“Gravity Wave Diagnostics and Characteristics in Mesoscale Fields”

Christopher G. Kruse and Ronald B. Smith

Accepted to JAS with major revisions

- Describes nearly the same method to compute energy fluxes used in forecasts during DEEPWAVE
- Includes method verification and analysis of four gravity wave events:
  - Deep propagating (40+ km) mountain waves
  - Attenuated mountain waves
  - Southern Ocean jet generated gravity waves
  - Tasman Sea convection generated gravity waves
- Will gladly share a copy of the current manuscript

New Zealand Mountain Waves and Attenuation Within WRF

Christopher Kruse
and
Ronald Smith

Outline

1. 6-km WRF "Long Run" Verification

2. Dominant Wave Scales in RF04, RF09 According to 2-km WRF

3. Mountain Wave Attenuation/GWD in 6-km WRF
   - Compared with MERRA reanalysis param GWD

Future Work: Effects of Lower Stratospheric GWD

WRF Setup

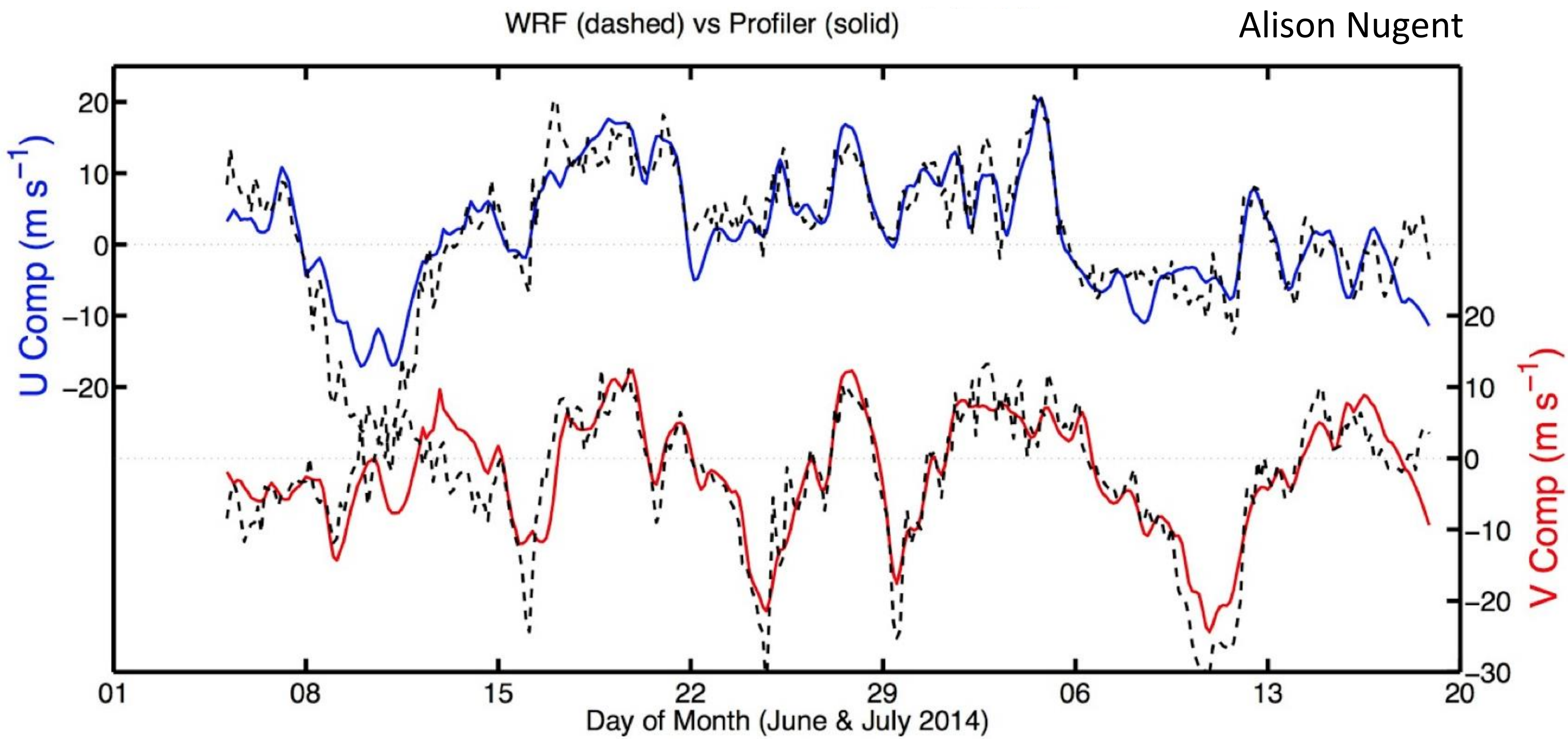
- Long Run
  - 6-km Resolution, 110 vertical levels, top at ~45 km
  - 24 May – 31 July 2014
  - Continuous Simulation: only initialized twice within that period
  - Only forced through boundary conditions (BCs)
  - BCs provided by ECMWF analysis grids every three hours
  - Output frequency: 3 hr

- Event Runs
  - 6-km domain forced by ECMWF, 2-km nest
  - 150 vertical levels, top at ~45 km
  - 30 hour simulations
  - Output frequency: 1 hr

Wind Profiler/Long Run Comparison

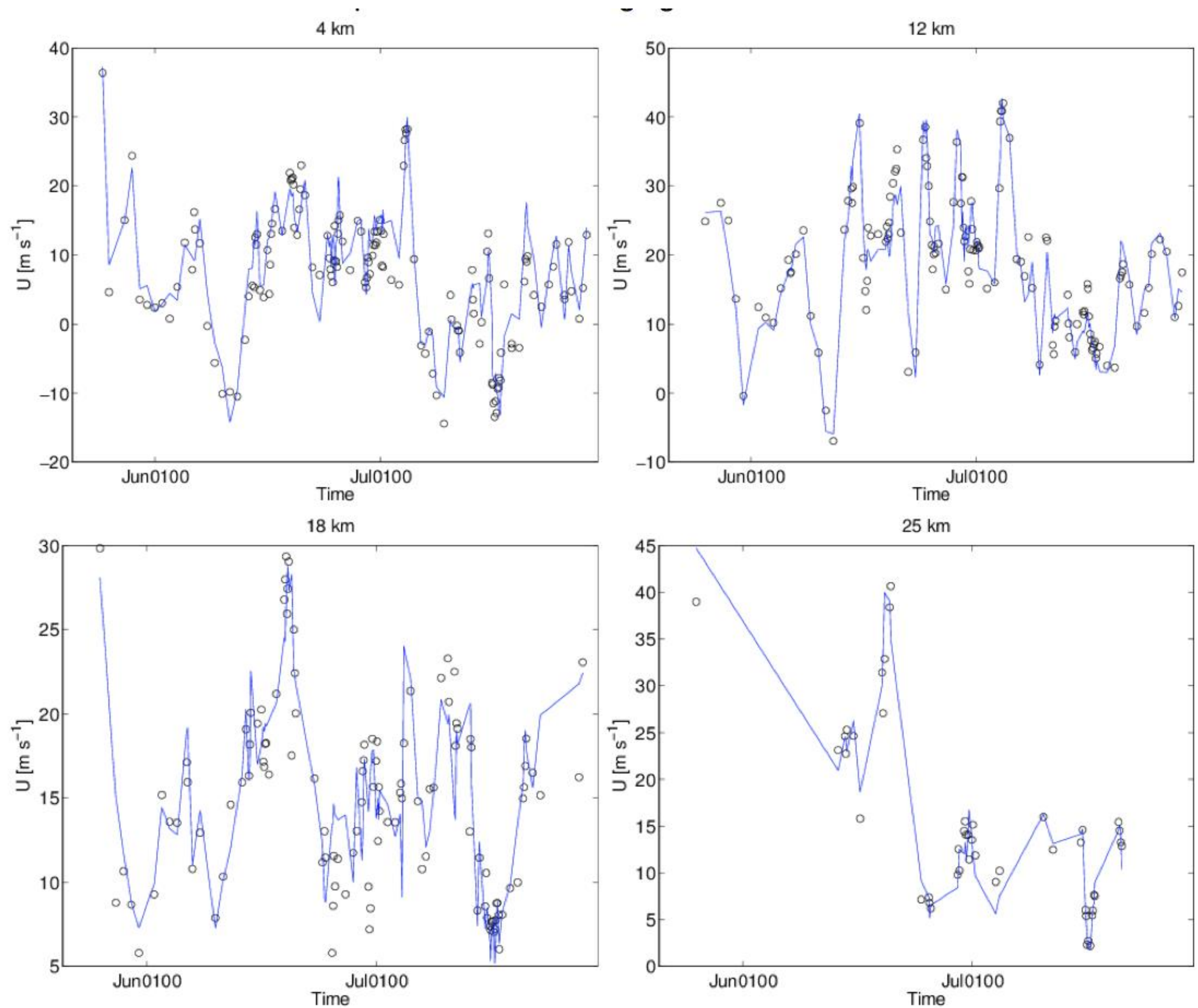
z = 1 km

Alison Nugent



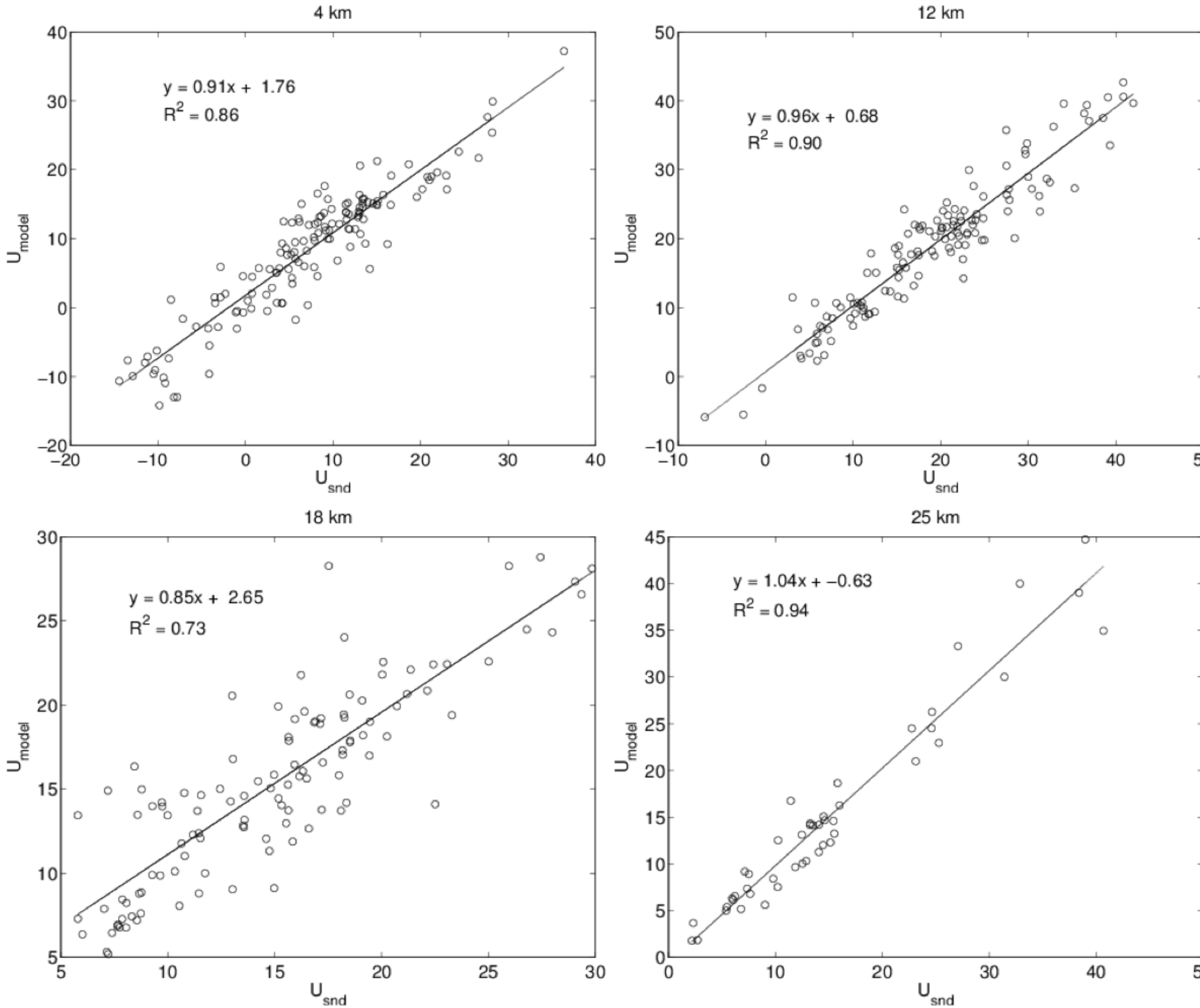
- 3 hour running avg smoothed profiler measurments (solid)
- Instantaneous WRF Long Run winds at same x,y,z (dashed)

Hokitika Sounding/Long Run Comparison



- WRF horizontally averaged over 60x60 km area (blue)
- ISS sounding measurements vertically averaged over 2 km depth (circles)

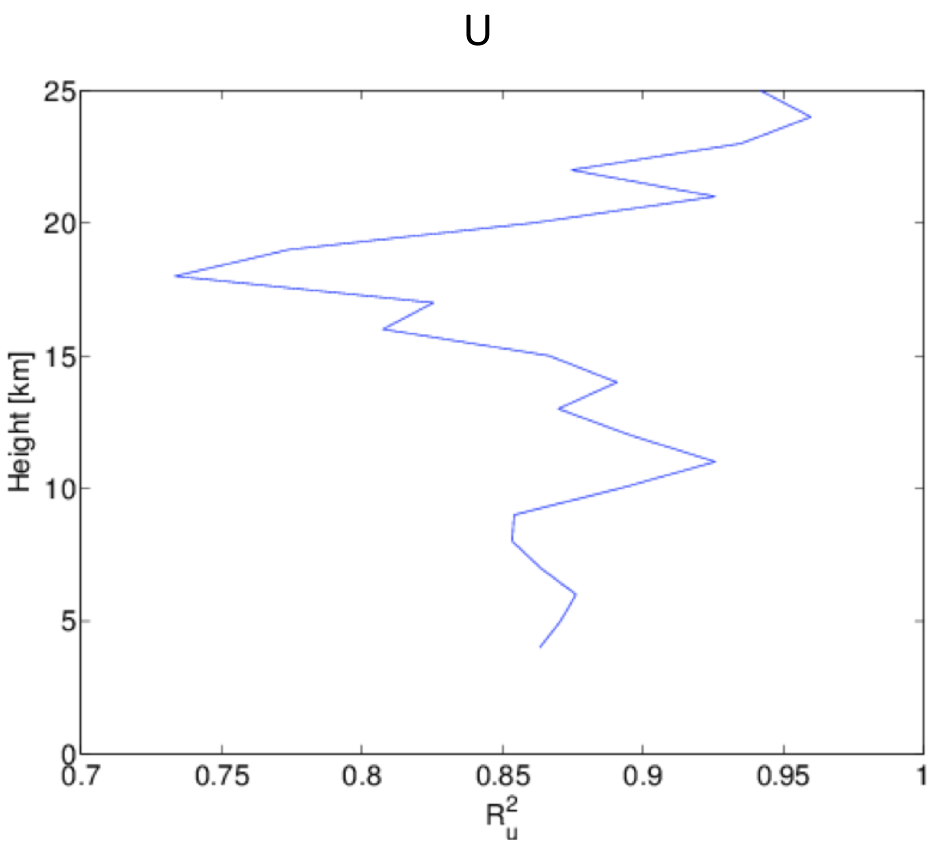
Hokitika Soundings: Long Run vs. Obs

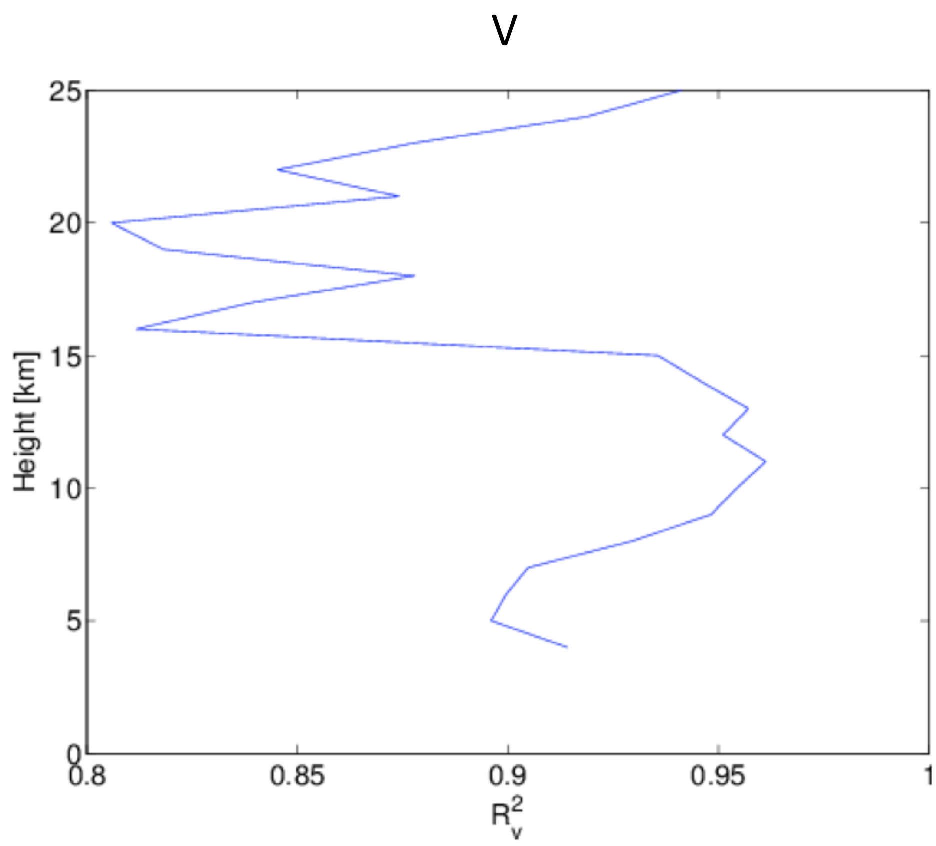


- WRF horizontally averaged over 60x60 km area (blue)
- ISS sounding measurements vertically averaged over 2 km depth (circles)

ISS Soundings: Z vs. R^2

- Linear fit R^2 value as a function of height



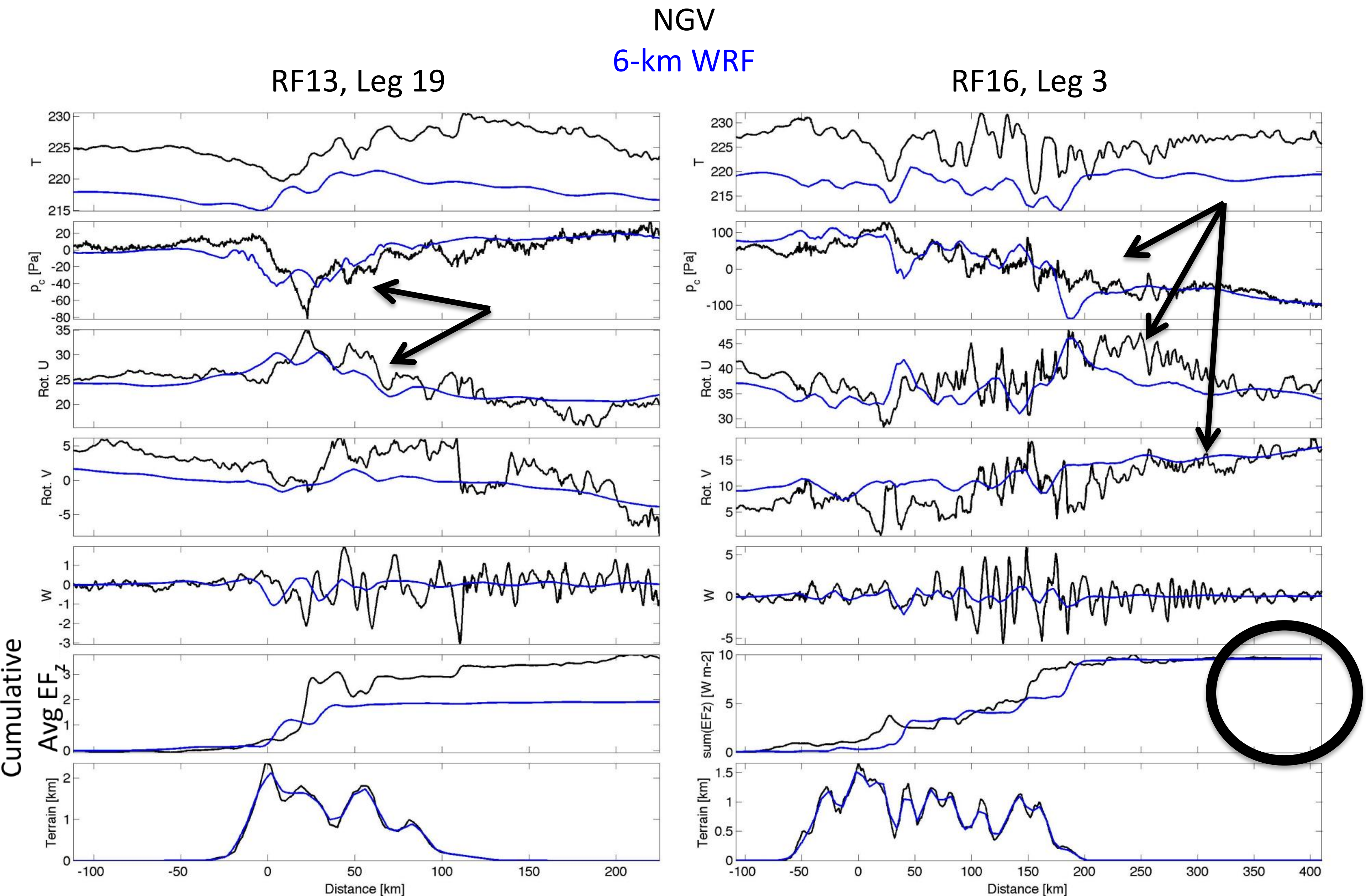


- Why poor agreement between 15-20 km?
  Poor representation of frequent wave breaking there?

