Deep Spatial Ray Modeling of the RF22 Gravity Wave Event

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With thanks to:

DEEPWAVE Instrument Teams

NAVGEM Reanalysis Teams

COAMPS Forecasting Team

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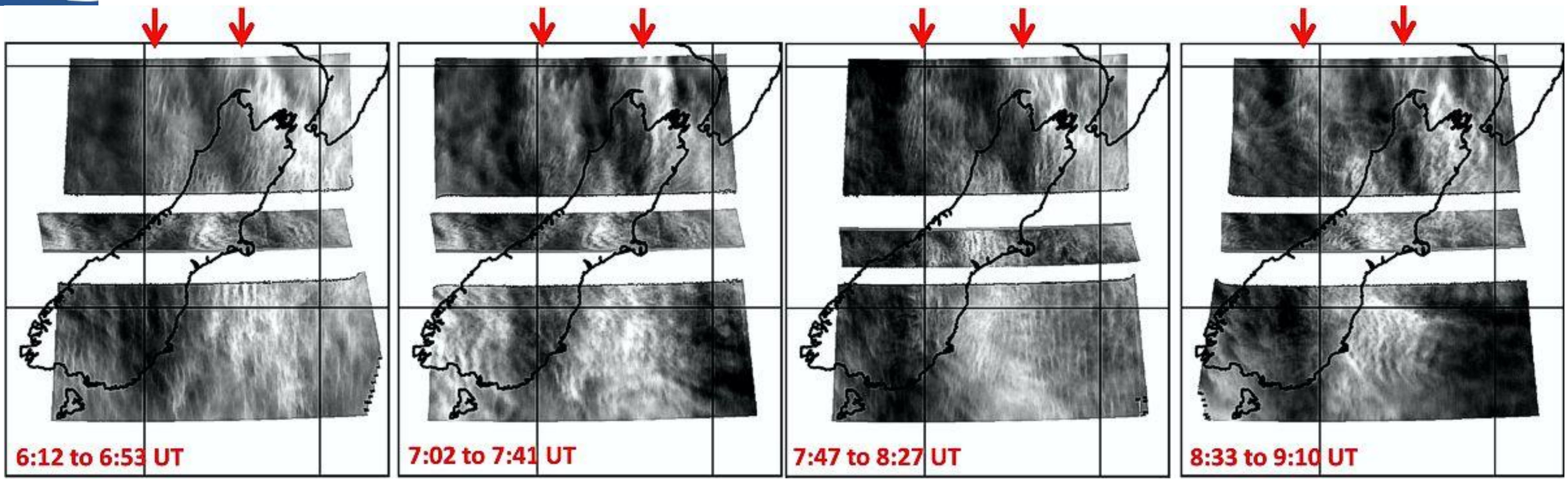
RF22: 13 July 2014

- Very large amplitude waves (λ_h~200-300 km) forecast in the upper stratosphere over the South Island **with odd phase orientation**
- Preceded by strong surface forcing previous night and early in day (sampled by DLR Falcon), which abated at flight time
- Transient surface forcing associated with evolving frontal passage
- Anomalously strong stratopause jet at the time

Hypotheses to be tested by RF22

1. Slow deep vertical propagation of mountain waves forced 12-24 hours earlier
2. Nonorographic gravity waves generated by frontal passage
3. Nonorographic waves generated in situ by stratopause jet instabilities
4. Spurious waves incorrectly forecast by the models

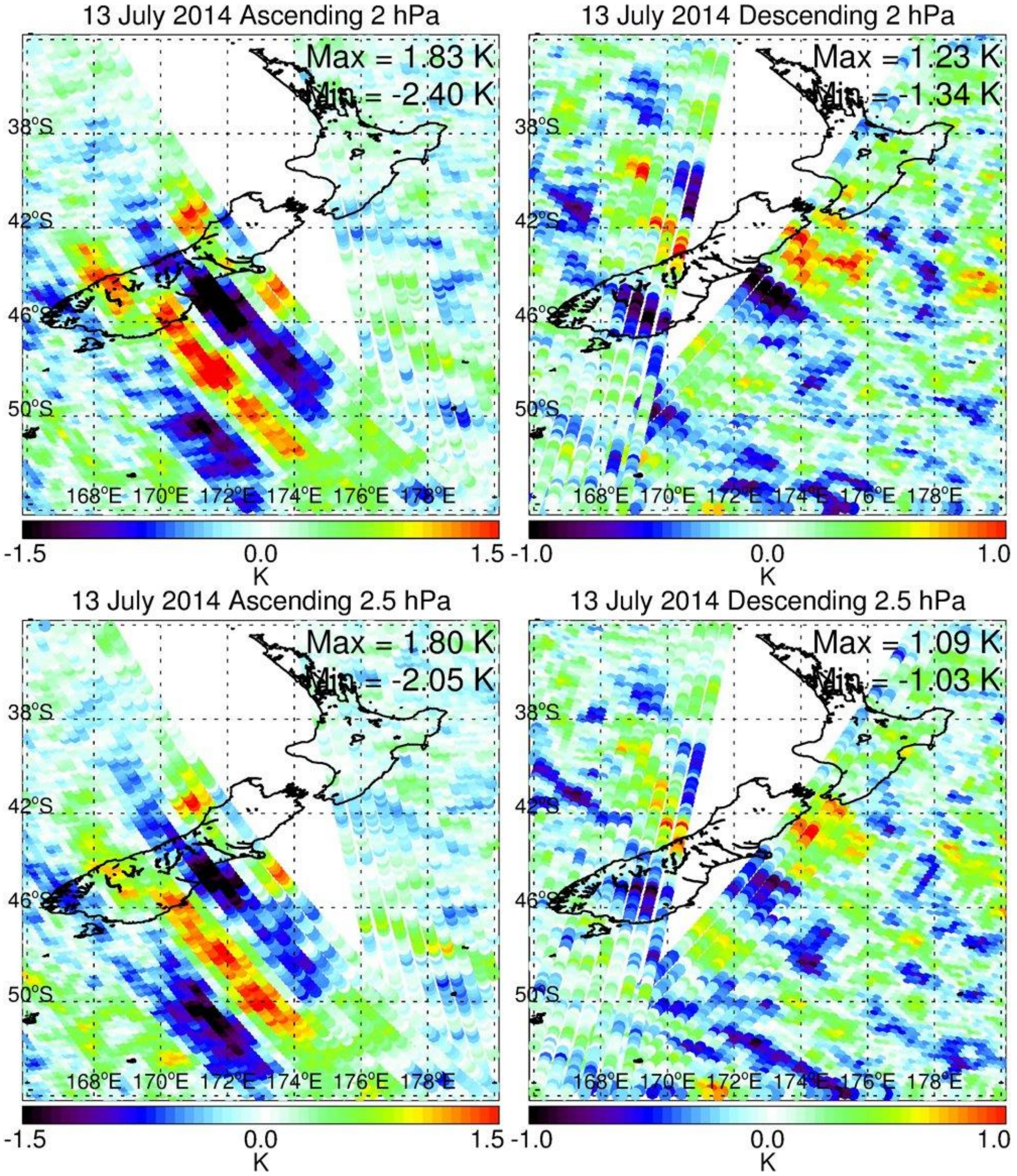
RF22 Obs Provided Initial Answers



RF22 Hypotheses

1. Slow deep vertical propagation of mountain waves forced 12-24 hours earlier
2. ~~Nonorographic gravity waves generated by frontal passage~~
3. ~~Nonorographic waves generated in situ by stratopause jet instabilities~~
4. ~~Spurious waves incorrectly forecast by the models~~

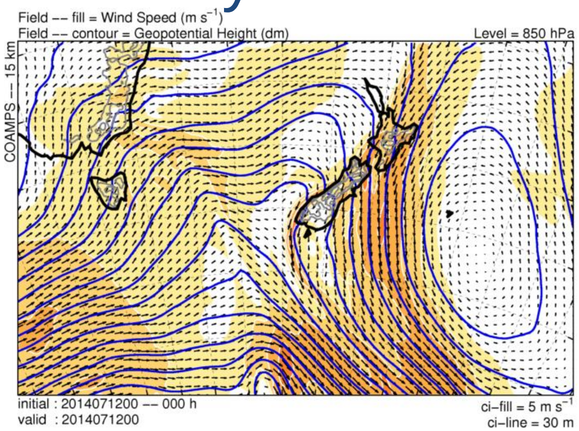
What is the Origin of the Observed Phase Orientation?



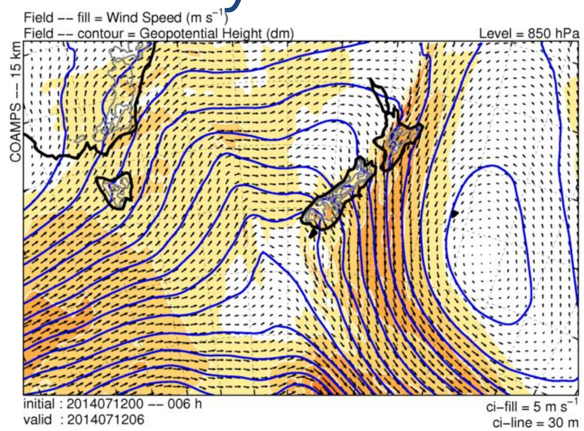
850 hPa Surface Forcing

- peaks ~12-30 hours prior to RF22, much weaker 0-12 hours before takeoff

12 July 0000 UTC



12 July 0600 UTC



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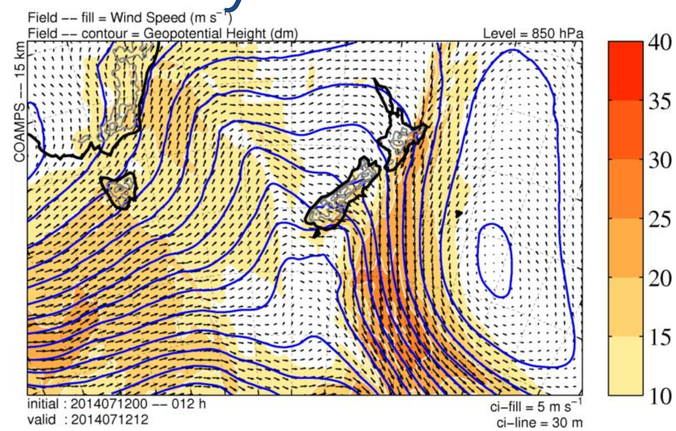
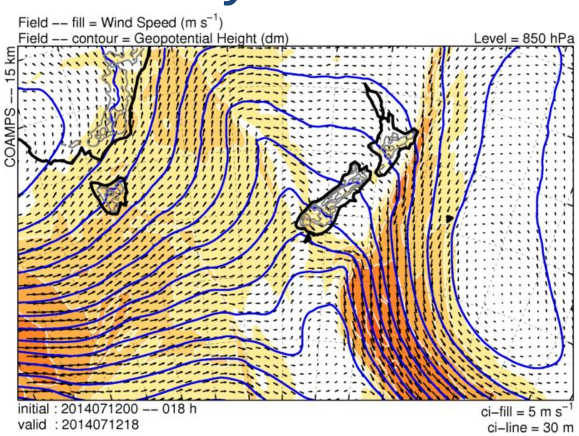


