Characteristics and Physics of Stratospheric Mountain Wave Attenuation over New Zealand

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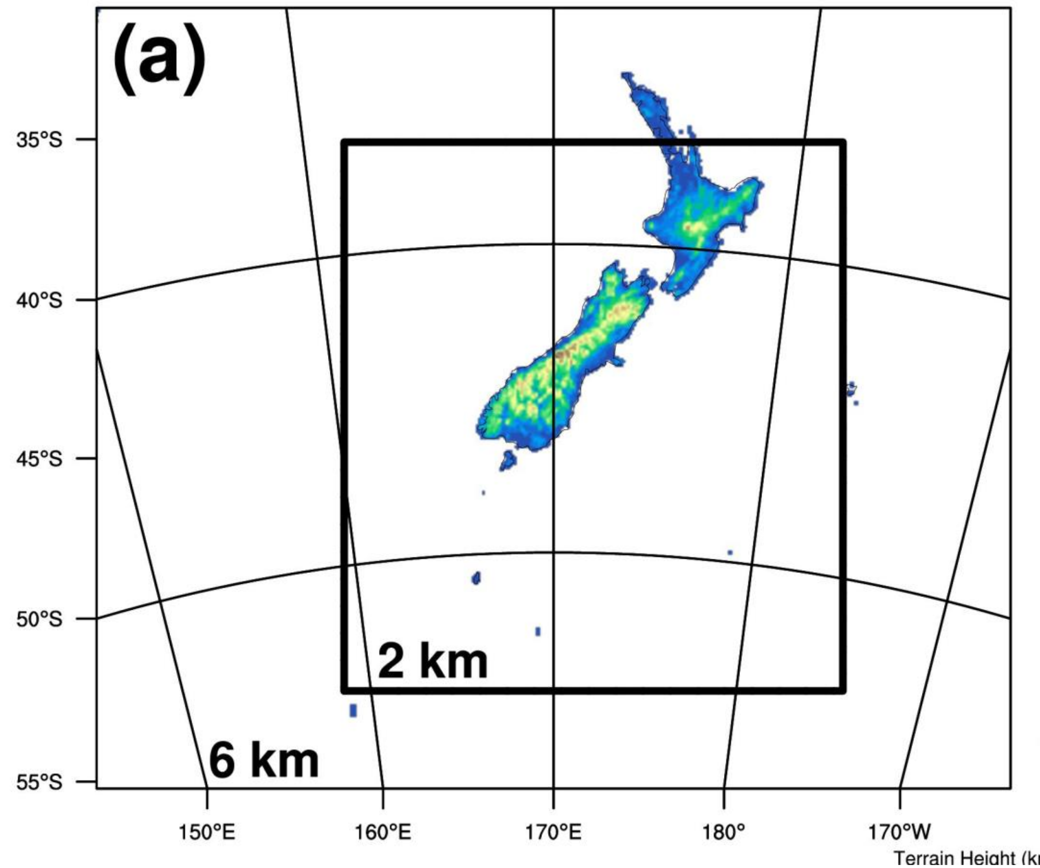
WRF Simulations

Two types of simulations

1. Long Run
   - 6-km resolution
   - 24 May – 1 Aug
   - Initialized once

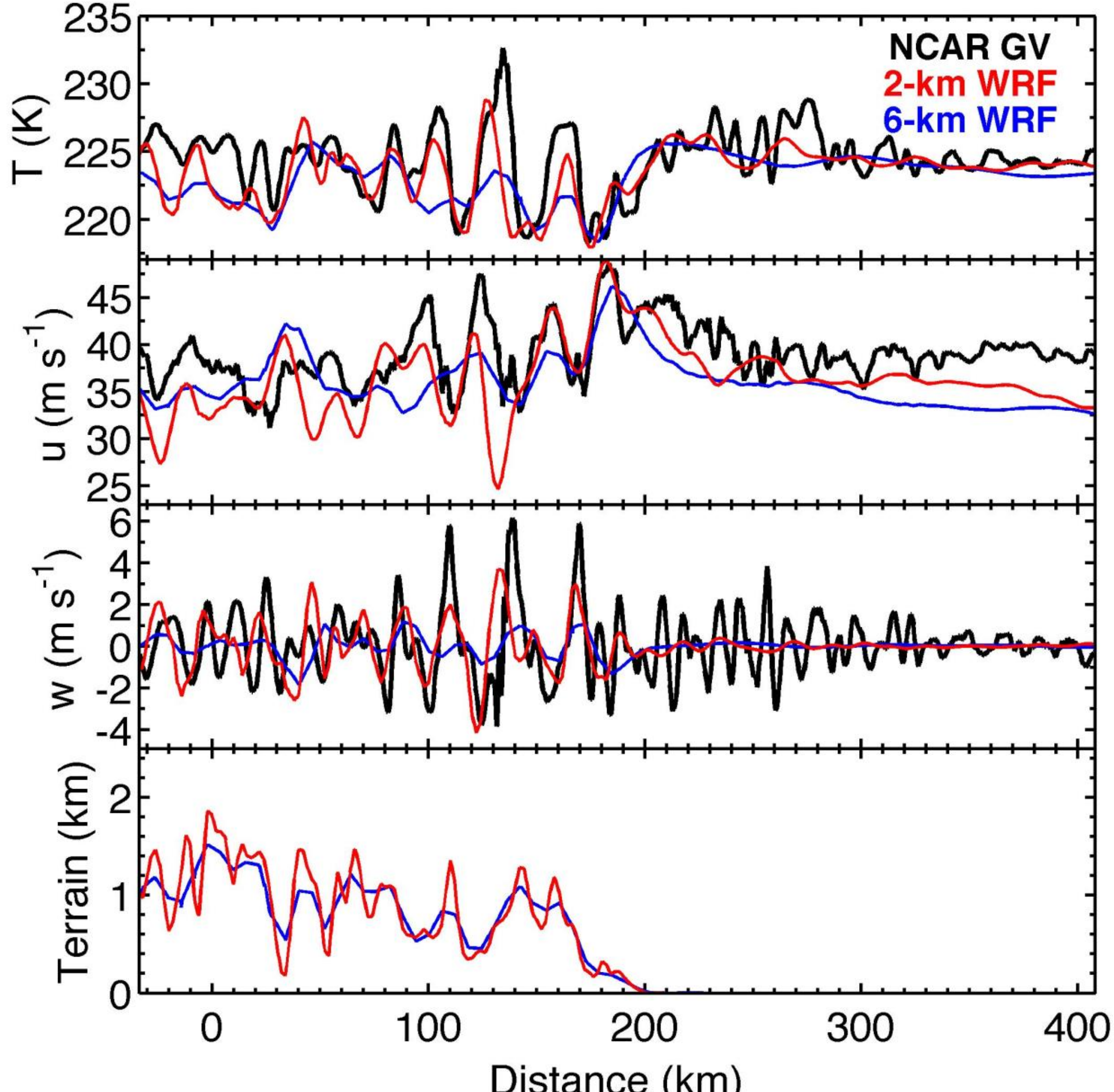
2. Event Runs
   - Nested to 2-km res
   - Initialized for each event of interest
   - Five runs completed
   - RFs included: RF04, RF08, RF09, RF12, RF13, RF14, RF16 FF01, FF02, FF04, FF05



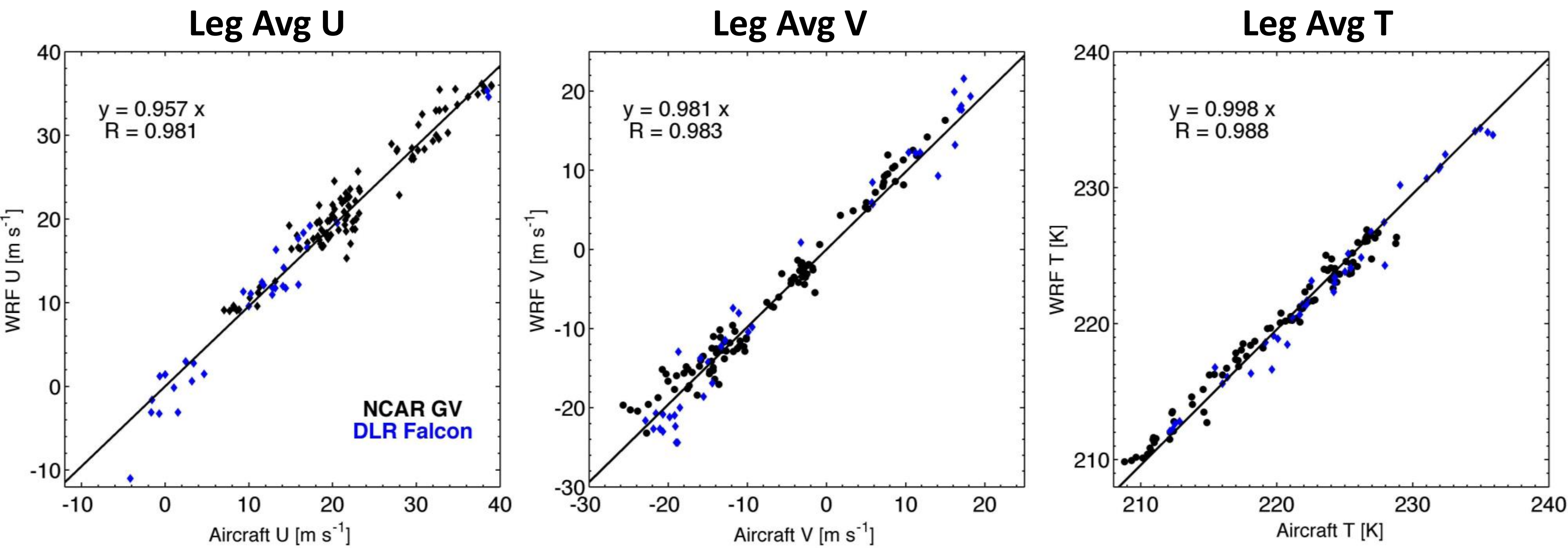
Flights Through Simulated and Actual Atmospheres

Strongest EF_z and MF_x observed on this leg

RF16 Leg 1

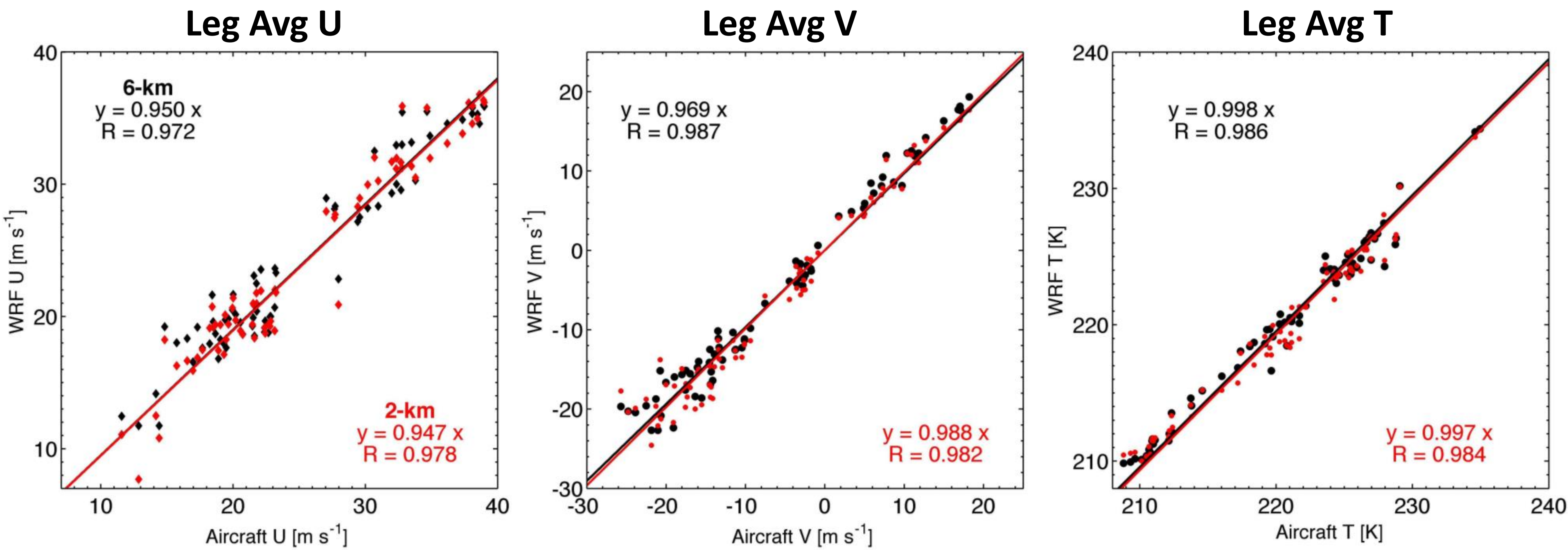


Long Run Aircraft Validation



- Compared against 135 NGV (black) and DLR Falcon (blue) cross-mountain legs

Long Run, Event Run Aircraft Validation

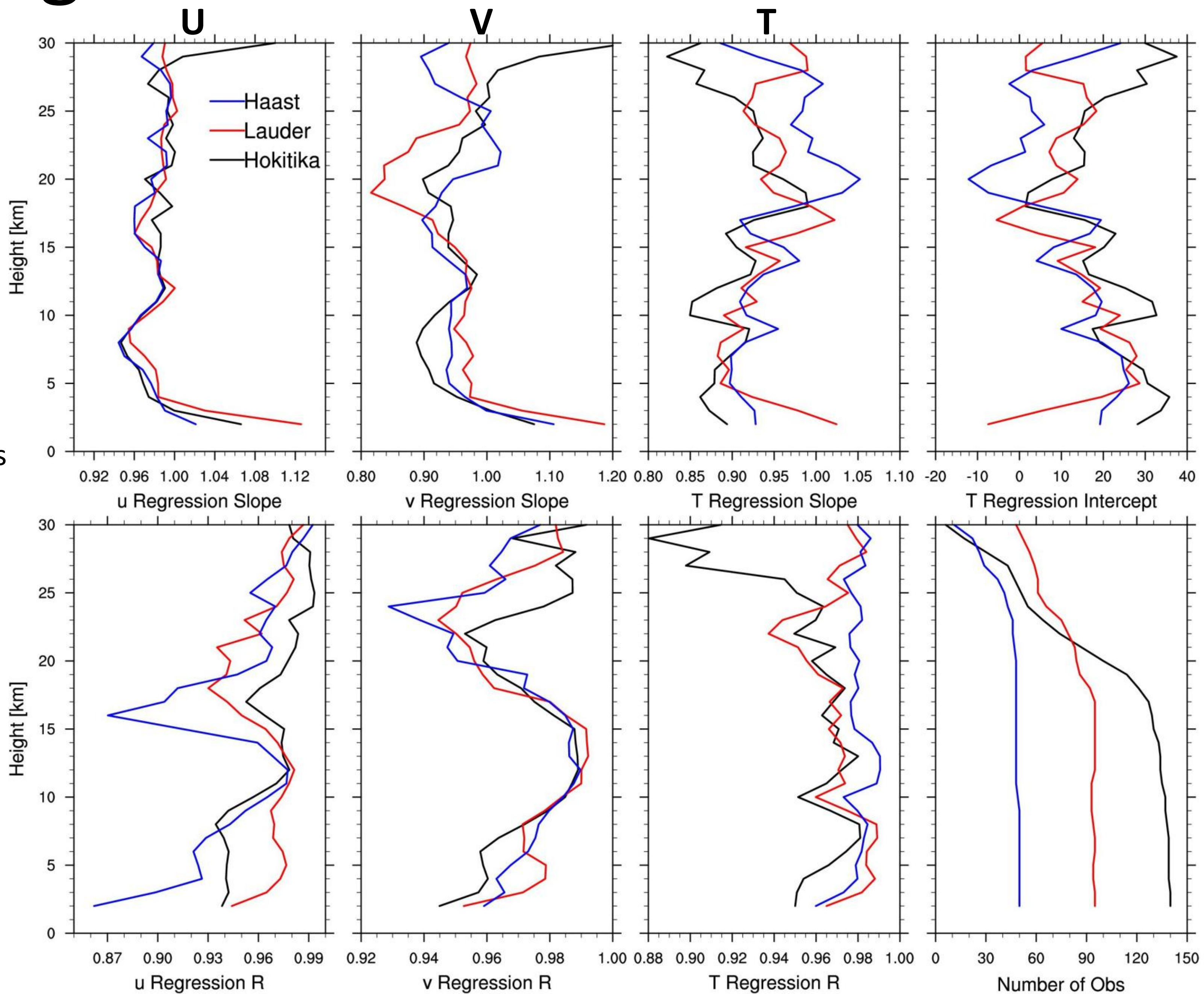


- Compared against the 74 NGV and DLRF legs flown within the Event Runs
- Two main differences: higher resolution and more recent initialization in Event Runs
- These differences apparently do not improve or degrade WRF performance in terms of leg averaged quantities

Long Run Radiosonde Validation

WRF vs **6-km** Long Run

4-km Vertical Moving Avg Applied to Simulated and Observed Sondes



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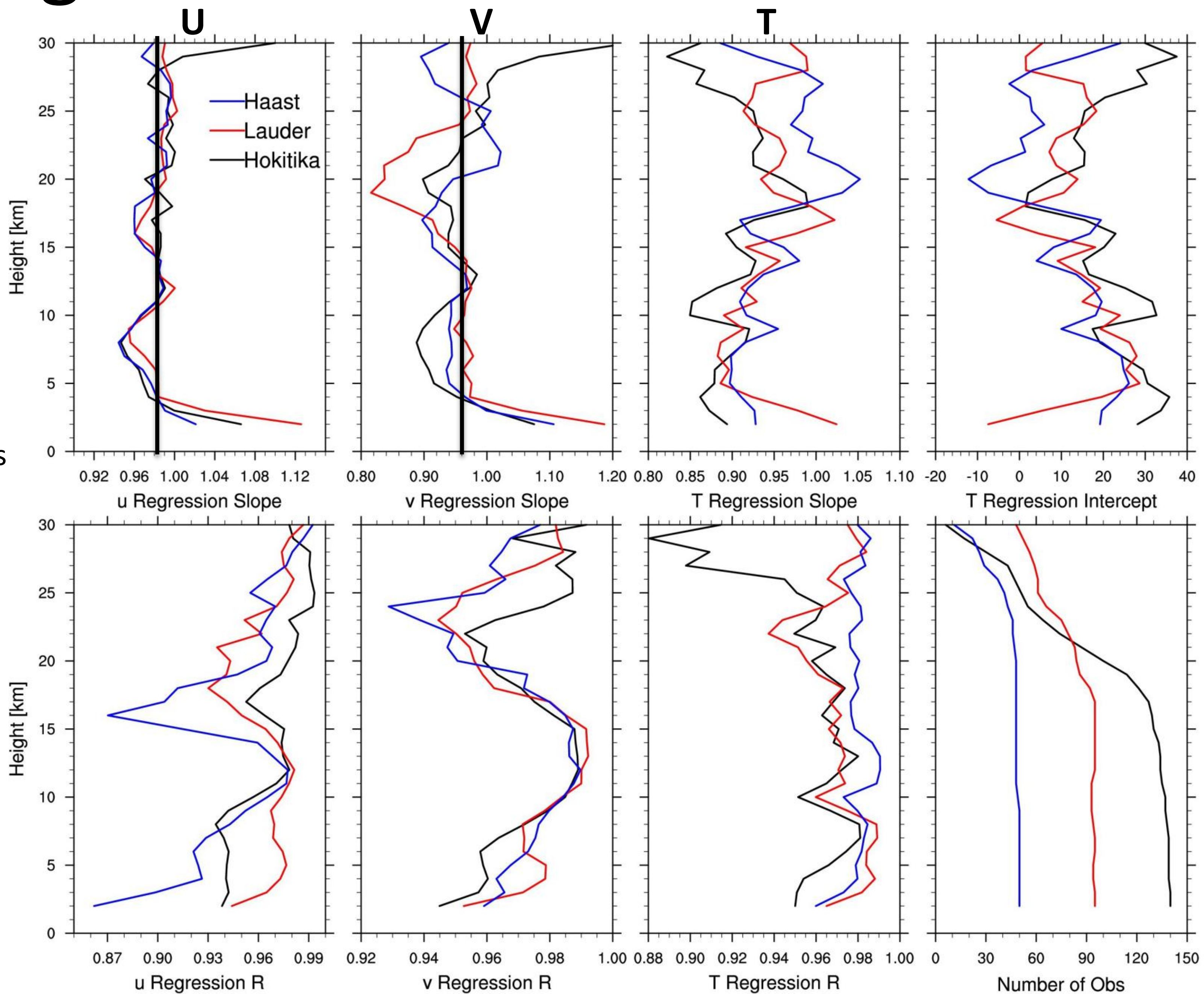

Long Run Radiosonde Validation

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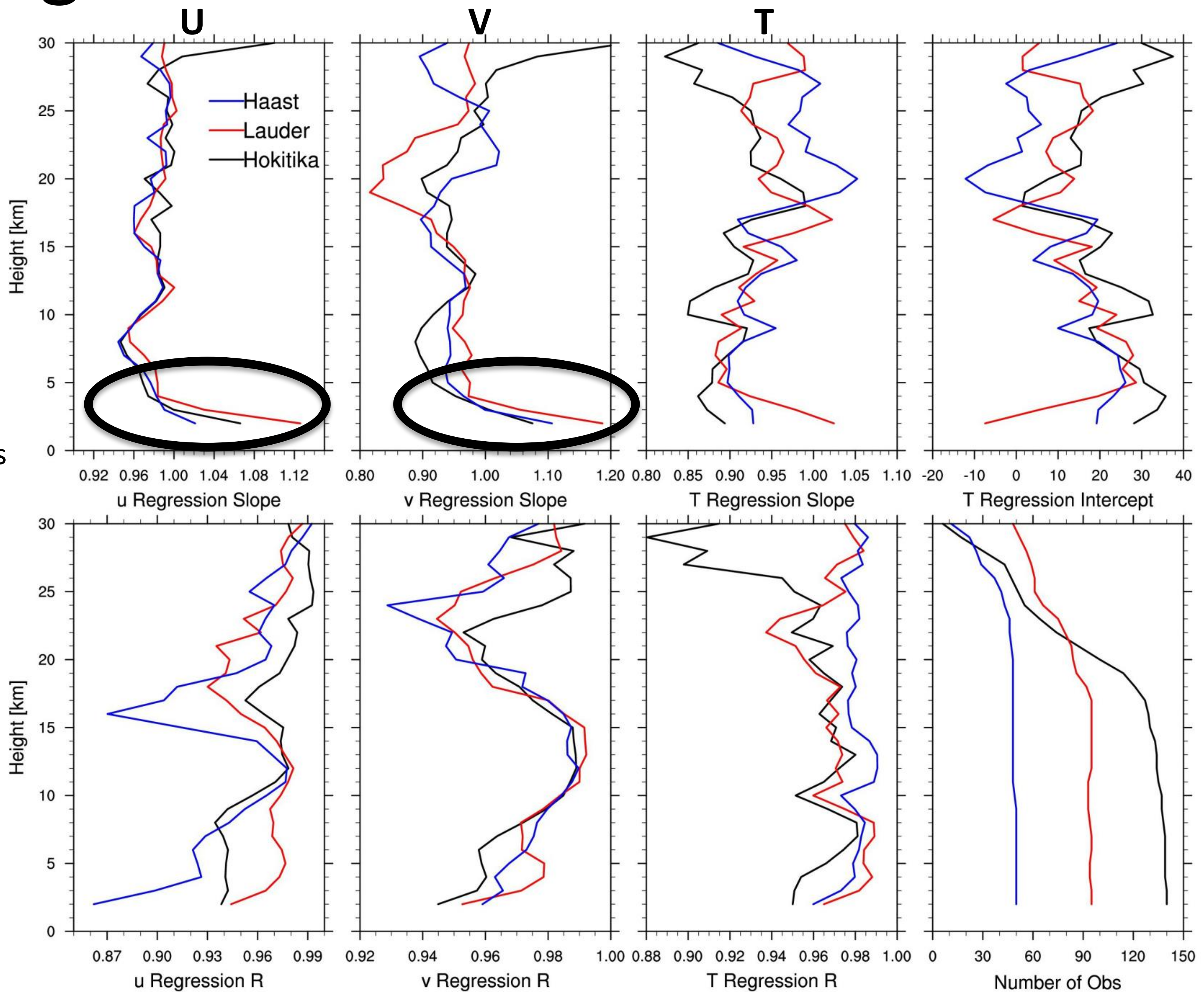
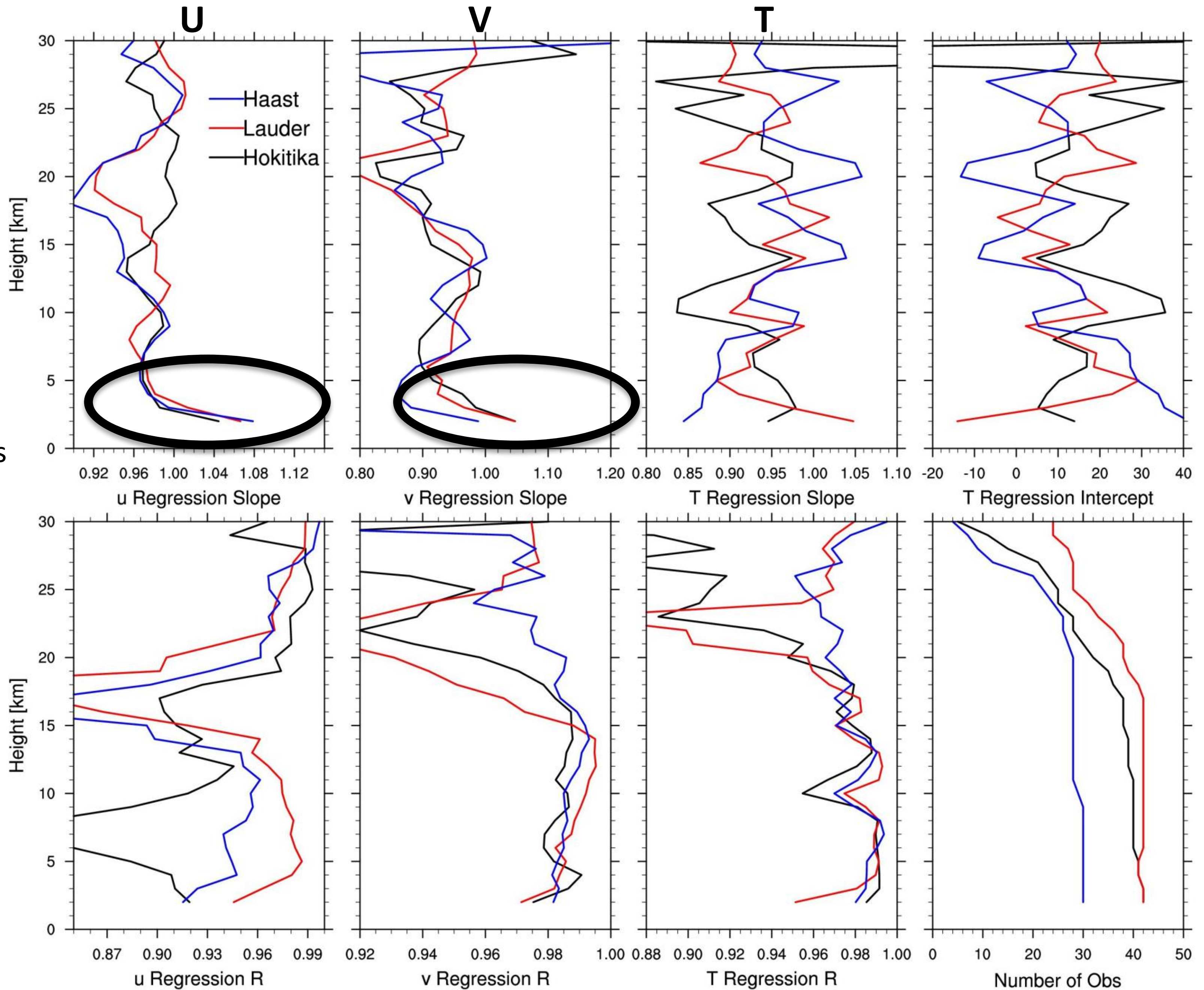
4-km Vertical Moving Avg Applied to Simulated and Observed Sondes



Event Run Radiosonde Validation

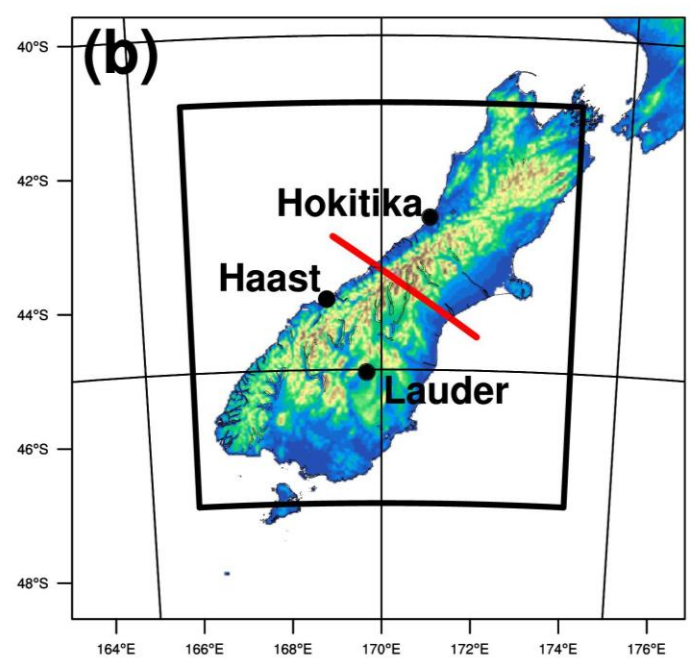
WRF vs **2-km** Long Run

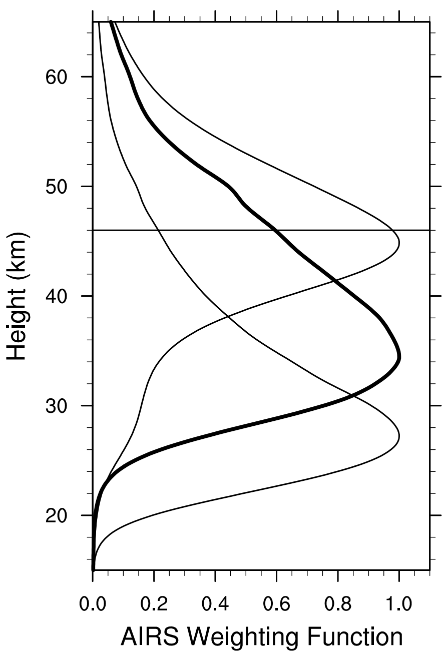
4-km Vertical Moving Avg Applied to Simulated and Observed Sondes

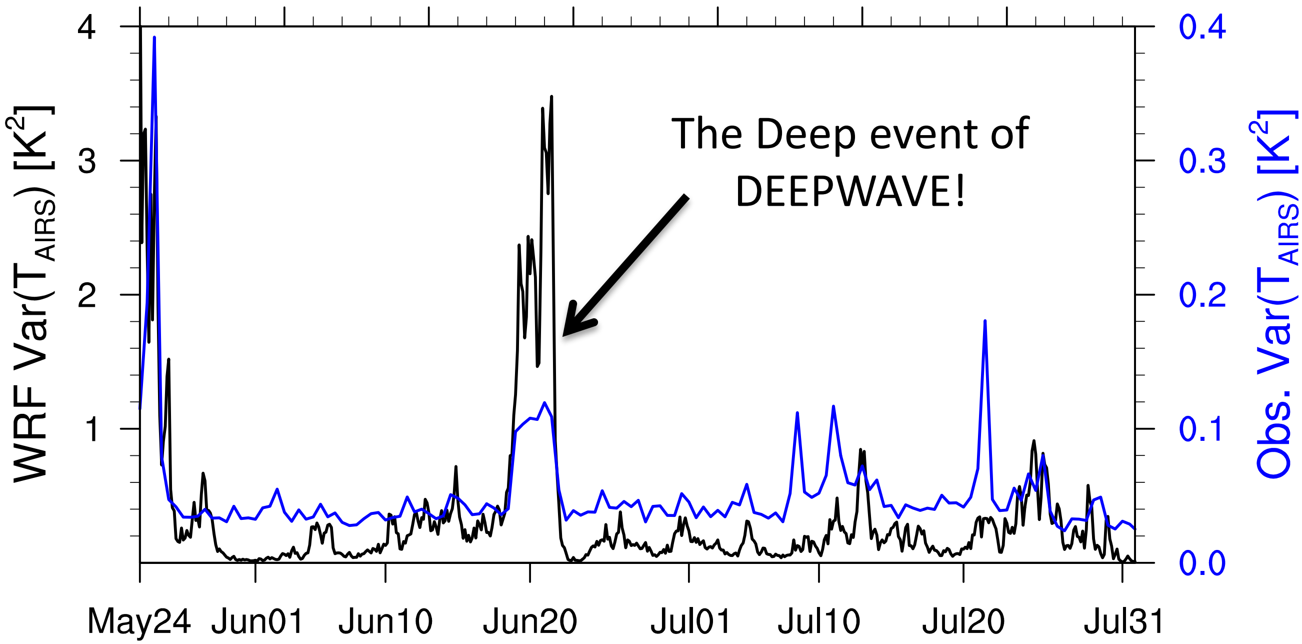


AIRS Validation (Courtesy of Steve Eckermann)

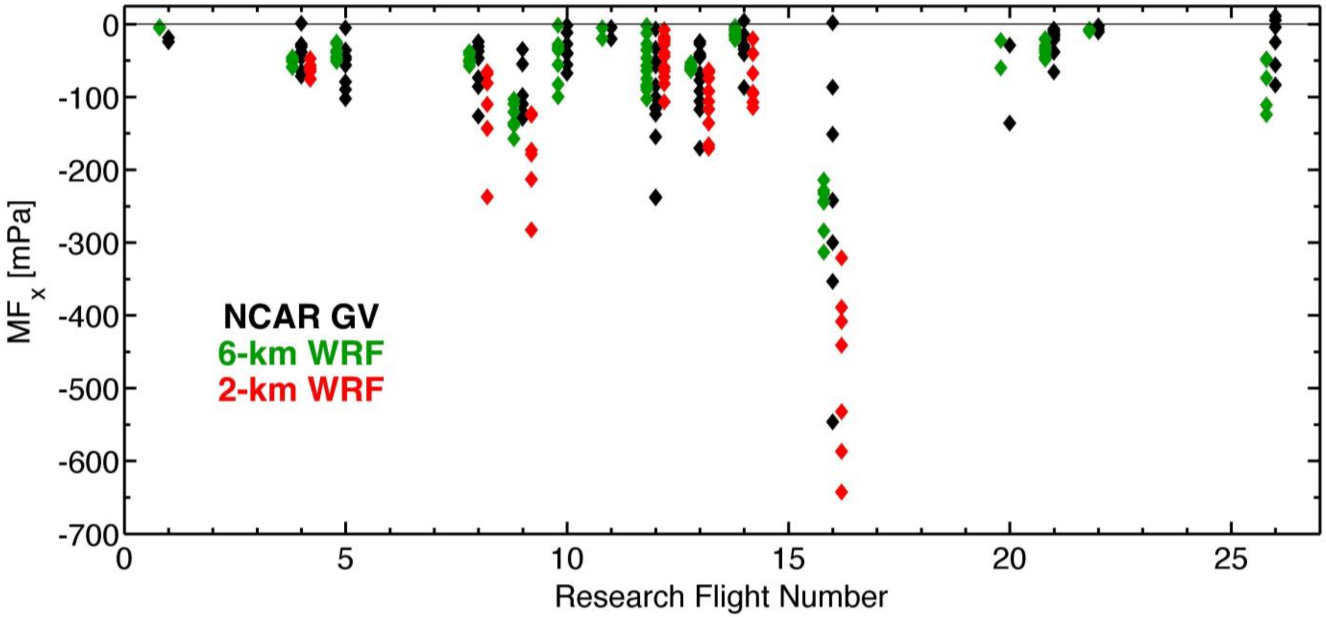
- Applied AIRS weighting functions to 3-D WRF fields to produce 2-D simulated AIRS fields
- Computed temperature variance over the box at right
- Qualitative agreement at 7 hPa, but WRF variances ~10x higher