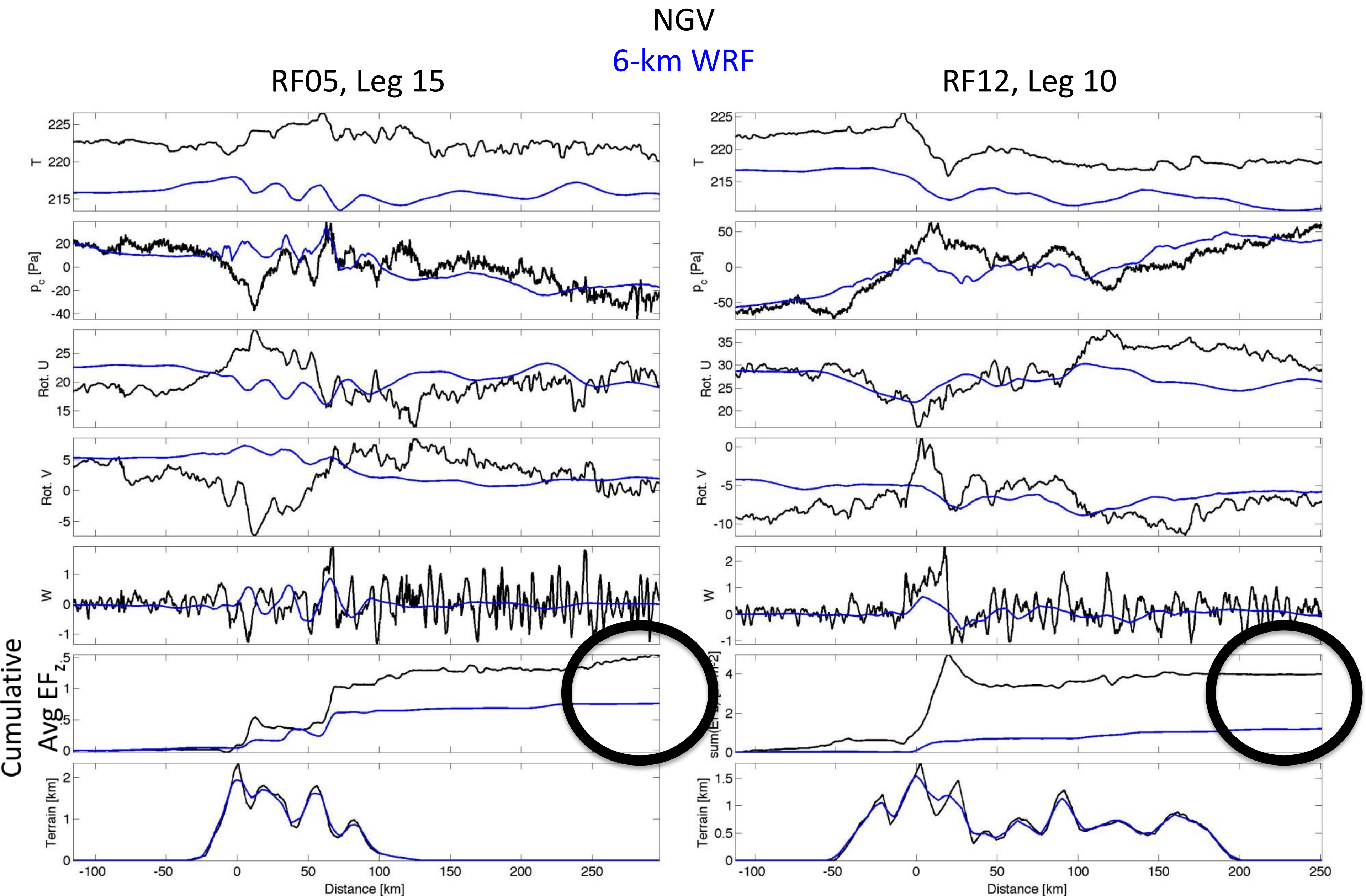
Aircraft/Long Run Comparisons

- Interpolated 6-km Long Run parameters to every aircraft measurement in space and time
  - Via 4-D linear interpolation
  - “Flight through the model” for all RFs
- Allows “apples to apples” comparisons

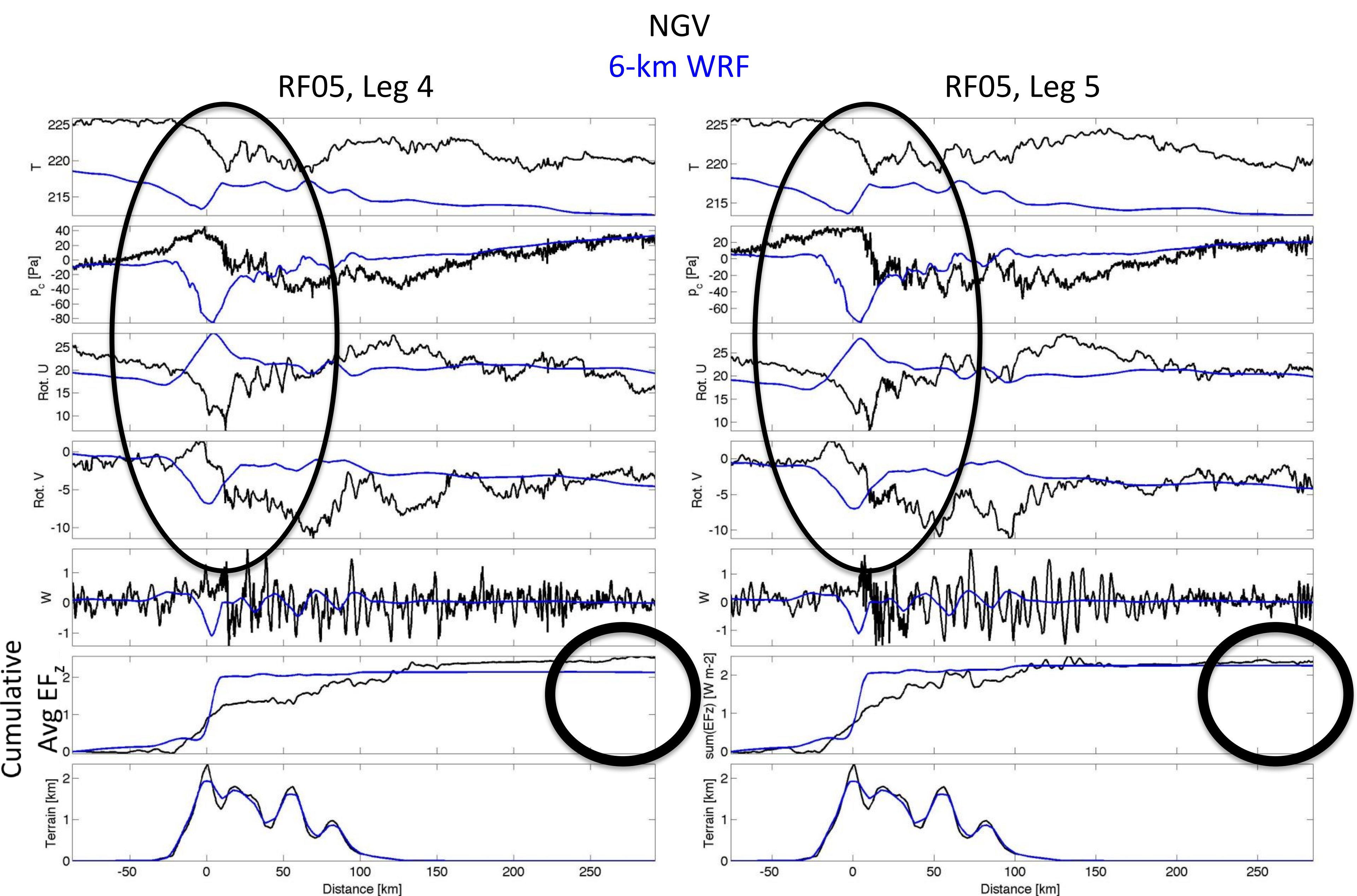
Leg Comparisons: Good



Leg Comparisons: Bad

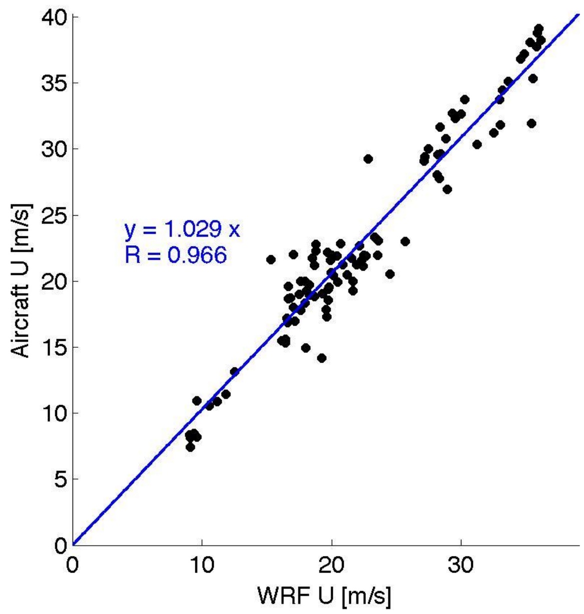


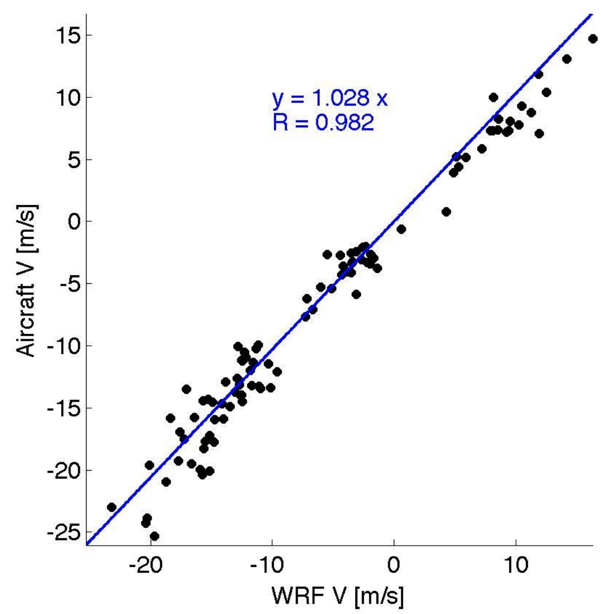
Leg Comparisons: Phase Shifted

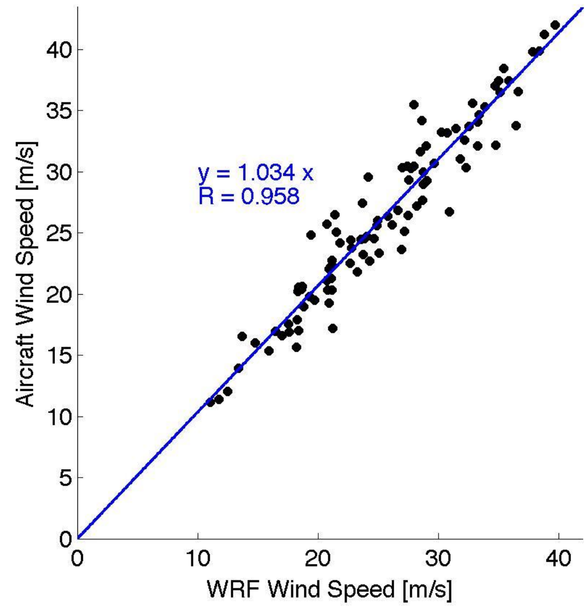


Aircraft/Long Run Wind Comparison

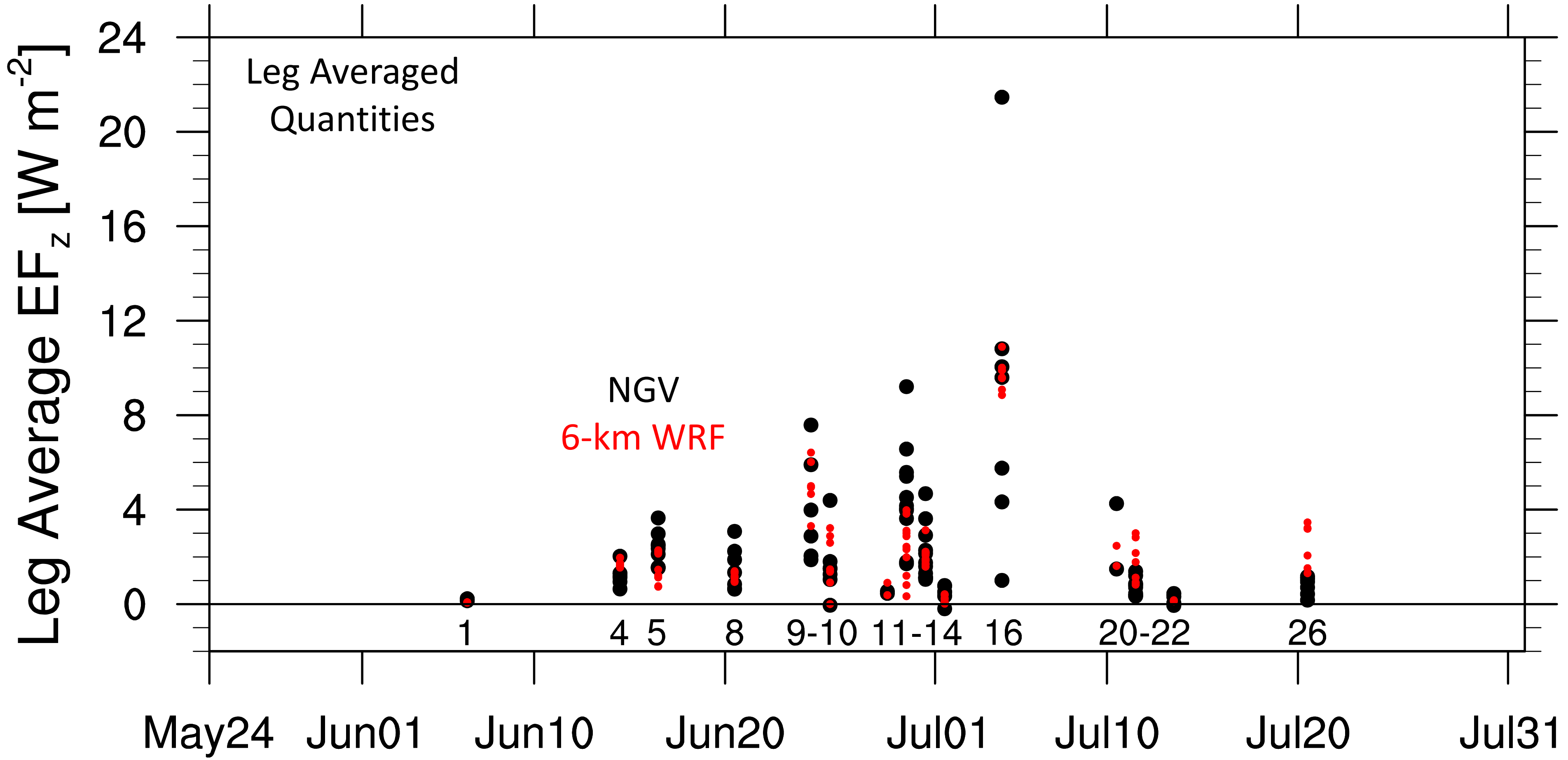
Leg Averaged Quantities



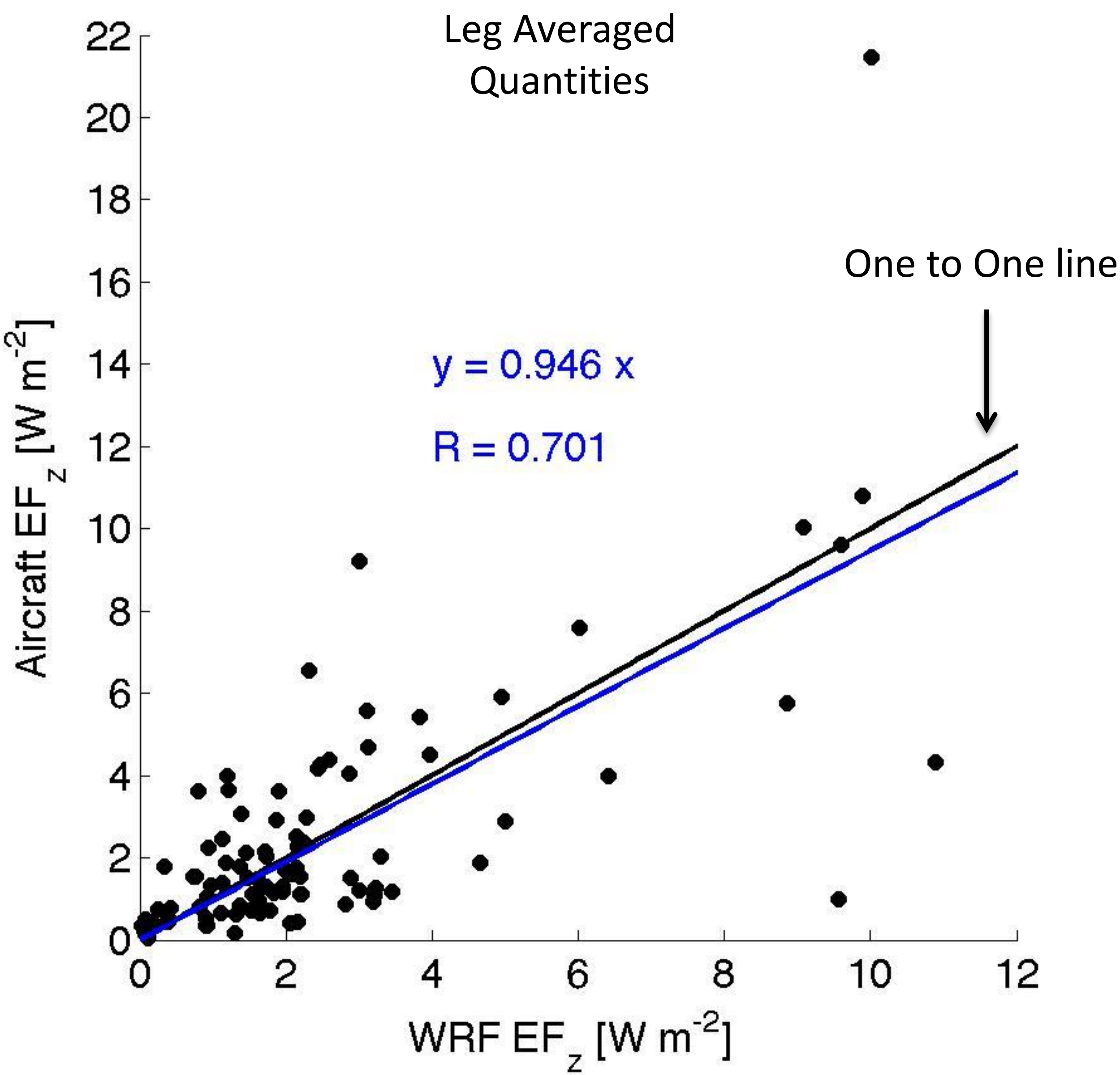




Aircraft/Long Run EFz Comparison



Aircraft/Long Run EFz Comparison



Long Run Verification Summary

- Background winds are well represented within the Long Run
  - Probably do not change quickly
- Leg avg EF_z quite variable within events (observations even more so)
  - Not be predictable
- WRF has some skill in predicting event **mean** leg avg EF_z
- Long Run **is currently available** in the DEEPWAVE data archive

2. Dominant Wave Scales

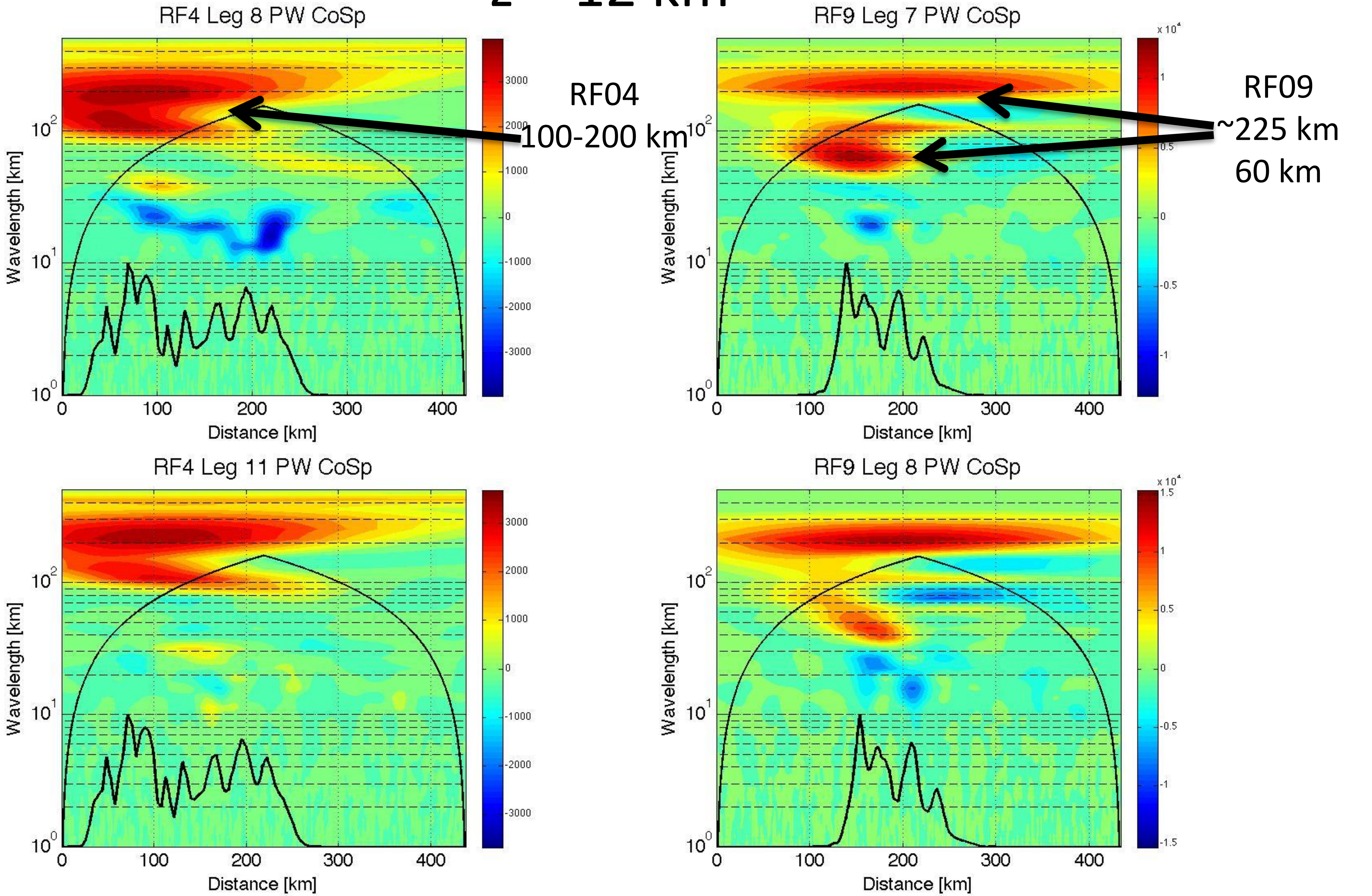
- What are the dominant flux carrying wavelengths according to 2-km WRF?
- Are there important long wavelengths not resolvable with the ~400 km DEEPWAVE legs

Method:

- Calculate EF_z wavelet co-spectra east-west over model domain (~1000 km)

