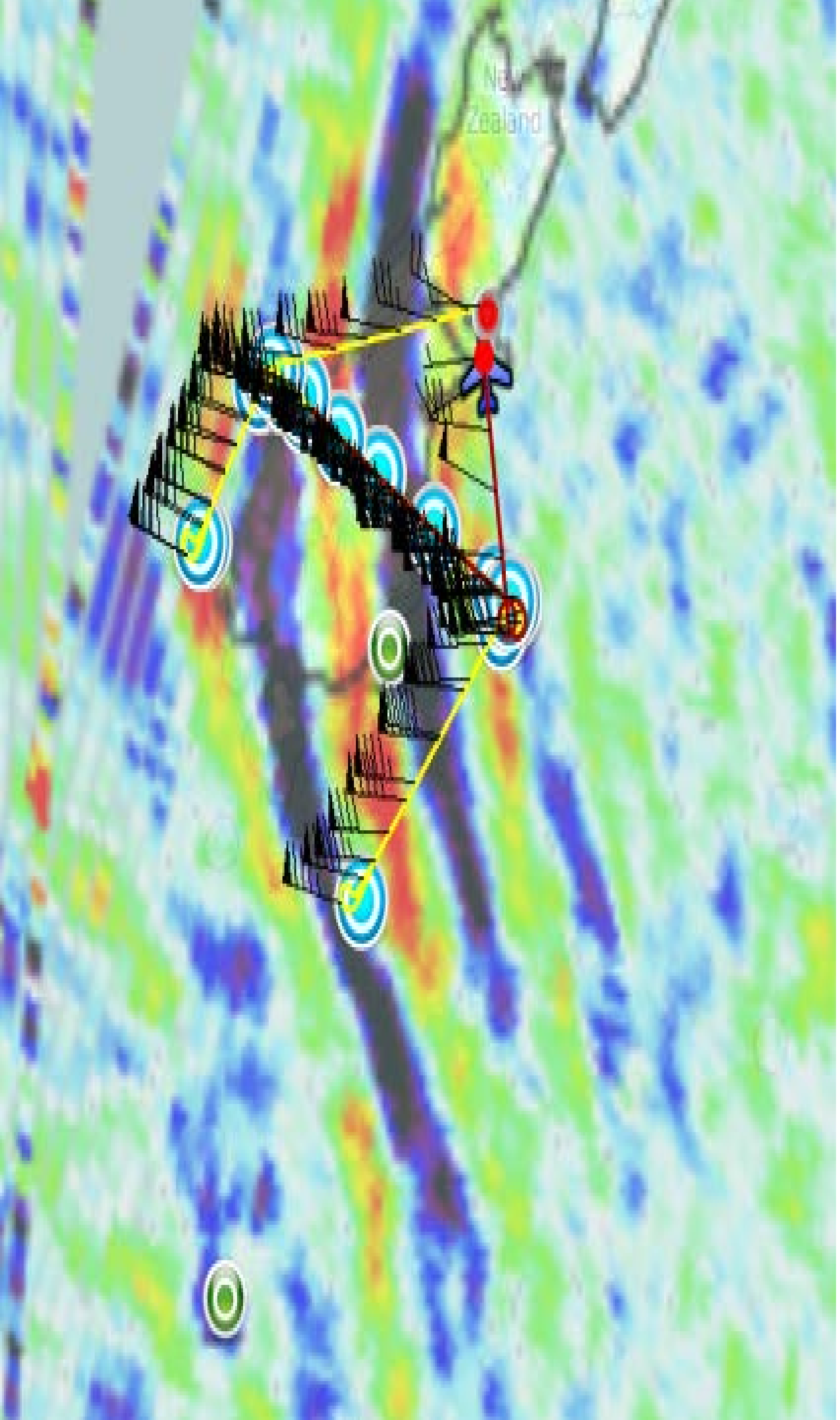


Trailing Waves from New Zealand

Q. Jiang et al., NRL Monterey, CA

December 2016

Trailing Wave IOPs

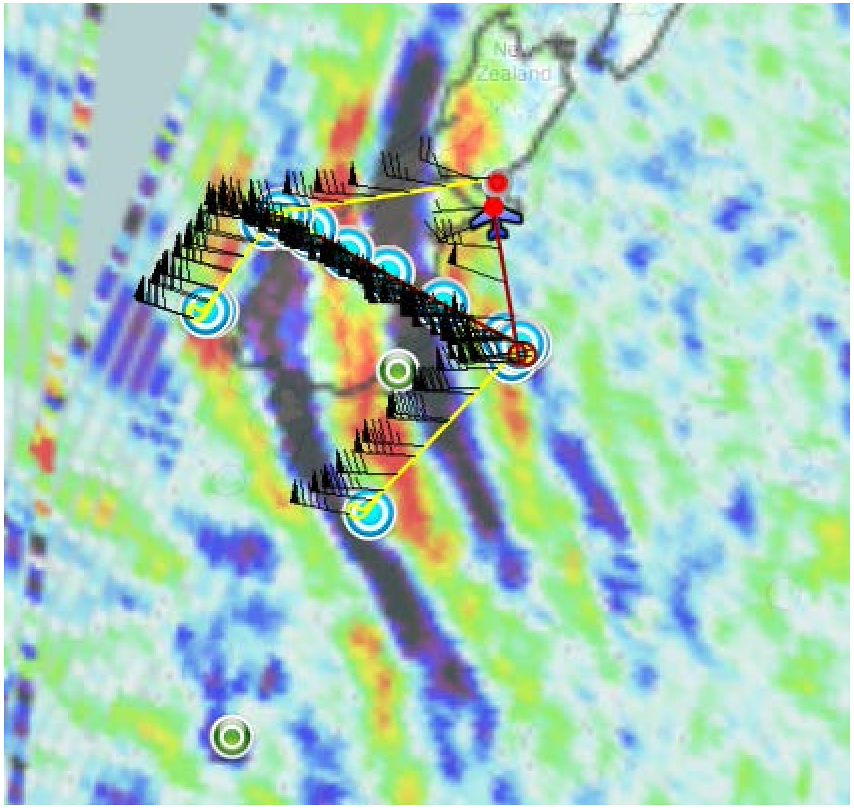
IOP/RF#/Date	IOP Objectives	COAMPS Simulations
IOP3a/RF03: 0755-1230 UTC, 13 June	Predictability	48-h forecast cold-started from 1200 UTC 12 June 2014
IOP3b/RF04: 0700-1445 UTC, 14 June	Trailing Waves over S. Island	
IOP6/RF07: 0555-1456 UTC, 19 June	GW generated by terrain and frontal system	48-h forecast cold-started from 1200 UTC 18 June 2014
IOP7/RF08: 0653-1346 UTC, 20 June	Trailing Waves over S. Island	

Trailing Wave IOPs

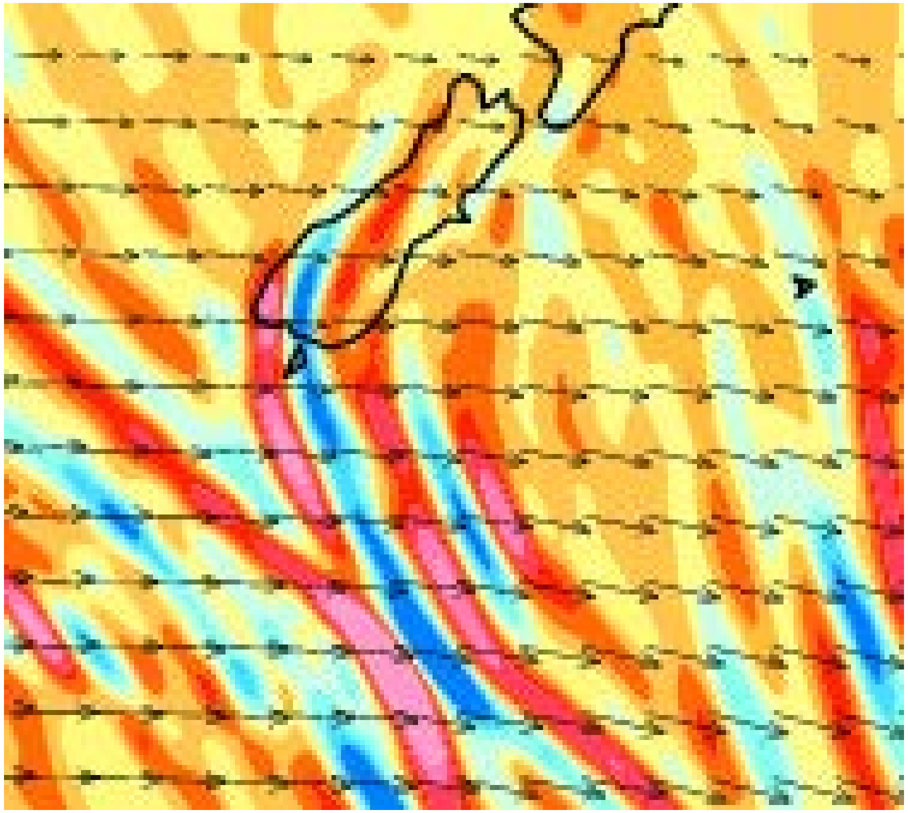
IOP/RF#/Date	IOP Objectives	COAMPS Simulations
IOP3a/RF03: 0755-1230 UTC, 13 June	Predictability	48-h forecast cold-started from 1200 UTC 12 June 2014
IOP3b/RF04: 0700-1445 UTC, 14 June	Trailing Waves over S. Island	
IOP6/RF07: 0555-1456 UTC, 19 June	GW generated by terrain and frontal system	48-h forecast cold-started from 1200 UTC 18 June 2014
IOP7/RF08: 0653-1346 UTC, 20 June	Trailing Waves over S. Island	

Simulation I: IOP 3b/RF04

AIRS @1319 UTC 14 June 2014 (2mb)



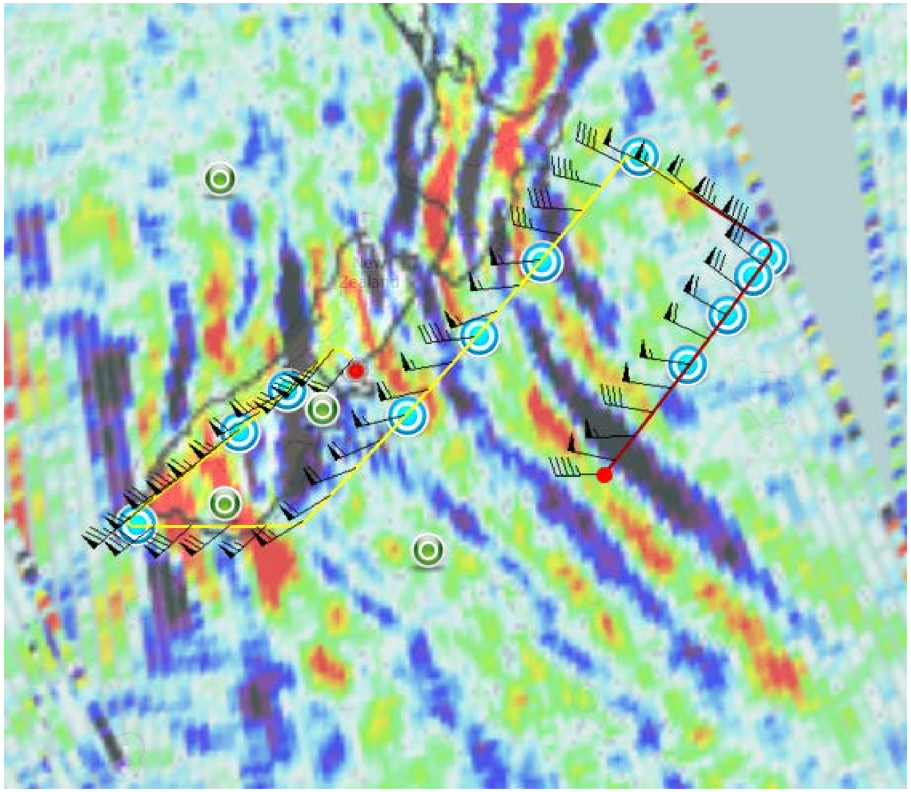
W @ 30km valid at 1200 UTC, 14 June 2014