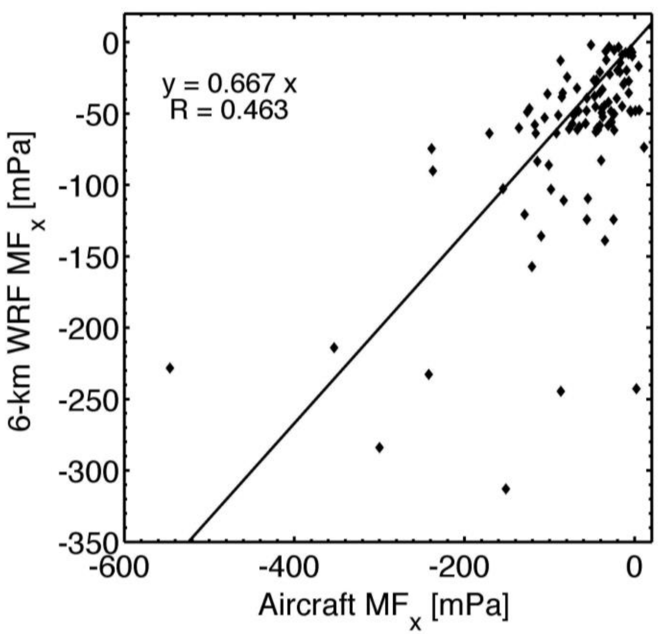


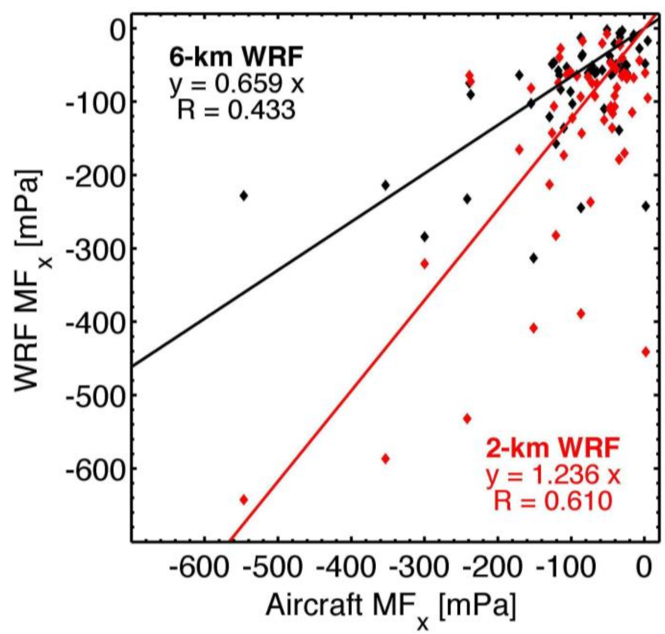




Momentum Flux Validation







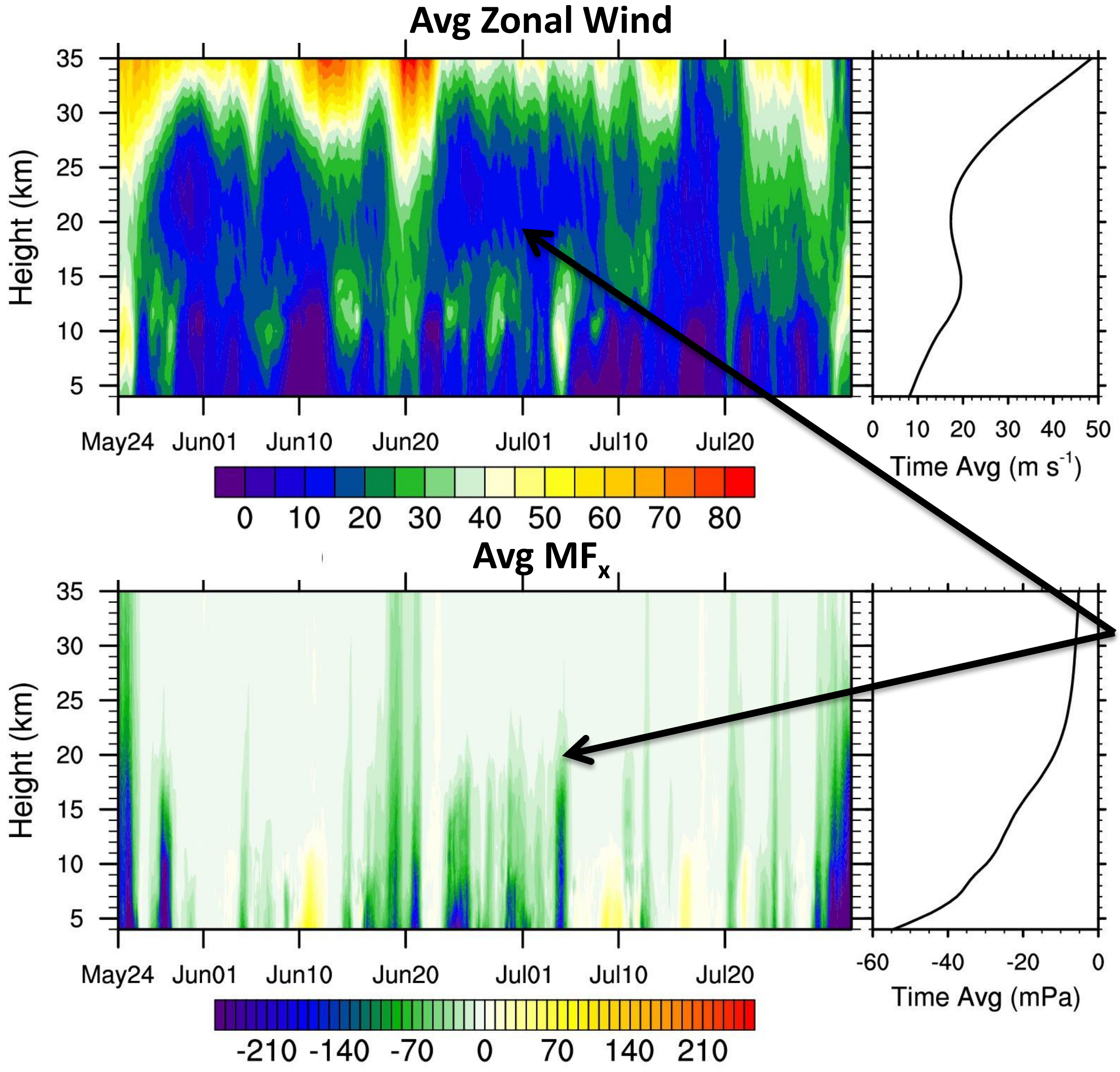
- Significant intra-event MF_x variability
- Long Run doesn't reproduce MF_x variability, but gets means right
- Event Runs do reproduce MF_x variability, but too strong with MF_x
- Significant scatter => little MF_x predictability on short (<6 hour) time scales

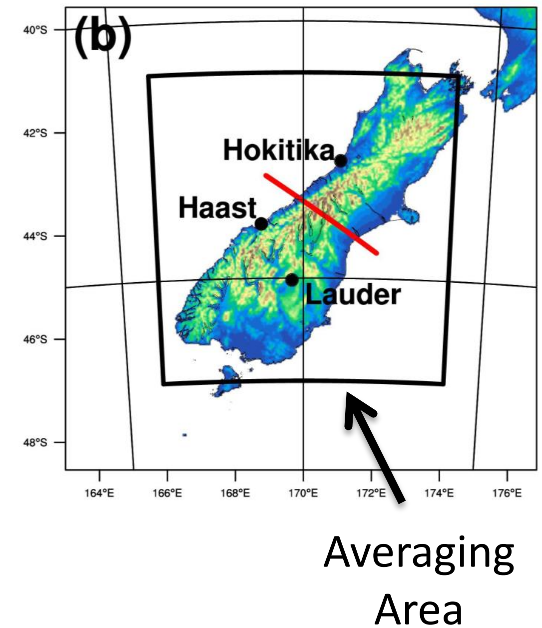
	6-km $\overline{MF}_x$	2-km $\overline{MF}_x$
# of Legs	97	58
Slope	0.667	1.236
R	0.463	0.610
Bias	3.838	-46.584
% Bias	5.56	50.7
MAE	40.554	78.735
% MAE	58.76	85.69

Validation Summary

- 6-km and 2-km resolution simulations reproduce mean quantities during DEEPWAVE
  - More recent initialization, higher resolution of Event Runs doesn't improve or degrade comparison
- Long Run reproduces event mean MF_x (~5% weak bias)
  - Despite stronger than observed winds
  - Suspect increased winds countered by decreased model terrain height
- Little MF_x predictability on short (<6 hours) time scales
  - Suspect this is due to non-linear generation below, attenuation above, or just due to sampling a complex, time-varying MF_x field
- Deep and shallow events in AIRS data are also deep and shallow in WRF

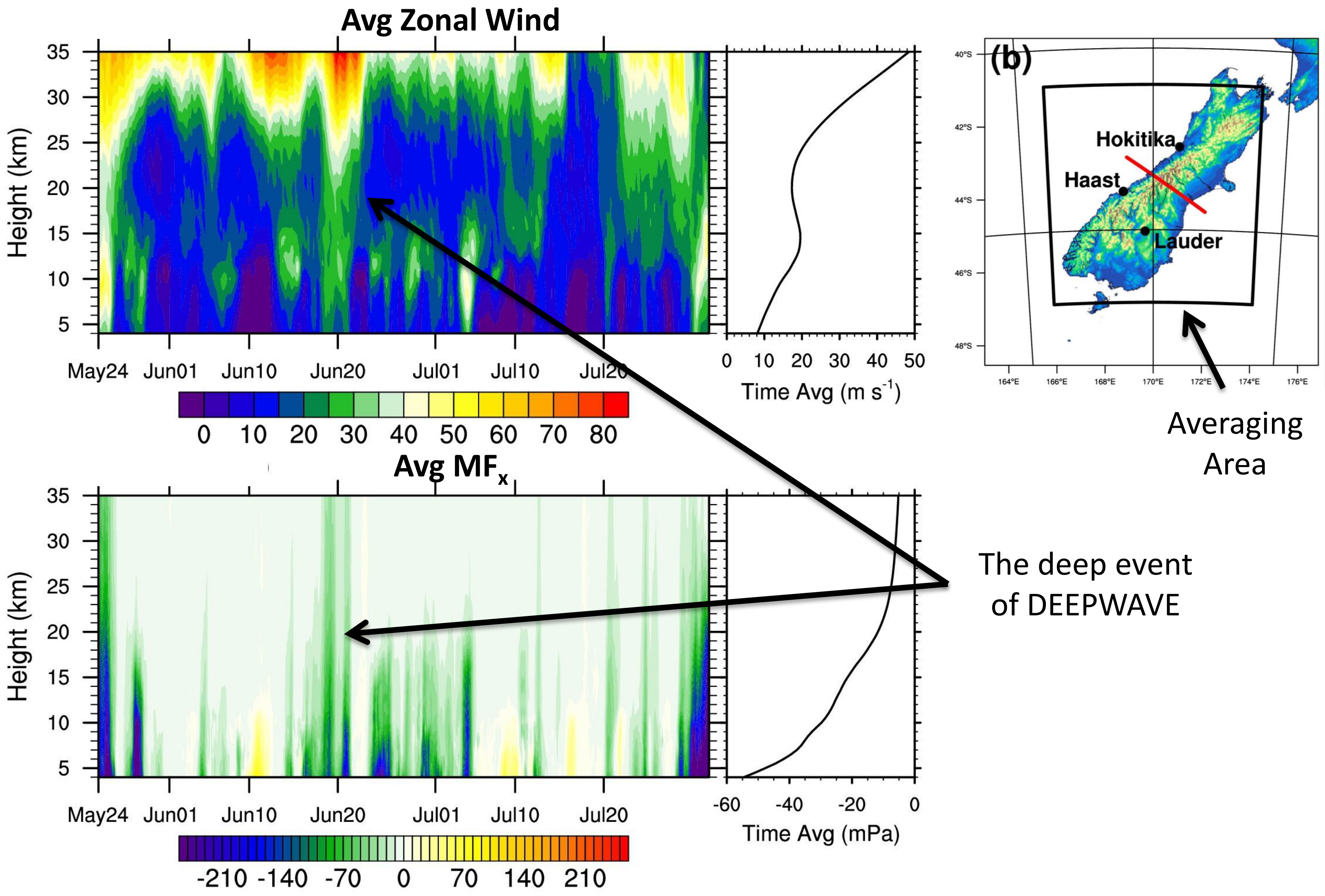
Winds, MF_x over New Zealand



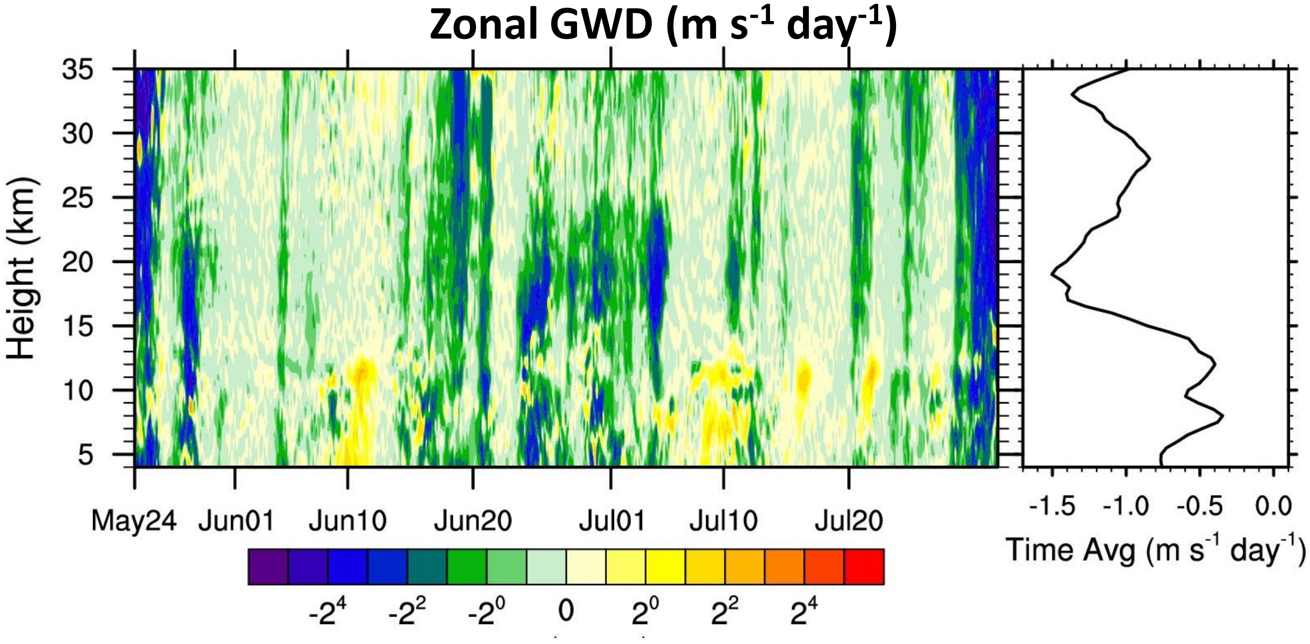


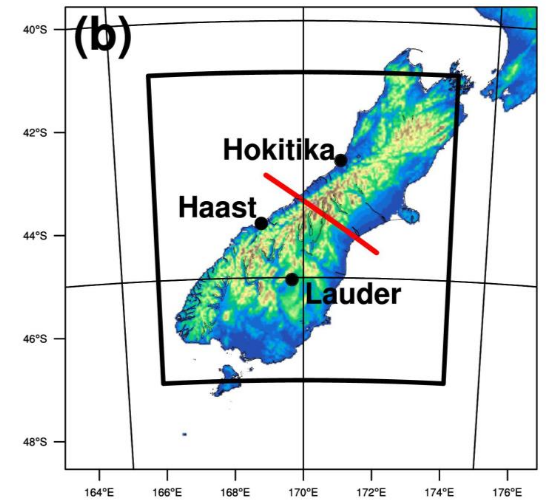
- Little mountain wave MF_x gets through the weak wind Valve Layer

Winds, MF_x over New Zealand

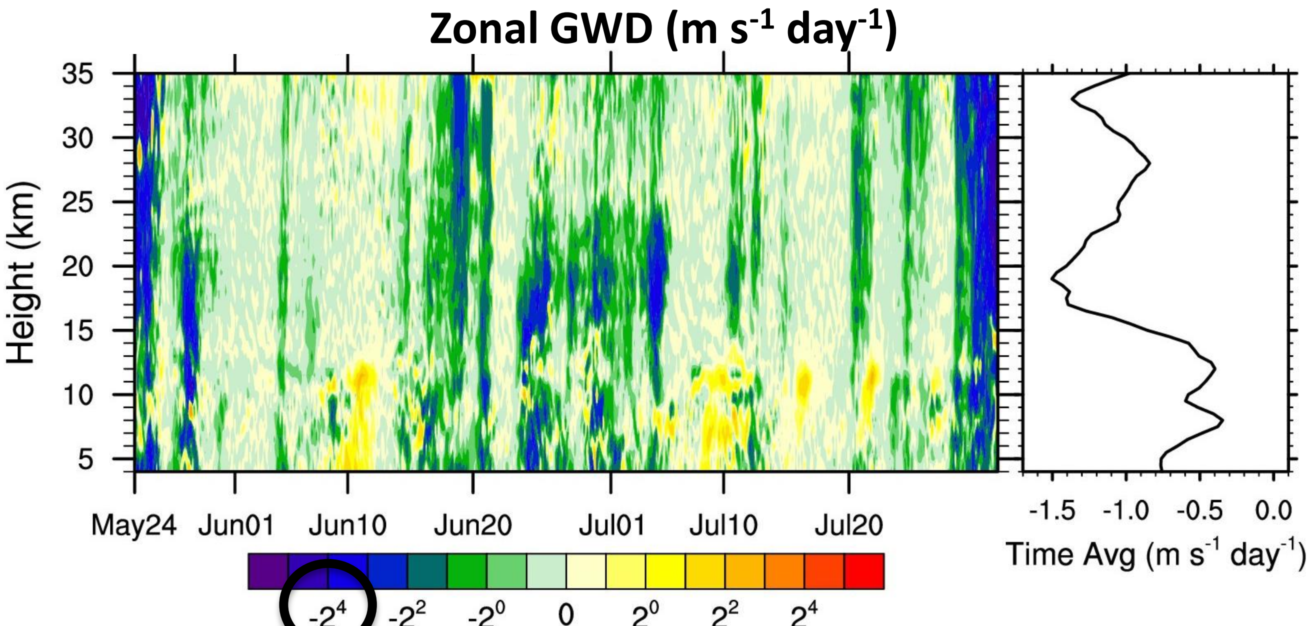


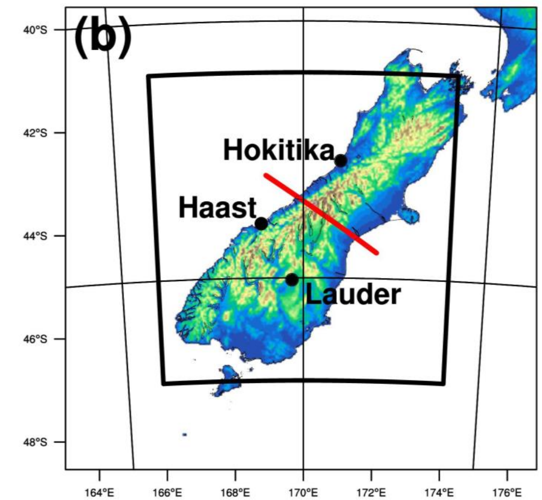
GWD Comparison b/t WRF, MERRA

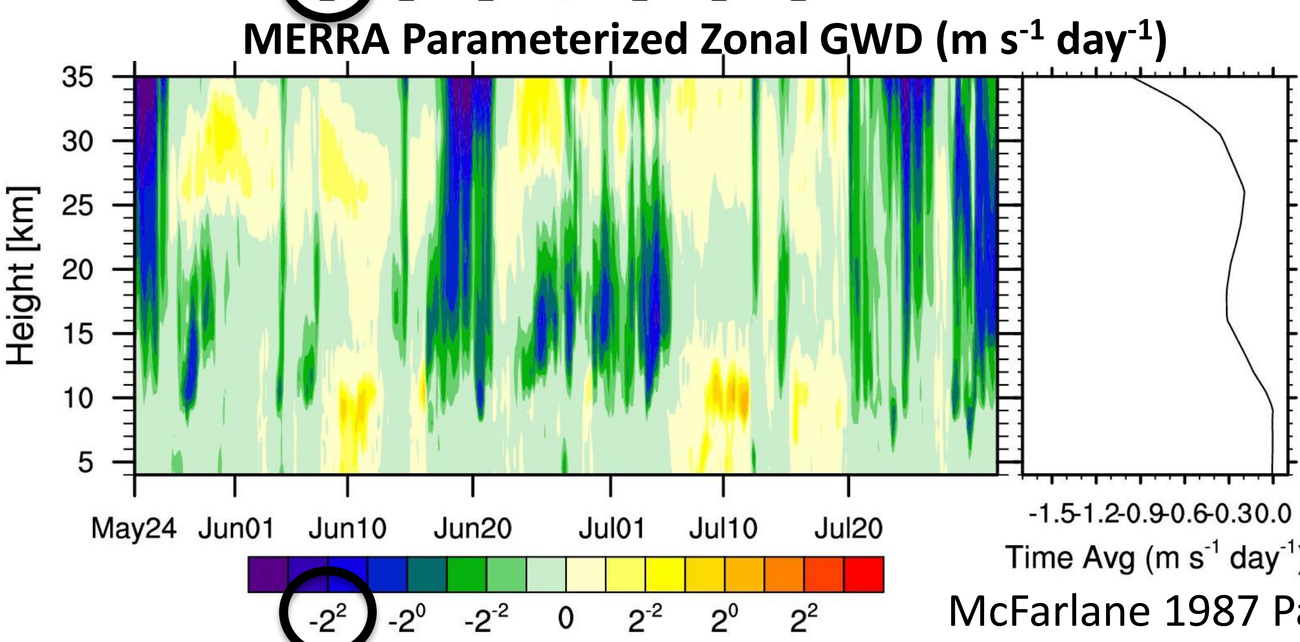




NZ Mountain Waves and Attenuation



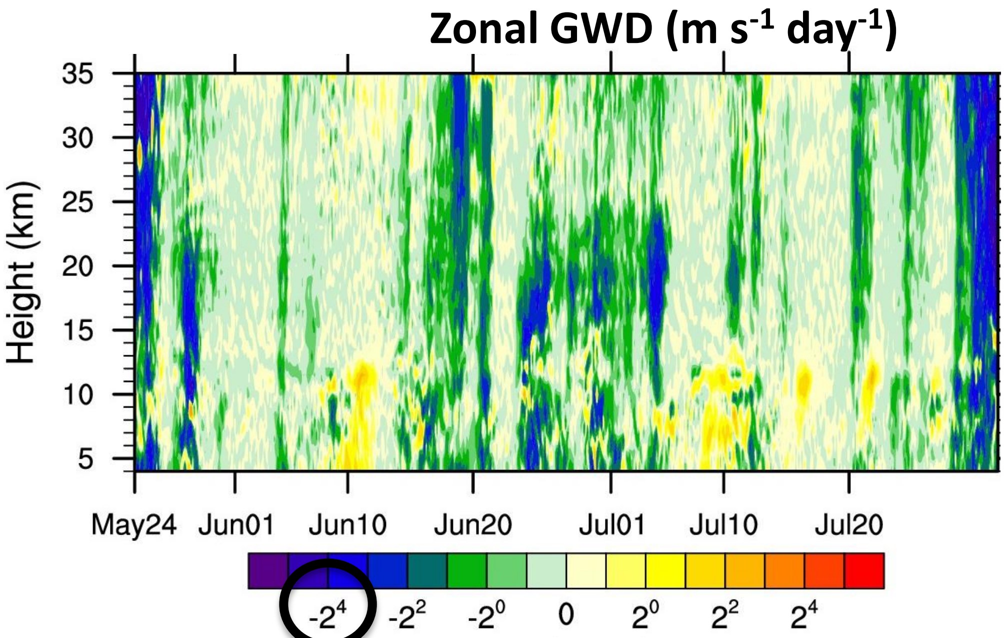


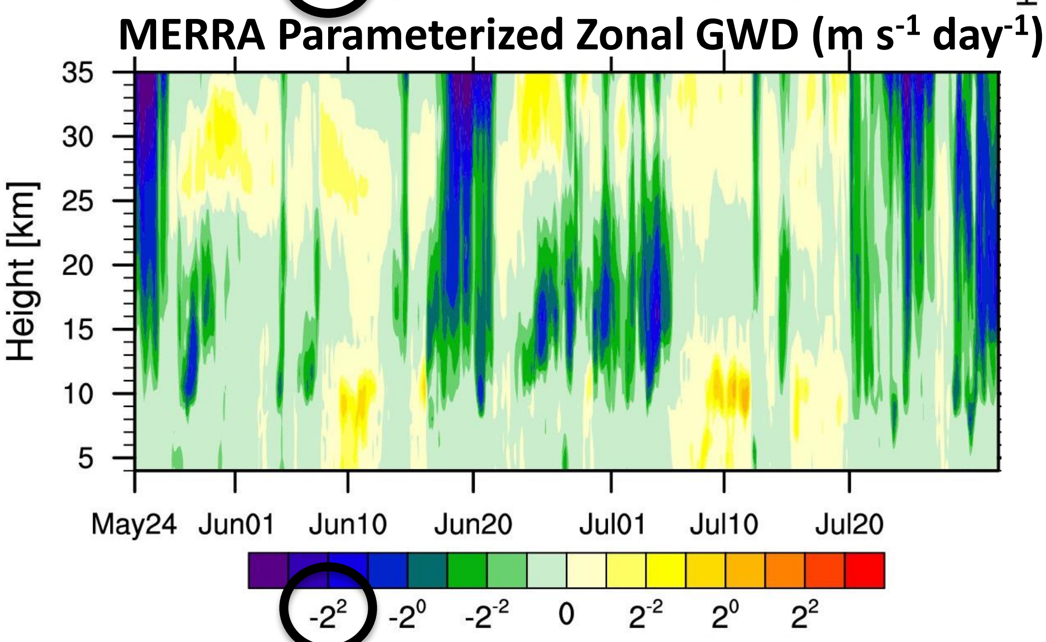


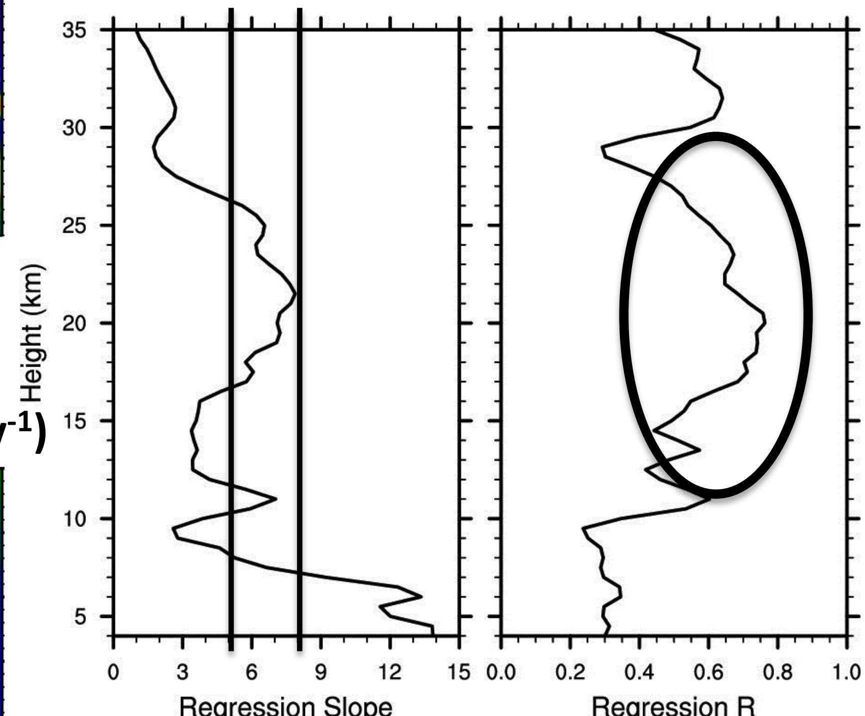
- Qualitatively, good vertical and temporal agreement of zonal GWD

McFarlane 1987 Param.

NZ Mountain Waves and Attenuation

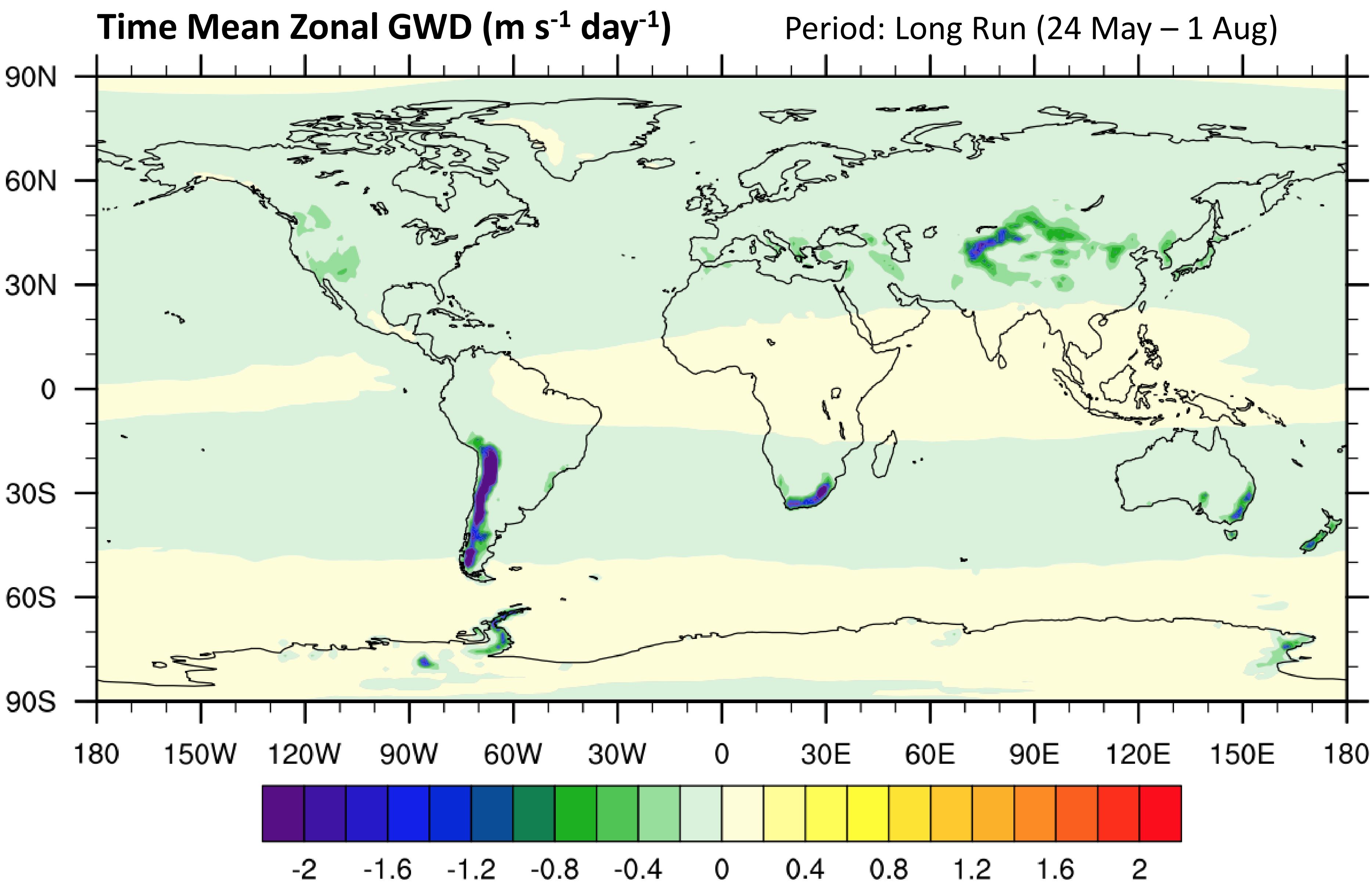






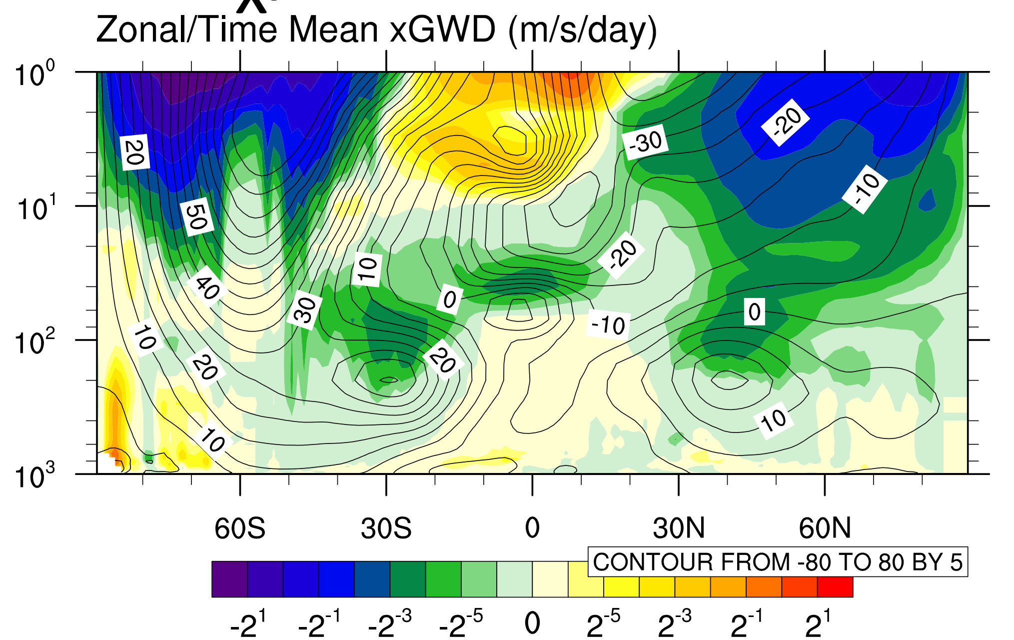
- Quantitatively, best agreement in Valve Layer
- WRF GWD 5-8 times larger than MERRA in this layer
- Worst agreement in troposphere

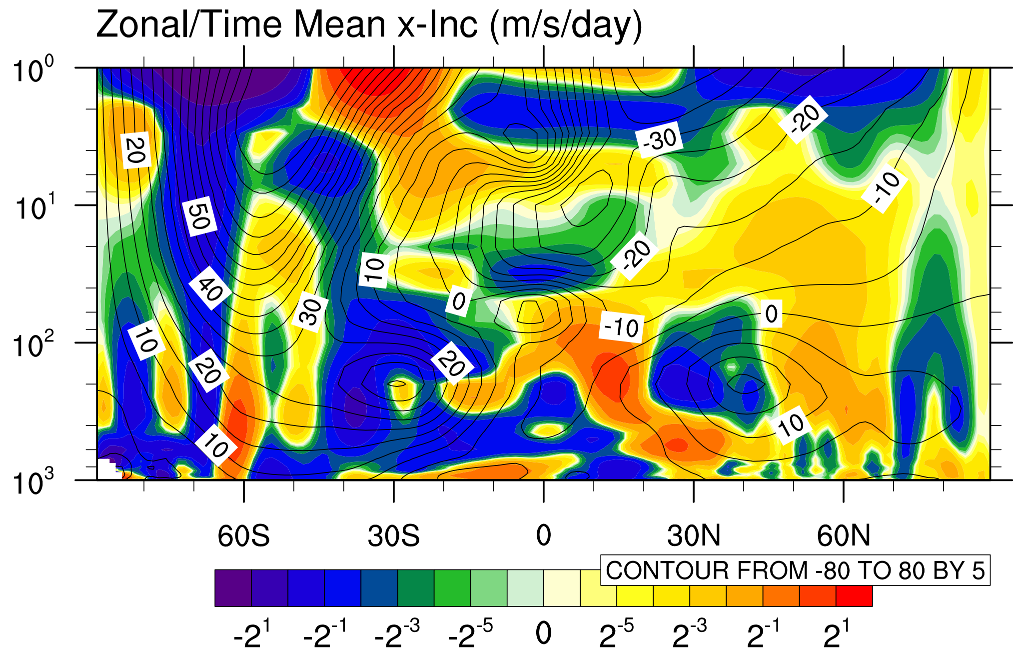
Global Time Avg MERRA GWD_x



MERRA Winds, GWD_x, Increments

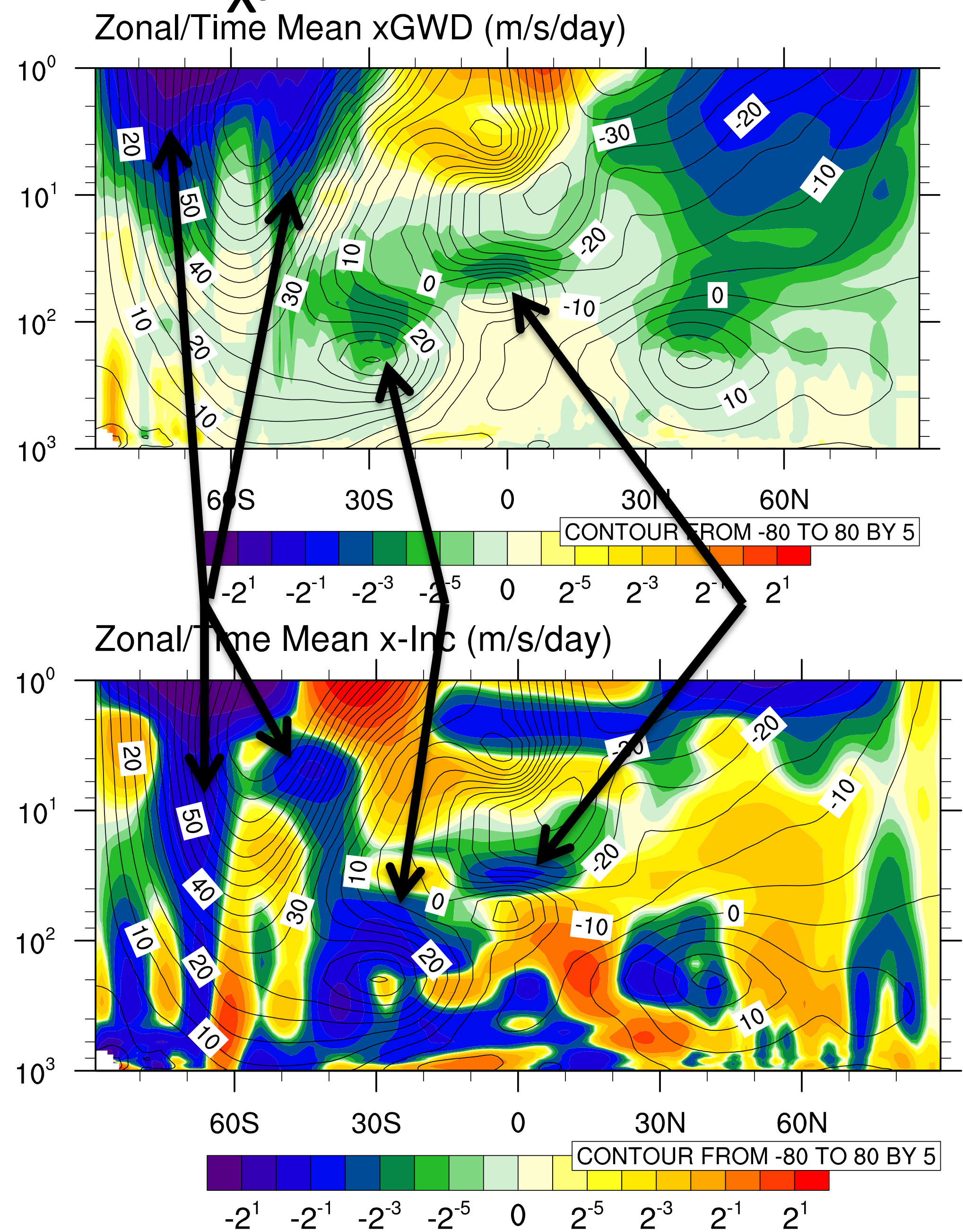
- Increments
  - Six hourly model errors, expressed as a tendency
  - used to correct the model to observations
  - For u, v, has units of acceleration
  - Interpreted by McLandress et al. (2012) as a missing GWD in the model