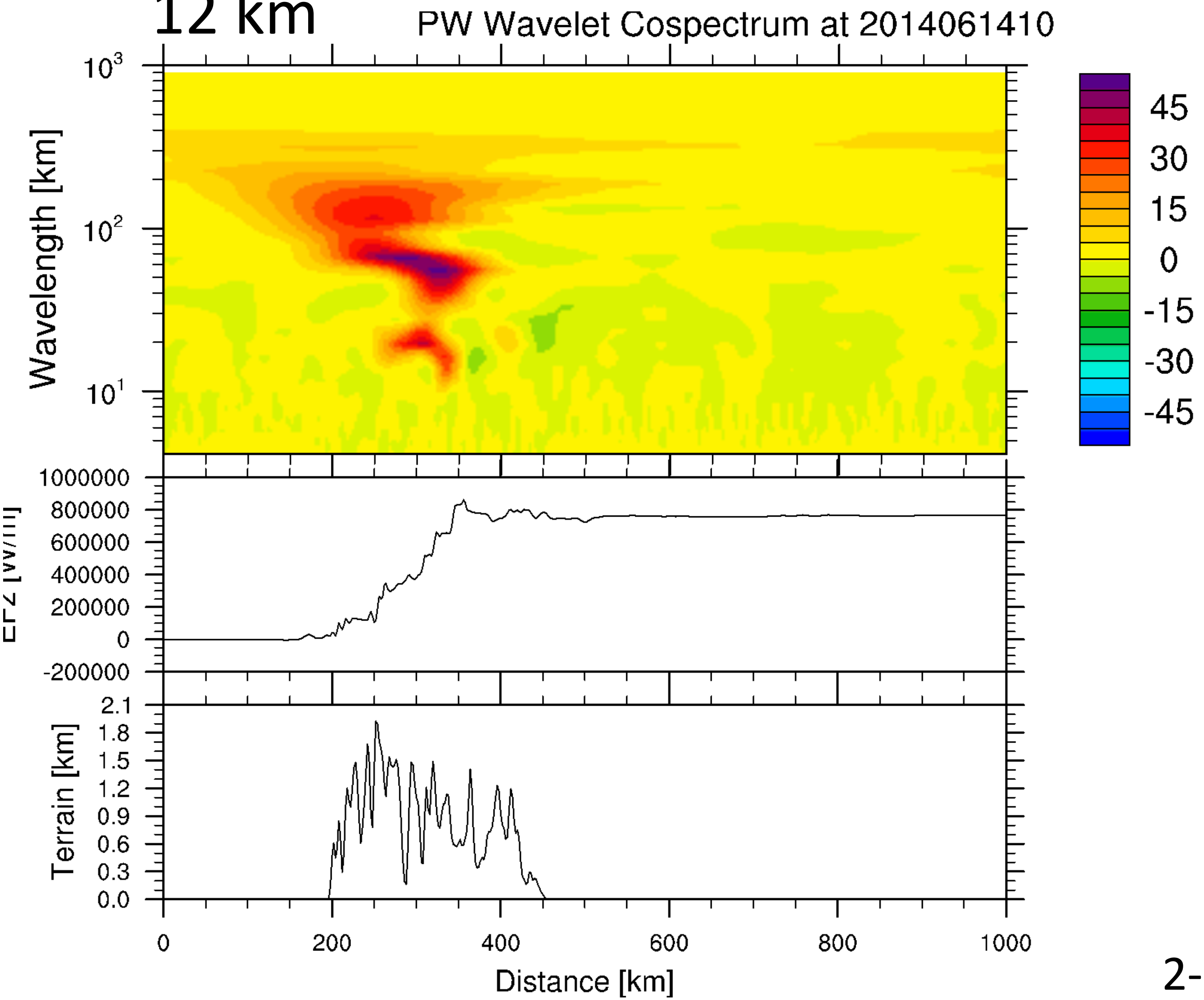
Observed Scales

z = 12 km



Simulated Scales: RF04 Snapshot

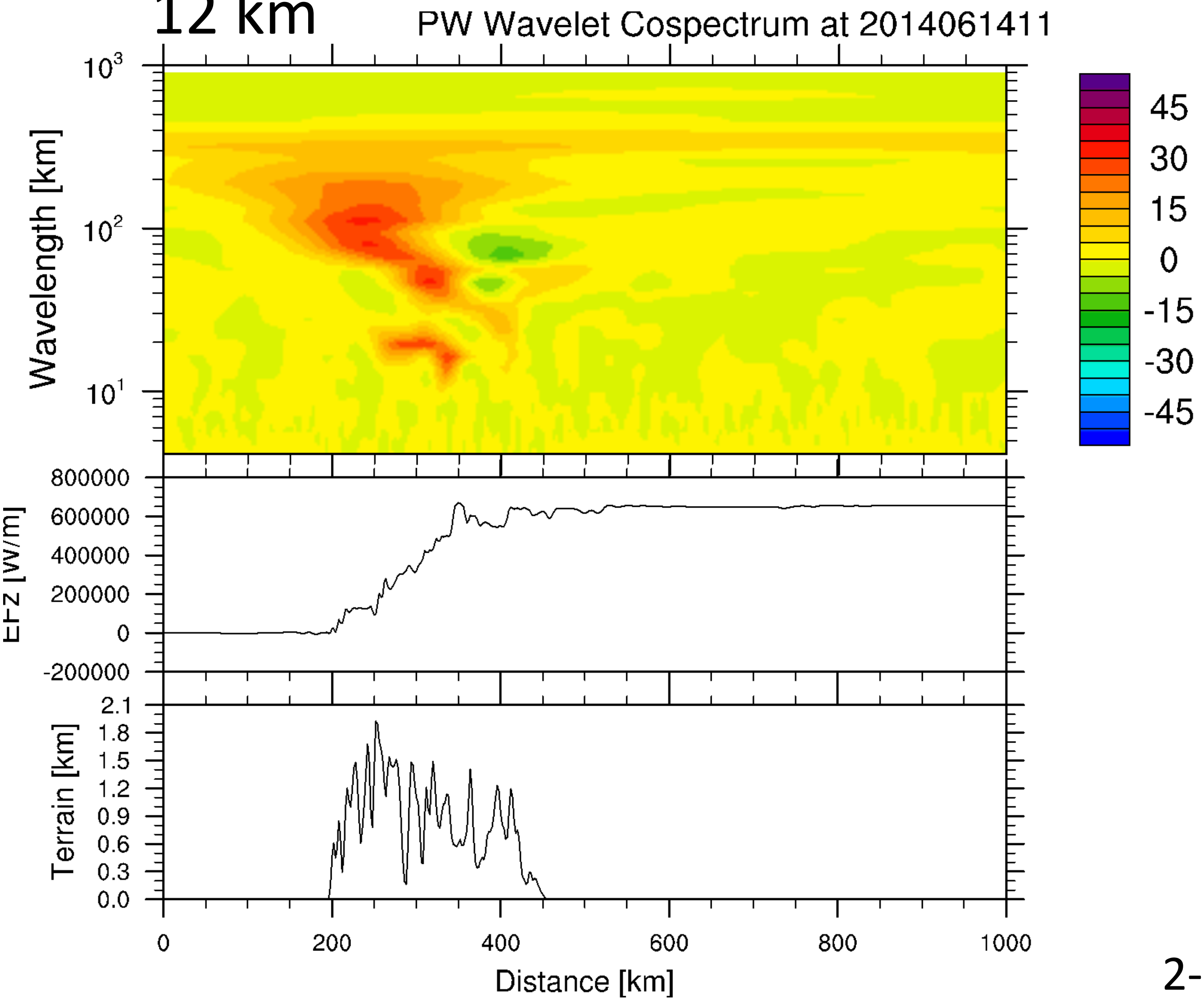
12 km



2-km WRF

Simulated Scales: RF04 Snapshot

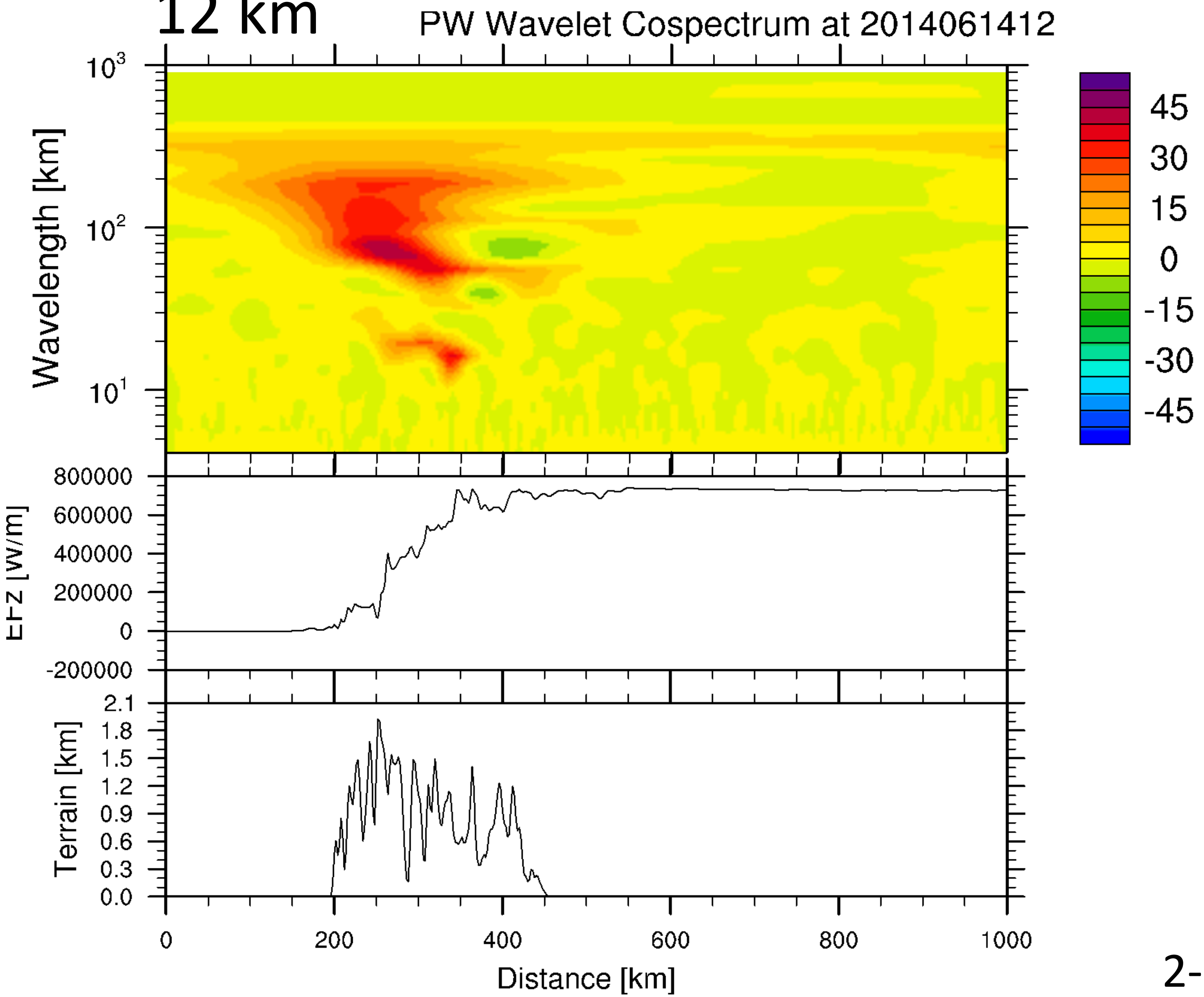
12 km



2-km WRF

Simulated Scales: RF04 Snapshot

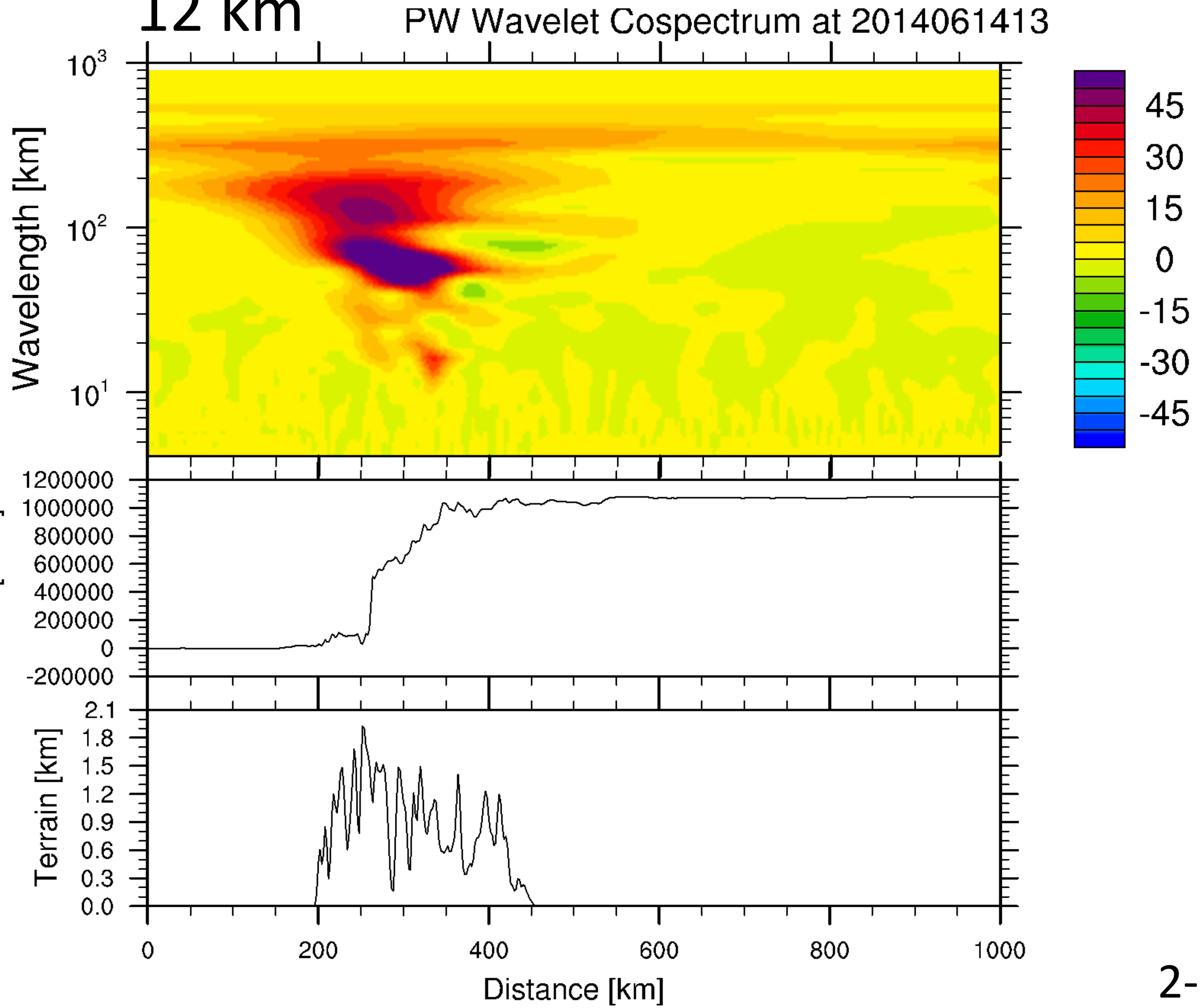
12 km



2-km WRF

Simulated Scales: RF04 Snapshot

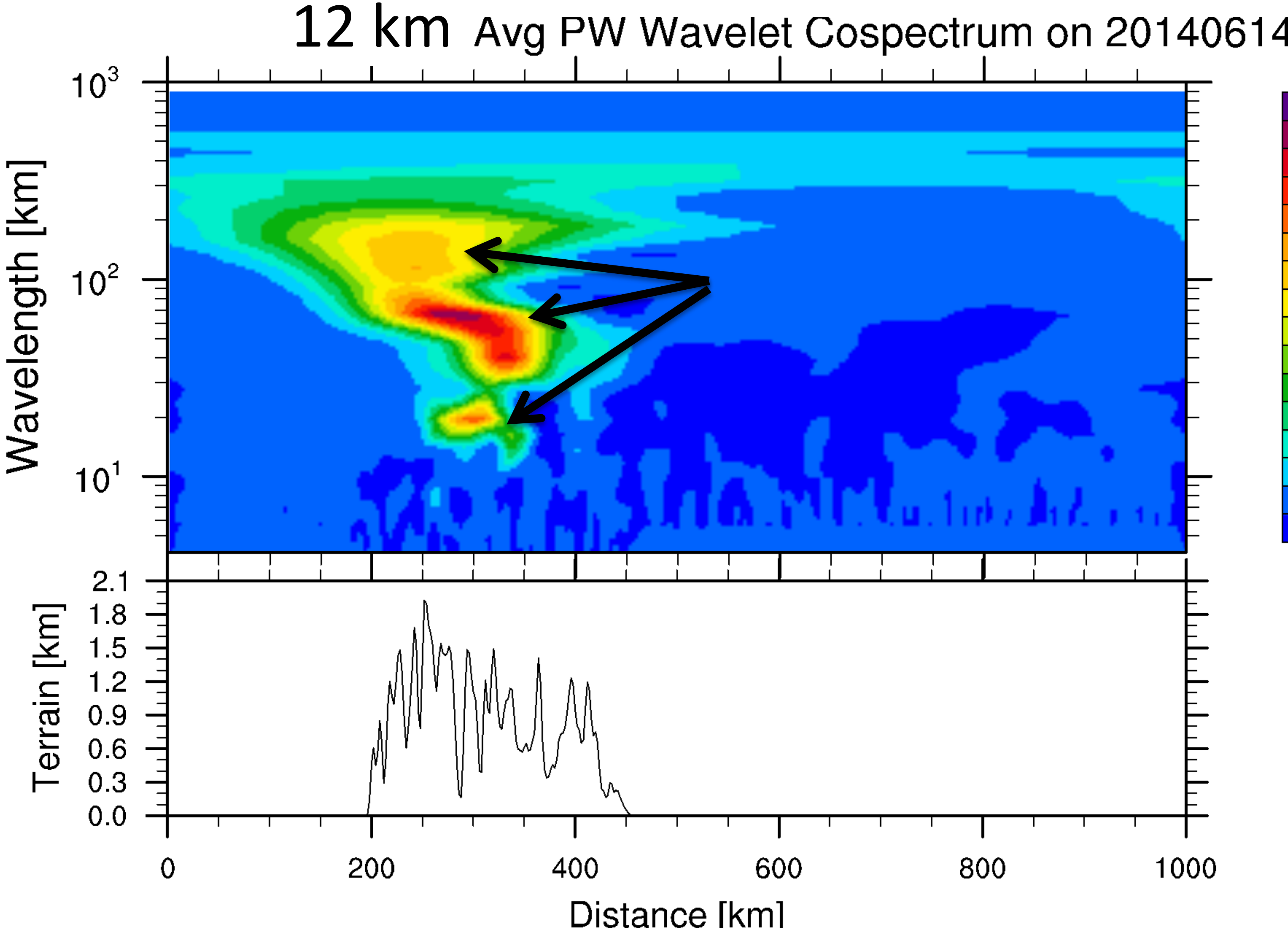
12 km



2-km WRF

Avg EF_z Cospectrum: RF04

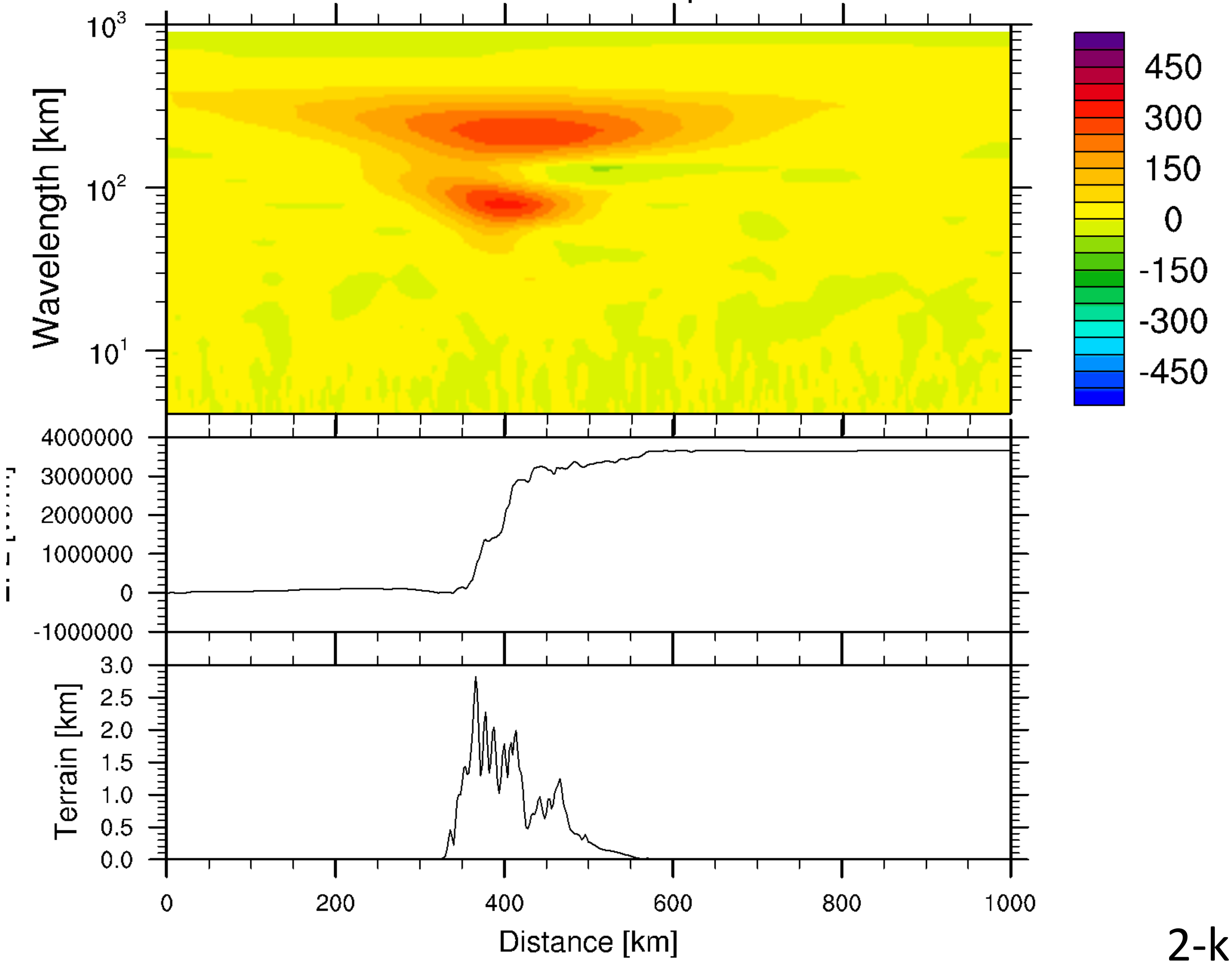
12 km



2-km WRF

RF09 Snapshot

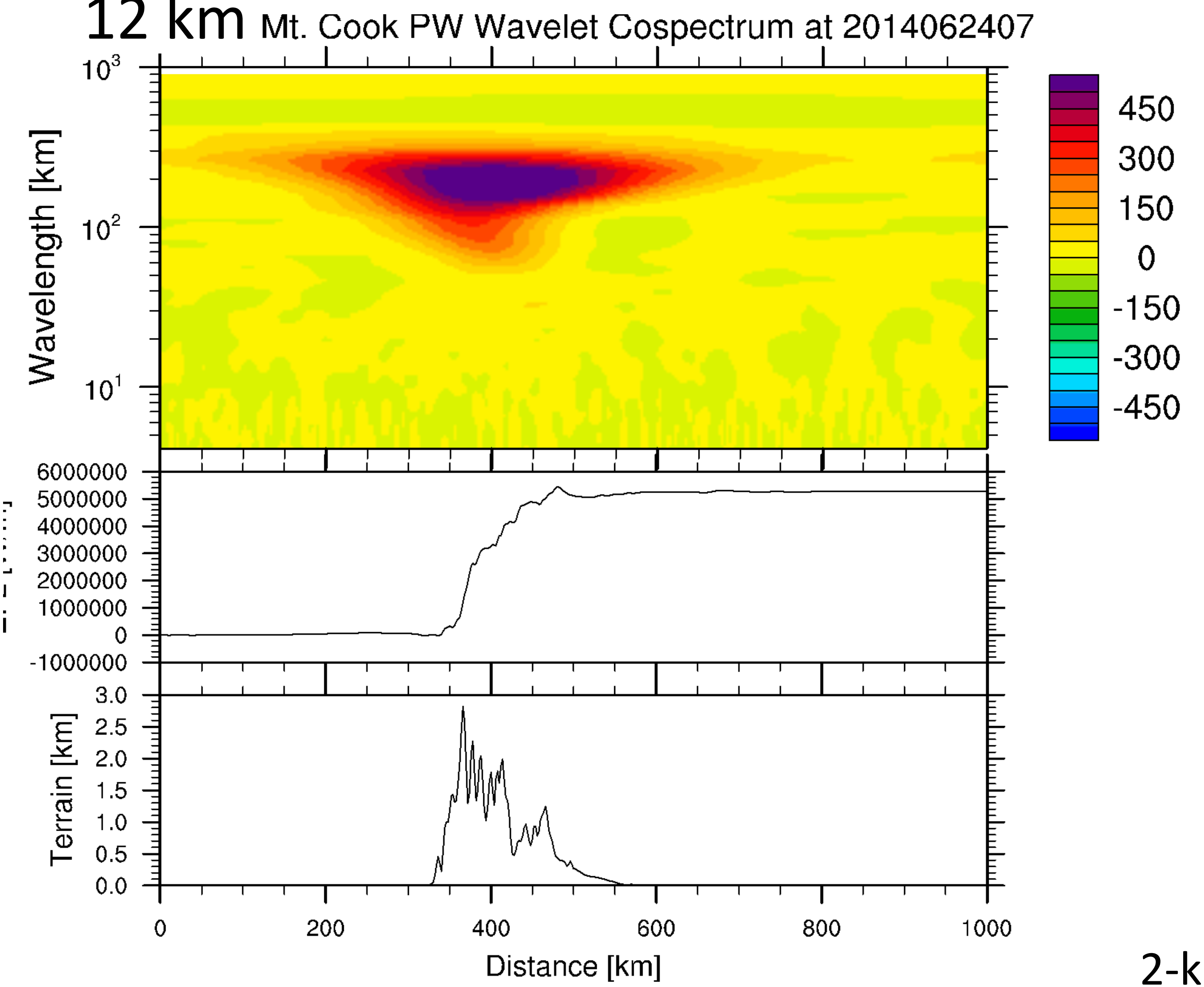
12 km



2-km WRF

RF09 Snapshot

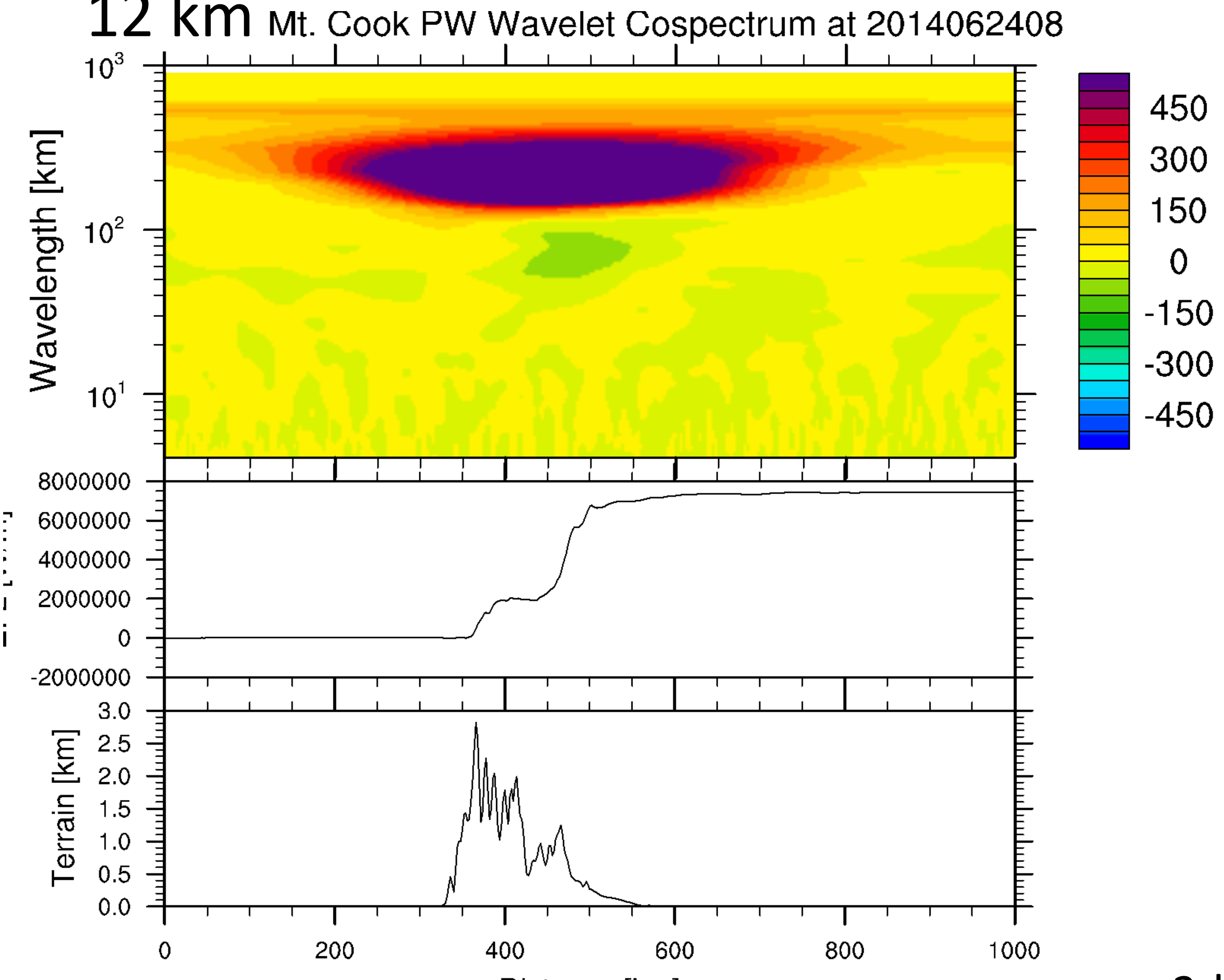
12 km



2-km WRF

RF09 Snapshot

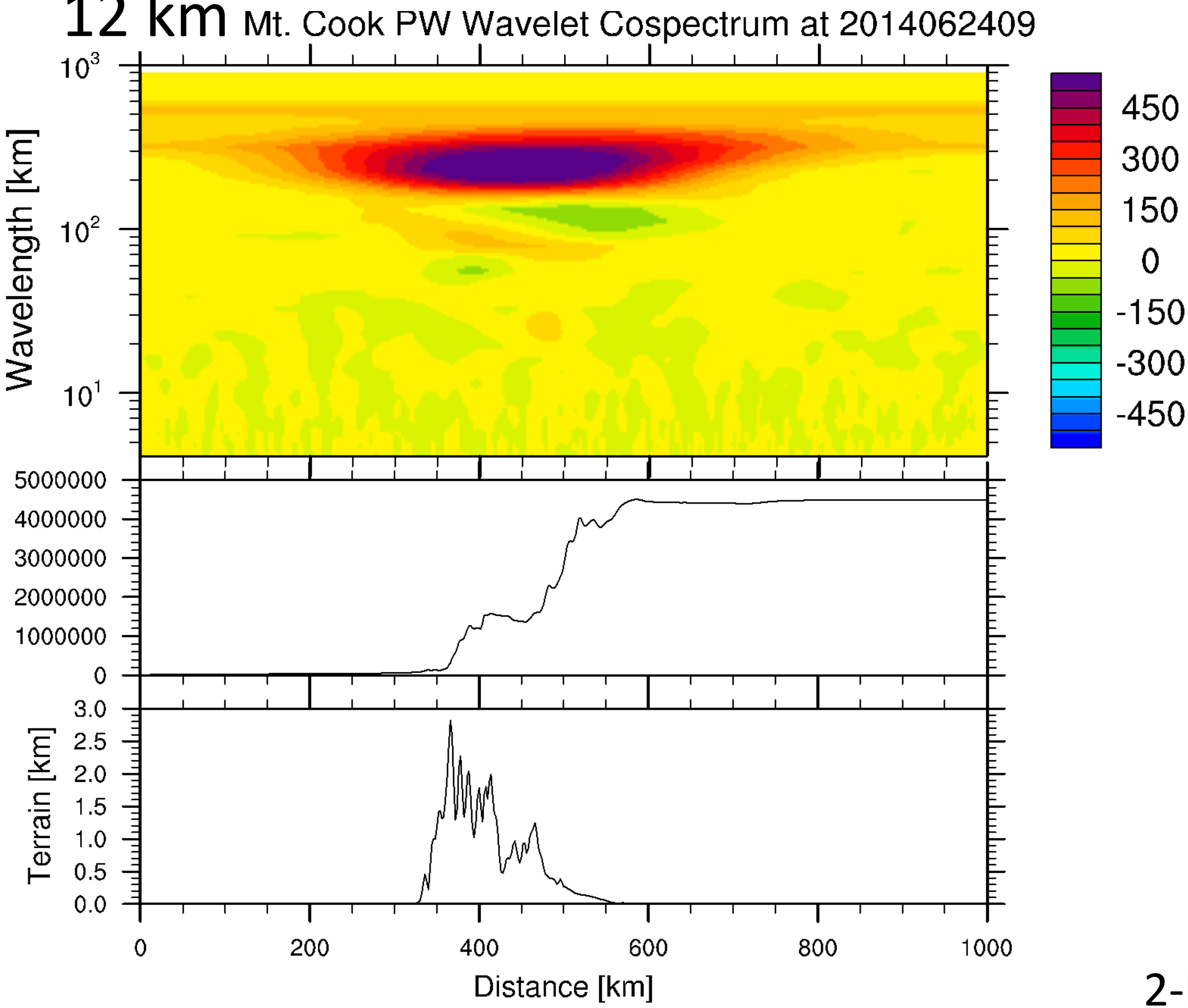