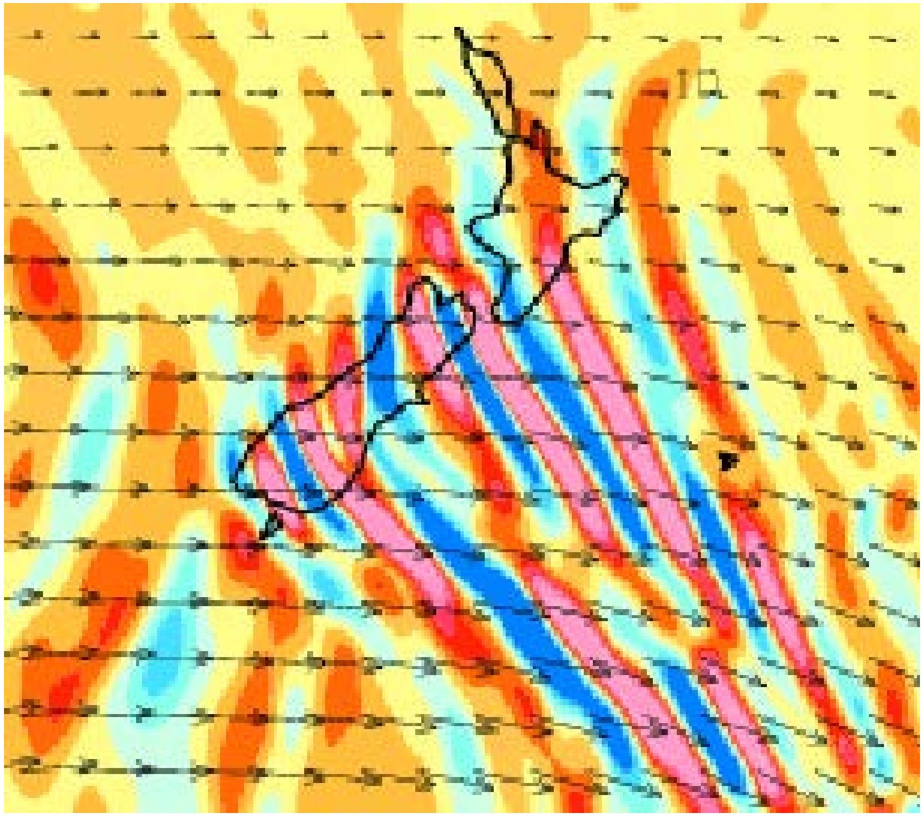
- **AIRS observed three-pairs of TWs from the South Island**
- **North-South Asymmetry**
- **Wavelength (spacing between two adjacent wave beams)~ 200 km**
- **COAMPS reproduced salient features of TWs**

Simulation II: IOP 6/RF07

Valid at 0230UTC 19 June 2014 (2mb)



W @ 30km valid at 1200 UTC, 19 June

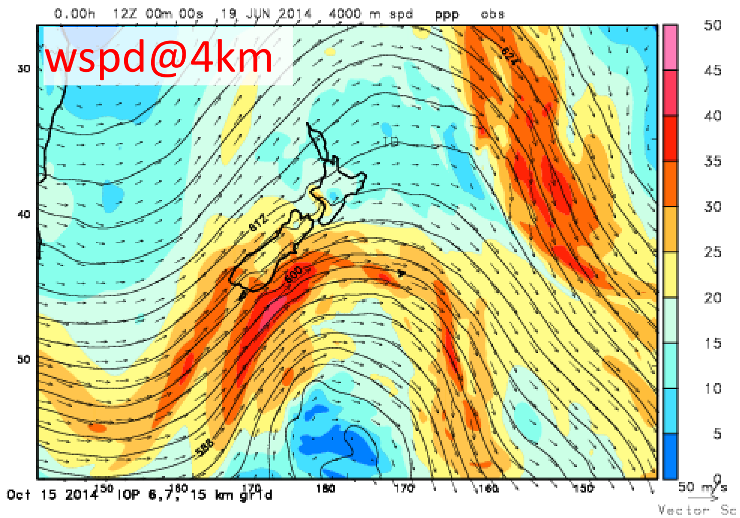


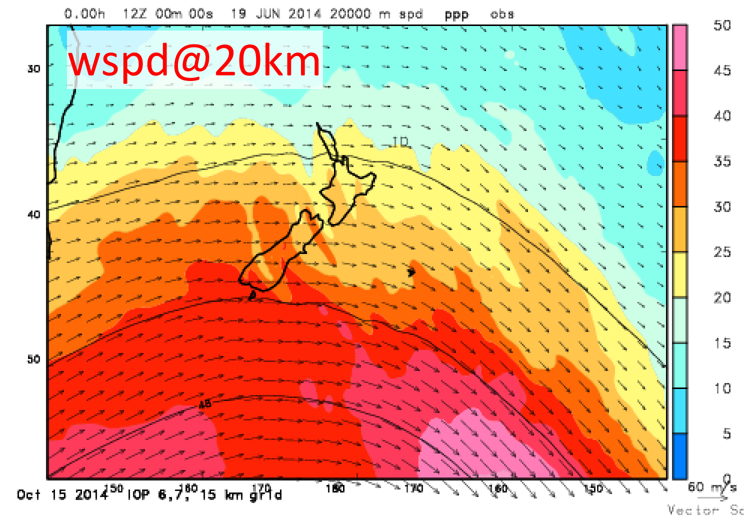
- North-South Asymmetry
- Wavelength~100-150 km
- Qualitative agreement between AIRS and COAMPS

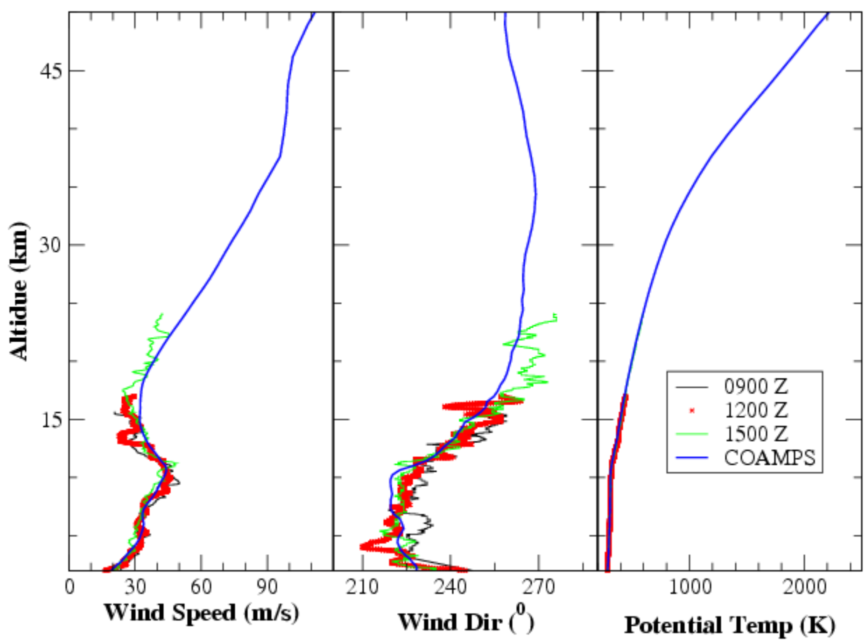
Objectives

- Characterize trailing waves from New Zealand
  - Characteristic wavelength, etc.
  - Energy/momentum transfer
- Explore formation mechanisms:
  - Wave source?
  - Favorite large-scale conditions?
  - Factors/processes that account for the N-S asymmetry?

Synoptic Conditions for IOP 6

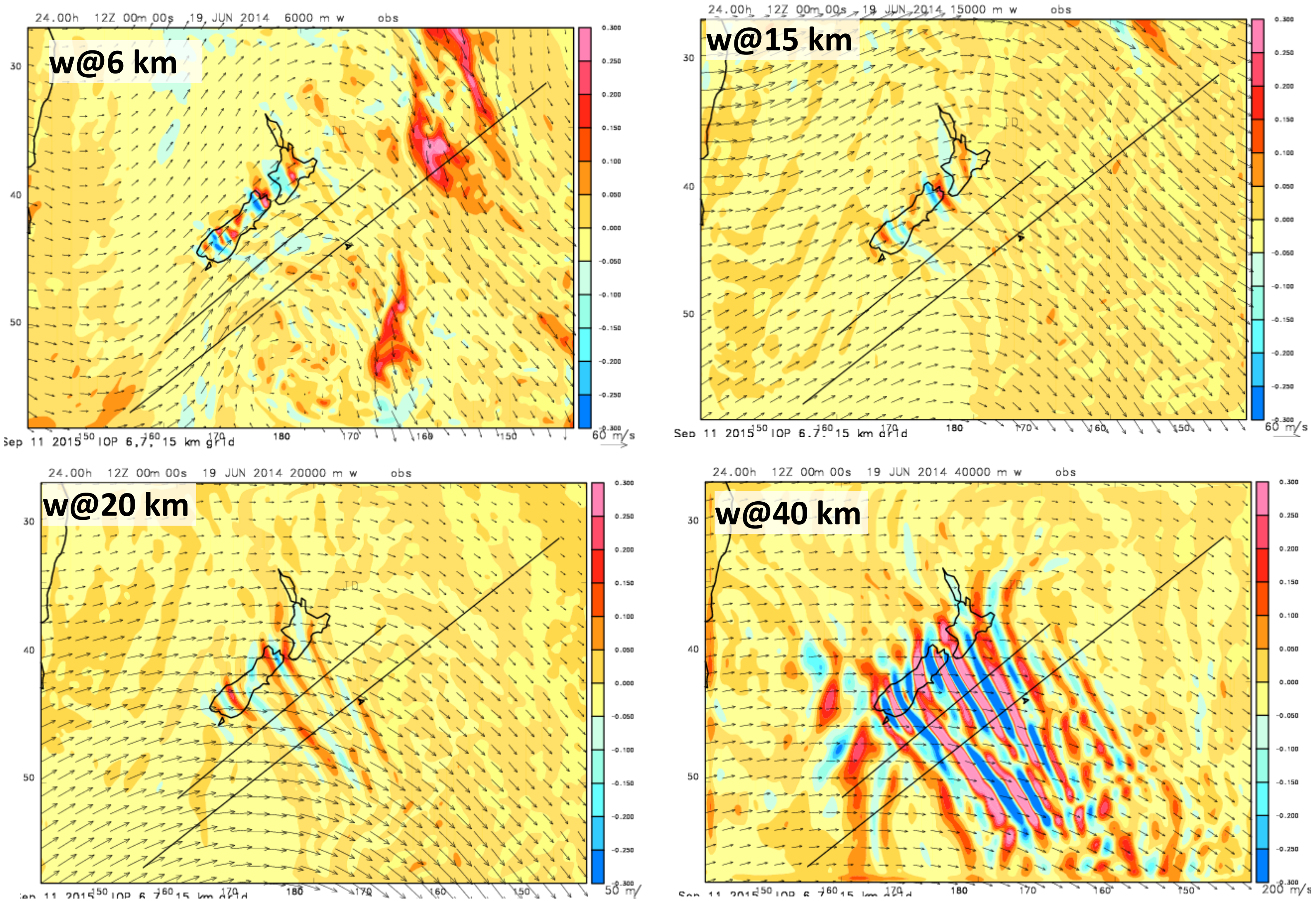






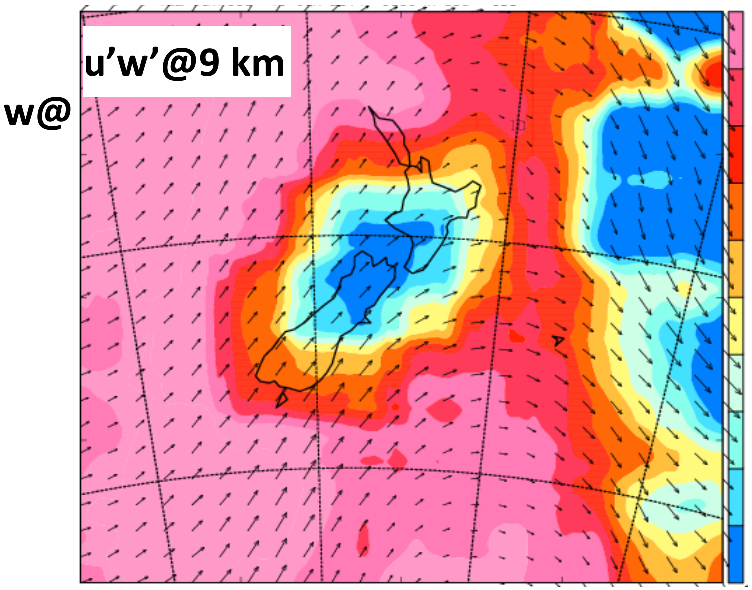
- Strong SSW-ly jet in troposphere and westerlies in stratosphere
- Directional shear in lower troposphere and near tropopause (UTLS)
- Meridional shear in zonal winds in stratosphere (dU/dy<0)
- COAMPS simulated profiles compare favorable with those from radiosondes

