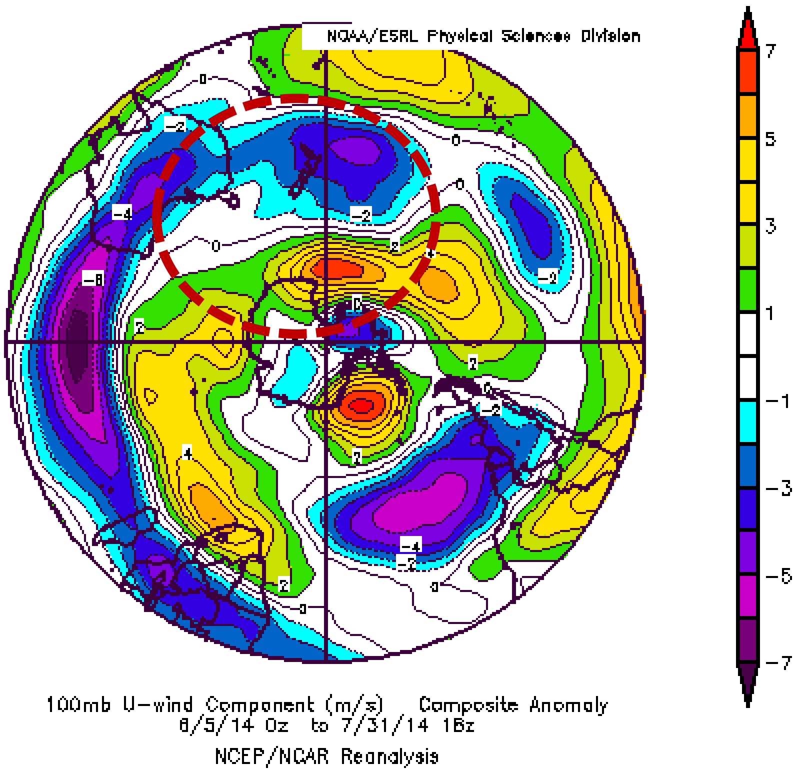


- Strong upper tropospheric / lower-stratospheric ridge to SE of NZ
- Weaker westerly flow in the 250-hPa jet than average.

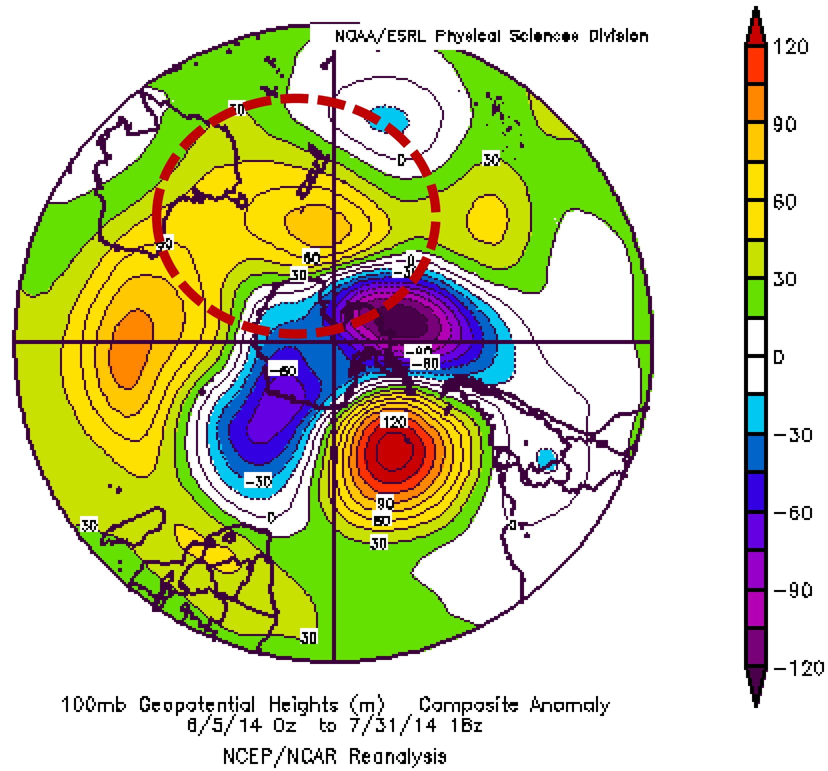
Large-Scale Flow During DEEPWAVE

NCEP/NCAR Reanalysis Anomaly
100-hPa

Zonal Wind Anomaly



Geopotential Height Anomaly

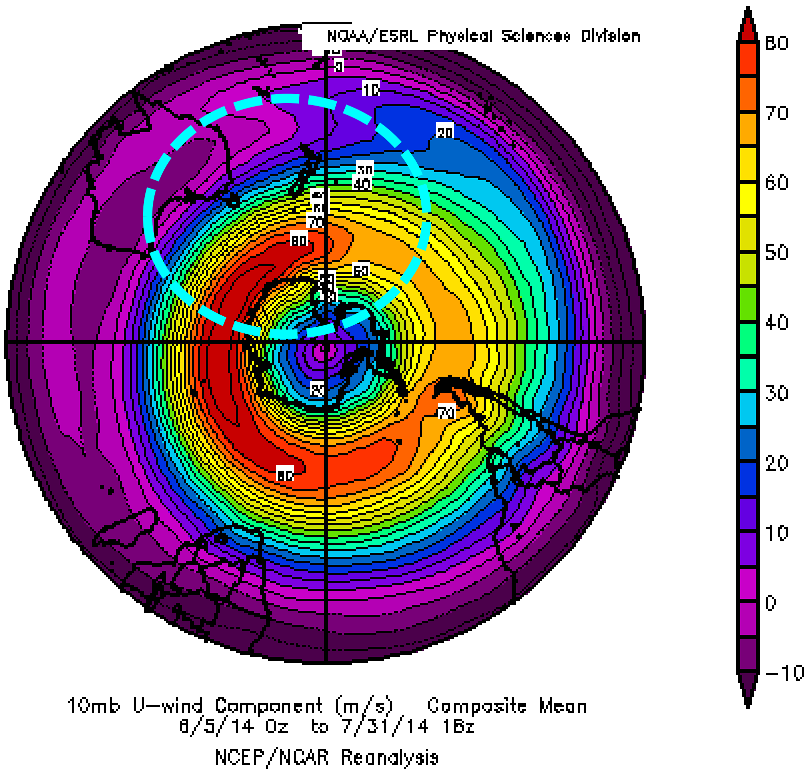


- Strong ridge at 100 hPa over New Zealand
- Weaker westerly flow at 100 hPa than average.

