Modeling Study of :

- **Stratospheric waves Trailing Waves over New Zealand**
- **Non-orographic waves over Southern Ocean**

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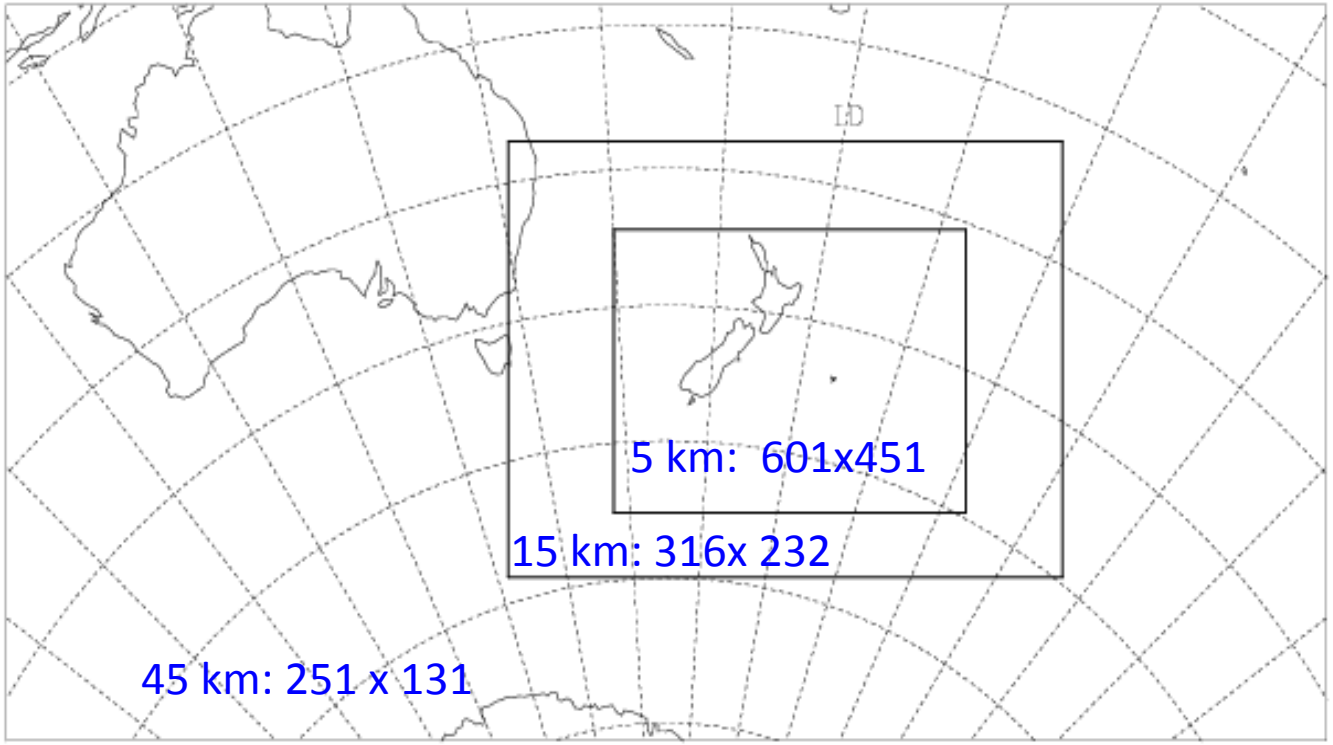
Stratospheric Trailing Waves over New Zealand

- Characterize trailing waves
- Identify wave sources
- Investigate the role of TW in momentum/energy transfer
- Explore interaction between TW and wind shear as TW propagating through a deep atmosphere

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	

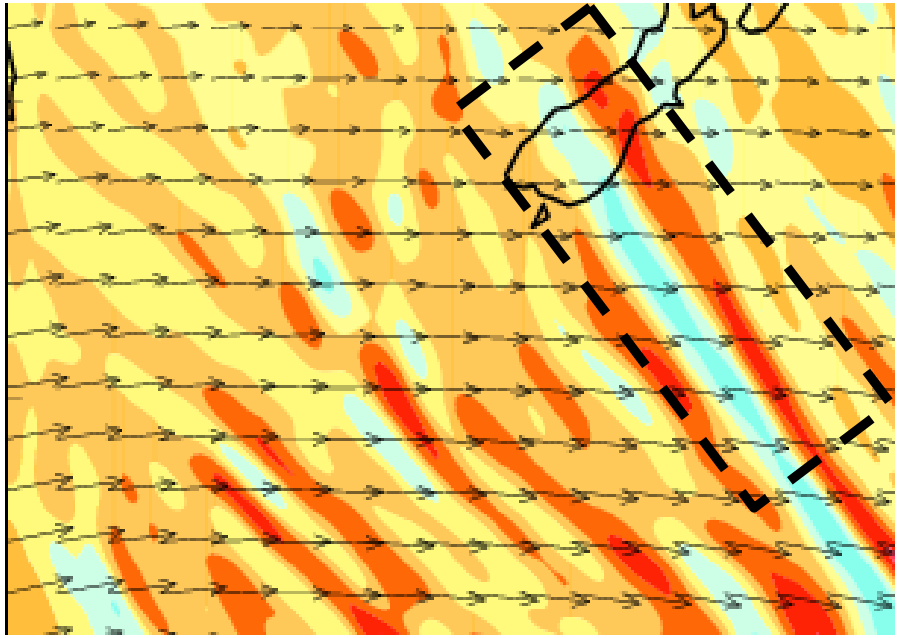
COAMPS Model Configuration



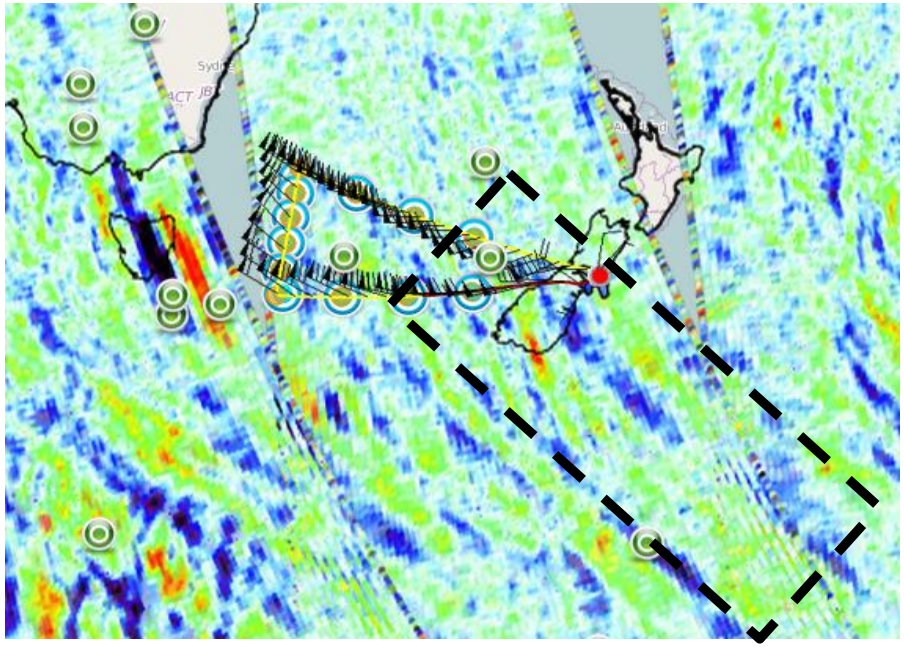
- Three-level nested grids: 45, 15, and 5 km
- 86 vertical levels up to 0.2 mb (~ 60 km)
- Bottom of sponge layer: 45 km

Simulation I: IOP 3a/RF03

W @ 30km from valid at 1500 UTC, 13 June 2014



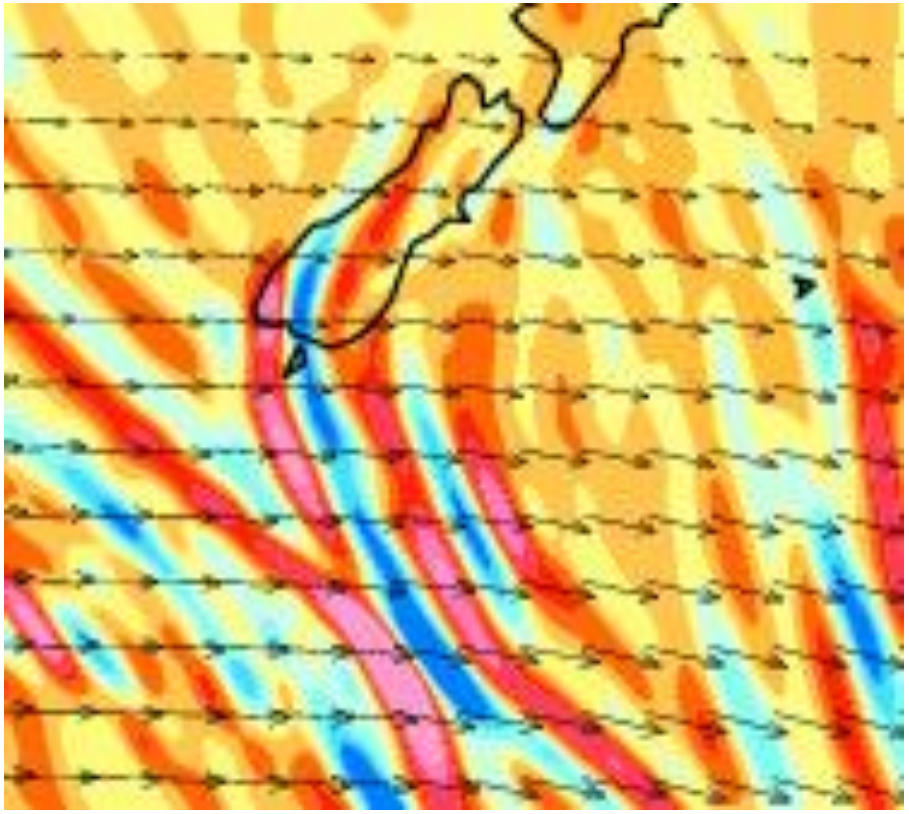
AIRS @ 0307 UTC 13 June (2mb-4mb)



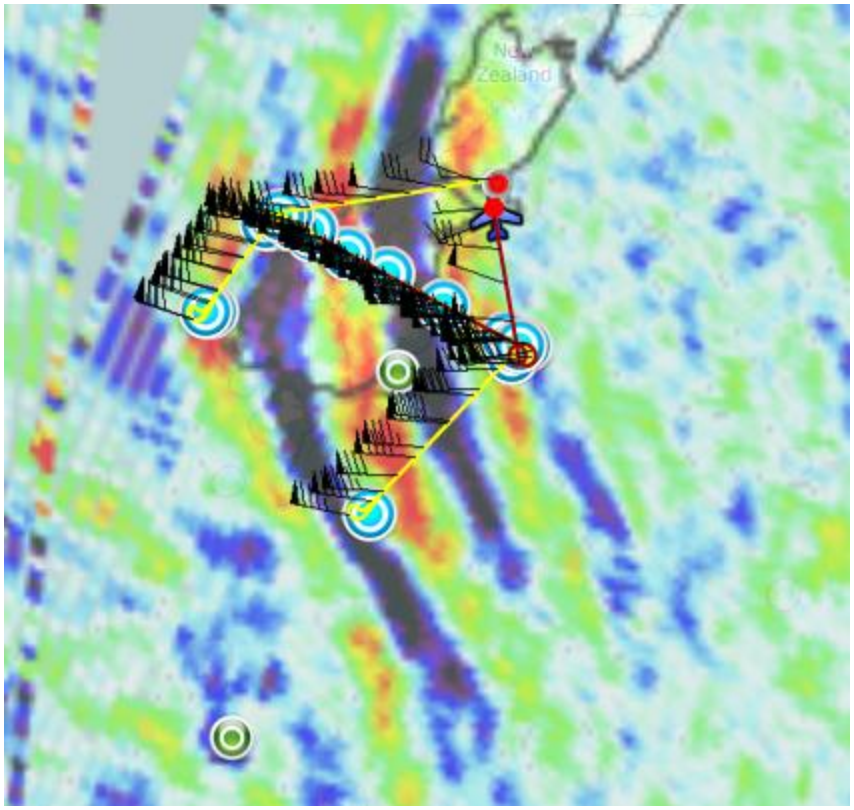
- AIRS observed/COAMPS simulated a few waves trailing from the South Island during RF03
- Waves are found to the south of SI, likely originated from non-orographic sources.