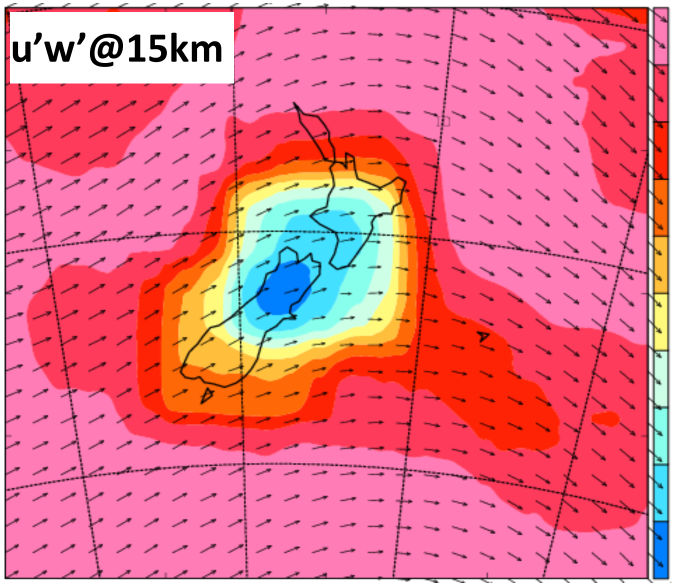
Vertical Variation of TW (IOP 6)

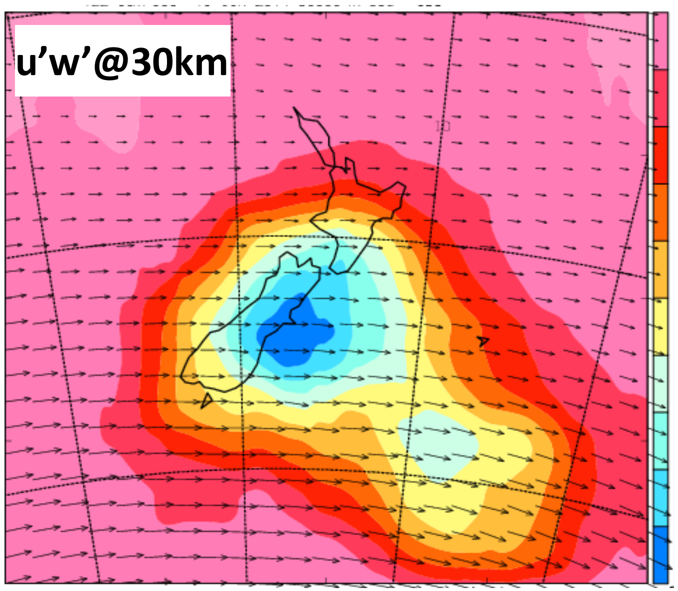


- **Waves are confined over or in the vicinity of terrain below 15 km**
- **Trailing waves develop above 20 km where winds are nearly westerly**
- **In general, TWs are vertically-coherent**

Momentum Fluxes

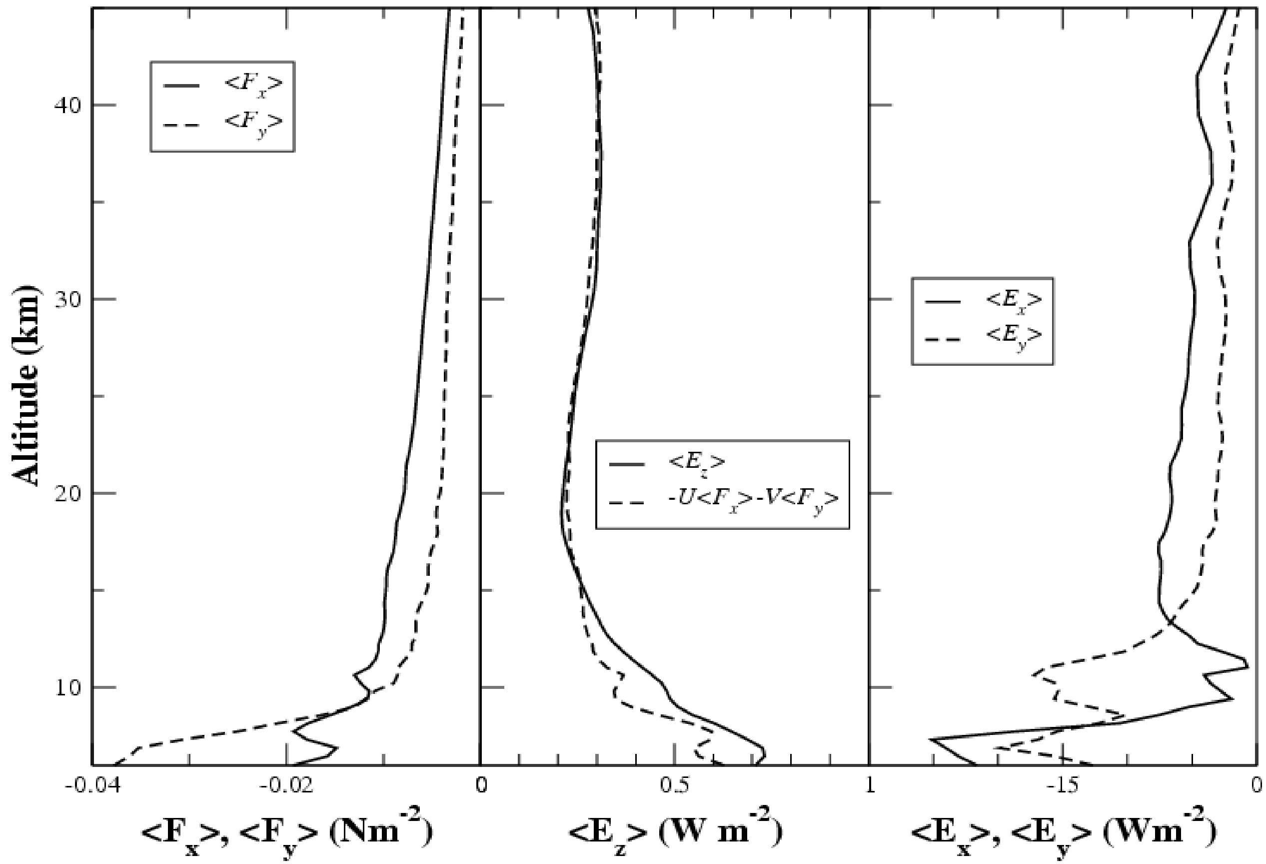






- Trailing waves carry negative (positive) momentum (energy) flux
- Momentum/energy flux is largely concentrated in an area over NZ in troposphere
- A significant fraction is carried downstream approximately along TW phase-lines in stratosphere

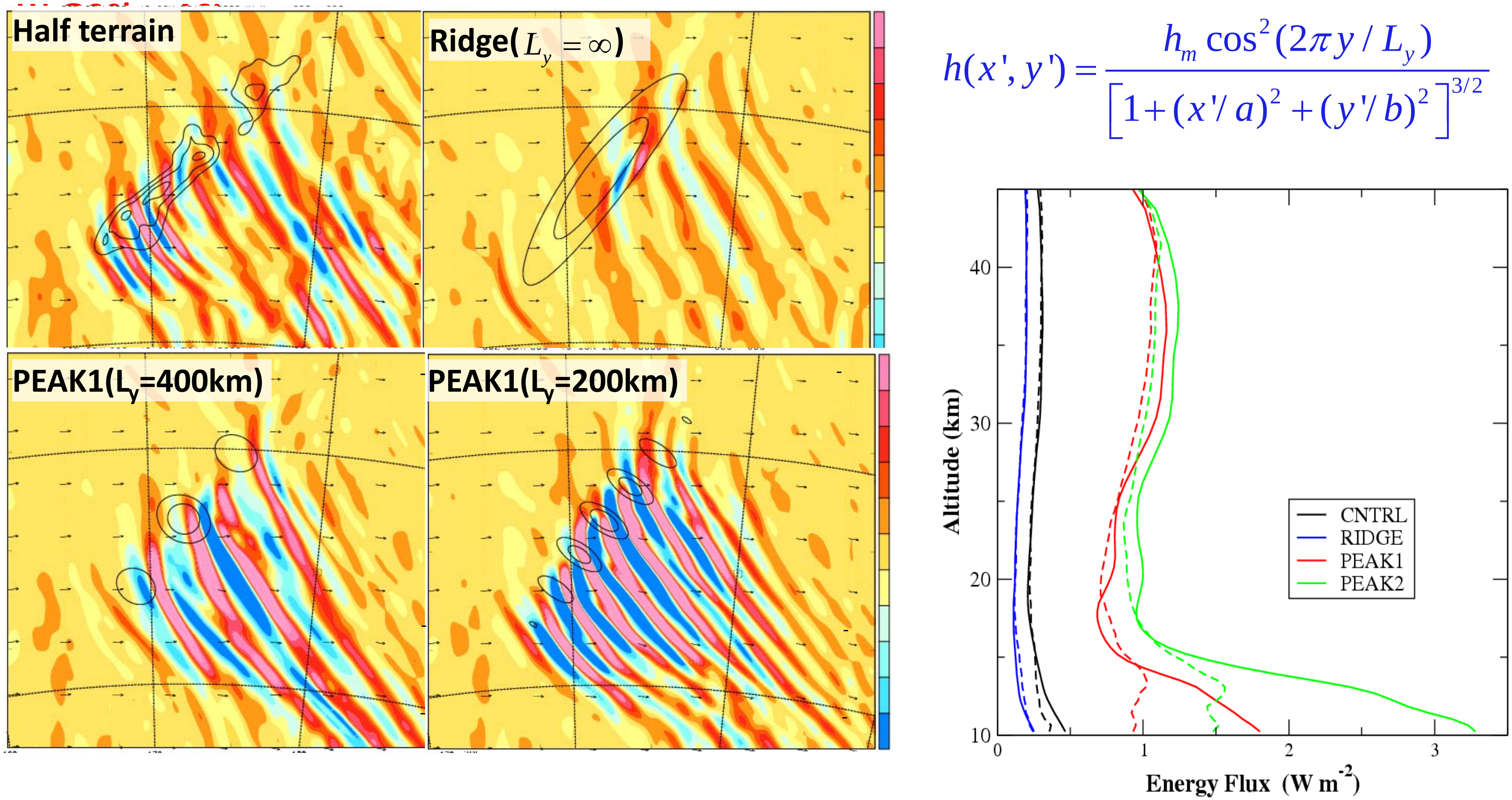
Wave Momentum/Energy Flux Profiles



- Momentum flux is negative and exhibits a sharp decease across the UTLS
- Energy flux is positive and increases with height between 15-30km
- The two satisfy Eliassen-Palm theorem to a good approximation
- Horizontally, waves propagate southwestward