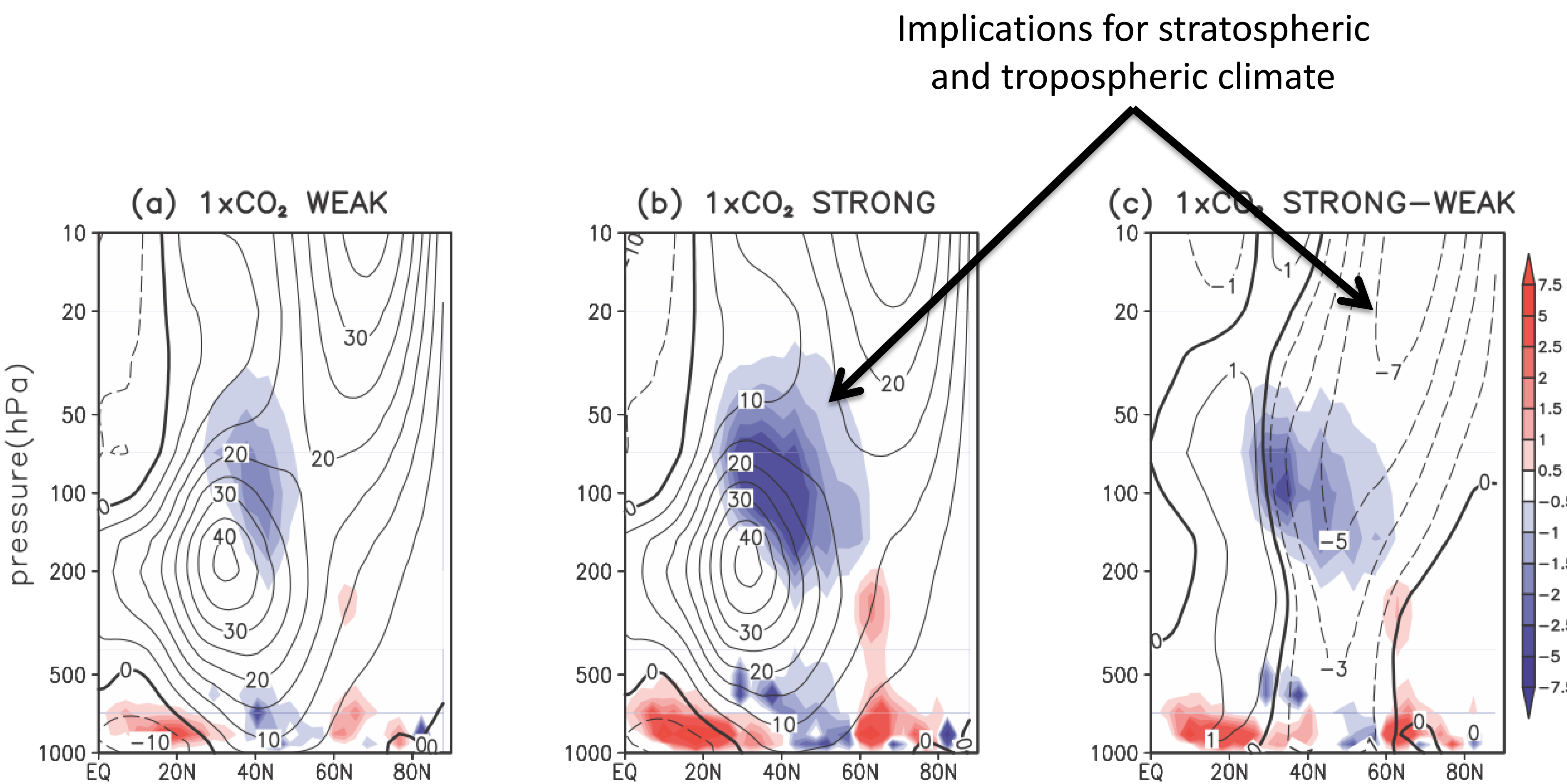


MERRA Winds, GWD$_x$, Increments

- Increments
  - Six hourly model errors, expressed as a tendency
  - used to correct the model to observations
  - For u, v, has units of acceleration
  - Interpreted by McLandress et al. (2012) as a missing GWD in the model
- Negative increments collocated with regions of GWD in stratosphere
  - 4-8 times the GWD, too



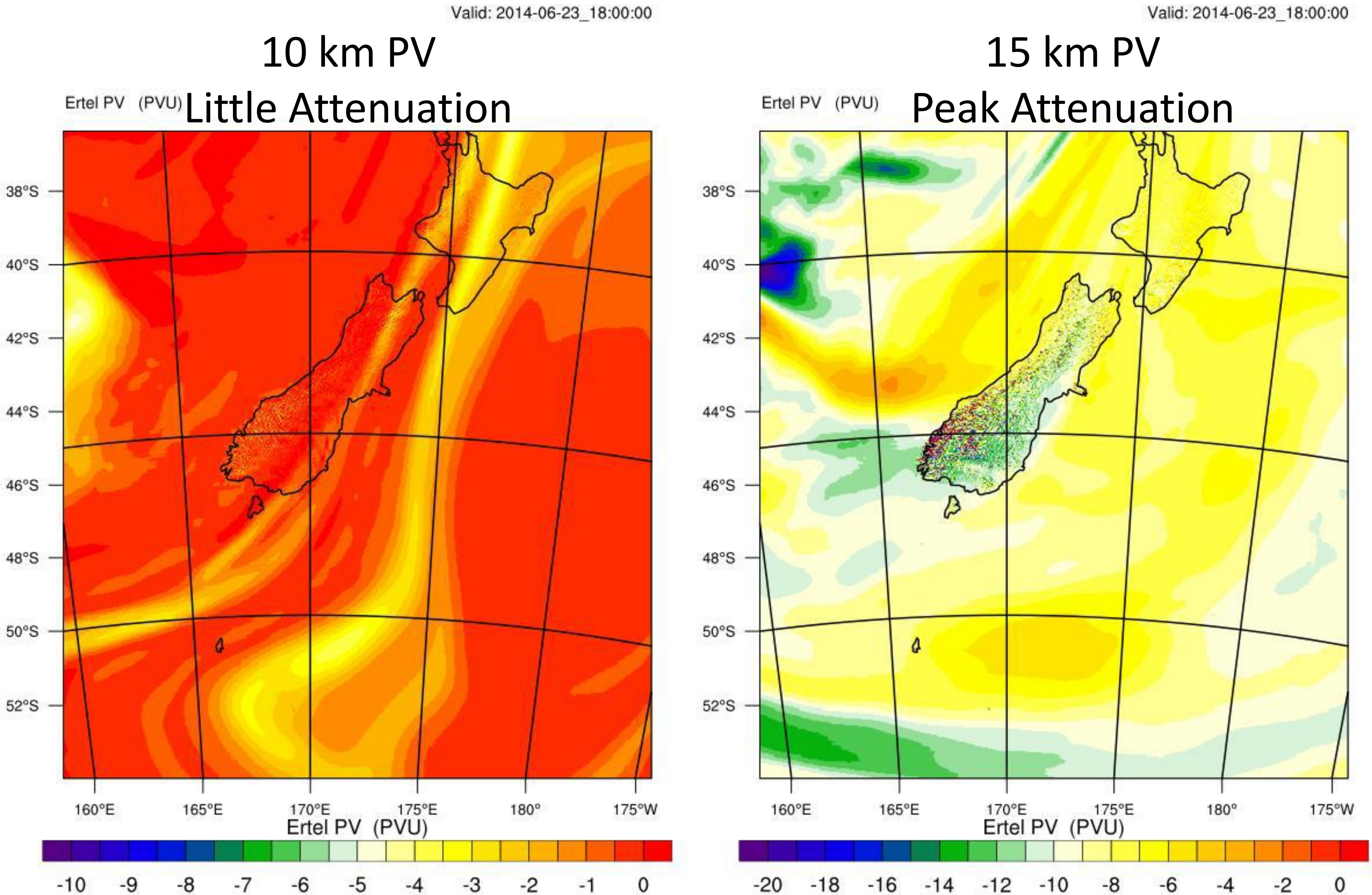
Implications



(Sigmond and Scinocca 2010)

- Sigmond and Scinocca (2010) found that increased mid-latitude lower-stratospheric GWD altered propagation of planetary Rossby waves and their forcing of the stratospheric circulation

Ertel PV

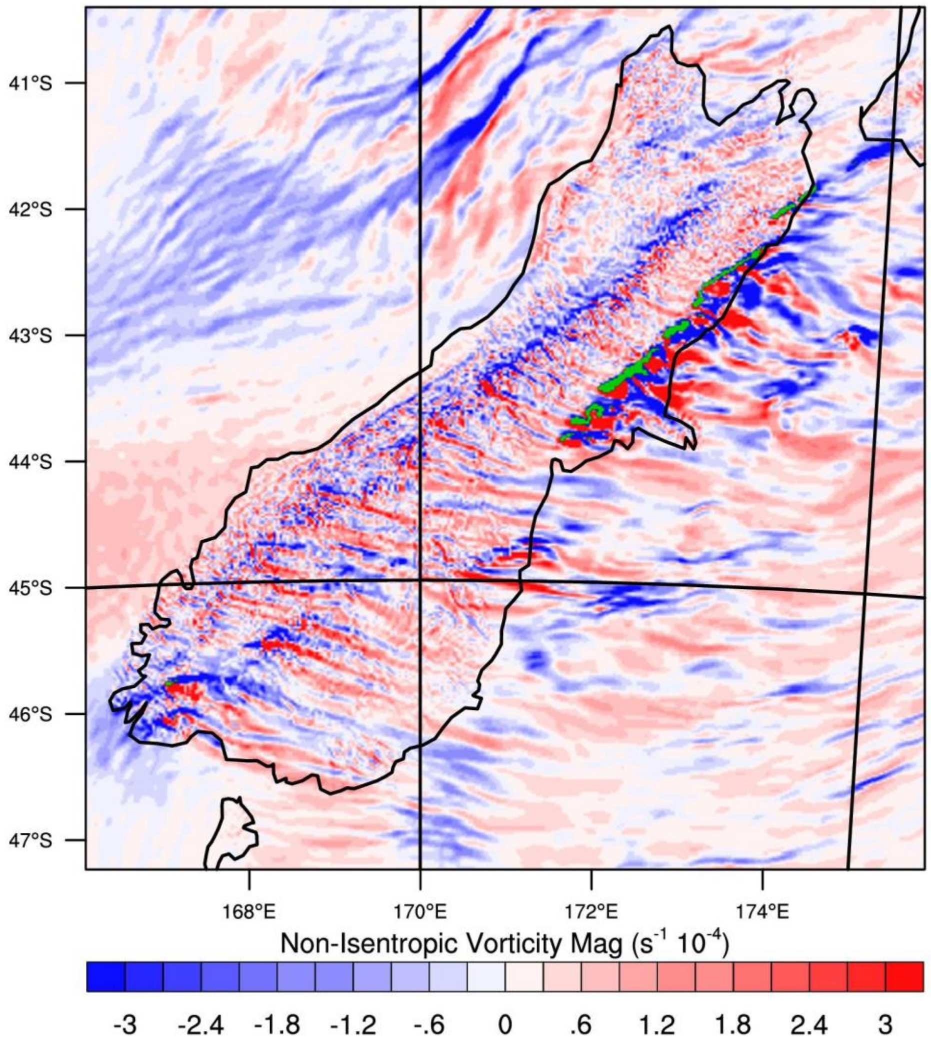


2km WRF

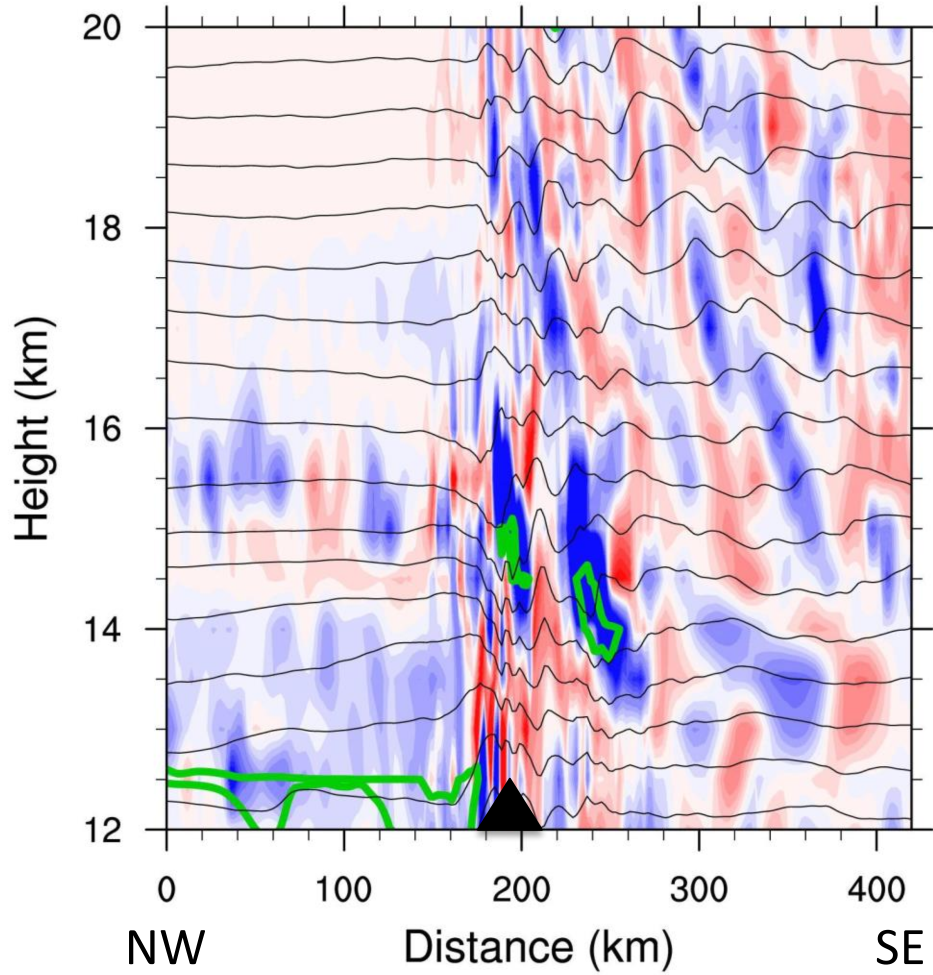
Non-Isentropic Vorticity

$$NIV = \vec{\omega} \cdot \nabla\theta$$

16-km NIV



Section over Mt. Cook



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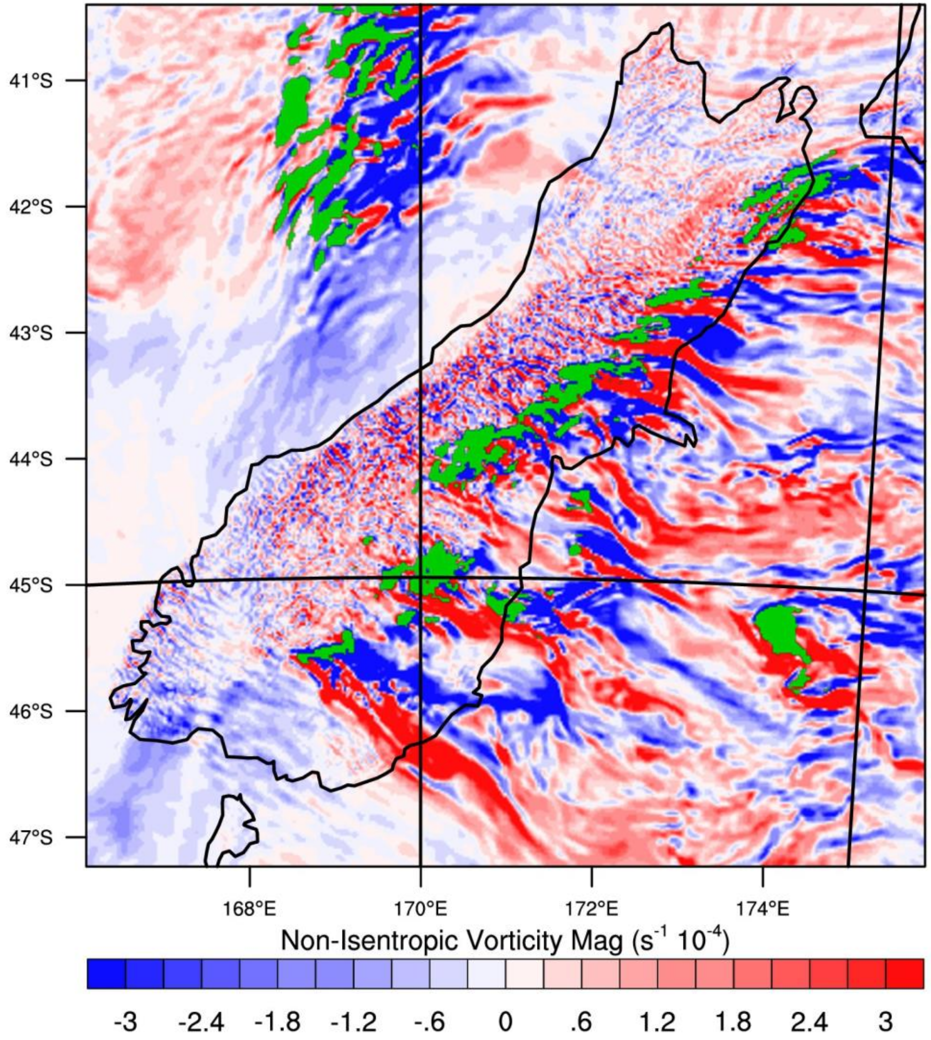

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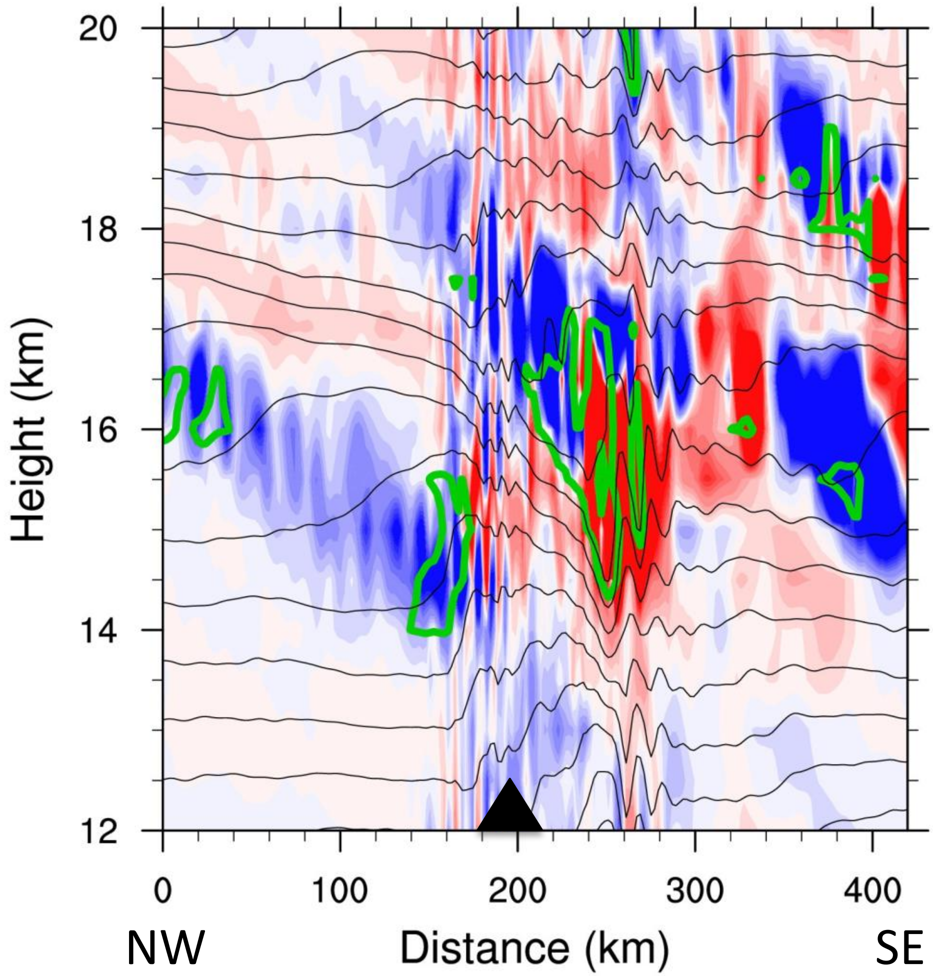


2km WRF

Conclusions

- The Long Run reproduces wave environment and event mean MF_x, but hourly MF_x unpredictable
- MERRA GWD 5-8 times smaller than WRF in the Valve Layer!
  - Some evidence MERRA puts in an unphysical forcing in same regions of GWD to correct the model
- Attenuation is horizontally and vertically inhomogenous
  - PV/NIV generated in regions of low Ri
  - These regions periodic in the vertical

Recent and Ongoing Work

Kruse, C. G. and R. B. Smith, 2015: **Gravity Wave Diagnostics and Characteristics in Mesoscale Fields**. *J. Atmos. Sci.*, **72**, 4372–4392. doi: http://dx.doi.org/10.1175/JAS-D-15-0079.1

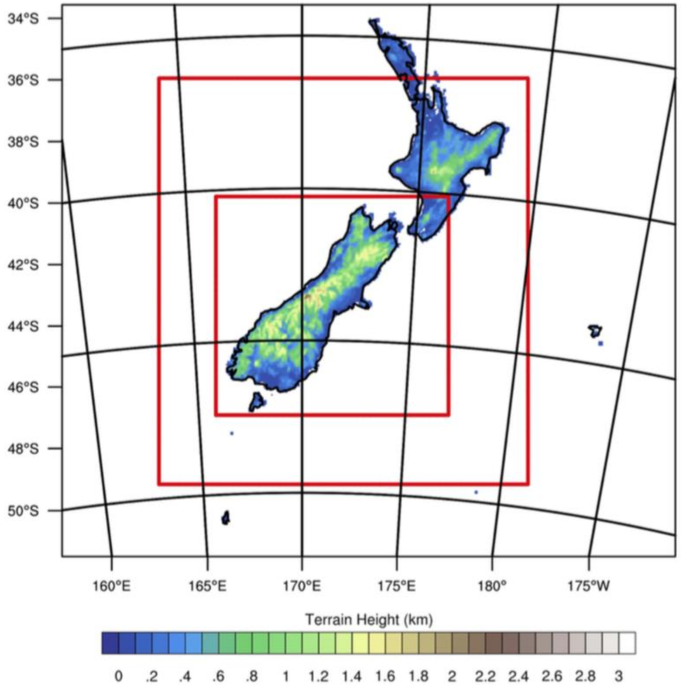
Smith, R. B., A. D. Nugent, C. G. Kruse, D. C. Fritts, J. D. Doyle, S. D. Eckermann, M. J. Taylor, A. Dörnbrack, M. Uddstrom, W. Cooper, P. Ramashkin, J. Jensen, and S. Beaton, 2015: **Stratospheric Gravity Wave Fluxes and Scales during DEEPWAVE**. *J. Atmos. Sci.*, under review.

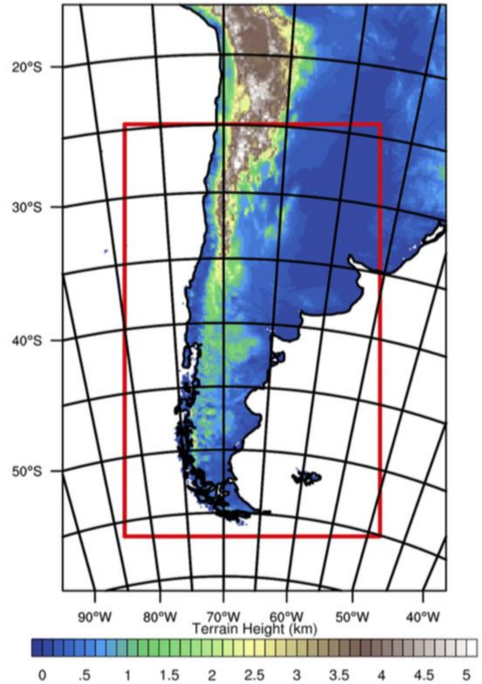
Kruse, C. G., R. B. Smith, and S. D. Eckermann, 2016: **Characteristics and physics of a mid-latitude lower-stratospheric mountain wave "valve layer."** *J. Atmos. Sci.*, in prep.

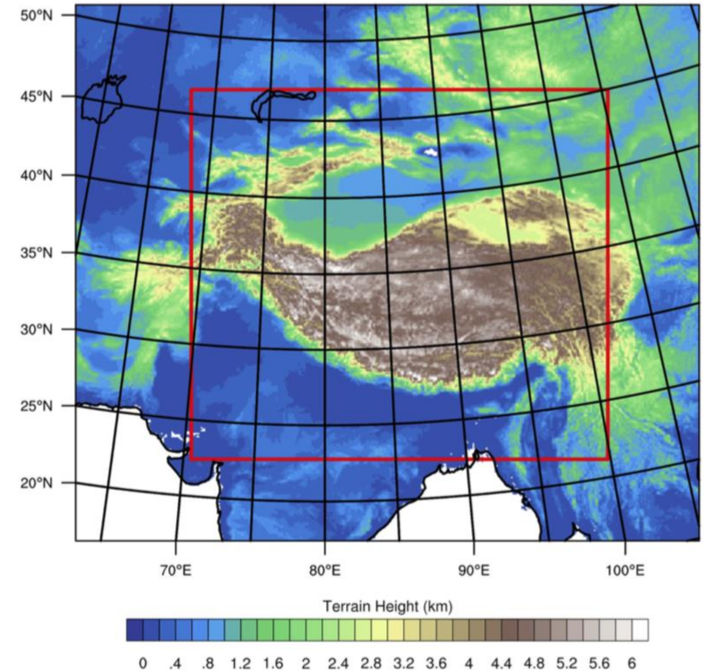
Watson, C. D., C. G. Kruse, A. D. Nugent, A. Takeishi, C. J. Tsai, R. B. Smith, 2016: **The occurrence of convection in orographic precipitation over the Southern Alps in New Zealand**. In prep.

Future Work

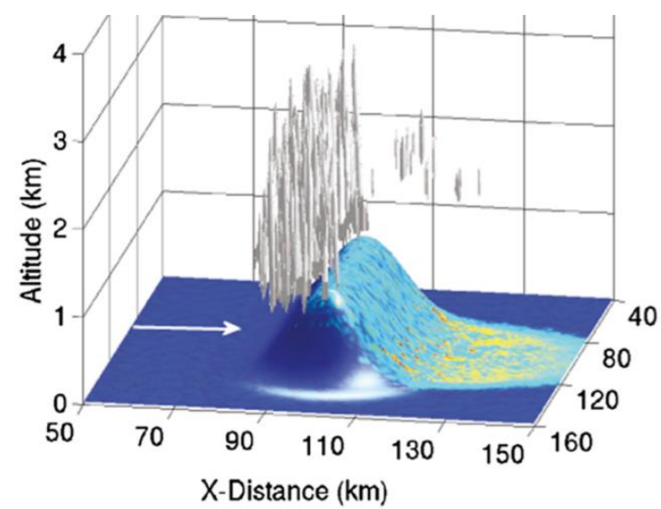
- 1,000,000 Yellowstone core hours to work with now







- Will do more realistic Long Runs, Event Runs
- Also, 3-D Idealized runs with simple turbulence
  - Look at attenuation and flow responses



Future Work

Additionally,

1. Short waves on the TIL (Ron)
2. Non-linear wave generation: transience and scale downshifting (Ron and Chris)
3. 20 June deep event of DEEPWAVE (Ron and Chris)
4. Gravity wave generation by mountains and convection in the tropics (Gang)

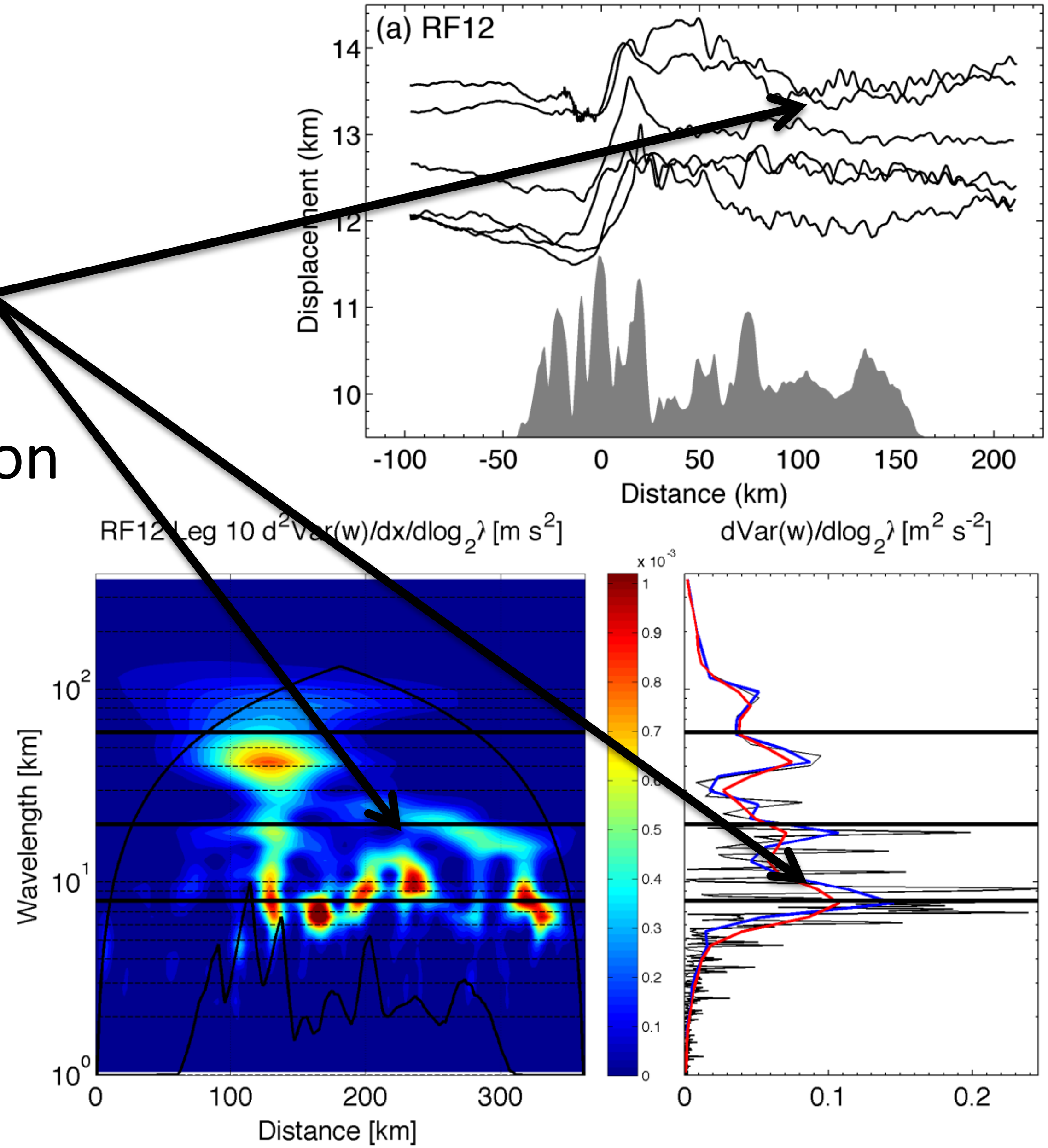
Thanks

Future Work

Ron's interested in:

Short waves

Non-linear generation mechanisms

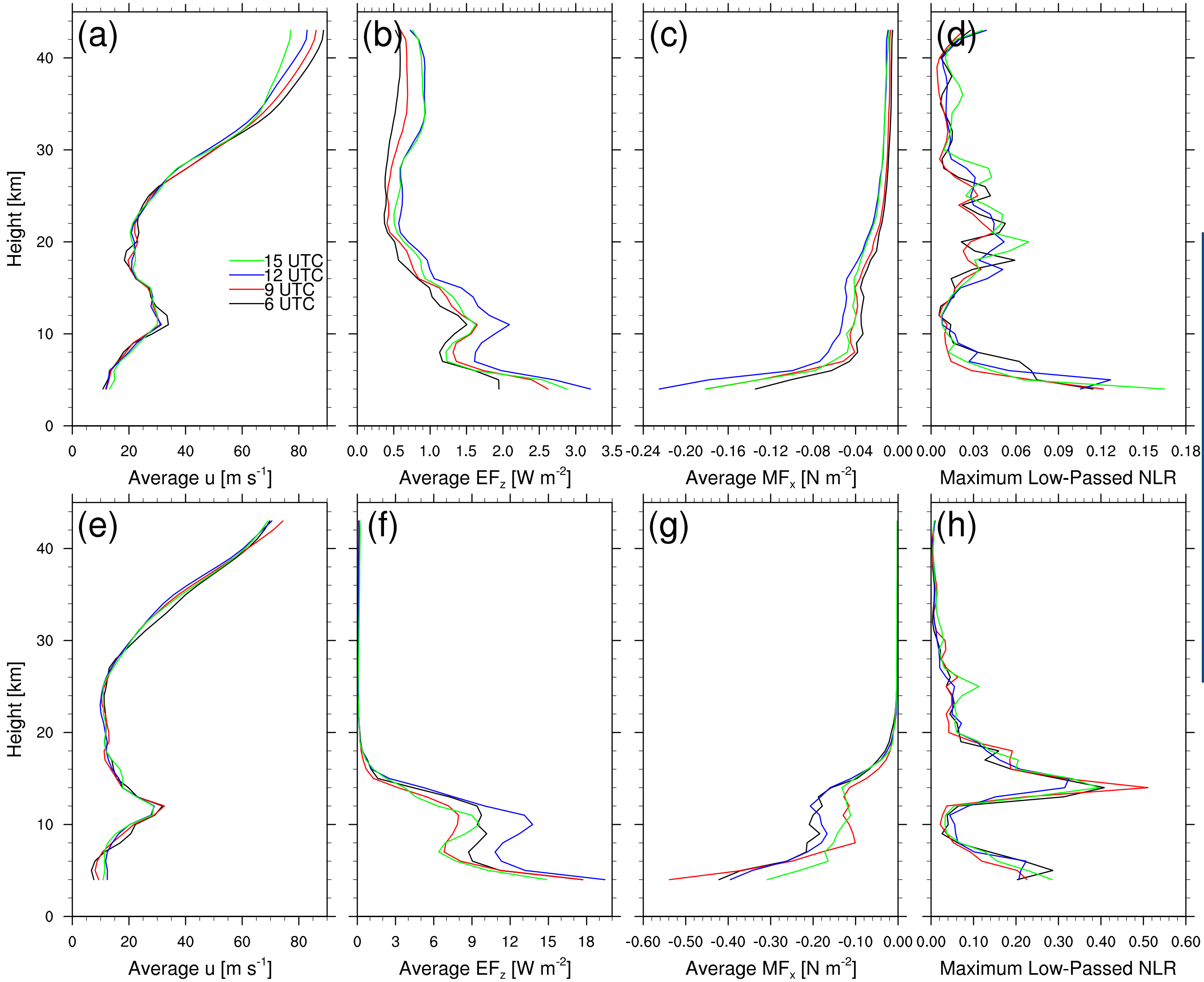


Example GW Diagnostic Profiles

$\overline{u}$ $\overline{EF}_z = \overline{p'w'}$ $\overline{MF}_x = \bar{\rho}\,\overline{u'w'}$ $NLR = \frac{|\mathbf{u}'|^2}{|\overline{\mathbf{u}}|^2}$

14 June

24 June



Flux Quantities averaged over South Island

Fluxes within realistic simulations computed via method proposed by Kruse and Smith (2015), in press.

