The Deep-Propagating Gravity Wave Experiment (DEEPWAVE): A Comprehensive Airborne and Ground-Based Measurement Program Based in New Zealand in 2014

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A long history of airborne mountain wave studies

The earliest MW studies employed balloons and gliders in N. Africa and Europe (Queney, 1936a,b; Kűttner, 1938, 1939; Manley, 1945)

The Sierra Wave Project (1951-2 and 1955)

- 1951-2 phase used only gliders, 1955 phase also employed powered aircraft
- led to key theoretical advances (Queney, 1947; Scorer, 1949; Long, 1953, 1955)

Mountain wave studies over the Rockies – (Lilly, Kuettner, and colleagues, 1968-1982)

- NCAR, other aircraft, new in-situ instrumentation, vertical profiling

Many more recent studies used research and commercial aircraft (ALPEX, FASTEX, GASP, MAP, PYREX, SOLVE, T-REX, others)

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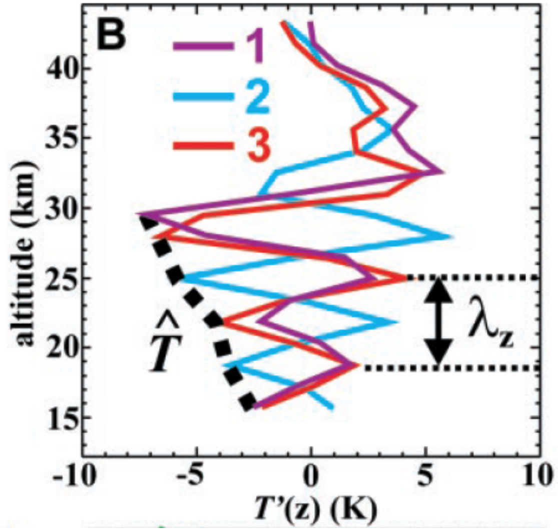
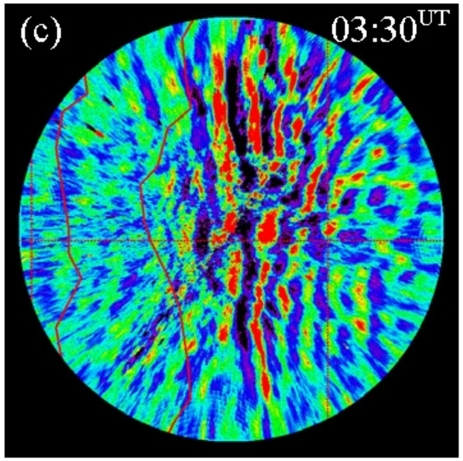
But new satellite & ground-based data also revealed MW penetration to much higher altitudes

Eckermann and Preusse (1999), Smith et al. (2009)

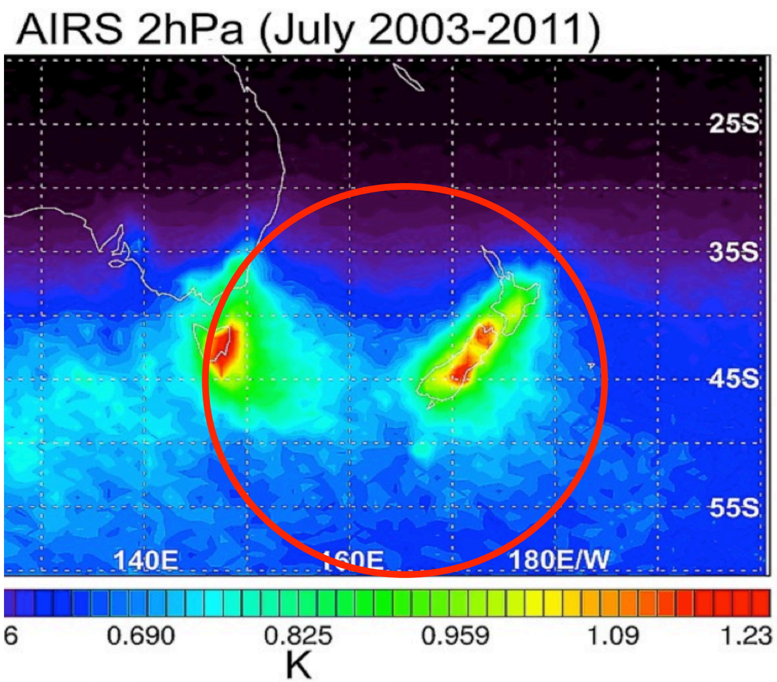


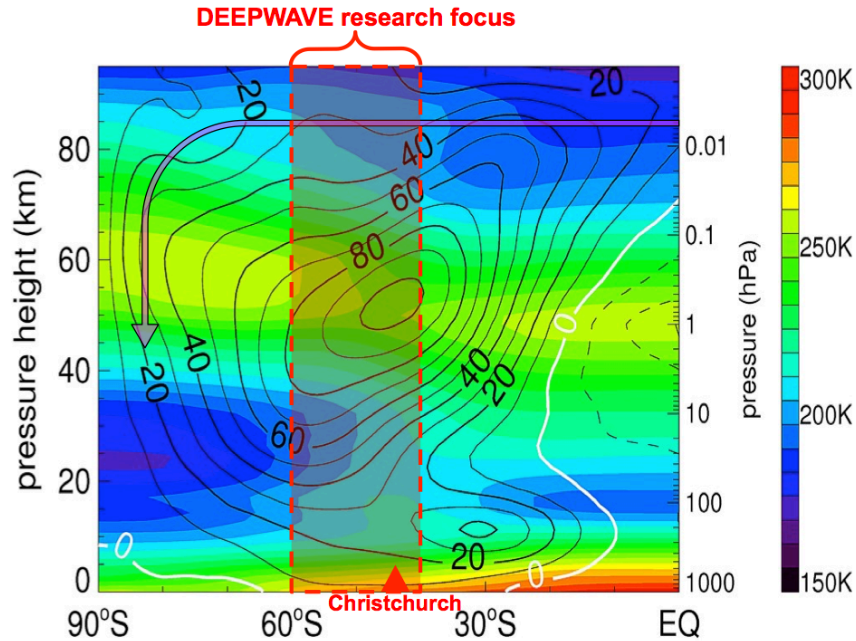


OH airglow ~87 km

DEEPWAVE plan – characterize Gravity Wave propagation and dynamics from their sources to regions of dissipation

- airborne & ground-based measurements over major source "hotspot"





NSF/NCAR Gulfstream V (GV)