12 July 1800 UTC



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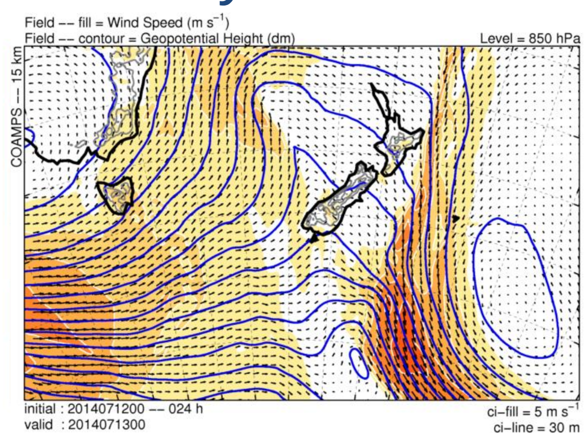

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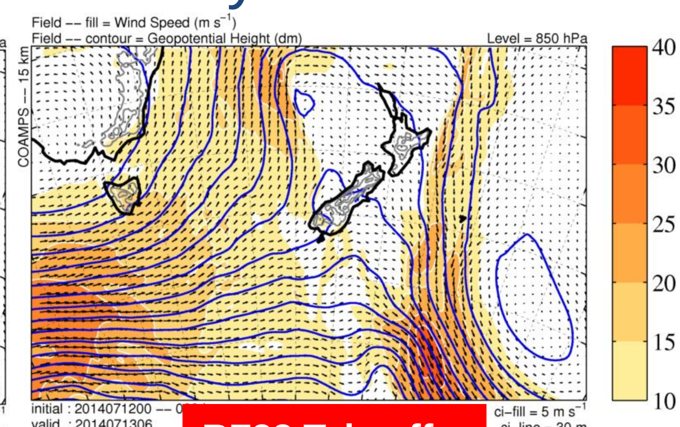
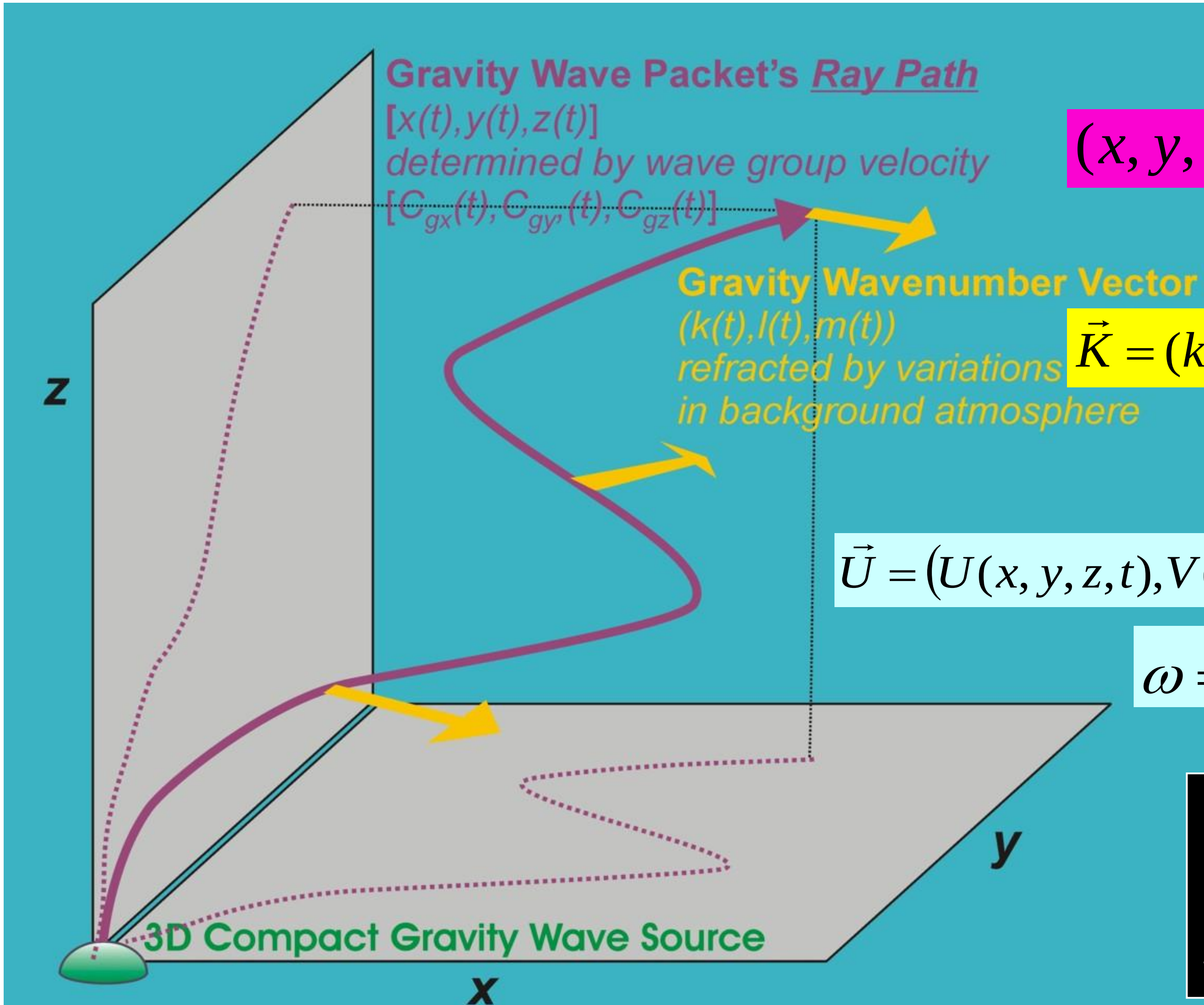


RF22 Takeoff

Spatial Ray Tracing

GROGRAT
Gravity-wave Regional Or Global RAy Tracer



$$(x, y, z)$$

$$C_{gx} = \frac{dx}{dt} = \frac{\partial \Omega}{\partial k} = U + C_{gx}^{\text{int}}$$

$$C_{gy} = \frac{dy}{dt} = \frac{\partial \Omega}{\partial l} = V + C_{gy}^{\text{int}}$$

$$C_{gz} = \frac{dz}{dt} = \frac{\partial \Omega}{\partial m} = W + C_{gz}^{\text{int}}$$

$$\vec{K} = (k, l, m)$$

$$\frac{dk}{dt} = -k\frac{\partial U}{\partial x} - l\frac{\partial V}{\partial x} + \ldots$$

$$\frac{dm}{dt} = -k\frac{\partial U}{\partial z} - l\frac{\partial V}{\partial z} + \ldots$$

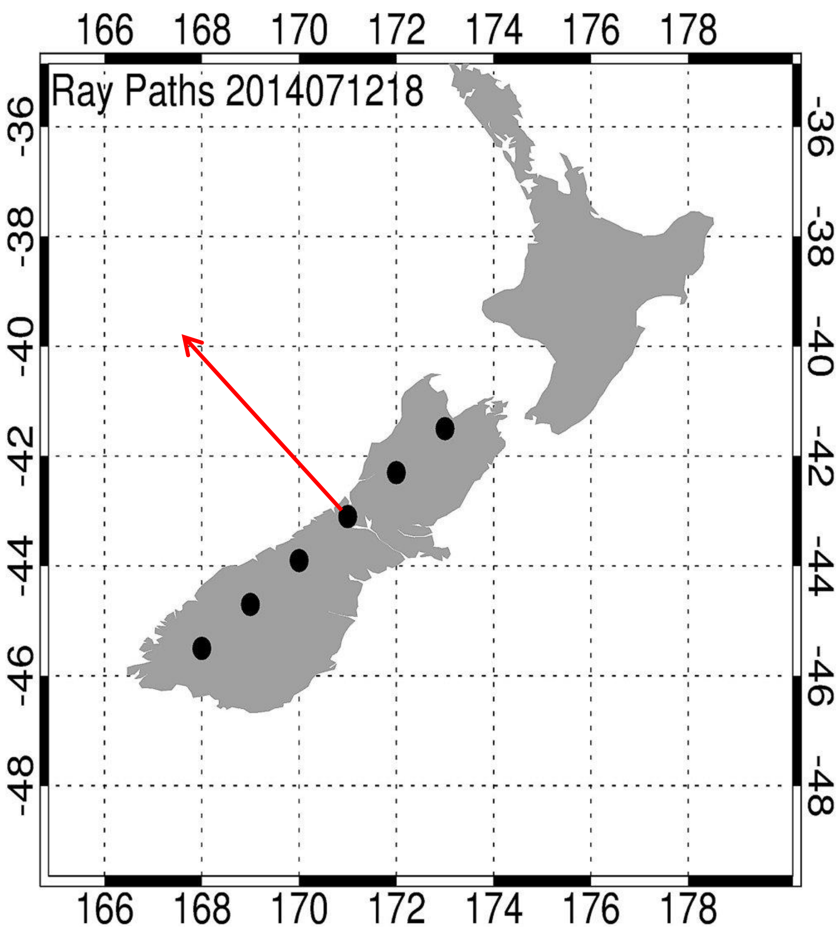
$$\vec{U} = \left(U(x, y, z, t), V(x, y, z, t), W(x, y, z, t)\right)$$