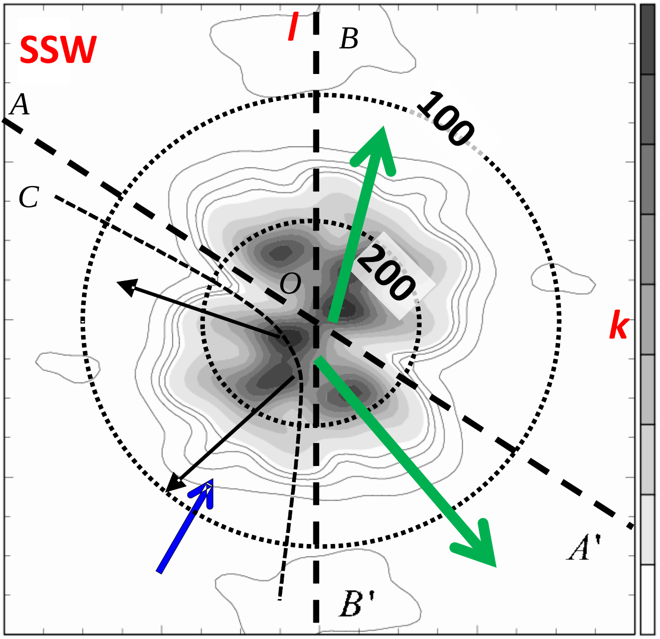
Terrain Sensitivity Experiments

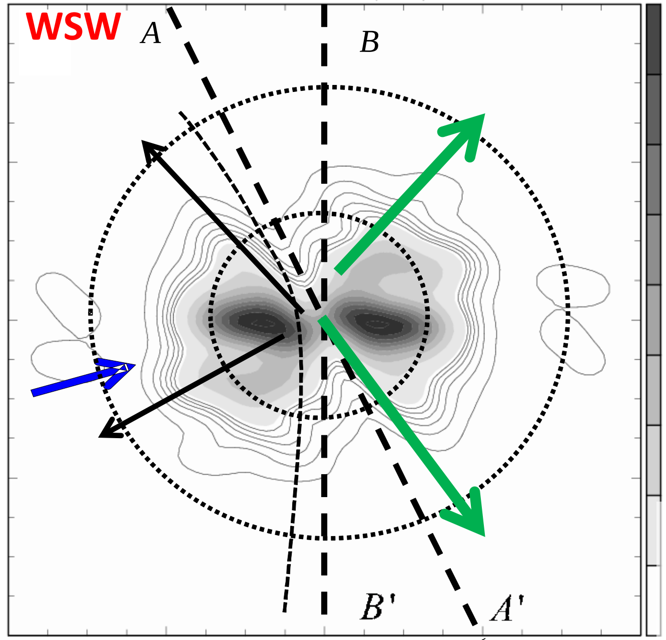
$$h(x',y') = \frac{h_m \cos^2(2\pi y / L_y)}{\left[1+(x'/a)^2+(y'/b)^2\right]^{3/2}}$$



- **Amplitude of TWs is approximately proportional to terrain height**
- **Further confirm that terrain is the source of TWs**
- **Wave length and wave beam orientation vary with terrain details**
- **Eliassen-palm theorem becomes invalid for nonlinear waves**

Vertical Velocity Spectra ($\hat{w}\hat{w}^*$) with Real Terrain





w @ Mountaintop Level:

$$w \sim \vec{V} \bullet \nabla h$$

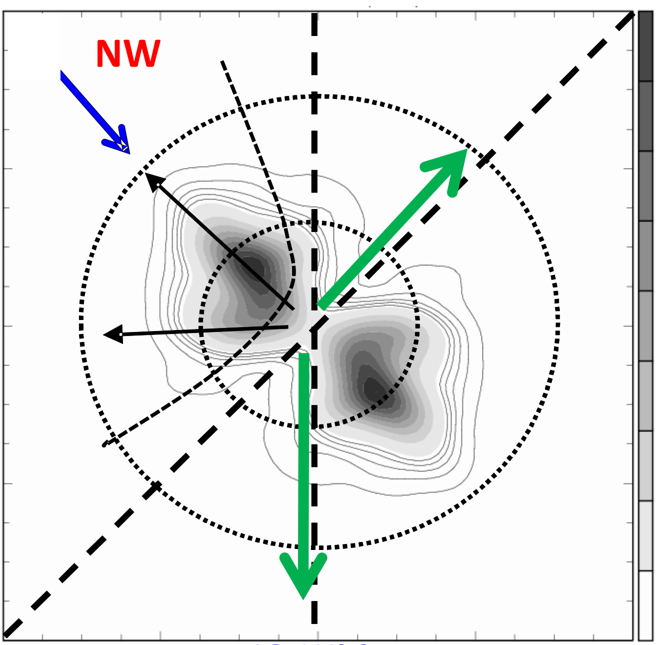
$$w(x,y) \leftrightarrow \hat{w}(k,l)$$

Ω-Critical Level:

$$\Omega = \vec{V} \bullet \vec{K} = 0$$

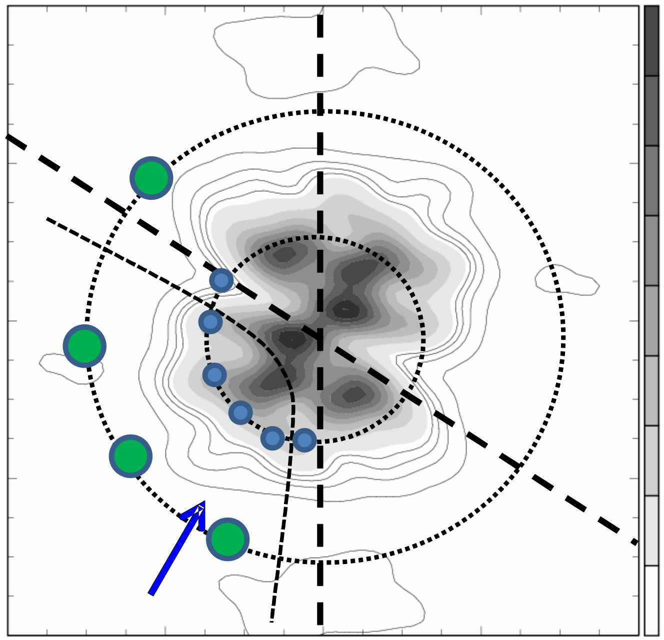
Jones-Critical Level:

$$\Omega^2 - f^2 = 0$$

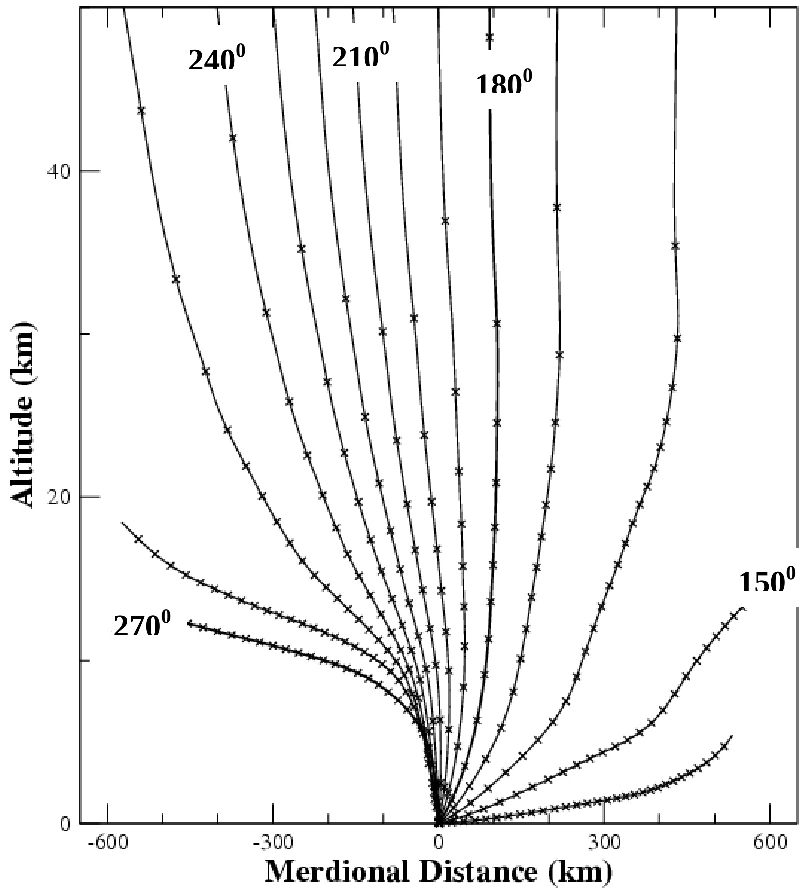


- Perturbations near wave source are sensitive to mountaintop wind direction and terrain details
- Orientations of TW beams are sensitive to wind direction
- Critical levels only allow a fraction of perturbation energy entering stratosphere
- Cutoff wavelength due to Jones-critical level varies with wave angle ($UK\cos\theta > f$)

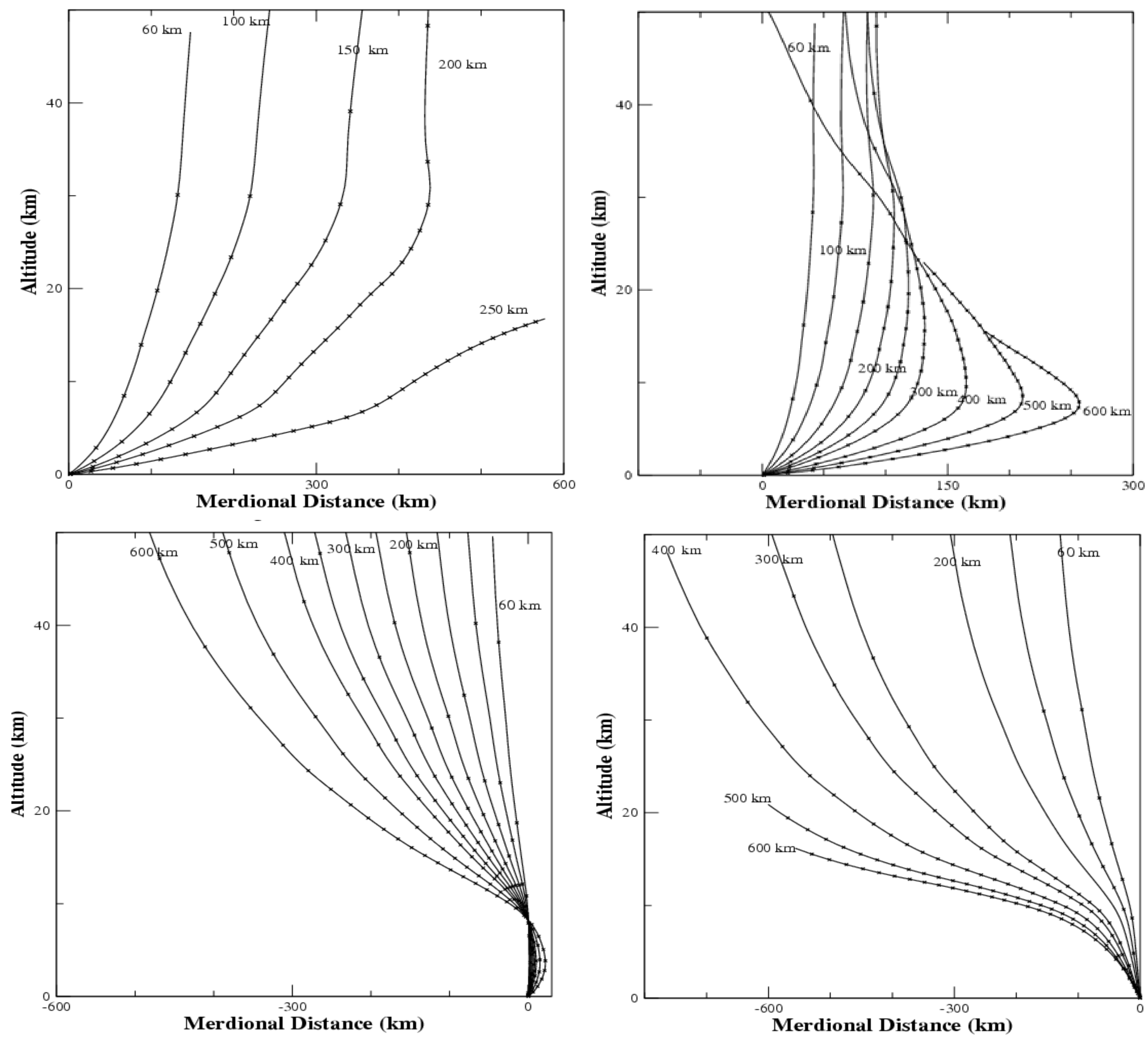
Ray Paths (y-z)