DLR Falcon

GV sodium and UV lidars

Na lidar: ~0.2 W & 9.8 W beams

– ρ_{Na}(z) and T(z) ~75-105 km

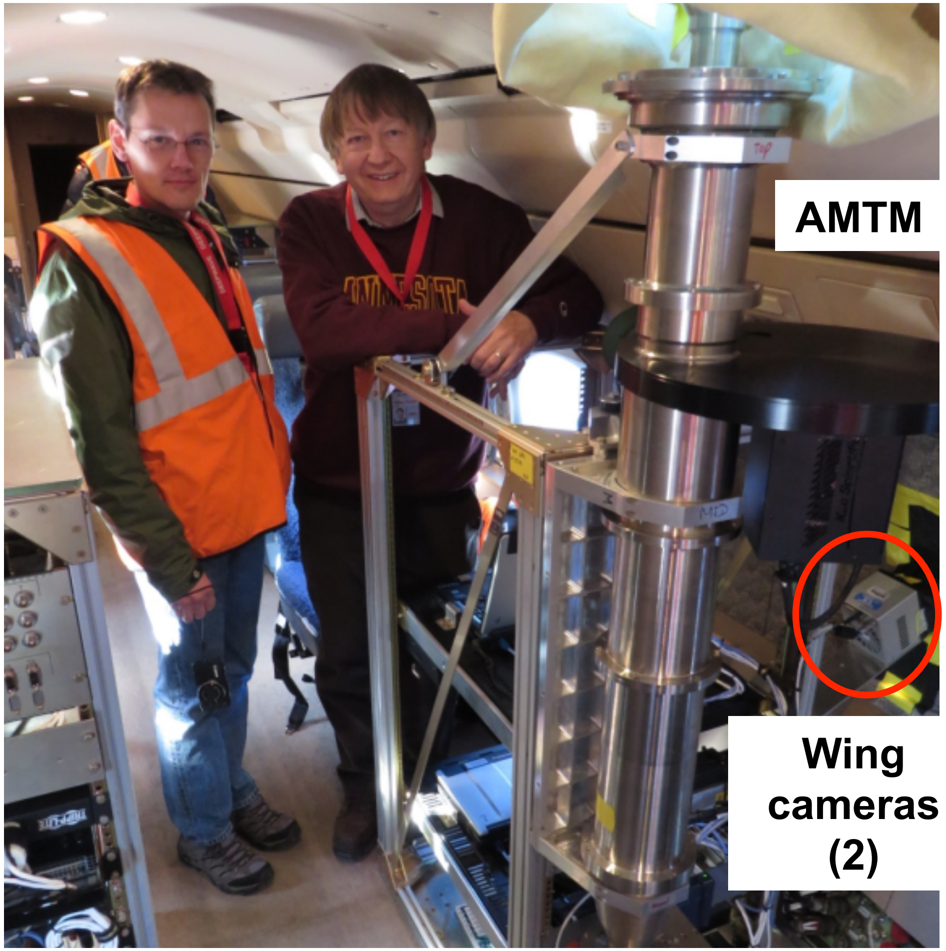
UV lidar: ~5 W pulsed

– densities & temperatures ~20-60 km

Advanced Mesosphere Temperature Mapper & "Wing" cameras

- AMTM: vertical viewing, T'(x,y) along track

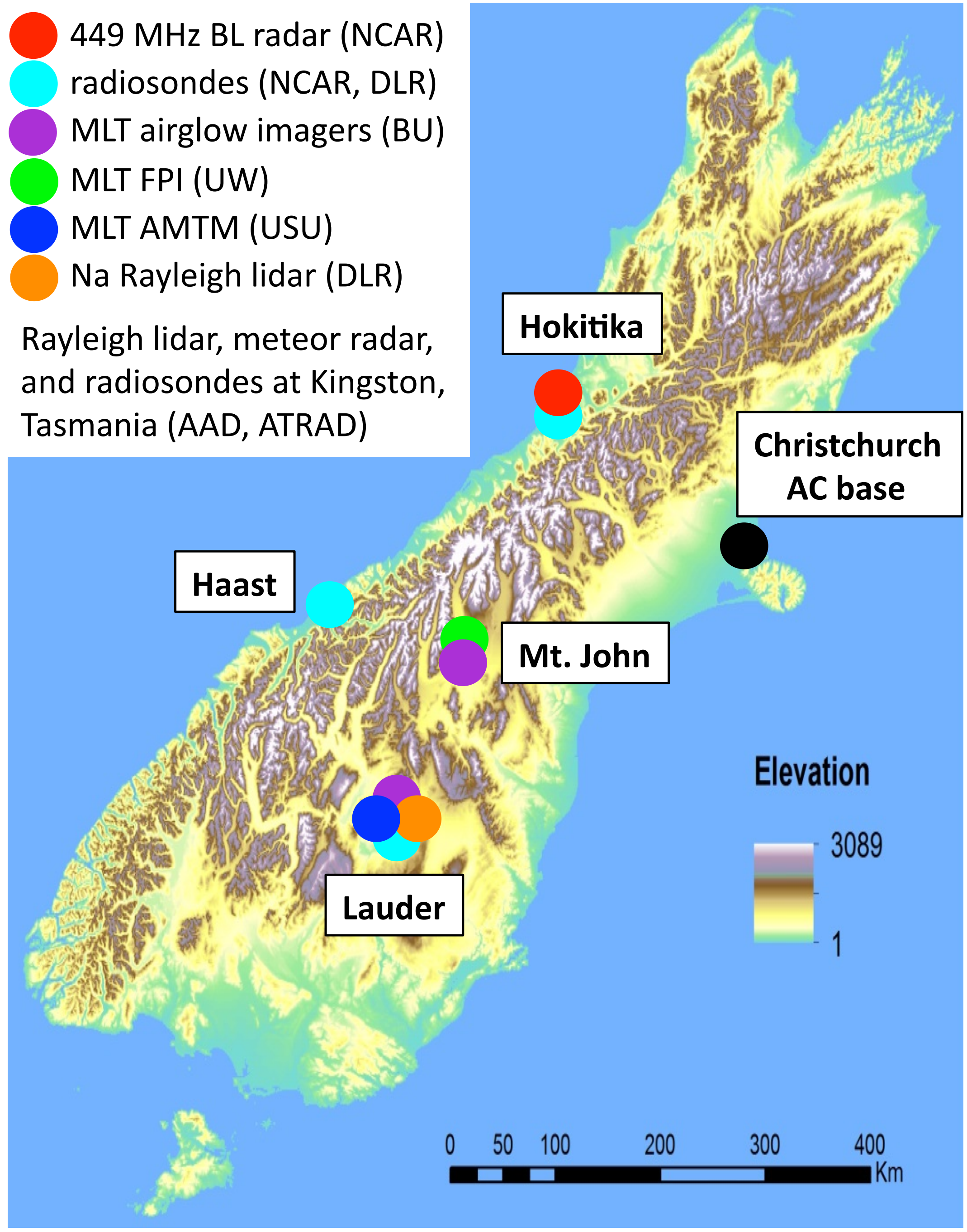
- IR Wing cameras to achieve ~900 km cross-track imaging of GWs at ~85 km



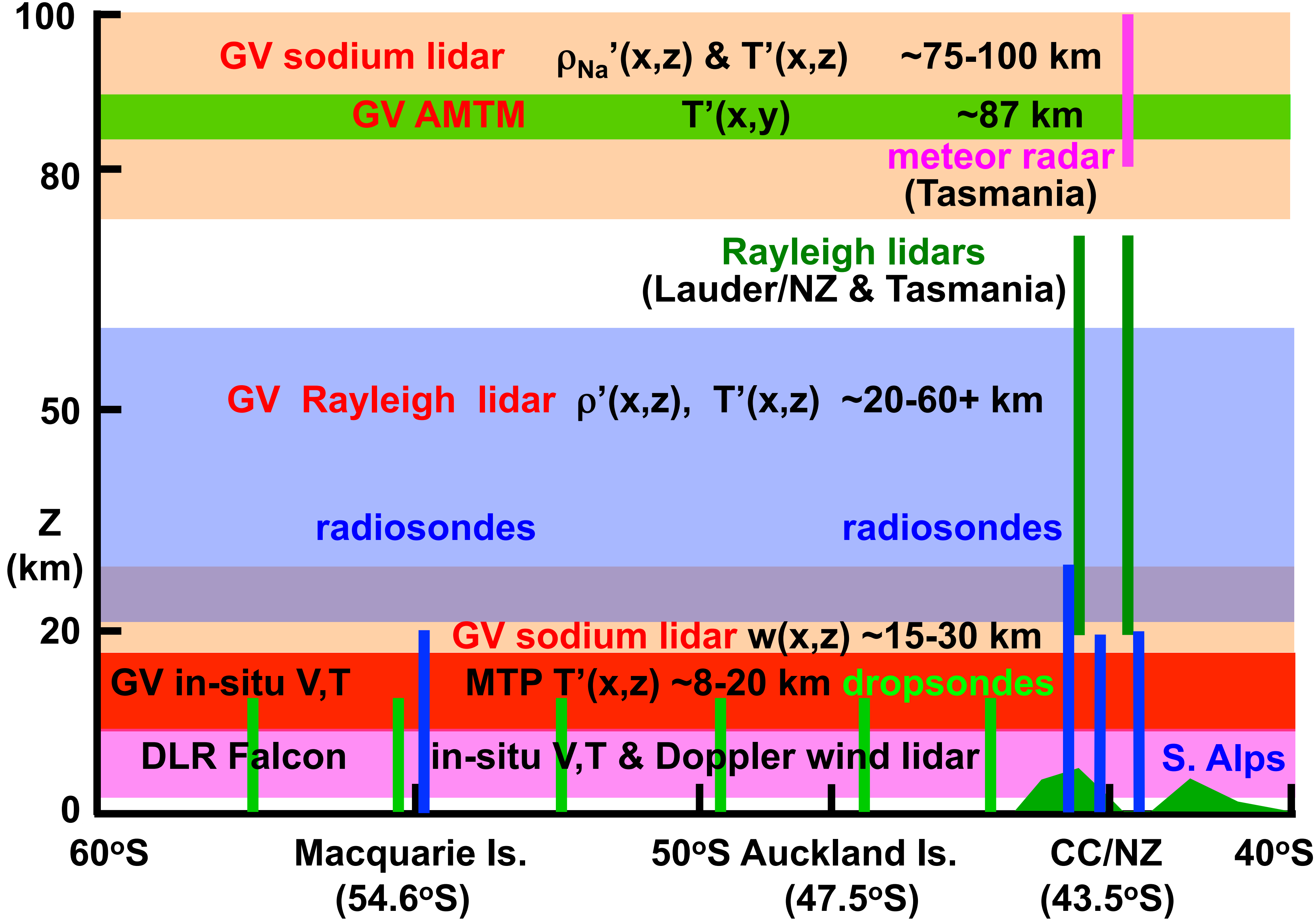
DEEPWAVE also employed extensive GB instrumentation

primary instrumentation on NZ South Island

also new Rayleigh lidar and meteor radar on Tasmania specifically to support DEEPWAVE