Simulation I: IOP 3b/RF04

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

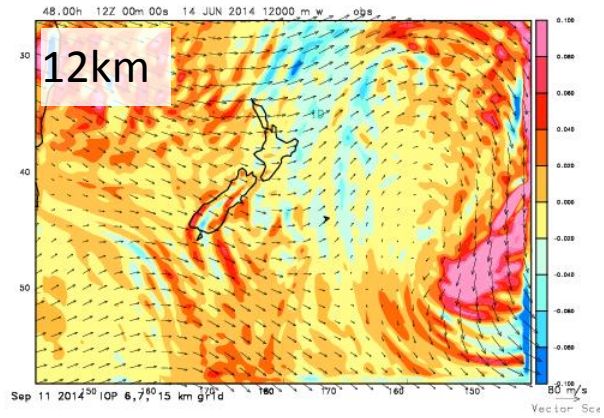


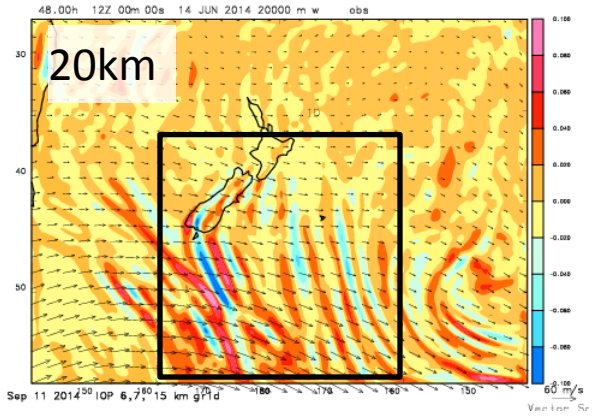
AIRS @1319 UTC 14 June 2014 (2mb)

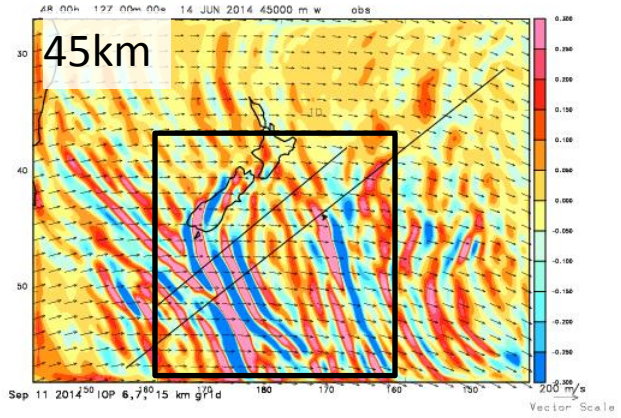


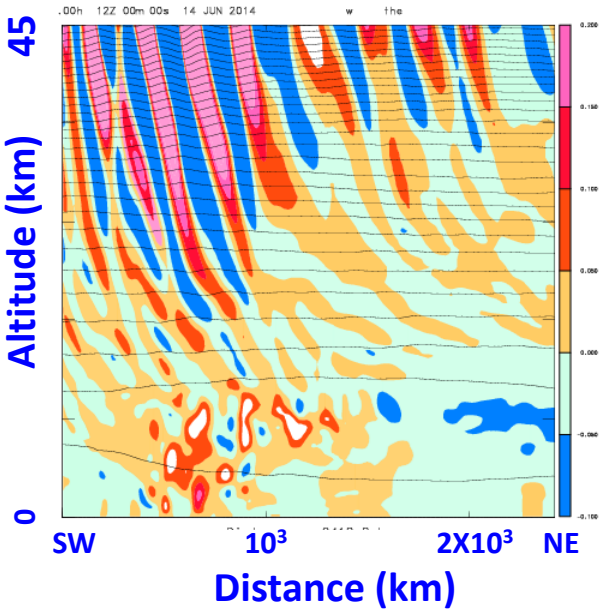
- AIRS observed three-pairs of TWs from the South Island
- COAMPS was right on

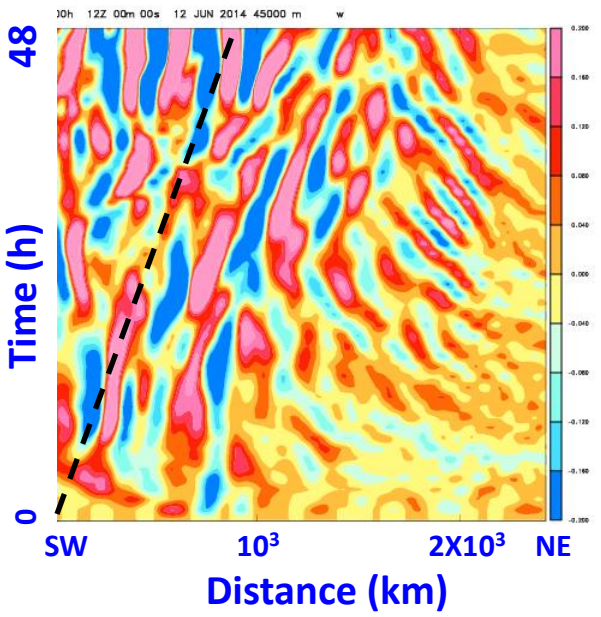
Simulated wave characteristics (IOP3b)







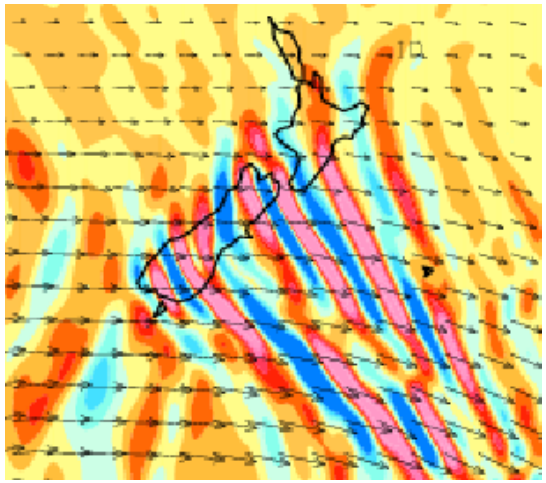




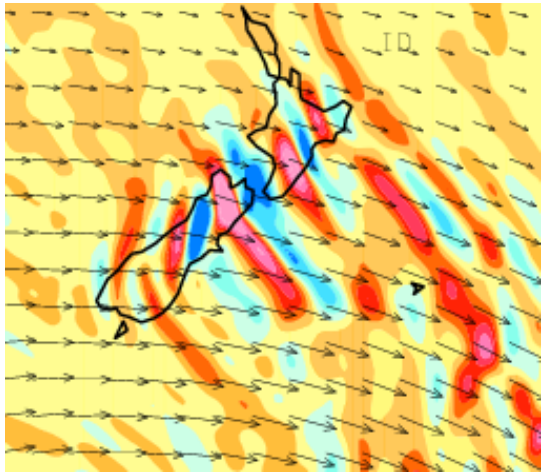
- Deep trailing waves (12-45 km)
- Longer at higher altitude
- Along-flow wavelength: ~ 200 km
- Vertical wavelength: >10 km in stratosphere
- Upstream tilting of phase lines
- Quasi-stationary (c~5 m/s or less)

Simulation II: IOPs 6-7/RF07 RF08

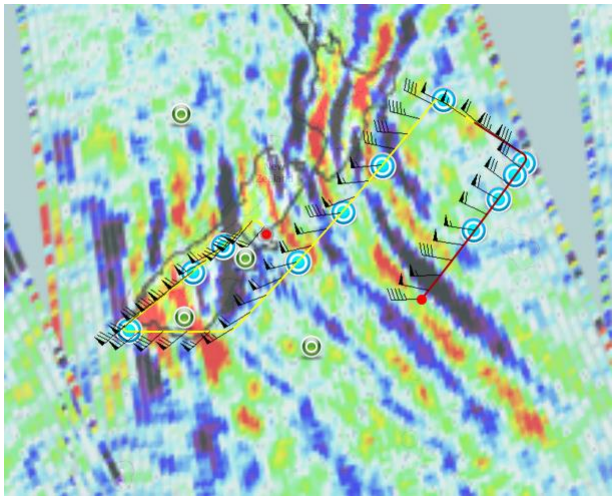
W @ 30km valid at 1200 UTC, 19 June



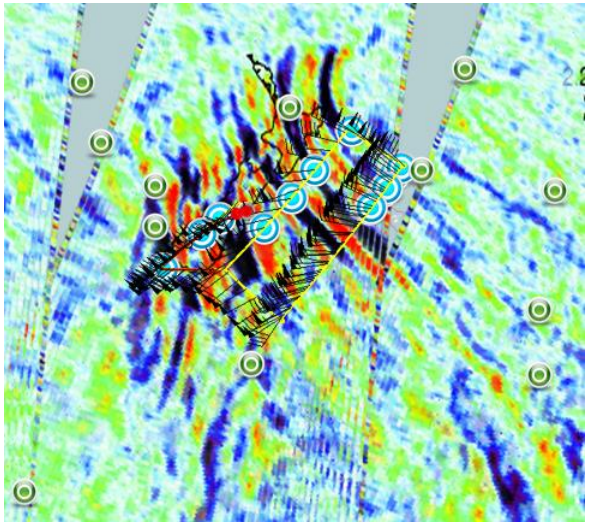
W @ 30km valid at 1200 UTC, 20 June



Valid at 0230UTC 19 June 2014 (2mb)

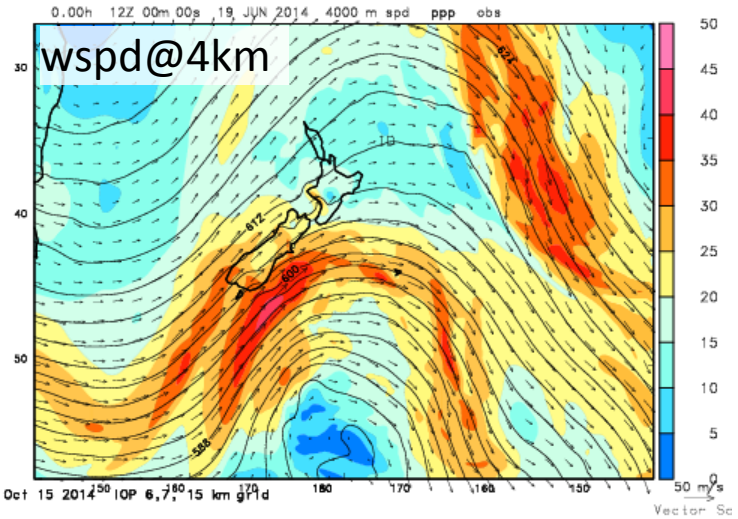


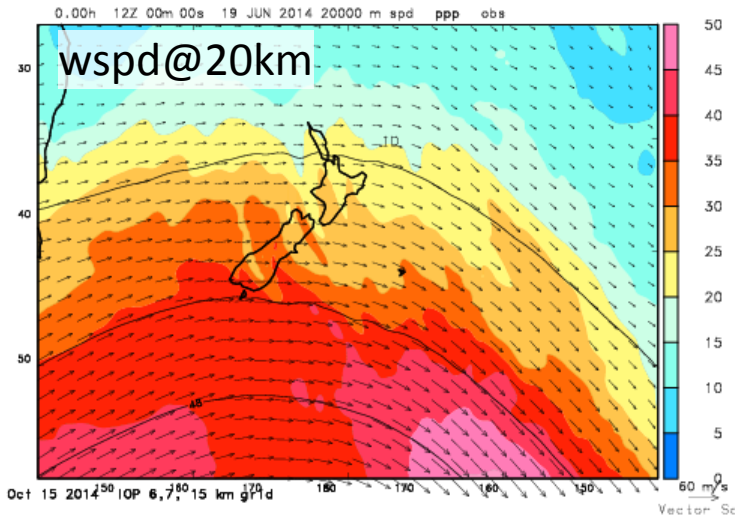
Valid at 1443 UTC 19 June 2014 (2mb)

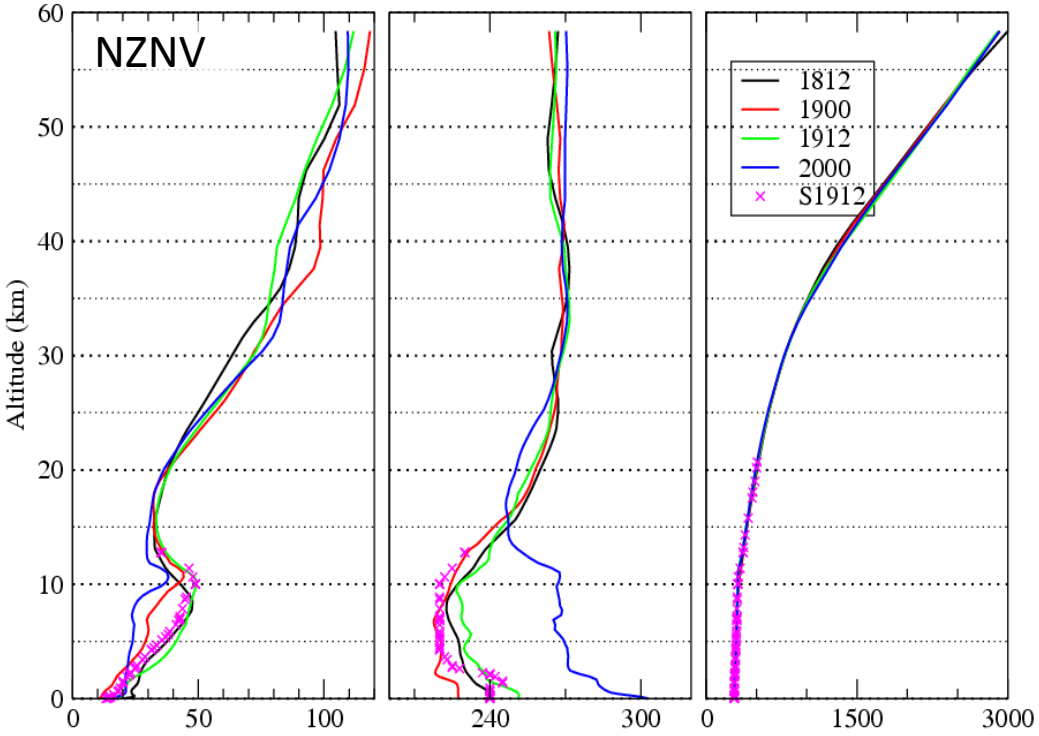


- Evolution from long TW to more 2D waves over NZ.
- Inter-wave spacing ~130-200 km
- Qualitative agreement between AIRS and COAMPS