$K_0 = 2\pi / (200km)$



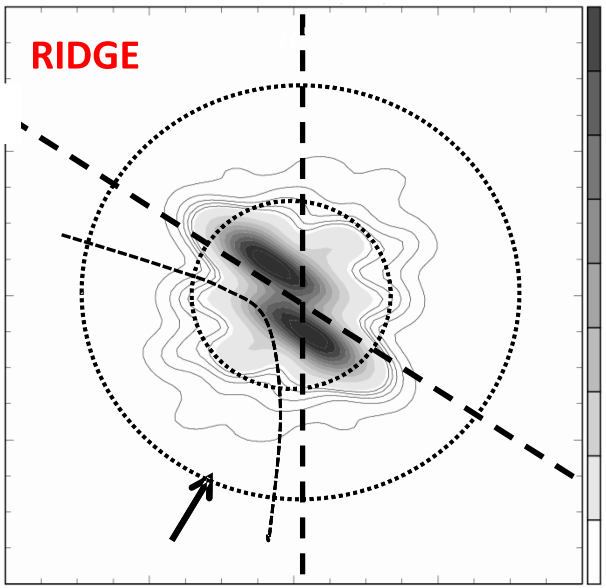
Ray-Paths (Y-Z)

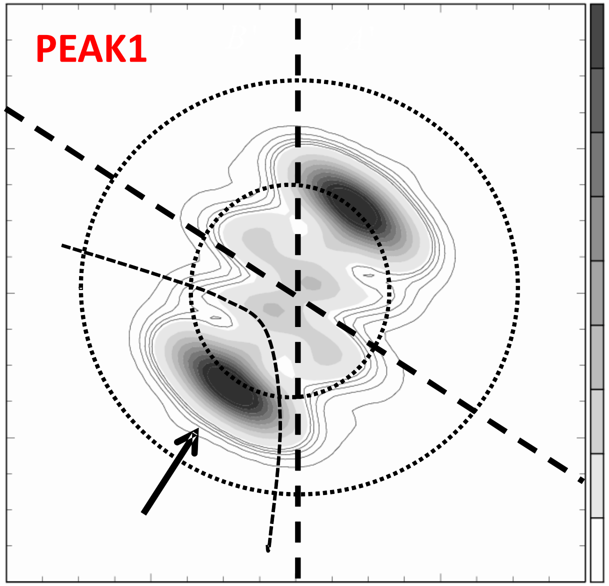

60 km
100 km
150 km
200 km
250 km
Altitude (km)
Merdional Distance (km)
0
20
40
0
300
600
60 km
100 km
200 km
300 km
400 km
500 km
600 km
Altitude (km)
Merdional Distance (km)
0
20
40
0
150
300
600 km
500 km
400 km
300 km
200 km
60 km
Altitude (km)
Merdional Distance (km)
0
20
40
-600
-300
0
400 km
300 km
200 km
60 km
500 km
600 km
Altitude (km)
Merdional Distance (km)
0
20
40
-600
-300
0

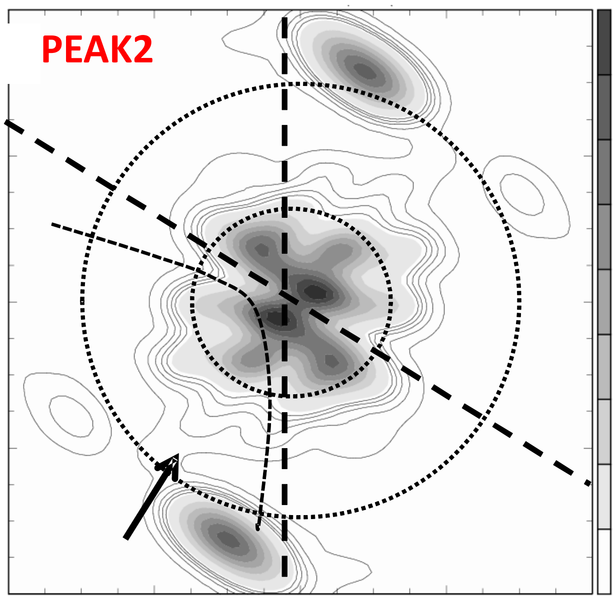
Summary

- Peaks and Valleys in the Southern Alps are the wave source of TWs.
- Wave characteristics are largely determined by the interaction between terrain and mountaintop winds, and are subject to critical level filtering
- TW transfers a substantial fraction of wave momentum flux upward and toward the stratospheric jet core, which may become significant in the upper stratosphere
- The energy and momentum fluxes follows the Elassen-Palm theorem reasonably well.
- Characteristic TW wavelengths are typically between 100-400 km. For shorter (<100 km) waves, waves are confined in the vicinity of wave source and wave refraction effect is small; for longer waves (>400 km), their vertical group velocity is too slow or they are subject to Jones critical level absorption or reflection.
- The N-S asymmetry is due to a) mountaintop wind direction, b) critical level absorption, and c) refraction by the meridional shear of zonal winds in stratosphere

Vertical Velocity Spectra for Idealized Terrain

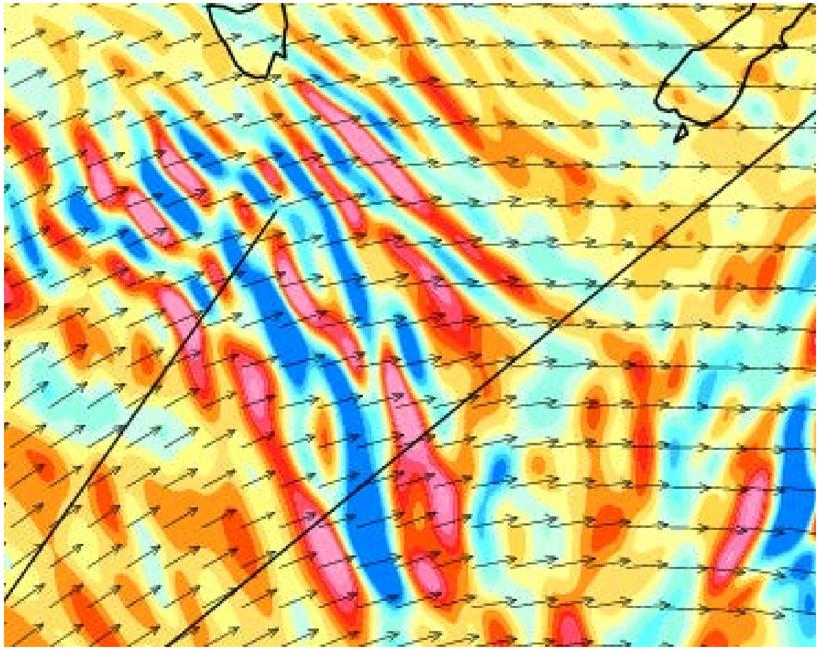


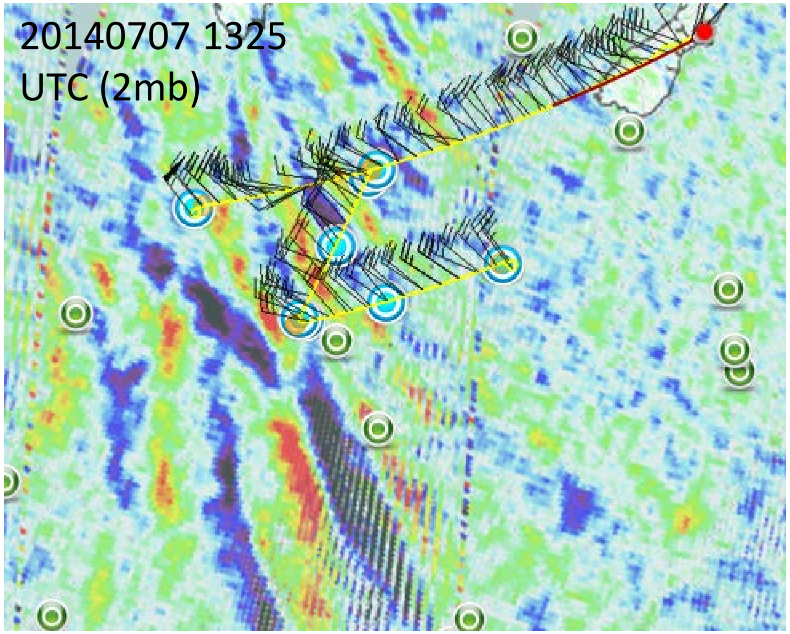




- **Dominant contribution comes from finer scale terrain**

Simulation I: IOP12a



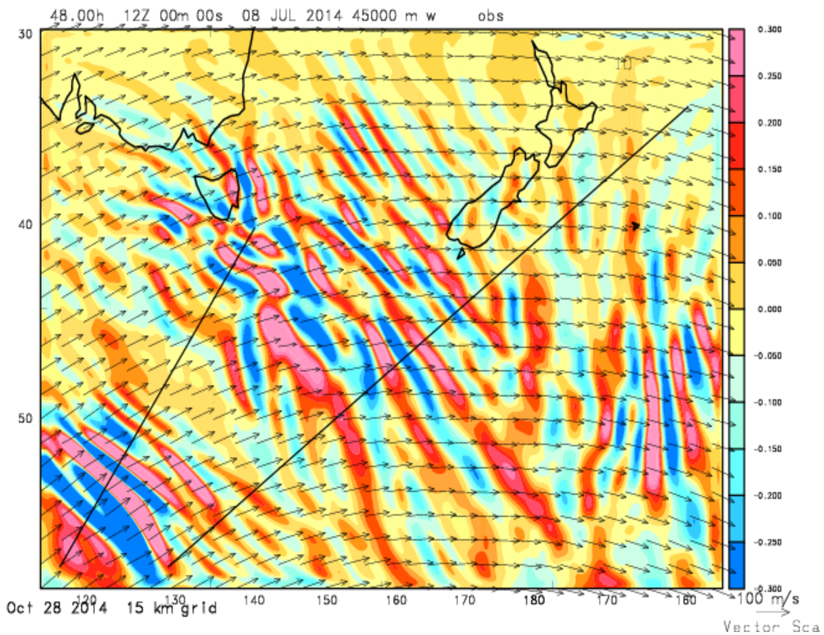


- COAMPS captured the deep (15-45 km) long (300-500 km) NOGW

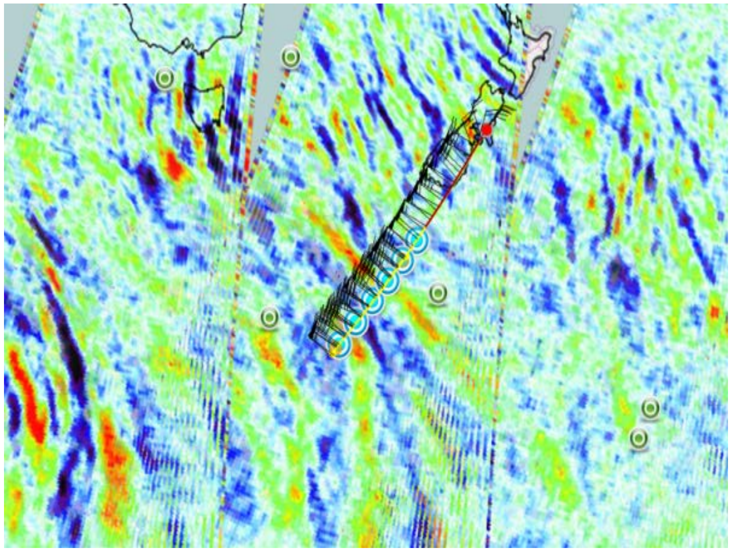
- Deep NOGW: visible between 30-2 mb!
- Located more south-west at 0218 UTC.
- Weaker on day 2 while propagating northeastward.