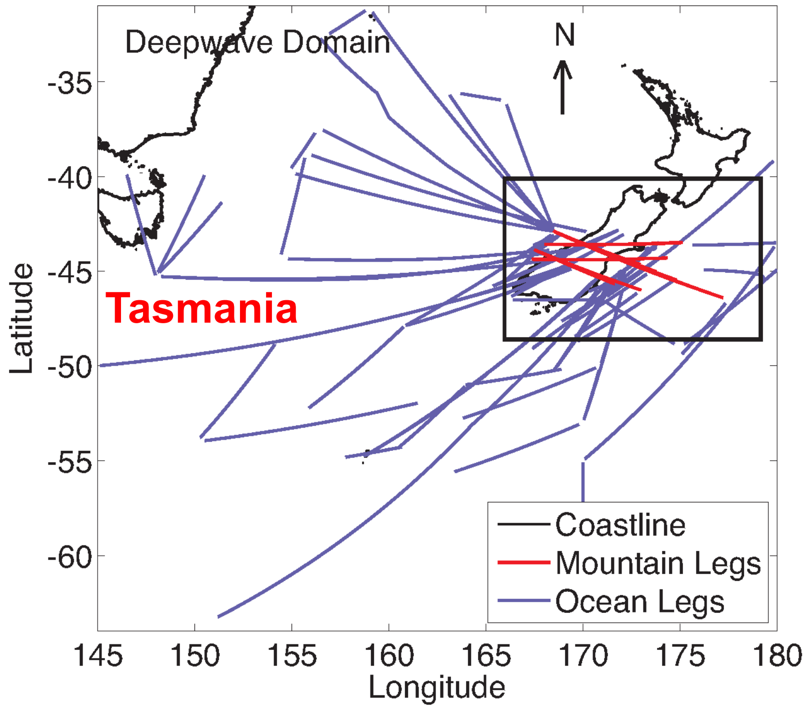
DEEPWAVE measurement capabilities

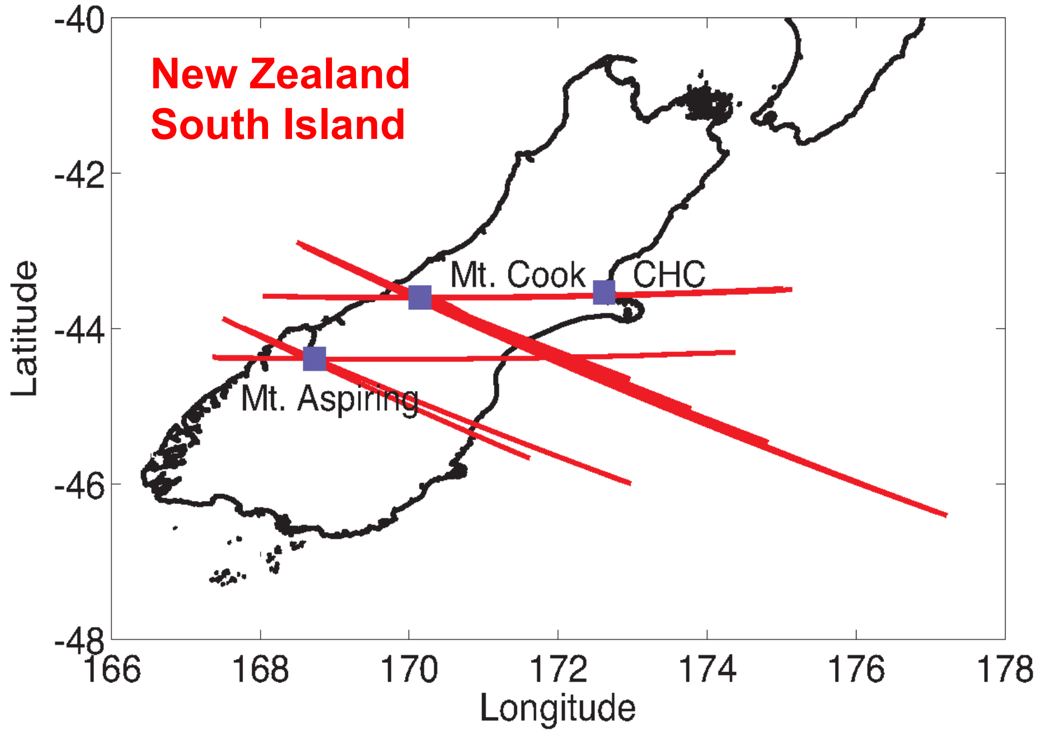


DEEPWAVE Flight Tracks

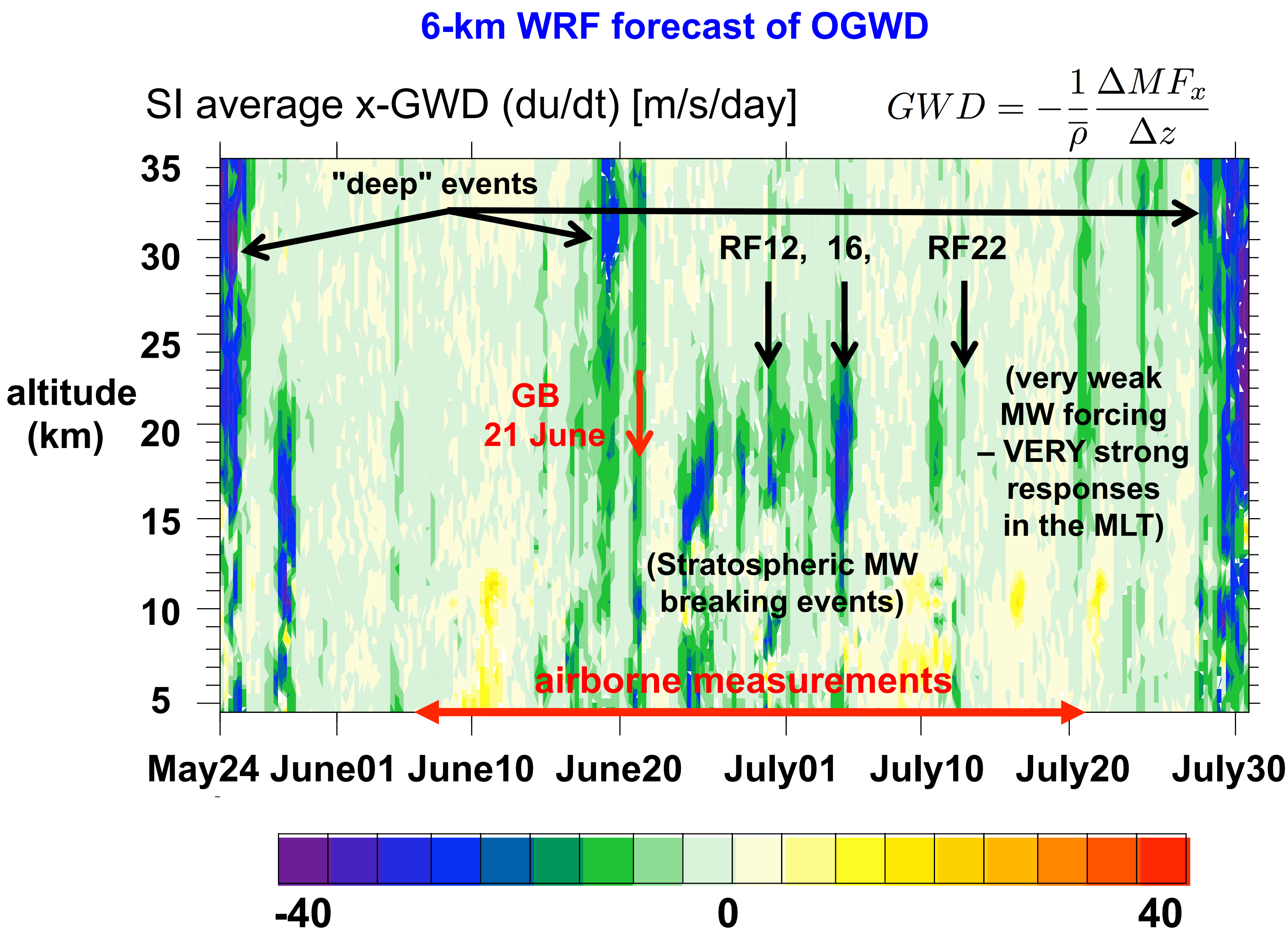
- multiple GV and Falcon flights targeted mountain waves over NZ, Tasmania, and Southern Ocean islands

- other flights targeted jet stream, frontal, and convective sources

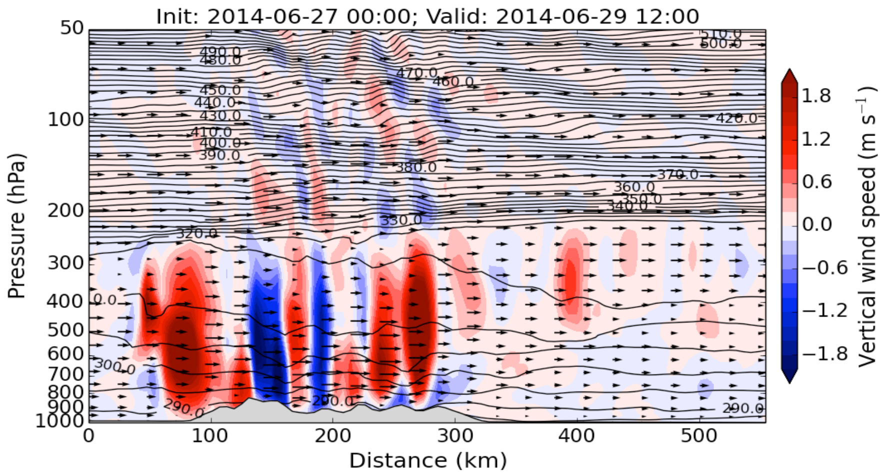




South Island average GWD – 6-km WRF model

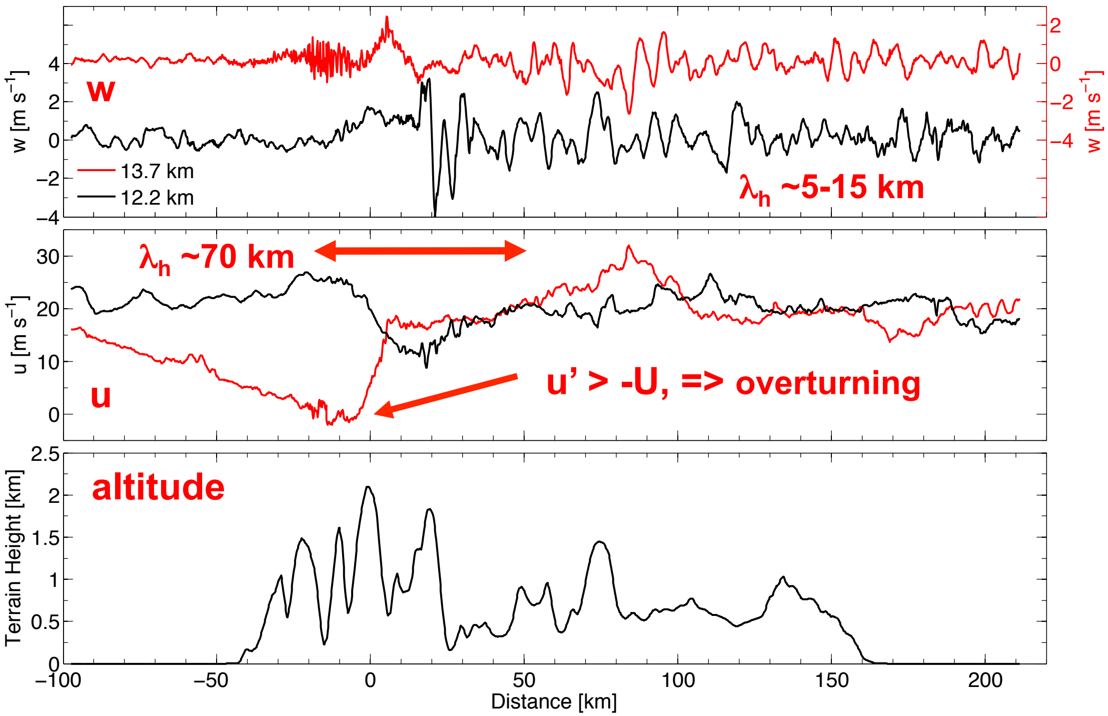


RF12 (29 June) – strong cross-mountain flow - weak stratospheric flow, breaking at GV flight altitudes