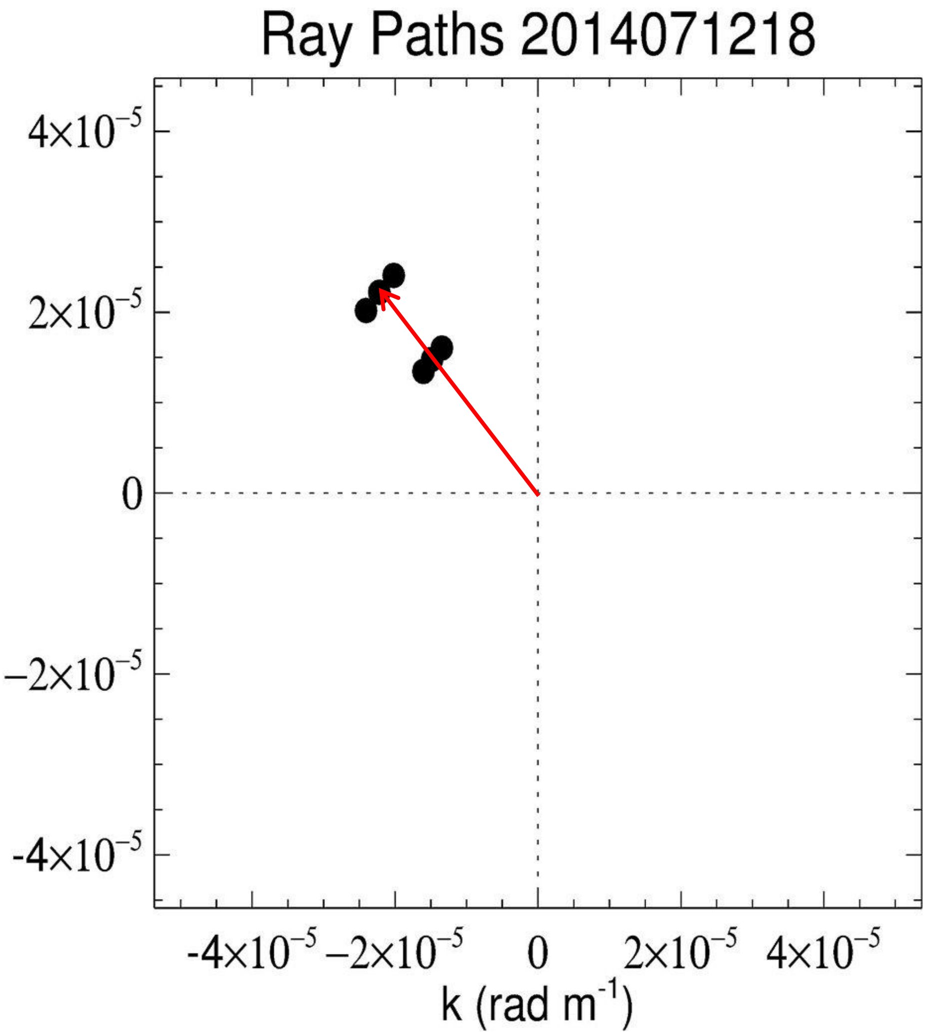
$$\omega = \Omega - \vec{K}.\vec{U}$$

Ray Group Trajectory and Wavenumber Refraction Equations

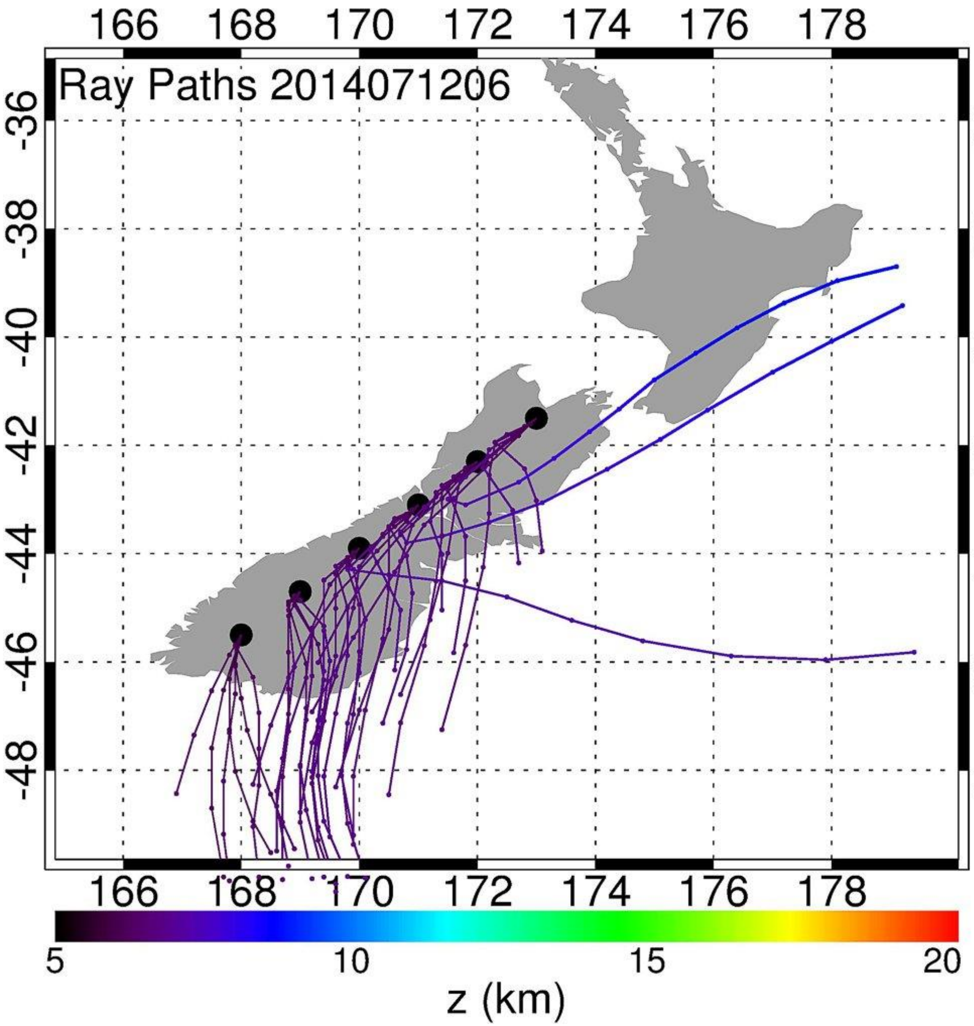
d/dt = differentiation following the wave group (ray) motion

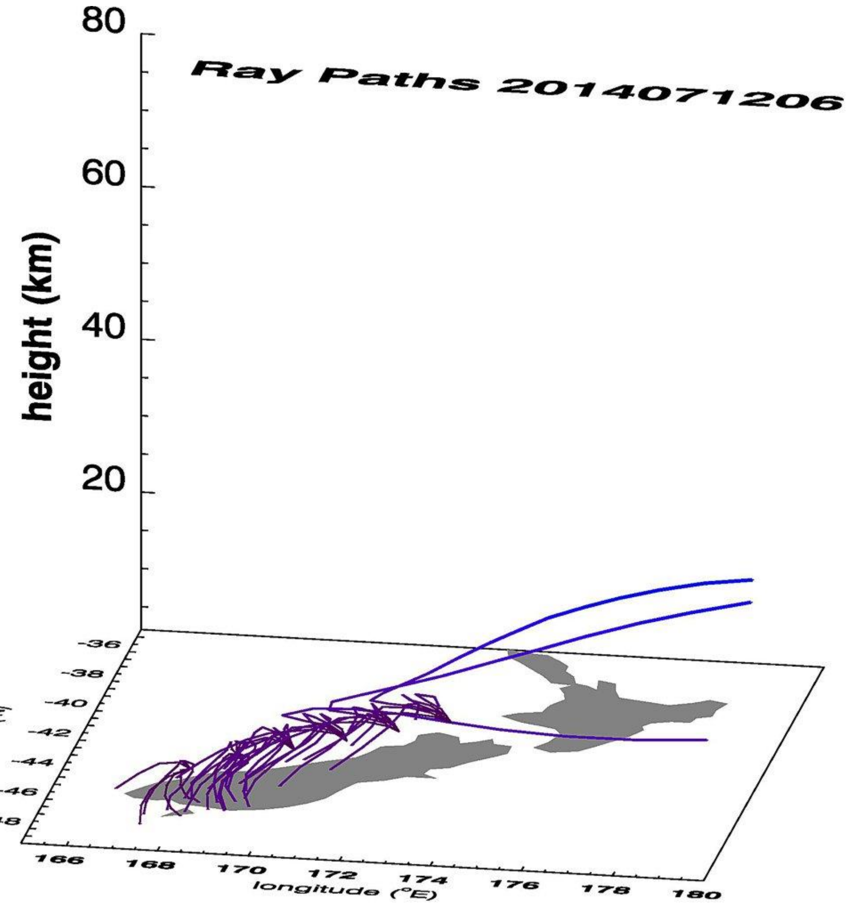
Spatial Ray Tracing





Spatial Ray Trajectory: 12 Jul 06Z

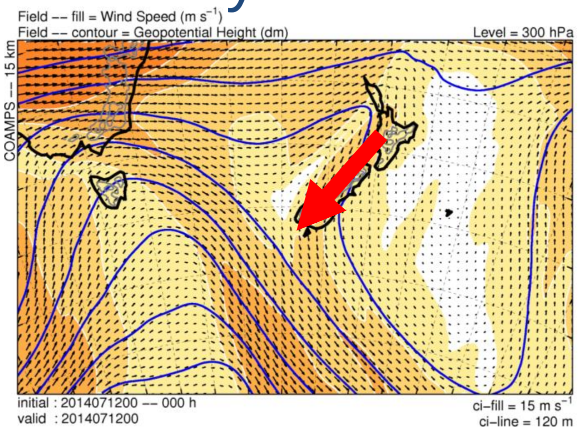




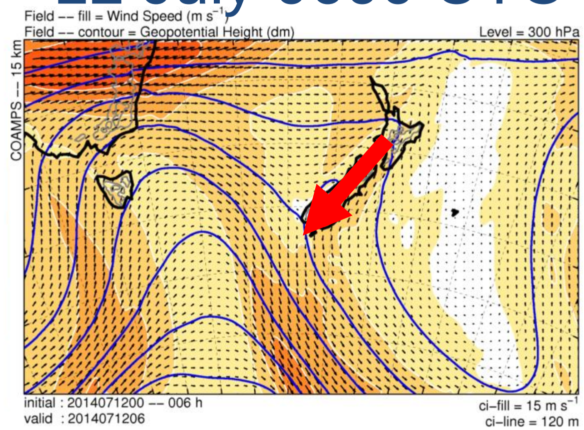
Filtering by 300 hPa Winds

- Directional critical levels up to 1200 UTC filters waves
- After 1200 UTC weak (but transmitting) flow