Simulation I: IOP12b/RF19

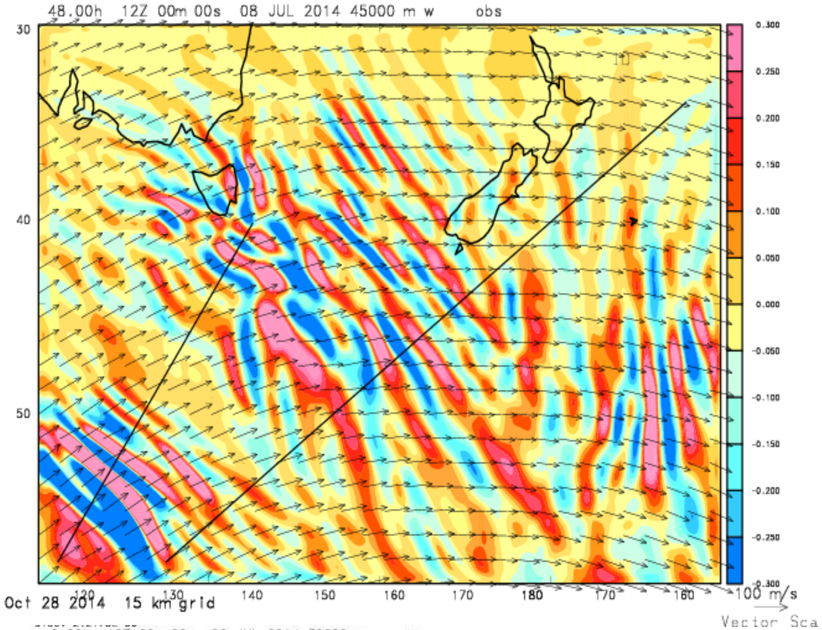
20140708 1200 UTC (45 km)

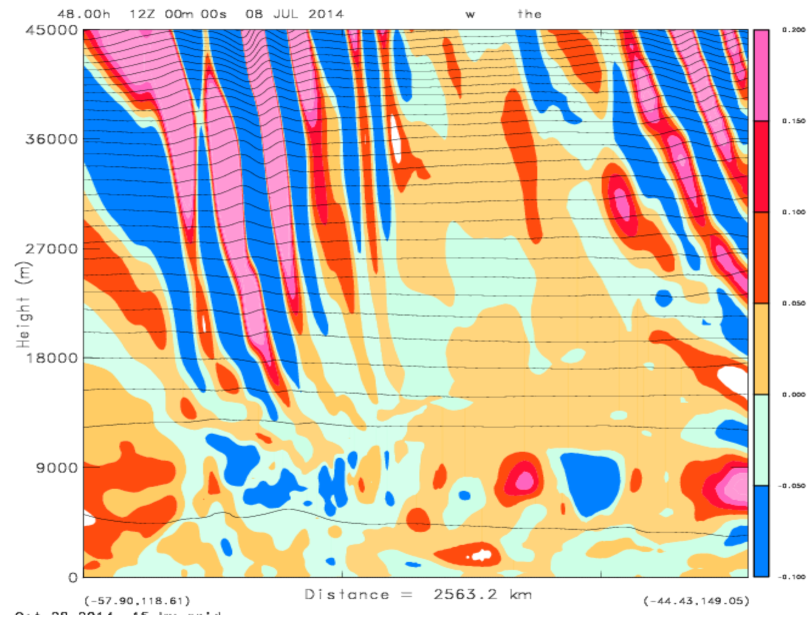


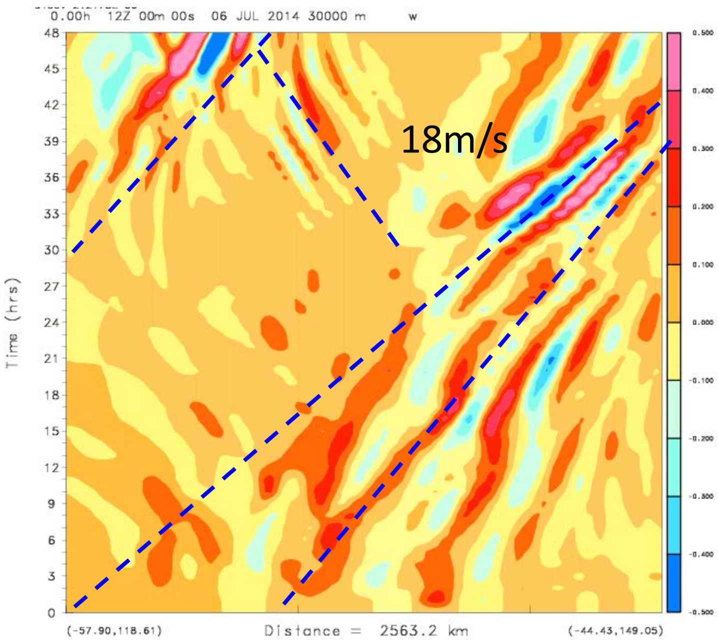
20140708 1407 UTC (2-4 mb)



Simulation I: IOP12b/RF19

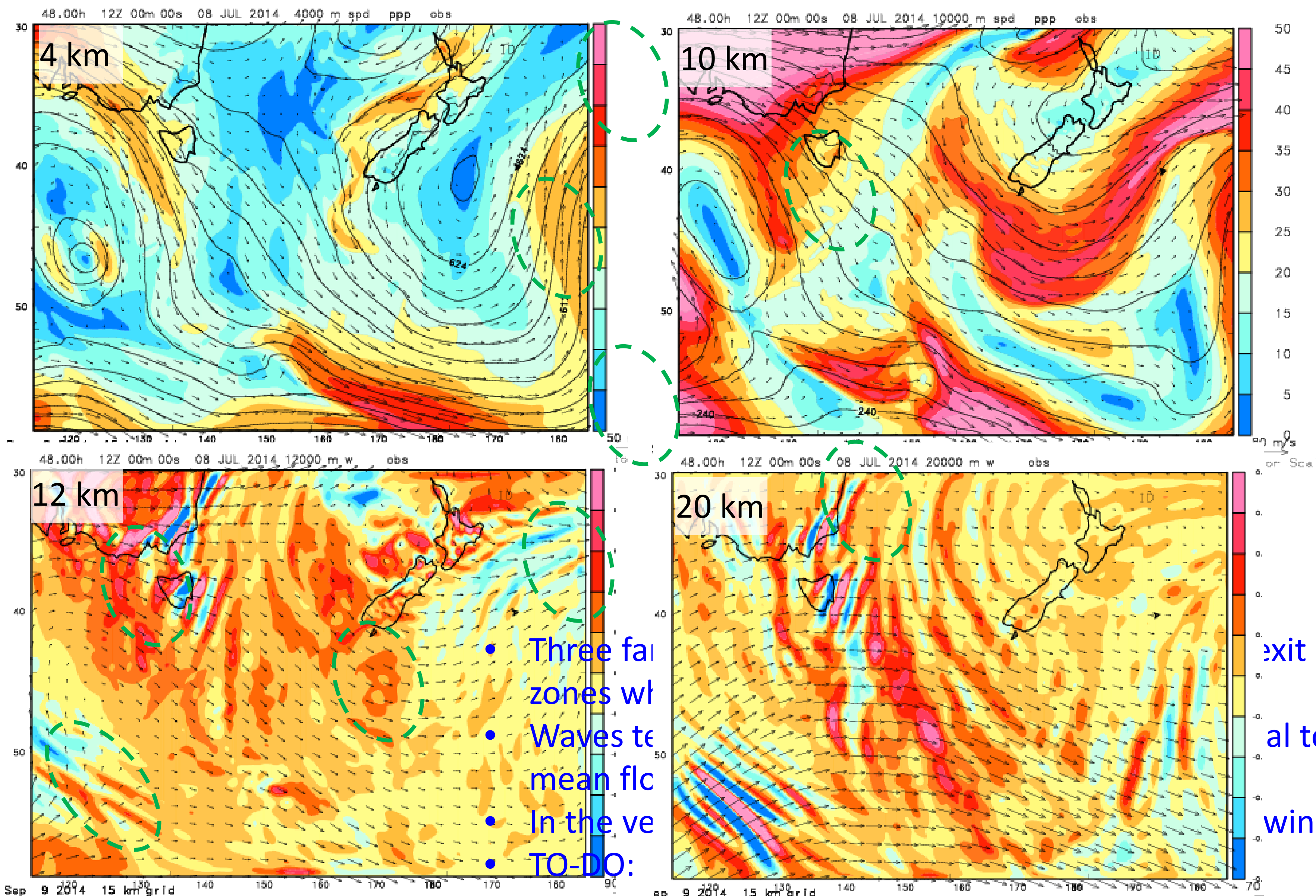






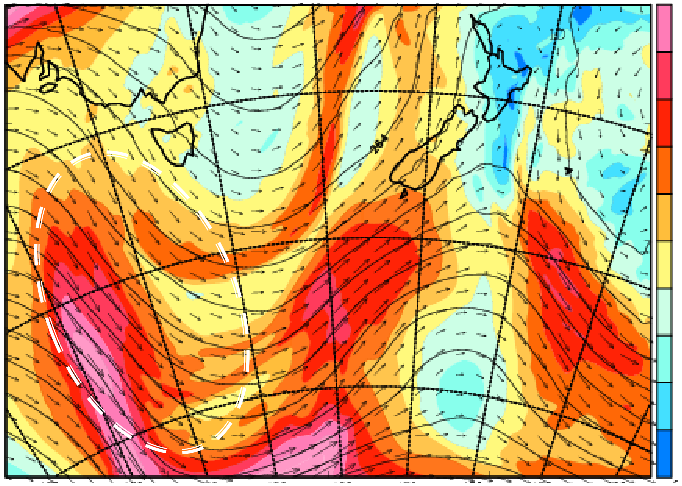
- AIRS: Deep waves lower-left (10-40 km)
- Propagating downwind/upwind
- GV observed L_x = 200 and 400 km
- VCRS shows mostly upward waves and some downward waves (energy flux diagnosis is needed)
- Three wave groups: two downstream ~ 18m/s and one upstream propagating
- TODOS: A larger domain simulation
- Momentum/energy flux calculation

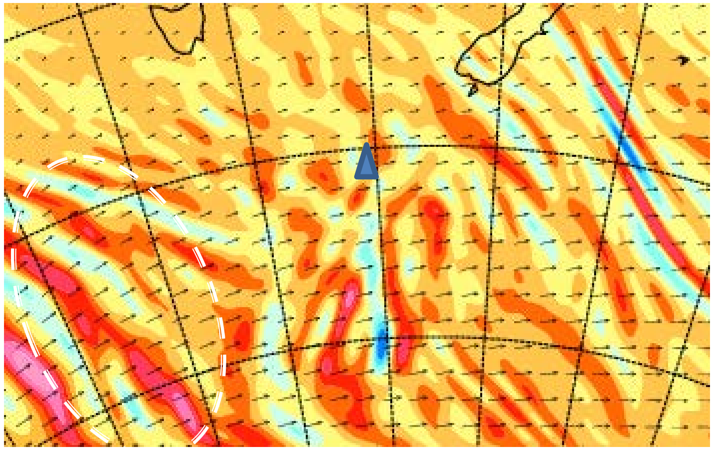
Synoptic Conditions (IOP 12)

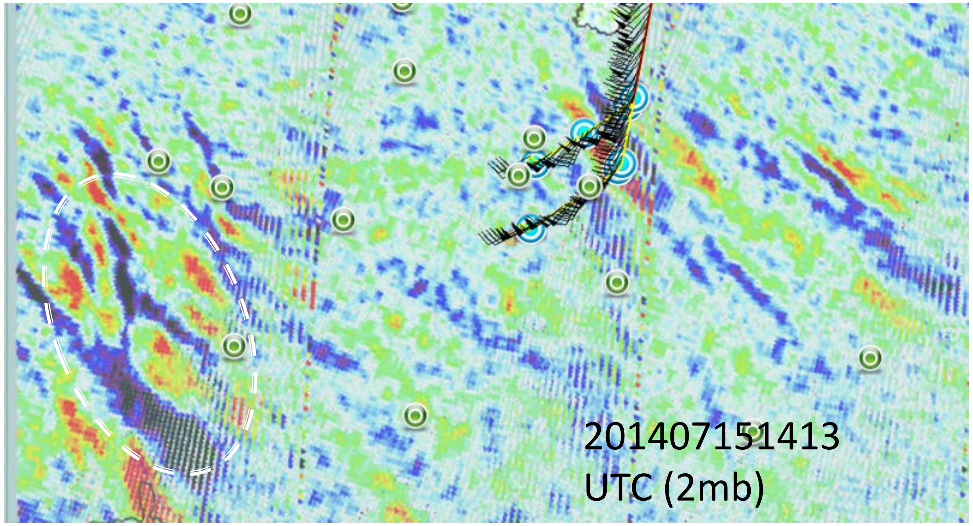


- Three fa… exit
  zones wh…
- Waves te… al to the
  mean flo…
- In the ve… wind.
- TO-DO:
  - Box analysis of waves (wave modes, momentum/energy fluxes, steadiness/speed, etc.)