12 km



2-km WRF

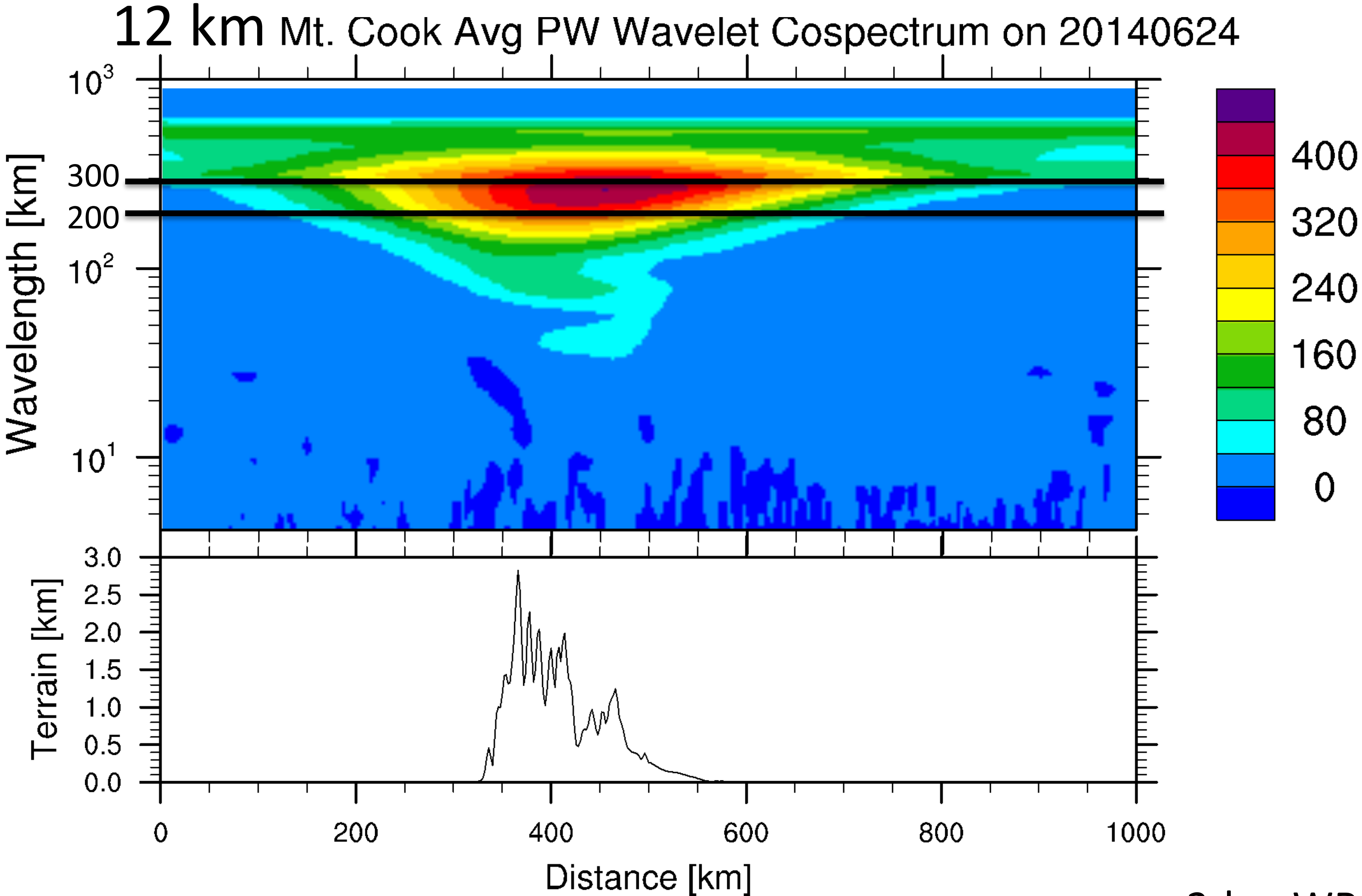
RF09 Snapshot

12 km



2-km WRF

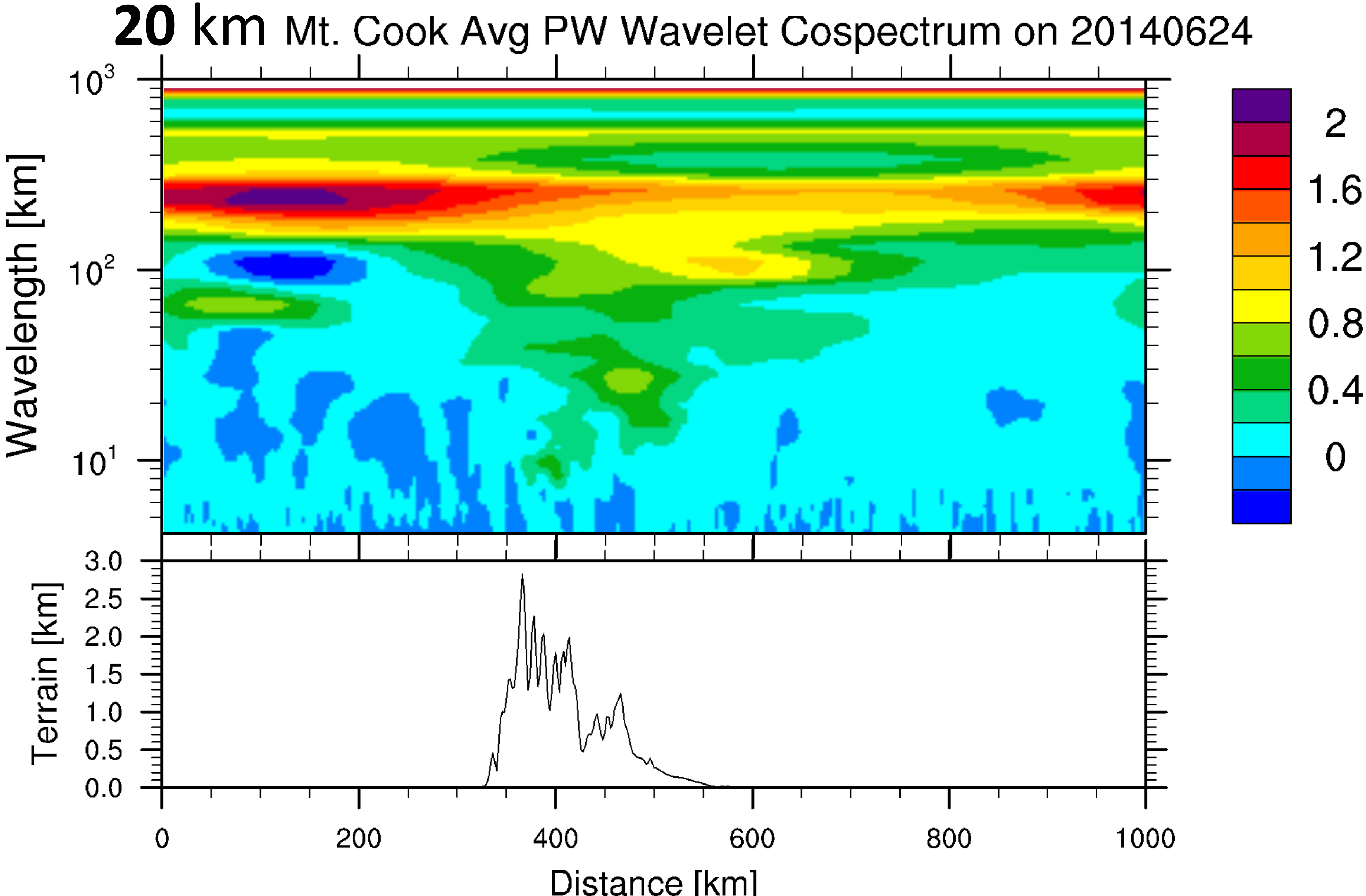
Avg EF_z Cospectrum: RF09



2-km WRF

Avg EF_z Cospectrum: RF09

20 km

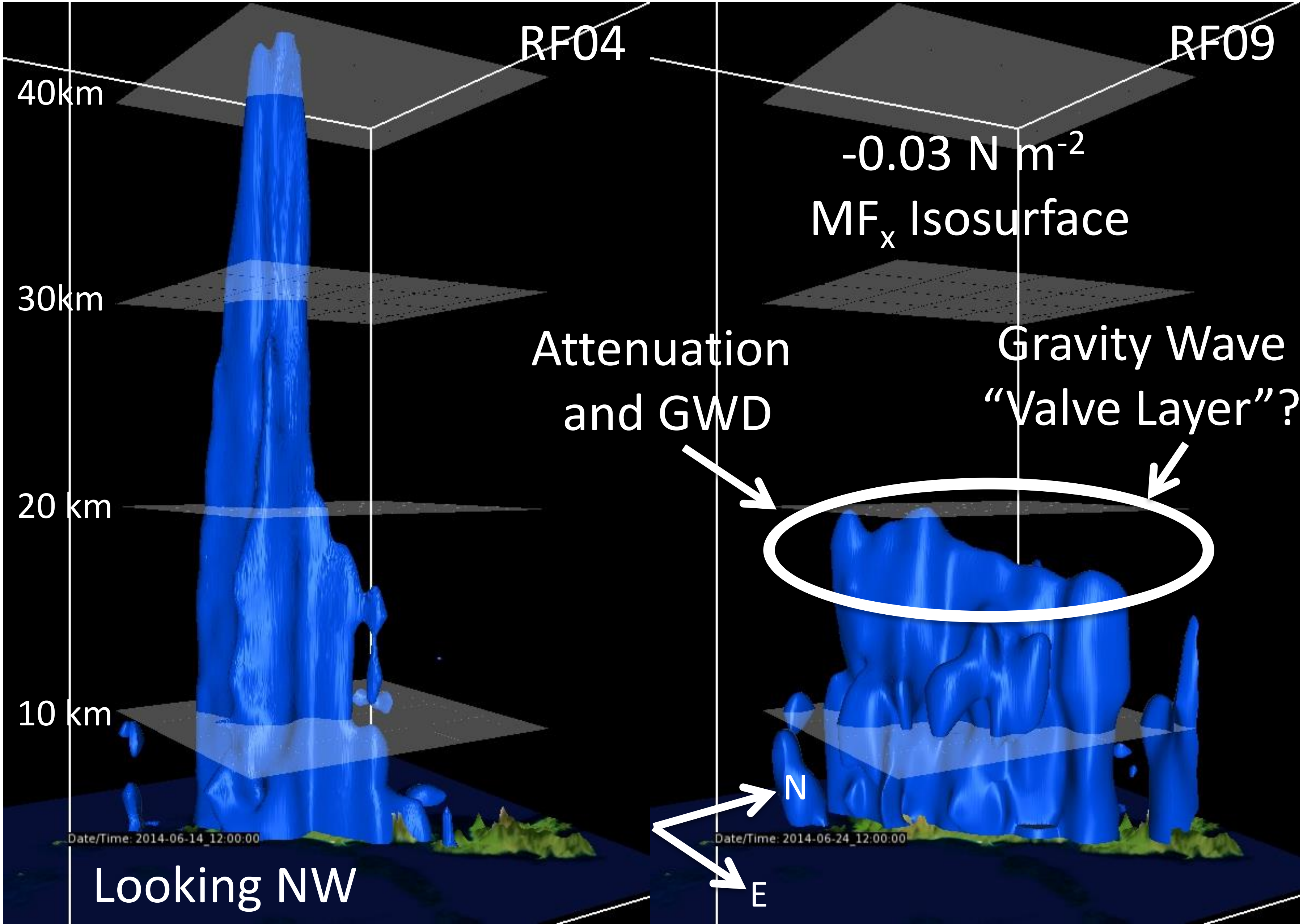


2-km WRF

Scale Summary

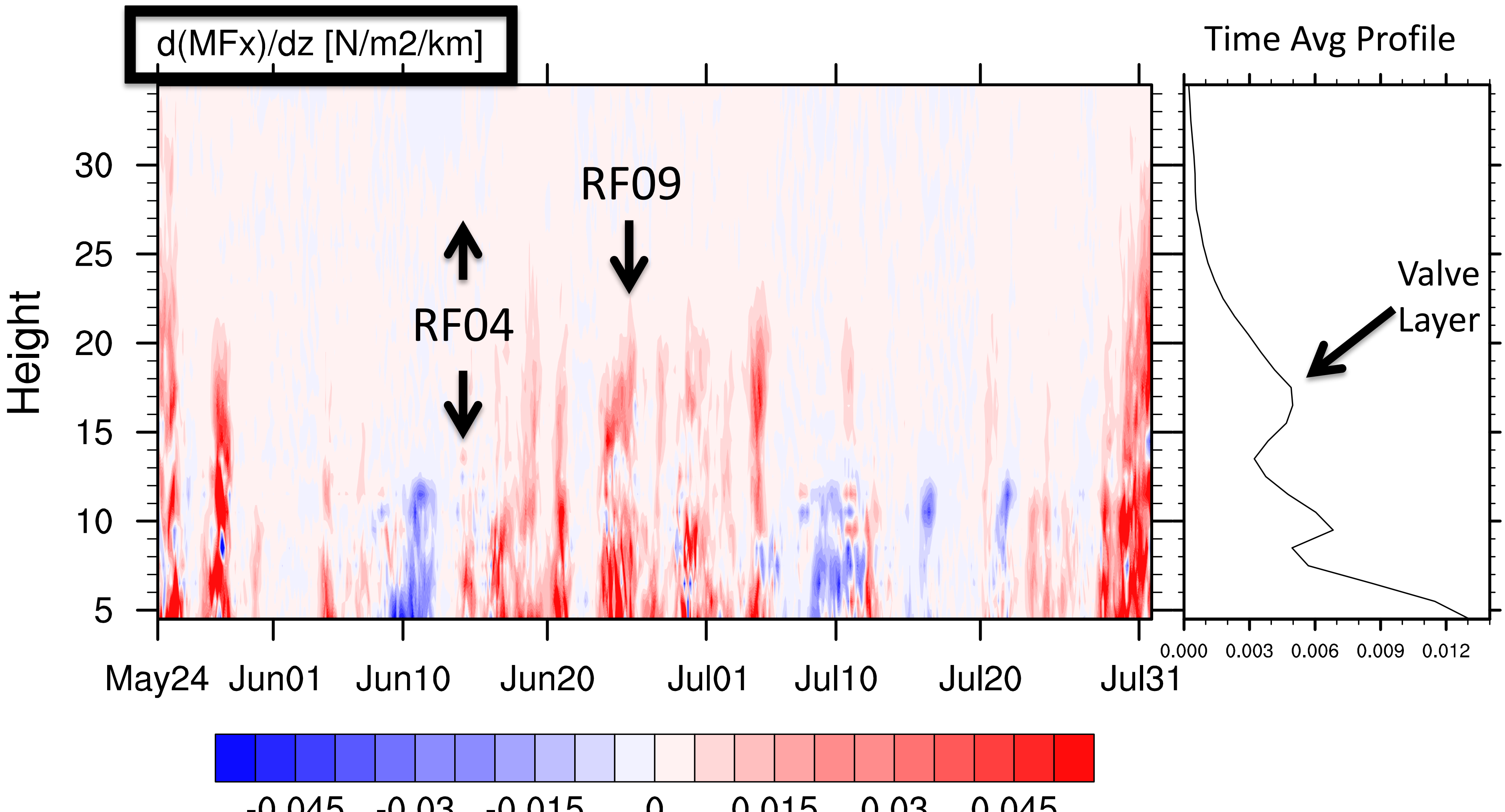
- Important flux carrying wavelengths within 2-km WRF range from 20-250 km
  - Depends on event (and maybe transect location)
  - Long wavelengths in aircraft wavelets also in WRF
- Longer aircraft legs would not reveal longer wavelength fluxes according to WRF
- Wave fluxes above attenuation regions seem random, do not resemble waves below
  - Will better quantify spectral changes through attenuation layers