WRF 6-km model:

strong tropospheric response, MW breaking in lower stratosphere

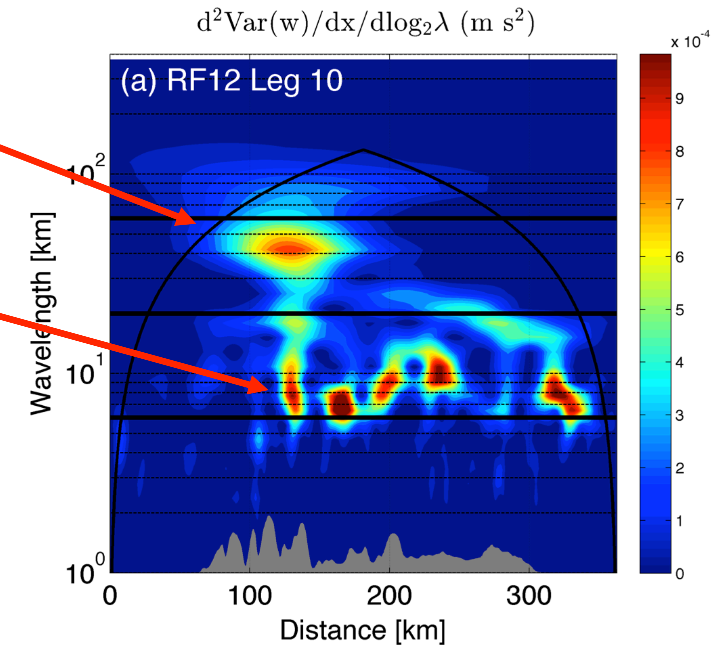


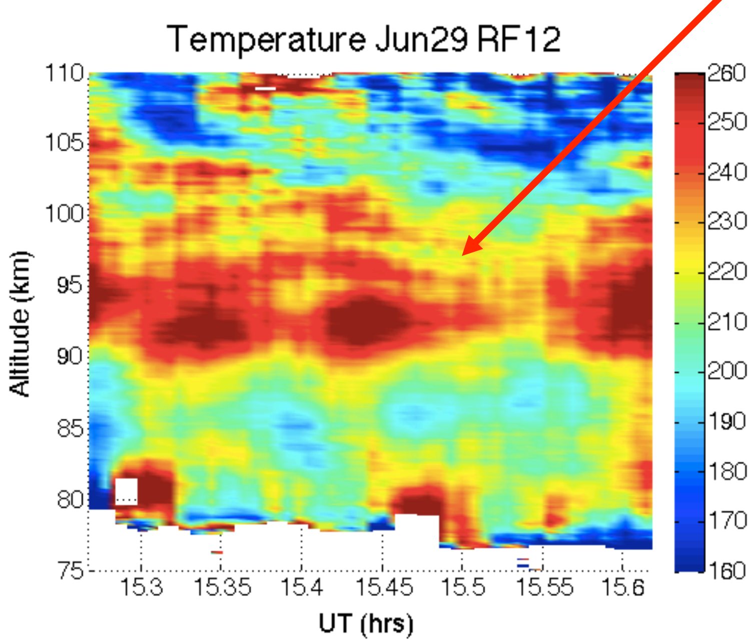
Two flight legs over Mt. Aspiring:

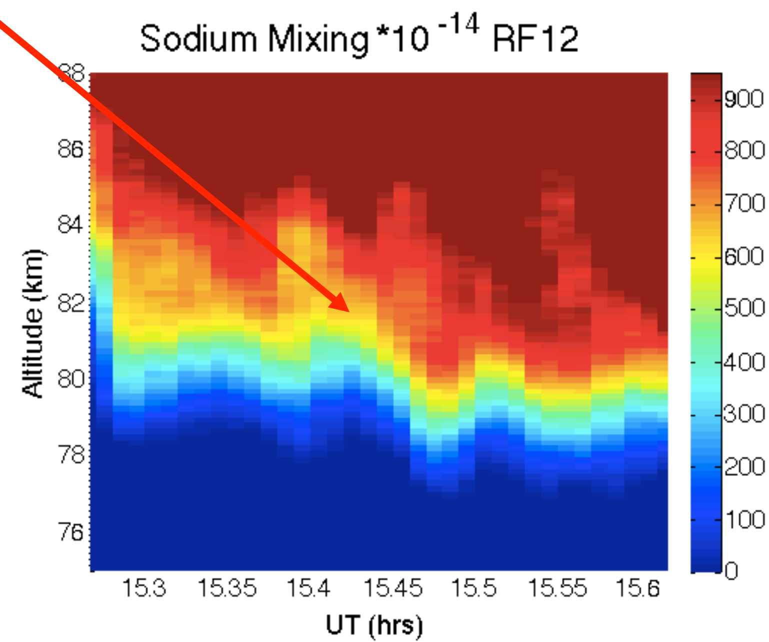
z=12.2 km; z=13.7 km

RF12 – MWs seen at flight level extend into the thermosphere

- apparent propagating MWs at λ_h ~20-70 km over terrain
- trapped lee waves at λ_h ~5-15 km over and leeward of terrain
- breaking in stratosphere reduces MW amplitudes
- further breaking in the mesosphere
- influences extend into the thermosphere







RF16 (4 July) – strong MW forcing, weak stratospheric winds

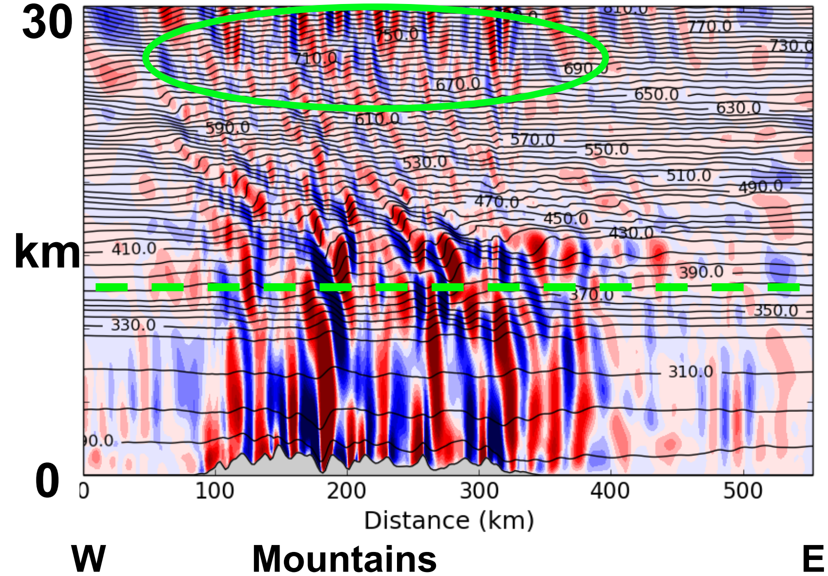
WRF forecast:

- strong MW forcing at scales ~30+ km scales
- MW breaking in weak stratospheric flow
- significant secondary GWs ~25-30 km

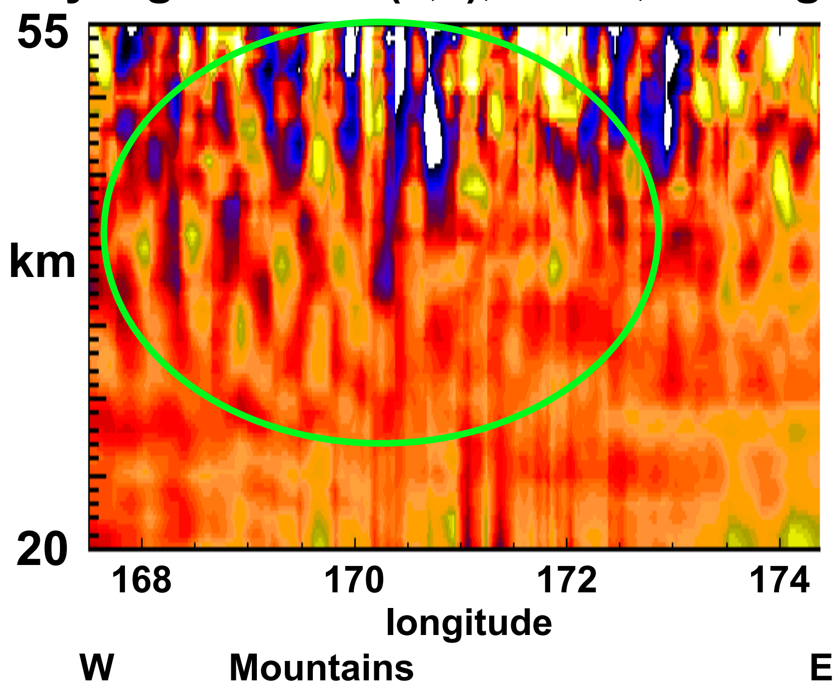
Rayleigh lidar reveals:

- weak GWs at ~20-30 km
- both westward and eastward-propagation over terrain > 25 km
- amplitudes increase rapidly above ~30 km

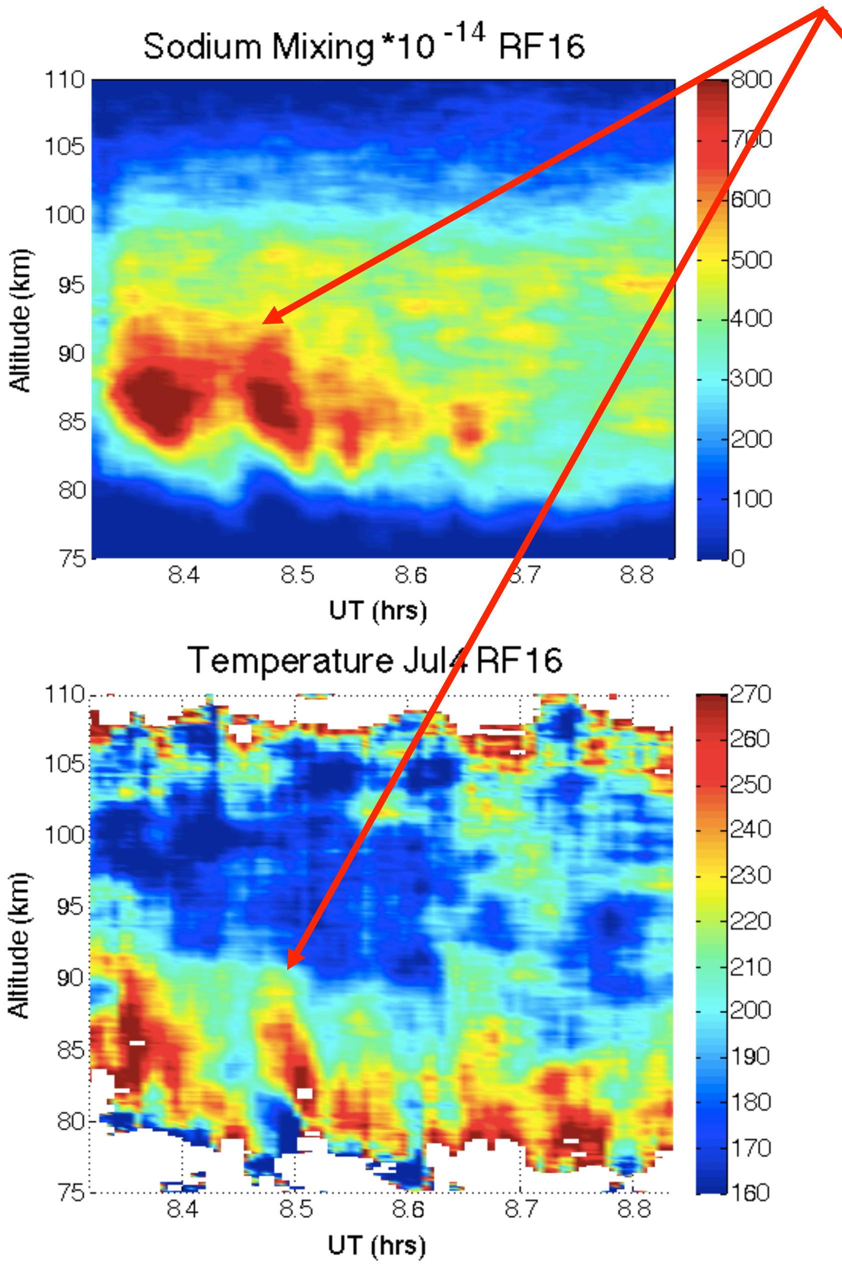
WRF w(x,z) – 2-km resol.

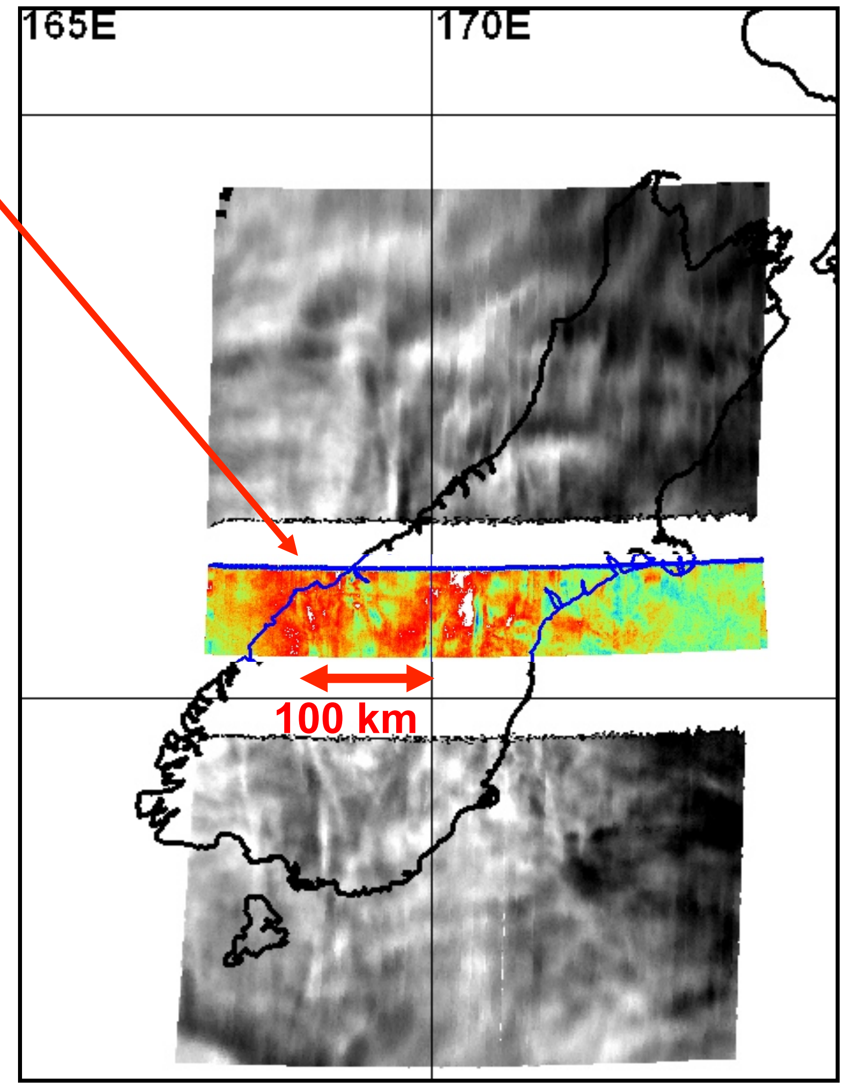


Rayleigh lidar T' (x,z), ±15 K, RF seg. 3



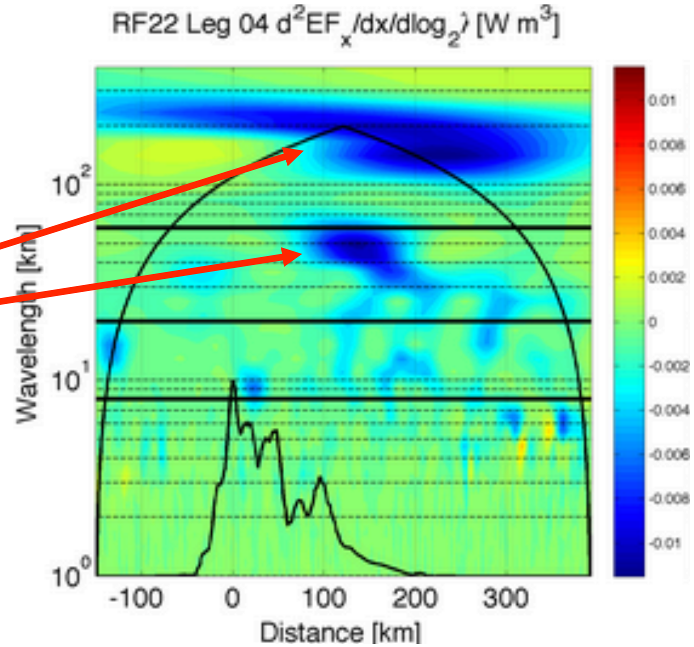
RF16 – strong strat. winds enable penetration to high alts.
- λ_h ~30-100 km MWs with large-amps./MFs in the MLT