Comparison with AIRS (IOP14, 14-15 July)



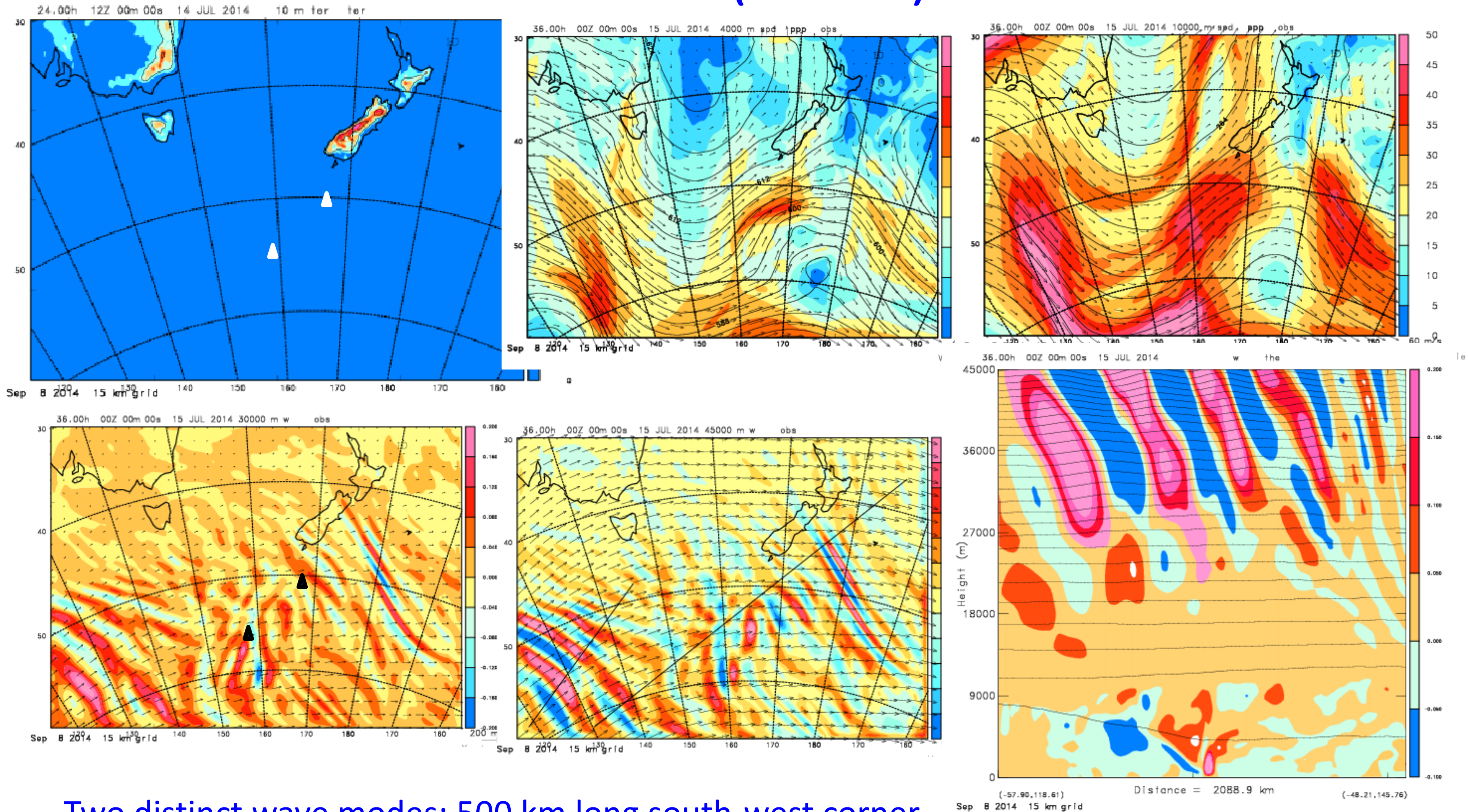




- Deep NOGW: visible between 60-2 mb!
- "Amplitude" varied over the 2-day period.
- Multiple wave modes (wavelength: 150-500km)

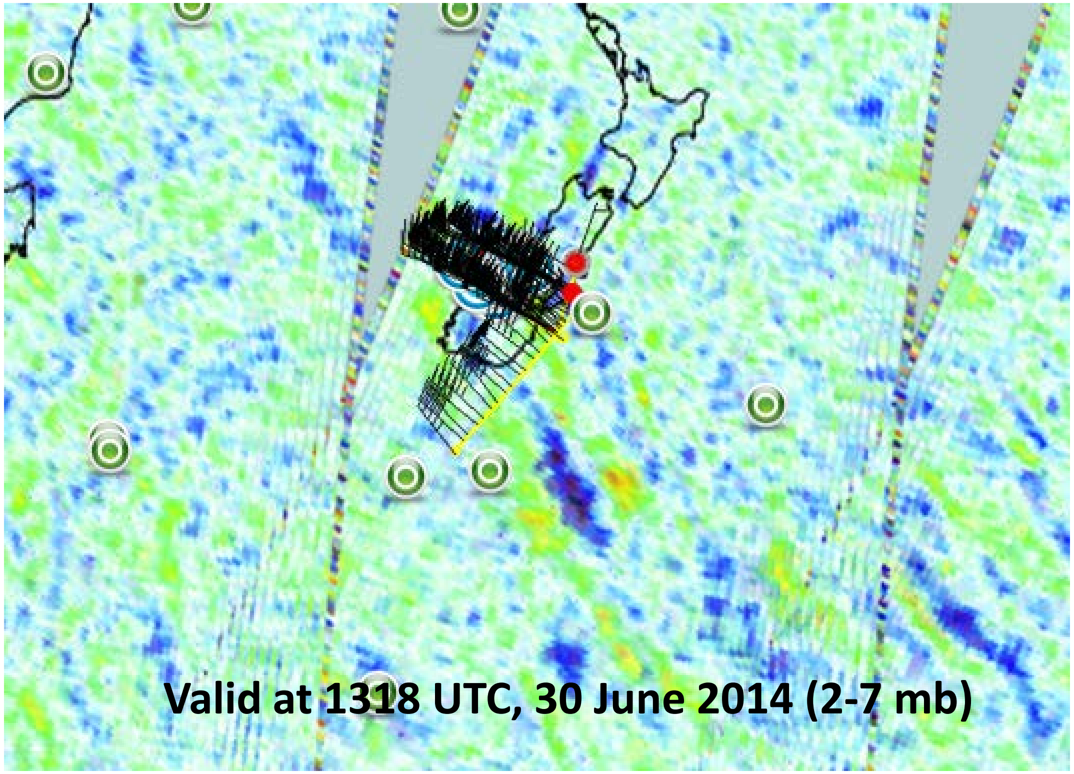
- COAMPS captured the deep (15-45 km) long (300-500 km) NOGW

IOP 14 (15 km)



Two distinct wave modes: 500 km long south-west corner 200 km in the lee of SI. Both are only evident in stratosphere (>15 km) where they tilt against mean winds, implying upward energy propagation

Simulation III: IOP 9 (RF13)



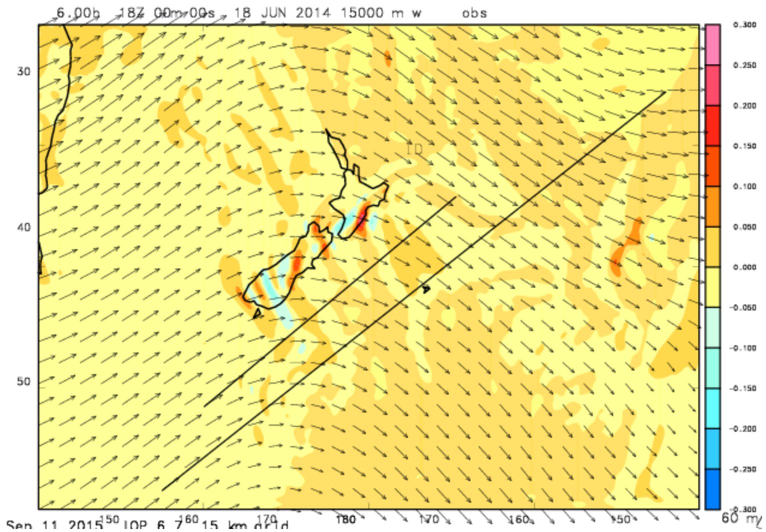
Science Issues

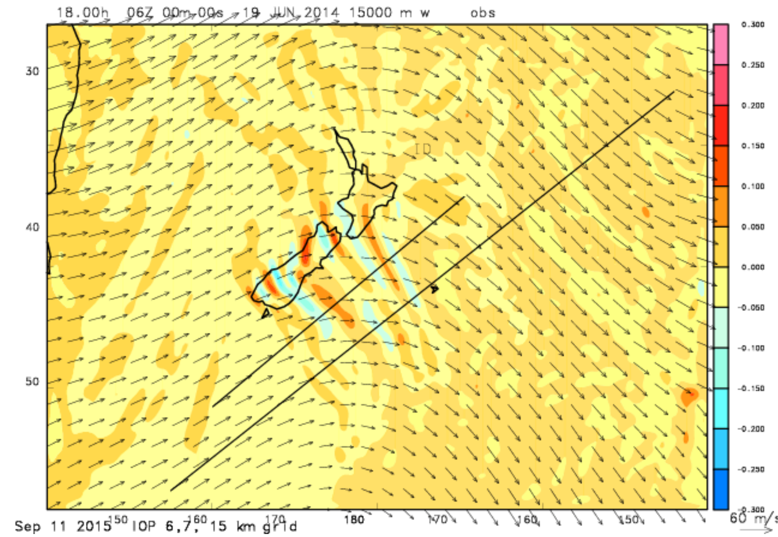
w@6 km

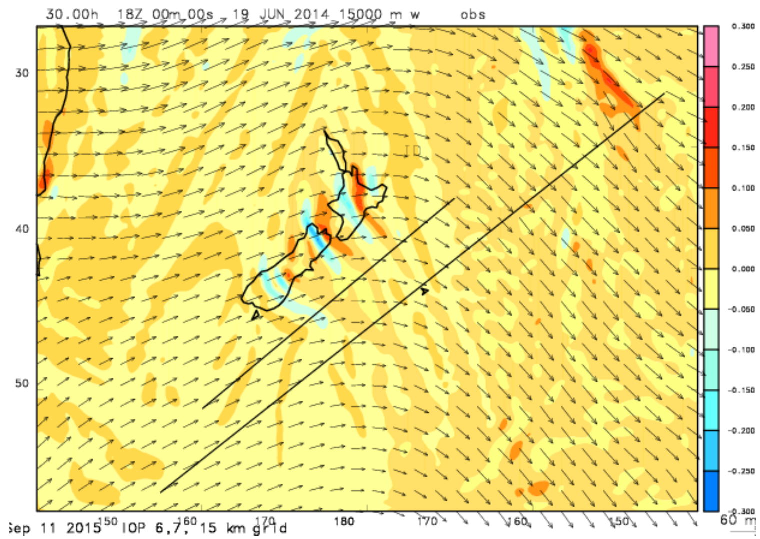
- <u>Model validation</u>:
  - Cold-start COAMPS simulations capture gross features of trailing waves revealed by AIRS.
  - More quantitative comparisons down the road

- <u>Science Questions</u>:
  - Is terrain the source of TW?
  - What determines TW characteristics (wavelength, number of wave banners…)
  - What's their role in vertical momentum transfer?
  - What are the roles of vertical and lateral shear in TW propagation?
  - ….
- <u>Preliminary Diagnosis of IOP 6 simulation</u>