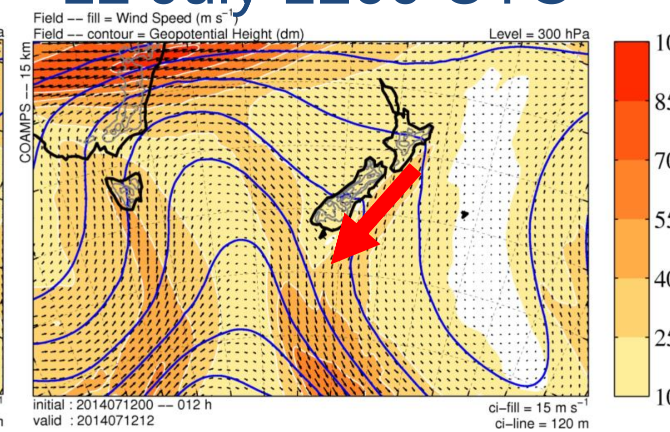
12 July 0000 UTC



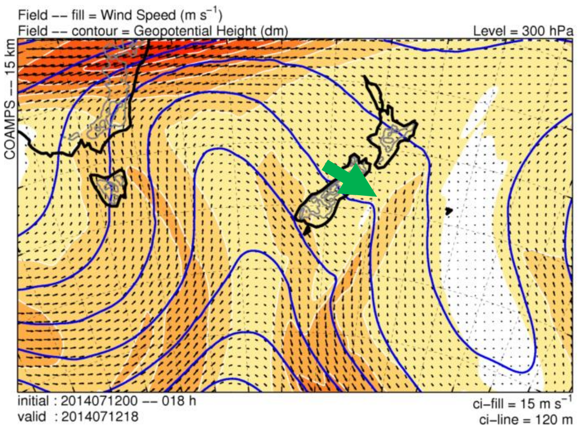
12 July 0600 UTC



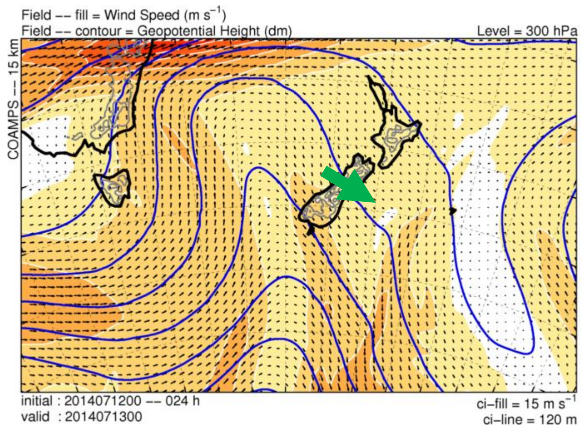
12 July 1200 UTC



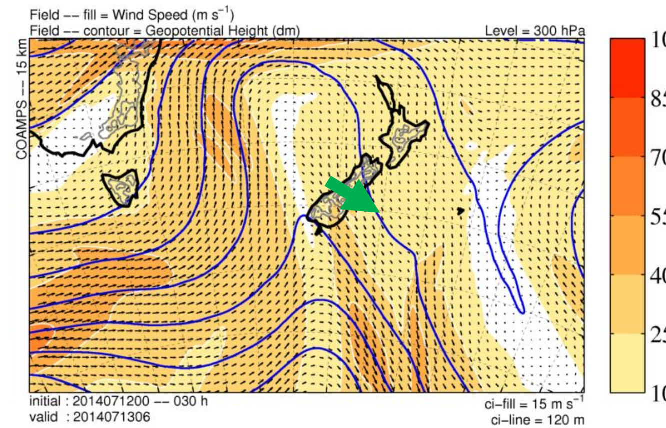
12 July 1800 UTC



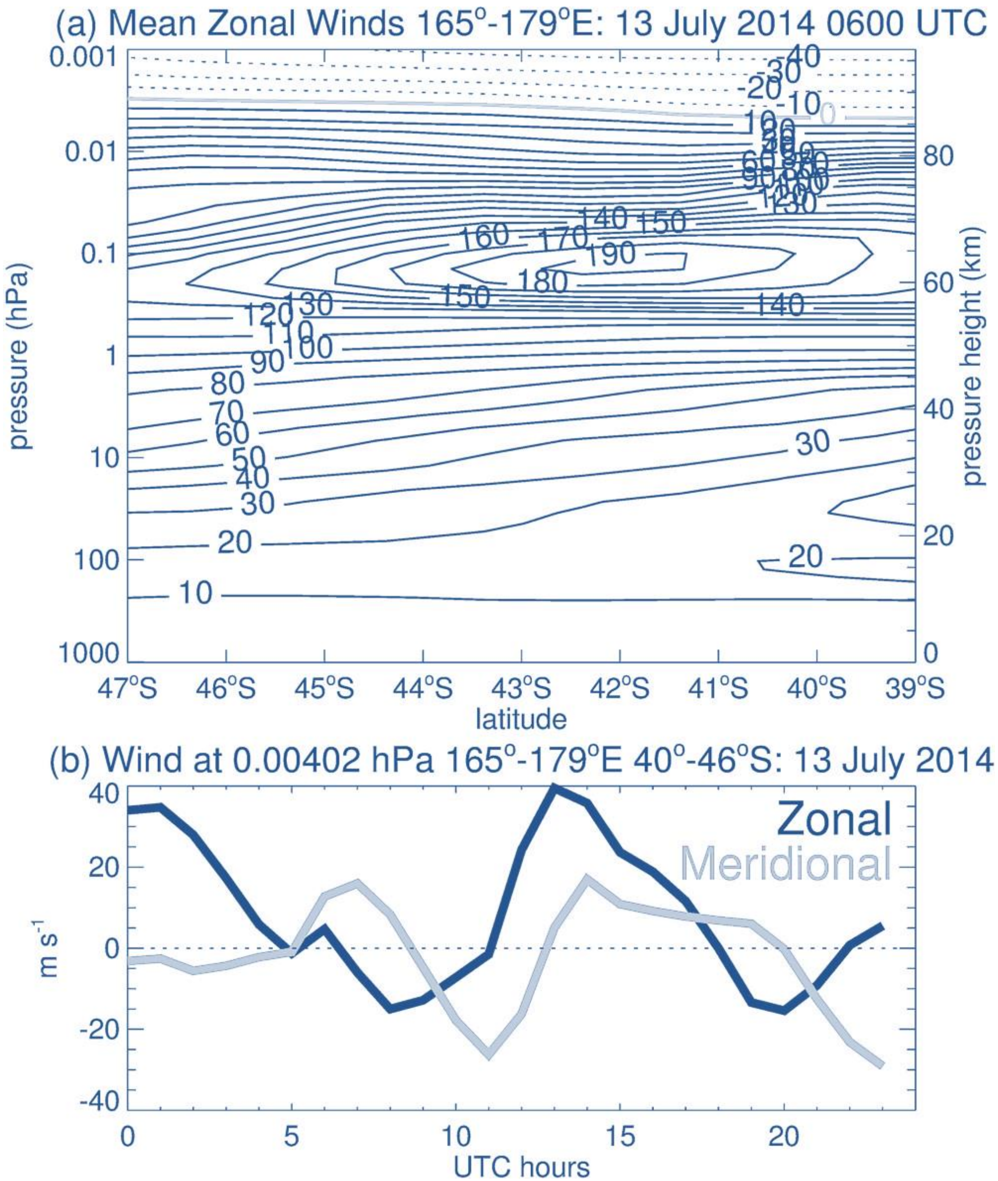
13 July 0000 UTC



13 July 0600 UTC



RF 22 Zonal Winds: 13 July 0600Z



For RF22 and RF23 NAVGEM MLT reanalysis over South Island yields:

1. weakening or reversal to mean easterlies

2. Strong semidiurnal tides

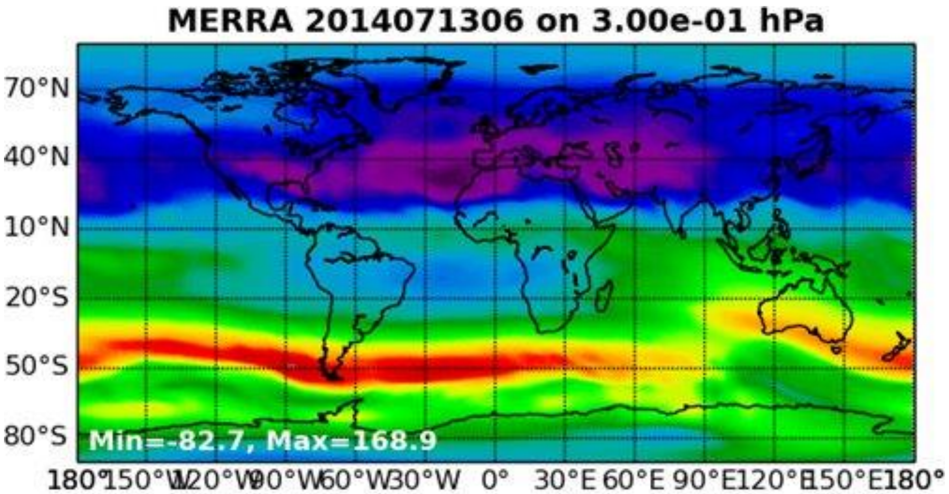
MLT MW observations suggest westerlies persist to ~90 km