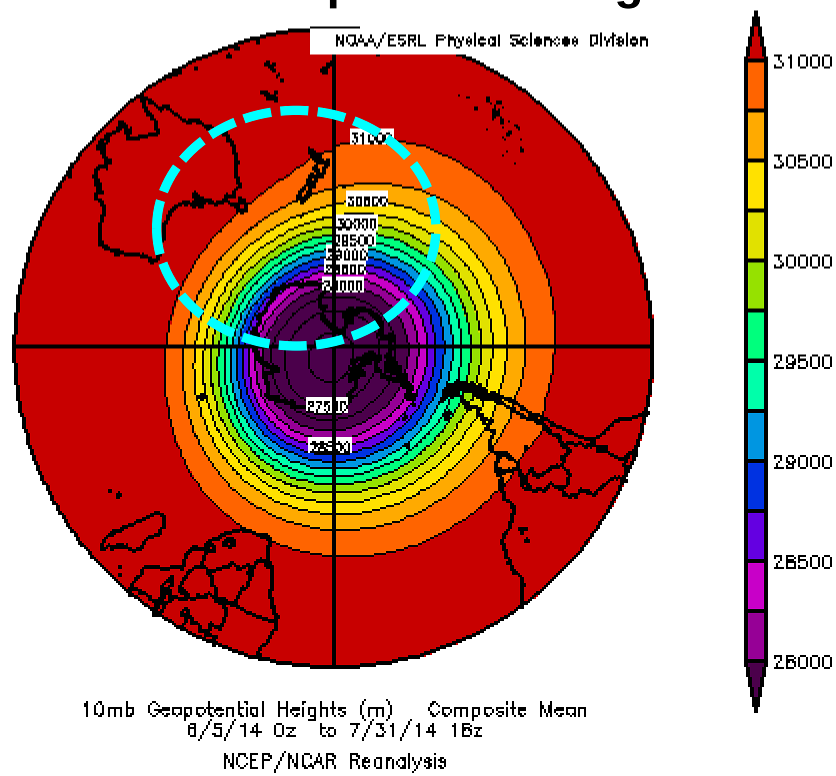
Large-Scale Flow During DEEPWAVE

NCEP/NCAR Reanalysis Anomaly
10-hPa

Mean Zonal Wind



Mean Geopotential Height

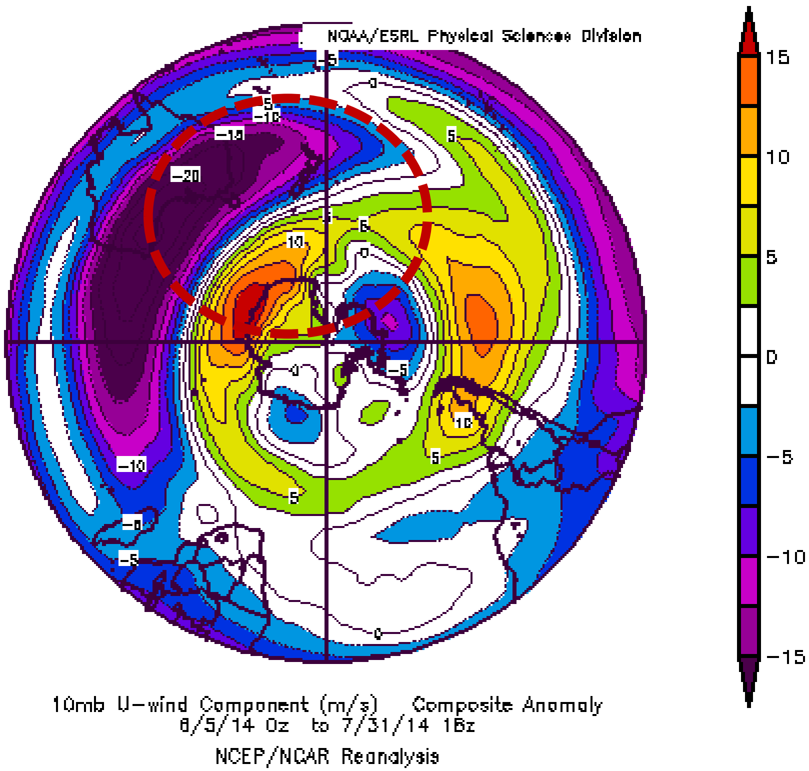


- Mean polar vortex jet maximum just south of the South Island.
- Annular vortex shape, strongest winds to the SW of South Island.