2km WRF

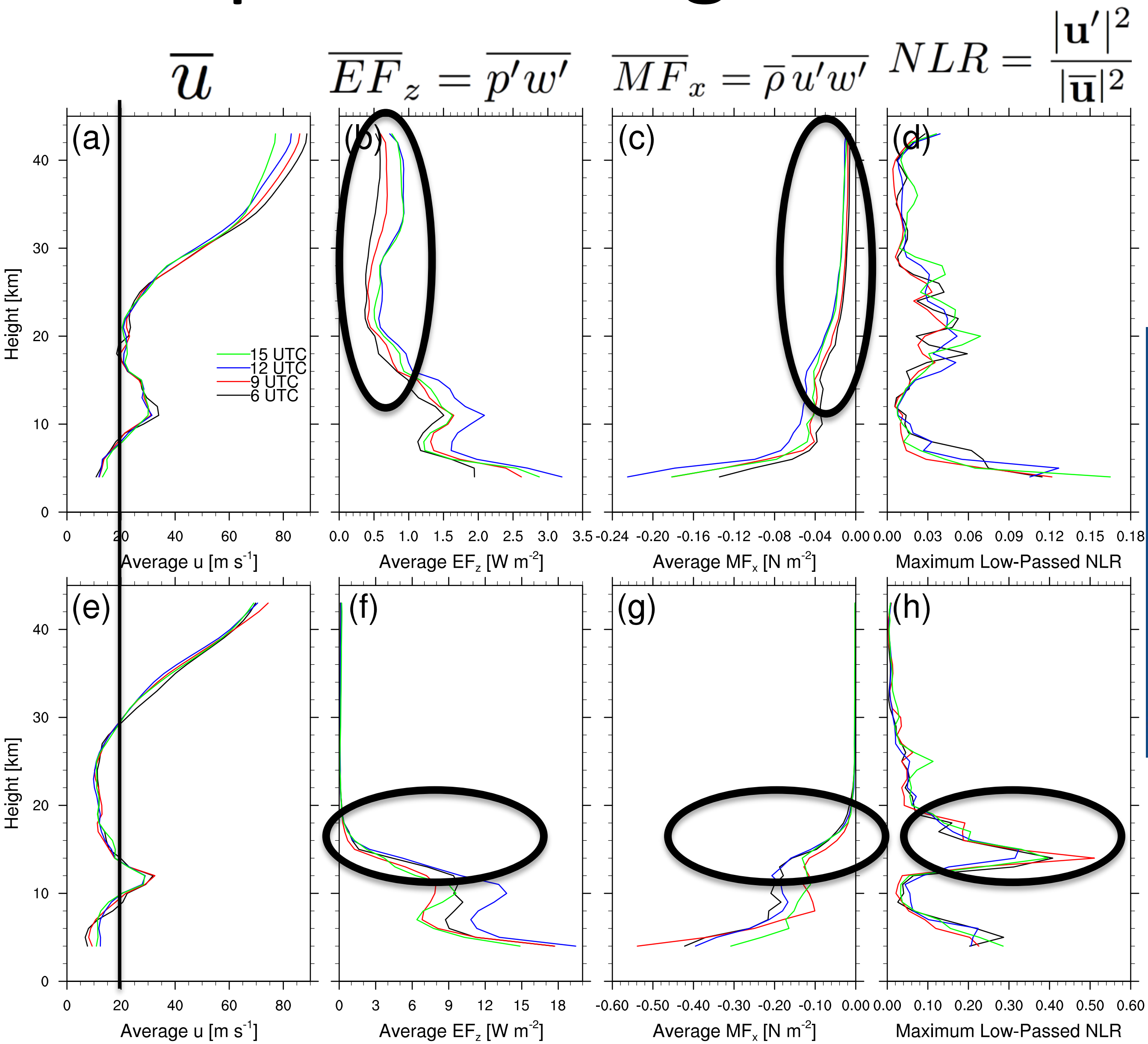
Example GW Diagnostic Profiles

14 June

Deep Event

24 June

Shallow Event



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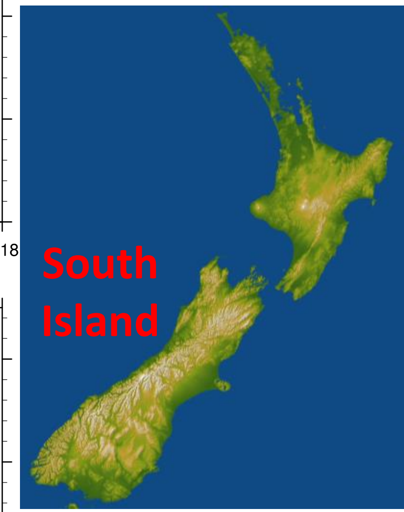

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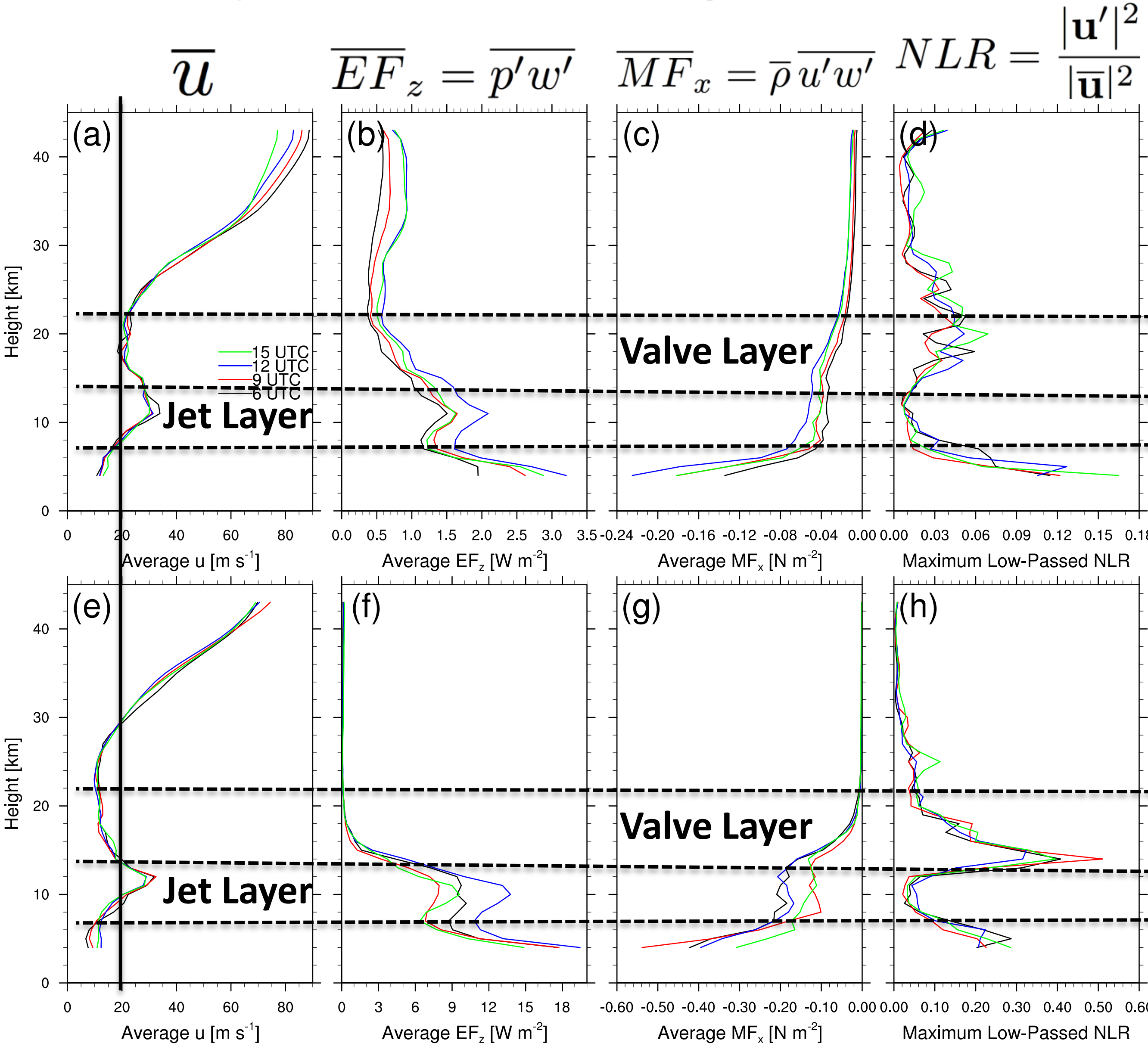

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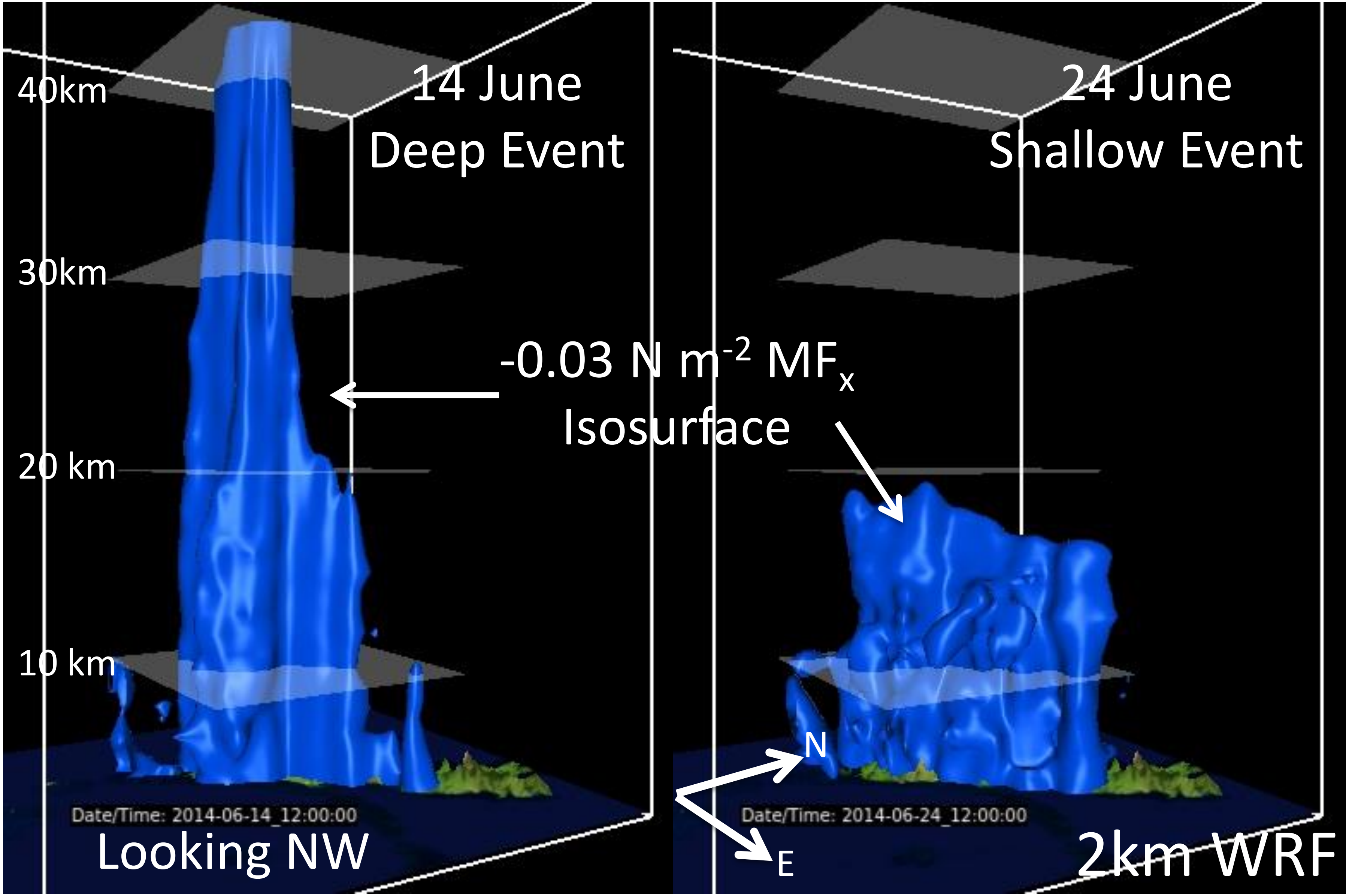
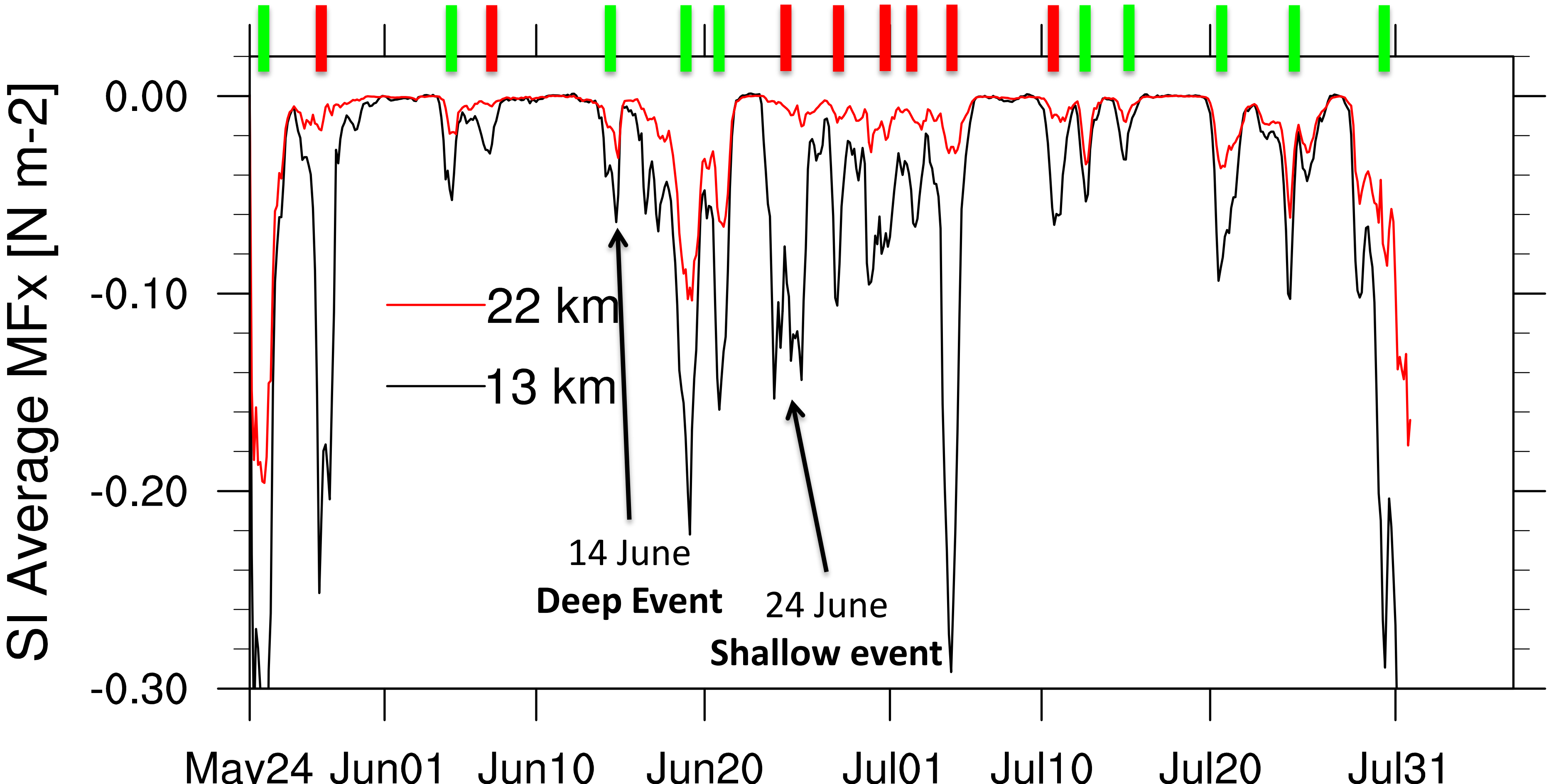
2km WRF

Low-Passed MF_x Towers



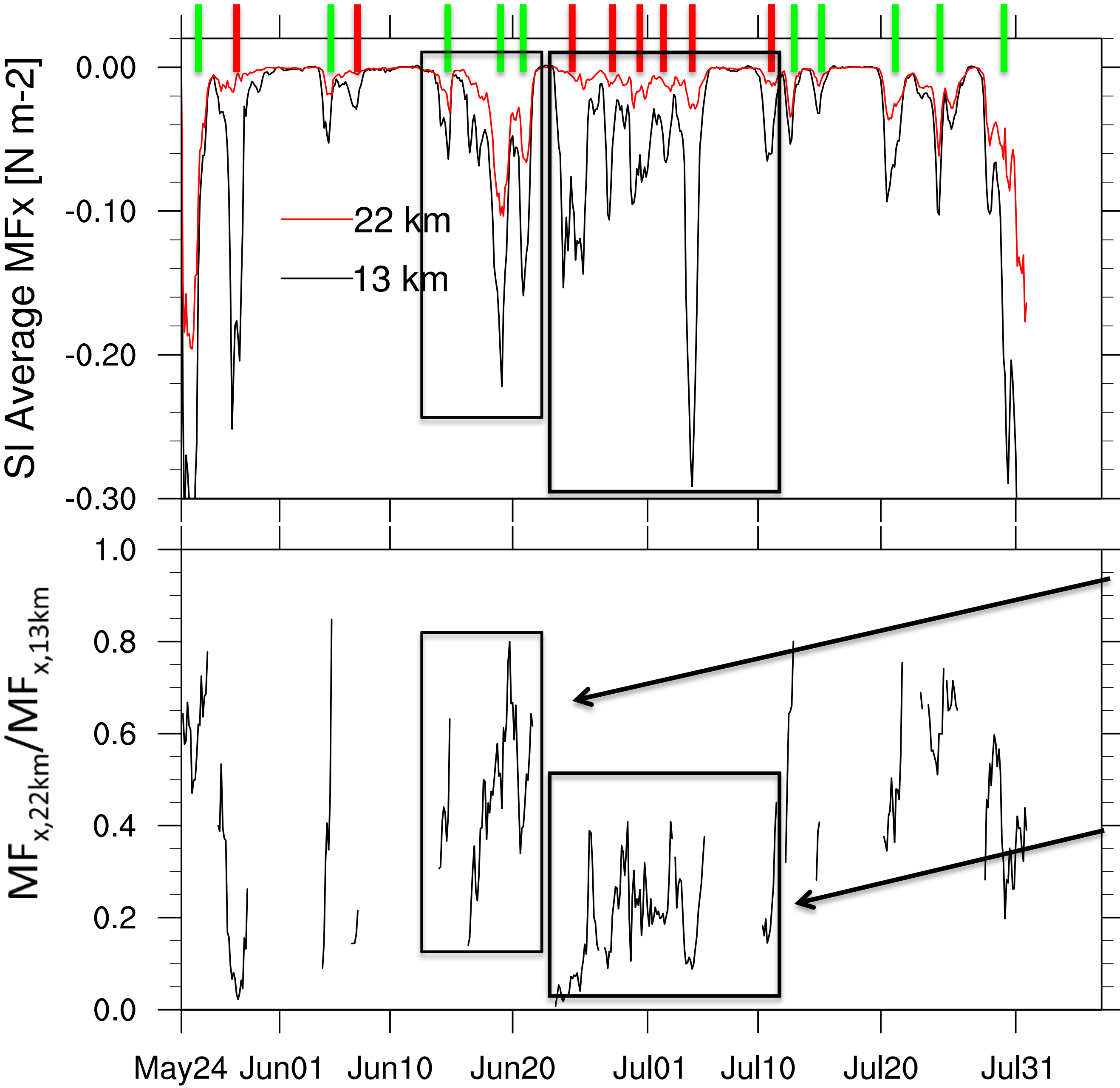
How often is this GW Valve “Off”?



6km WRF

- 18 events
- 8 do not get past valve (red)
- ~50% of events strongly attenuated

How strong is the attenuation?



Deep Events:
~50% MF reduction

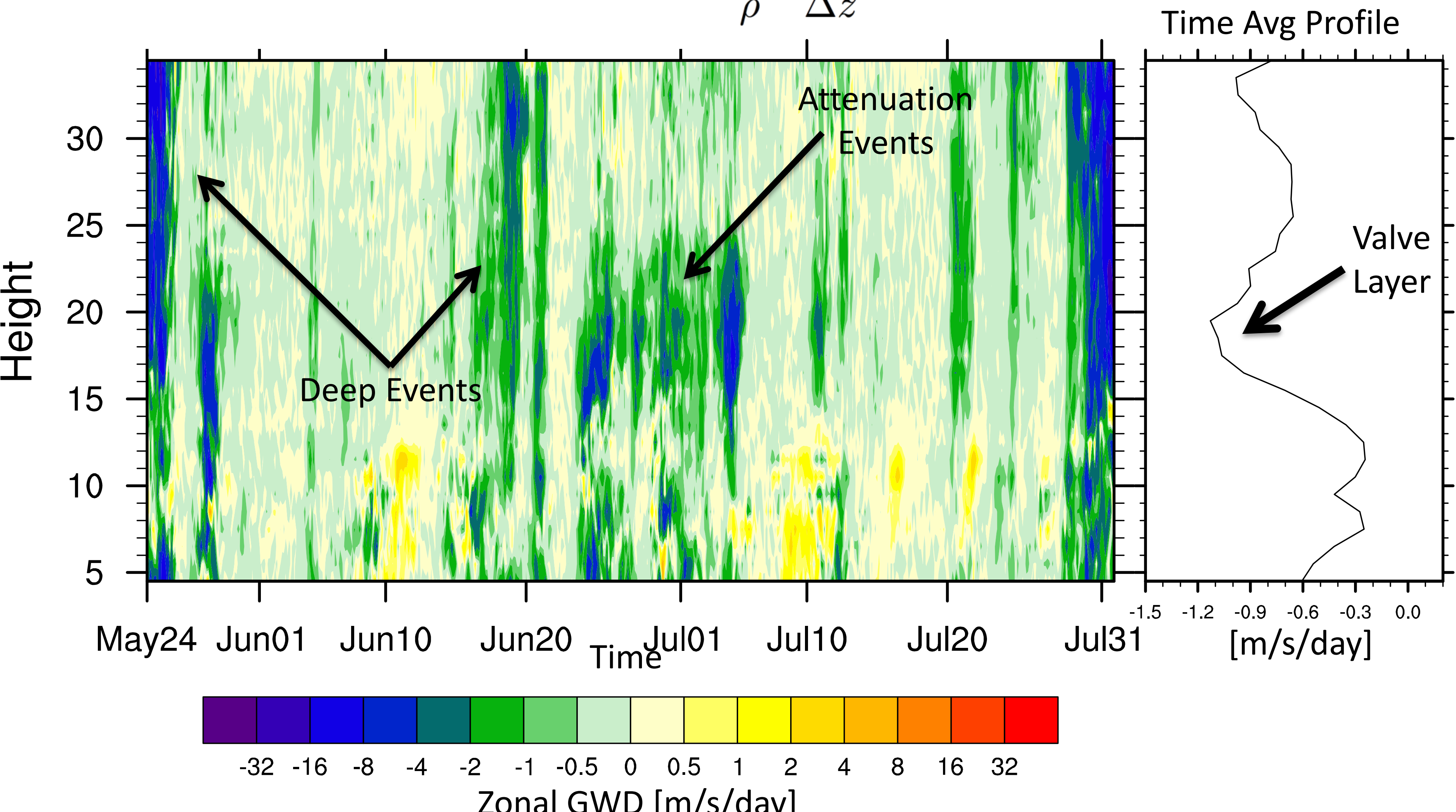
As little as 40% reduction

Attenuation Events:
>80% MF reduction with largest 13 km fluxes

As low as 90% reduction

South Island Avg Zonal GWD Acceleration

$$GWD = -\frac{1}{\overline{\rho}}\frac{\Delta MF_x}{\Delta z}$$



6km WRF

Gravity Wave Attenuation and PV

- Ertel Potential Vorticity (PV)

$$PV = \frac{\vec{\omega} \cdot \nabla\theta}{\rho} \qquad \frac{DPV}{Dt} = \tilde{\omega} \cdot \nabla\dot{\theta} + \frac{\nabla\theta}{\rho} \cdot (\nabla \times \vec{F})$$

Gravity Wave Attenuation and PV

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- PV conserved for non-attenuating gravity waves:

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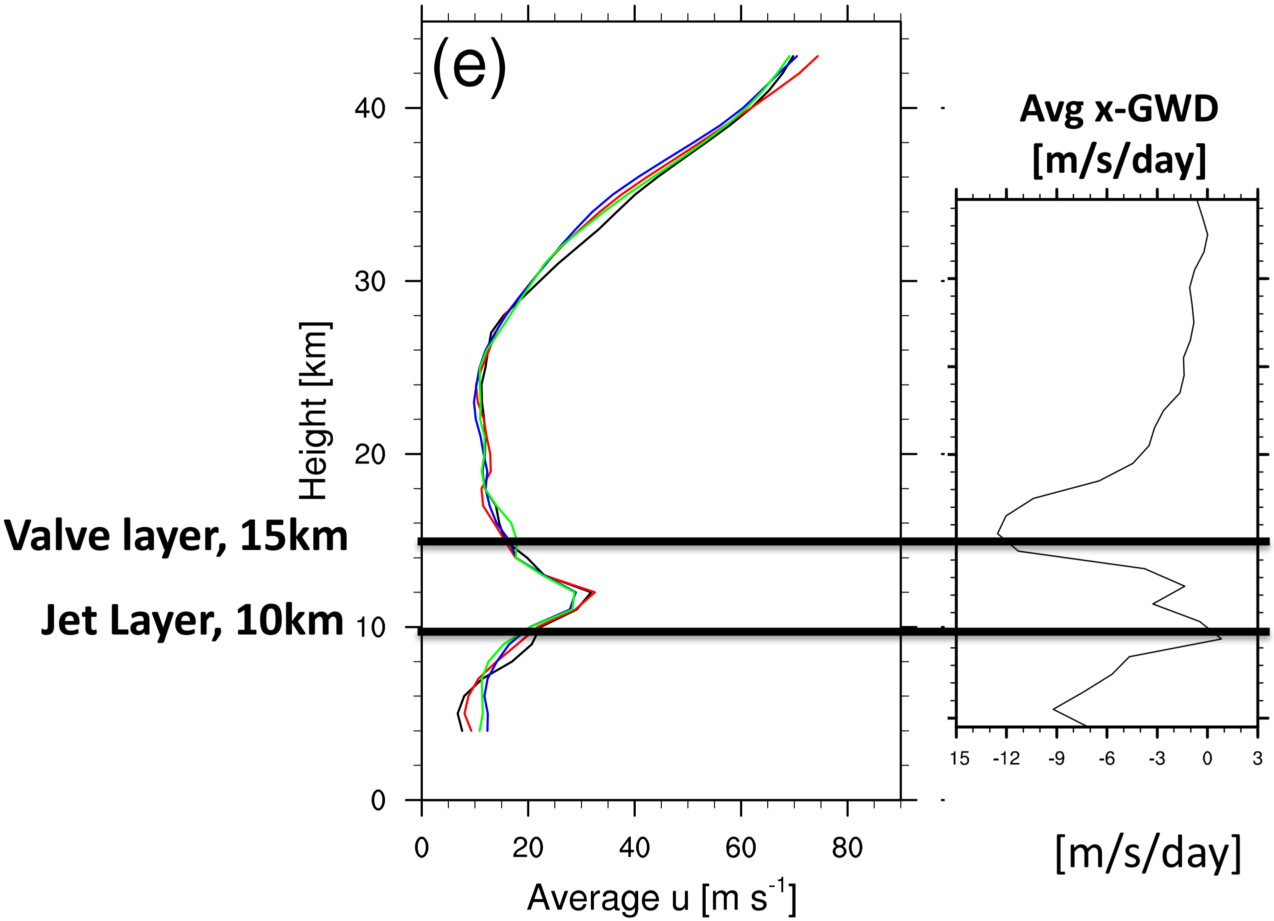
$$\frac{DPV}{Dt} = \tilde{\omega} \cdot \nabla\cancel{\dot{\theta}} + \frac{\nabla\theta}{\rho} \cdot (\nabla \times \cancel{\vec{F}})$$

- PV conservation invalidated in breaking regions?

$$\frac{DPV}{Dt} = \tilde{\omega} \cdot \nabla\cancel{\dot{\theta}} + \frac{\nabla\theta}{\rho} \cdot (\nabla \times \vec{F})$$

  – PV Banners Generated?

Shallow Event Zonal GWD Acceleration

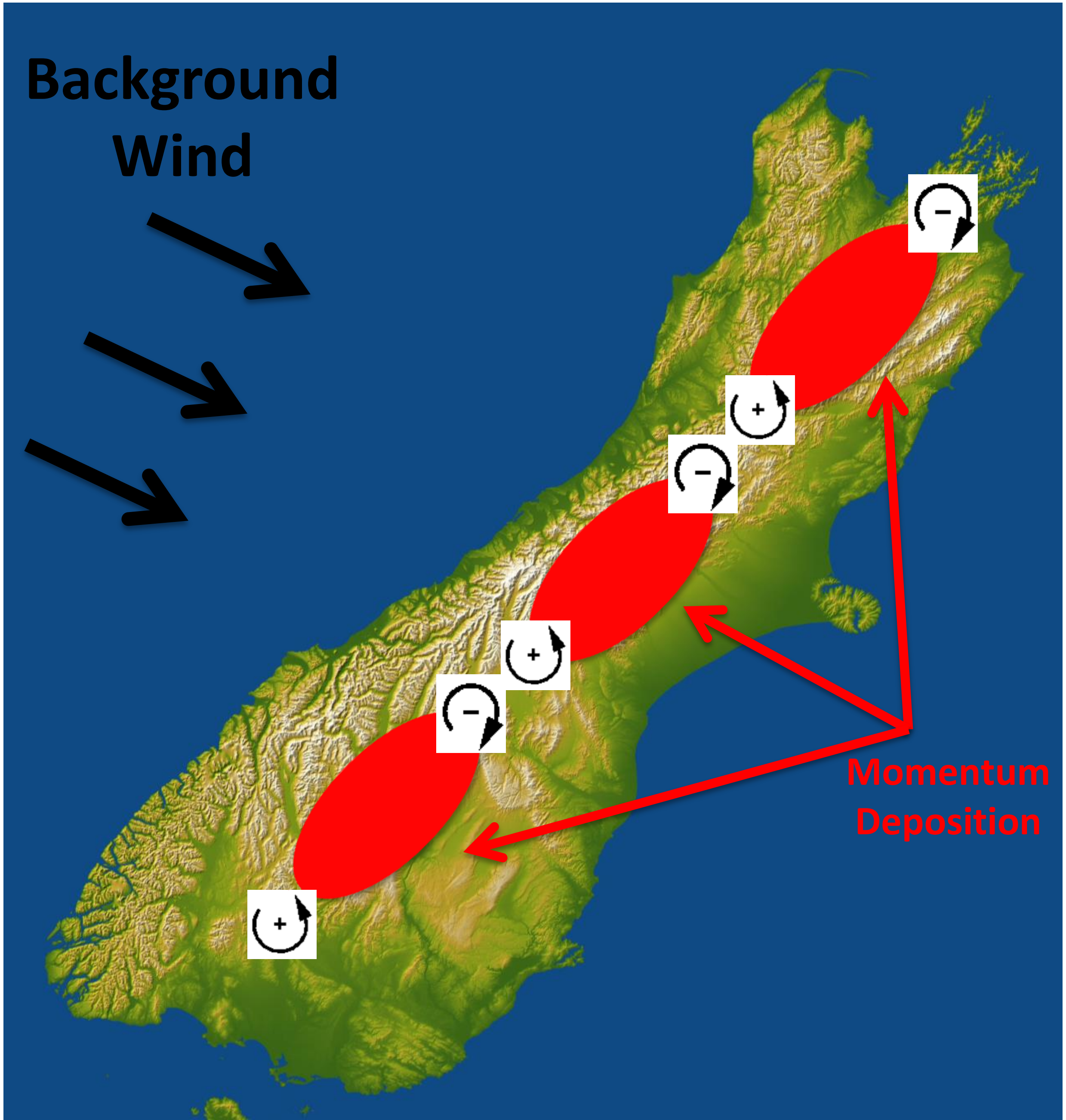


$$GWD = -\frac{1}{\overline{\rho}}\frac{\Delta MF_x}{\Delta z}$$

- Look at PV in Jet Layer & Valve layer

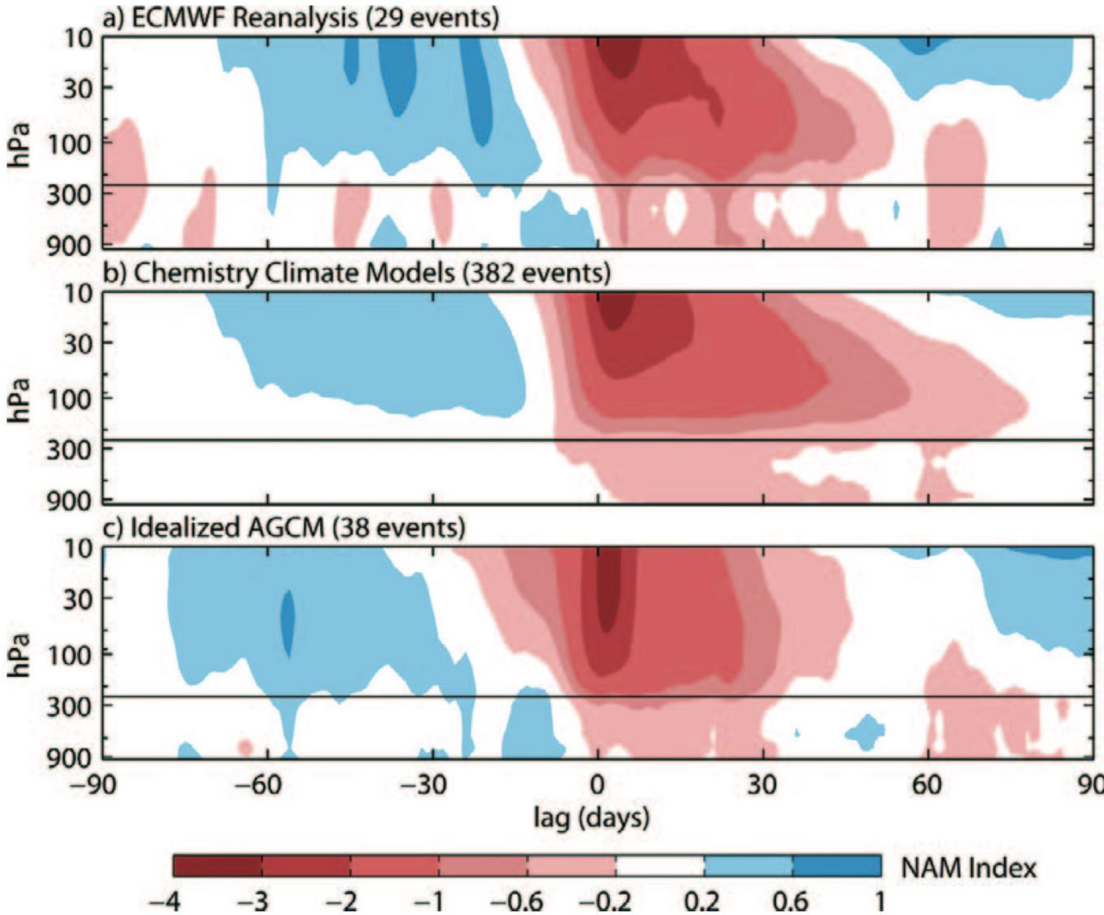
2km WRF

Conceptual Model of Breaking



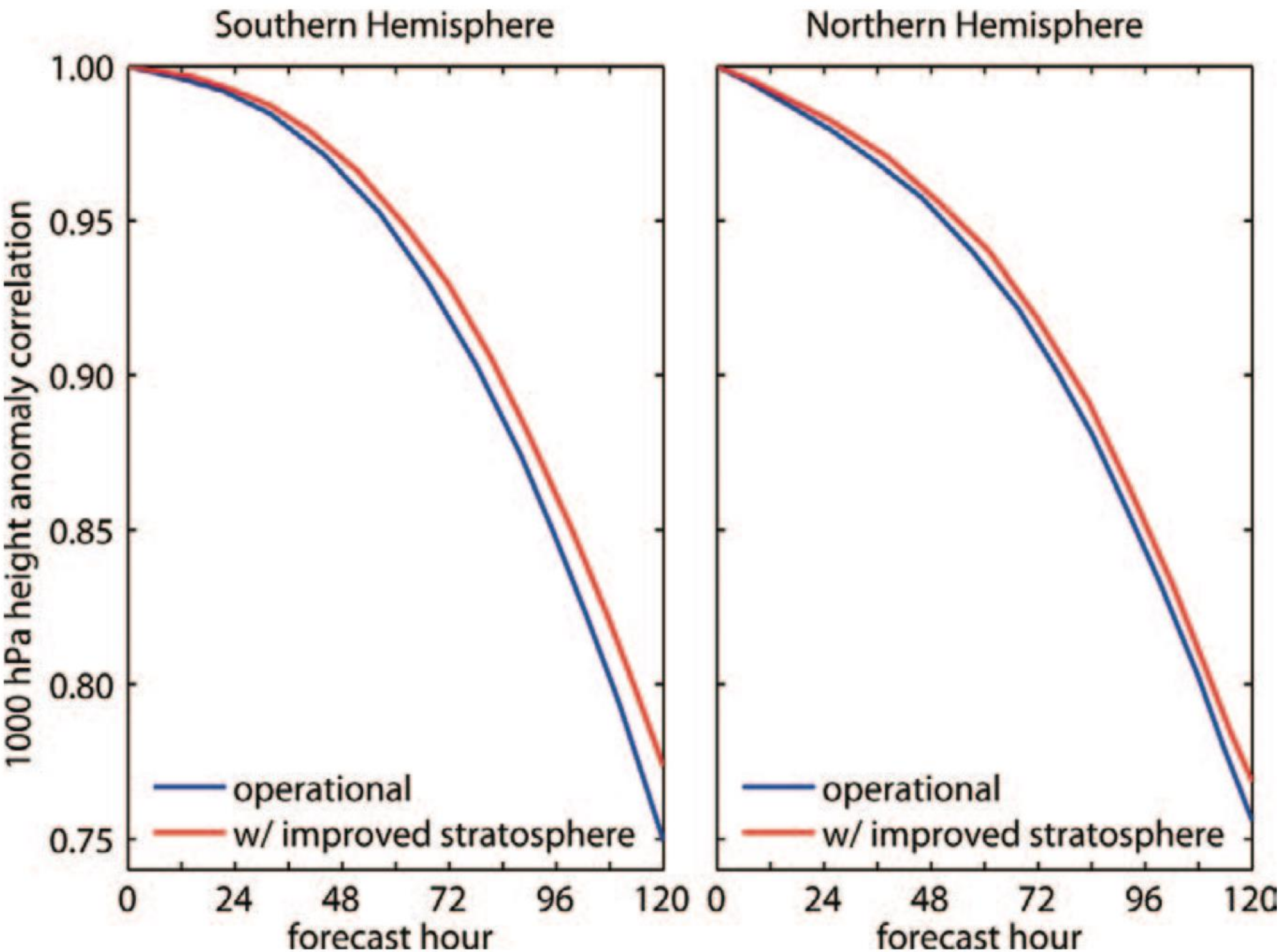
Stratosphere/Troposphere Coupling

- Stratosphere/Troposphere coupling is both ways
  - Coupled by gravity waves (GWs) and planetary waves (PWs)
- PWs and GWs affect stratosphere and stratospheric perturbations in turn affect the troposphere
- E.g., Sudden Stratospheric Warming events affect surface weather 1-4 weeks after onset



(Gerber et al. 2012)

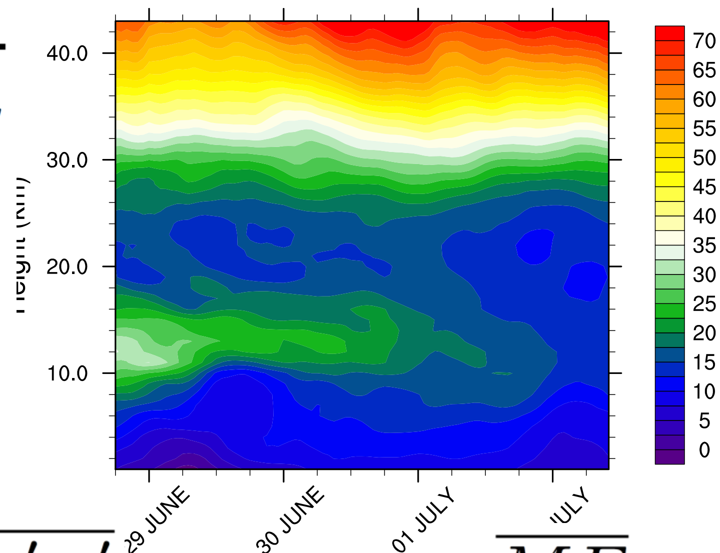
Extra: Including Stratosphere Improves Sfc Forecasts



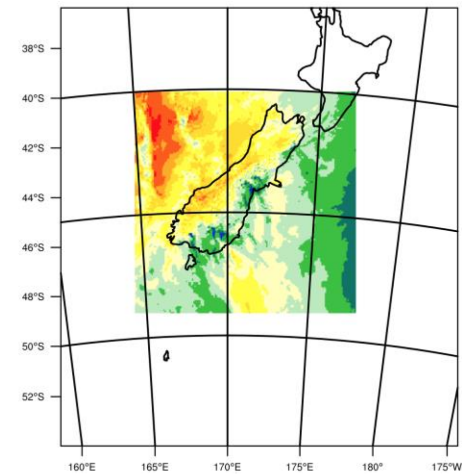
How does attenuation alter spectra?