Synoptic Conditions for IOPs 6 & 7

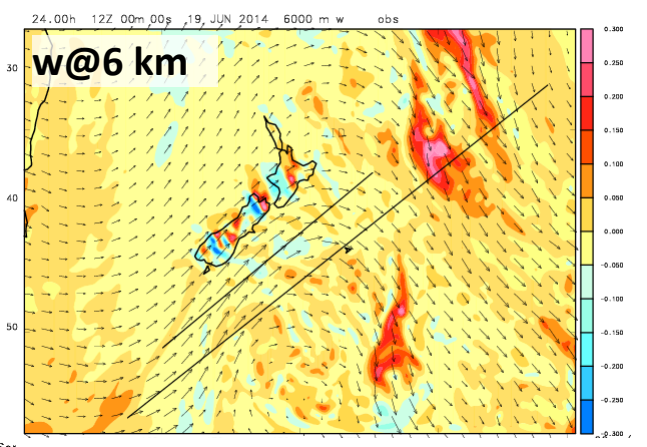


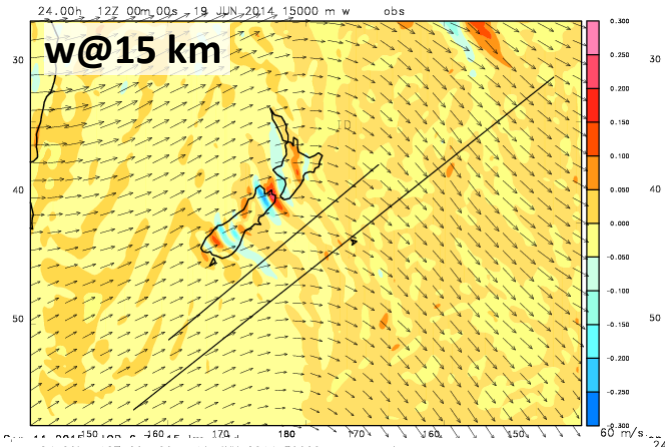


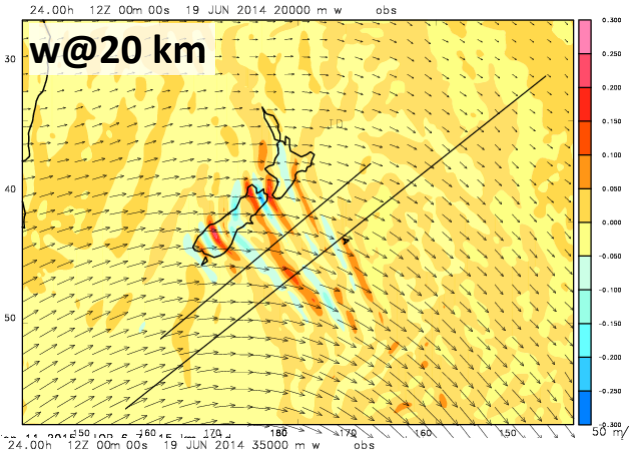


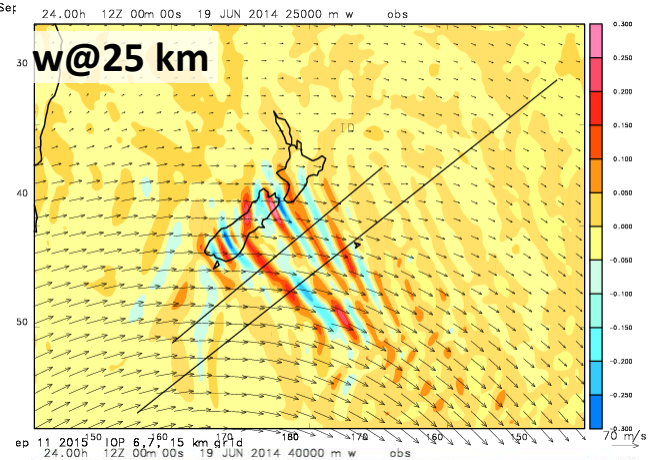
- Southwesterly in troposphere and Westerlies in upper stratosphere
- Slow directional shear and strong lateral shear (dU/dy<0)
- COAMPS did pretty well at least in troposphere

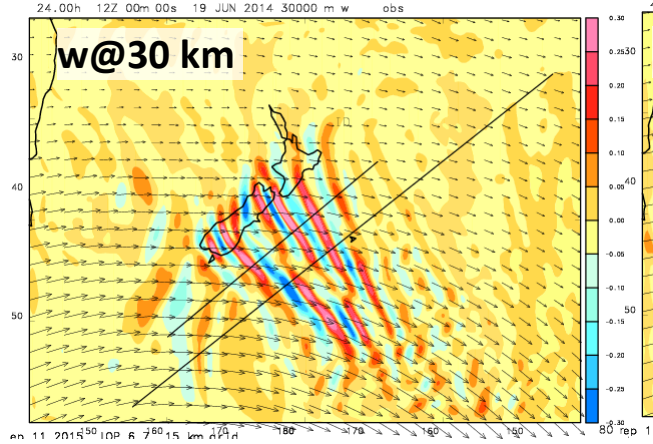
Vertical Variation of TW (IOP 6)

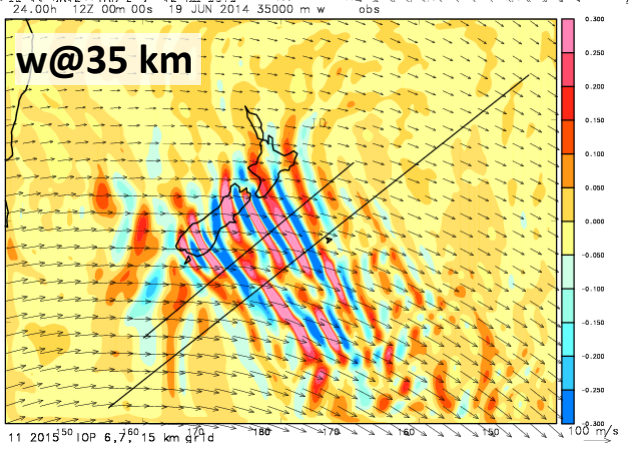


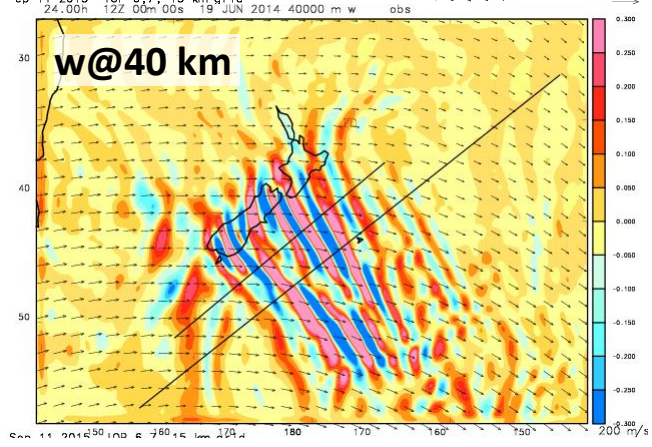








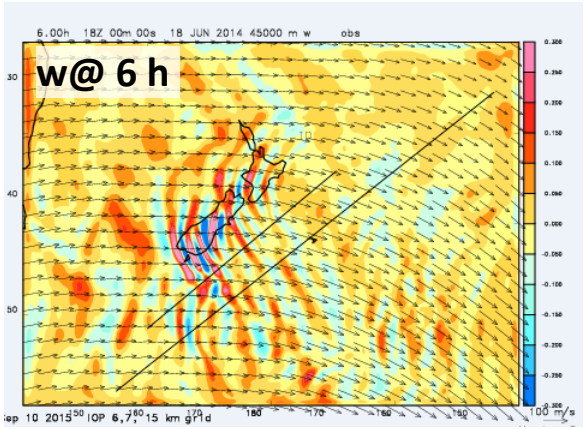


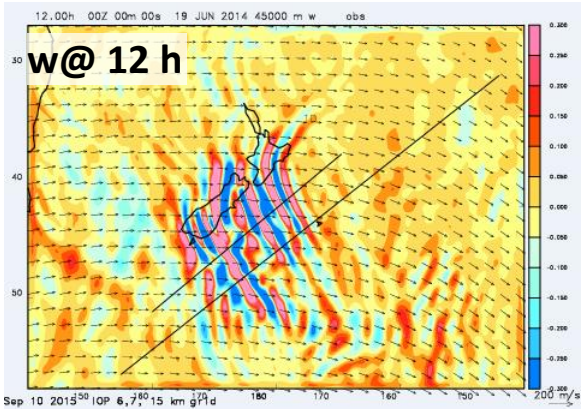


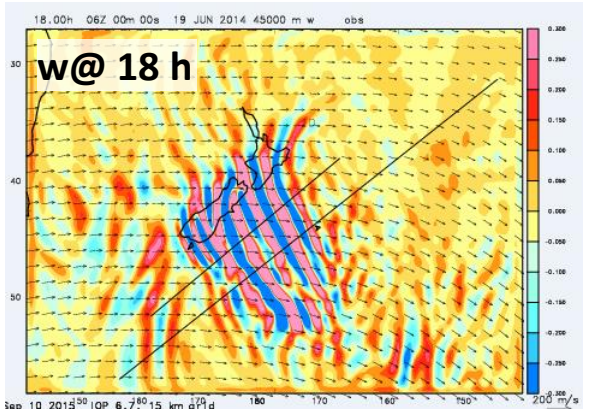
- Quasi-2D Waves over terrain below 15 km where winds are oriented along the terrain
- Trailing waves develop above 20 km where winds are nearly westerly
- In general, TWs are vertically-coherent