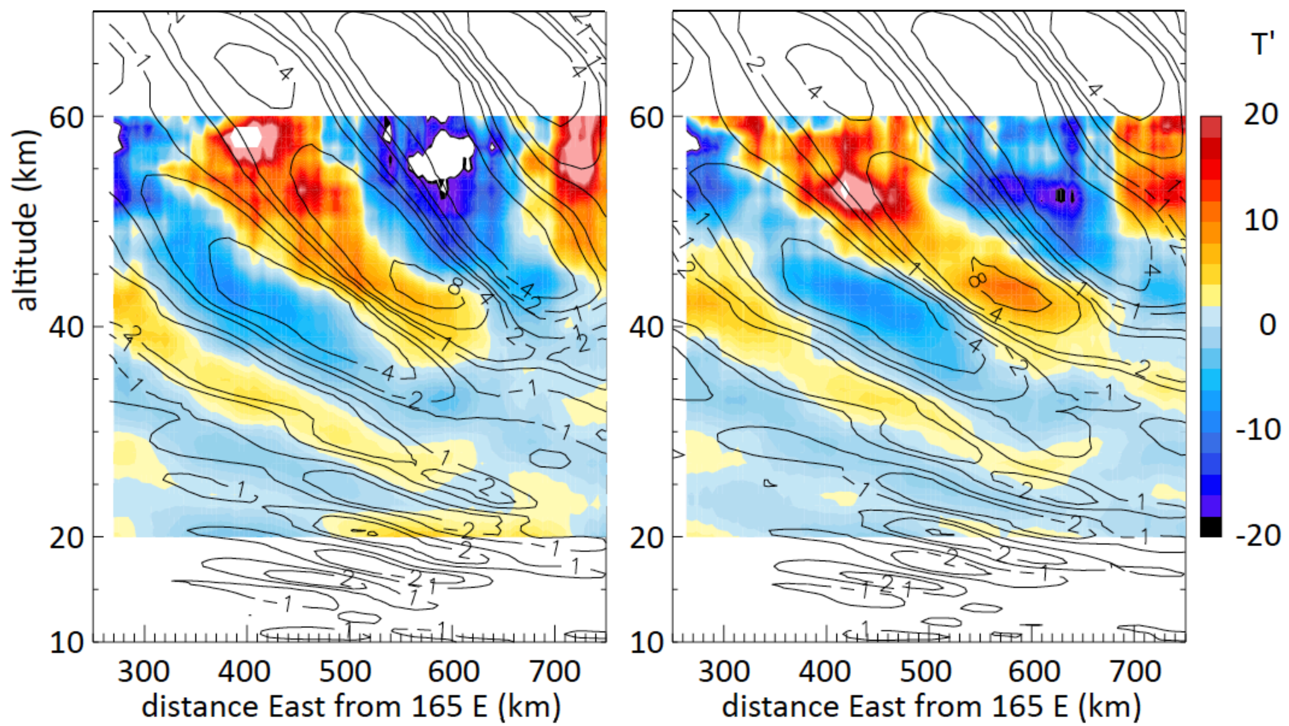
RF22 (13 July) – weak forcing

- predicted very weak MWs in WRF and other models at lower altitudes
- flight-level measurements reveal λ_h~30-60, 120-250 km



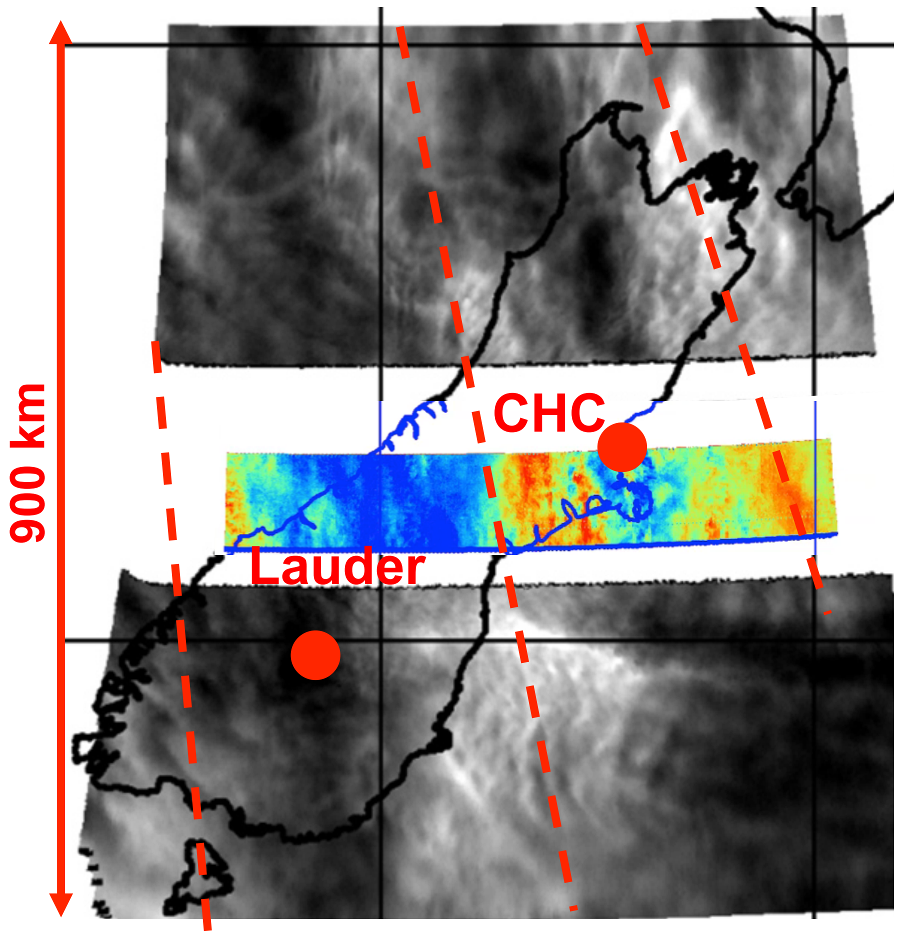
- Rayleigh lidar shows ~240-km MW growing strongly in altitude, λ_z increasing as U(z) increases, addit. GWs >50 km

- ECMWF captures λ_h~240 km MW, under-estimates *T'* by ~2-3 times

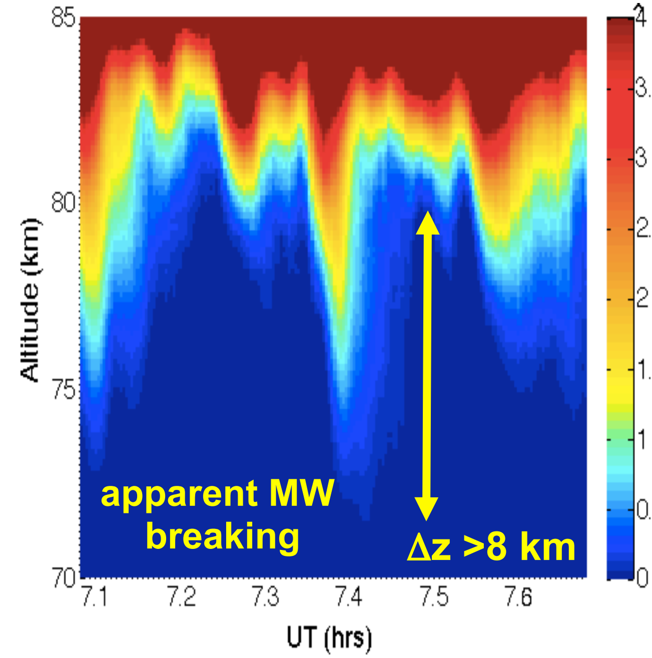


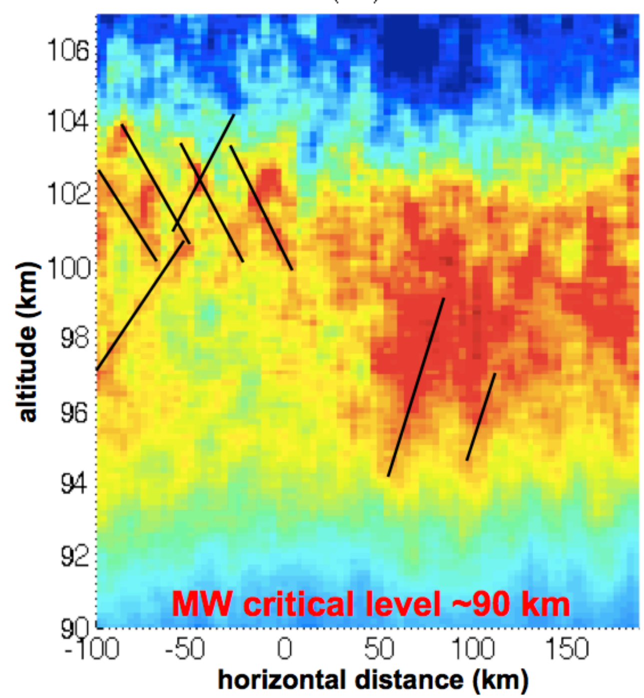
RF22 – MLT responses

- AMTM/IR Cam Keogram show T' ~10-25 K, λ_h ~30-240 km
- ρ_{Na}/ρ show
  - MWs have δz ~1-3 km, => λ_z ~15-20 km
  - secondary GWs above breaking region