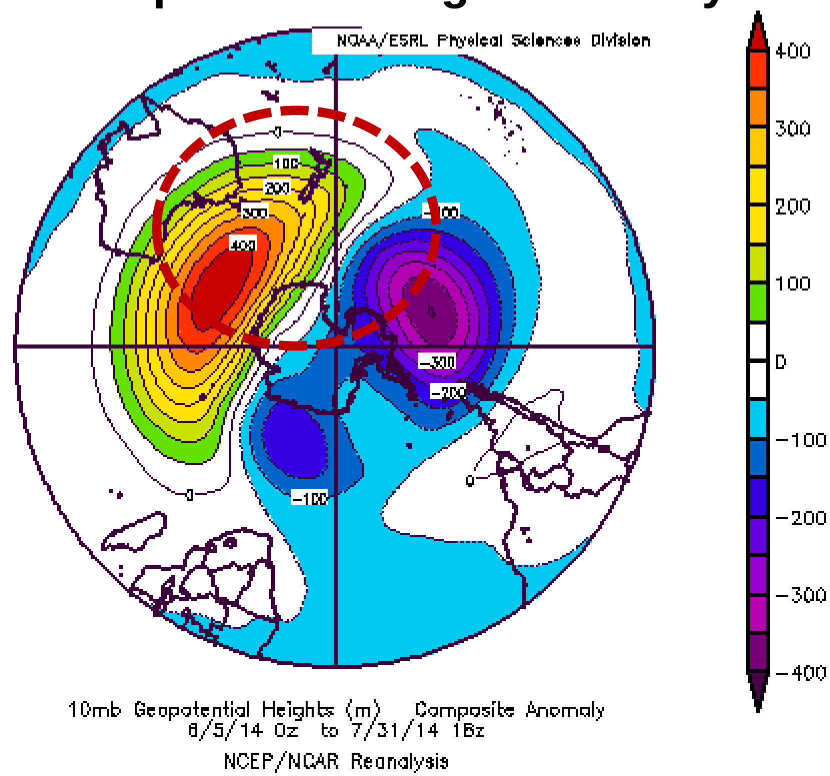
Large-Scale Flow During DEEPWAVE

NCEP/NCAR Reanalysis Anomaly
10-hPa

Zonal Wind Anomaly



Geopotential Height Anomaly

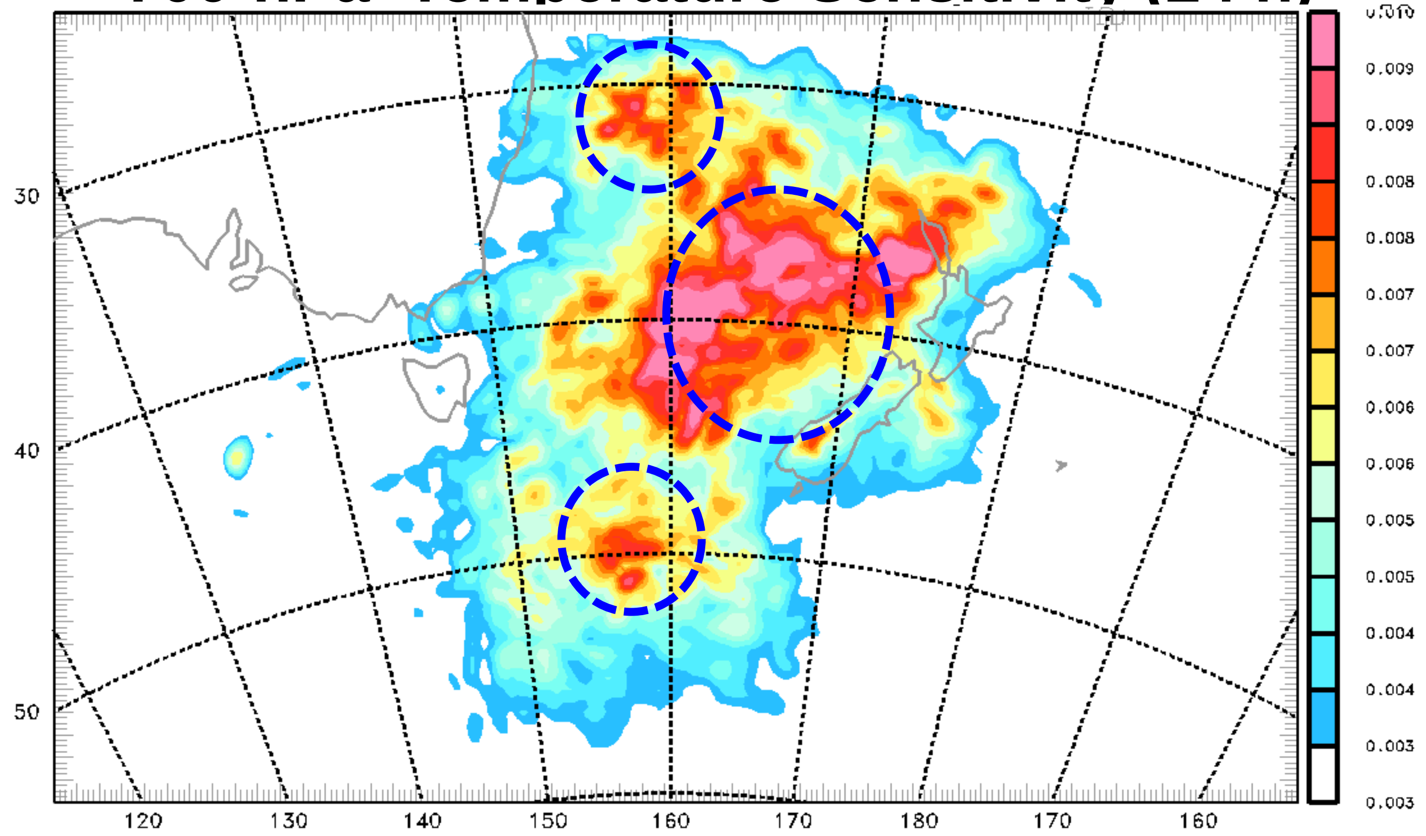


- Strong ridge at 10 hPa over New Zealand and extending to the west.
- Weaker westerly flow (large anomaly) at 10 hPa extending to the west.
- Polar vortex appears to be contracted and closer to pole near New Zealand.