FF01-02 Event

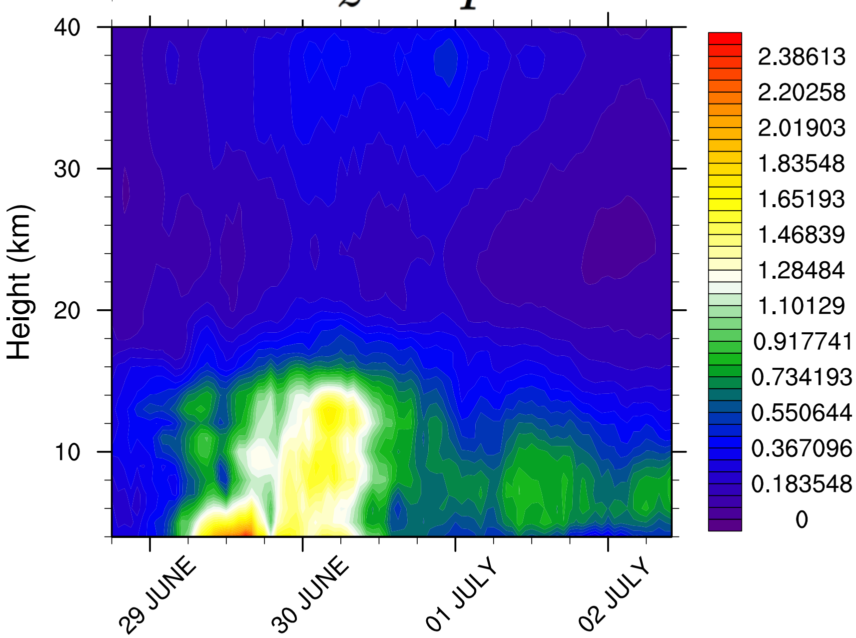
$$\overline{u}$$



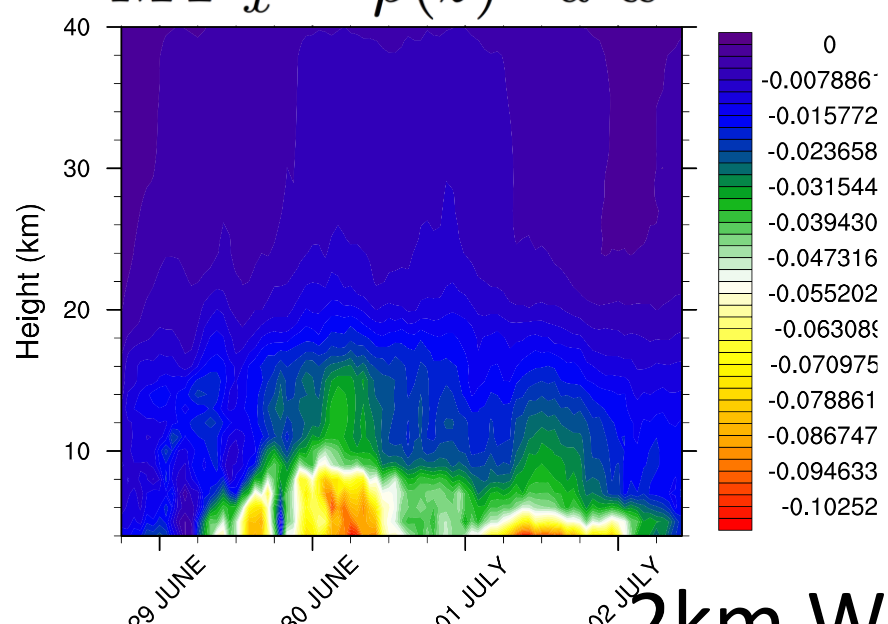
Area Considered



$$\overline{EF}_z = \overline{p'w'}$$



$$\overline{MF}_x = \overline{\rho}(z) \cdot \overline{u'w'}$$

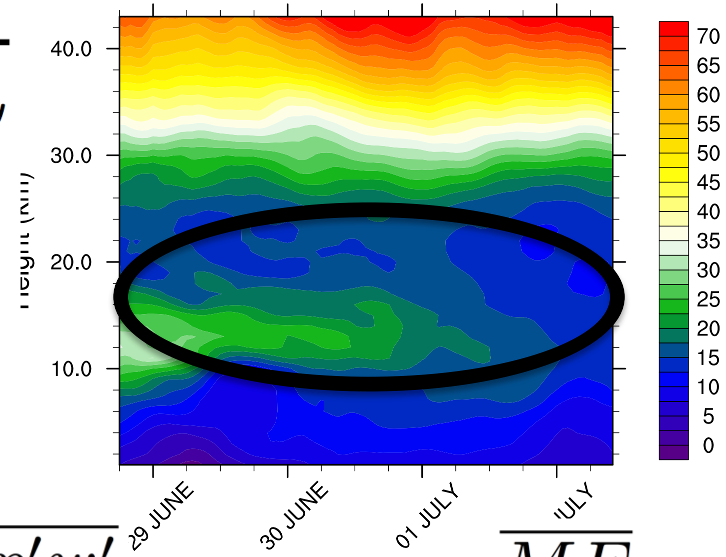


2km WRF

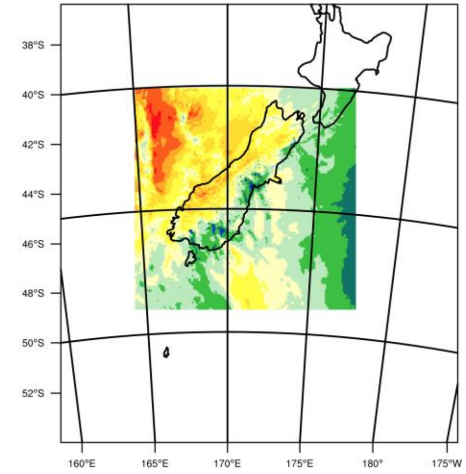
How does attenuation alter spectra?

FF01-02 Event

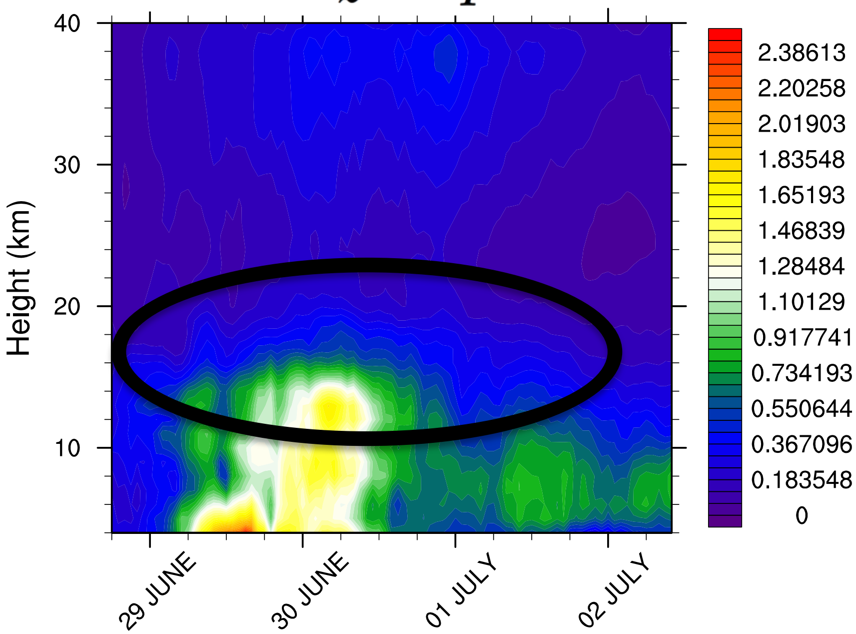
$\overline{u}$



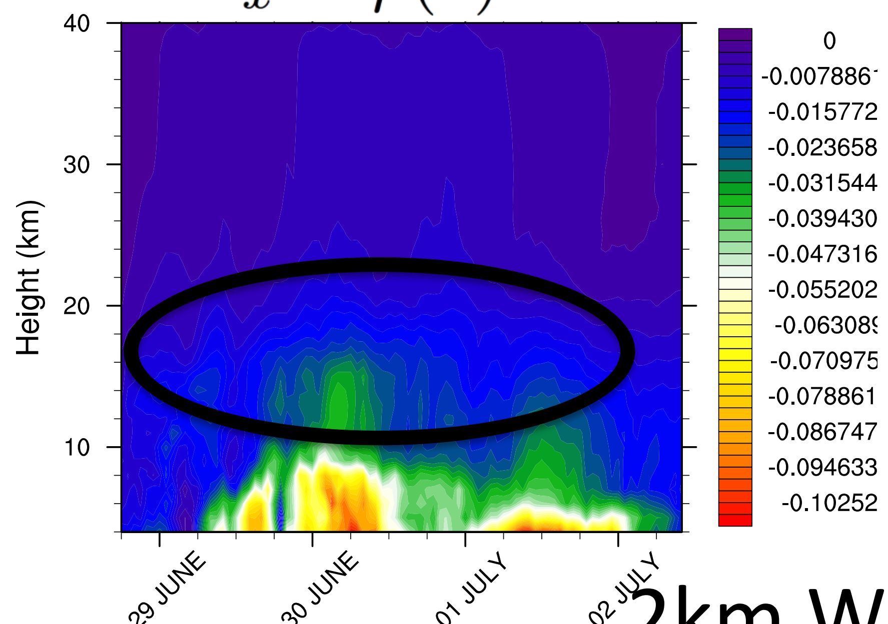
Area Considered



$$\overline{EF}_z = \overline{p'w'}$$



$$\overline{MF}_x = \overline{\rho}(z) \cdot \overline{u'w'}$$

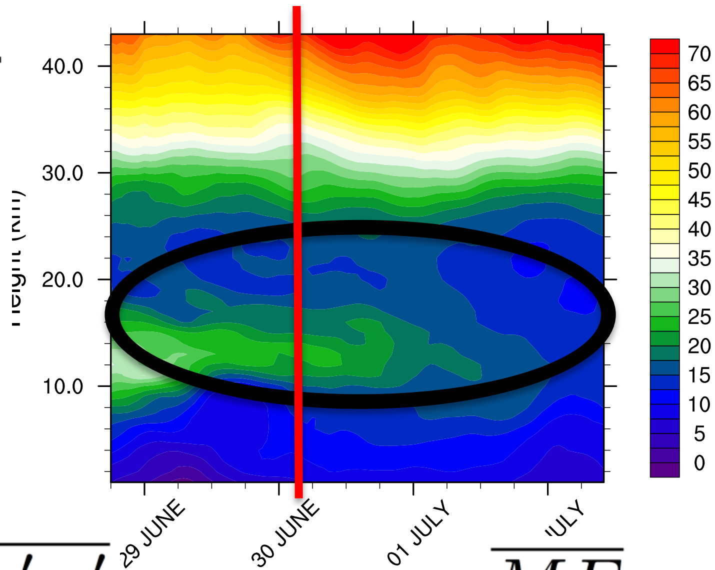


2km WRF

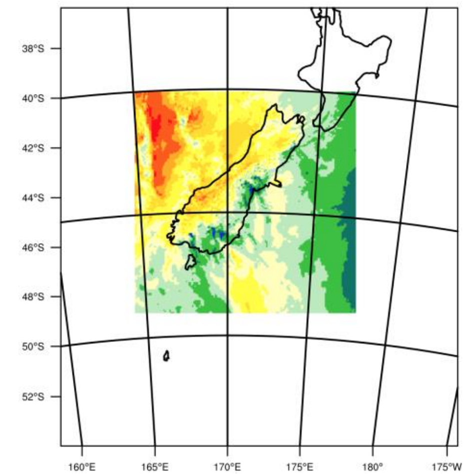
How does attenuation alter spectra?

FF01-02 Event

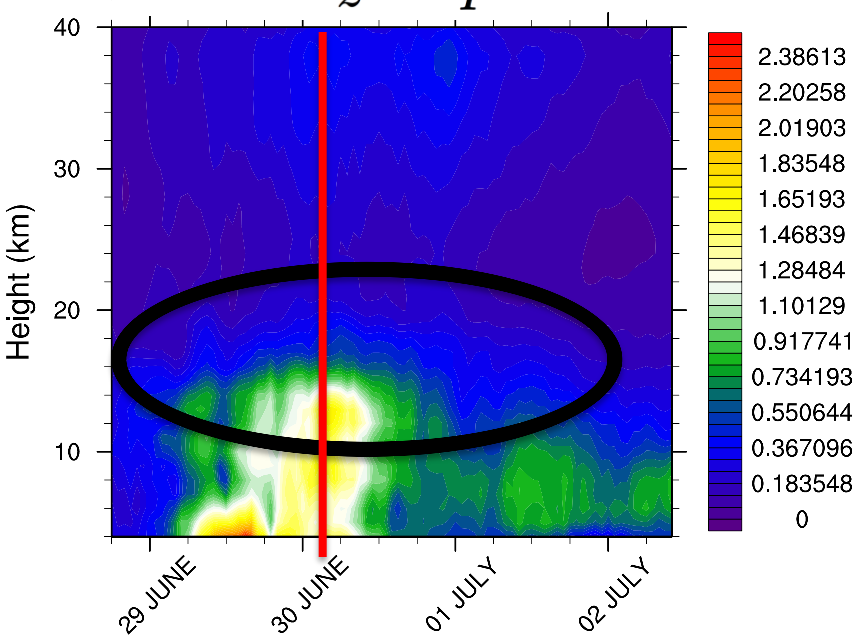
$\overline{u}$



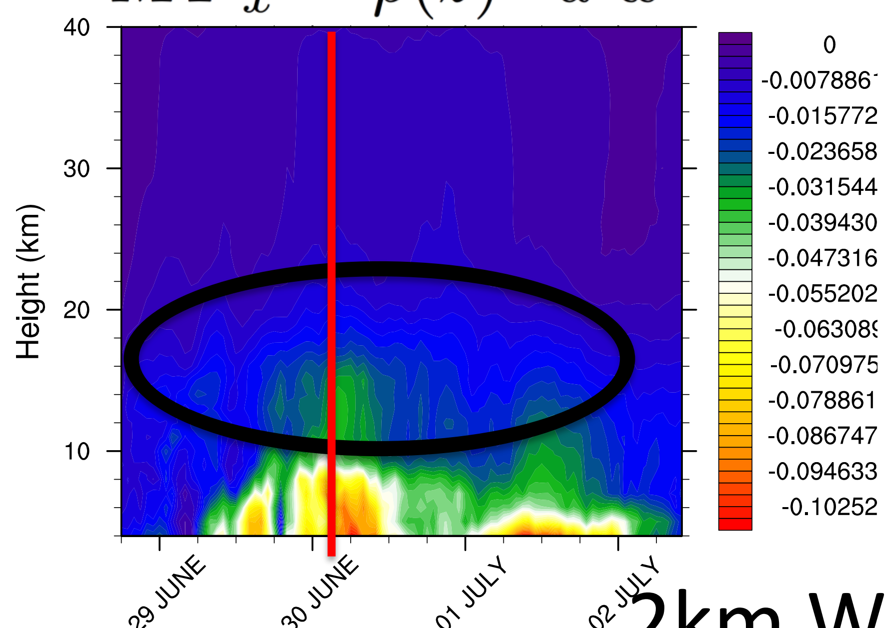
Area Considered



$$\overline{EF}_z = \overline{p'w'}$$



$$\overline{MF}_x = \overline{\rho}(z) \cdot \overline{u'w'}$$



2km WRF

How does attenuation alter spectra?

W Specta

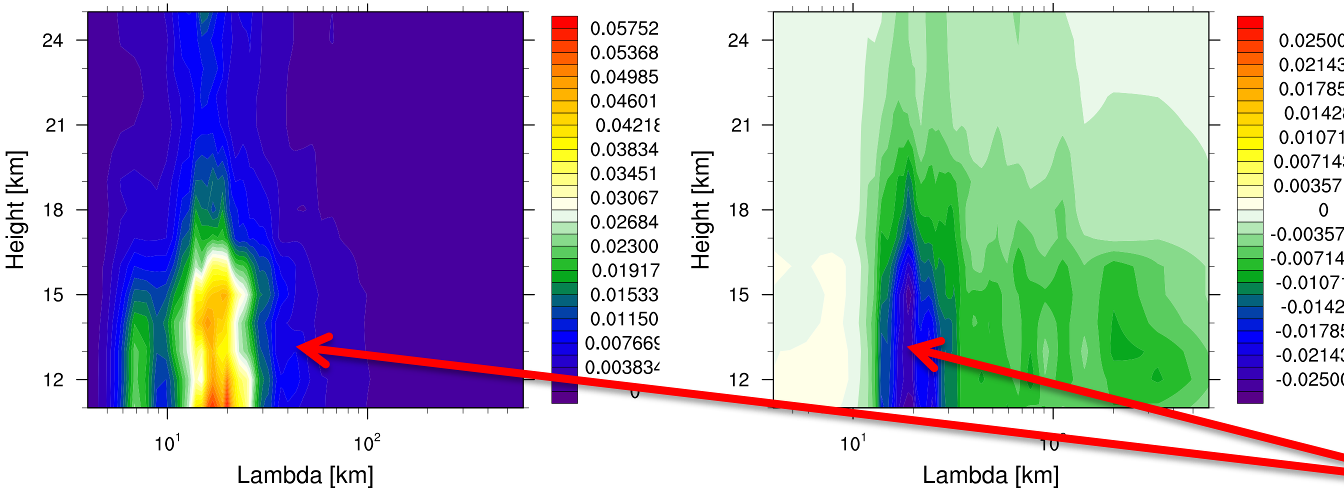
$$\sqrt{\overline{\rho}(z)}\frac{\partial}{\partial \ln\lambda}\sigma_w^2(\ln\lambda, z)$$

MF_x Spectra

$$\frac{\partial}{\partial \ln\lambda}MF_x(\ln\lambda, z)$$

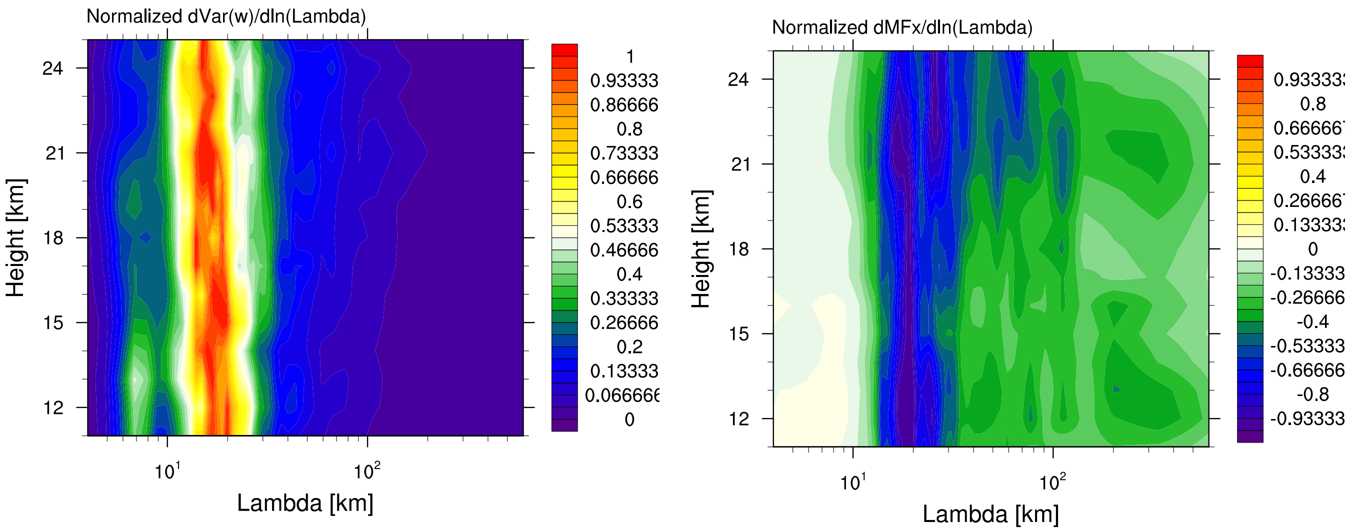
30 June 2014

3 UTC



MF$_x$ Conservation @ all scales

Spectra Normalized by max at every z



2km WRF

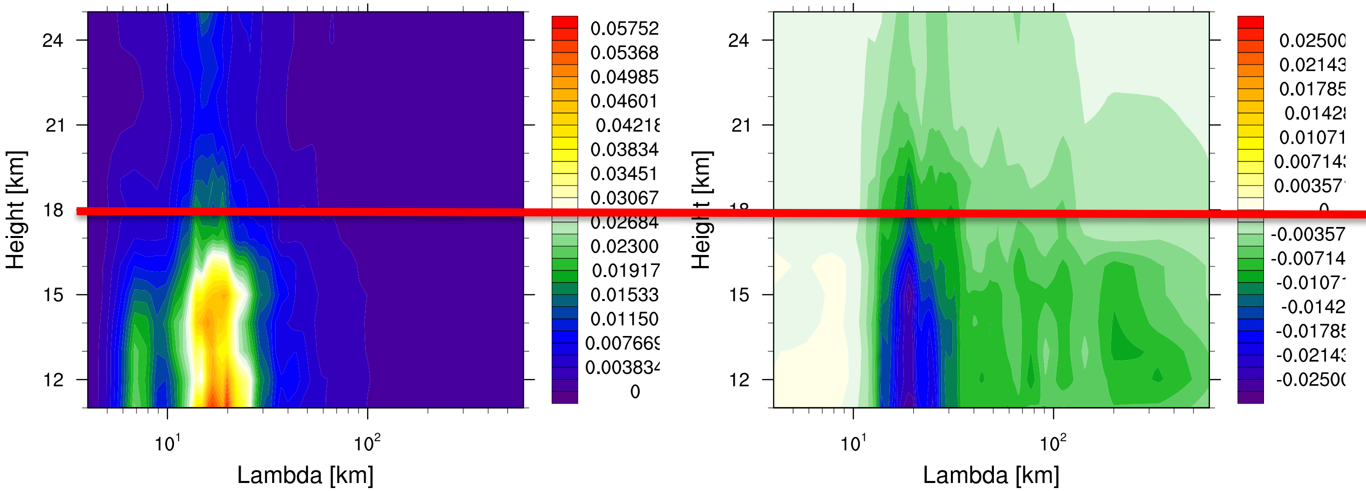
How does attenuation alter spectra?

W Specta | **MF$_x$ Spectra**

30 June 2014
3 UTC

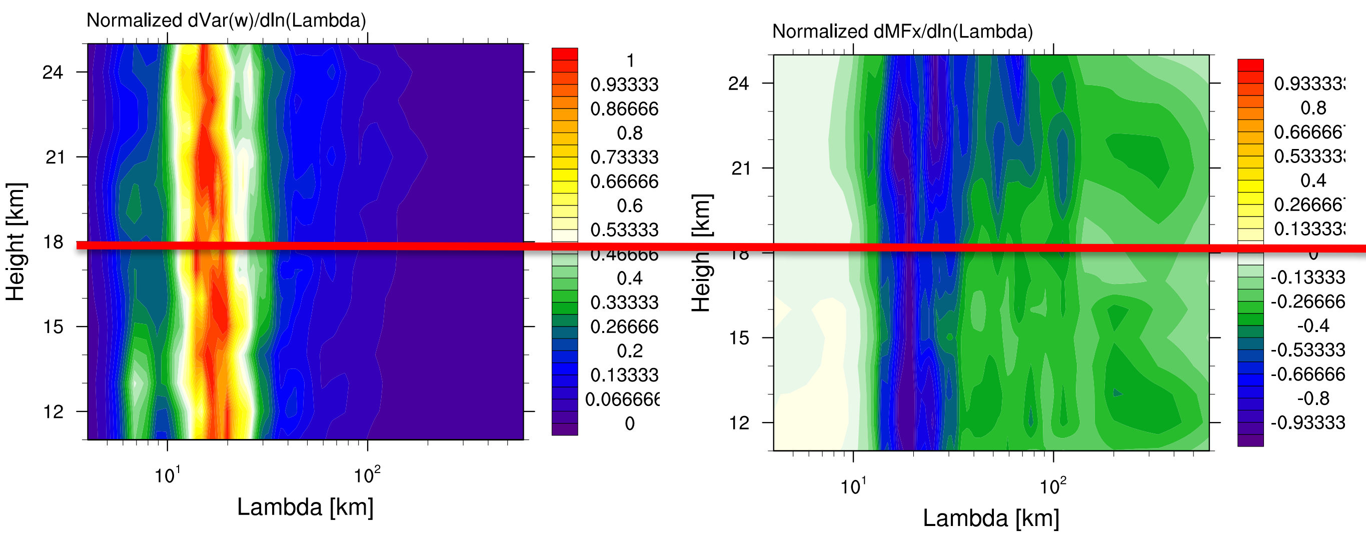
$$\sqrt{\bar{\rho}(z)}\frac{\partial}{\partial \ln \lambda}\sigma_w^2(\ln \lambda, z)$$

$$\frac{\partial}{\partial \ln \lambda}MF_x(\ln \lambda, z)$$



Attenuation
@ all scales

Spectra Normalized by max at every z



2km WRF

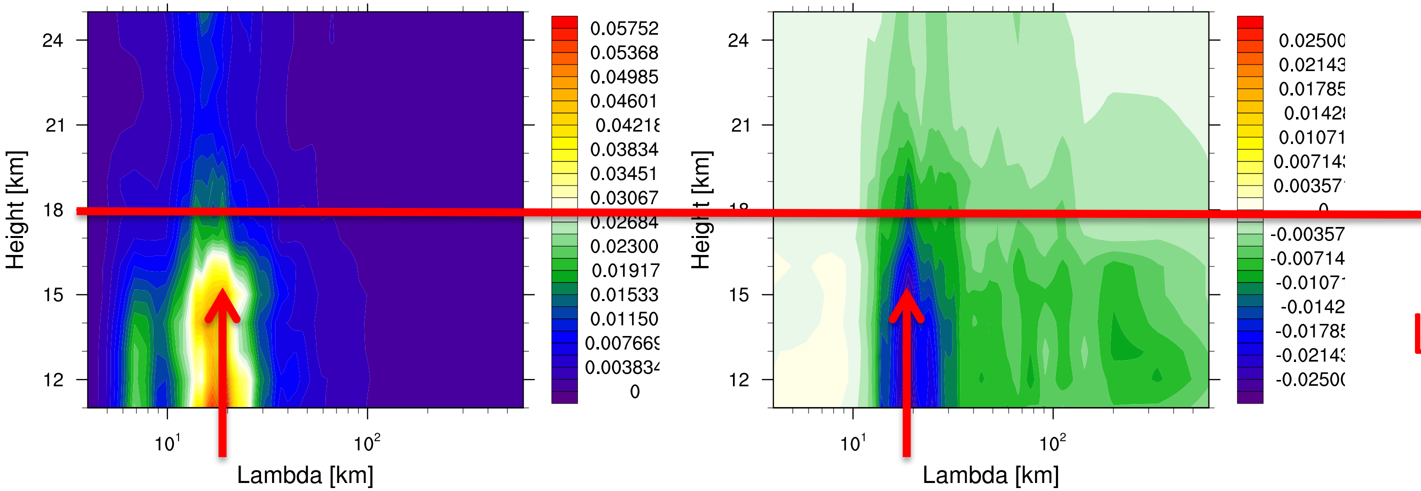
How does attenuation alter spectra?

30 June 2014
3 UTC

W Specta | **MF_x Spectra**

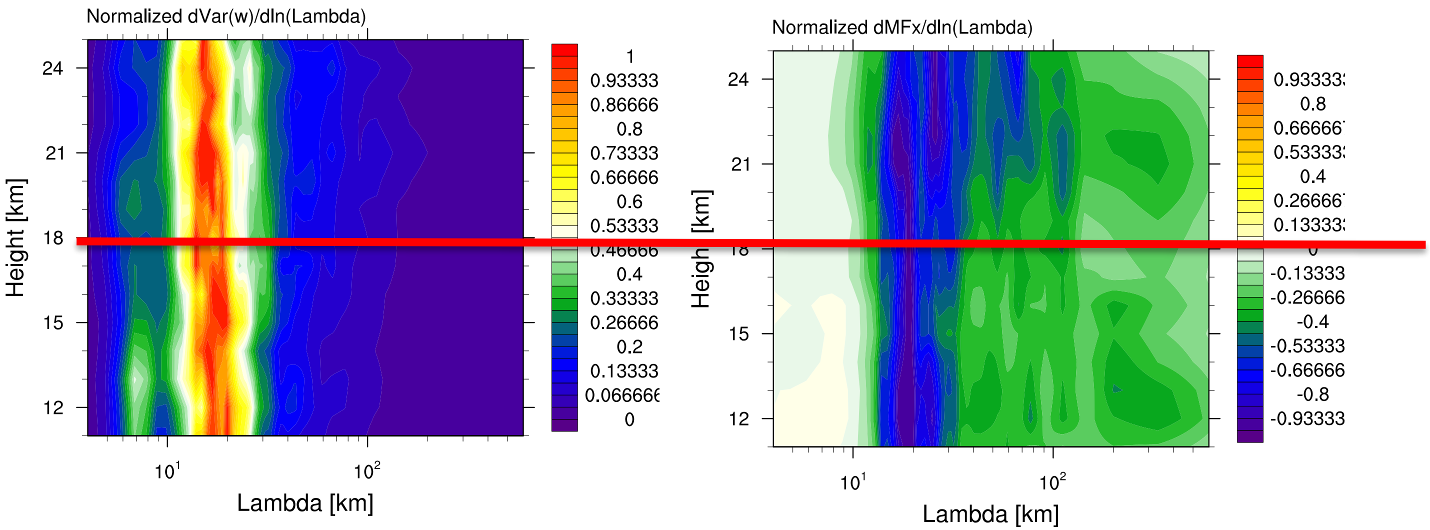
$$\sqrt{\bar{\rho}(z)}\frac{\partial}{\partial \ln \lambda}\sigma_w^2(\ln \lambda, z)$$

$$\frac{\partial}{\partial \ln \lambda}MF_x(\ln \lambda, z)$$



Largest Amplitude Waves Most Attenuated

Spectra Normalized by max at every z



2km WRF

How does attenuation alter spectra?

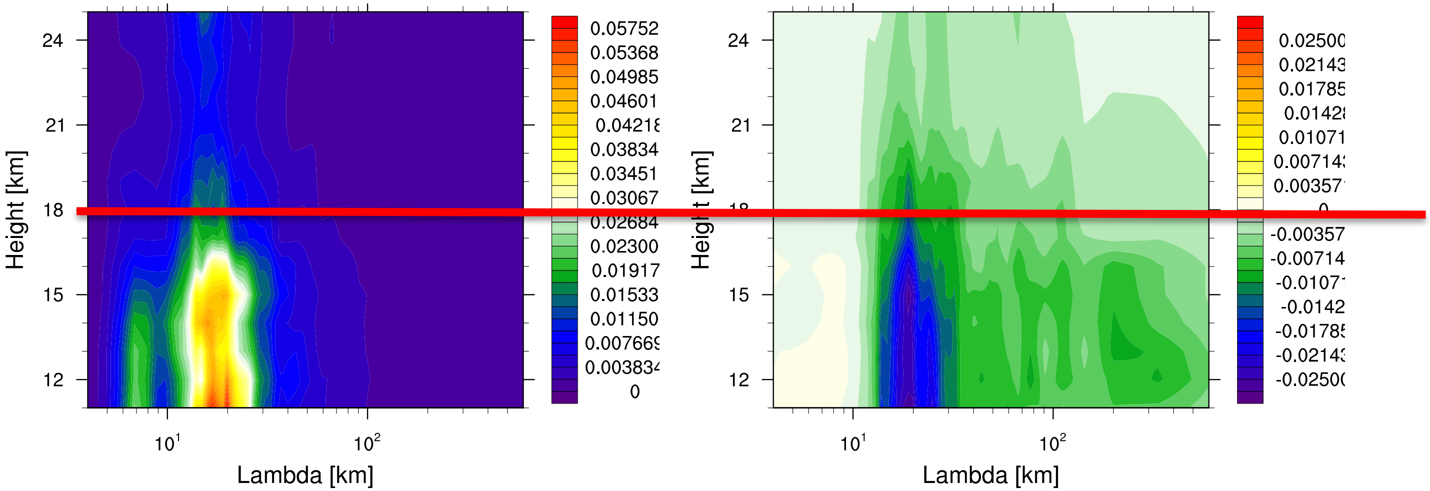
30 June 2014
3 UTC

W Specta

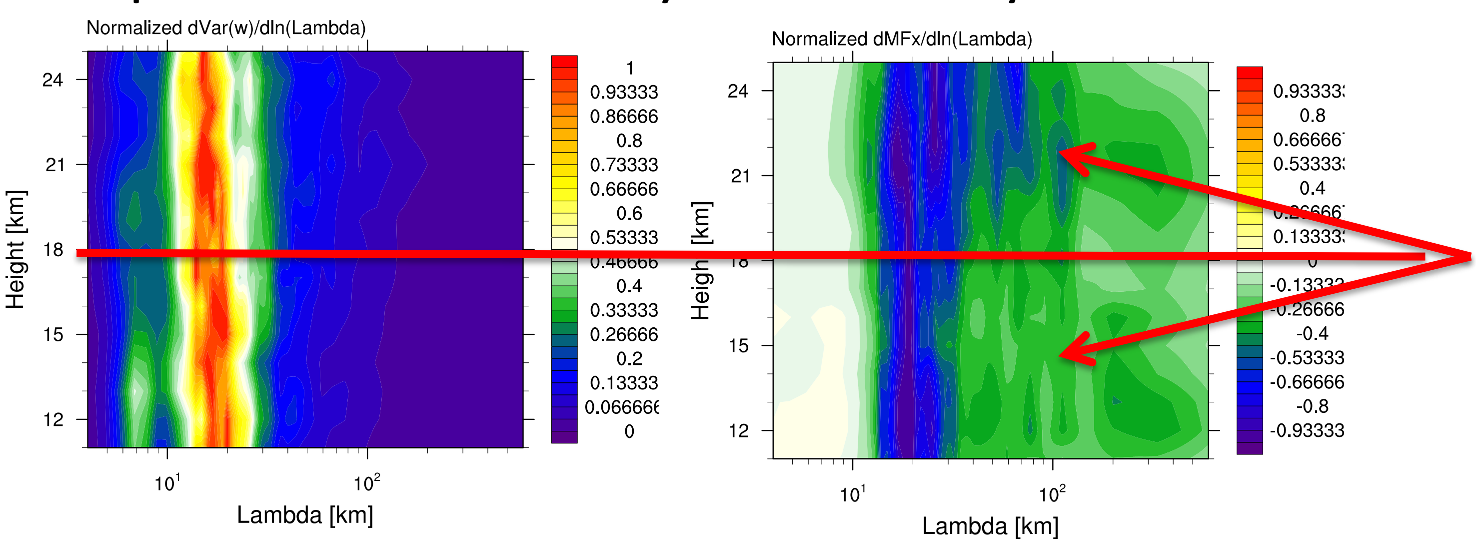
$$\sqrt{\bar{\rho}(z)}\frac{\partial}{\partial \ln\lambda}\sigma_w^2(\ln\lambda, z)$$

MF_x Spectra

$$\frac{\partial}{\partial \ln\lambda}MF_x(\ln\lambda, z)$$



Spectra Normalized by max at every z



Scales above breaking region existed below

2km WRF

How does attenuation alter spectra?