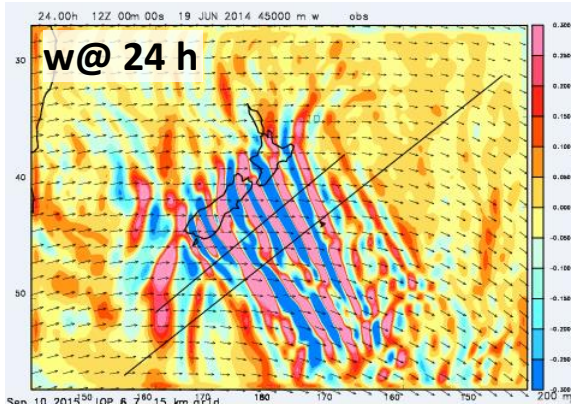
Evolution of stratospheric Waves

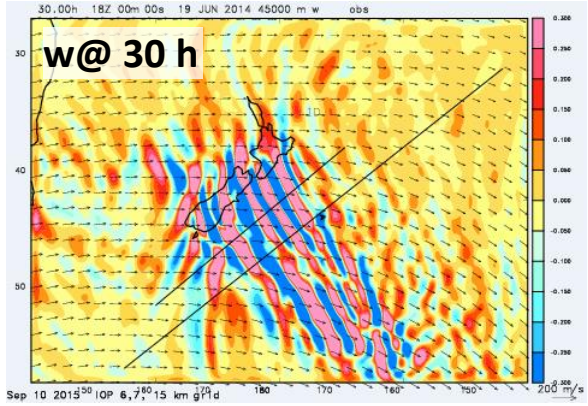
W @ 45 km ASL

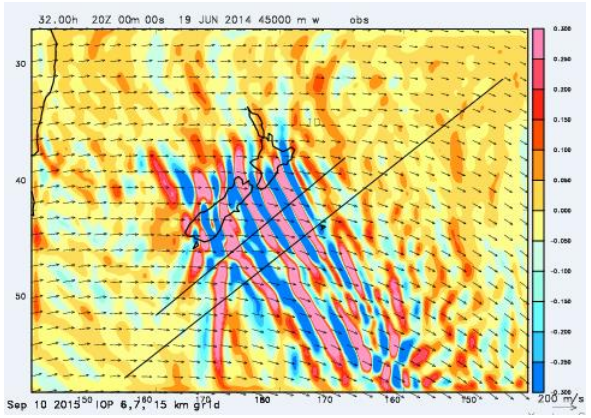






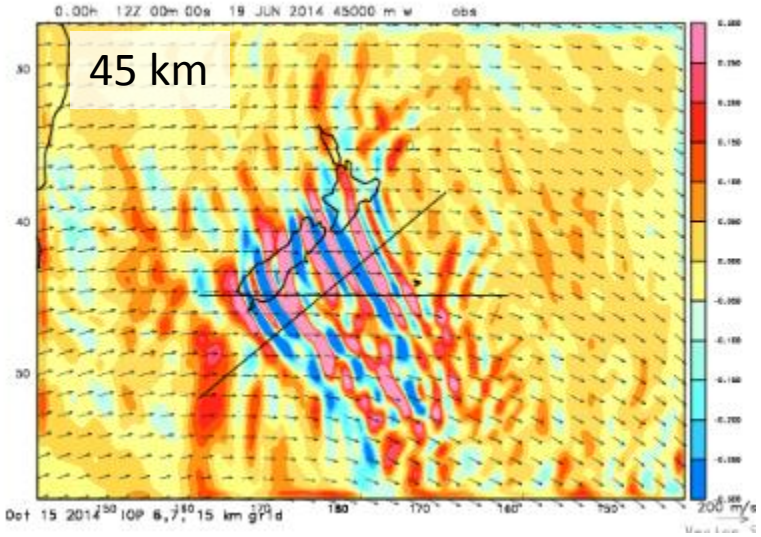


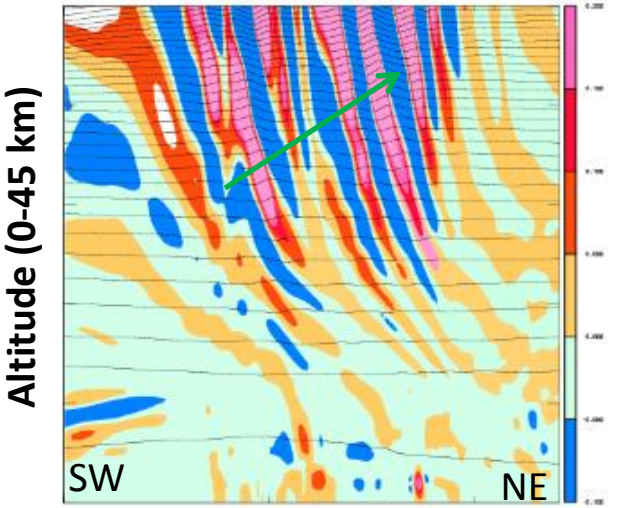


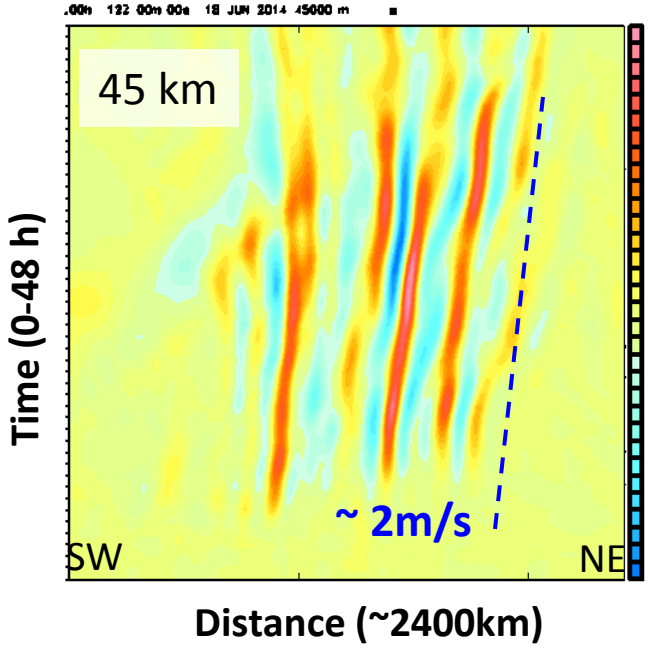


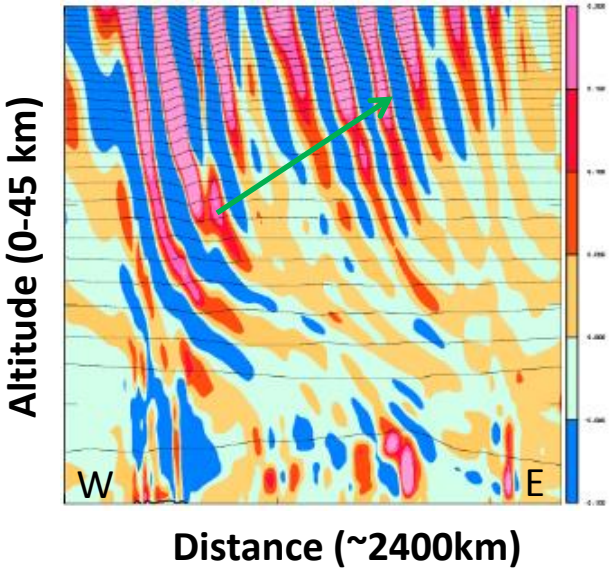
- Stratospheric TWs are fairly steady after the first 12h, implying relatively fast propagation in the vertical.
- While the TW length grows, their upstream ends are anchored over NZ islands, nearly stationary.

Characteristics of Simulated Trailing Waves (IOP 6)

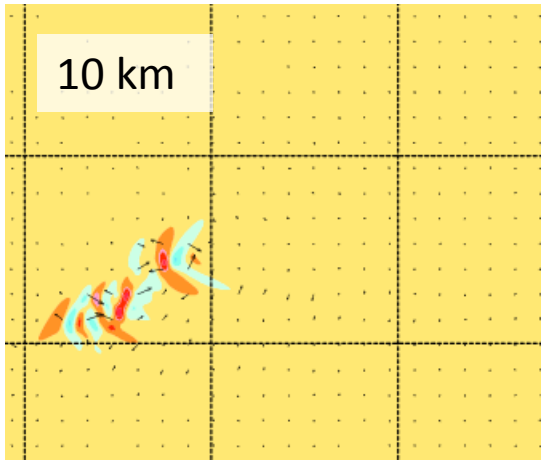


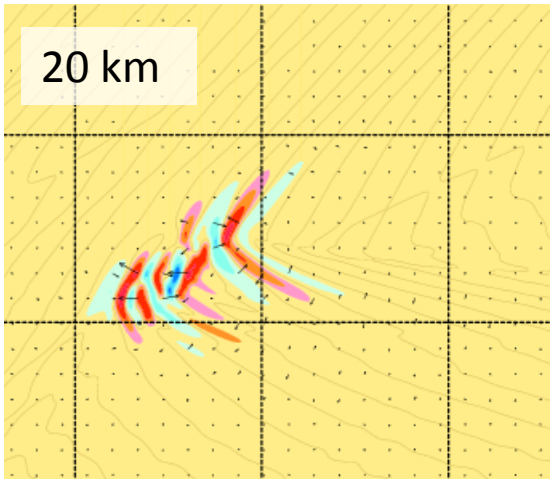


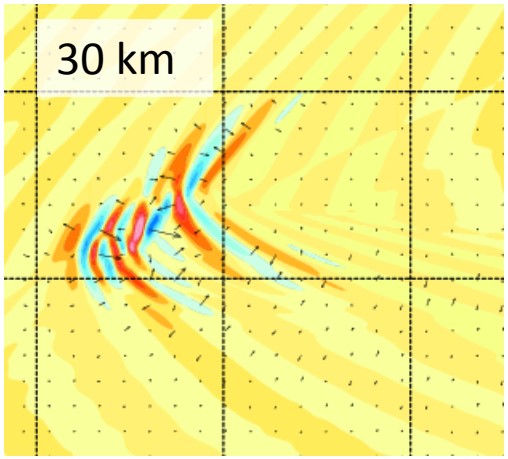


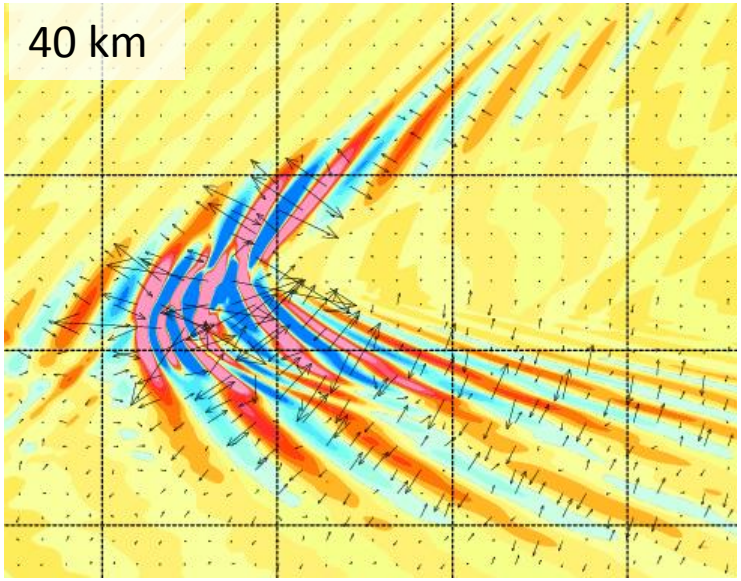


Linear Model Solutions



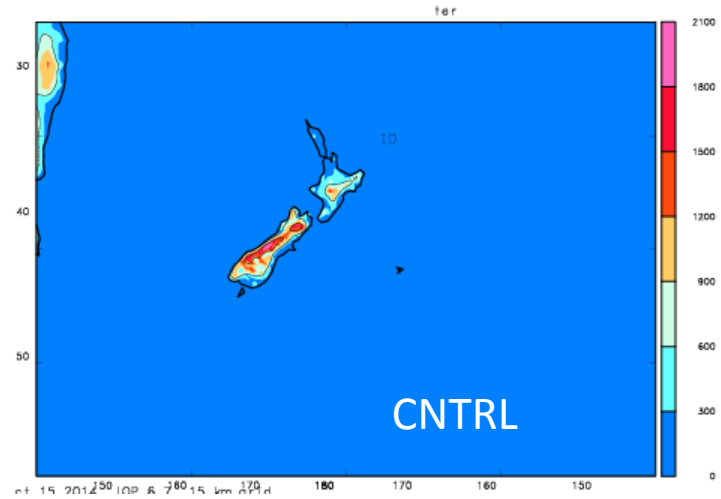


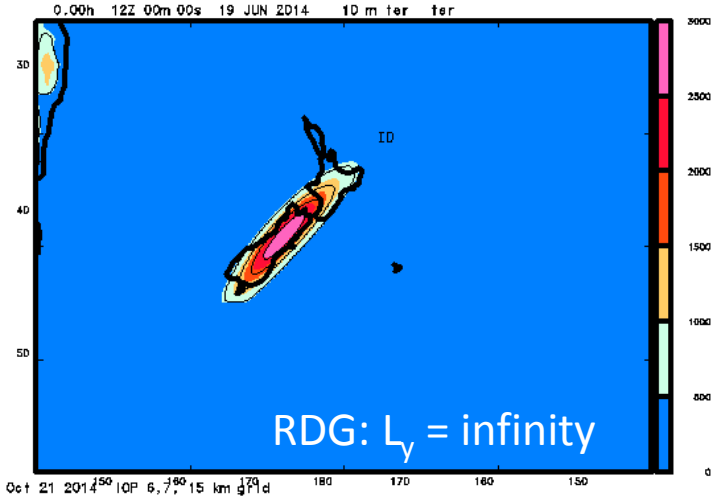




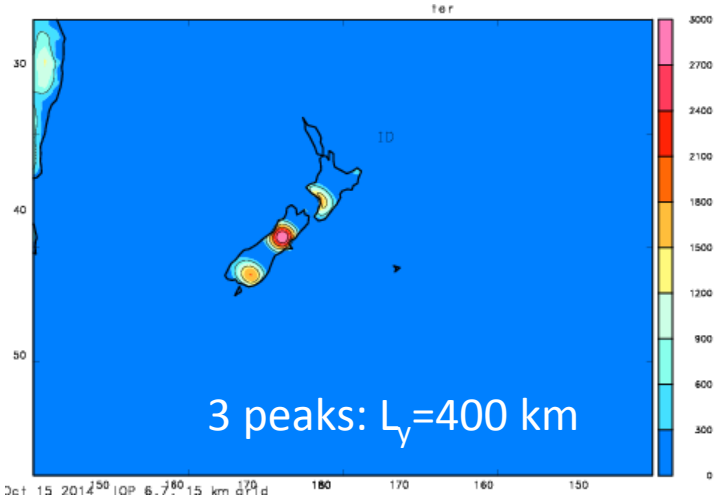
- **Left branch exists, implying the absence of the left branch in COAMPS/observation is likely due to wave refraction associated with lateral shear**
- **Right-branch is more pronounced and looks like TW at 40 km.**
- **Shorter waves downstream,**

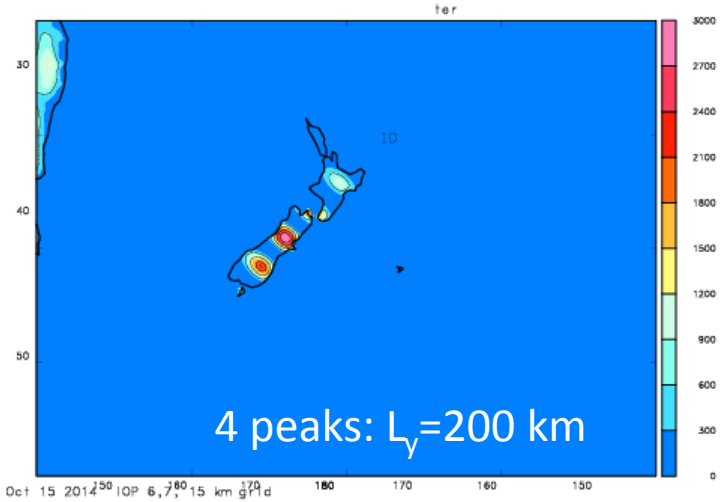
Terrain Sensitivity Simulations (IOP 6)