3. Mountain Wave Attenuation



South Island Avg MF_x Divergence

6-km WRF

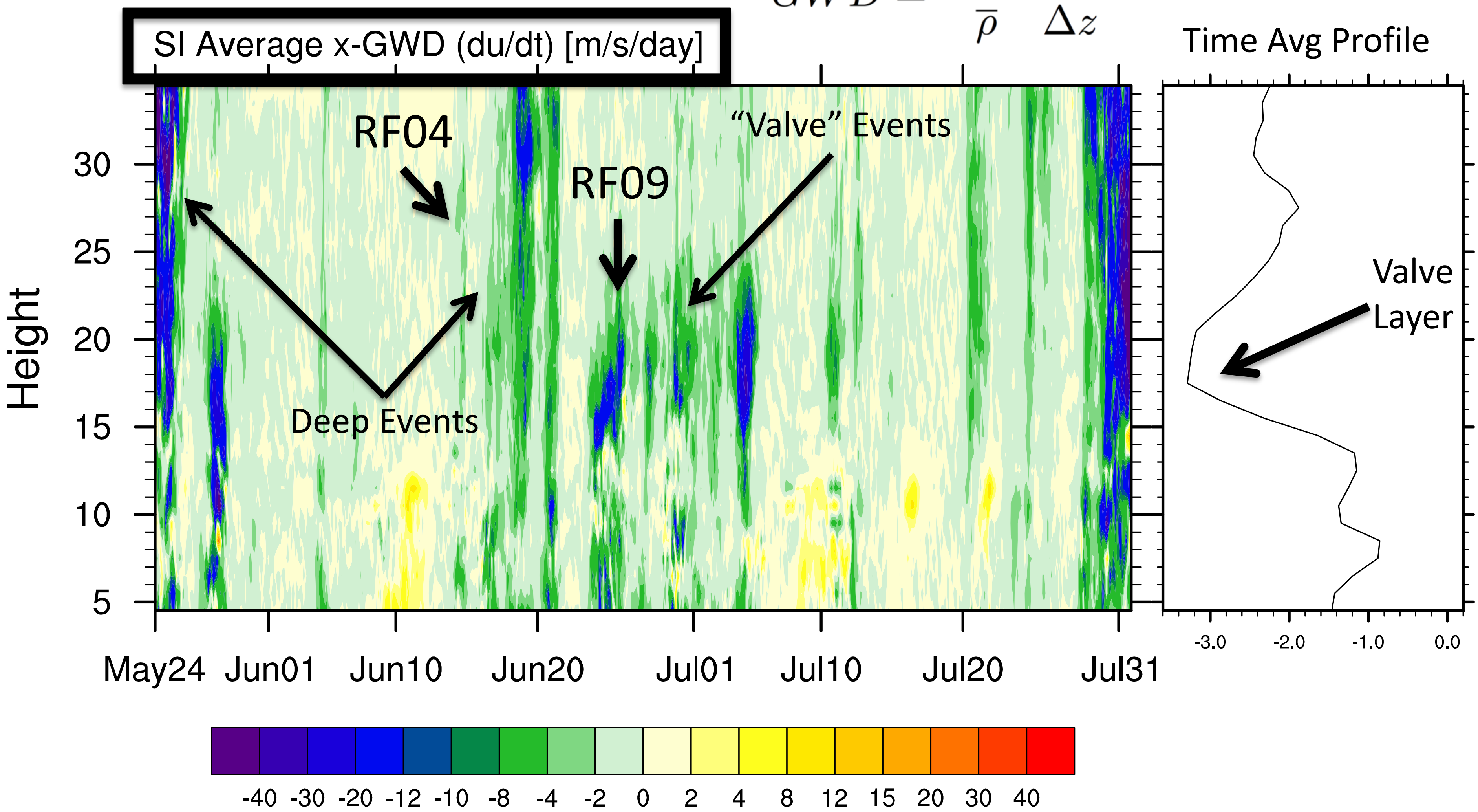


- Fluxes computed using 2-D filtering method proposed by Kruse and Smith 2015 (Accepted with revisions to JAS)

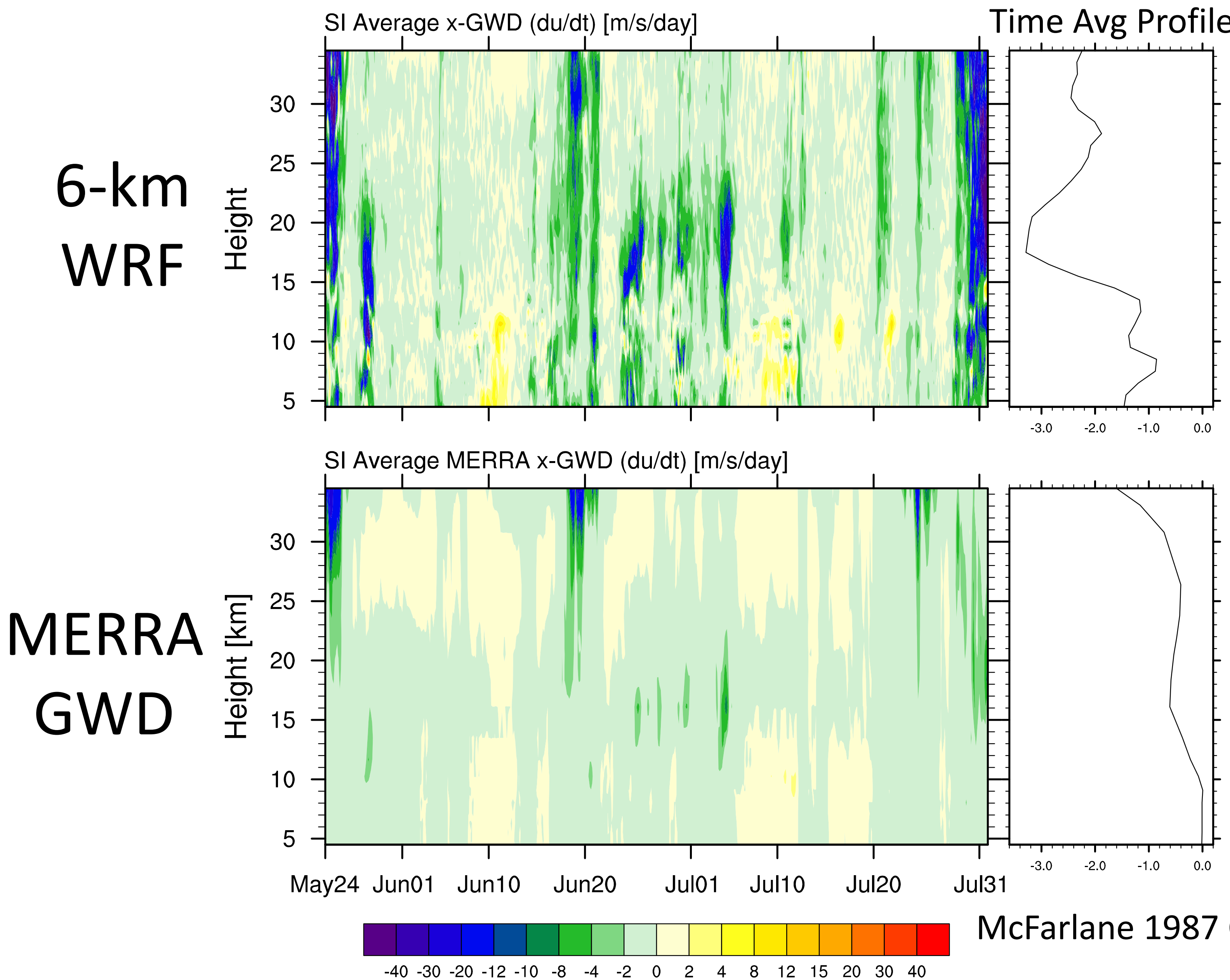
South Island Avg GWD Acceleration

6-km WRF

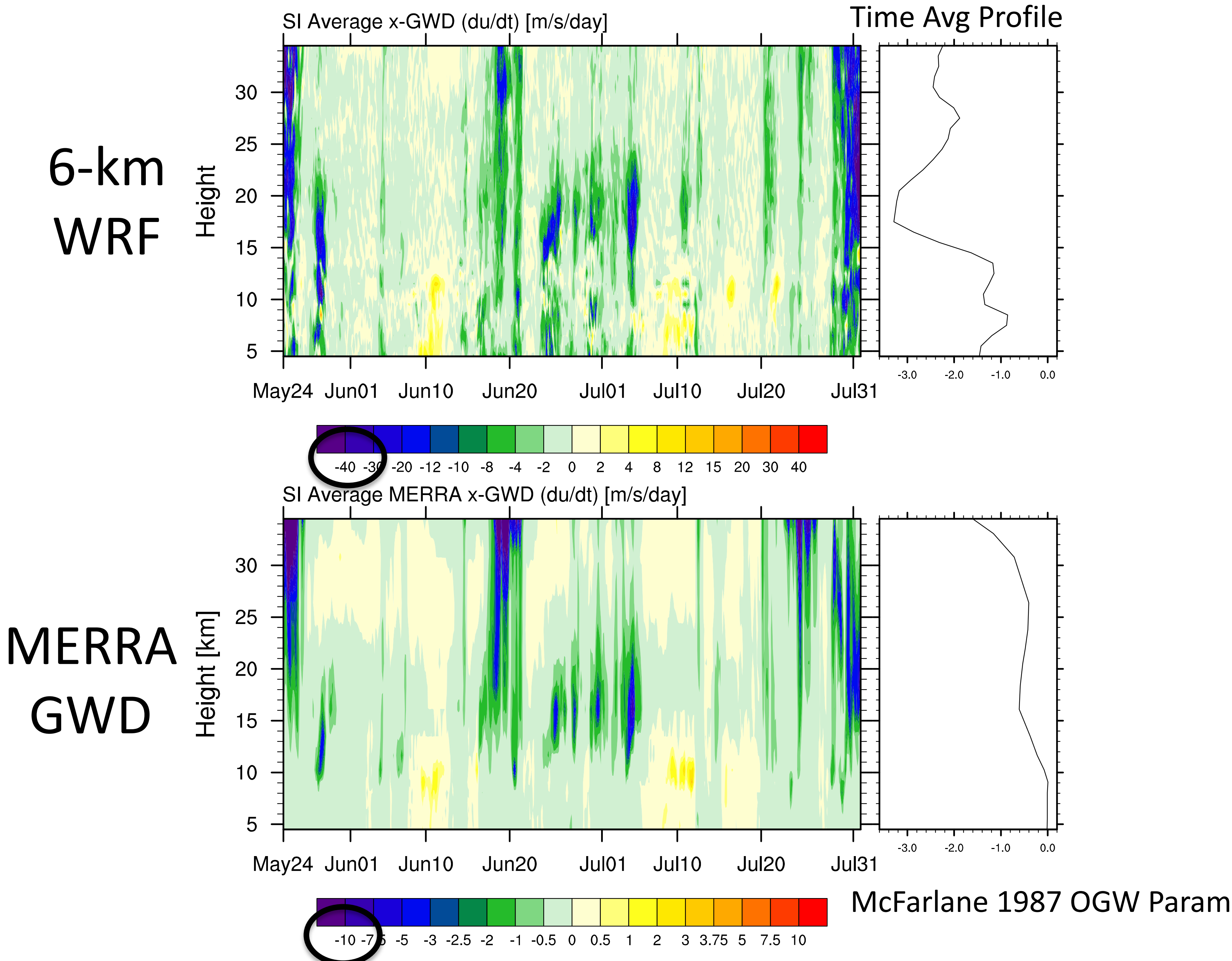
$$GWD = -\frac{1}{\bar{\rho}}\frac{\Delta MF_x}{\Delta z}$$



6-km WRF/MERRA GWD Comparison



McFarlane 1987 OGW Param


Time Avg Profile
6-km
WRF
SI Average x-GWD (du/dt) [m/s/day]
Height
May24 Jun01 Jun10 Jun20 Jul01 Jul10 Jul20 Jul31
-40 -30 -20 -12 -10 -8 -4 -2 0 2 4 8 12 15 20 30 40
MERRA
GWD
SI Average MERRA x-GWD (du/dt) [m/s/day]
Height [km]
-10 -7.5 -5 -3 -2.5 -2 -1 -0.5 0 0.5 1 2 3 3.75 5 7.5 10
McFarlane 1987 OGW Param

Valve Layer Summary

- Enhanced attenuation frequent in 15-20 km region during 2014 winter
  - In both units of force and deceleration
  - “Valve Layer”
- MERRA parameterized GWD structure agrees well with 6-km WRF resolved GWD, though significantly underestimated

Future Work

- Lower stratospheric attenuation

Questions

- What is the mechanism of attenuation?
- How do wave spectra change through “valve layer”?
- Is PV conservation invalidated in attenuation regions?

Gravity Waves and PV

- Ertel PV conserved in linear gravity waves

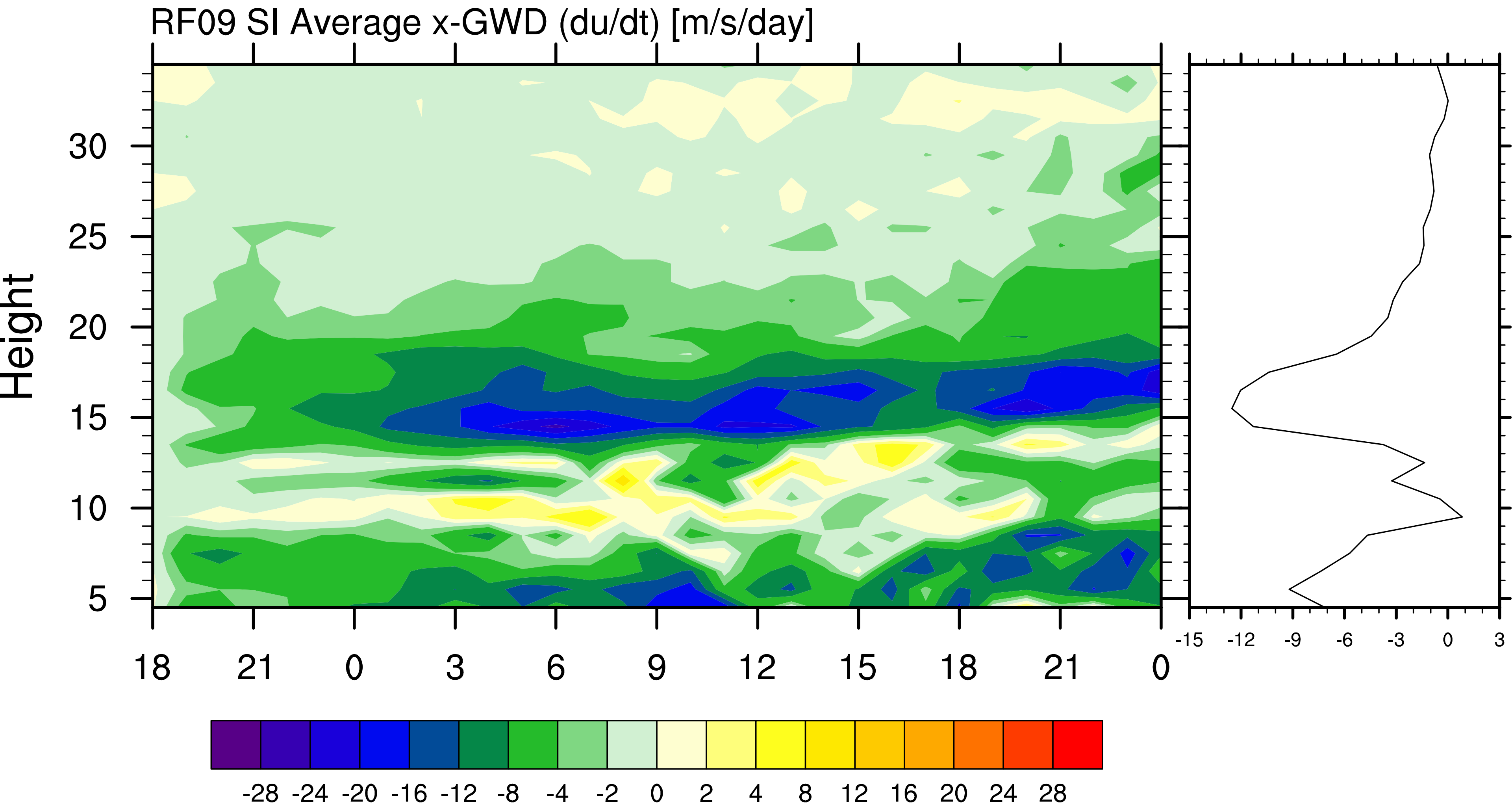
$$PV = \frac{\vec{\omega} \cdot \nabla\theta}{\rho} \qquad \frac{dPV}{dt} = 0$$

- PV conservation invalidated in attenuation regions?

$$\frac{dPV}{dt} = f(Turbulent\,Heat,\ Momentum\,Fluxes)$$

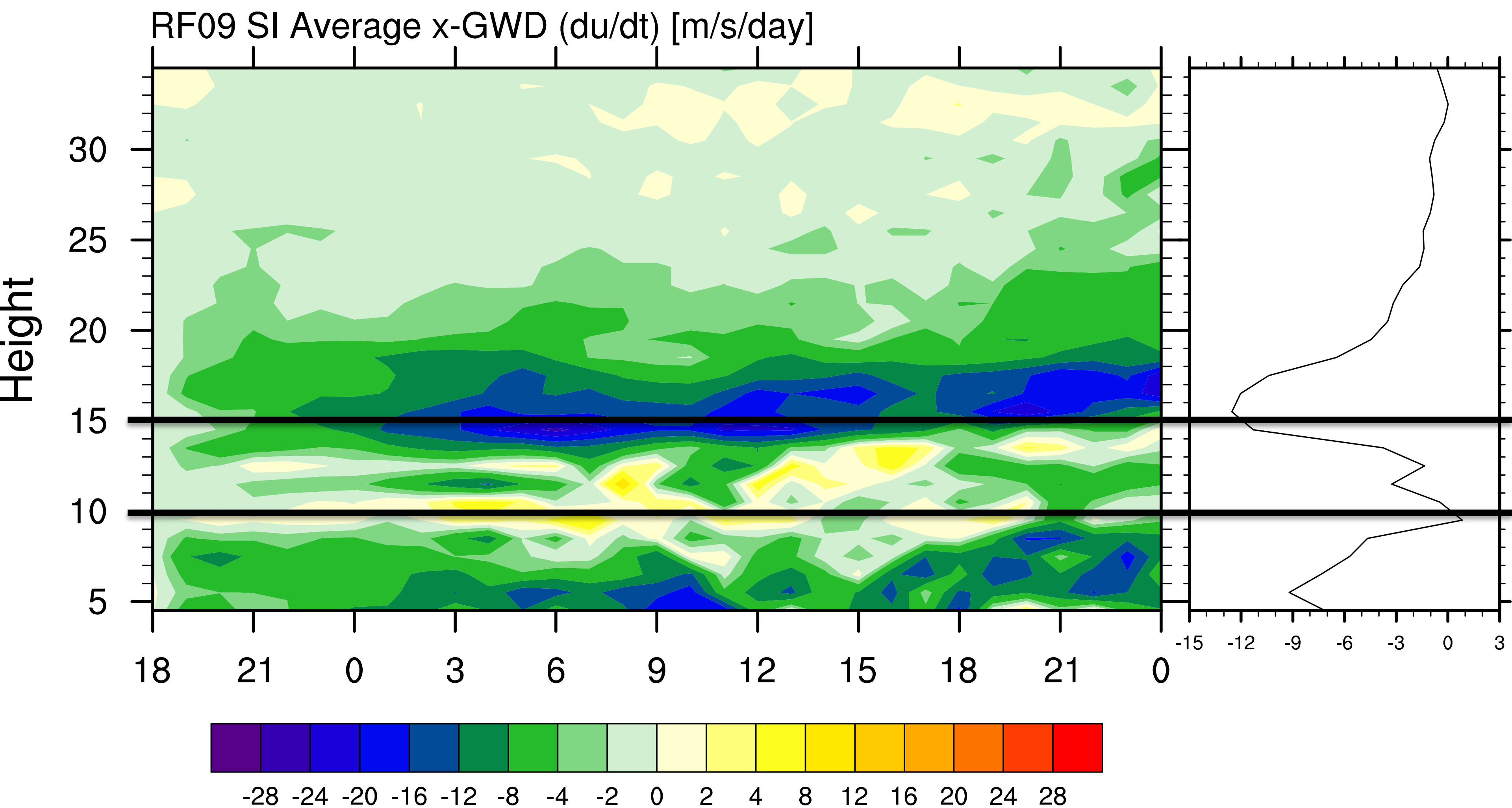
- Are PV banners generated?
  – I.e., PV generated via local GW attenuation, advected conservatively from there?