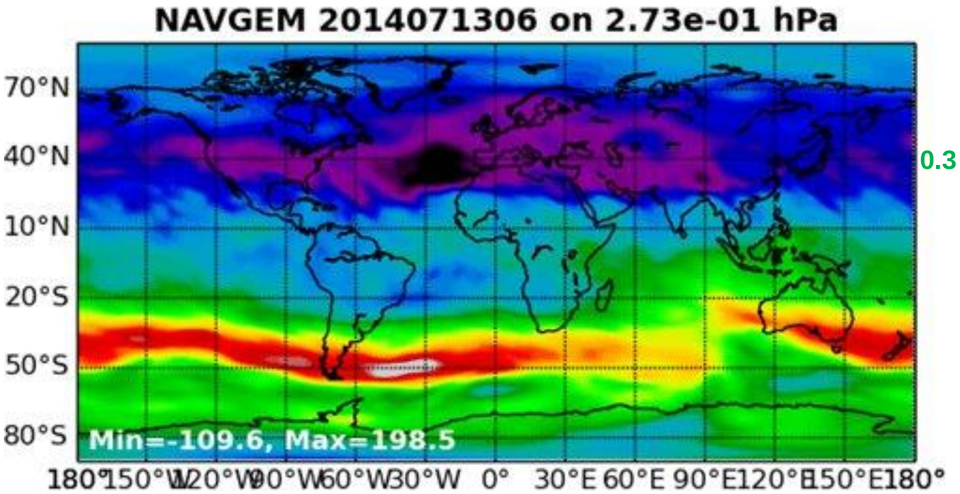
Untuned NGWD with large phase speeds may be responsible

Limited radar observations suggest semidiurnal tides ~10 ms^{-1} amplitude in winter MLT over New Zealand (Stening et al. JASTP 1995)

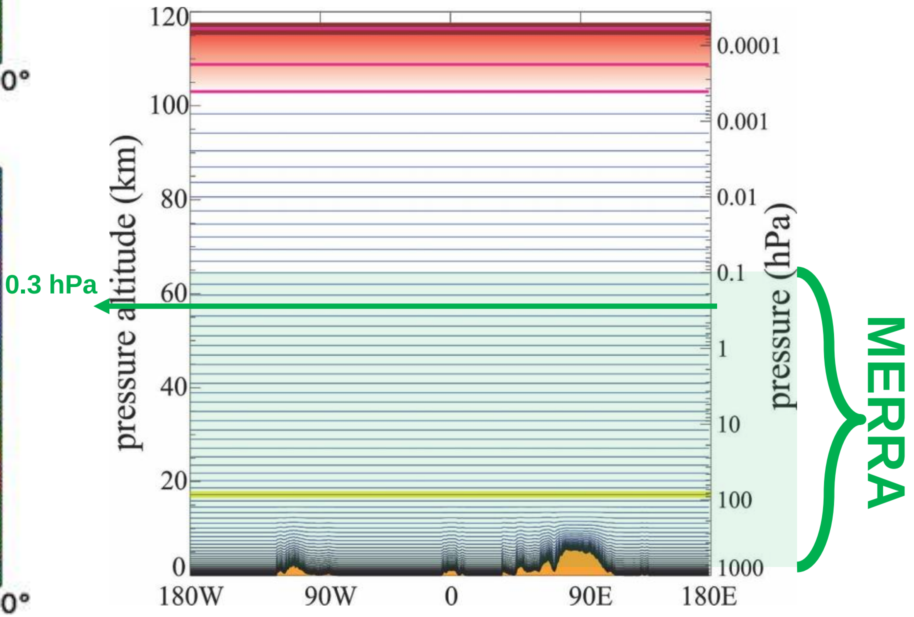
Really want to compare to Kingston meteor radar winds