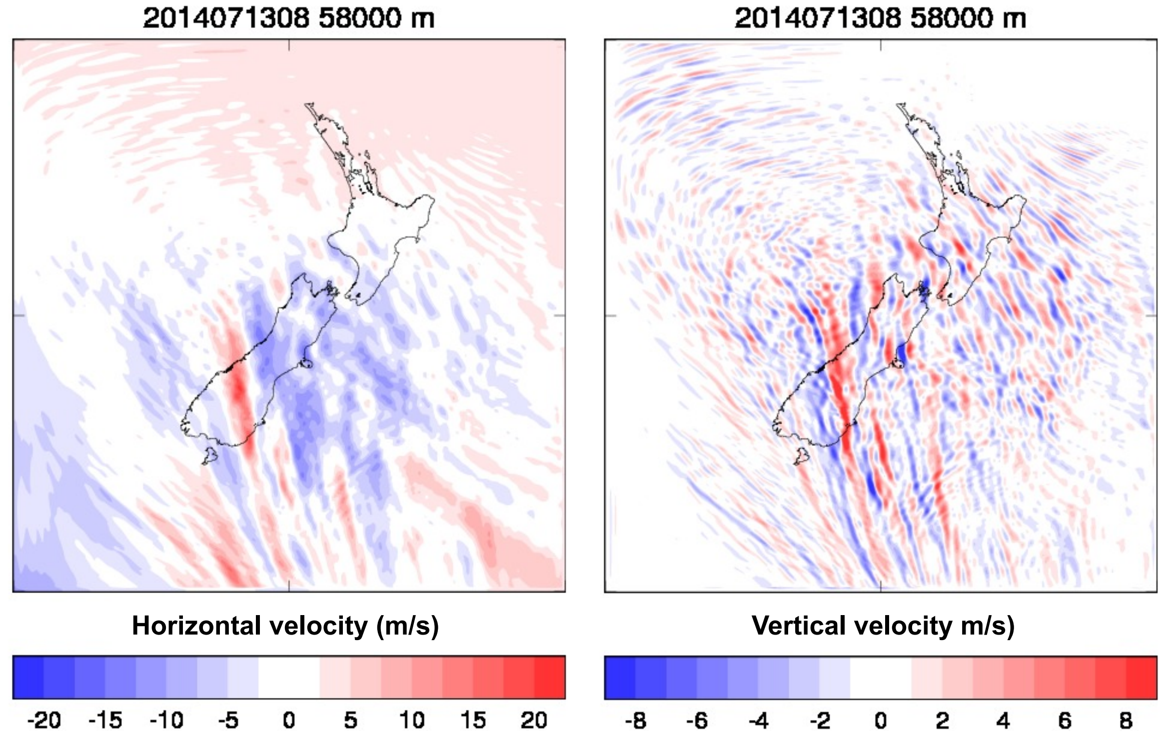


- λ_h ~25-80 km dominant in MLT

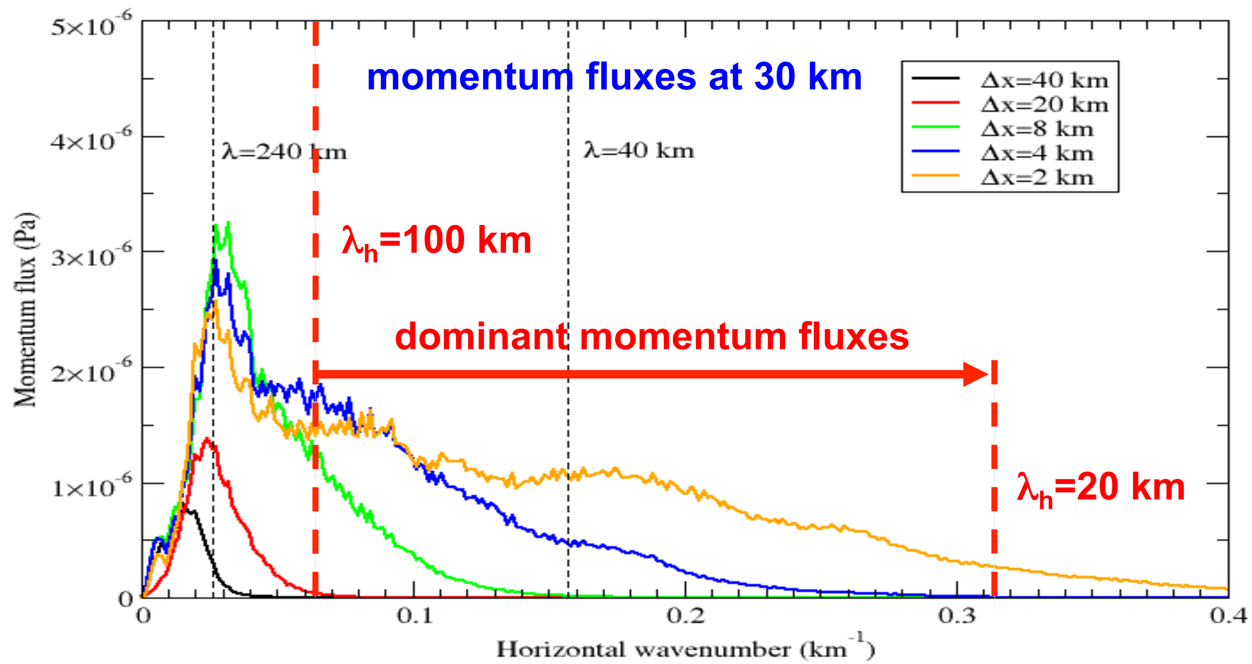




RF22 – UKMO UM 2-km mesoscale simulation to 80 km (S. Vosper)

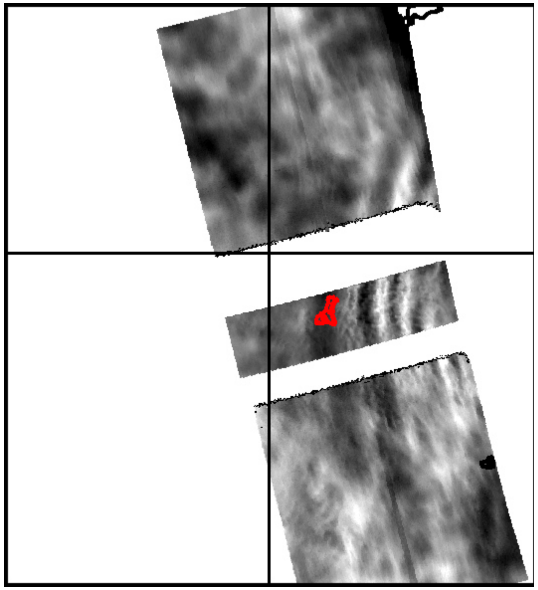


- MWs at 58 km have
  - u' ~25 m/s, w' ~2-10 m/s,
  - T' ~10-25 K,
  - λ_h ~25-240 km,
  - λ_z ~15-30 km



- momentum flux varies as <u'w'> ~u'T' (so peaks at intermediate scales)

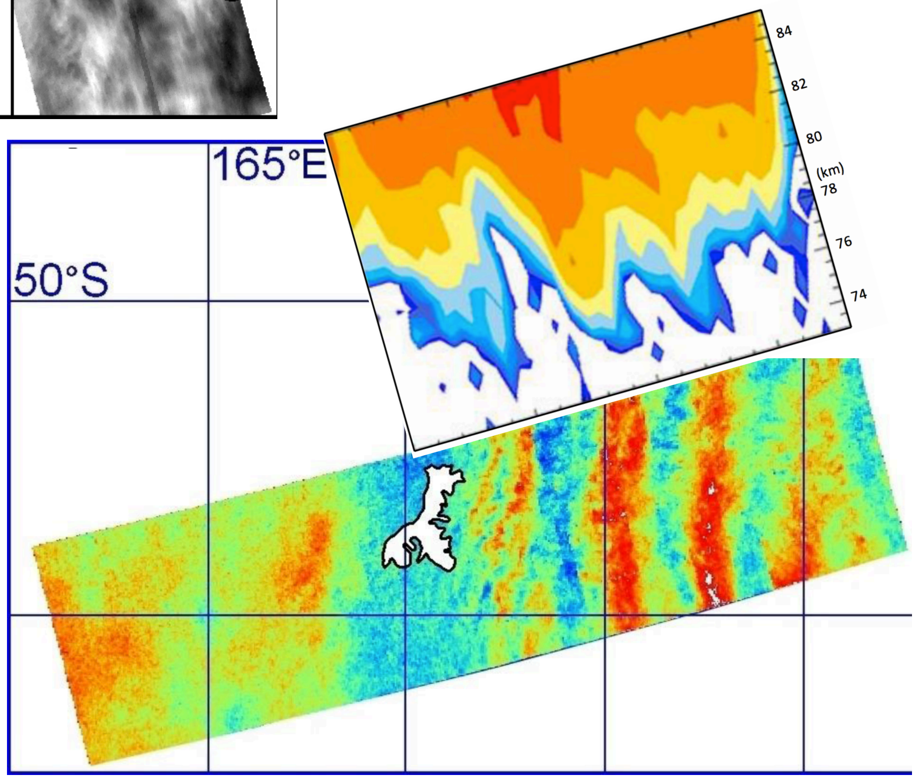
RF23 (14 July) – Auckland Is. MW event
- moderate forcing over a small island



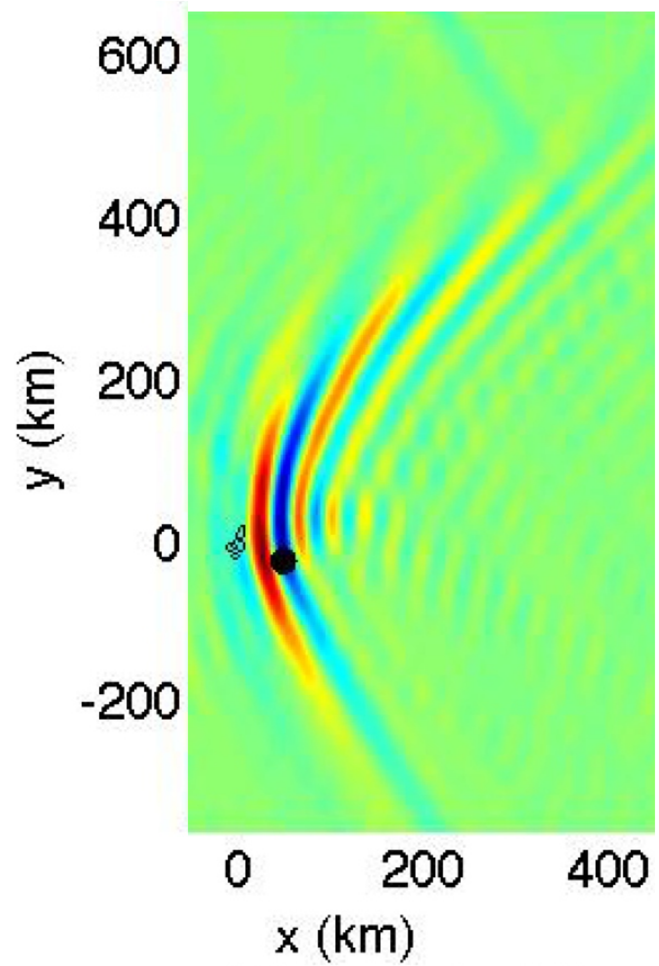
- first observation ~7 UT
- evolved and decayed over ~4 hr