Predictability of Deep Propagating GWs

June-July 2014 Mean

700-hPa Wind Speed and Heights (24h)
700-hPa Temperature Sensitivity (24 h)



- Mean 700-hPa flow was quite weak (2 month mean)
- Mean 700-hPa temperature sensitivity (24 h) is location over Tasman Sea to the west-northwest of New Zealand, with 3 main regions.

Predictability of Deep Propagating GWs

June-July 2014 Zonal Wind Sensitivity Maximum (m s^{-1})

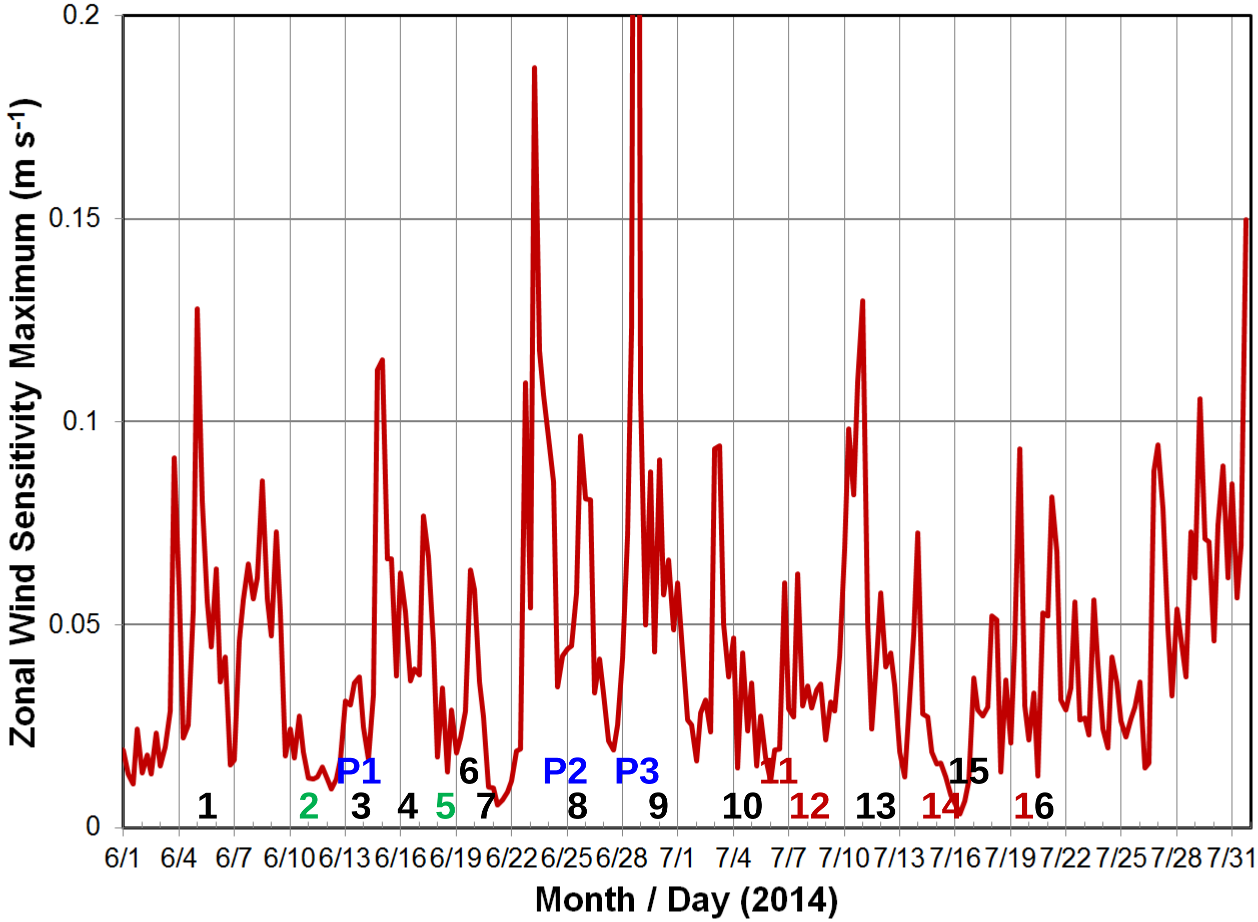
IOP #

NZ Flight

Tasmania

S. Ocean

Predict.