NTRN

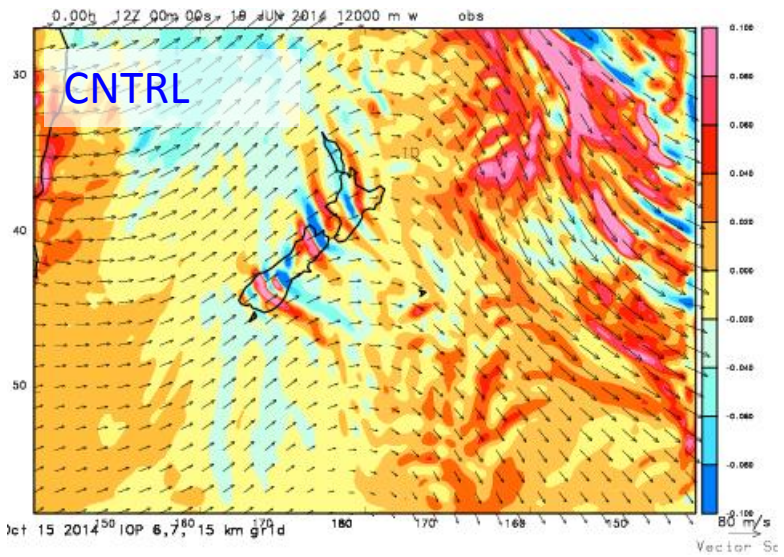


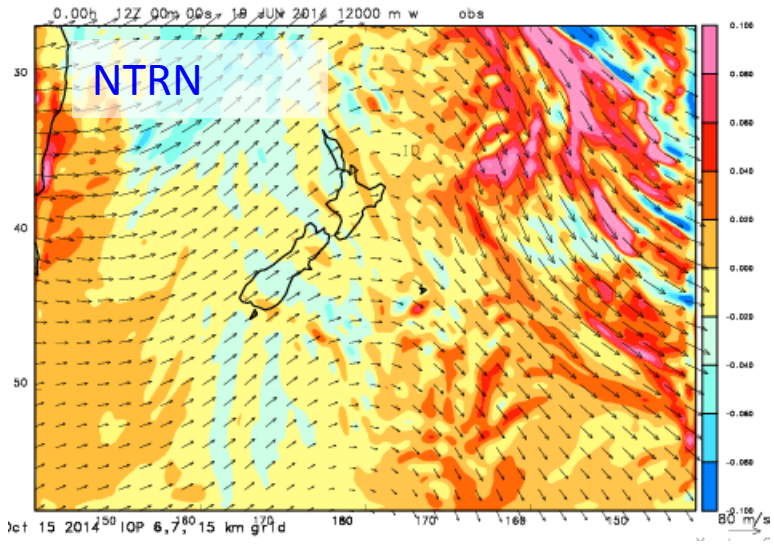


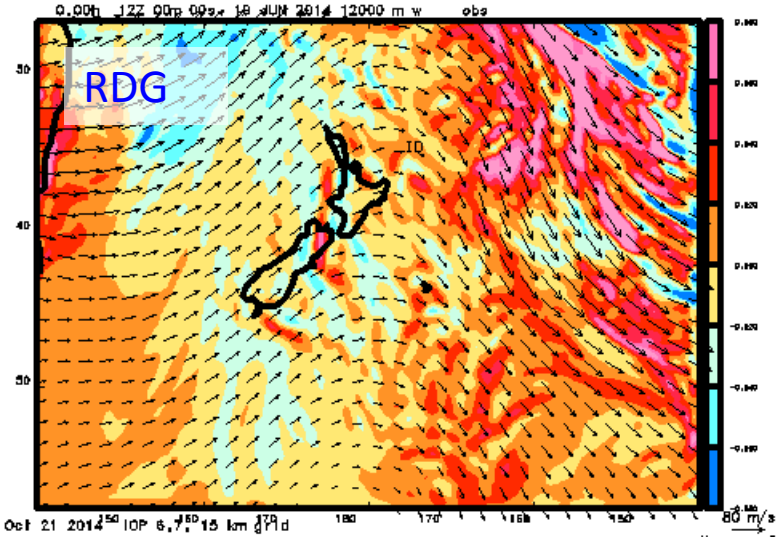
Idealized terrain:

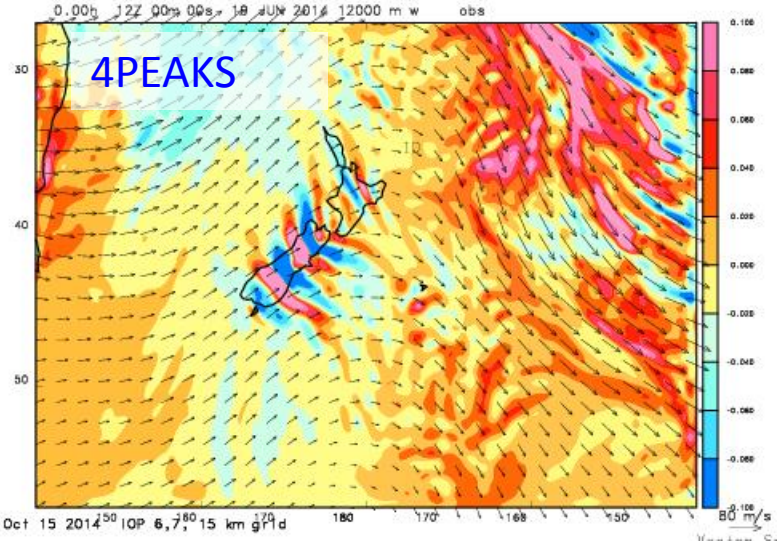
$$h(x',y') = \frac{h_m \cos^2(2\pi y / L_y)}{\left[1+(x'/a)^2+(y'/b)^2\right]^{3/2}}$$