- dz~2-3 km, T'~20-30 K

- peak <u'w'>~300 m^2/s^2

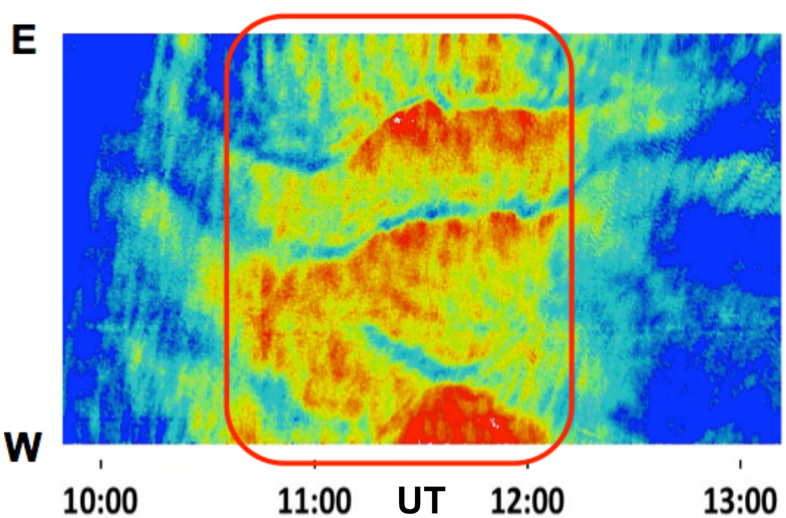


Fourier-ray tracing response at ~85 km (Broutman and Ma)

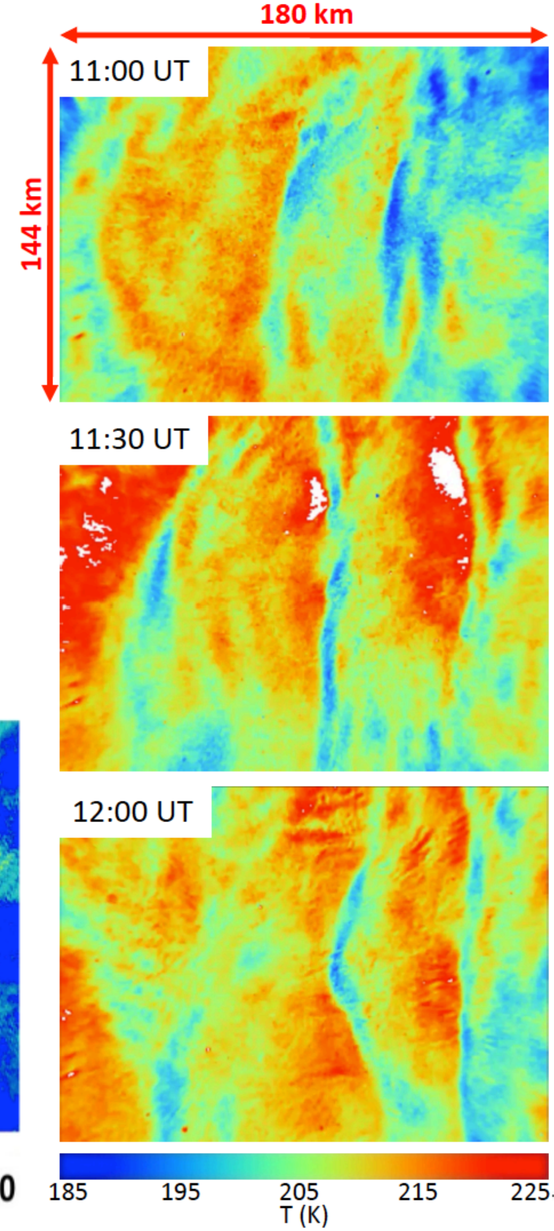


21 June – Large-Amplitude MWs

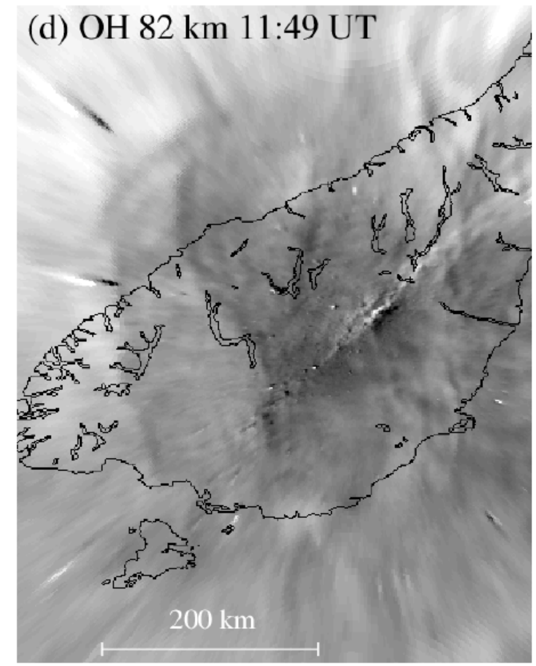
- apparently transient event ~1 hr
- scales vary from ~12 to 80 km
- "sawtooth" T(x) => strong overturning at ~87 km
- dominant MWs at ~85 km have δz >2km, T' ~20K, T ~210K, N ~0.02s^{-1}, λ_h ~65km, λ_z ~20-32 km
  => <u>$\langle u'w' \rangle$ ~400 m^{2}s^{-2} or greater</u>
- MWs seen by AIRS for ~4 days
- MW response is larger than NZ



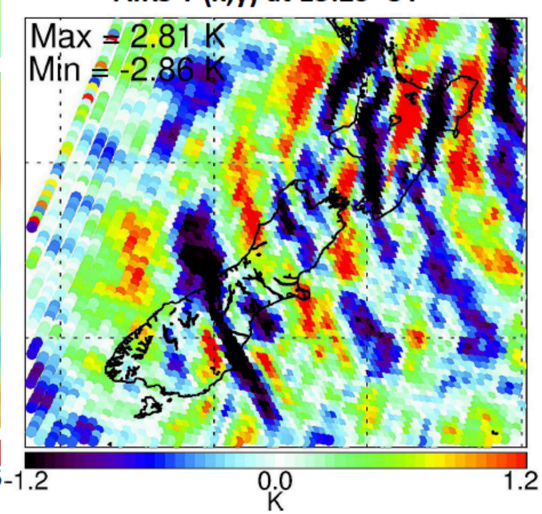
Lauder AMTM T(x,y) at 11-12 UT



Lauder OH imager 11:49 UT



AIRS T'(x,y) at 13:25 UT



Summary

- MWs achieved large amplitudes and fluxes in the stratosphere and MLT:
    - weak forcing enables "linear" propagation, very large amplitudes in the MLT
    - large MW amplitudes and/or weak winds yield breaking in the stratosphere, but continue propagating with smaller amplitudes
    - MW breaking (stratosphere or MLT) yields strong 2ndary GW generation
    - the largest momentum fluxes accompany smaller horizontal scales
        - λ_h<100 km dominate MLT fluxes during DEEPWAVE
        - local fluxes are often ~10-100 times mean values
            => stratospheric "hotspots" also extend much higher

- GWs from jet streams & fronts have larger λ_h, also penetrate to high altitudes

- larger-scale GWs modulate the propagation of smaller-scale GWs

- high-resolution global and regional models often do a good job of predicting the gross features of the observed responses, under-estimate amplitudes

- our field team of >100 researchers and support staff did a great job!

DEEPWAVE papers to date

Bossert, K., et al. (2015), Momentum flux estimates accompanying multi-scale gravity waves over Mount Cook, New Zealand, on 13 July 2014 during the DEEPWAVE campaign, J. Geophys. Res. Atmos., 120, 9323–9337, doi:10.1002/2015JD023197.

Eckermann et al. (2016), Dynamics of orographic gravity waves observed in the mesosphere over the Auckland Islands during the Deep Propagating Gravity Wave Experiment (DEEPWAVE), J. Atmos. Sci., in press.

Fritts, D. C., et al. (2016), The Deep Propagating Gravity Wave Experiment (DEEPWAVE): An Airborne and Ground-Based Exploration of Gravity Wave Propagation and Effects from their Sources throughout the Lower and Middle Atmosphere, Bull. Amer. Meteorol. Soc., 97(3), ISSN:0003-0007, 405-423, DOI:10.1175/BAMS-D-14-00269.1.

Kaifler, B., N. Kaifler, B. Ehard, A. Dornbrack, M. Rapp, and D. C. Fritts (2015), Influences of source conditions on mountain wave penetration into the stratosphere and mesosphere, Geophys. Res. Lett., 42, 9488–9494, doi:10.1002/2015GL066465.

Kruse, R. B., and Smith (2015), Gravity wave diagnostics and characteristics in mesoscale fields, J. Atmos. Sci., DOI:http://dx.doi.org/10.1175/JAS-D-15-0079.1.

Pautet, P.-D., M. J. Taylor, D. C. Fritts, K. Bossert, B. P. Williams, D. Broutman, J. Ma, S. D. Eckermann, and J. D. Doyle (2016), Large-amplitude mesospheric response to an orographic wave generated over the Southern Ocean Auckland Islands (50.7°S) during the DEEPWAVE project, J. Geophys. Res. Atmos., 121, doi:10.1002/2015JD024336.

Smith, R. B., et al. (2016), Stratospheric fluxes and scales during DEEPWAVE, J. Atmos. Sci., in press.

- others in progress …