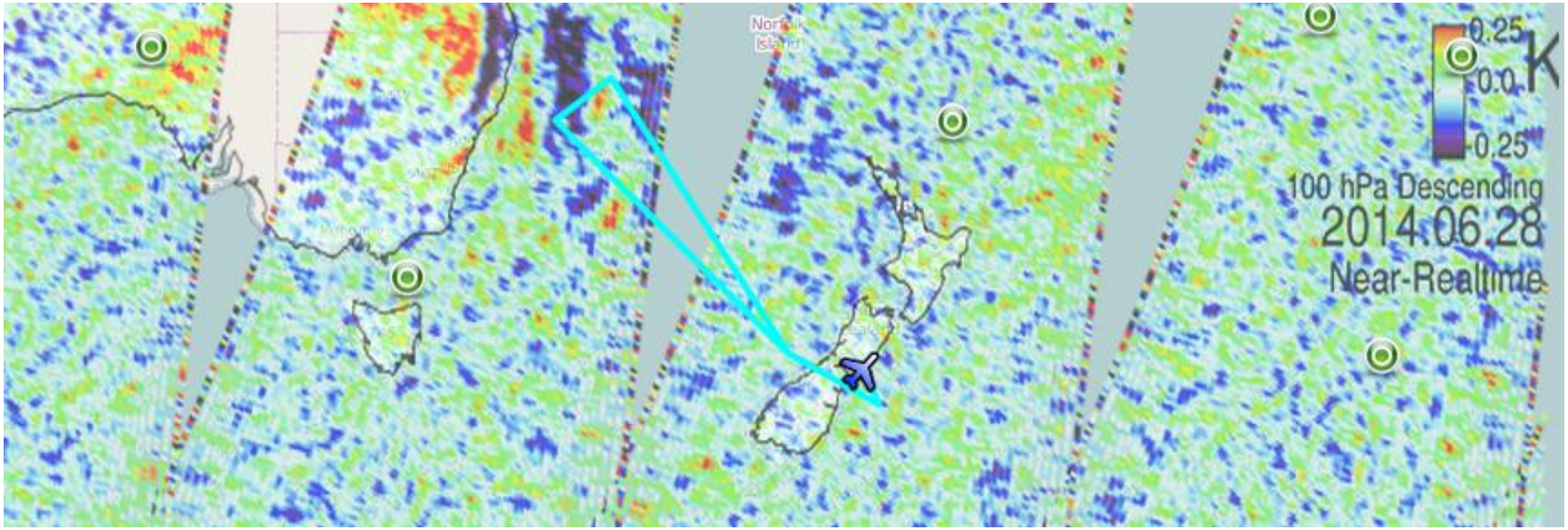


- Maximum sensitivity of the low-level wind speed over the S. Island (1 km deep response function) to the initial zonal wind component.
- Maximima correspond to the IOP periods in general.
- Largest zonal sensitivity peaks: IOPs 8 and 9, lesser 1, 4, 13

RF11 (IOP 9)

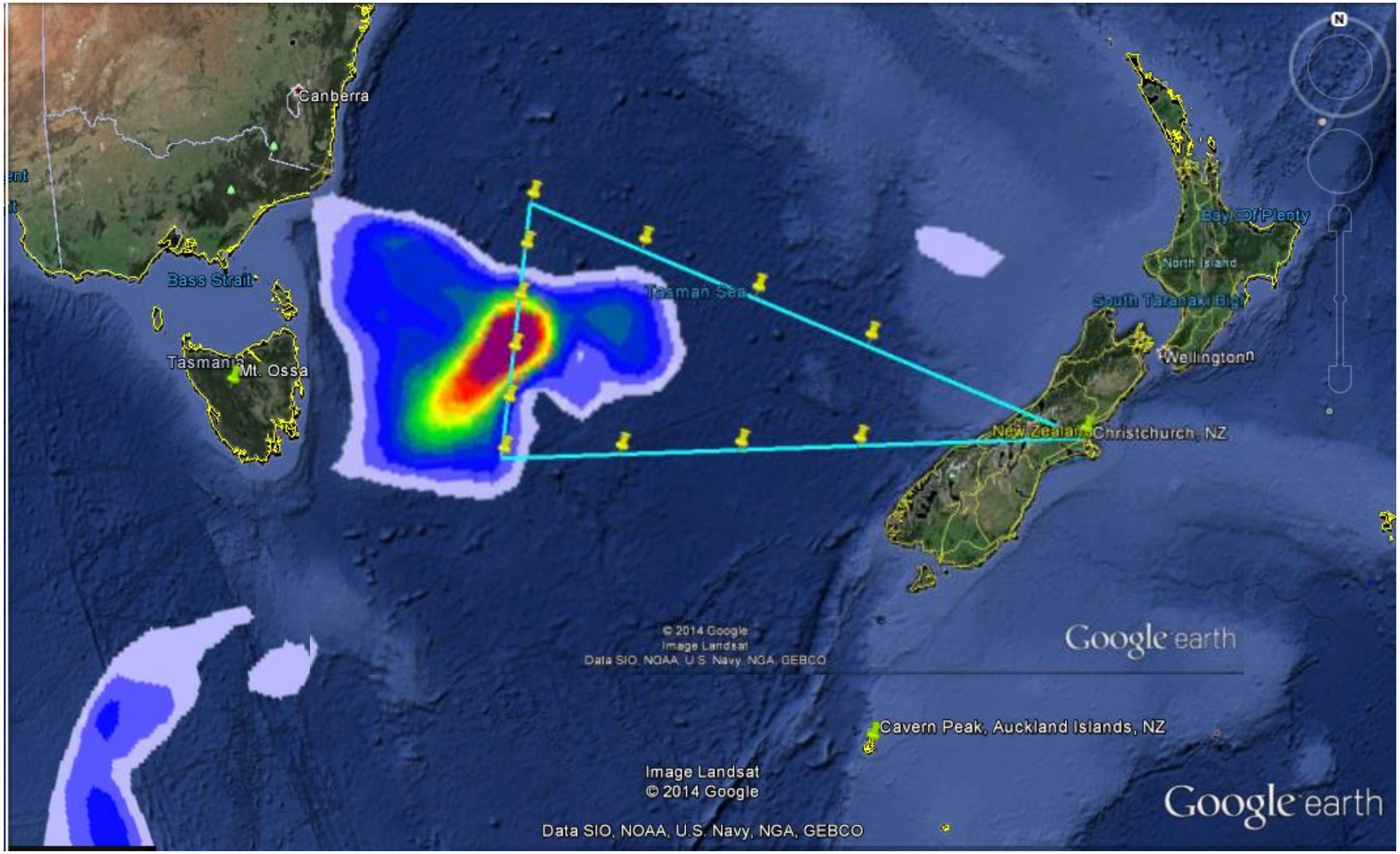
Large amplitude temperature perturbations apparent in the AIRS satellite observations near the time when the GV was flying.