MERRA v. NAVGEM for RF22
0.3 hPa: 13 July 2014 0600 UTC

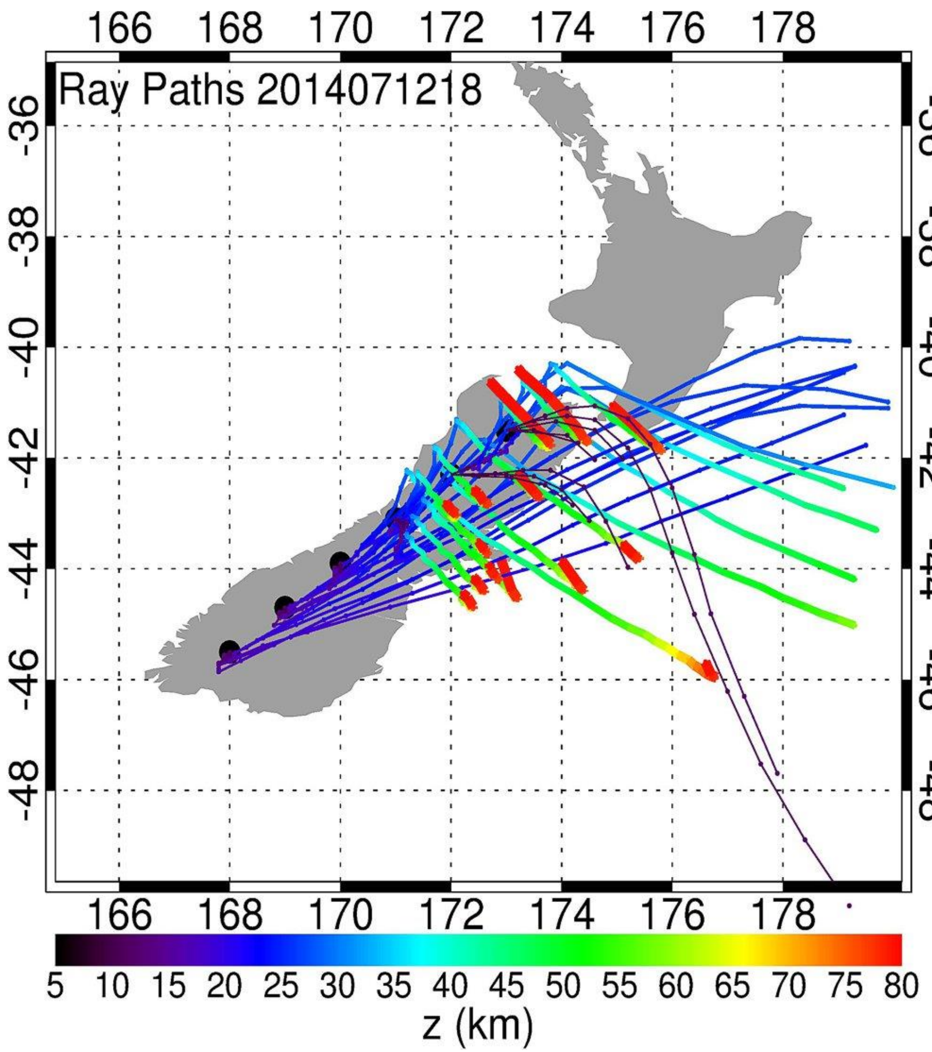


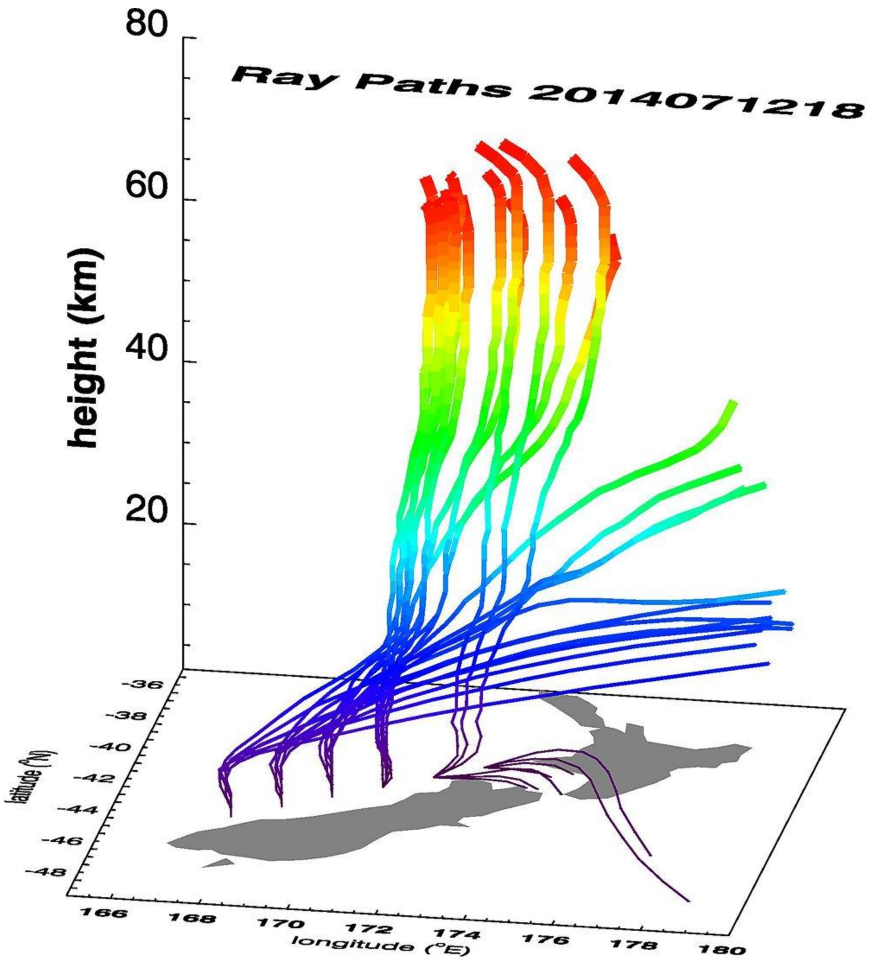


Strong deformed stratopause jet over New Zealand agrees well with MERRA

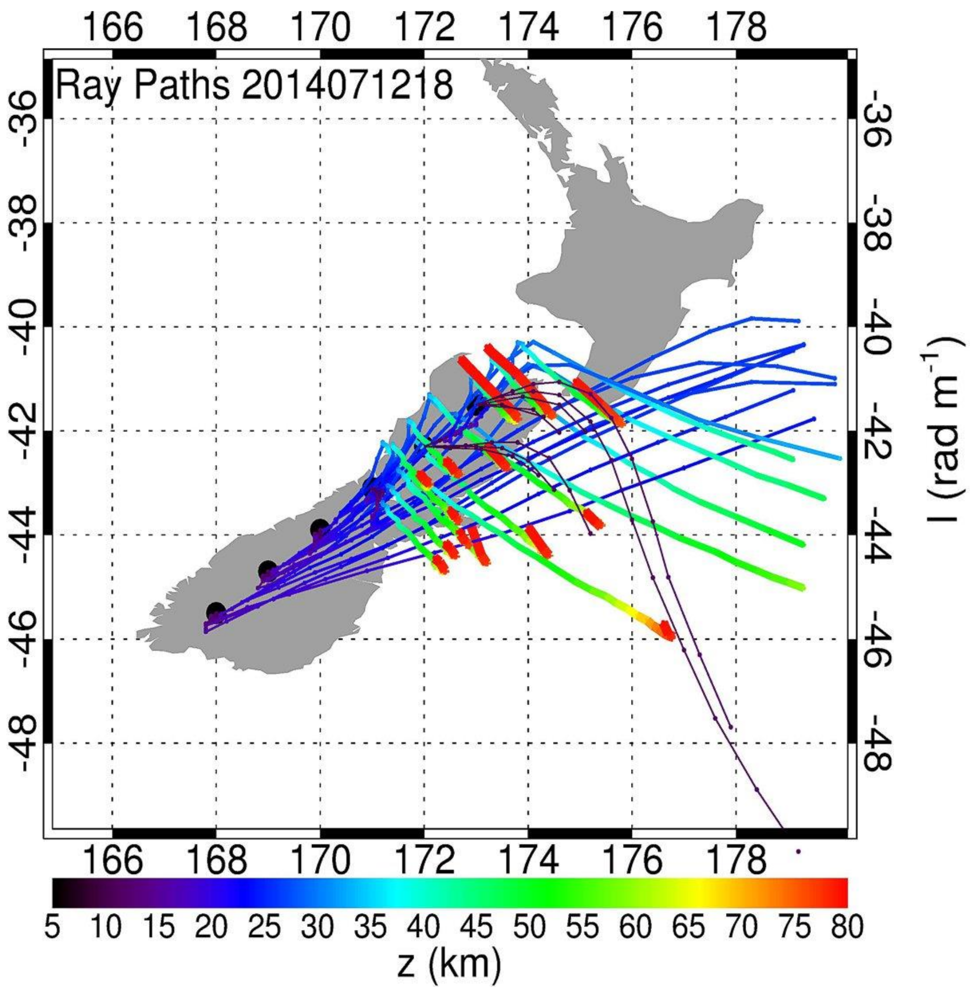


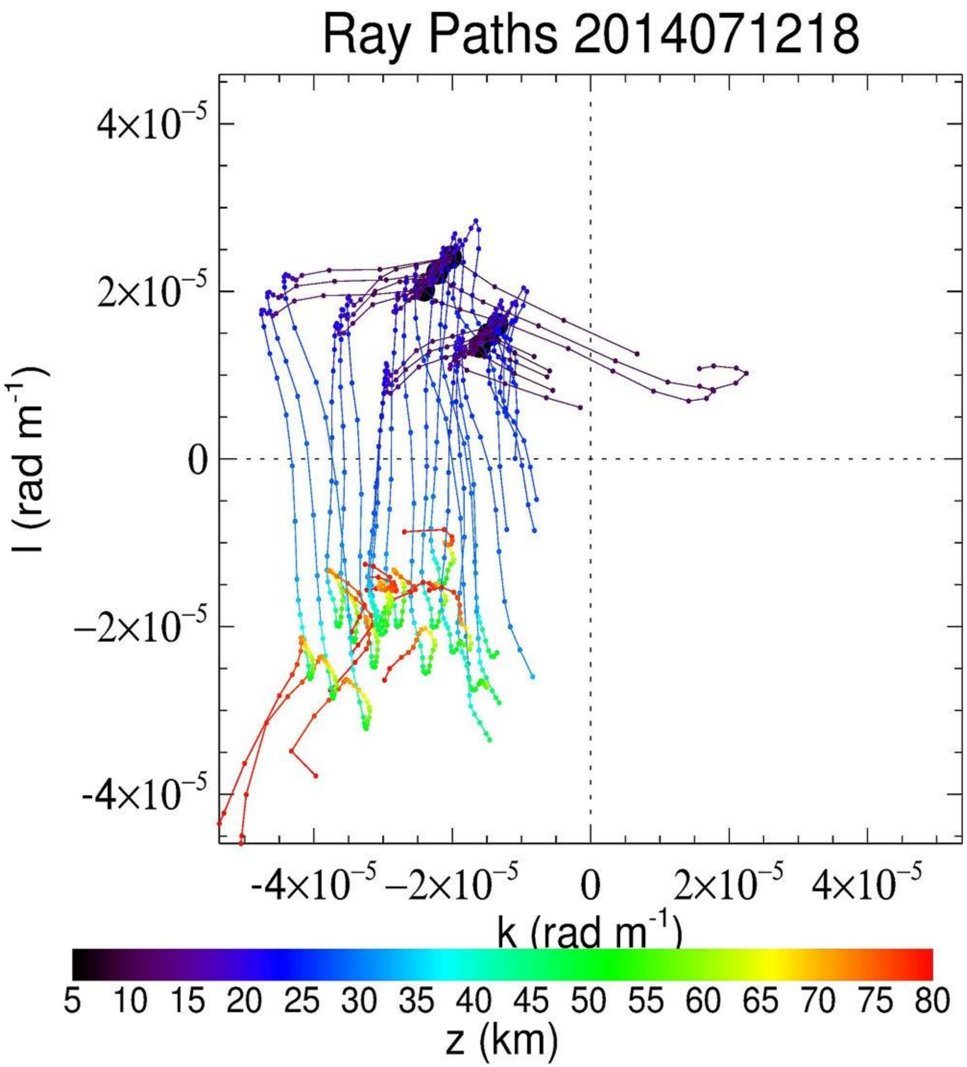
Spatial Ray Trajectory: 12 Jul 18Z



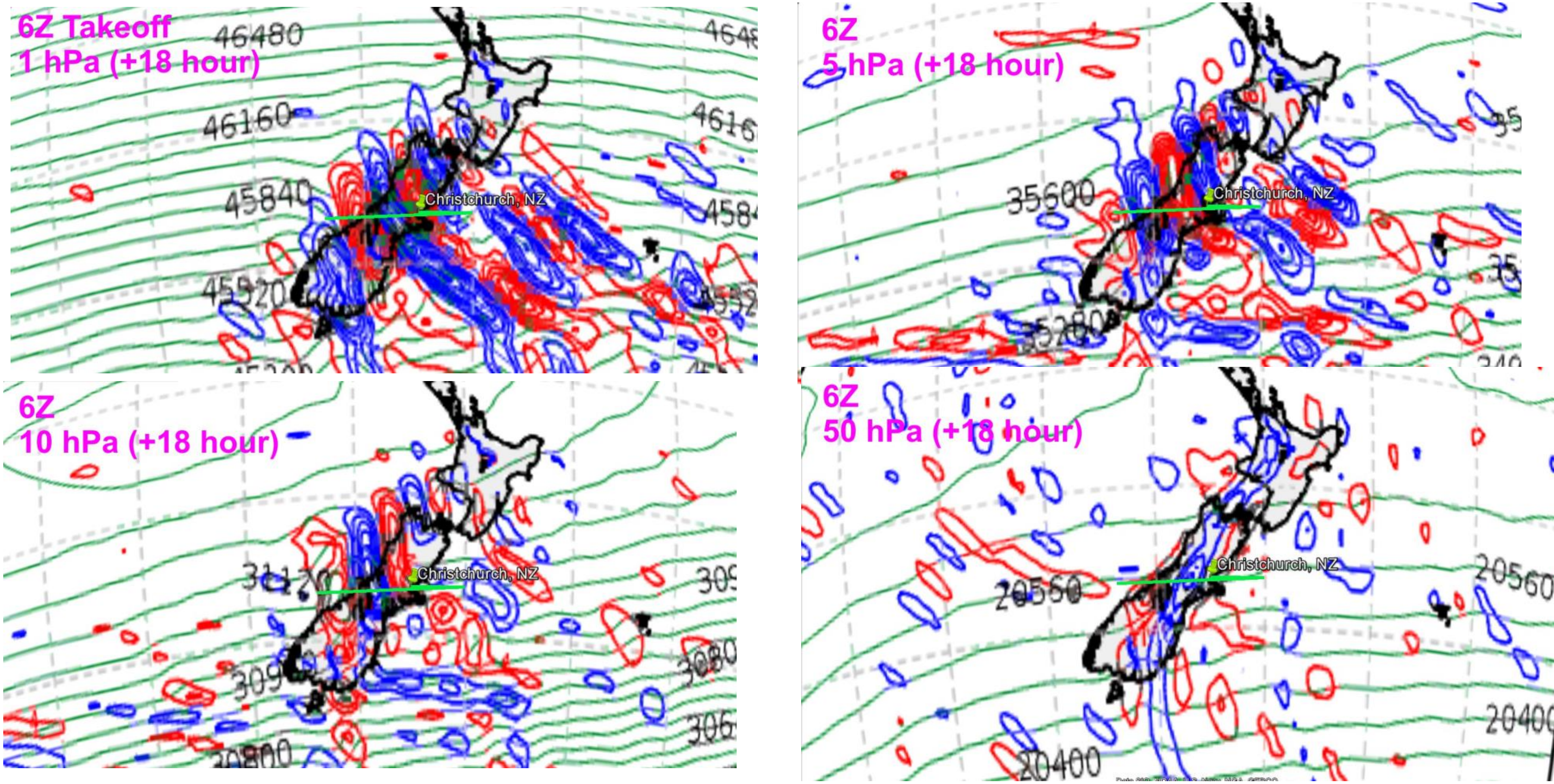


Lateral Refraction: 12 Jul 18Z

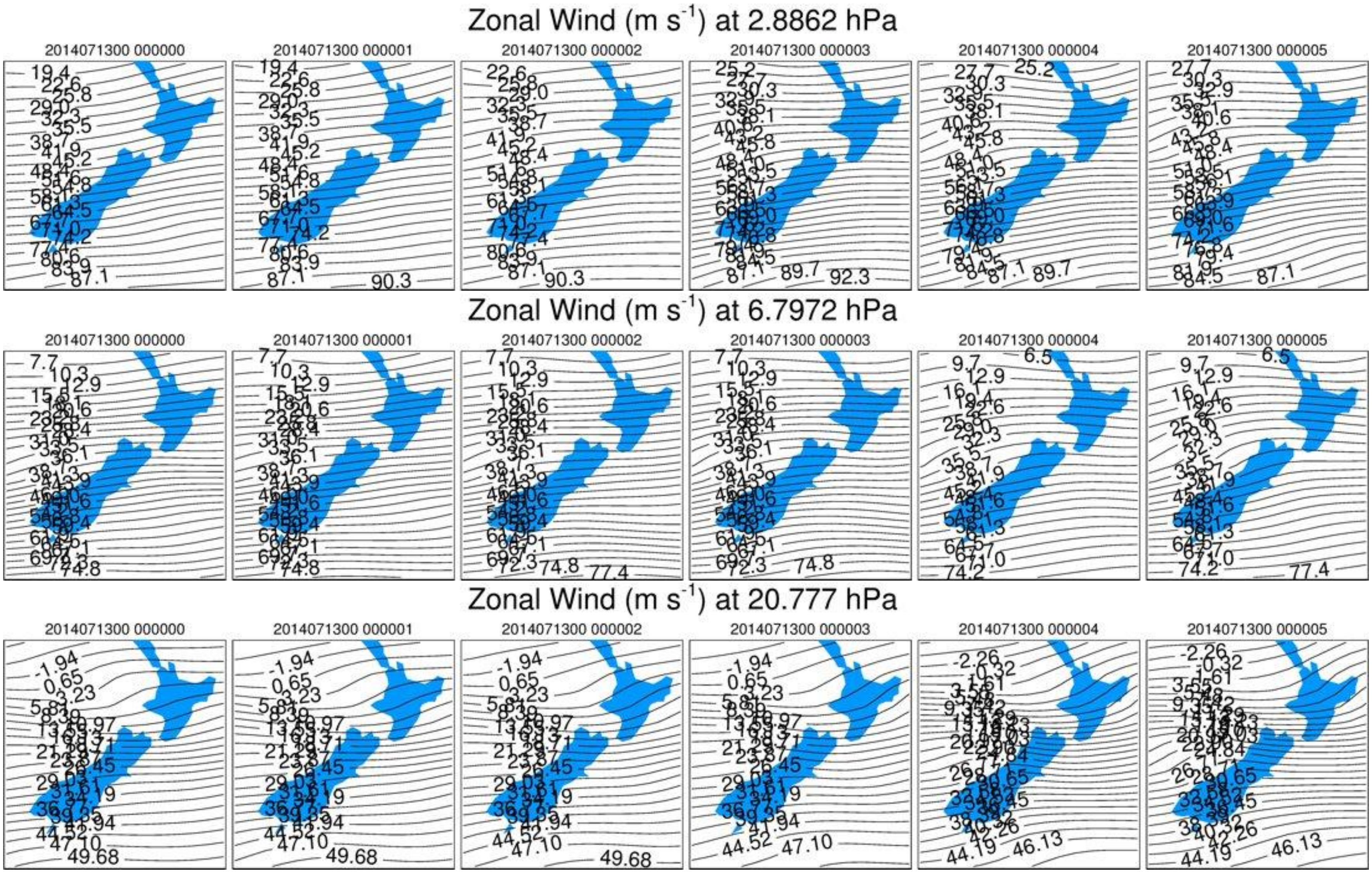