Tropospheric Waves



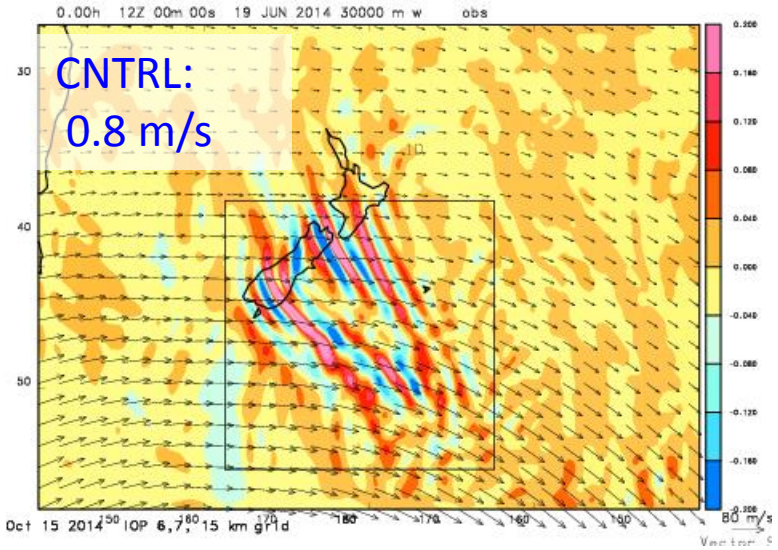


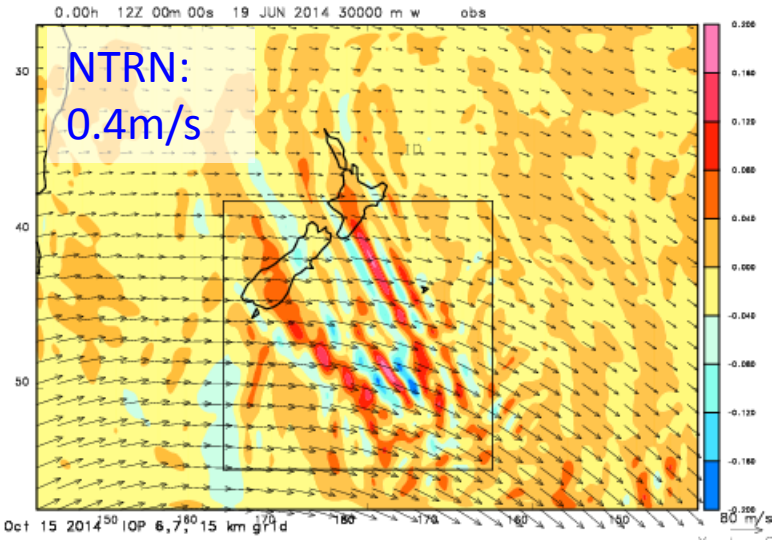


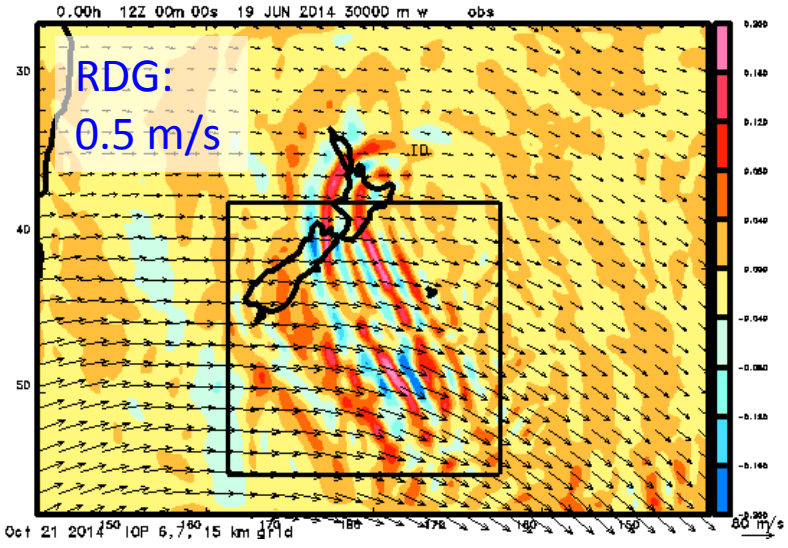


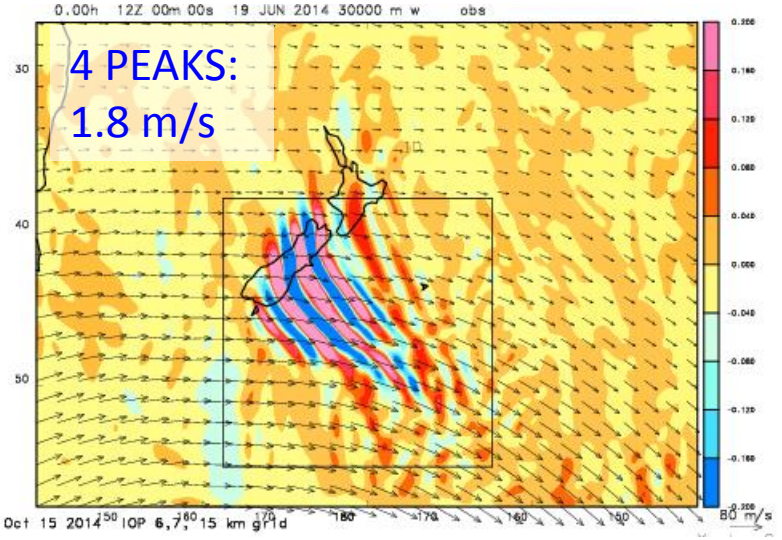
W @ 12 km ASL

Stratospheric Trailing Waves



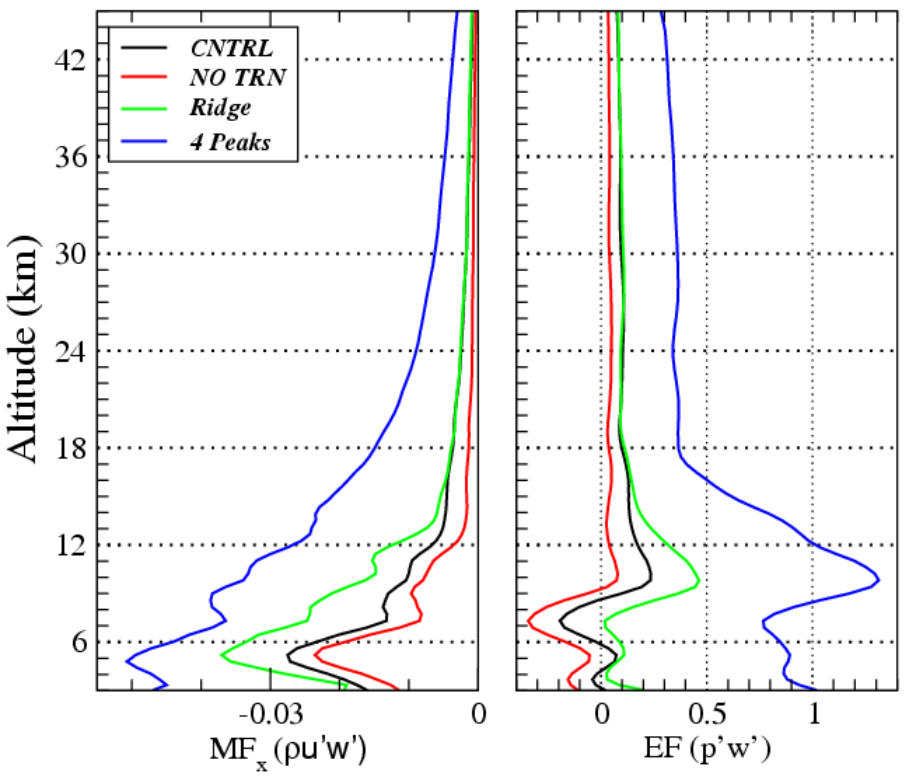


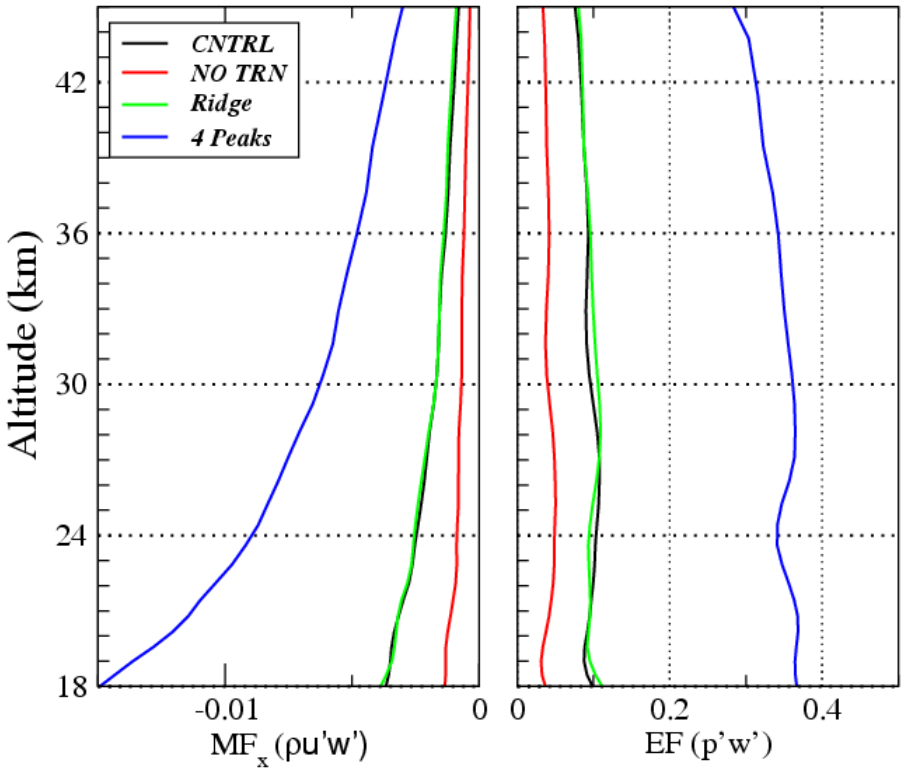




W @ 30 km ASL

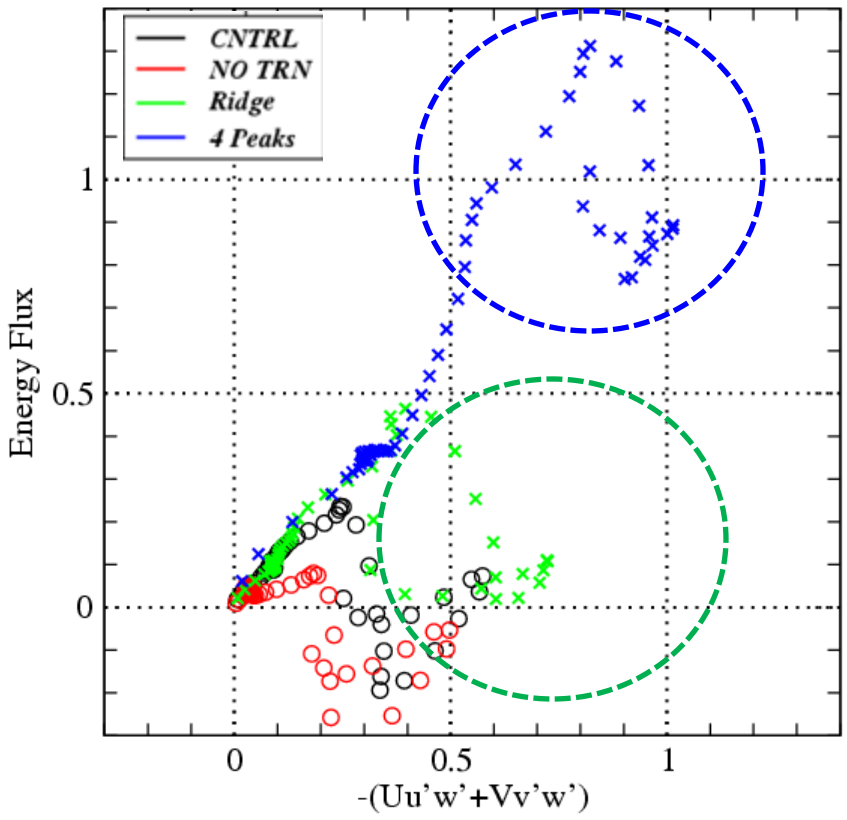
Wave Momentum/Energy Fluxes

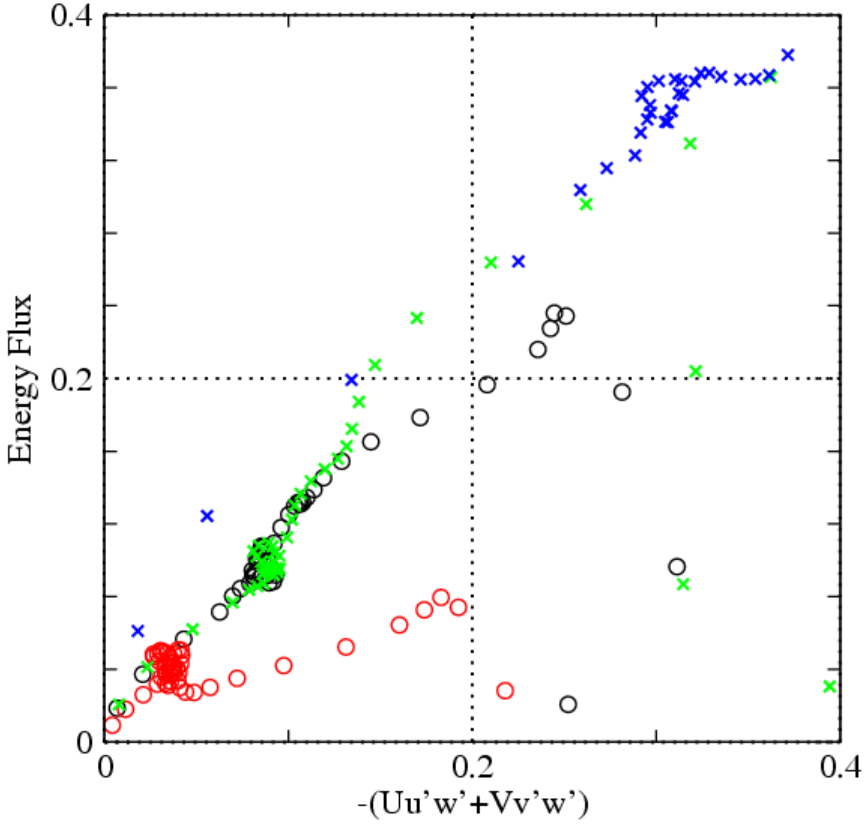




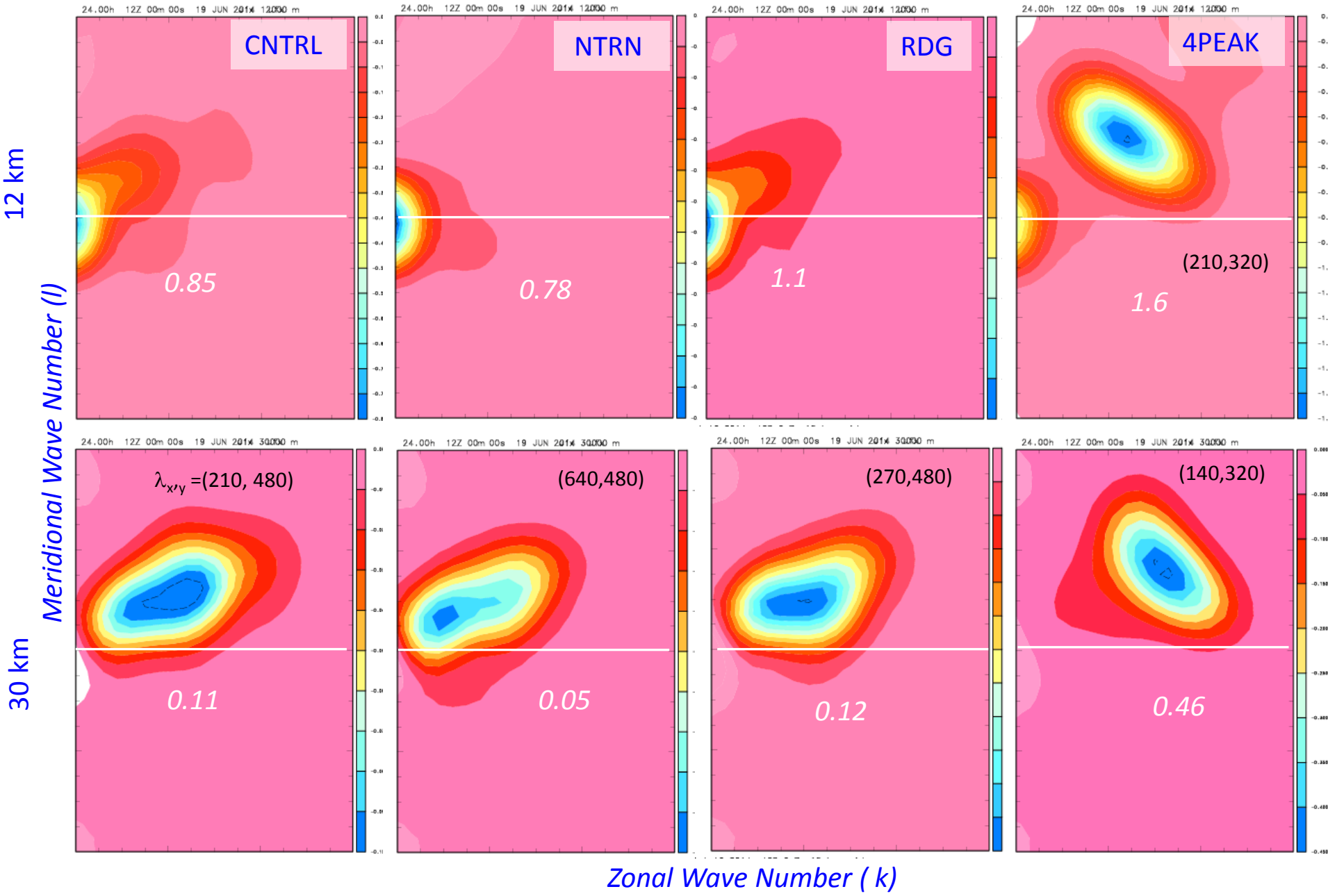
- Both are sensitive to terrain
- MF decreases sharply between 6-18 km (directional critical level absorption?)
- MF is relatively small in stratosphere

Wave Momentum/Energy Fluxes





Momentum Fluxes in Wave Number Space



Summary

- **Wave Source?**
  - Terrain, individual peaks
- **Does TW transfer MF in the vertical?**
  - Yes, but relatively small
- **What are the roles of vertical and lateral shear in TW propagation?**
  - Vertical directional shear causes the decrease of wave momentum flux with height
  - Lateral shear accounts for the left-right asymmetry
- **What determines TW characteristics?**
  - Terrain
  - Lateral/ vertical shear
- **What's TW?**
  - Wave phase-lines are oriented nearly perpendicular to the ridge-crest as opposed to ridge-parallel or parabolic left-right symmetric waves from a peak.
  - TW only appears in stratosphere and above
  - TW is usually accompanied by vertical directional shear and lateral shear

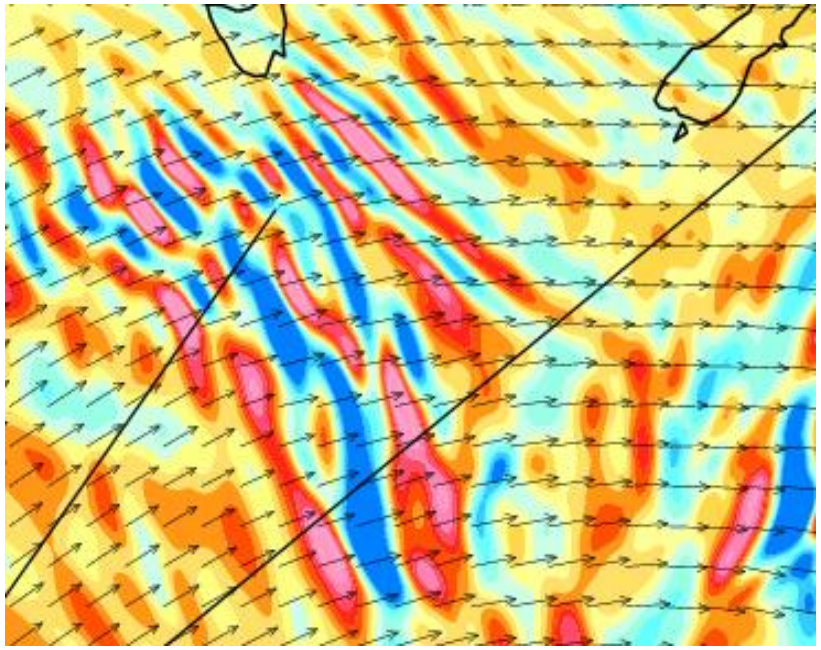
Non-Orographic GW over Southern Ocean

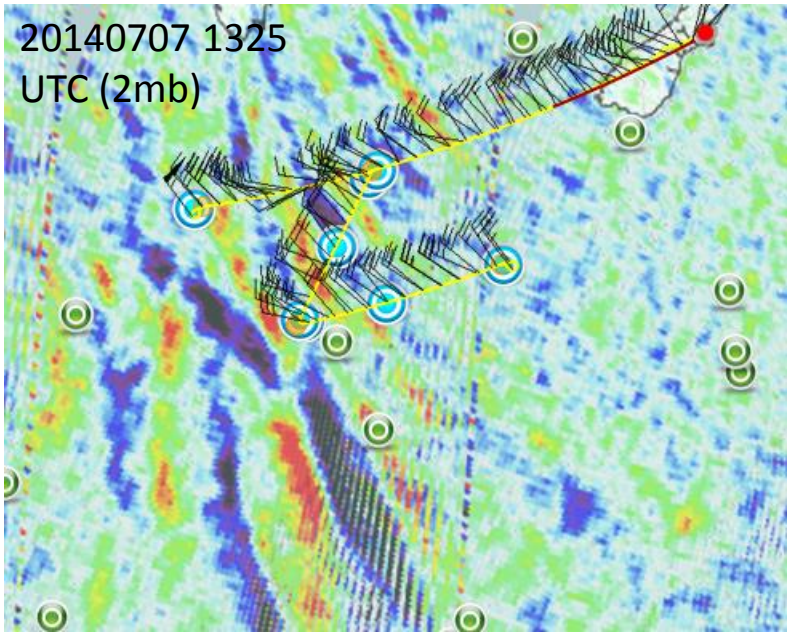
- Identify wave sources
- Investigate the role of NOGW in momentum/energy transfer
- Explore dynamics associated with NOGW propagation in a deep atmosphere