RF09 x-GWD Deceleration



2-km WRF

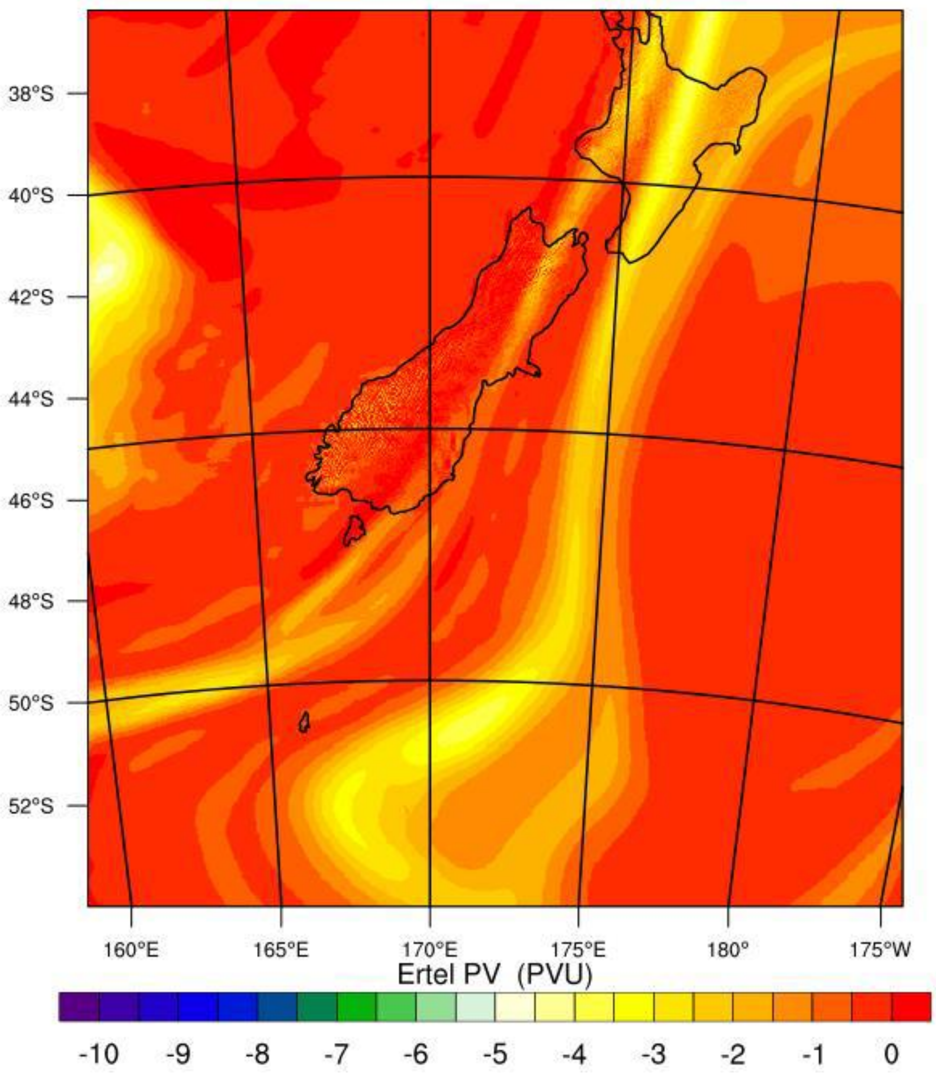
RF09 x-GWD Deceleration



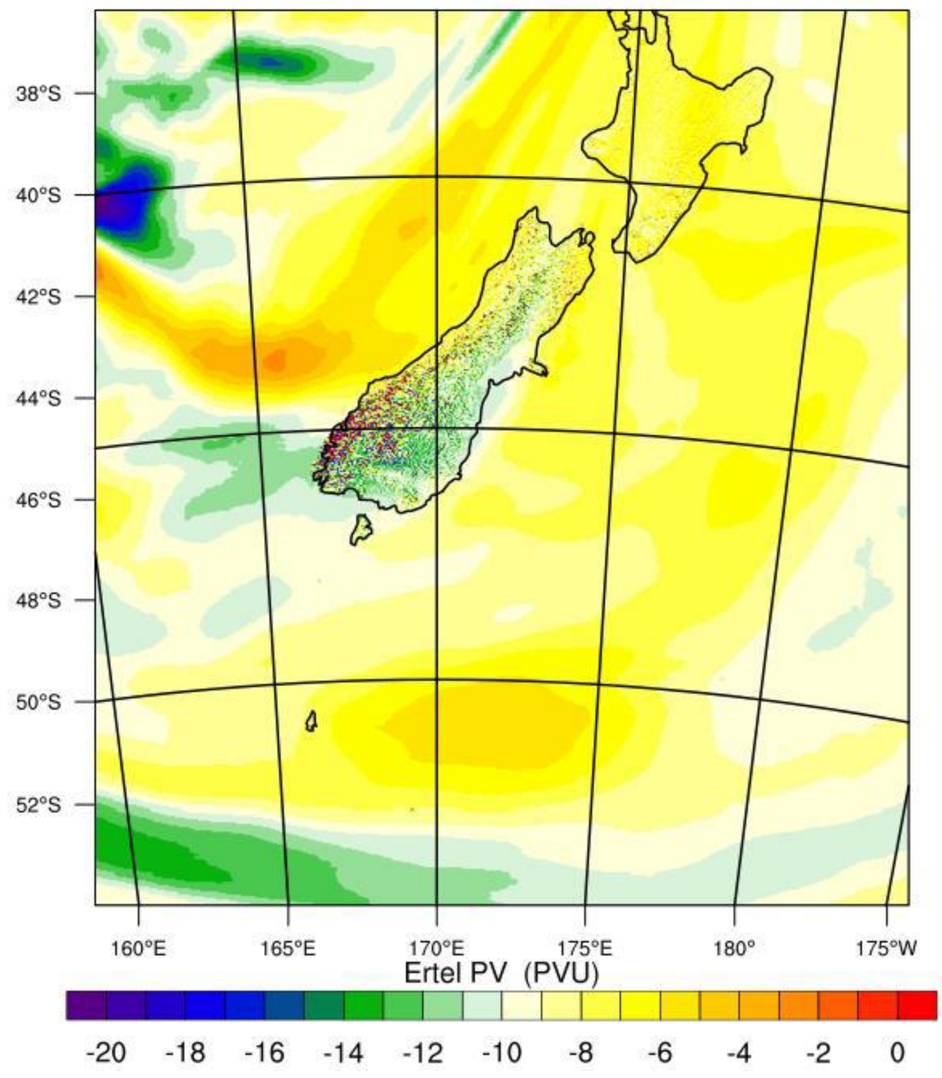
2-km WRF

Ertel PV

10 km PV



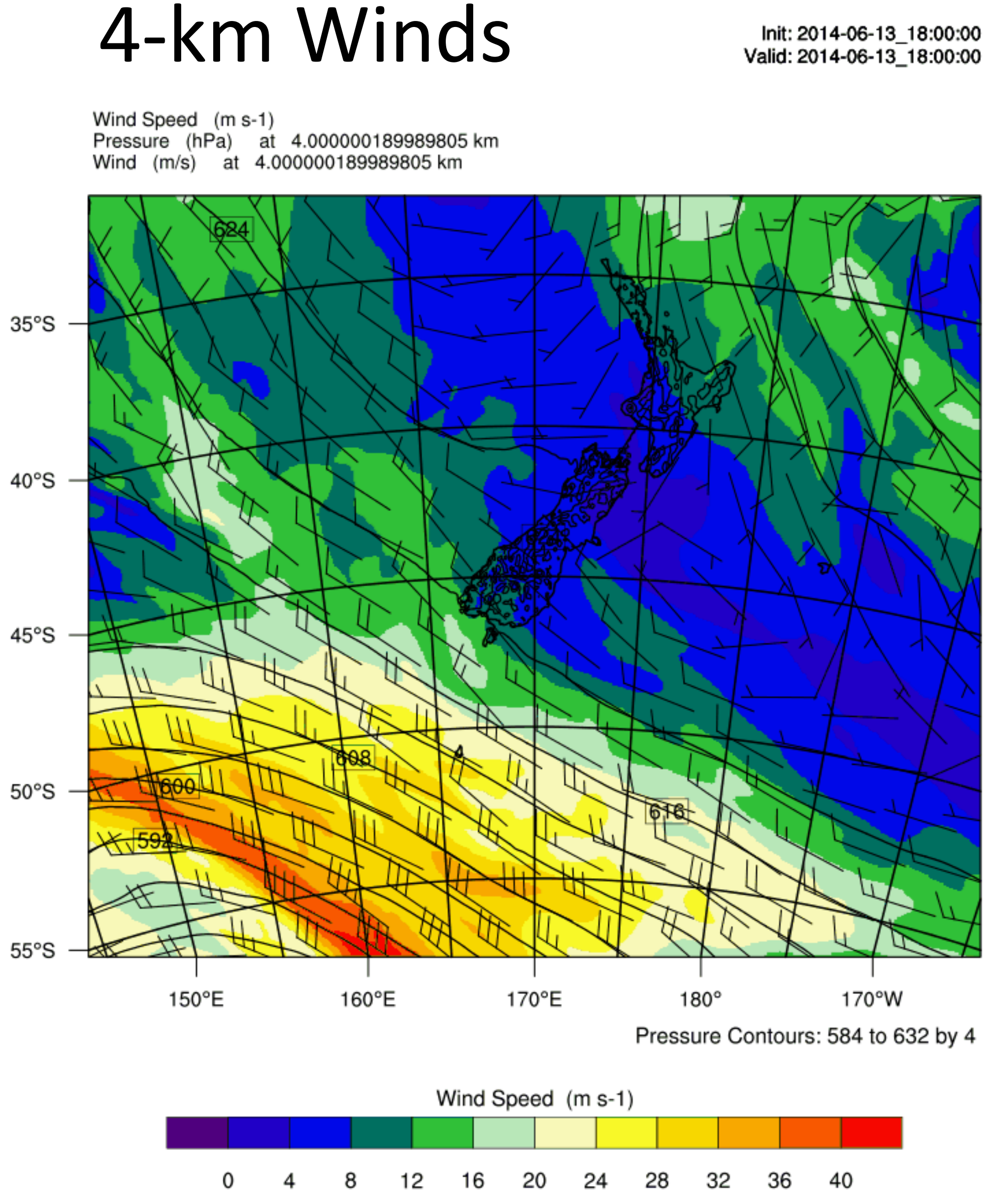
15 km PV



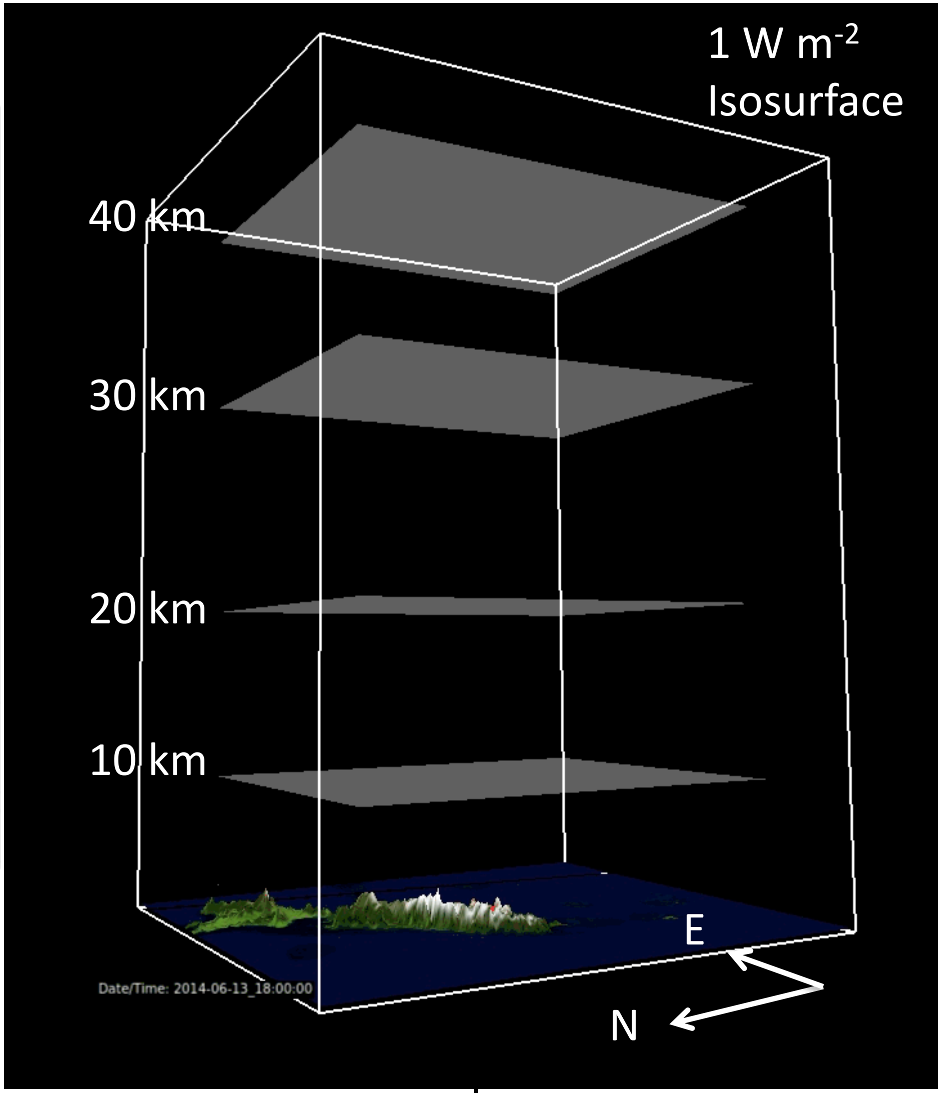
2-km WRF

Thanks

4-km Winds

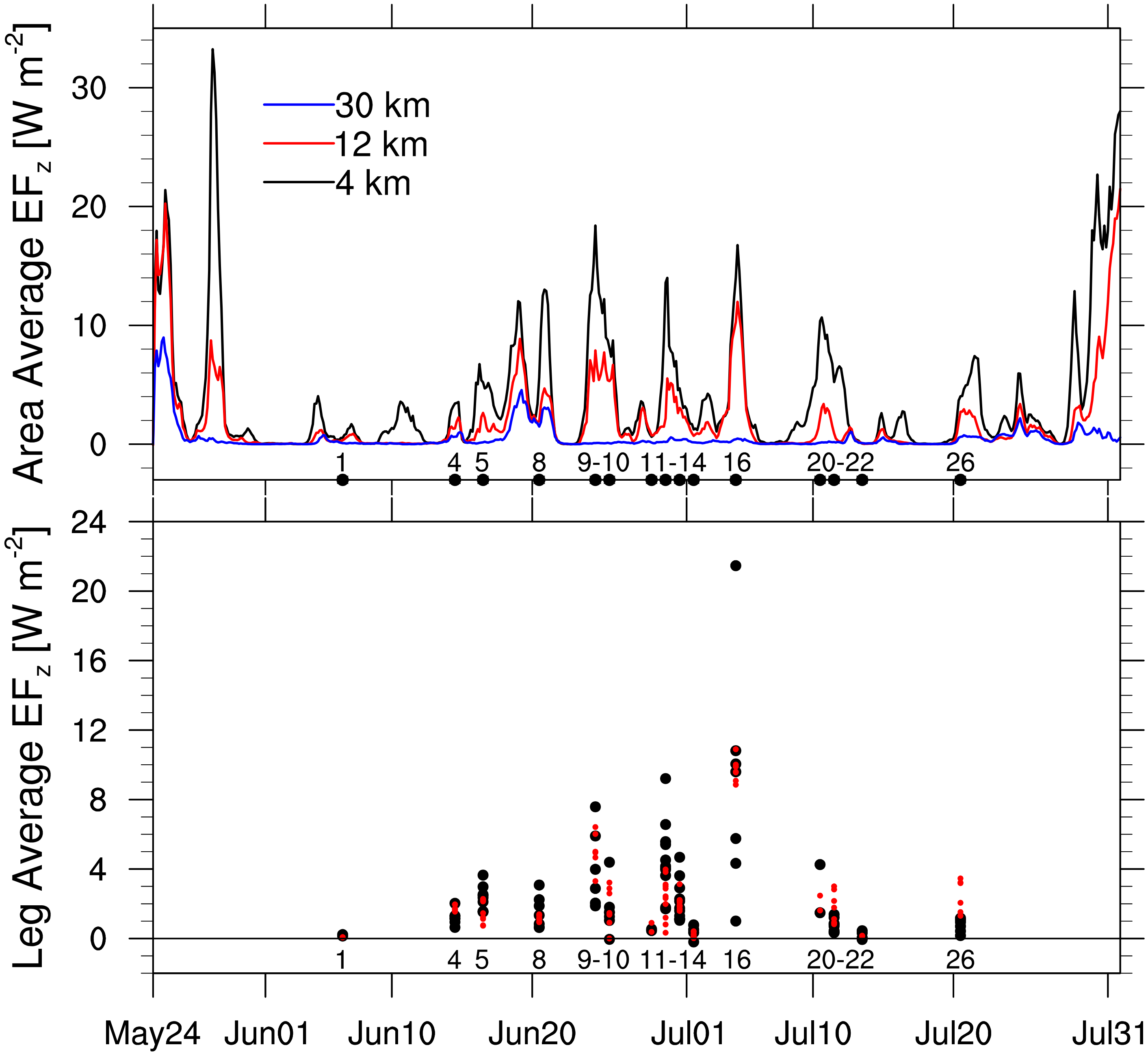


EF_z Low-Passed



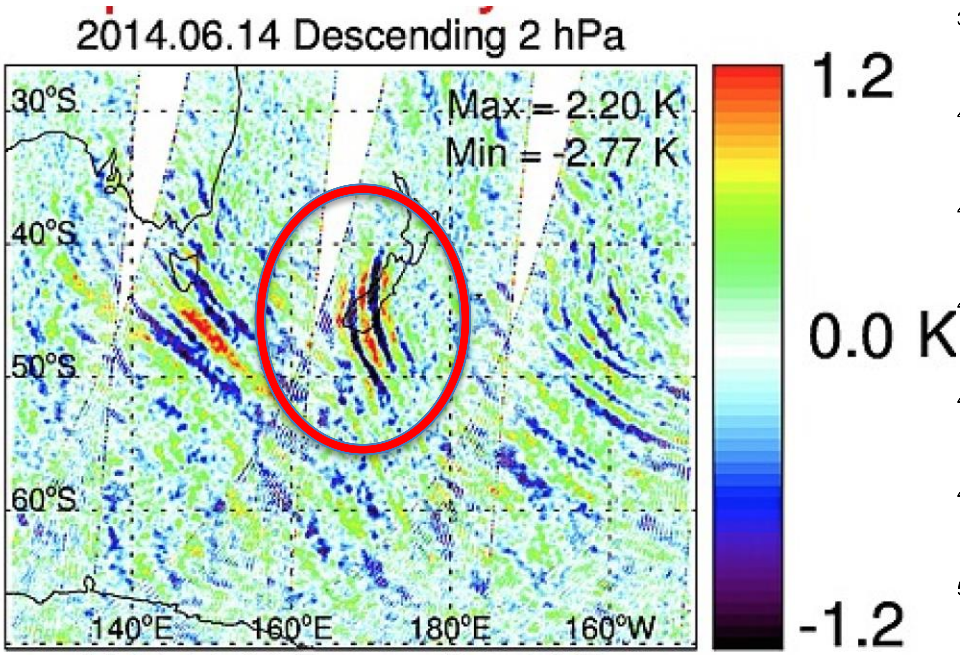
www.vapor.ucar.edu

WRF/Obs Leg Avg EFz Comparison



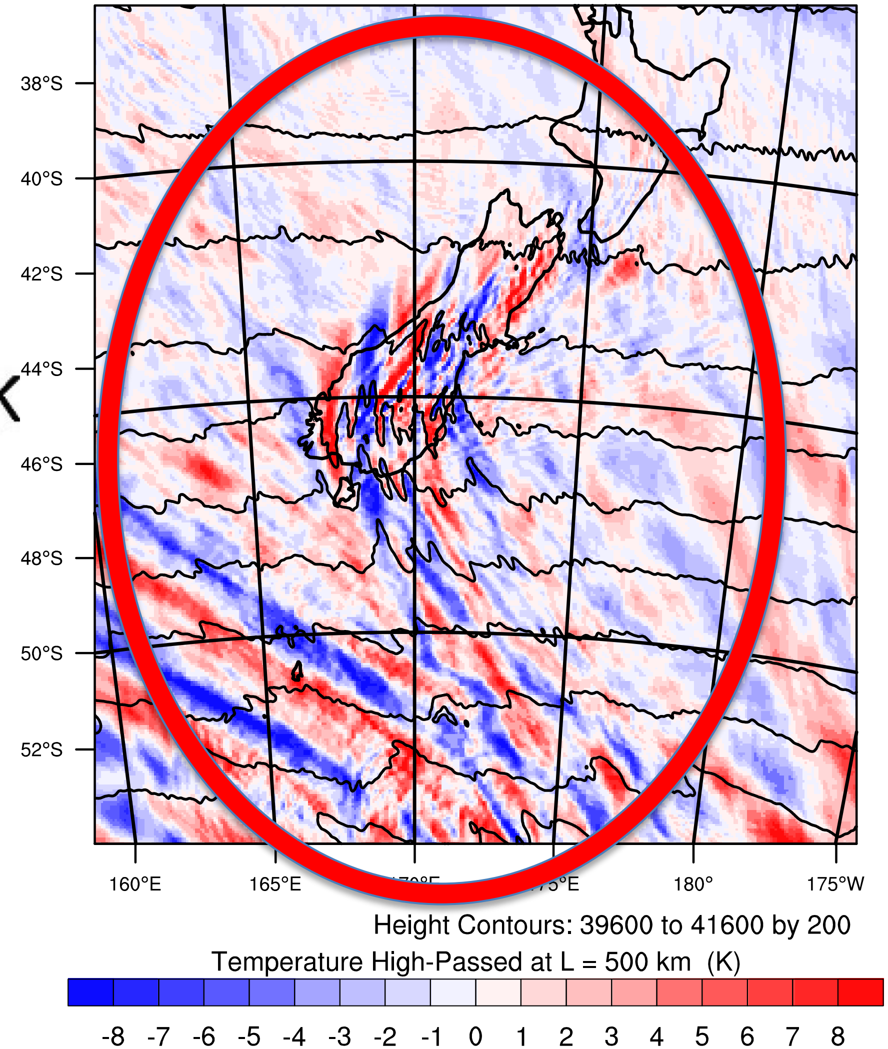
Extra: RF04 WRF/AIRS Comparison

2 hPa Satellite Observed T’
13:19 UTC



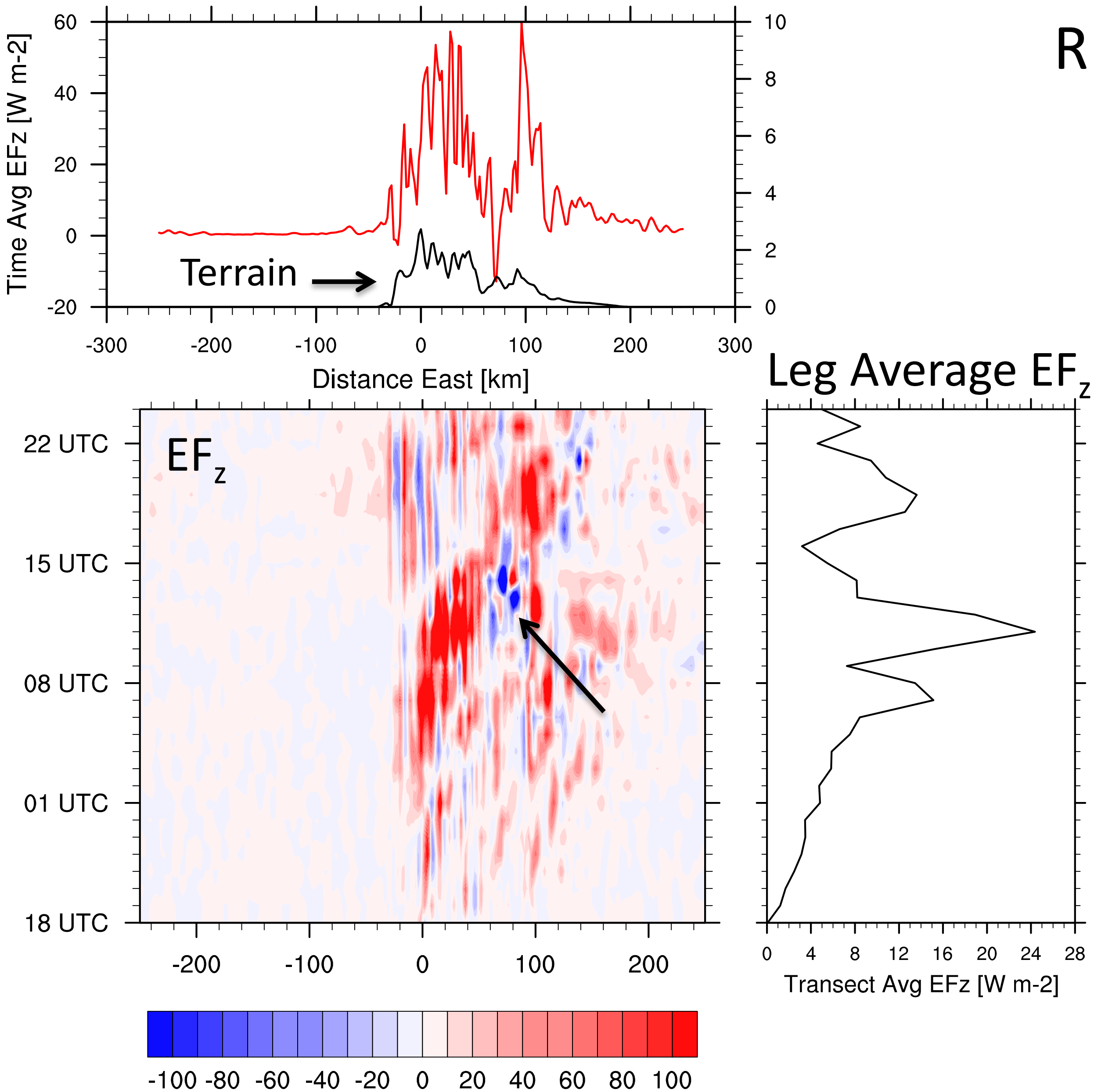
Steve Eckermann, NRL

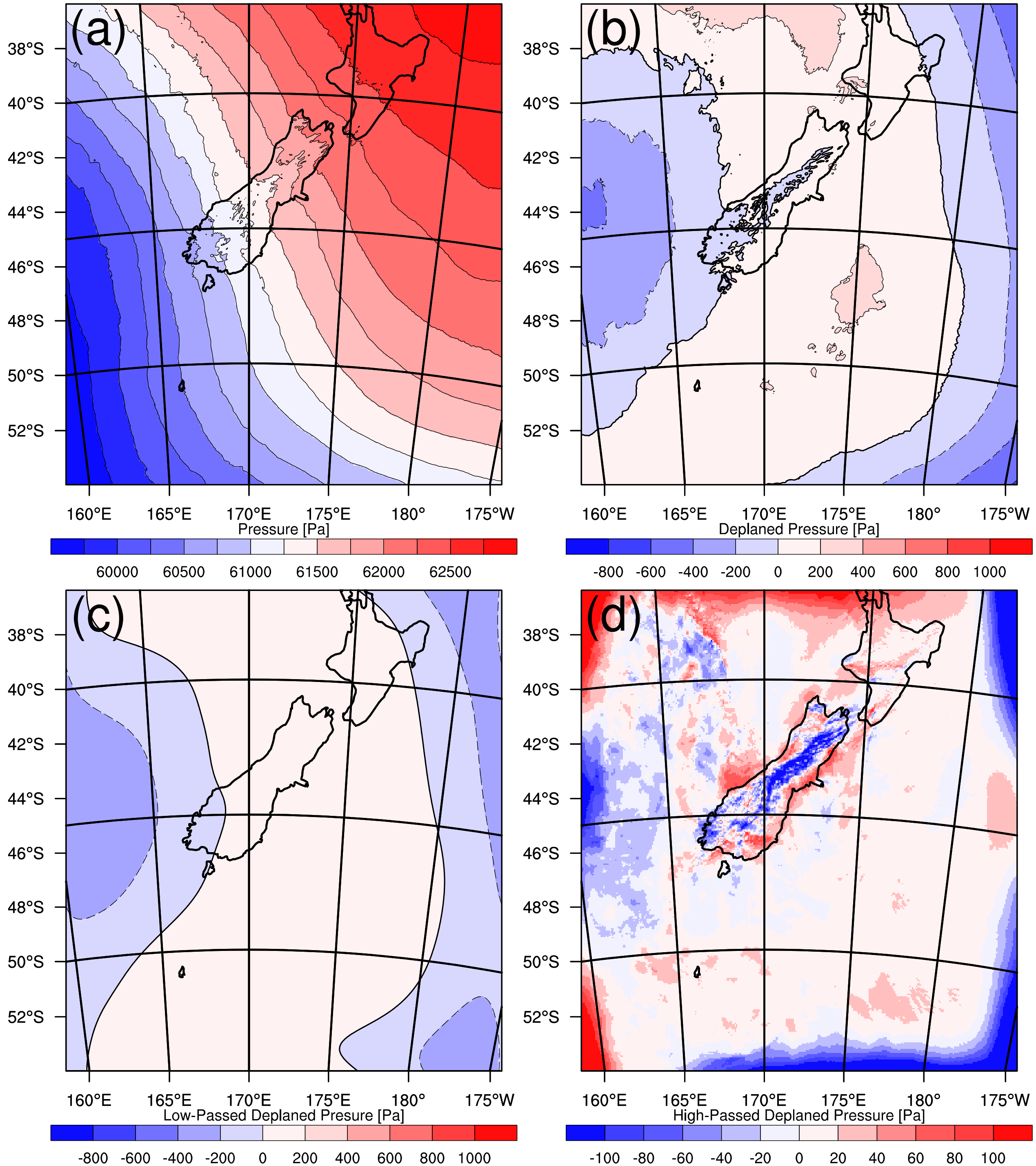
2 hPa Simulated T’
(High-Passed T, L = 500 km)
13:00 UTC