Evolution of Tropospheric Waves

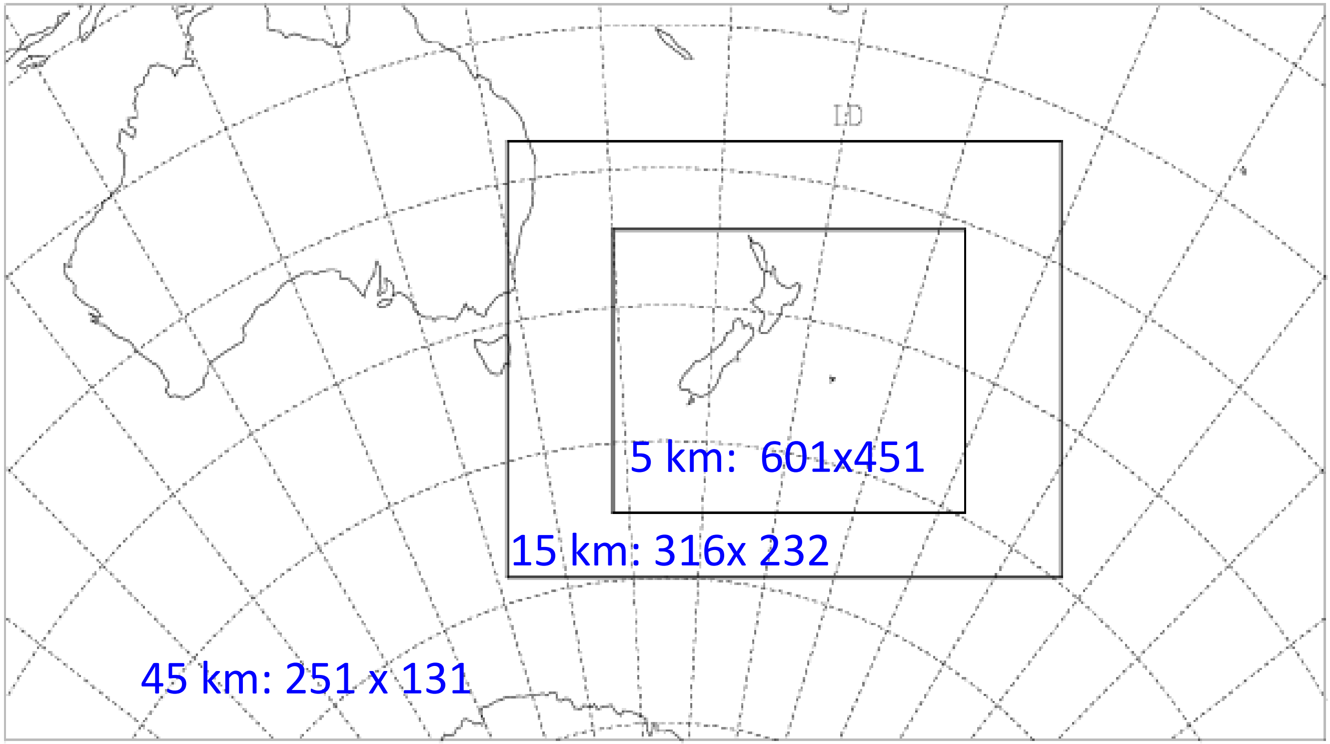






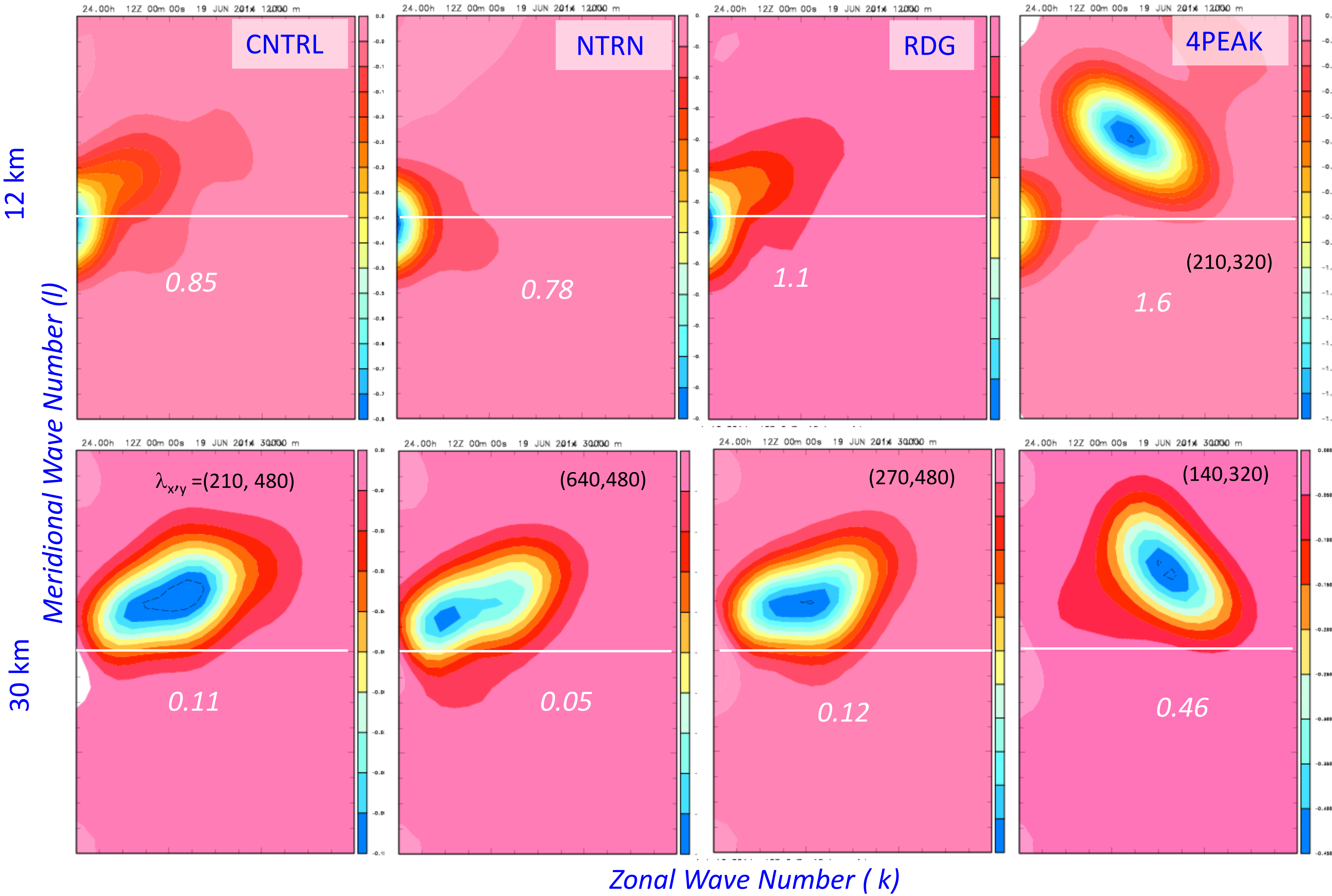
- Quasi-2D nearly stationary waves with phase lines oriented perpendicular to the incoming flow.
- Lower-right (or southeast) branch is more pronounced (why? The cyclonic/clockwise turning of winds?)
- Plot out a cross-section directly over NZ

COAMPS Model Configuration



- Three-level nested grids: 45, 15, and 5 km
- 86 vertical levels up to 0.2 mb (~ 60 km)

Momentum Fluxes in Wave Number Space



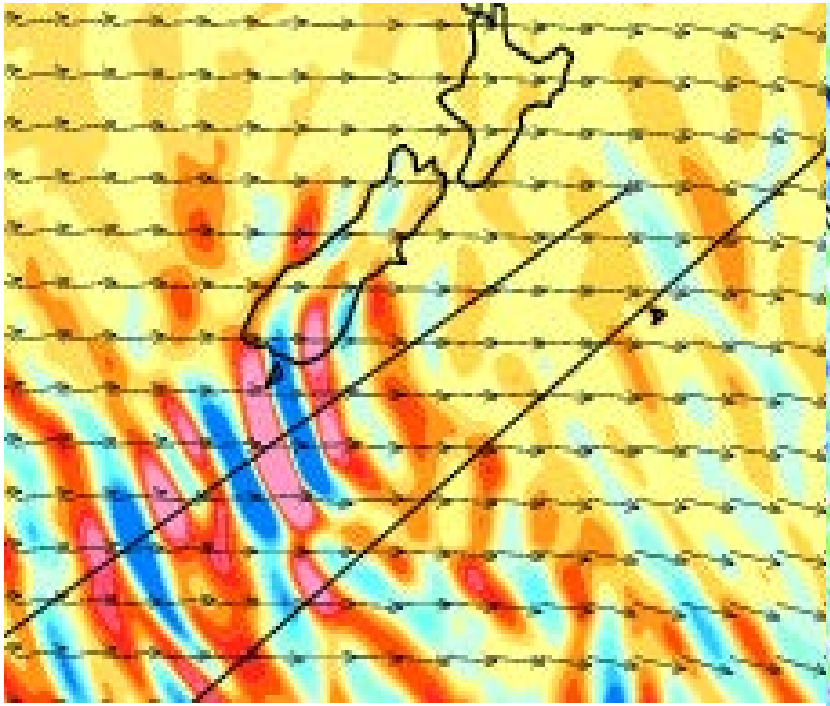
Non-Orographic GW over Southern Ocean

- Identify wave sources
- Investigate the role of NOGW in momentum/energy transfer
- Explore dynamics associated with NOGW propagation in a deep atmosphere

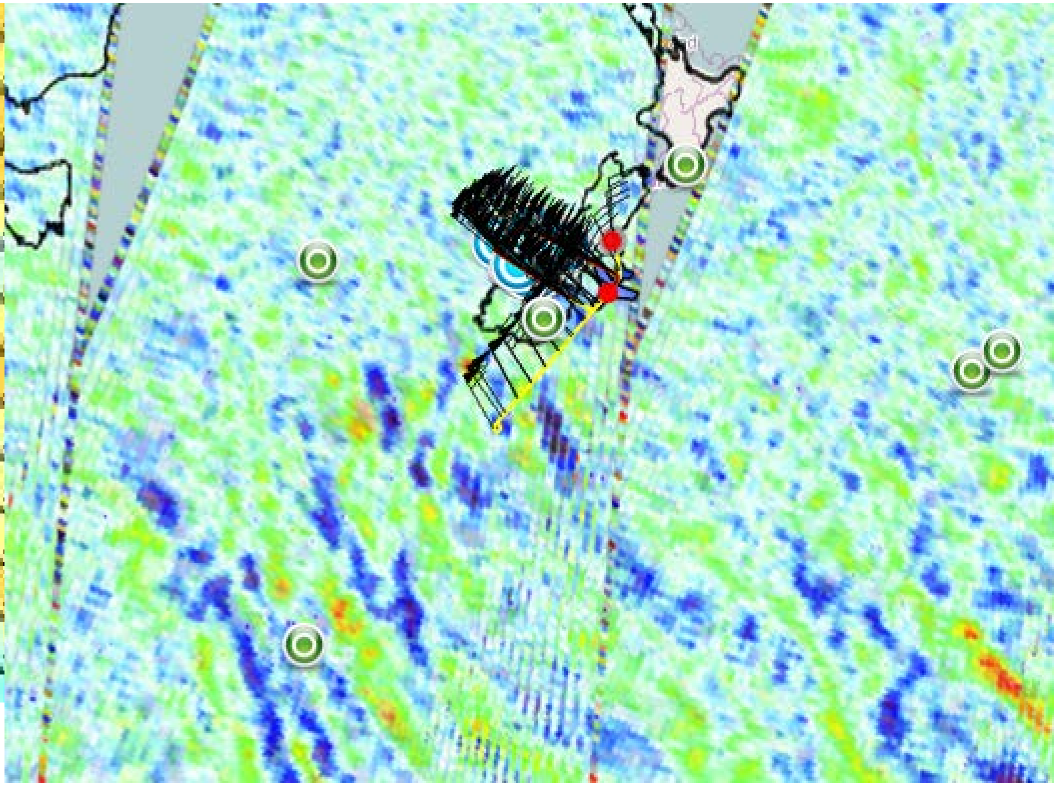
Non-Orographic Cases

IOP/RF#/Date	Objectives	Comments
IOP12a/RF18 7 July 2014	deep NOGWs southeast of Tasmania apparently associated with upstream jet-exit region (Nice AIRS waves)	
IOP12b/RF19 8 July 2014	deep NOGWs south of the South Island apparently associated with upstream jet-exit region	MTM and sodium lidars reported seeing many wave structures over the South Island
IOP14a/RF23/14 July	deep propagating gravity waves over Auckland Islands and Macquarie	Saw evidence of gravity waves during the flight.
IOP14b/RF24/15 July	deep GW over Southern Ocean associated with spontaneous emission from a strong polar tropospheric jet (>80 m/s)	

Simulation III: IOP 9 (RF12)



W @ 30km from 15-km grid, valid at 1200 UTC, 29 June 2014



Valid at 1414 UTC, 29 June 2014 (2-7 mb)

Short trailing waves to the south of SI?