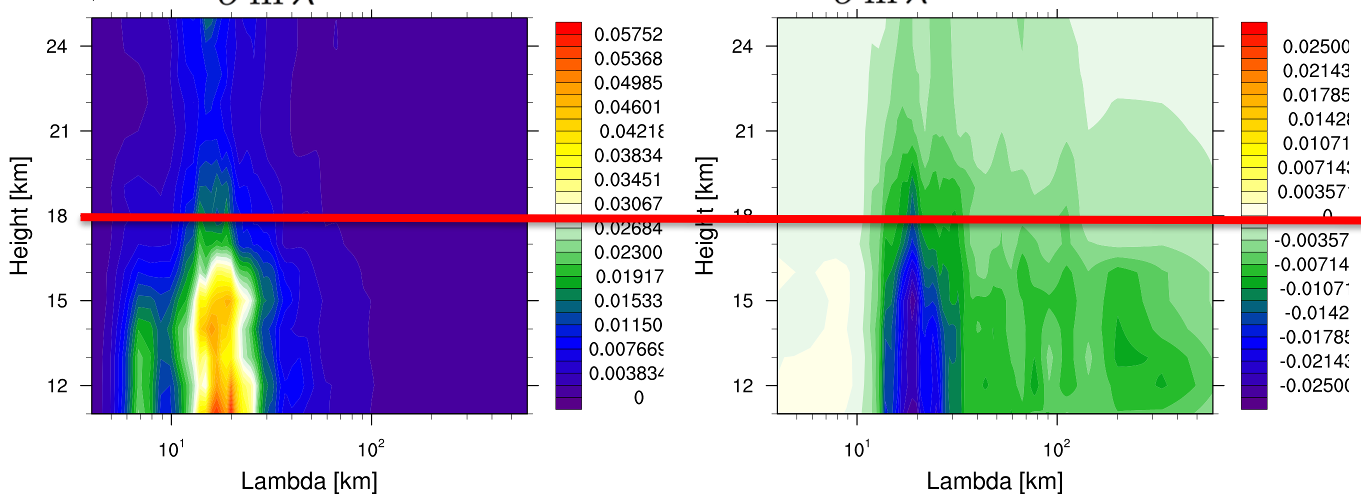
30 June 2014
3 UTC

W Specta

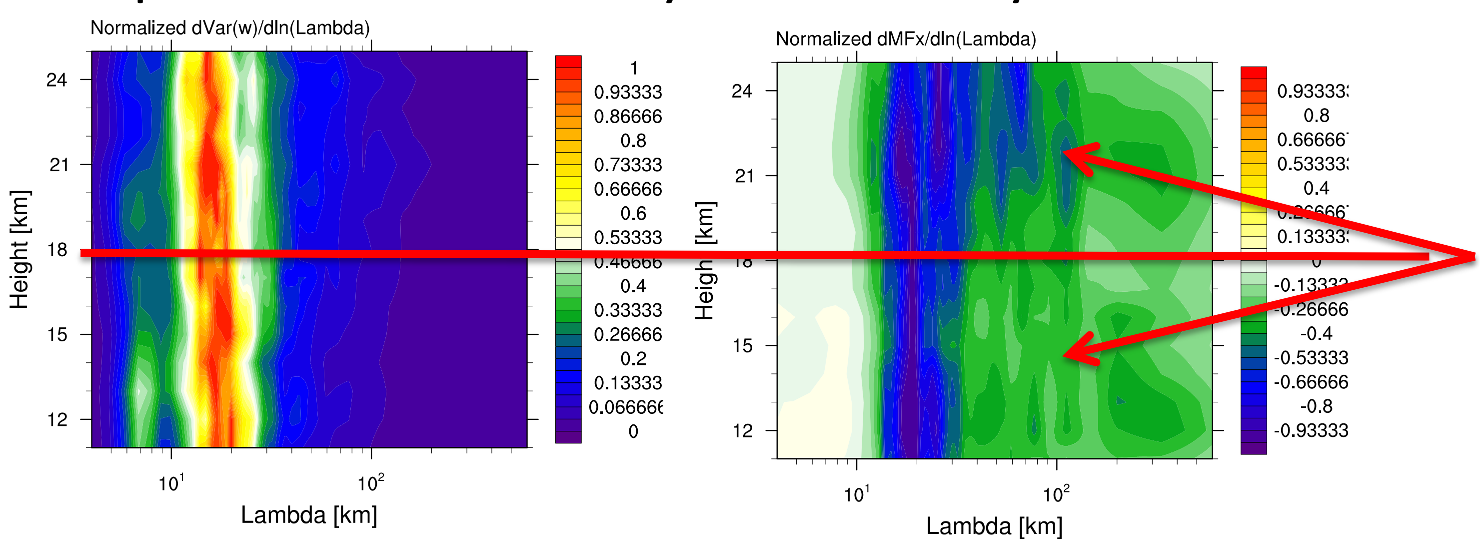
$$\sqrt{\overline{\rho}(z)}\frac{\partial}{\partial \ln \lambda}\sigma_w^2(\ln \lambda, z)$$

MF_x Spectra

$$\frac{\partial}{\partial \ln \lambda}MF_x(\ln \lambda, z)$$



Spectra Normalized by max at every z

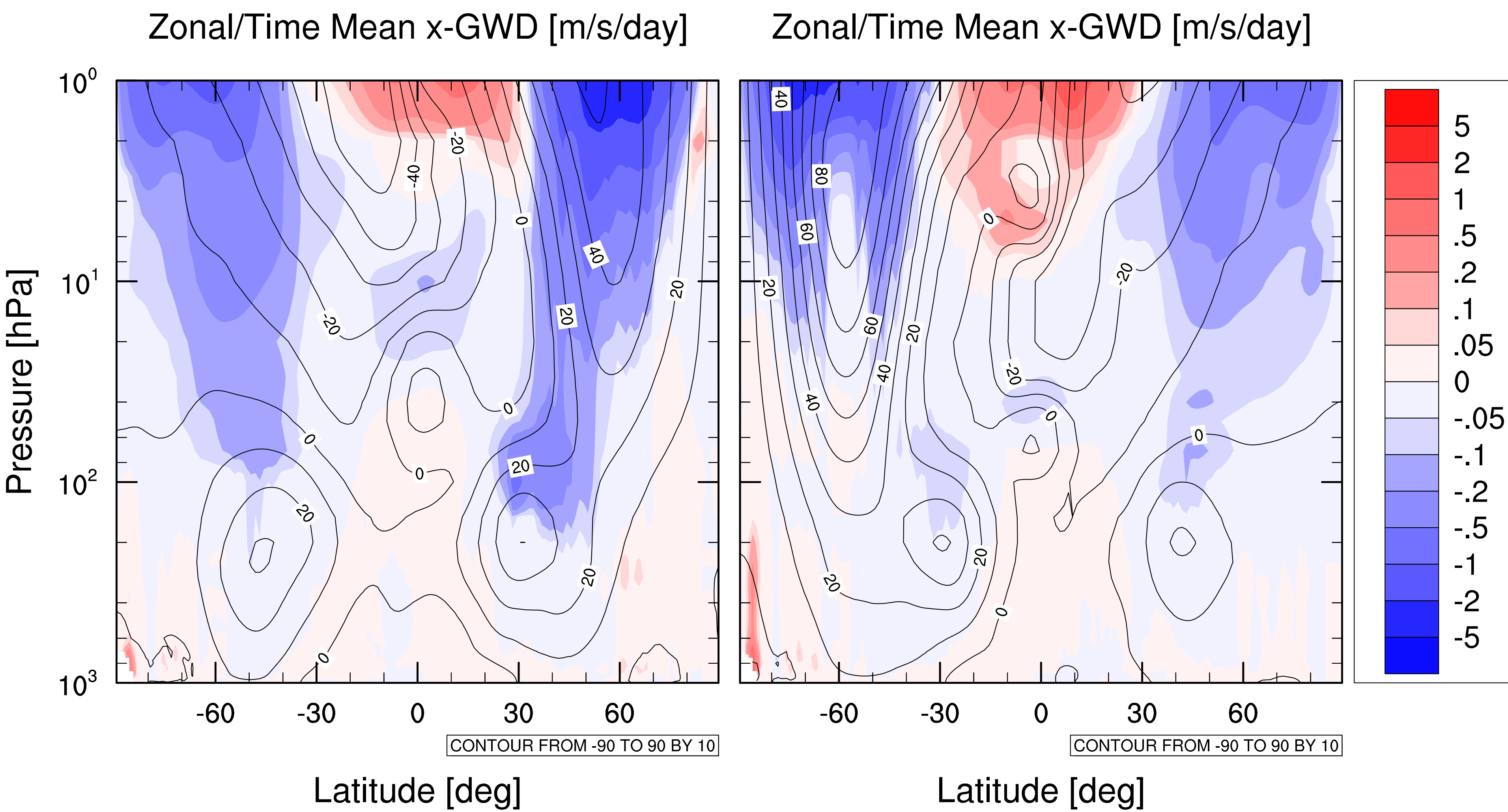


No new scales?
No secondary generation?

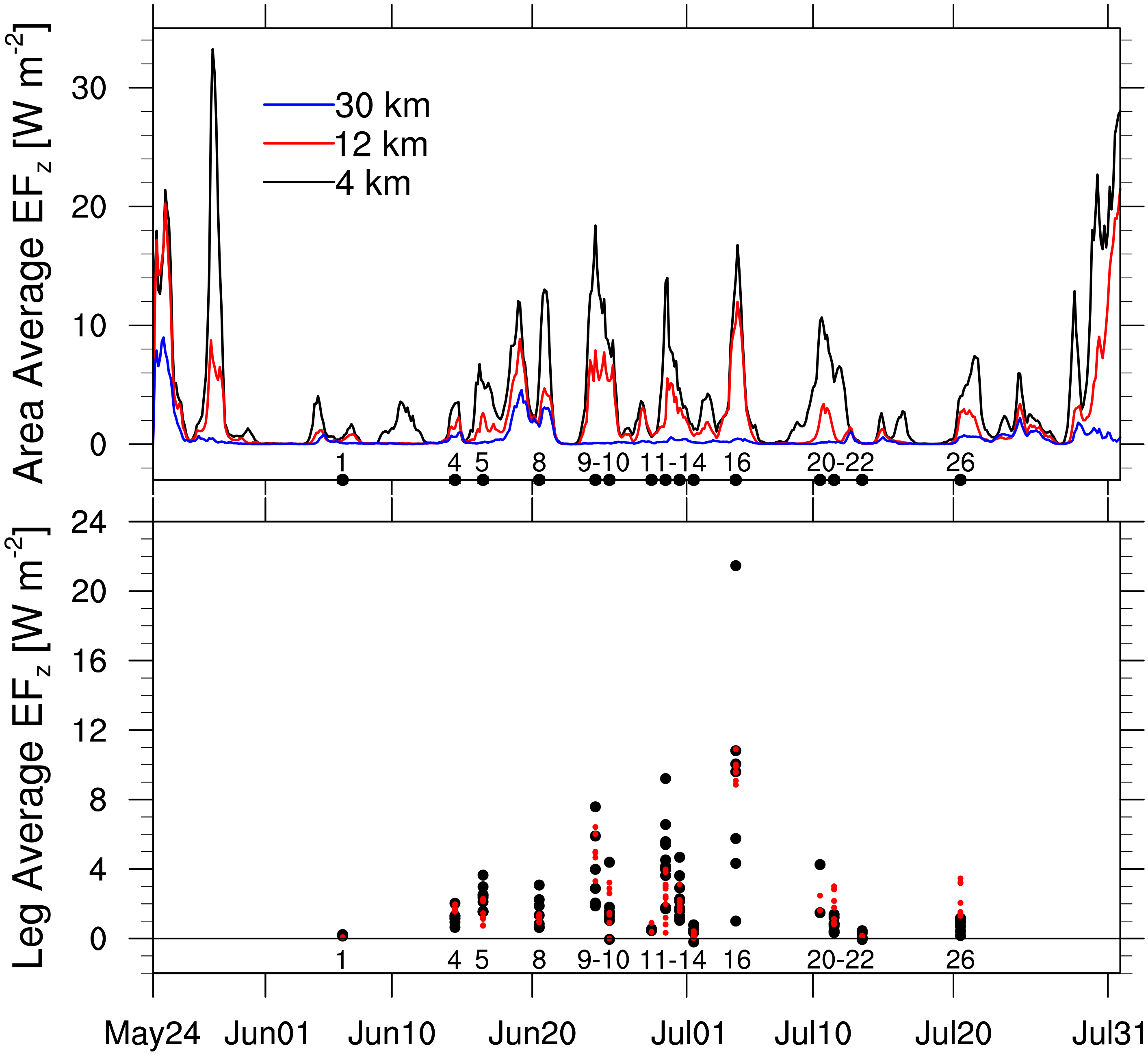
2km WRF

MERRA Zonal Winds, GWD

NH Winter (DJF) / SH Winter (DJF)



WRF/Obs Leg Avg EFz Comparison



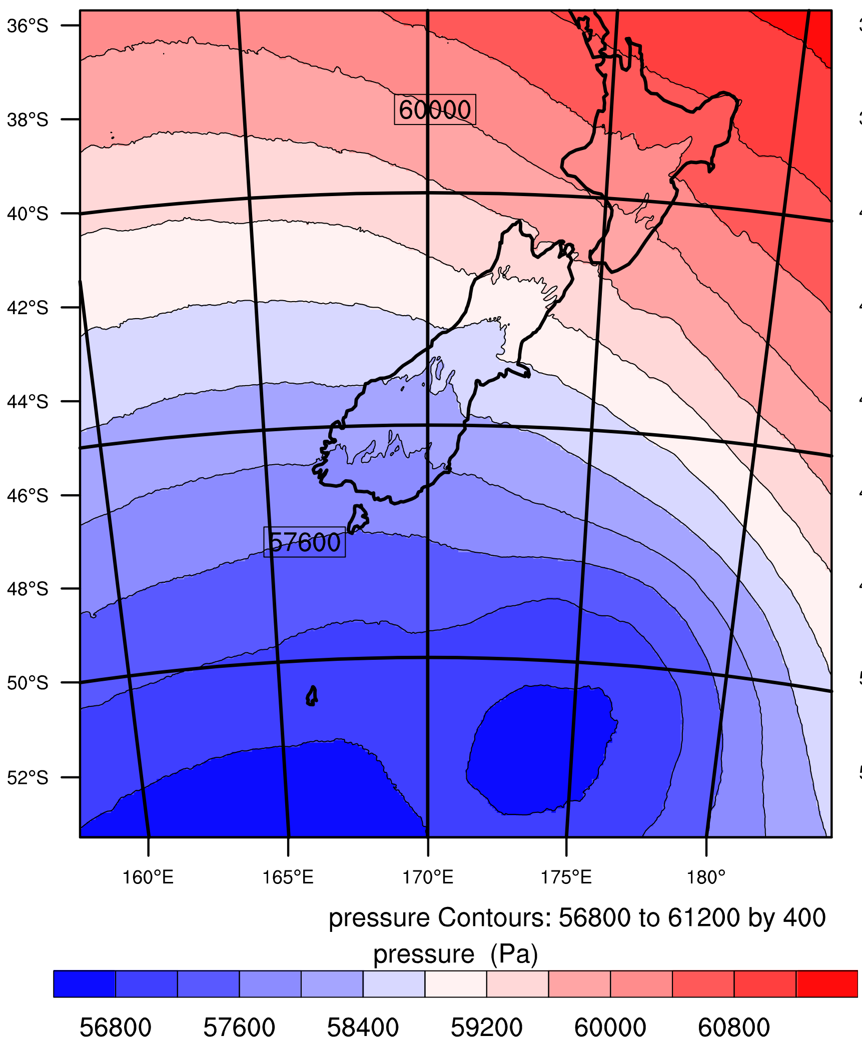
Quantifying Gravity Waves in WRF

- Kruse and Smith (2015) proposed a 2-D spectral filtering method involving
  1. Subtracting the best-fit plane
     - Reduces aperiodicity
  2. High-pass filtering
     - Removes scales larger than the cut-off scale L
  3. Computing quadratic diagnostics
     - E.g., vertical flux of zonal momentum: $MF_x = \overline{\rho} u' w'$

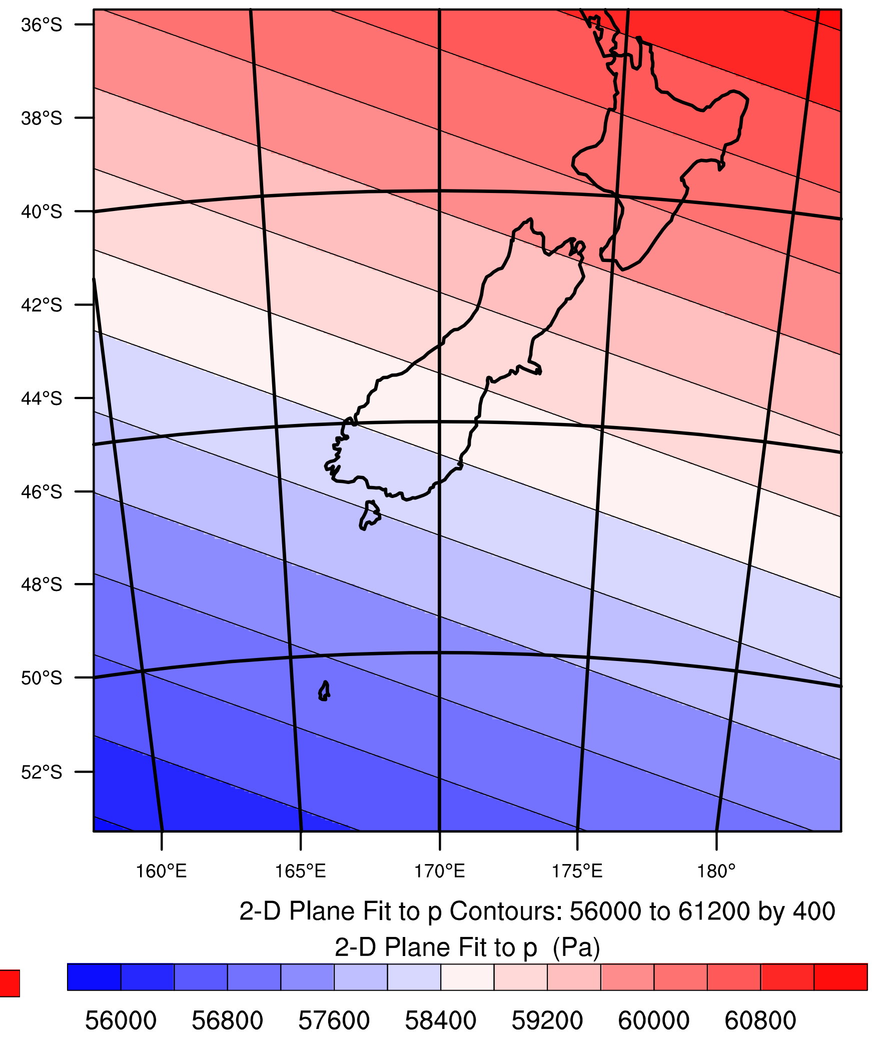
Perturbation Isolation Example

4-km

Full Pressure p



Best Fit Pressure Plane $\tilde{p}$

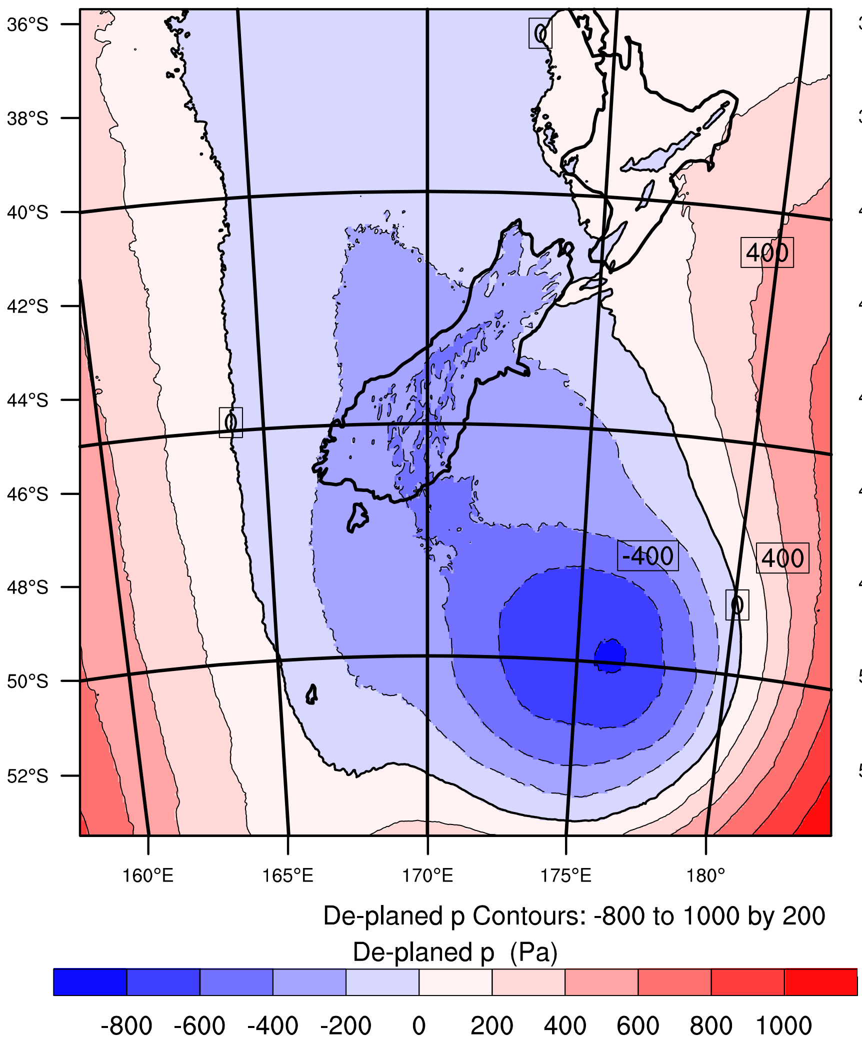


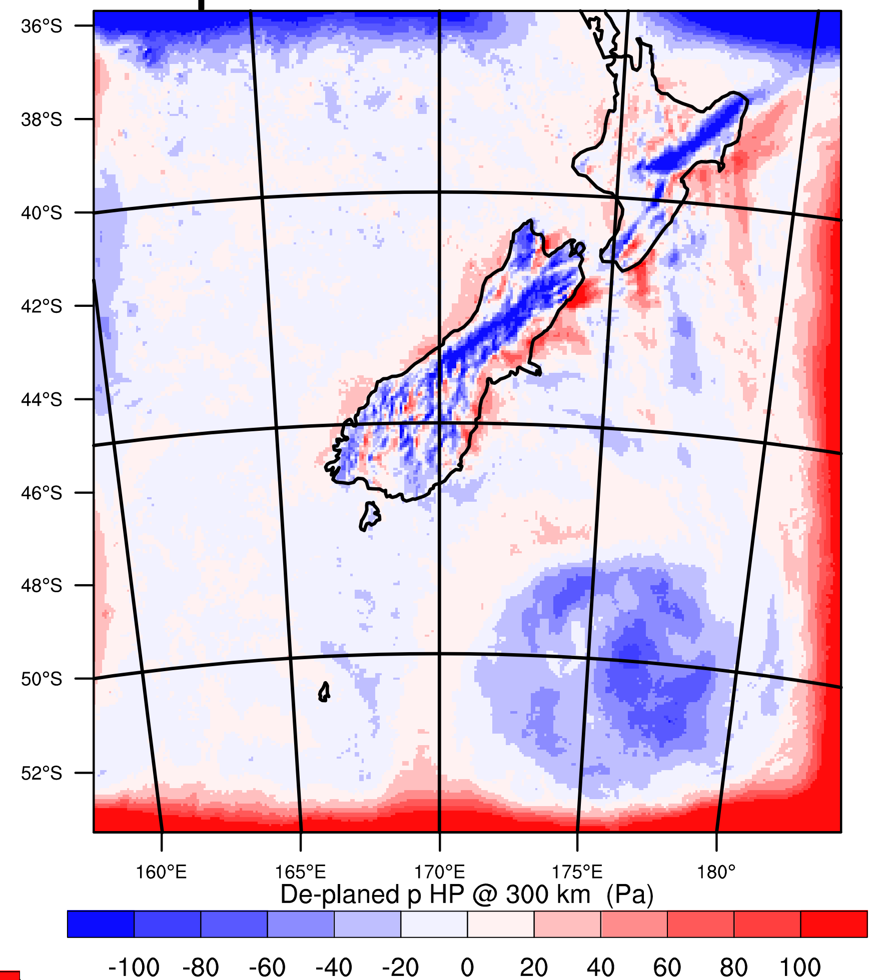
Perturbation Isolation Example

4-km

Deplaned Pressure $p - \tilde{p}$

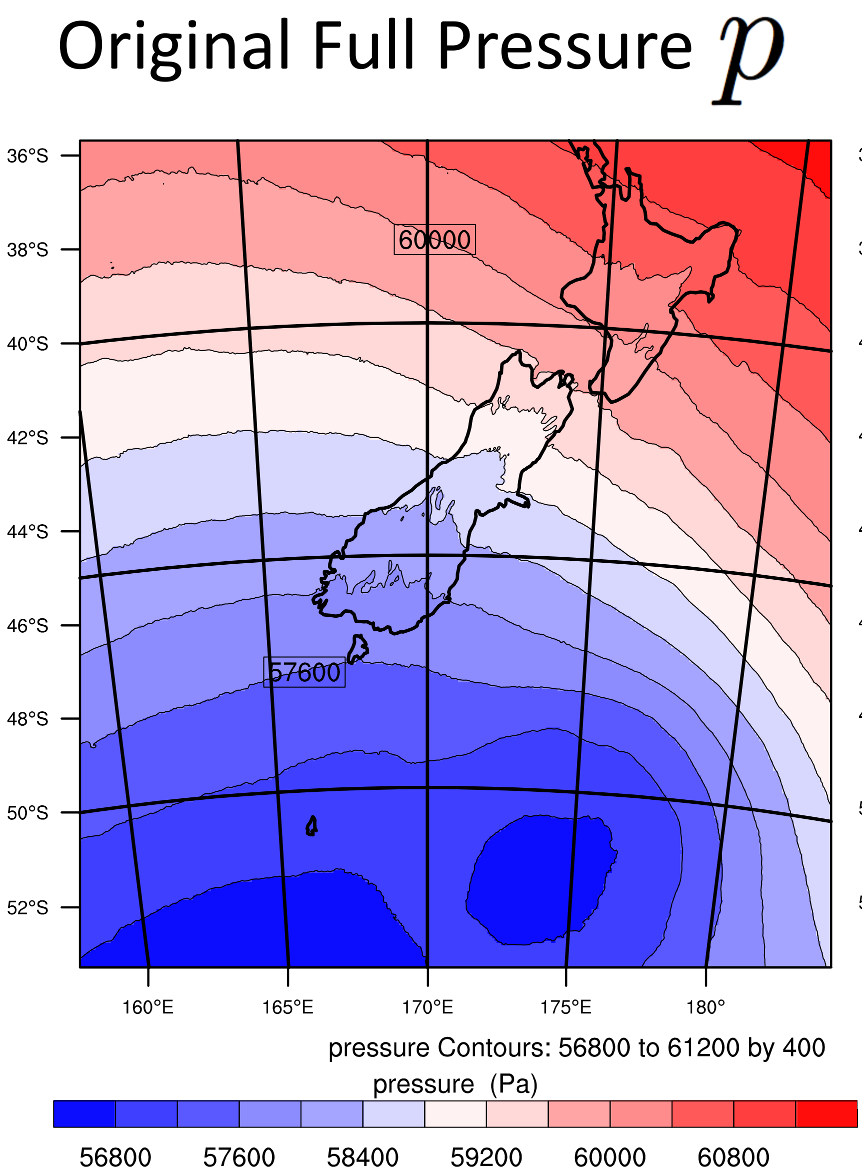
High-Passed Deplaned Pressure p'