AIRS at 100 hPa 1331Z 28 June



RF03 (IOP 3 Predictability Flight 1)

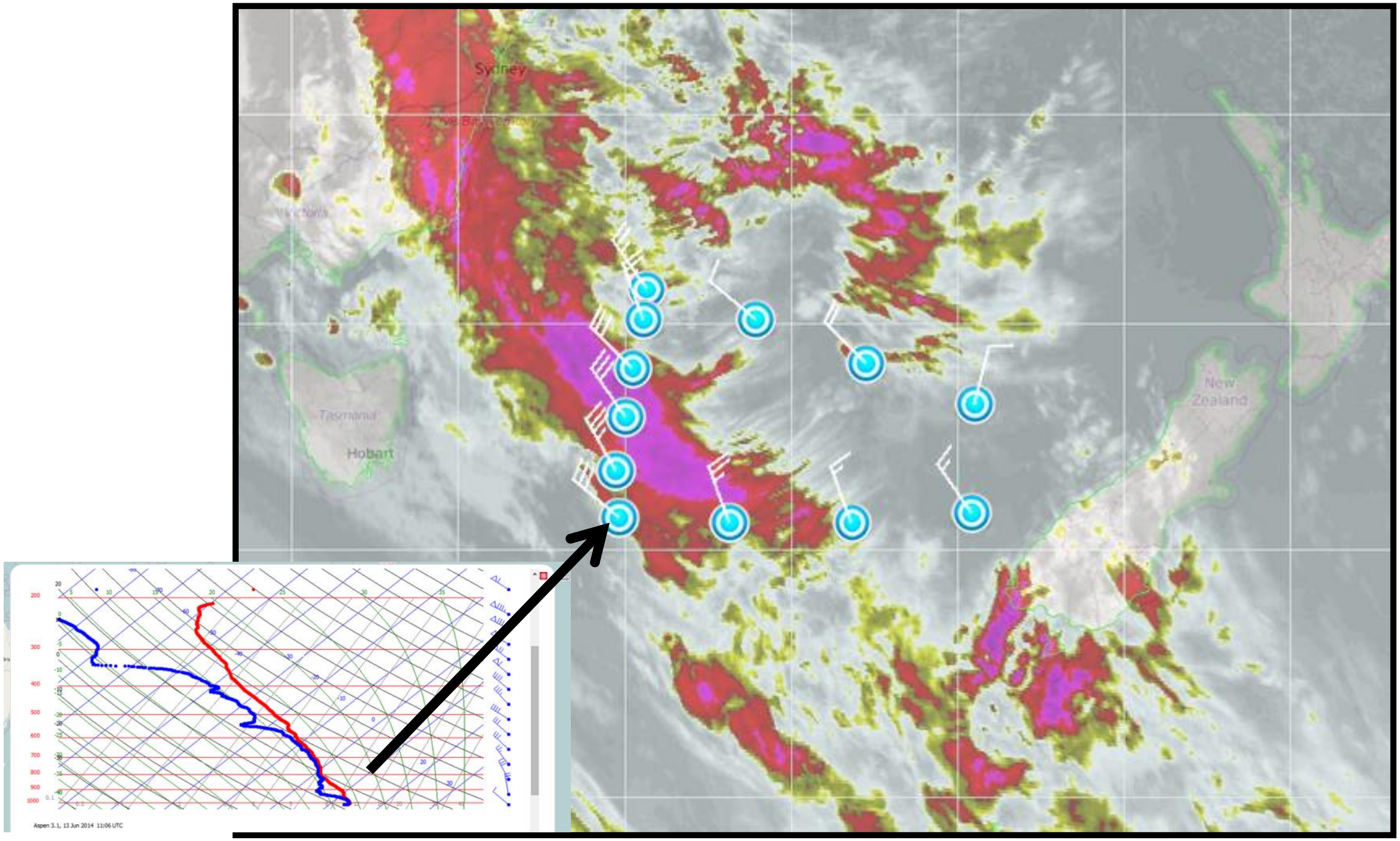
Total Energy of the Adjoint Optimal Perturbation at 12 UTC 13 June



Sampled a region of initial condition sensitivity upstream of the Southern Alps prior to a GW event that was observed in RF04, which was a strong gravity wave event with trailing waves).

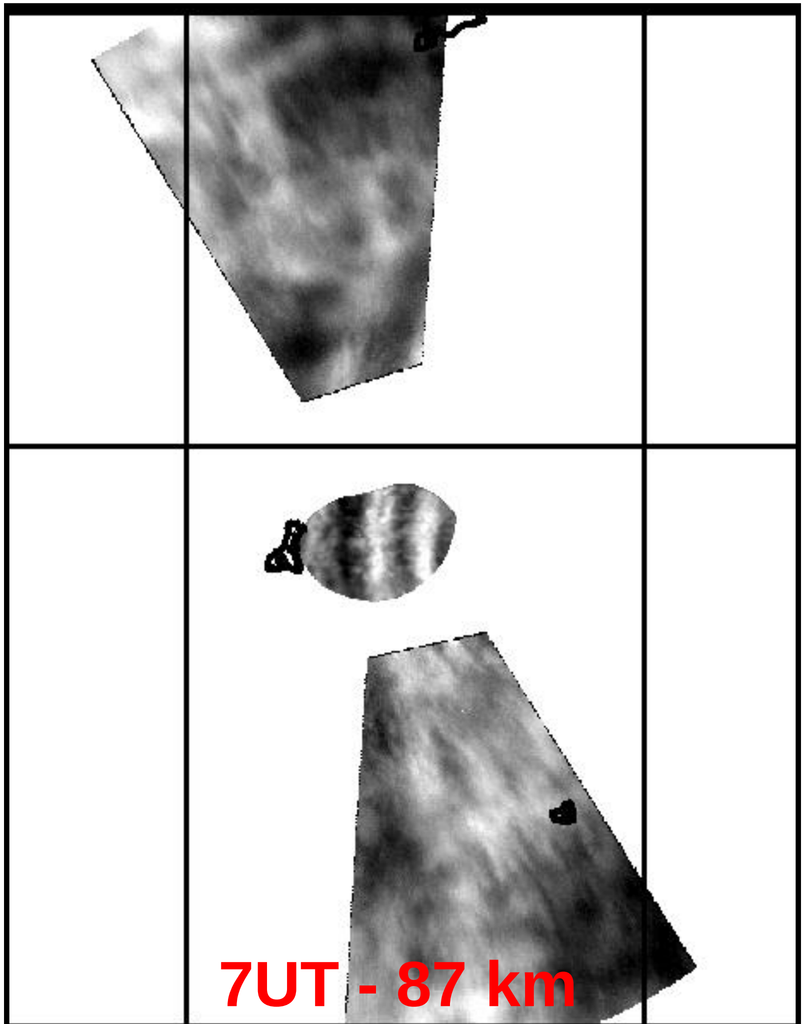
RF03 (IOP 3 Predictability Flight 1)