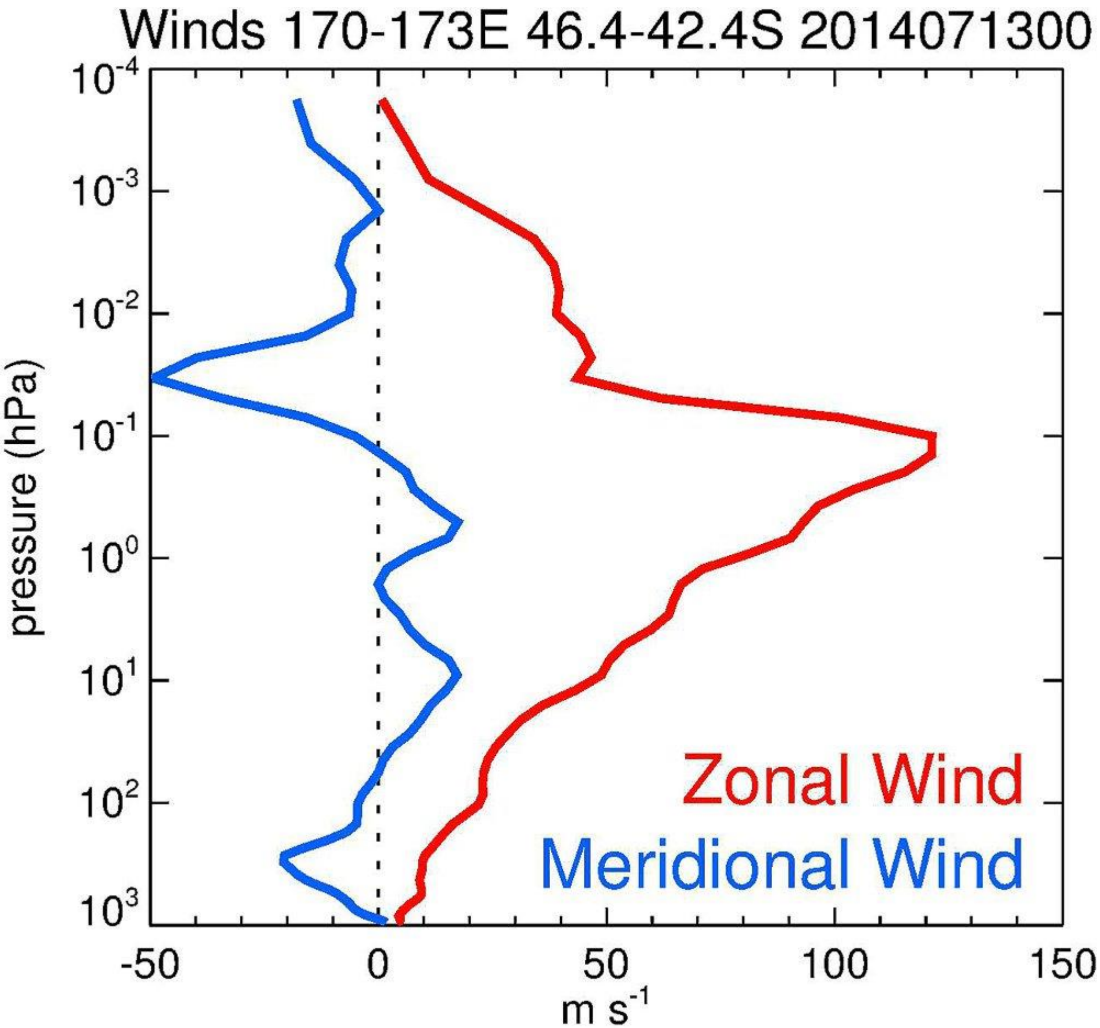
Phase Orientation Change in Lower Stratosphere



Strong Latitudinal Shear in Stratosphere



Propagation Times



$$c_{gz} = \partial\hat{\omega}/\partial m = U^2(z)k^2/N(z)k_h$$

$$k_h = (k^2 + l^2)^{1/2}$$

U~20 m s^{-1} N=0.02 s^{-1}

k_h=2π/(250 km)

→ c_{gz} = 0.5 m s-1

Time to propagate to 10 hPa (Δz~30 km)

t_{prop} = Δz/c_{gz}~16 hours

So a 250 km mountain wave spends a lot of time propagating through the troposphere and lower stratosphere