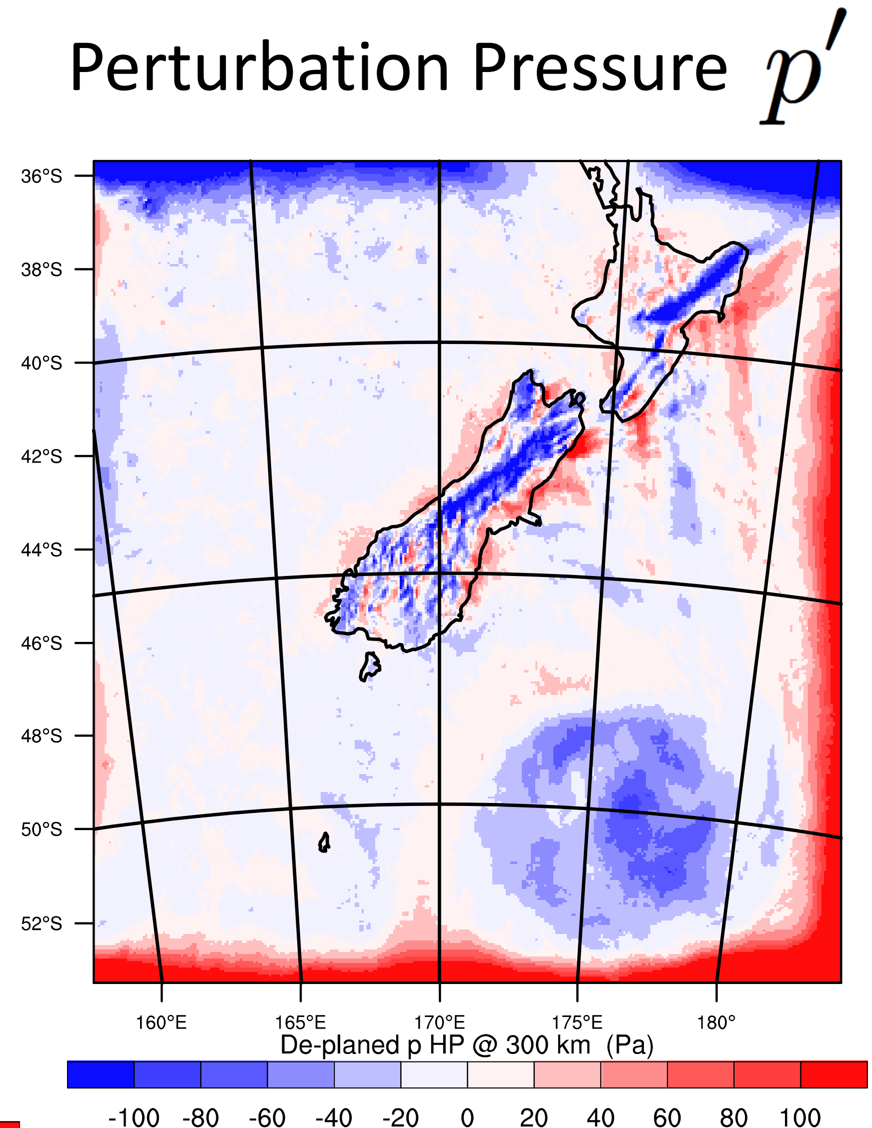




Perturbation Isolation Example

4-km

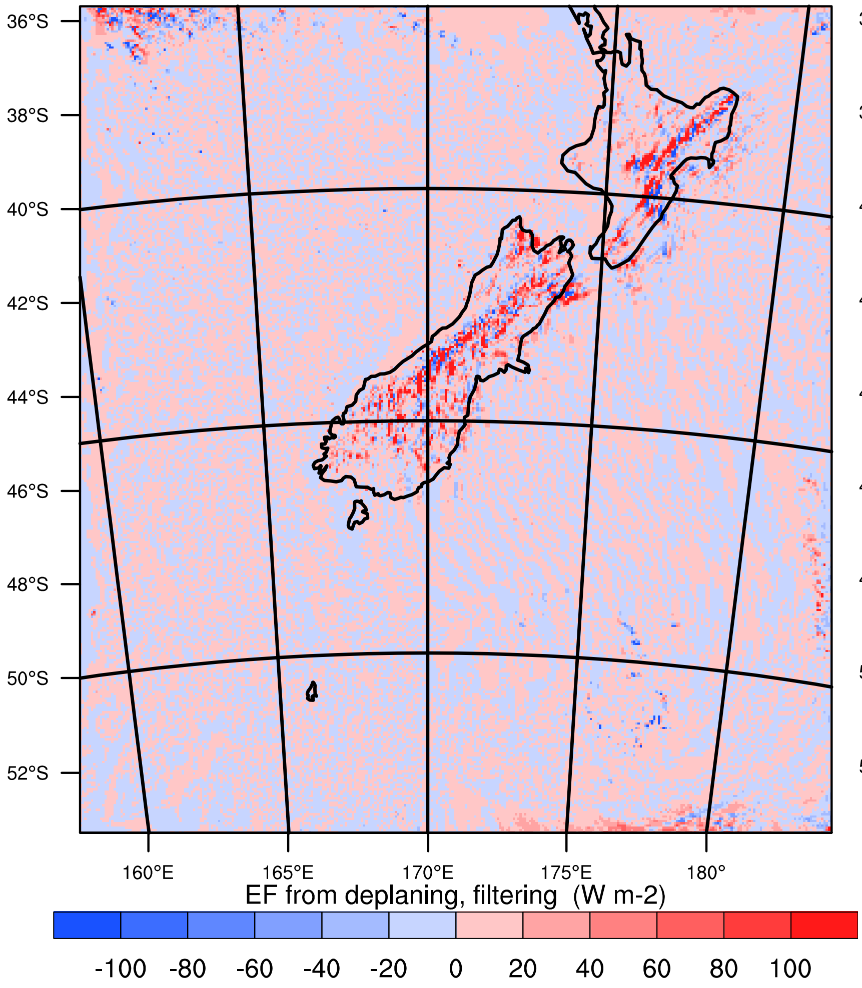




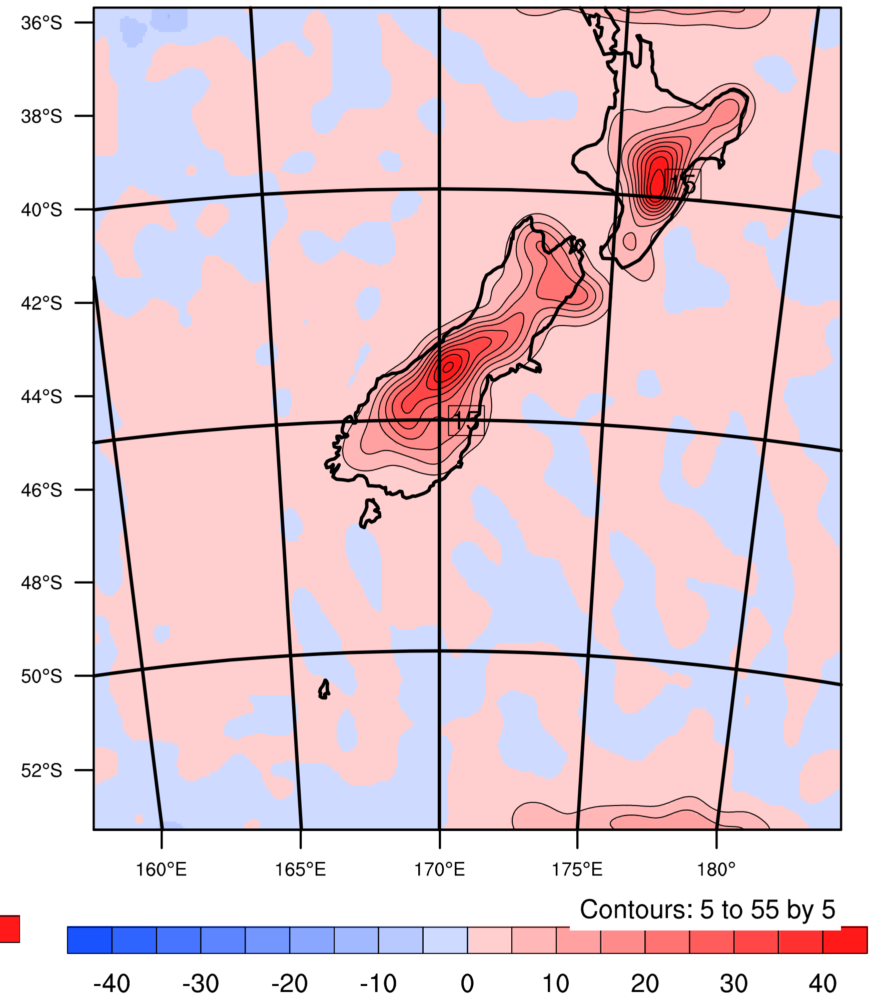
EF_z Diagnostic Example

4-km

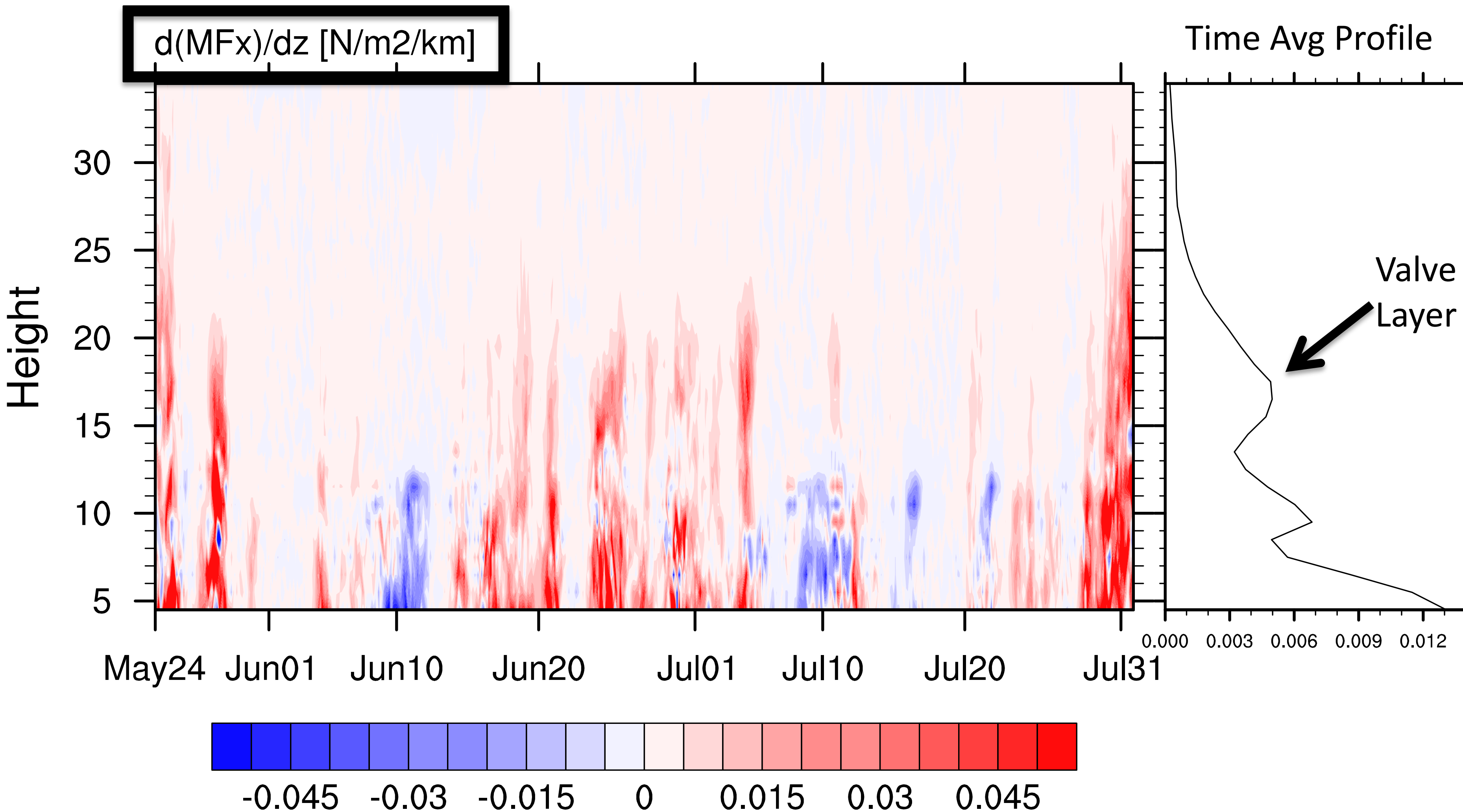
Raw $EF_z = p'w'$



Low-passed EF_z



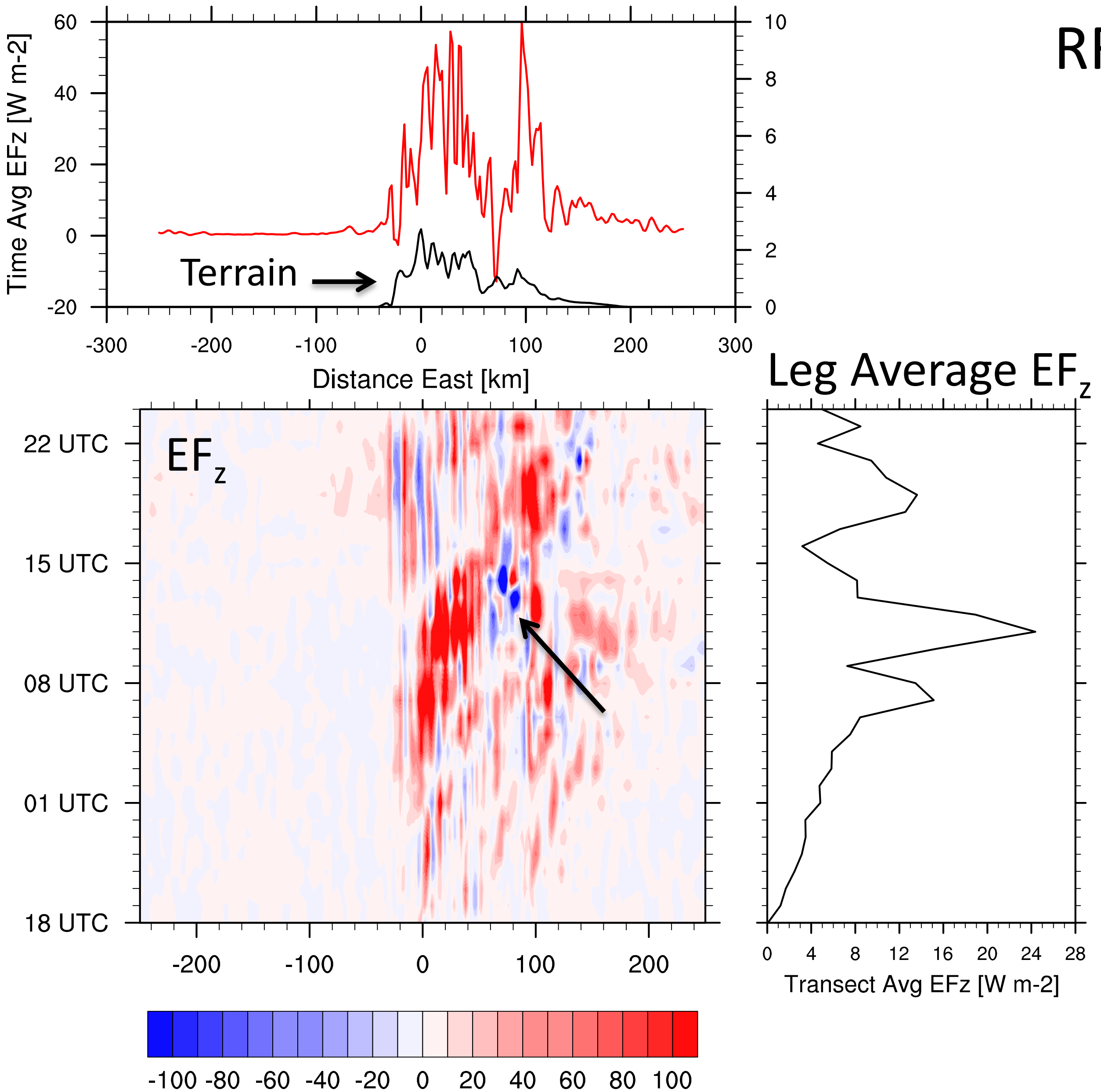
South Island Avg MF_x Divergence

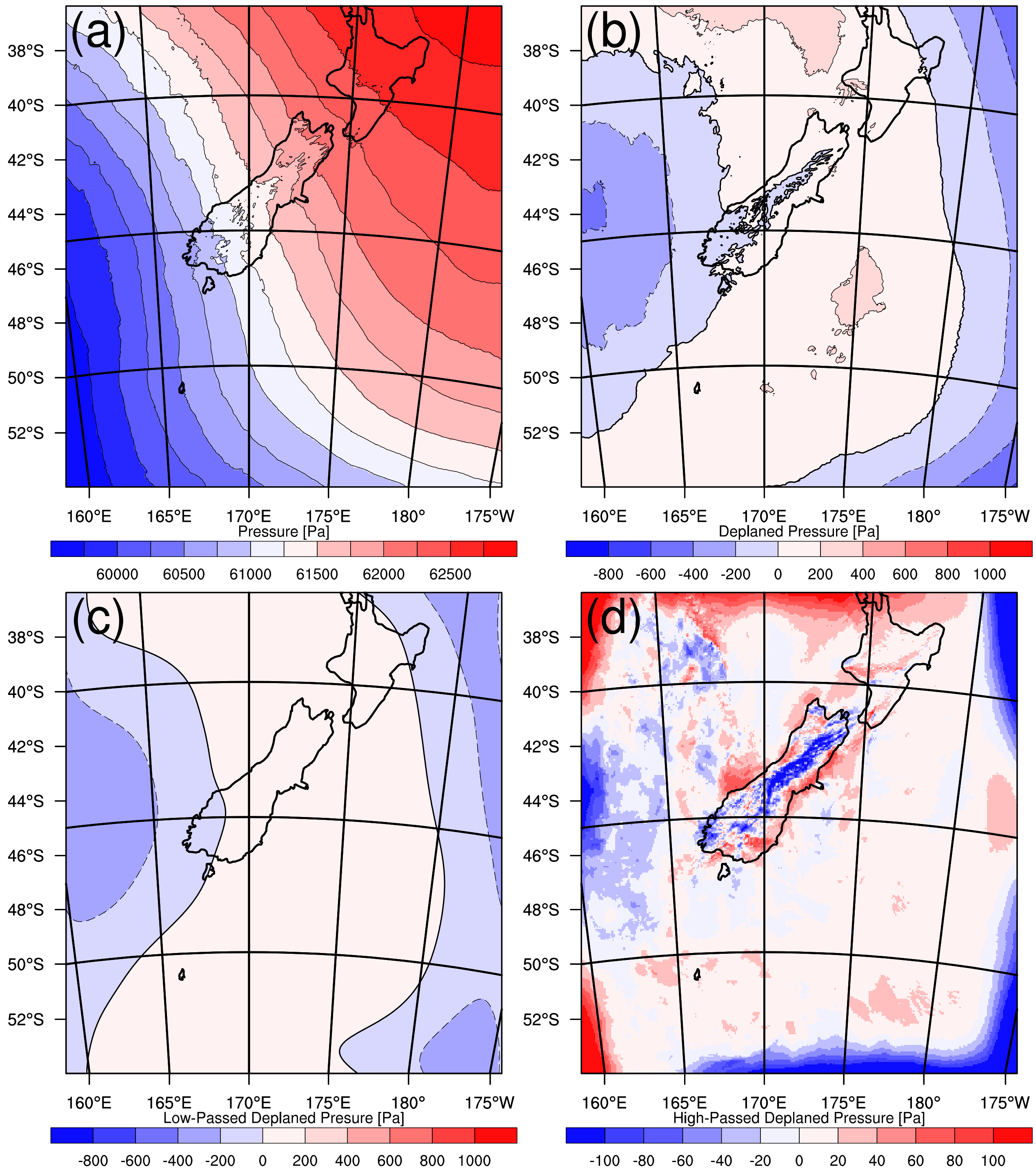


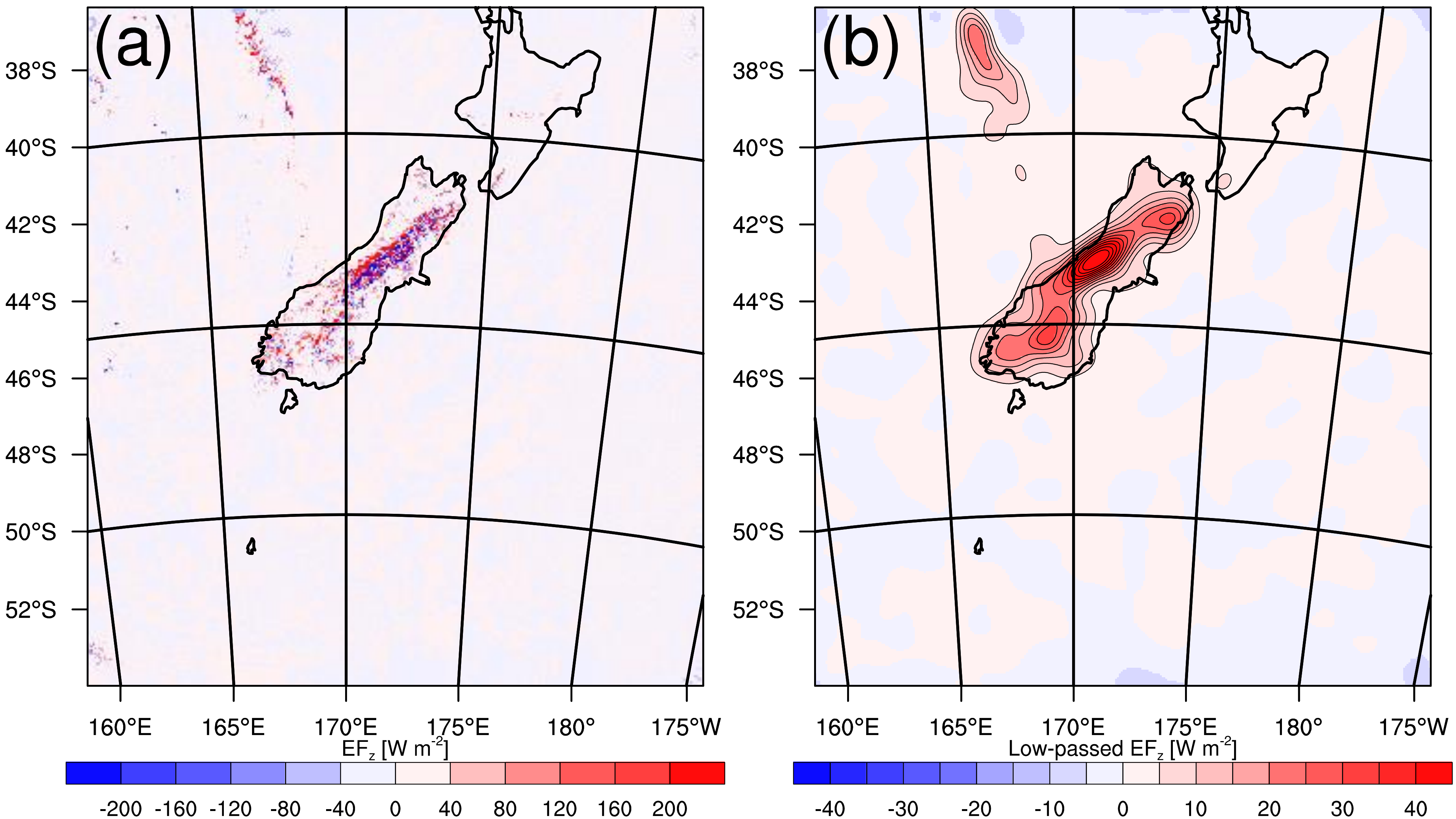
6km WRF

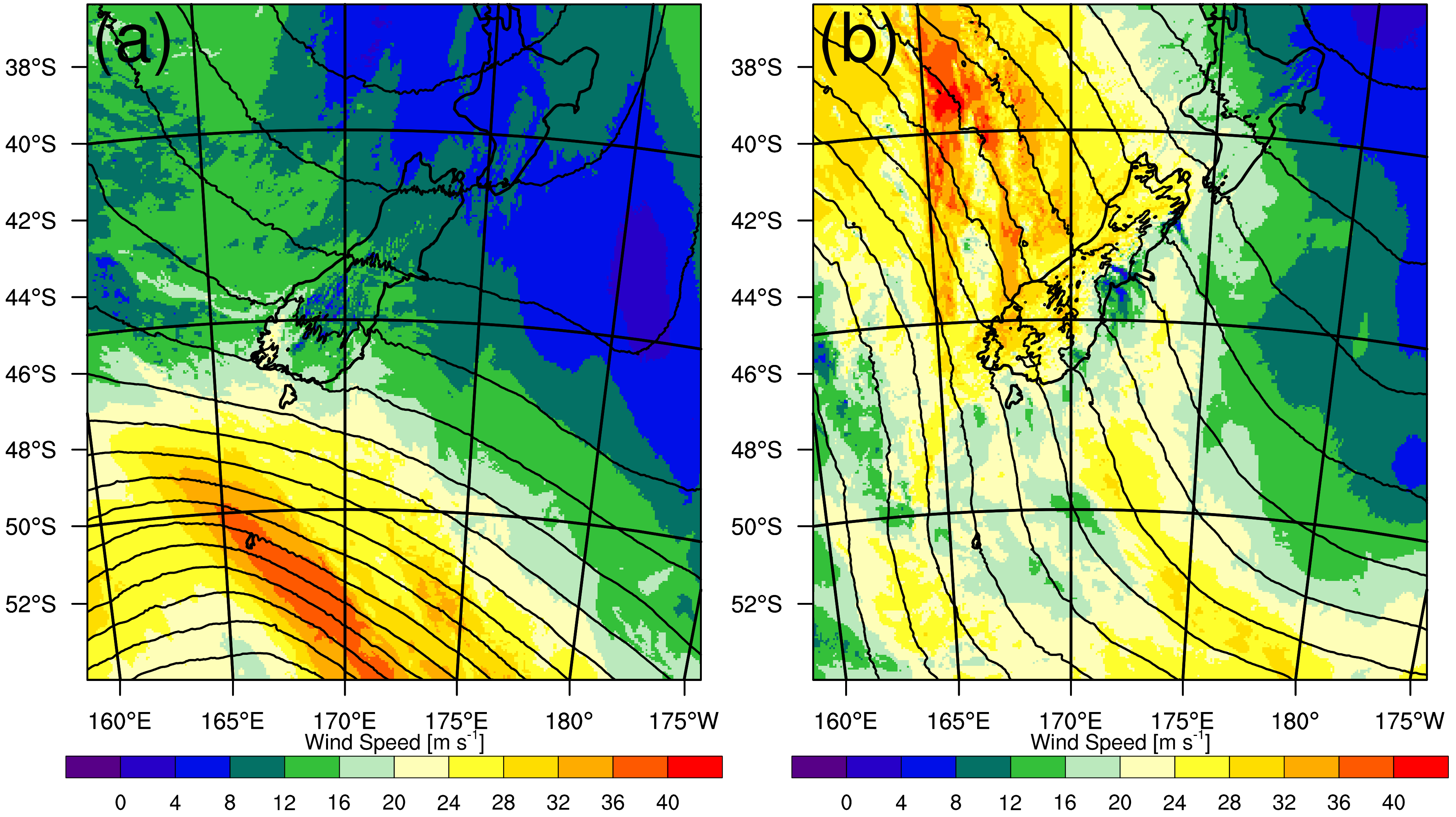
Leg Avg EFz Variability

RF09

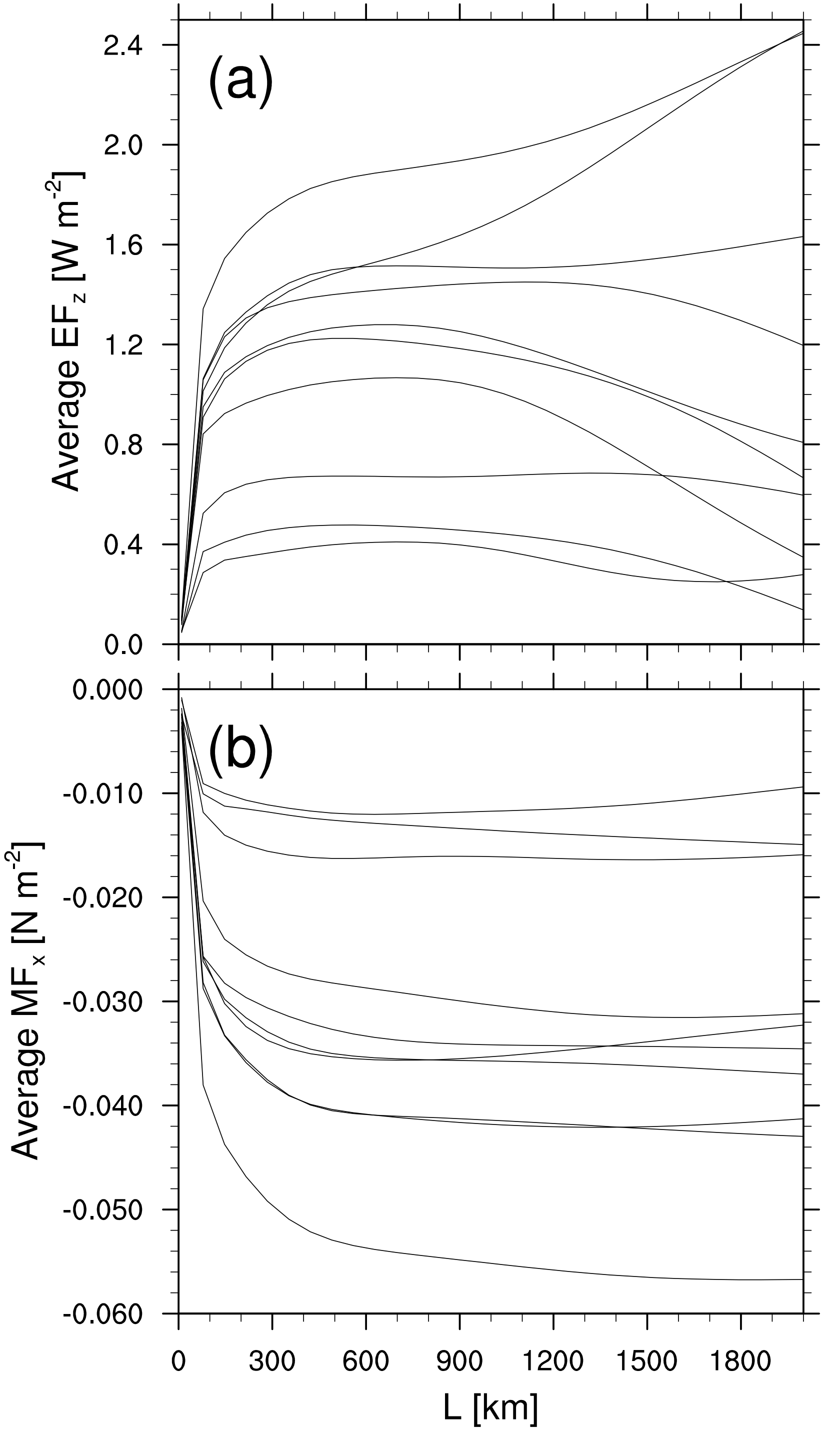



(a)
38°S
40°S
42°S
44°S
46°S
48°S
50°S
52°S
160°E
165°E
170°E
175°E
180°
175°W
Pressure [Pa]
60000
60500
61000
61500
62000
62500
(b)
Deplaned Pressure [Pa]
-800
-600
-400
-200
0
200
400
600
800
1000
(c)
Low-Passed Deplaned Presure [Pa]
(d)
High-Passed Deplaned Pressure [Pa]
-100
-80
-60
-40
-20
0
20
40
60
80
100


(a)
(b)
38°S
40°S
42°S
44°S
46°S
48°S
50°S
52°S
160°E
165°E
170°E
175°E
180°
175°W
EF_z [W m^{-2}]
-200 -160 -120 -80 -40 0 40 80 120 160 200
Low-passed EF_z [W m^{-2}]
-40 -30 -20 -10 0 10 20 30 40



(a)
(b)
38°S
40°S
42°S
44°S
46°S
48°S
50°S
52°S
160°E
165°E
170°E
175°E
180°
175°W
Wind Speed [m s-1]
0
4
8
12
16
20
24
28
32
36
40

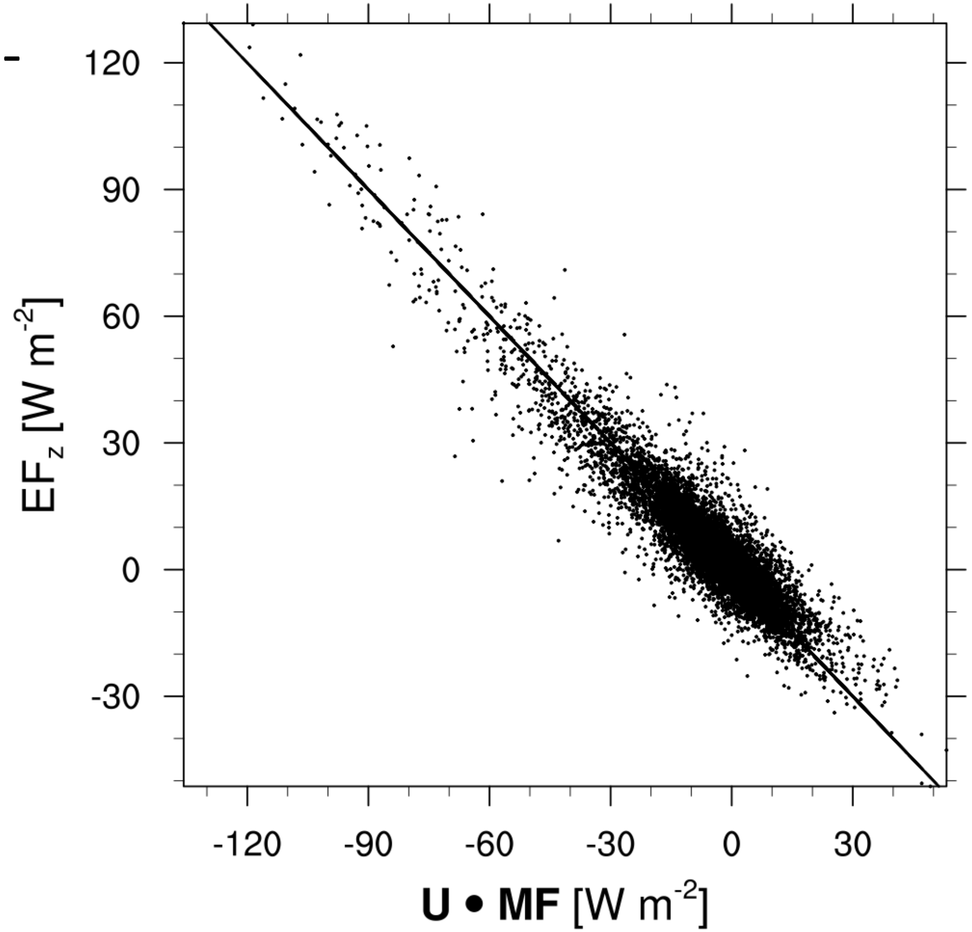

(a)
Average EF_z [W m^{-2}]
2.4
2.0
1.6
1.2
0.8
0.4
0.0
(b)
Average MF_x [N m^{-2}]
0.000
-0.010
-0.020
-0.030
-0.040
-0.050
-0.060
0
300
600
900
1200
1500
1800
L [km]

Method Verification

- Energy and momentum fluxes quantitatively satisfy the Eliassen-Palm theorem:

$$EF_z = -\overline{\mathbf{U}} \cdot \mathbf{MF}$$

(Eliassen and Palm 1961)

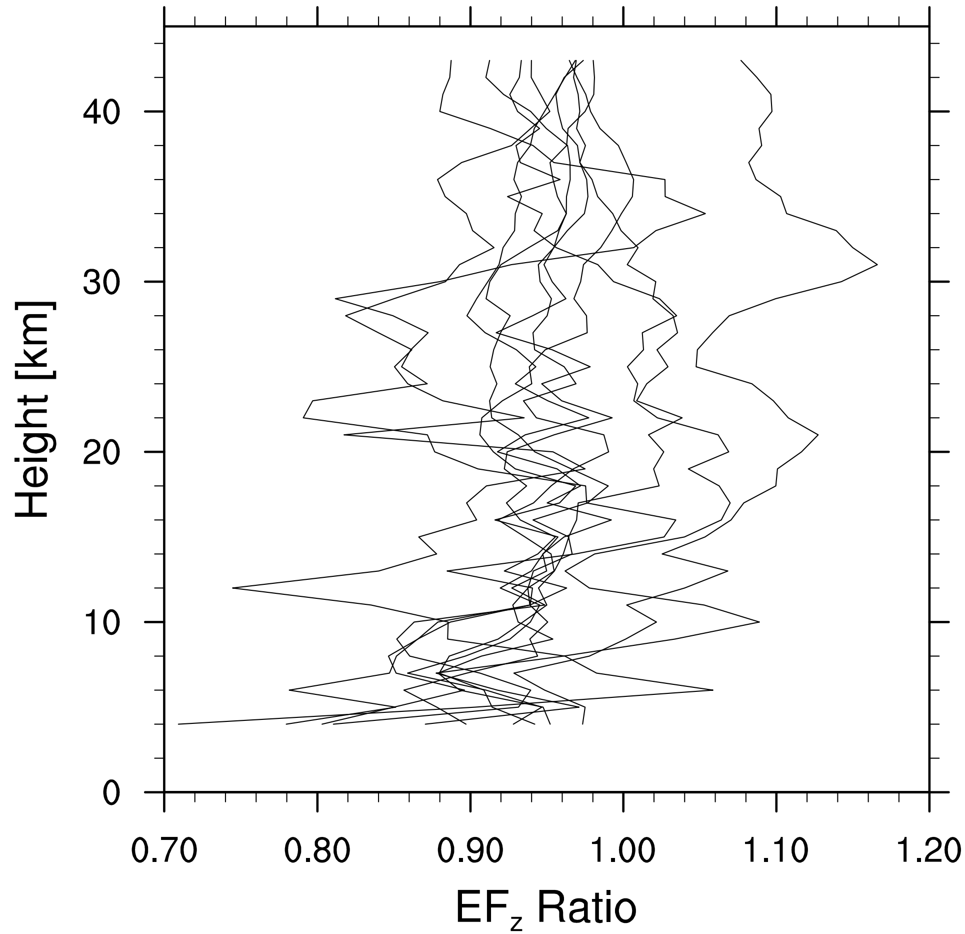


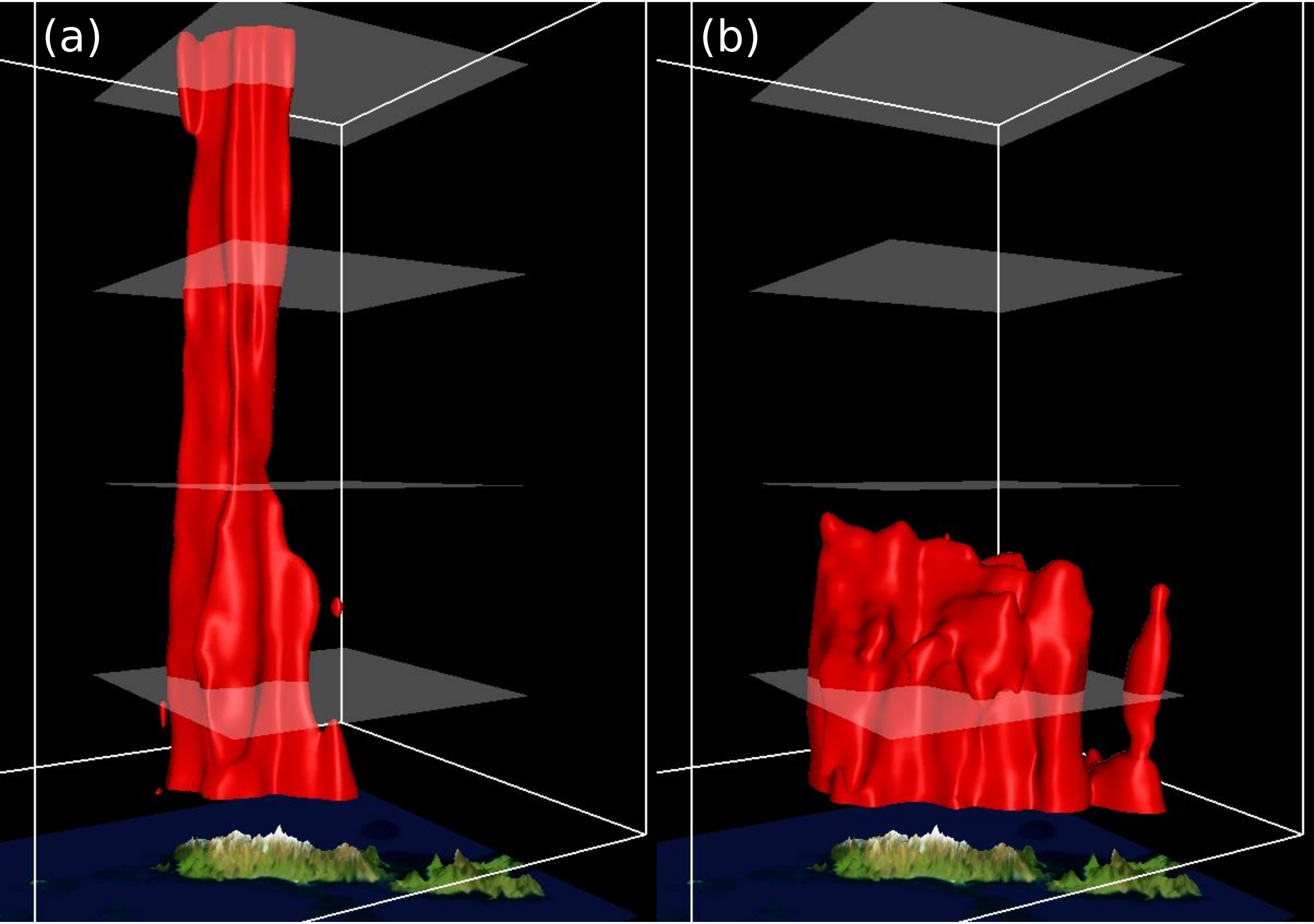
Method Verification

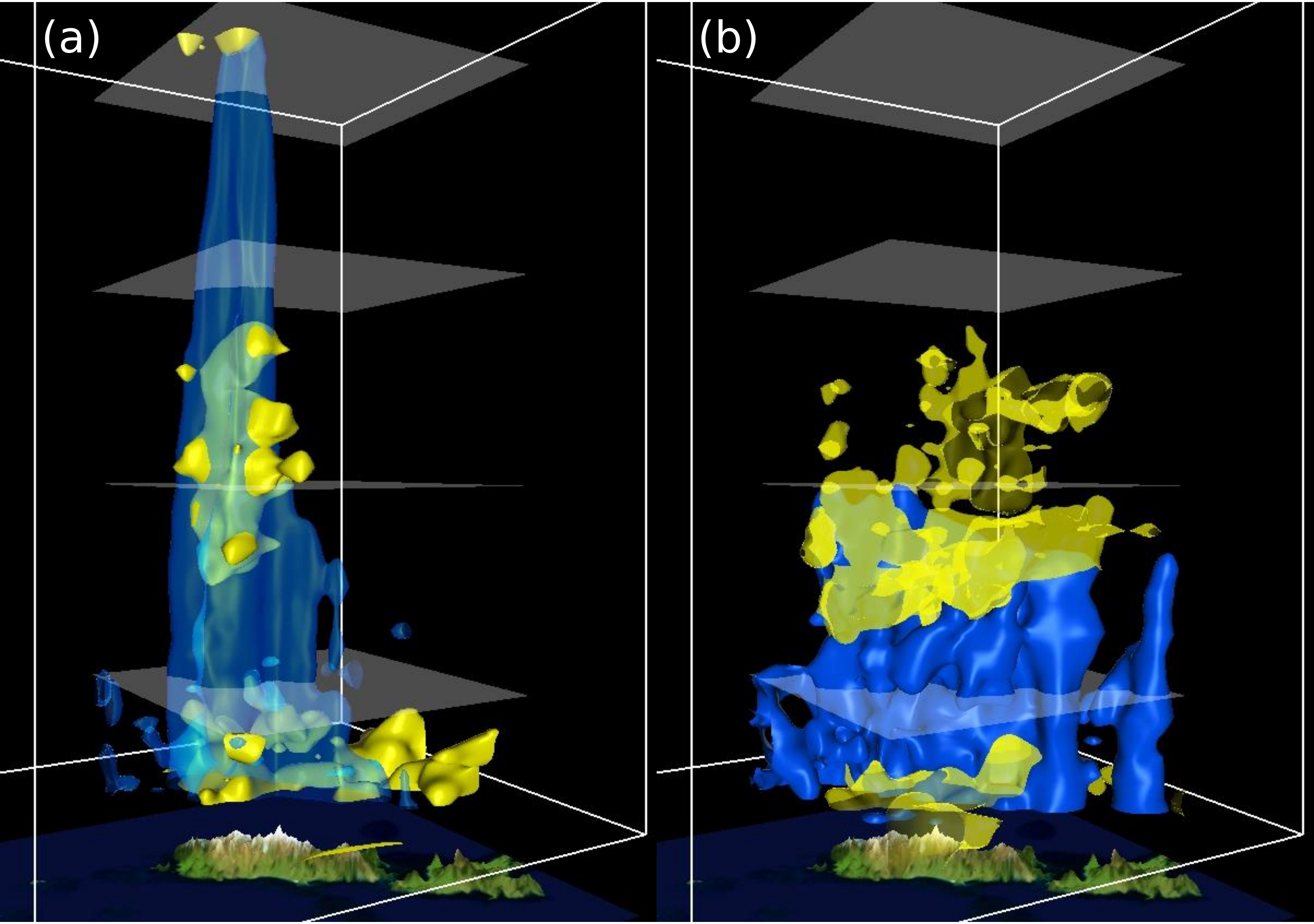
- Can also compute perturbation quantities by subtracting fields from a simulation with terrain from one without
- Compared the two methods via the following ratio:

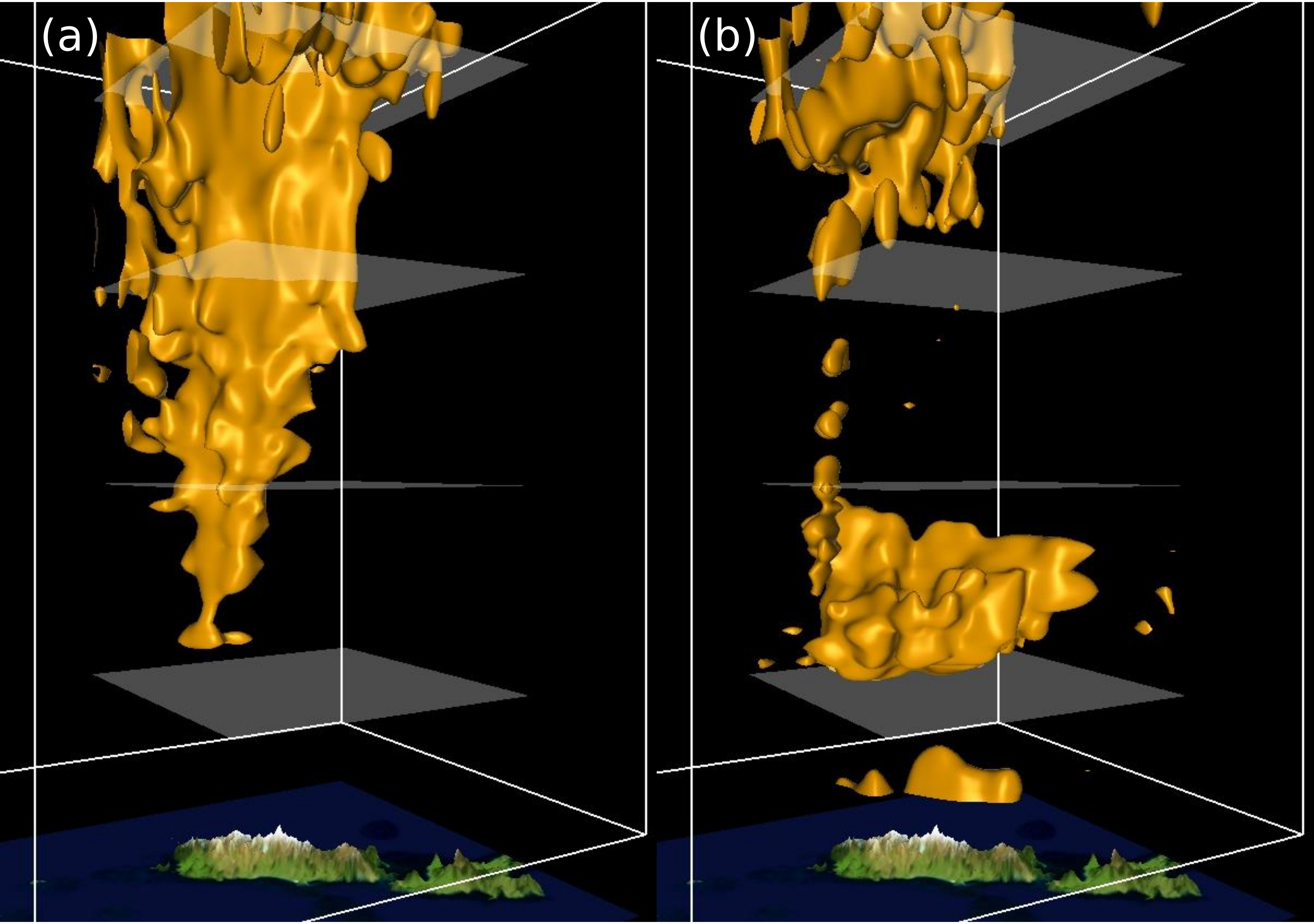
$$R = \frac{EF_{z_{filt}}}{EF_{z_{diff}}}$$

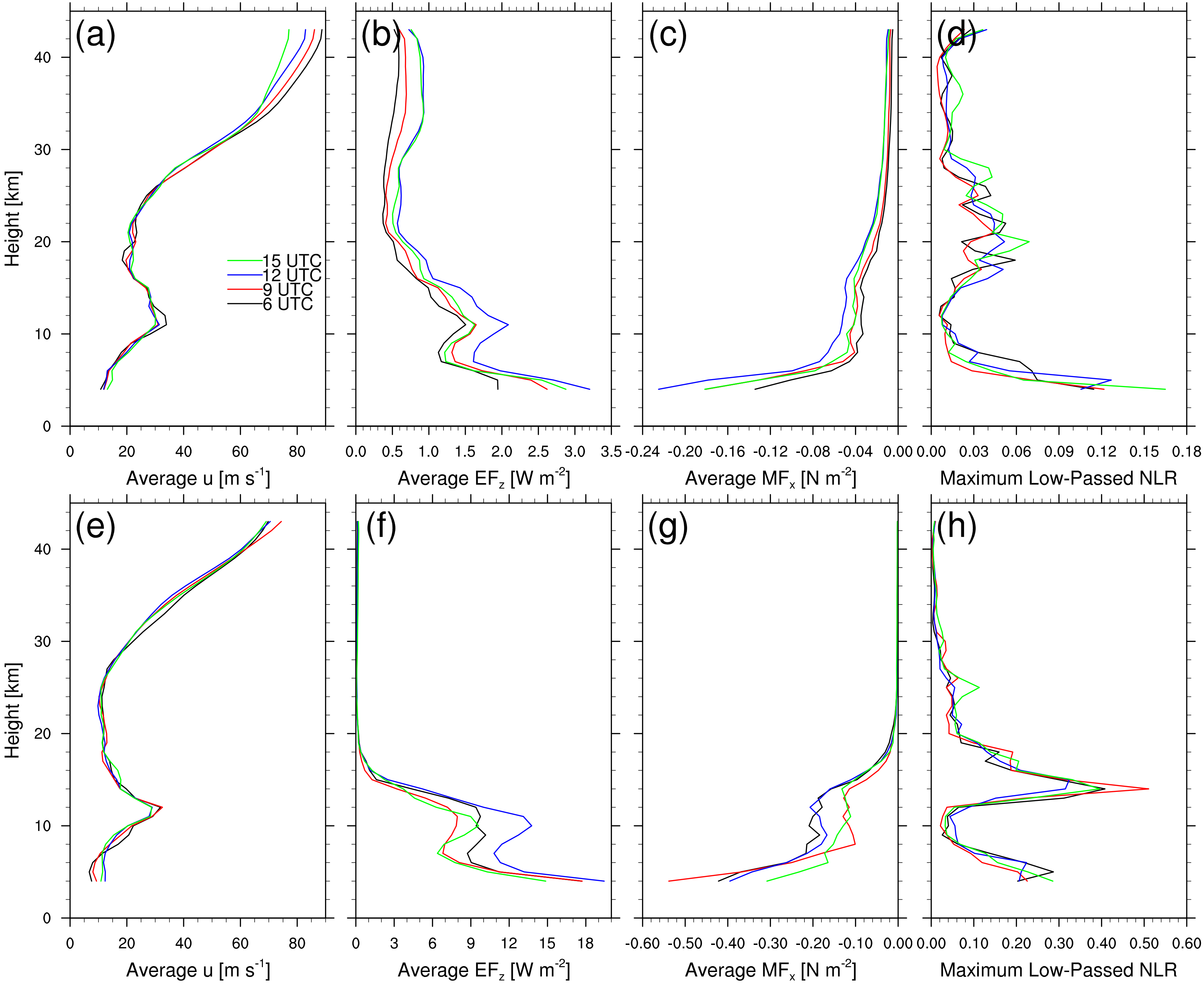
- The two very different methods typically agree within 10%



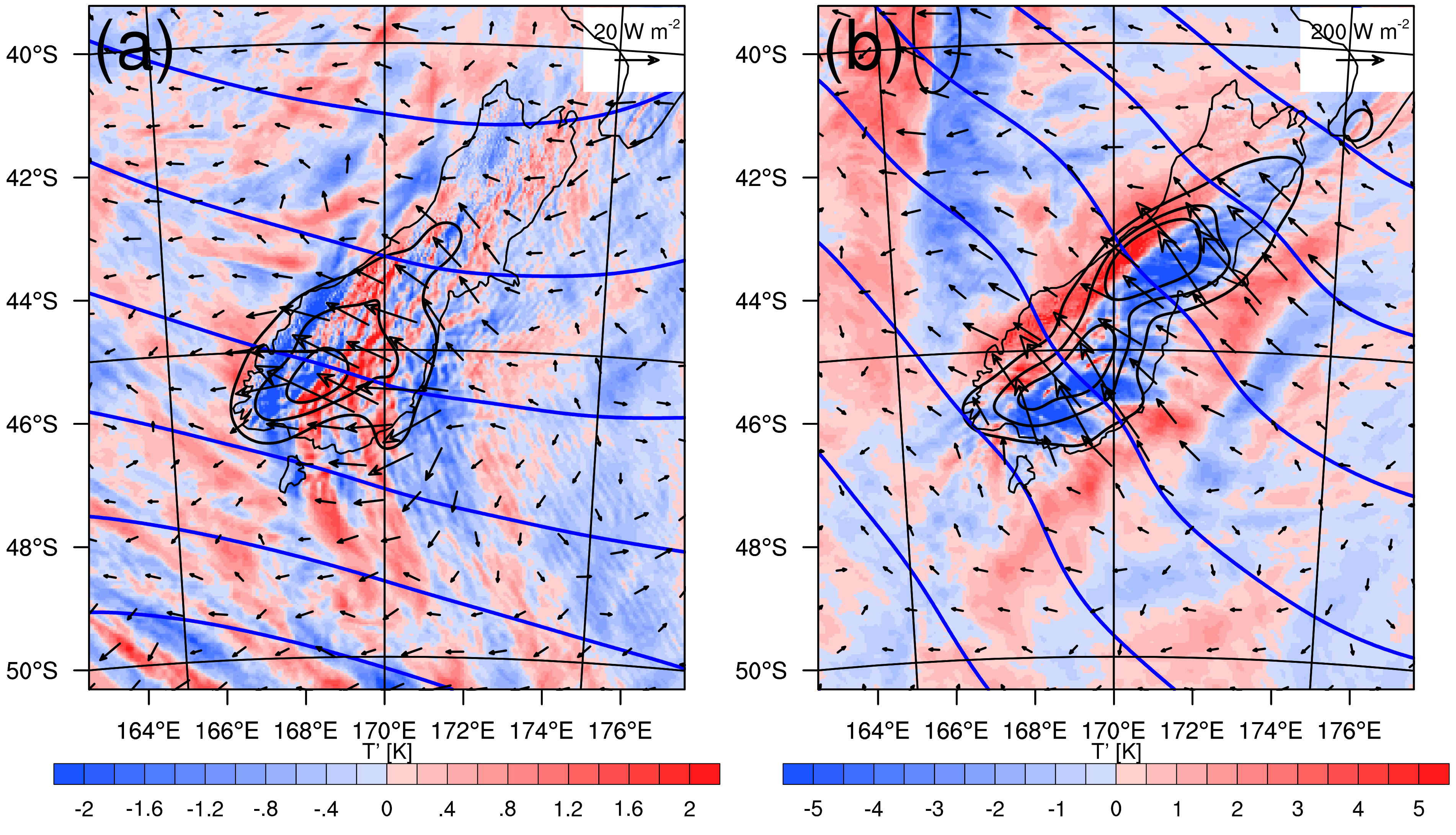

(a)
(b)

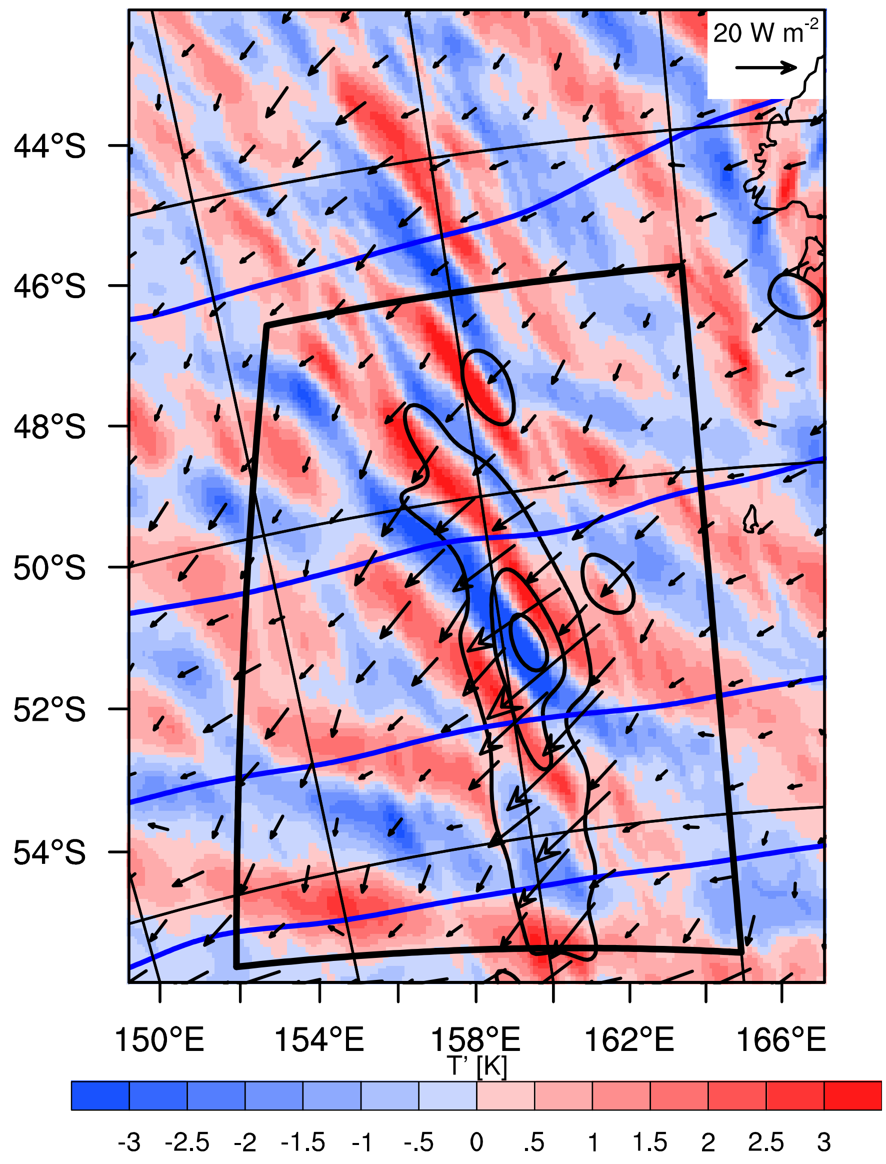

(a)
(b)


(a)
(b)

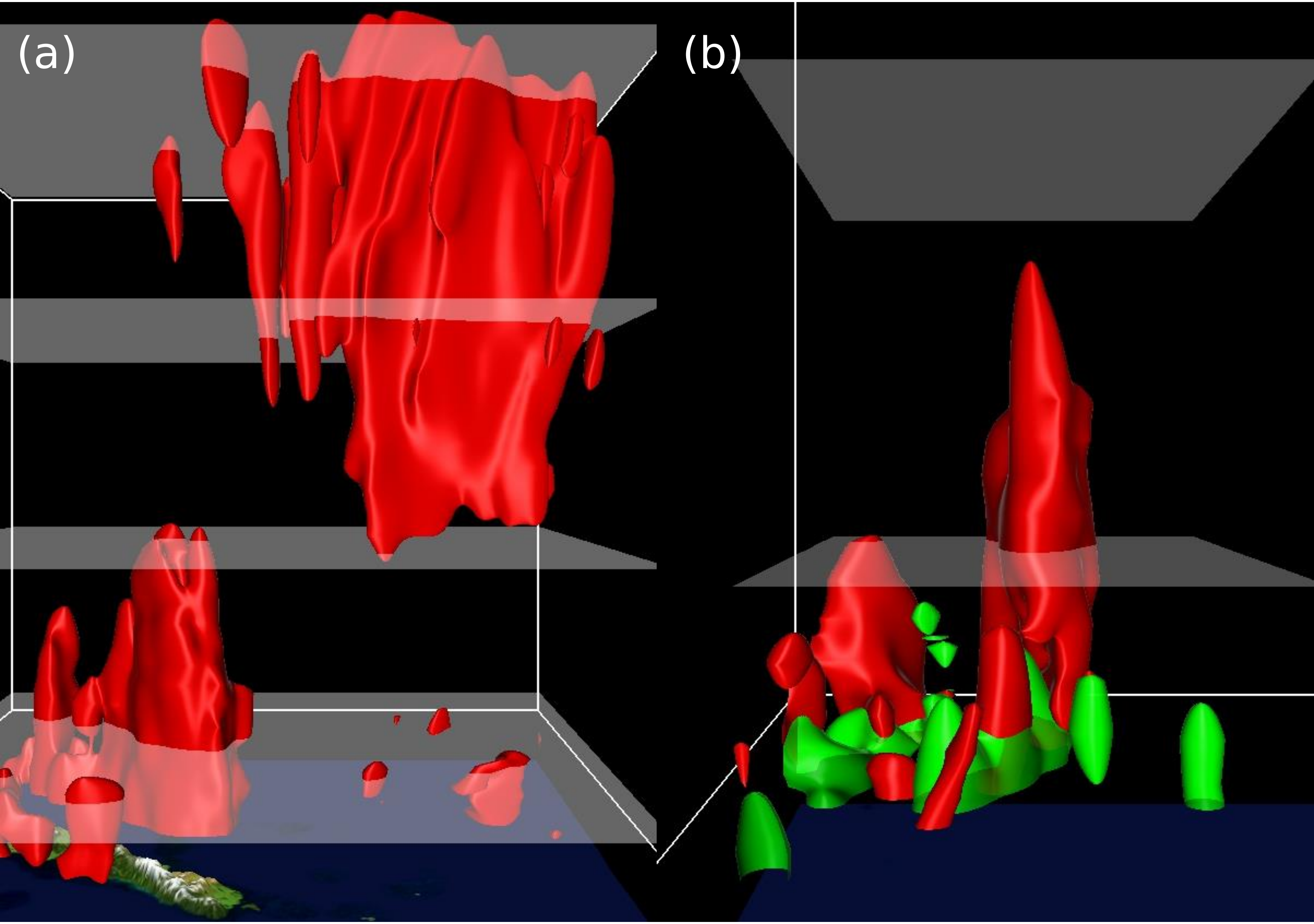


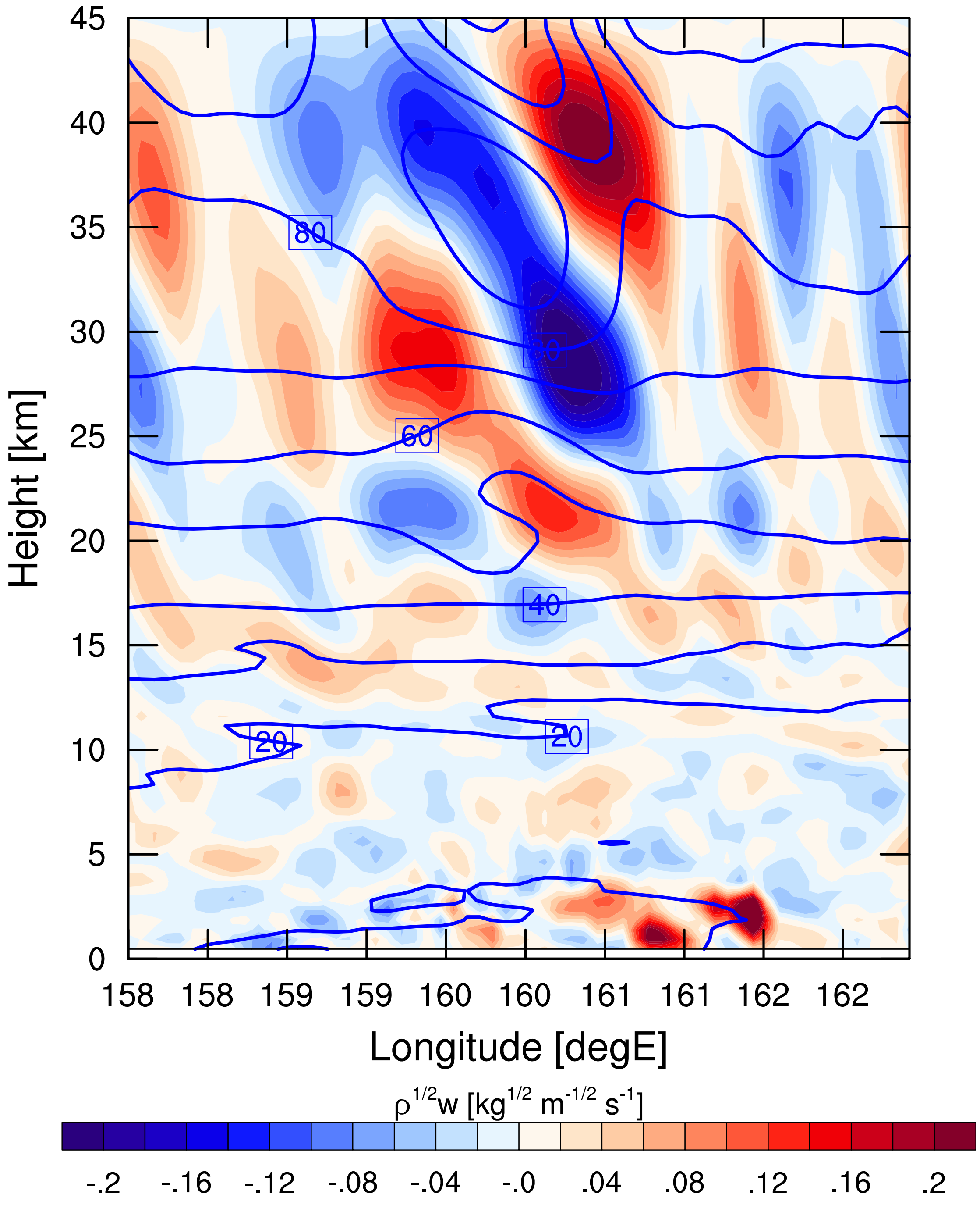
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
15 UTC
12 UTC
9 UTC
6 UTC
Height [km]
Average u [m s^{-1}]
Average EF$_z$ [W m^{-2}]
Average MF$_x$ [N m^{-2}]
Maximum Low-Passed NLR


(a)
20 W m⁻²
40°S
42°S
44°S
46°S
48°S
50°S
164°E
166°E
168°E
170°E
172°E
174°E
176°E
T' [K]
-2
-1.6
-1.2
-.8
-.4
0
.4
.8
1.2
1.6
2
(b)
200 W m⁻²
40°S
42°S
44°S
46°S
48°S
50°S
164°E
166°E
168°E
170°E
172°E
174°E
176°E
T' [K]
-5
-4
-3
-2
-1
0
1
2
3
4
5

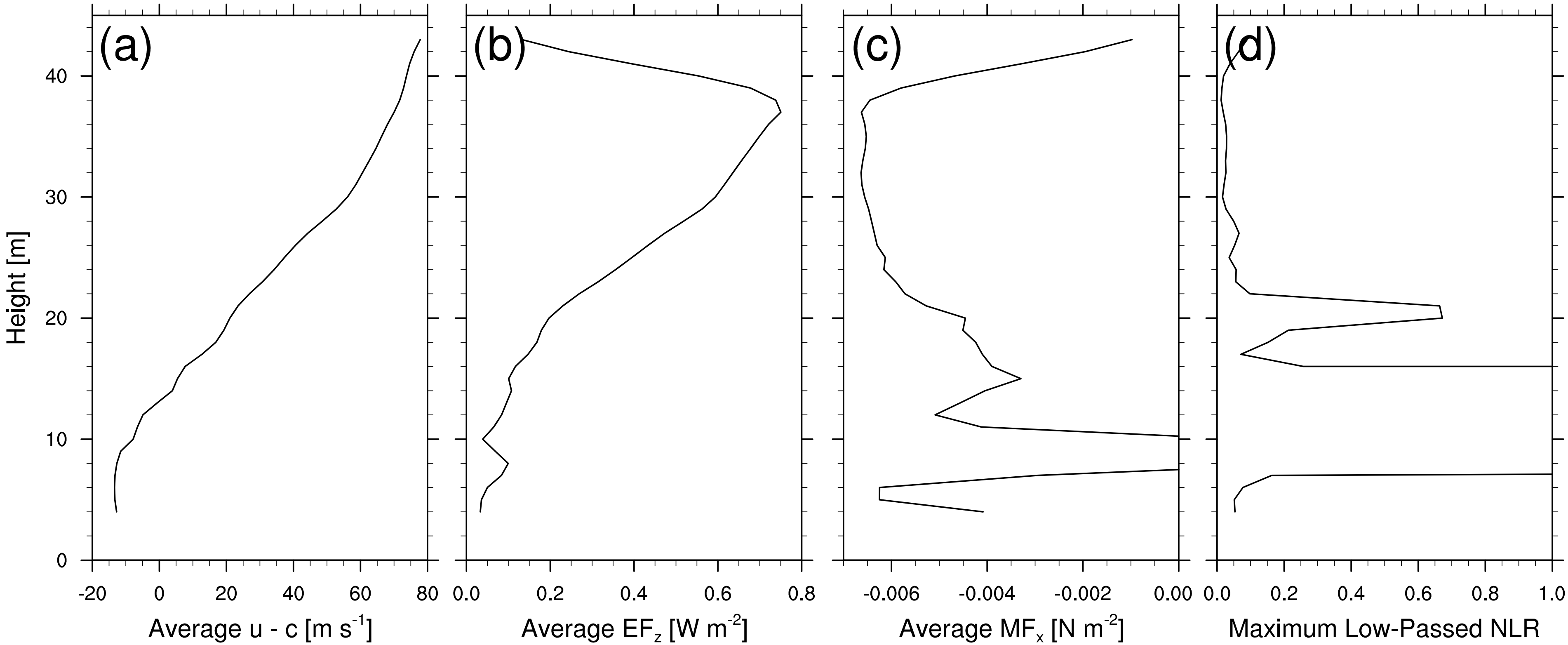


20 W m^-2
44°S
46°S
48°S
50°S
52°S
54°S
150°E
154°E
158°E
162°E
166°E
T' [K]
-3 -2.5 -2 -1.5 -1 -.5 0 .5 1 1.5 2 2.5 3

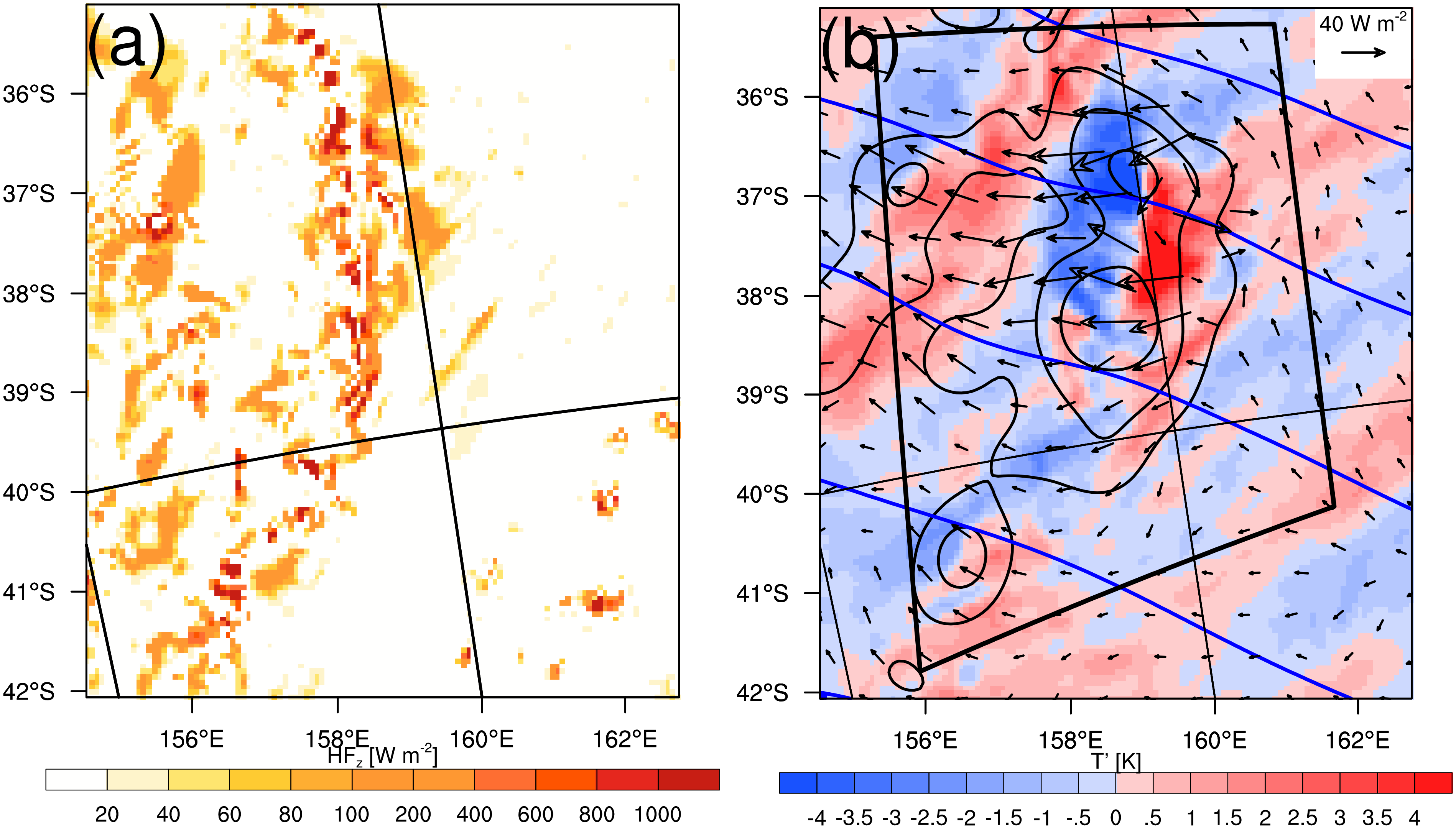

(a)
(b)



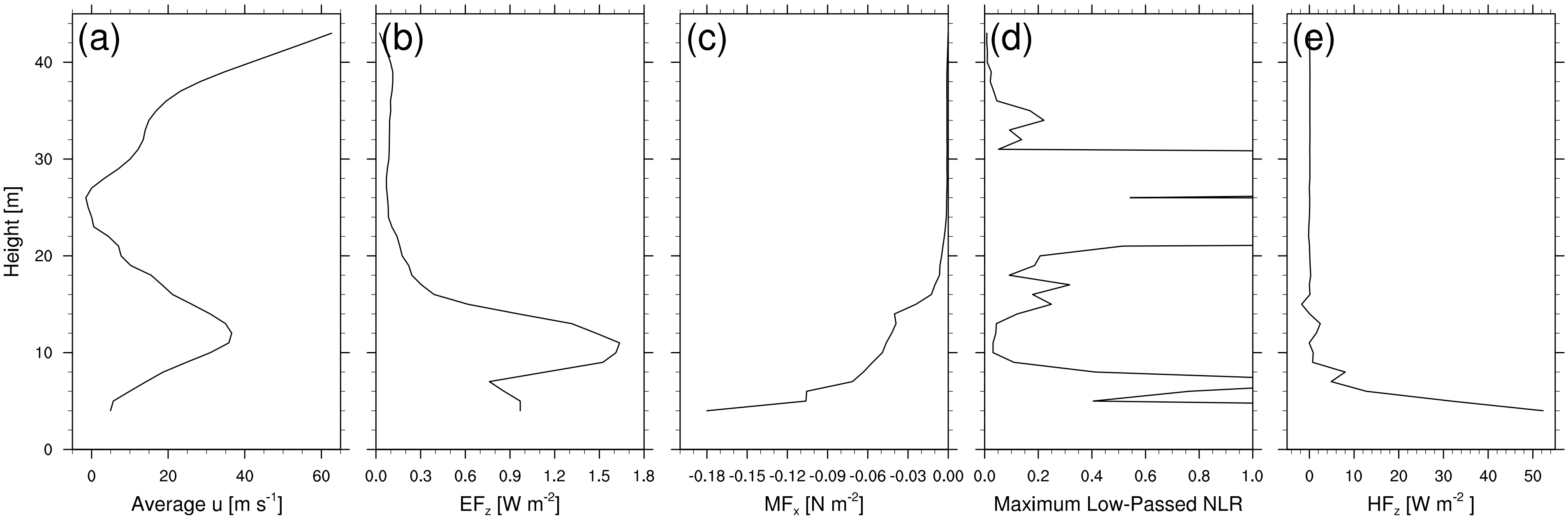
Height [km]
45
40
35
30
25
20
15
10
5
0
80
60
40
20
20
158
158
159
159
160
160
161
161
162
162
Longitude [degE]
ρ^1/2 w [kg^1/2 m^-1/2 s^-1]
-.2
-.16
-.12
-.08
-.04
-.0
.04
.08
.12
.16
.2

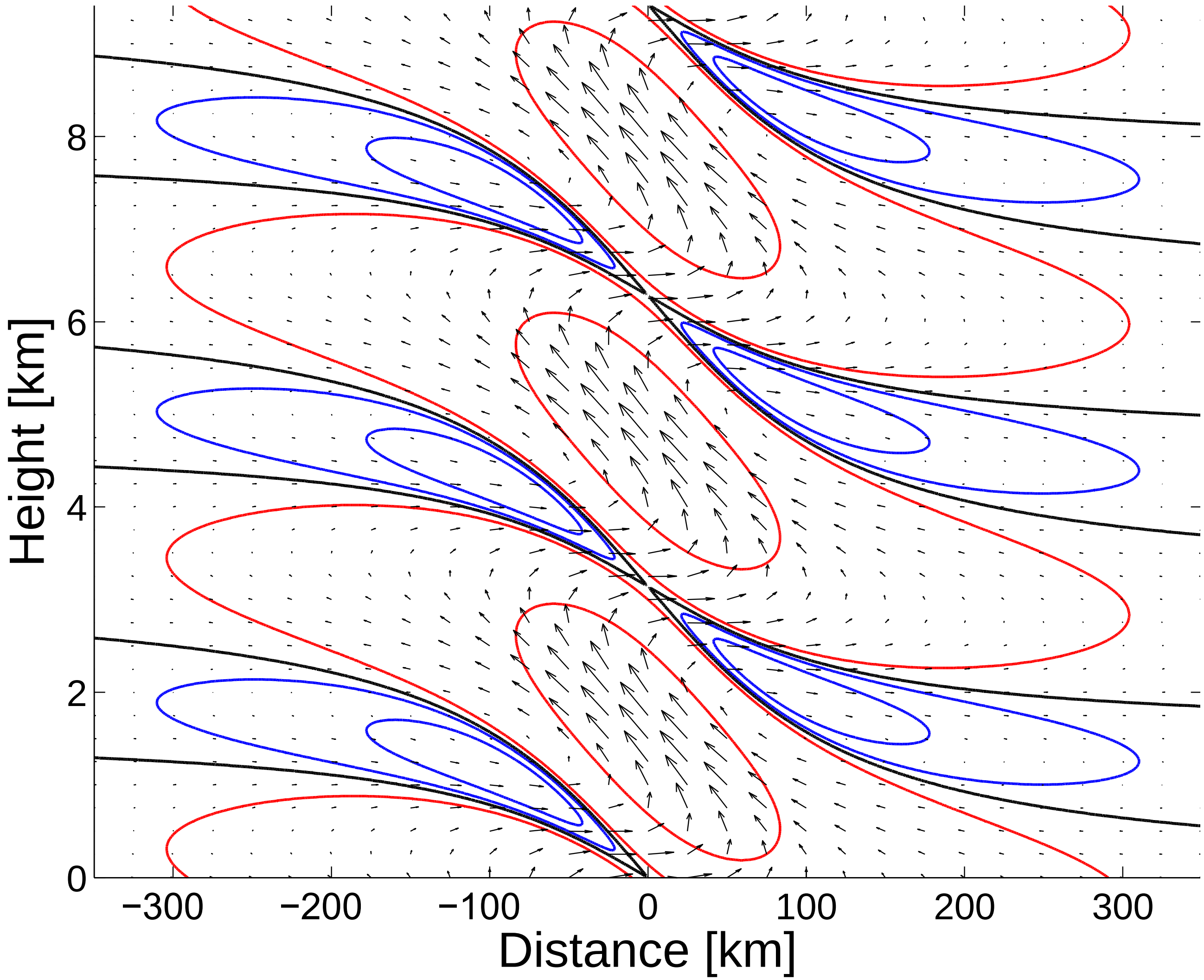


(a)
(b)
(c)
(d)
Height [m]
0
10
20
30
40
-20
0
20
40
60
80
Average u - c [m s^{-1}]
0.0
0.2
0.4
0.6
0.8
Average EF_z [W m^{-2}]
-0.006
-0.004
-0.002
0.00
Average MF_x [N m^{-2}]
0.0
0.2
0.4
0.6
0.8
1.0
Maximum Low-Passed NLR



(a)
36°S
37°S
38°S
39°S
40°S
41°S
42°S
156°E
158°E
160°E
162°E
HF_z [W m^-2]
20
40
60
80
100
200
400
600
800
1000
(b)
40 W m^-2
36°S
37°S
38°S
39°S
40°S
41°S
42°S
156°E
158°E
160°E
162°E
T' [K]
-4
-3.5
-3
-2.5
-2
-1.5
-1
-.5
0
.5
1
1.5
2
2.5
3
3.5
4


(a)
(b)
(c)
(d)
(e)
Height [m]
0
10
20
30
40
0 20 40 60
Average u [m s-1]
0.0 0.3 0.6 0.9 1.2 1.5 1.8
EFz [W m-2]
-0.18 -0.15 -0.12 -0.09 -0.06 -0.03 0.00
MFx [N m-2]
0.0 0.2 0.4 0.6 0.8 1.0
Maximum Low-Passed NLR
0 10 20 30 40 50
HFz [W m-2]



Height [km]
8
6
4
2
0
−300
−200
−100
0
100
200
300
Distance [km]