700-mb Droposonde Winds and IR

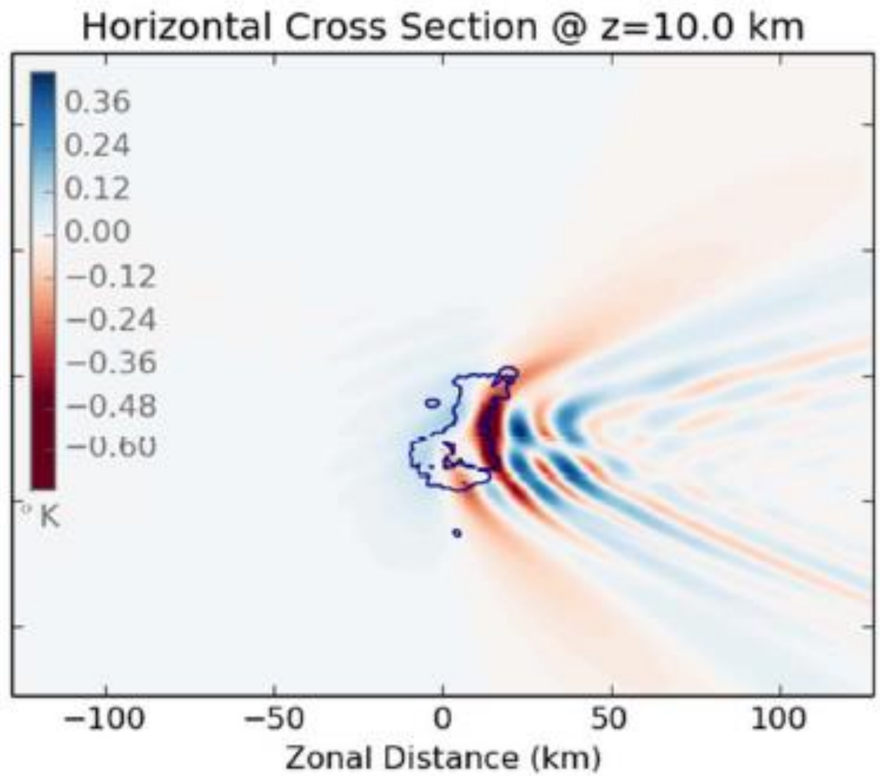


- Sensitivity maximum located near shortwave at 700 and 500 mb. Enhanced cloud shield and low-level jet in sensitive region.
- Dropsondes indicated shallow convection with moist layer
- Targeted dropsondes successfully observed this feature well.