Lateral Refraction

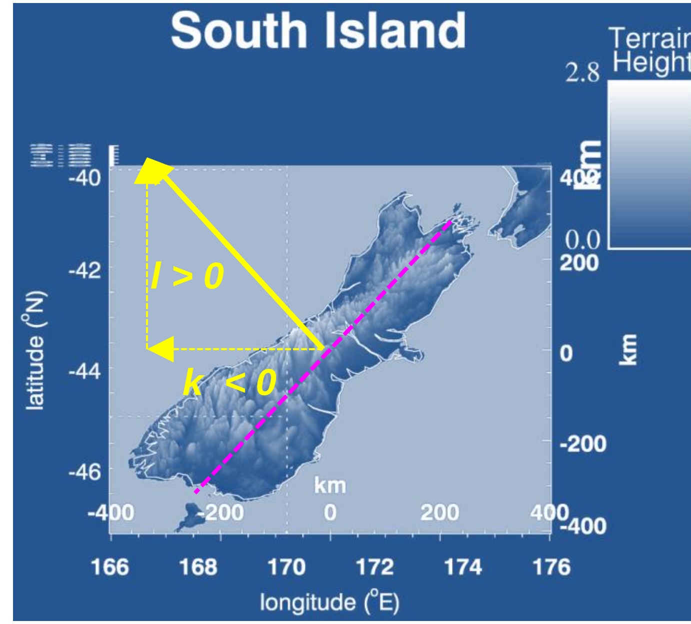
$$\vec{\boldsymbol{k}} = (k, l, m)$$

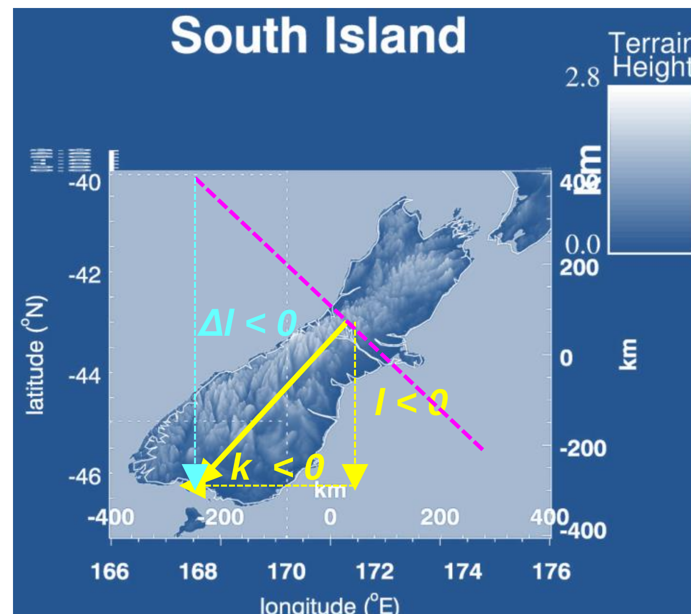
$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{C}_g . \nabla$$

$$\frac{dl}{dt} = -k \frac{\partial U}{\partial y}$$

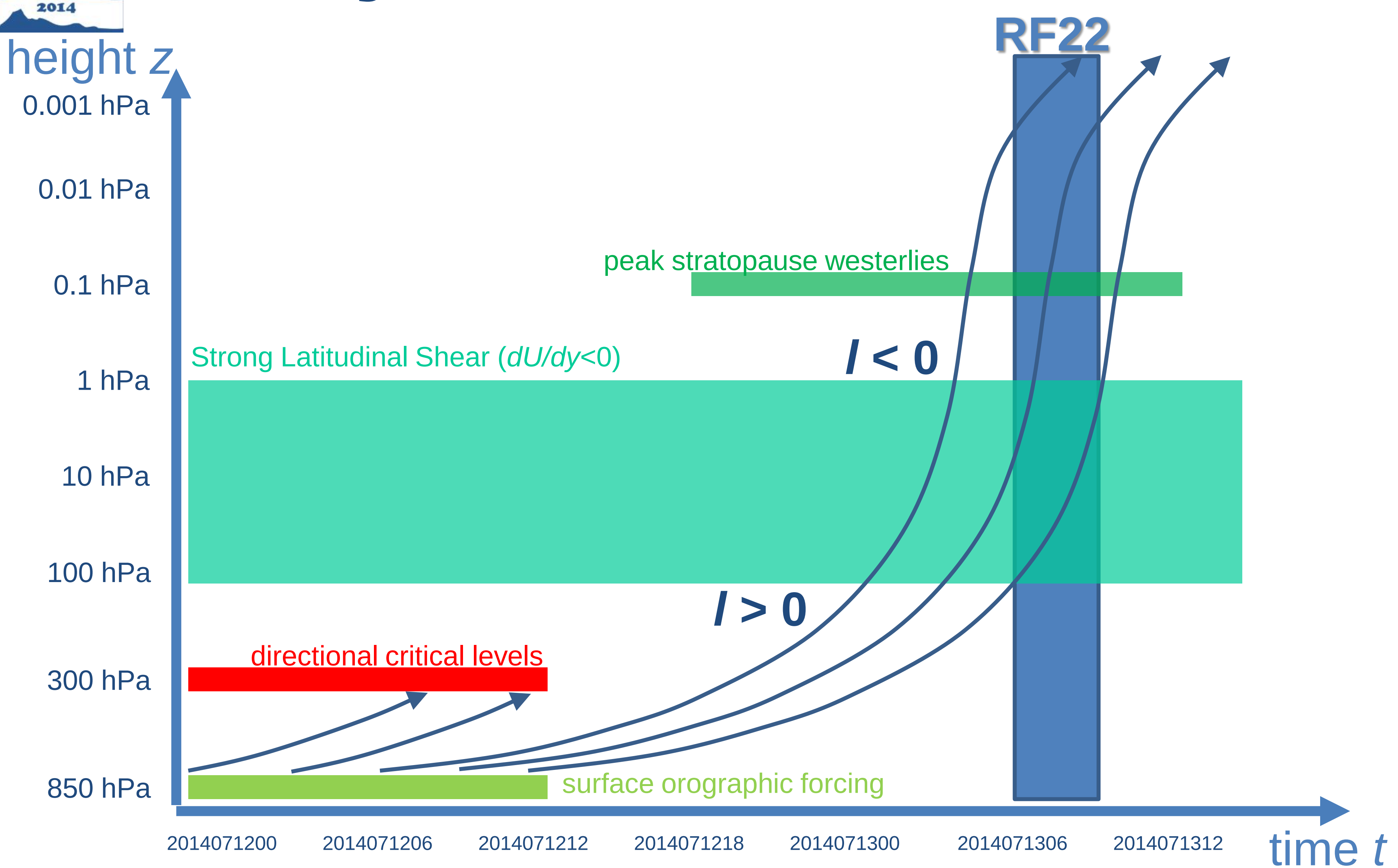
$$\boldsymbol{\Delta l = -k \frac{\partial U}{\partial y} \Delta t}$$

$$l > 0, -k\frac{\partial U}{\partial y} < 0, \Delta l < 0$$





Life Cycle of RF22 Wave Event

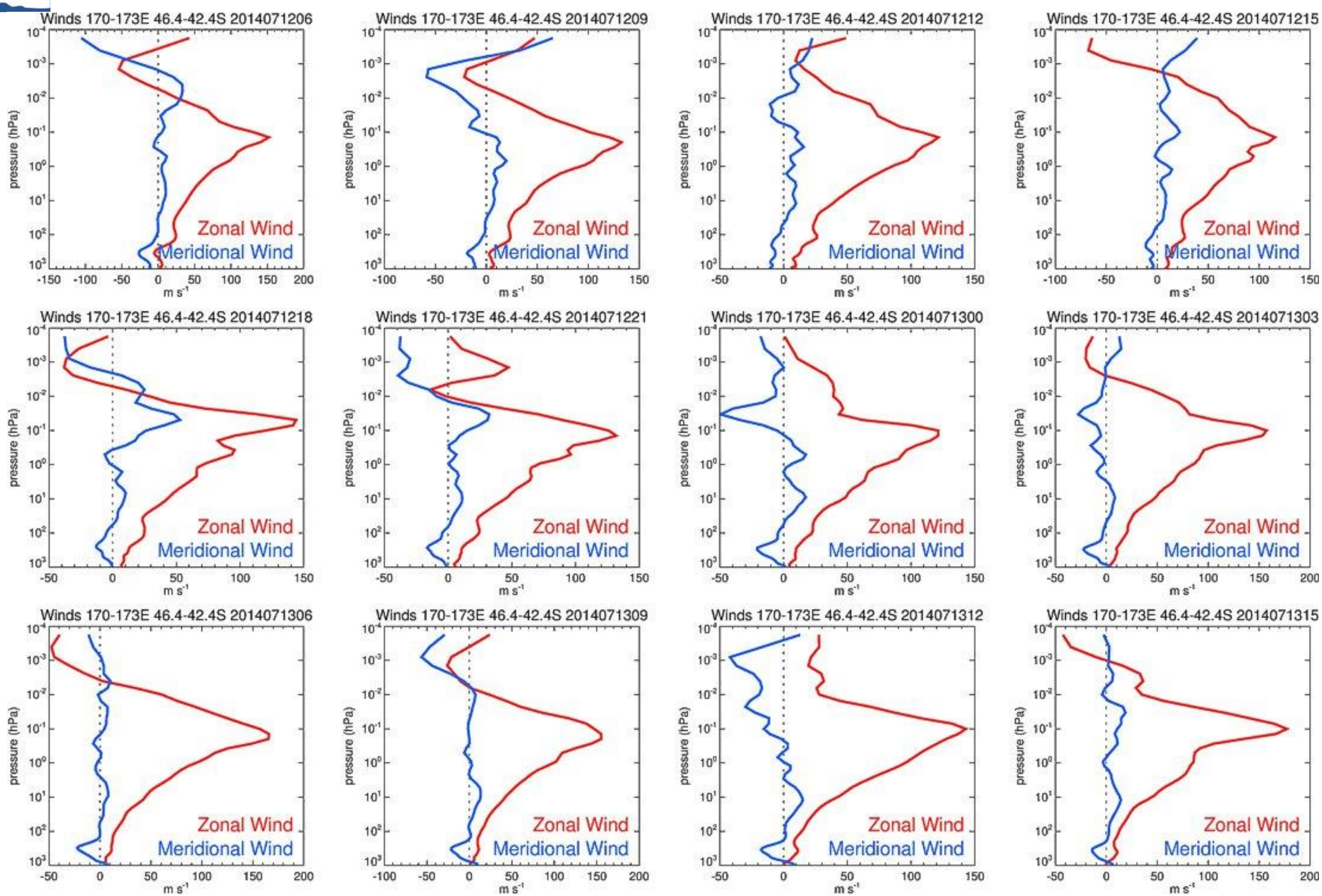


Summary

- We have provided a viable hypothesis for the unexplained phase structure of the large-amplitude RF22 mountain wave in terms of lateral refraction
- Other hypotheses (e.g., three dimensionality) remain to be tested but have weaknesses (e.g., South Island is not 3D at 200-300 km scales)
- If this theory holds up, may be the first ever definitive observational proof of lateral shear refracting a gravity wave: wider impacts (e.g. “remote recoil” drag theories)

BACKUP SLIDES

Wind Profiles over South Island



Spatial Ray Trajectory: 12 Jul 12Z