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 I: IOP12a



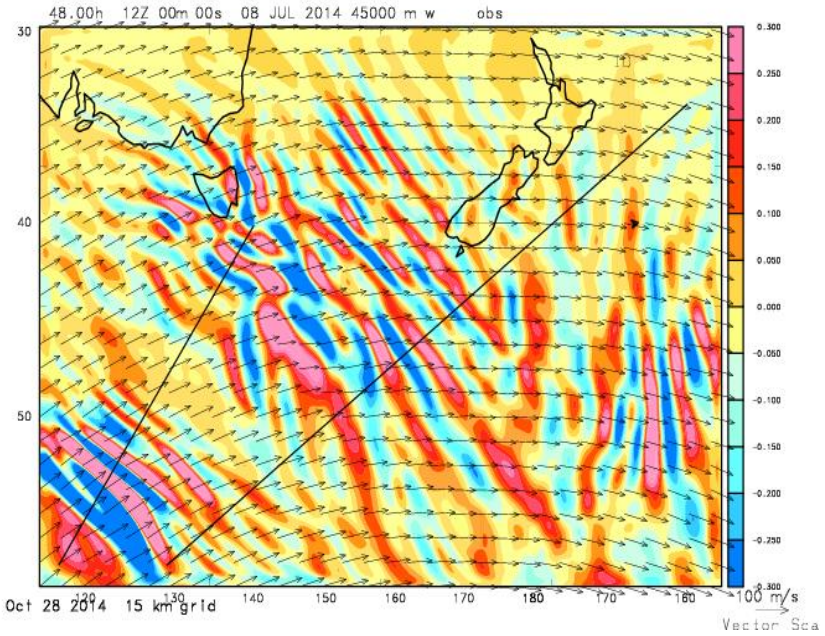


- COAMPS captured the deep (15-45 km) long (300-500 km) NOGW

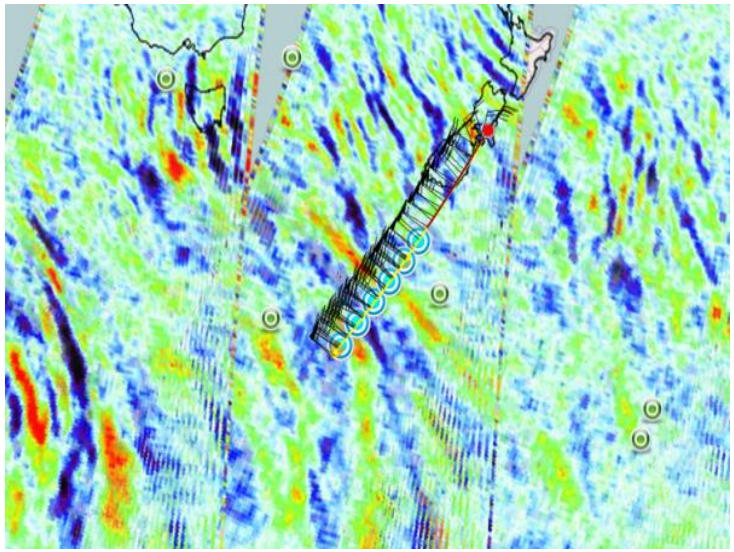
- Deep NOGW: visible between 30-2 mb!
- Located more south-west at 0218 UTC.
- Weaker on day 2 while propagating northeastward.

Simulation I: IOP12b/RF19

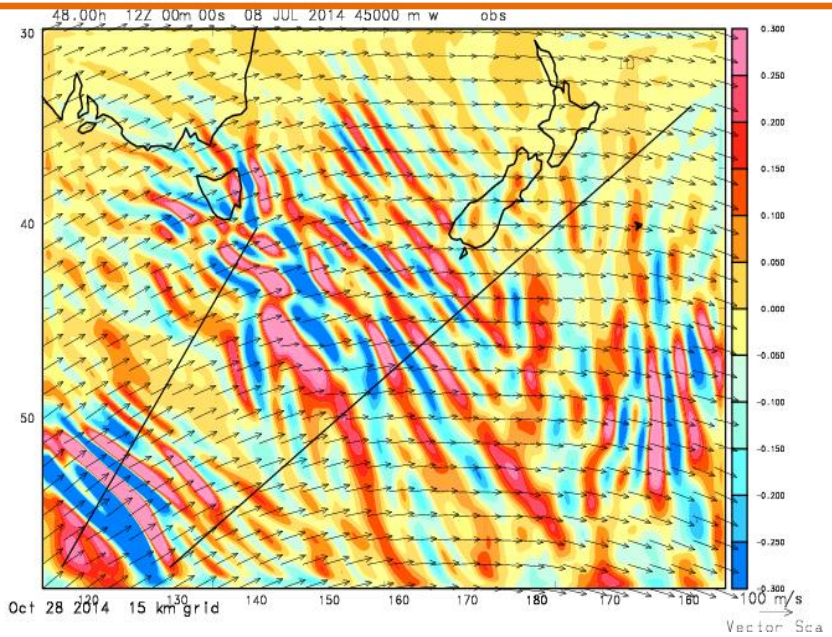
20140708 1200 UTC (45 km)

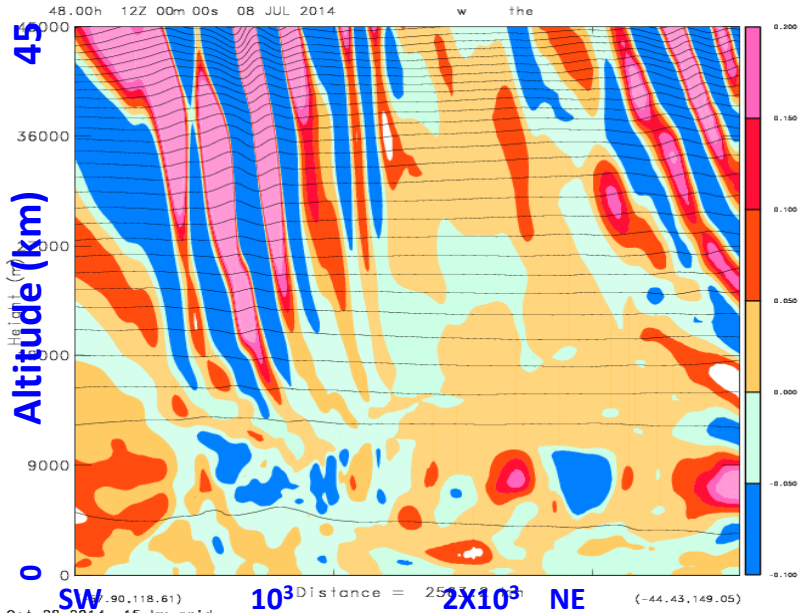


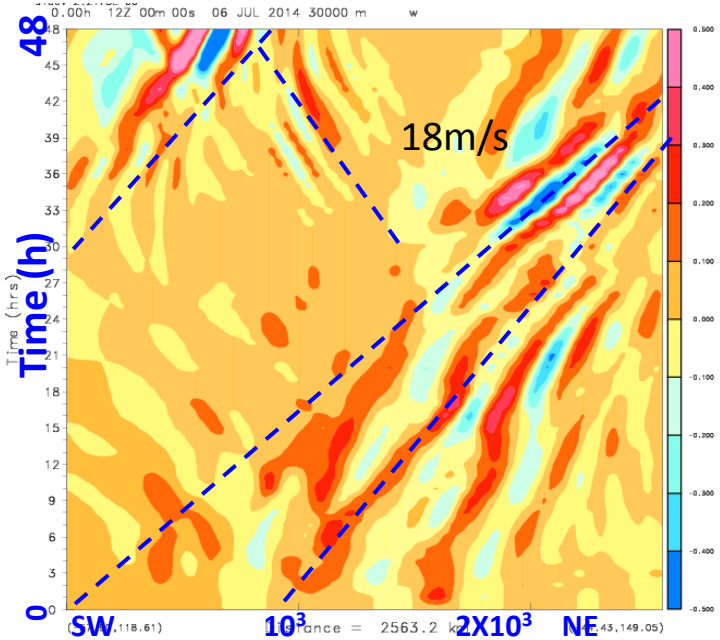
20140708 1407 UTC (2-4 mb)



Simulation I: IOP12b/RF19

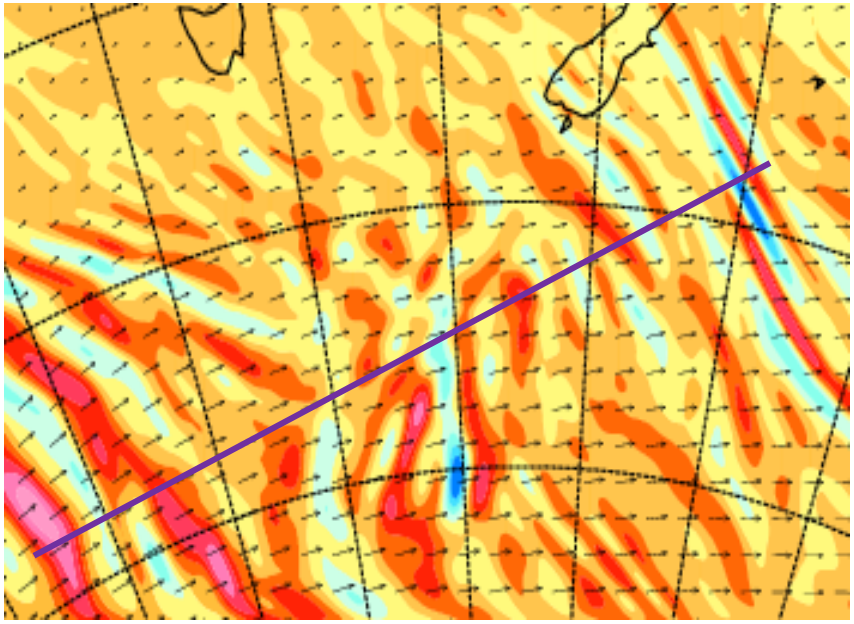


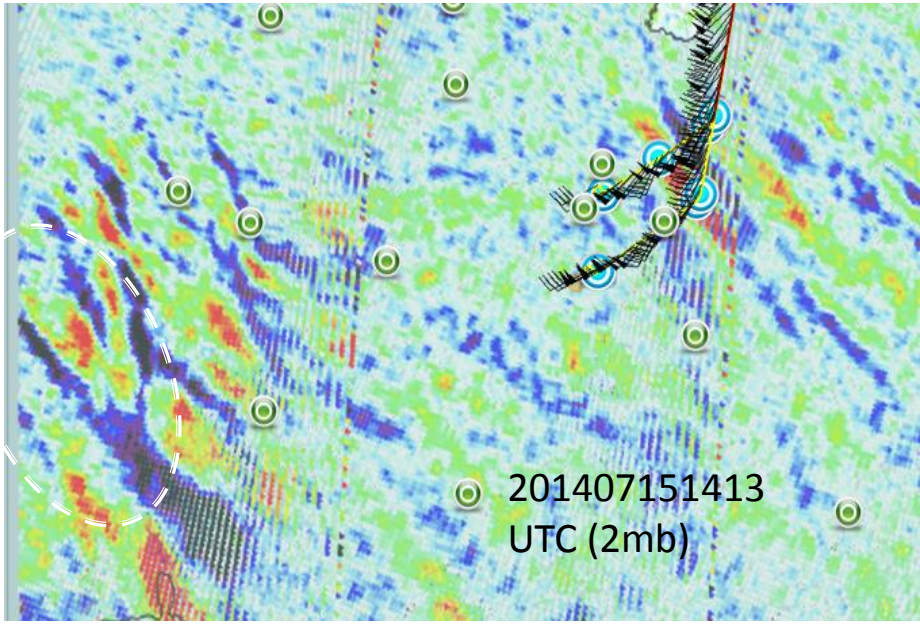


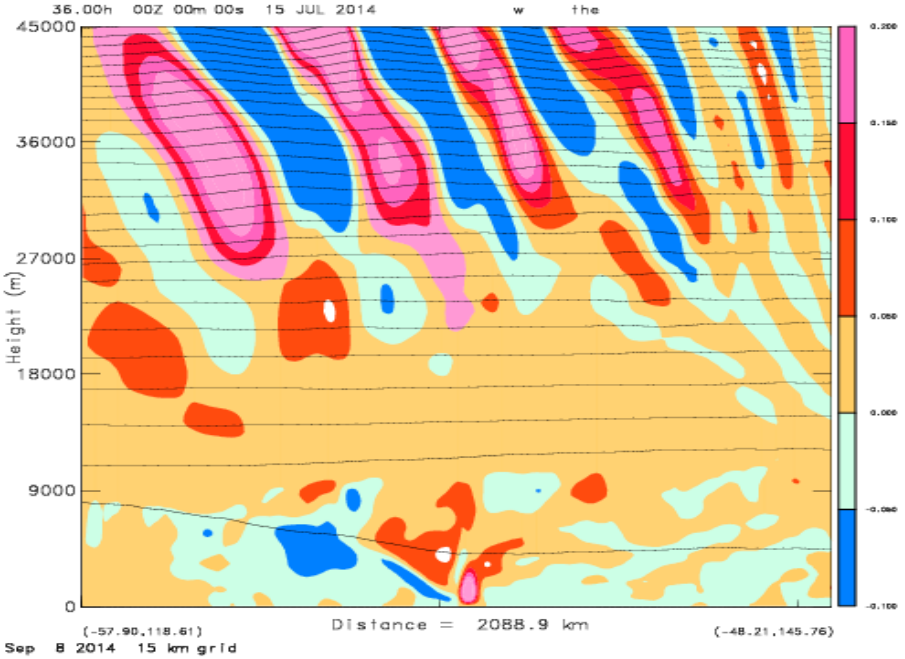


- AIRS: Deep waves lower-left (10-40 km)
- Propagating downwind/upwind
- Three wave groups: two downstream ~ 18m/s and one upstream propagating