Orographic Waves over Southern Ocean Islands - RF23

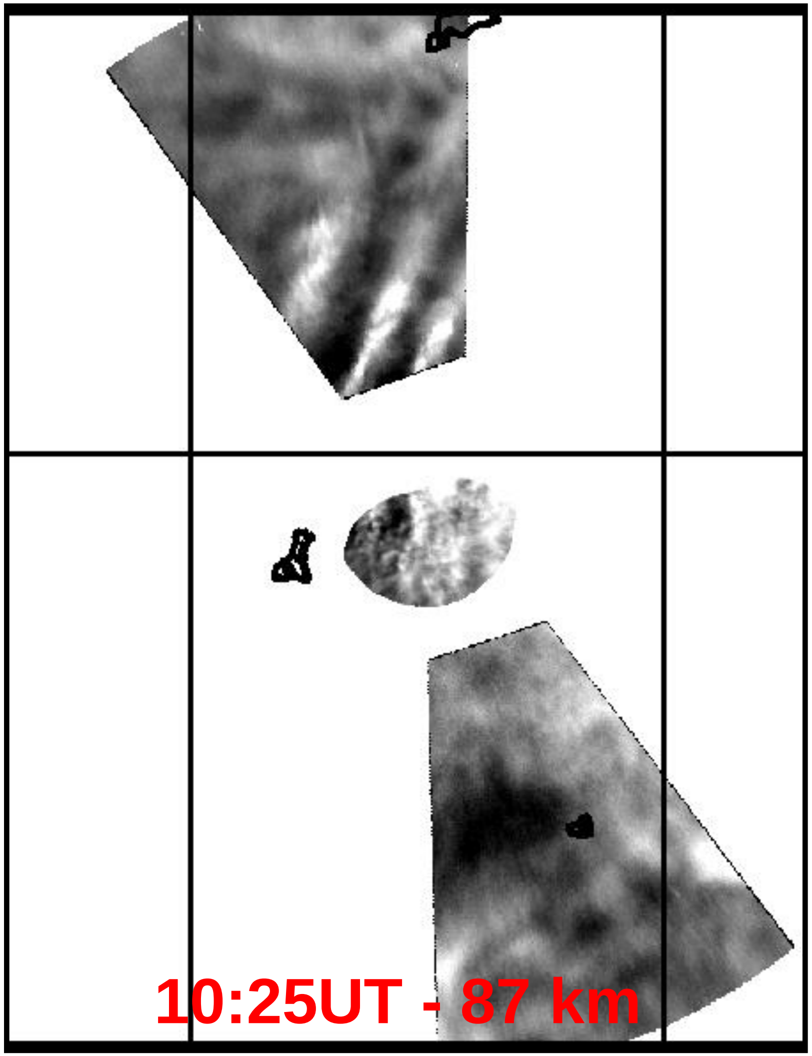


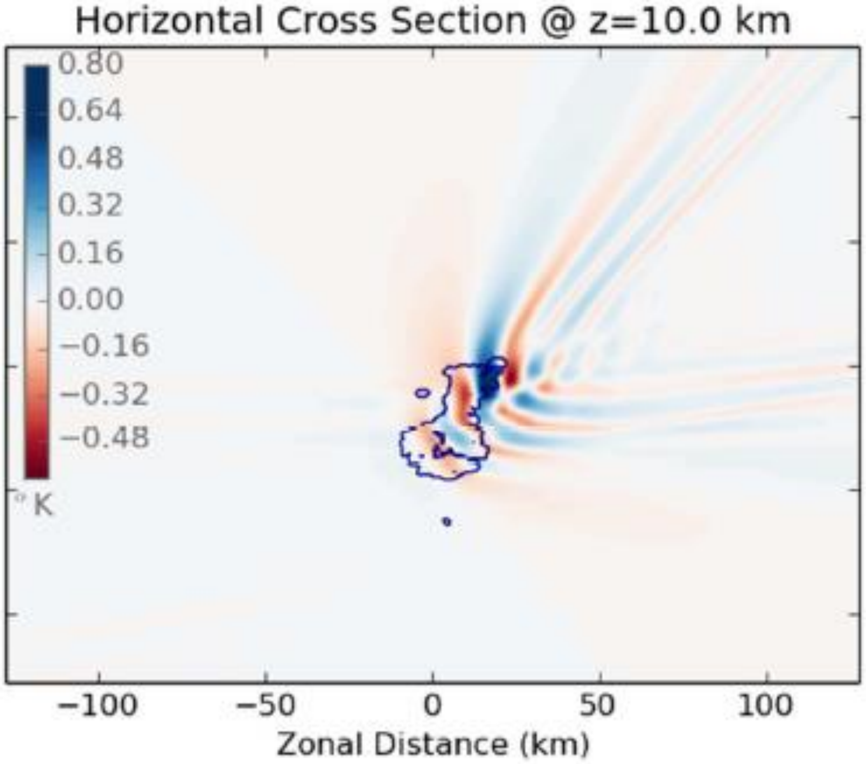
7UT - 87 km



6UT - 10 km (courtesy J. Ma)

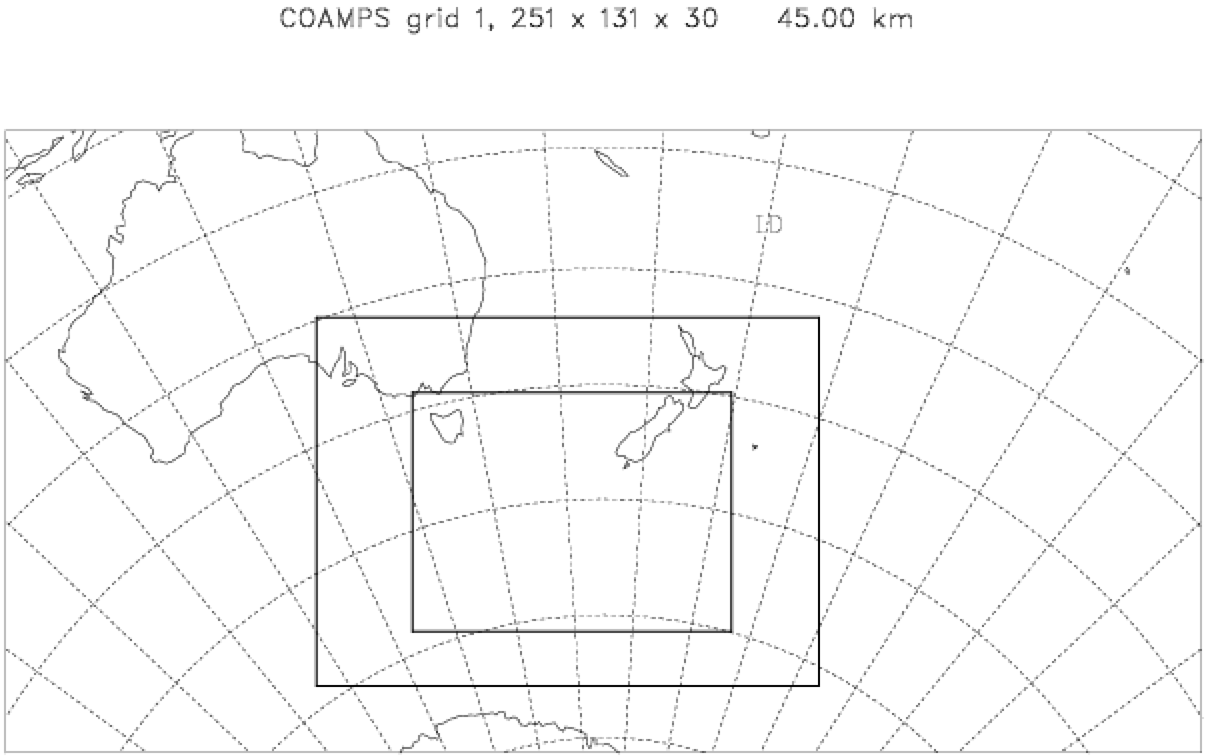
Orographic Waves over Southern Ocean Islands - RF23





9UT - 10 km (courtesy J. Ma)

COAMPS Domain



Three-level nested grids:
45 km: 251 x 131
15 km: 316x 232
5 km: 601x451

In vertical: 86 levels up to 0.2 mb (~ 60 km; same as in real-time runs)

Time: Cold start from 1200 UTC, 13 July to 1200 UTC, 15 July 2014.