Comparison with AIRS (IOP14, 14-15 July)





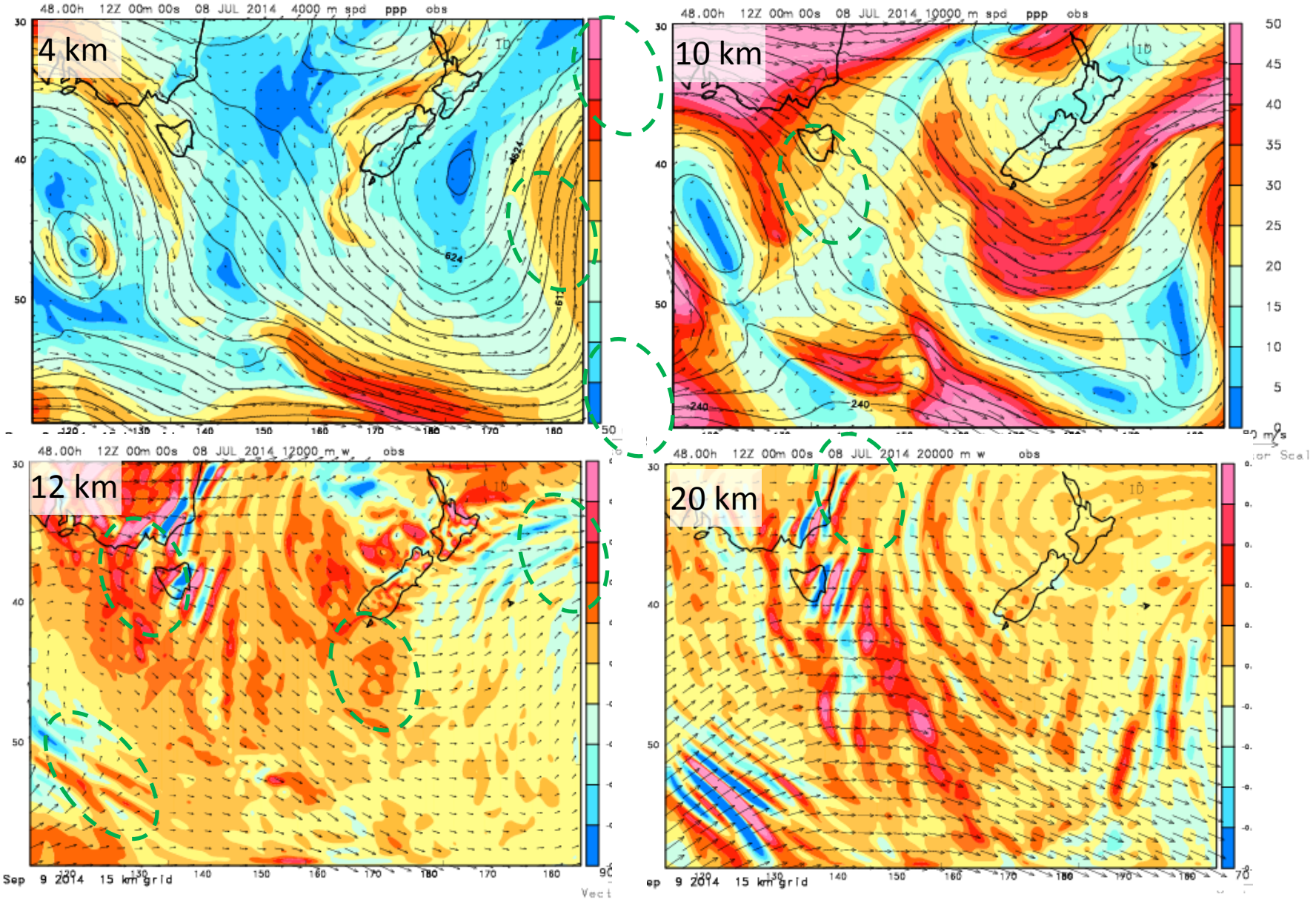


Two distinct wave modes:

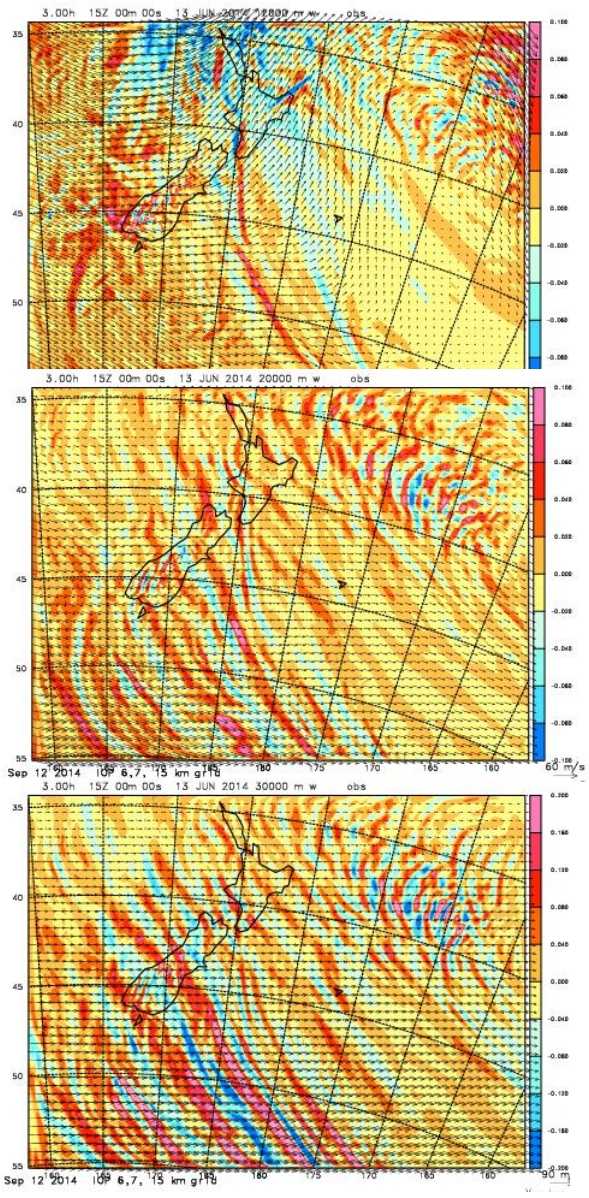
- **500 km long south-west corner**
- **~200 km in the lee of SI.**

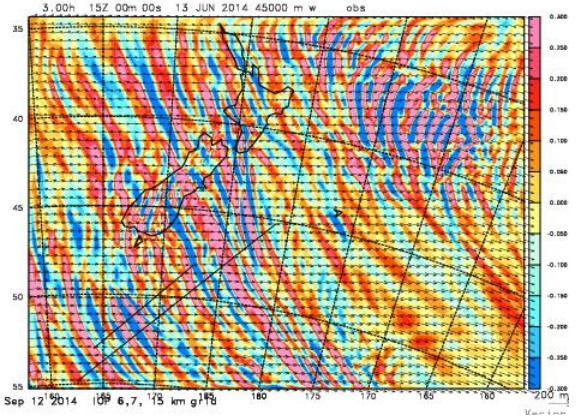
Both are only evident in stratosphere, where they tilt against mean winds, implying upward energy propagation

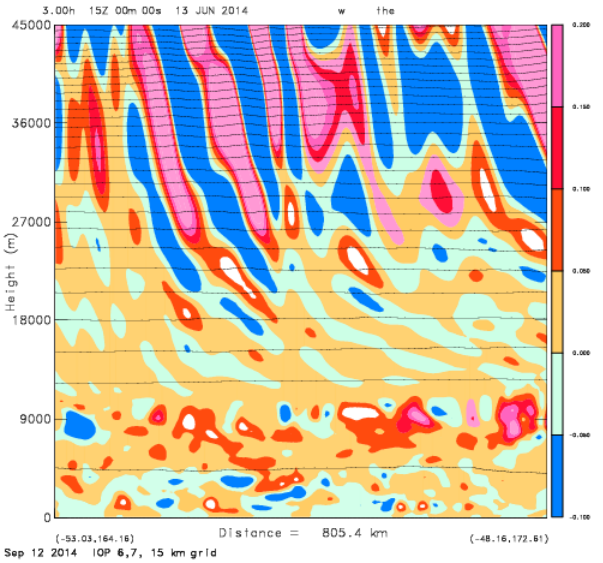
Synoptic Conditions (IOP 12)



Simulated wave characteristics (IOP2-3; 5-km)

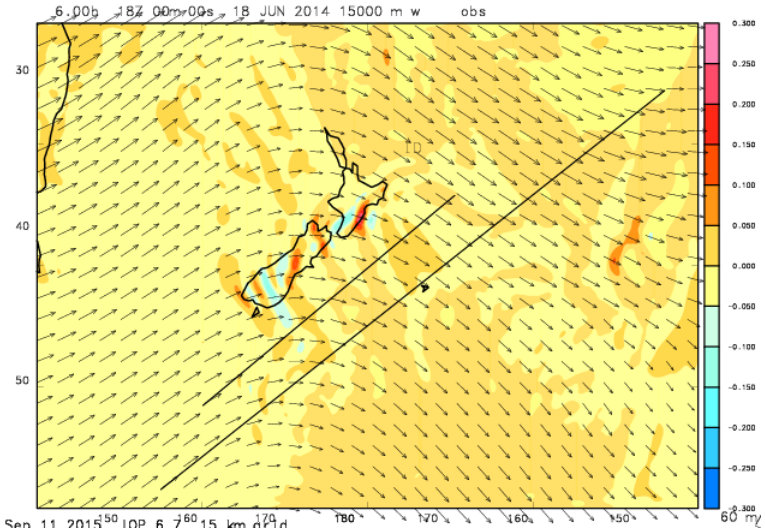


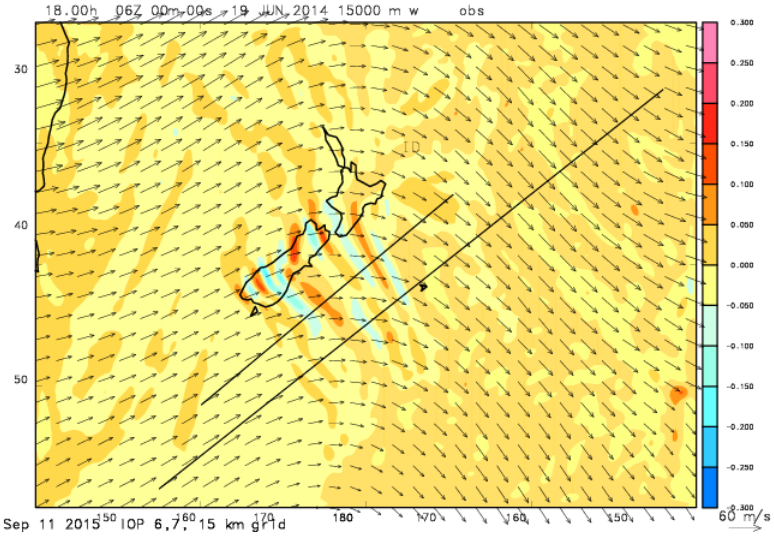


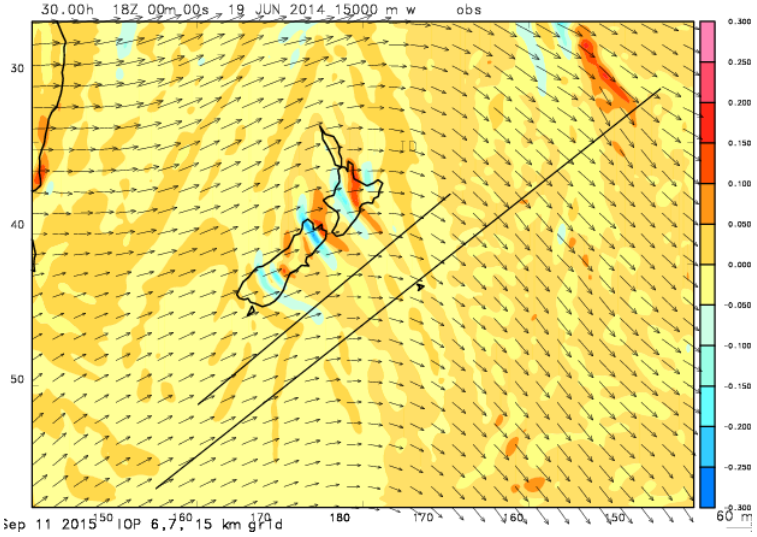


- Finer-scale perturbations with similar trailing wave patterns, implying that TW can be well-resolved in 15-km grid.

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