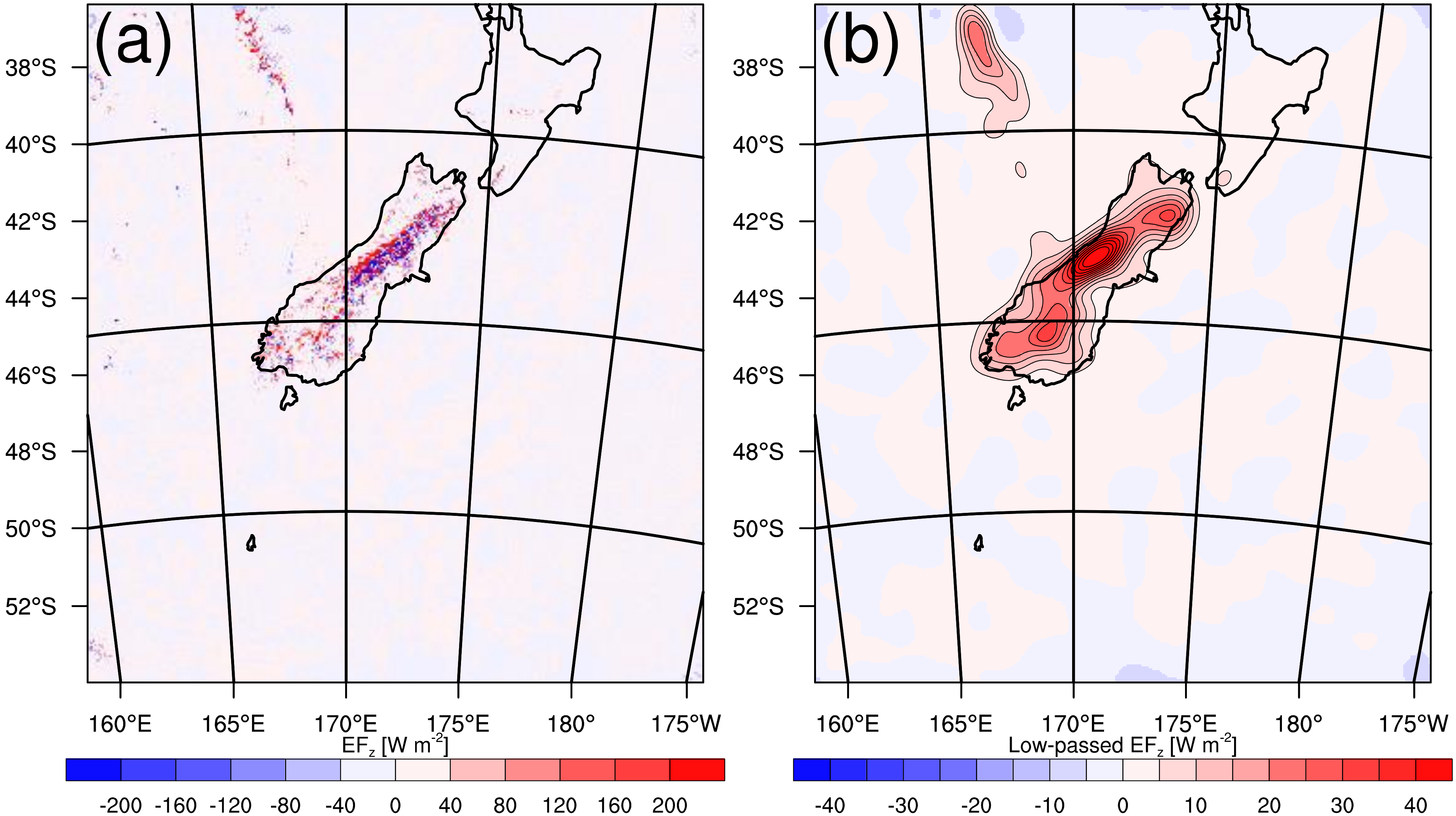


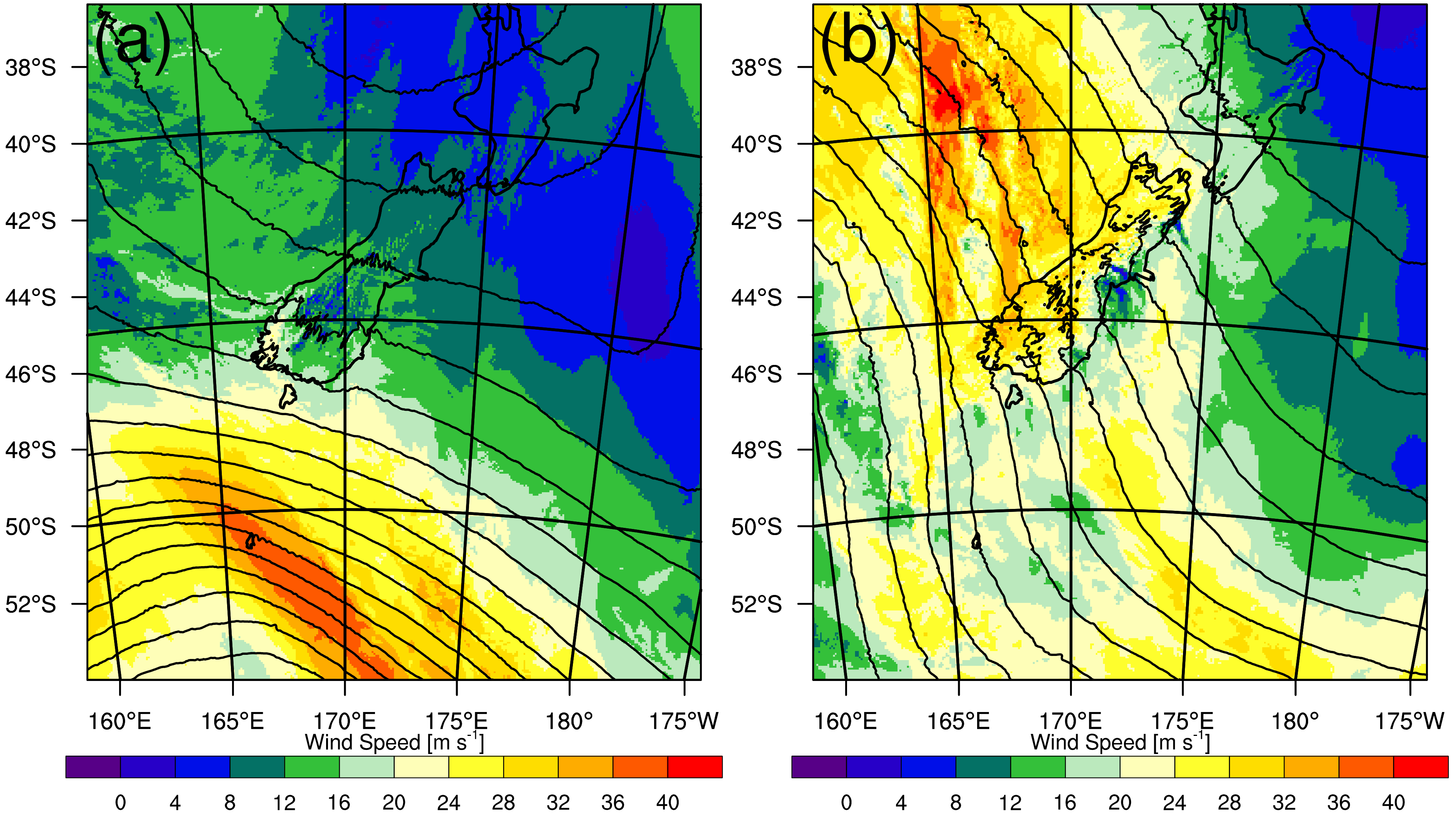
EF_z Transience?

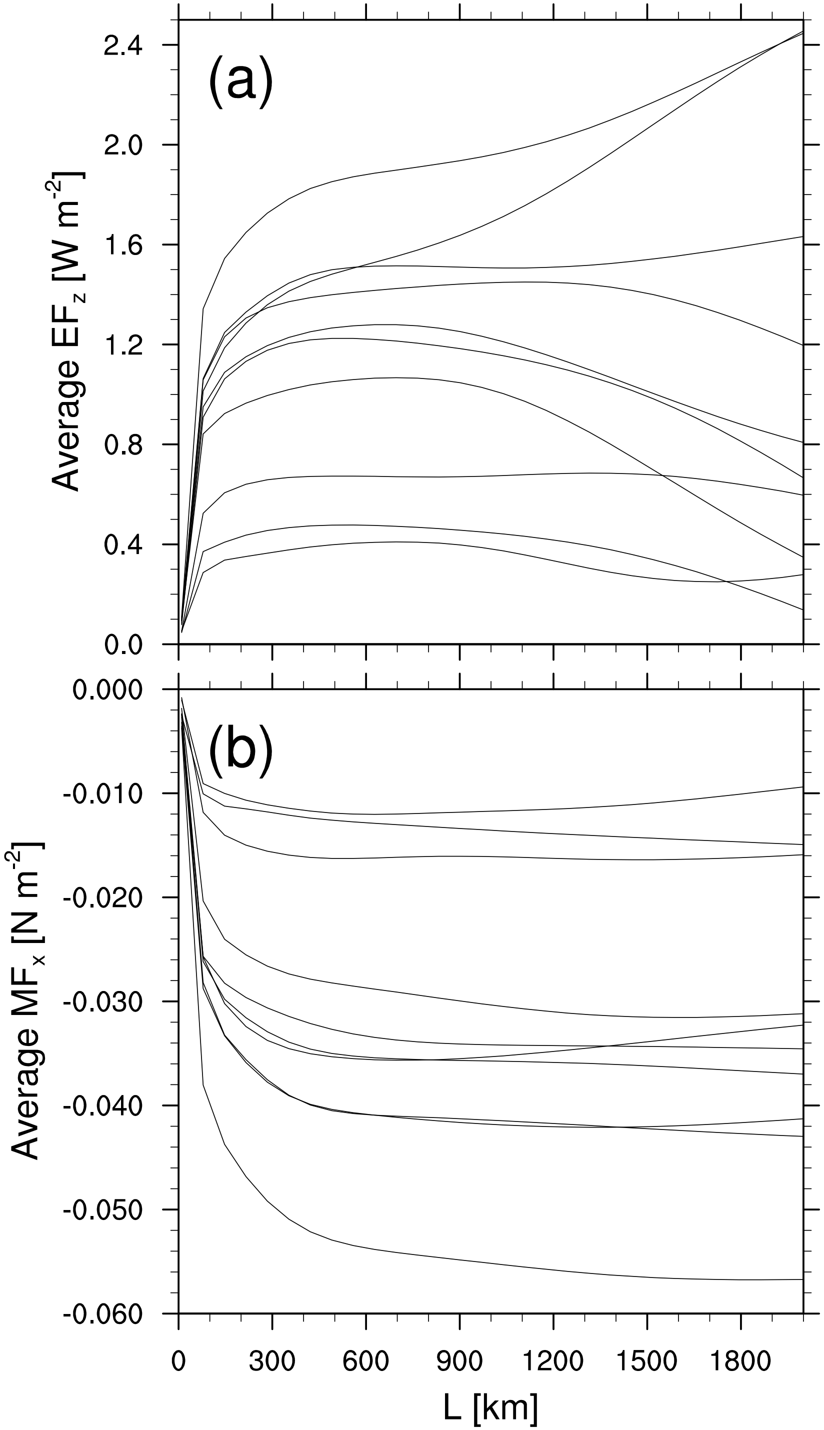
RF09




(a)
(b)
(c)
(d)
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
Deplaned Pressure [Pa]
-800 -600 -400 -200 0 200 400 600 800 1000
Low-Passed Deplaned Pressure [Pa]
-800 -600 -400 -200 0 200 400 600 800 1000
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
EFz [W m-2]
-200 -160 -120 -80 -40 0 40 80 120 160 200
Low-passed EFz [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



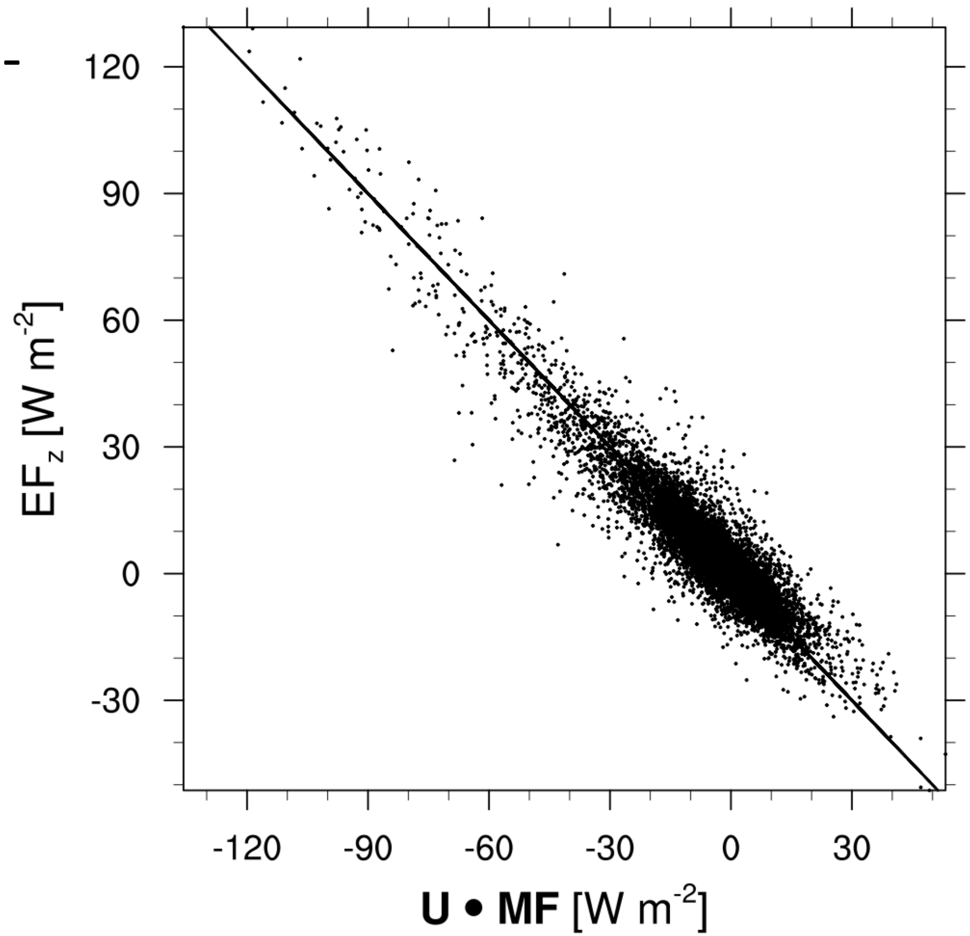
(a)
Average EF_z [W m^{-2}]
2.4
2.0
1.6
1.2
0.8
0.4
0.0
(b)
Average MF_x [N m^{-2}]
0.000
-0.010
-0.020
-0.030
-0.040
-0.050
-0.060
0
300
600
900
1200
1500
1800
L [km]

Method Verification

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

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

(Eliassen and Palm 1961)

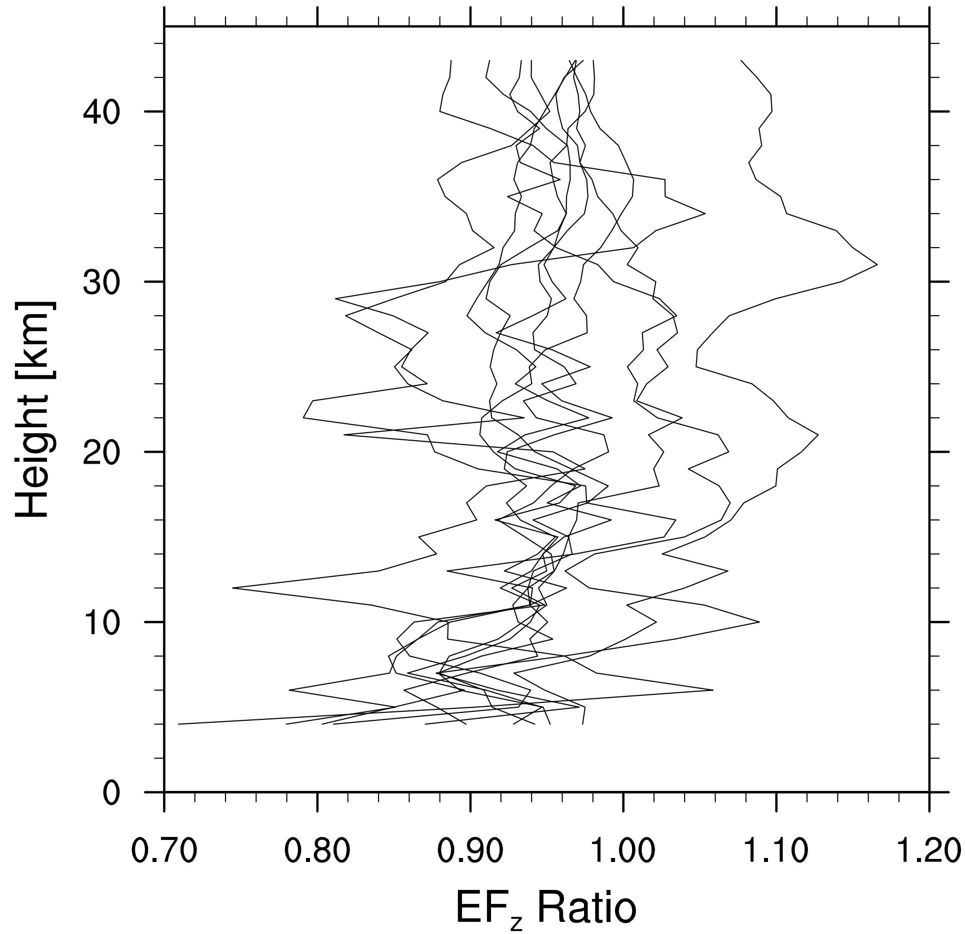


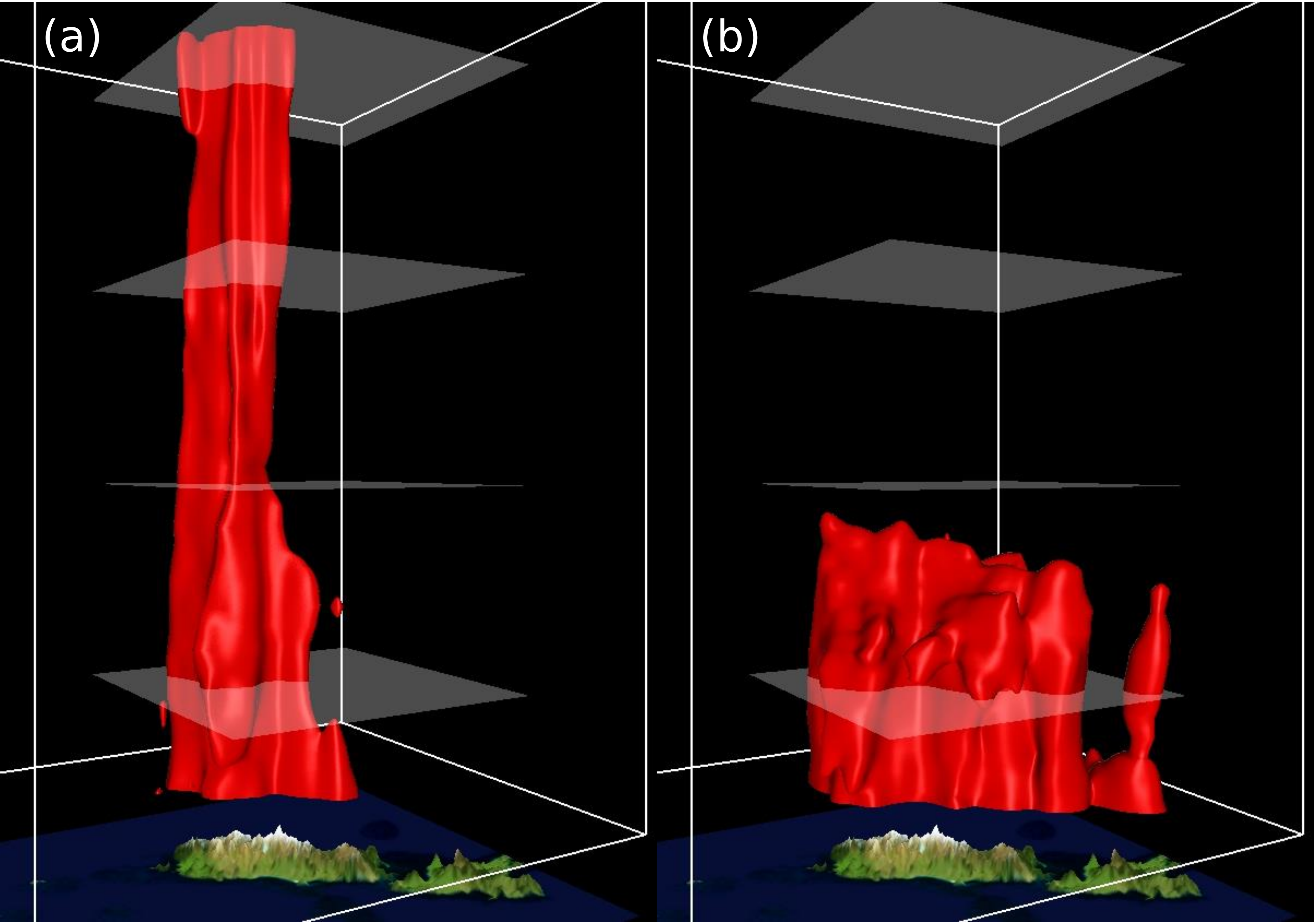
Method Verification

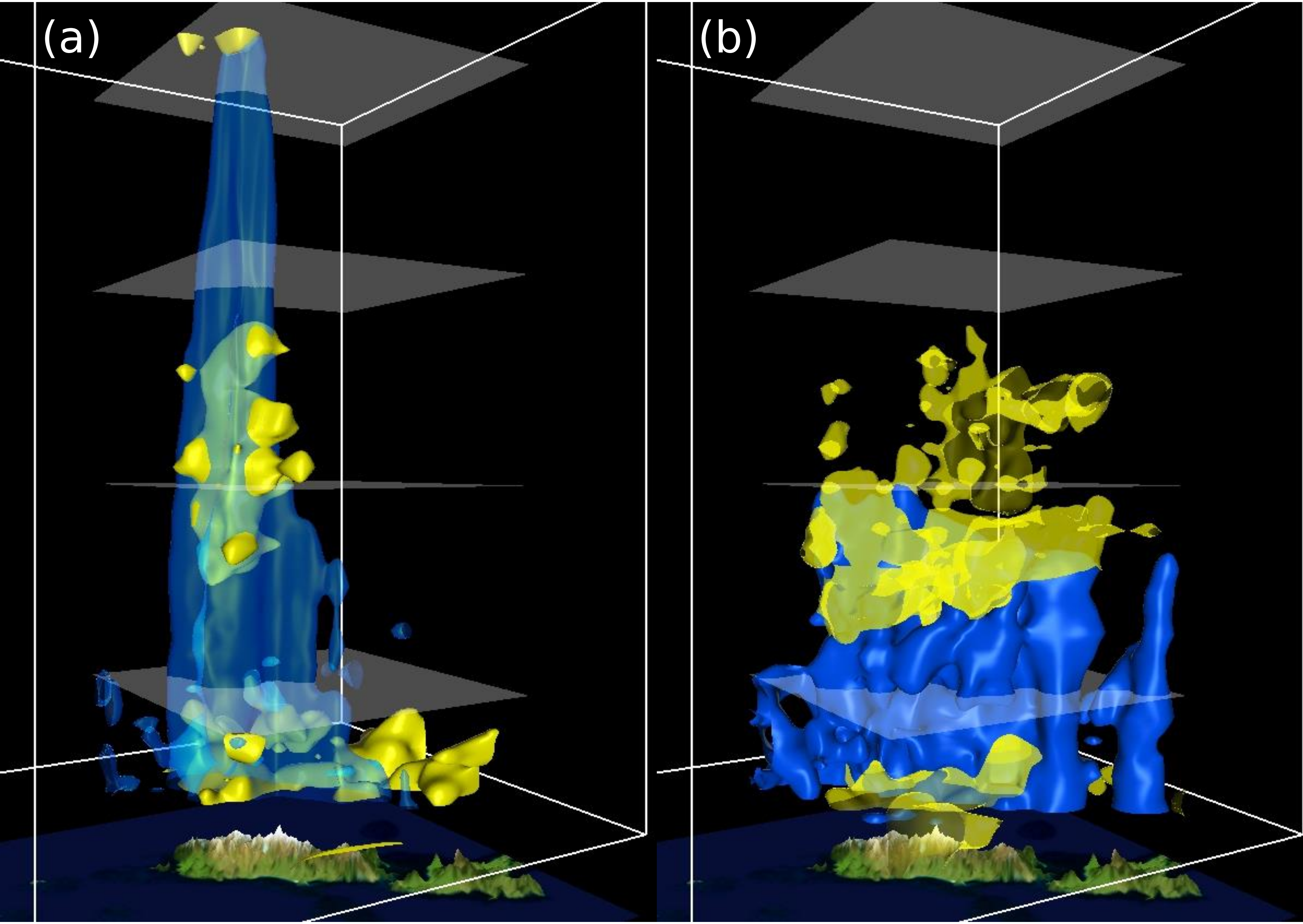
- Can also compute perturbation quantities by subtracting fields from a simulation with terrain from one without
- Compared the two methods via the following ratio:

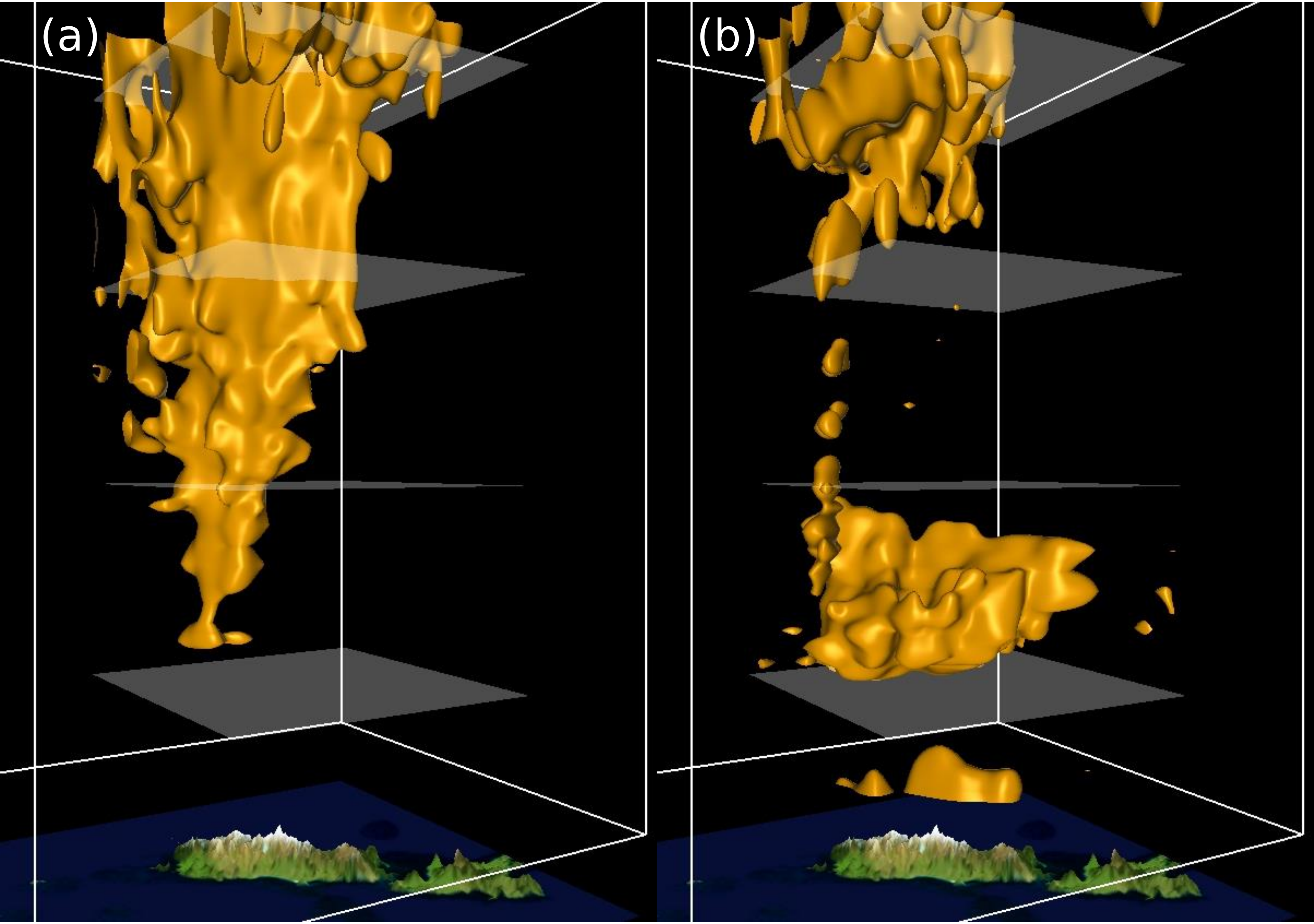
$$R = \frac{EF_{z_{filt}}}{EF_{z_{diff}}}$$

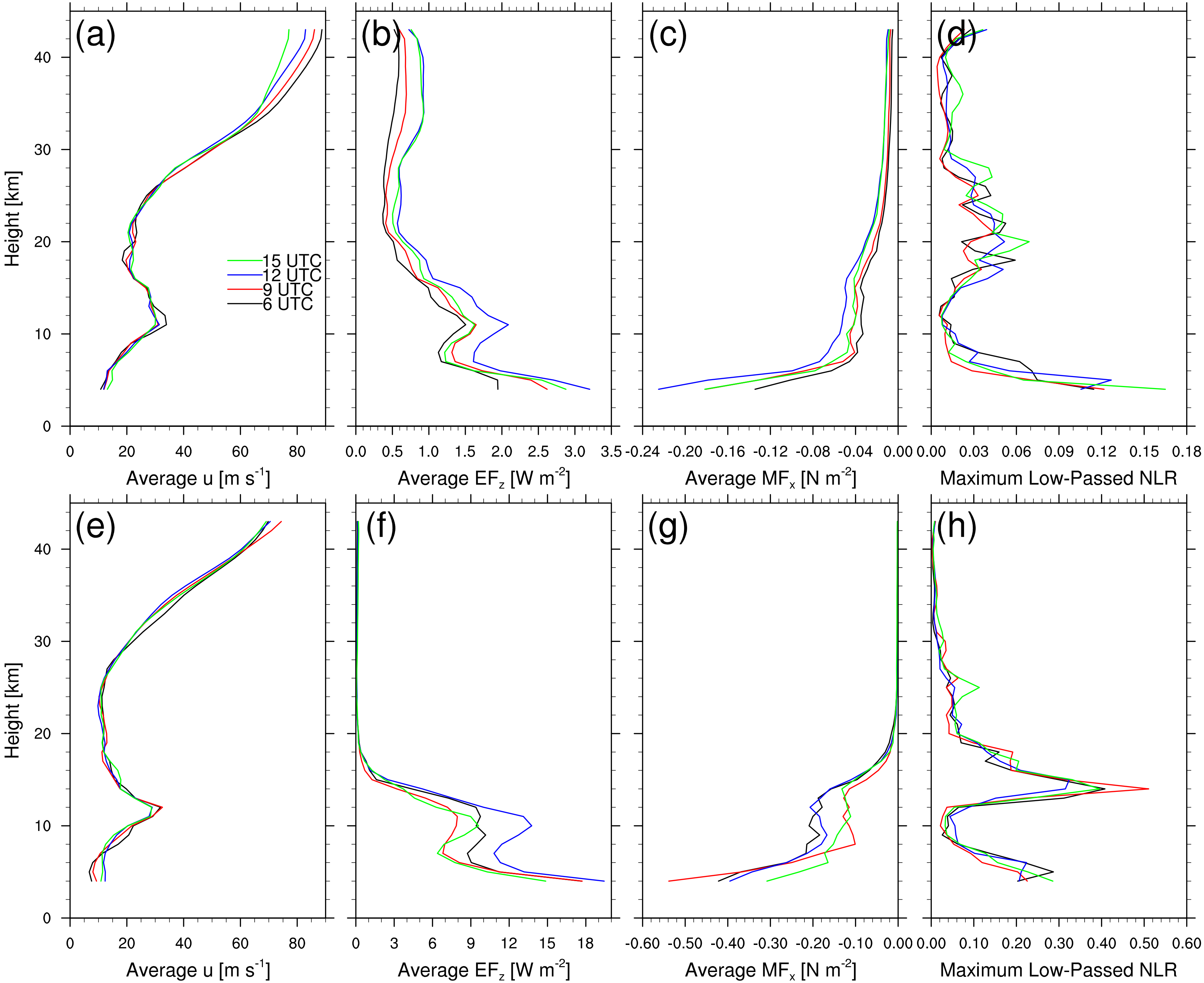
- The two very different methods typically agree within 10%



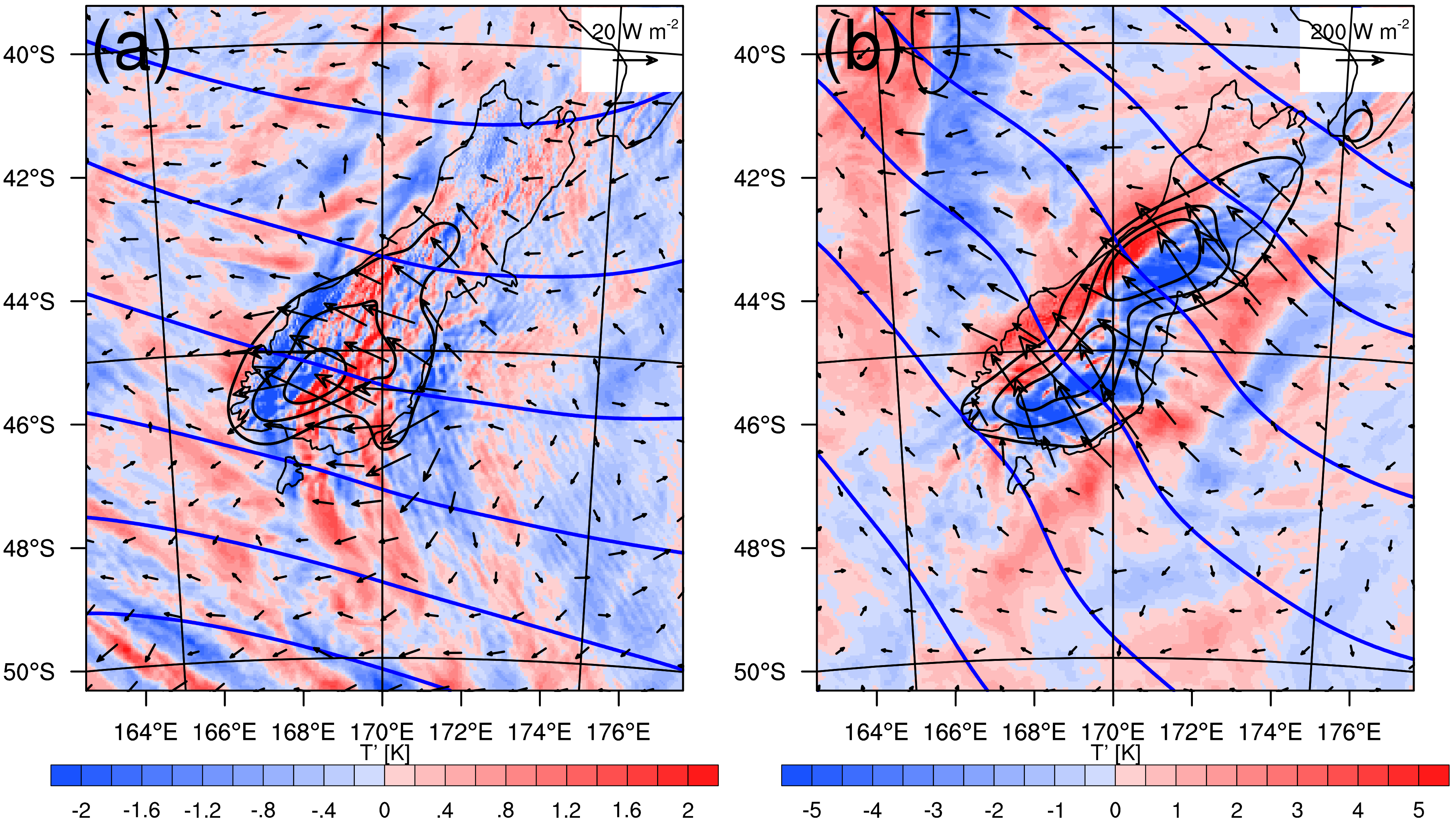

(a)
(b)

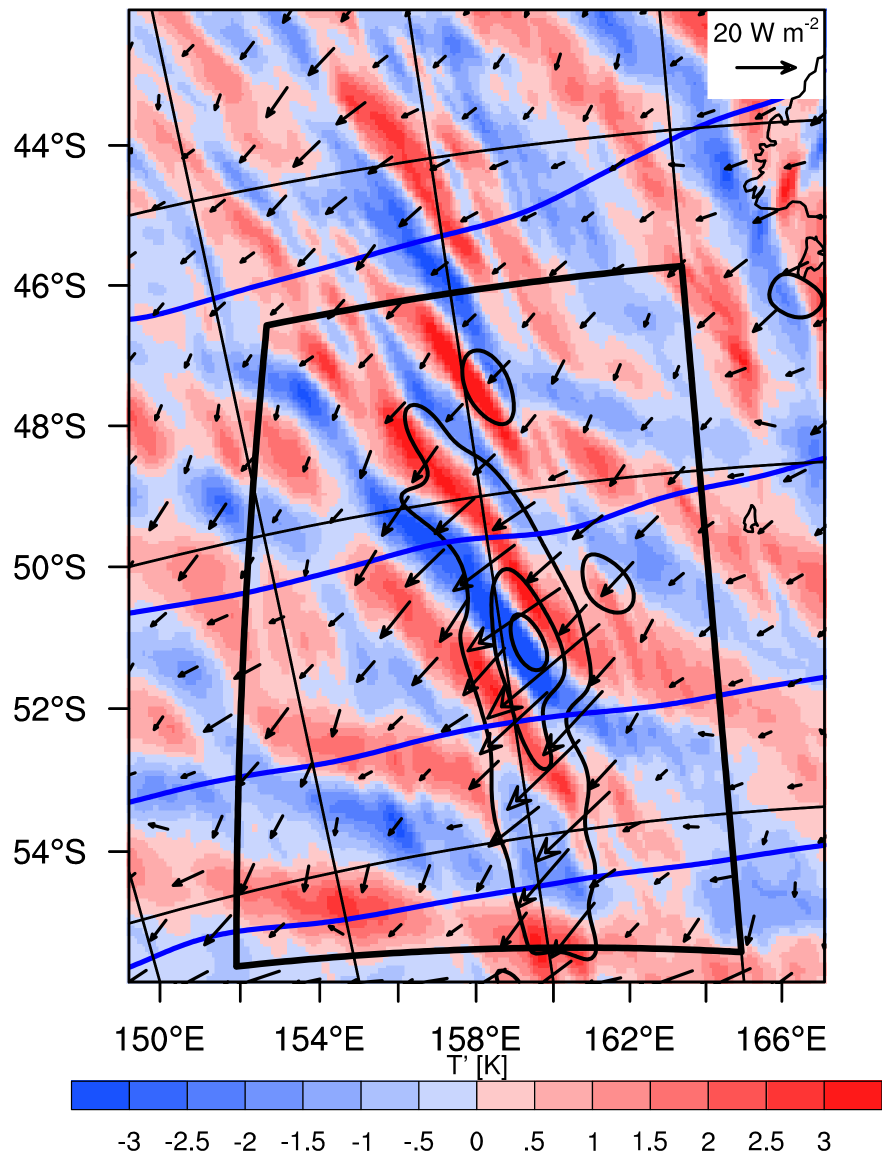

(a)
(b)


(a)
(b)

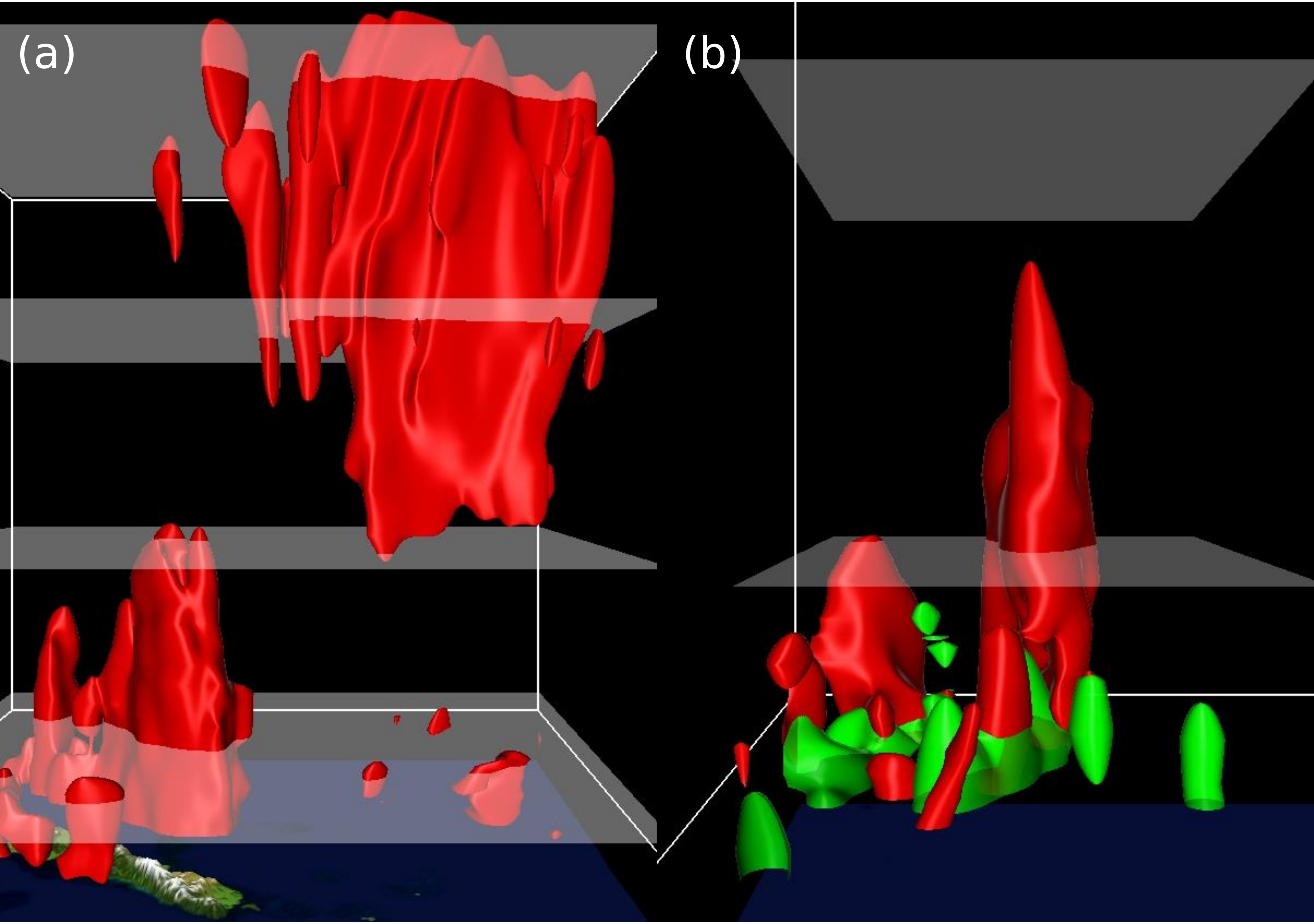


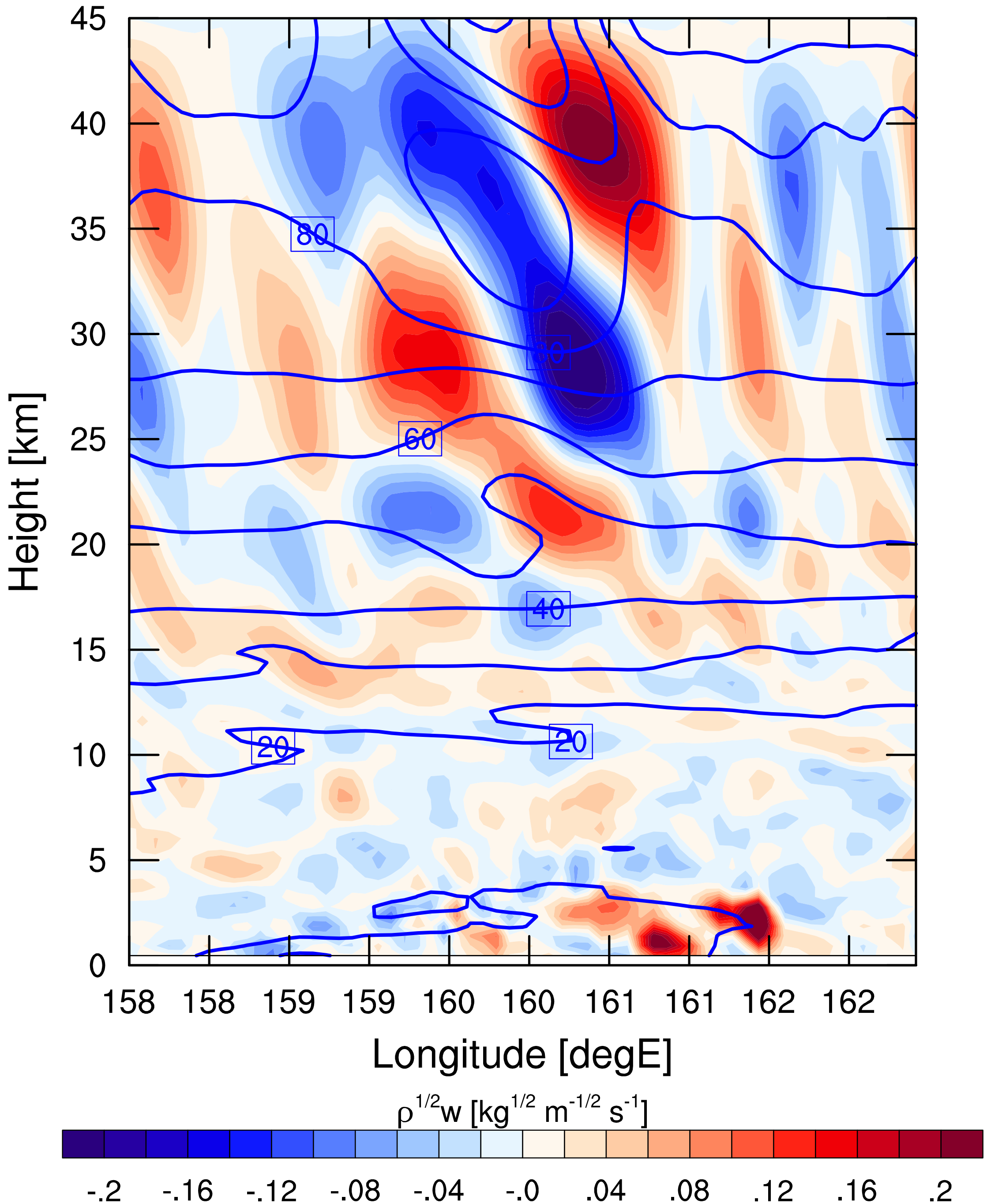
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
15 UTC
12 UTC
9 UTC
6 UTC
Height [km]
Average u [m s^{-1}]
Average EF$_z$ [W m^{-2}]
Average MF$_x$ [N m^{-2}]
Maximum Low-Passed NLR


(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

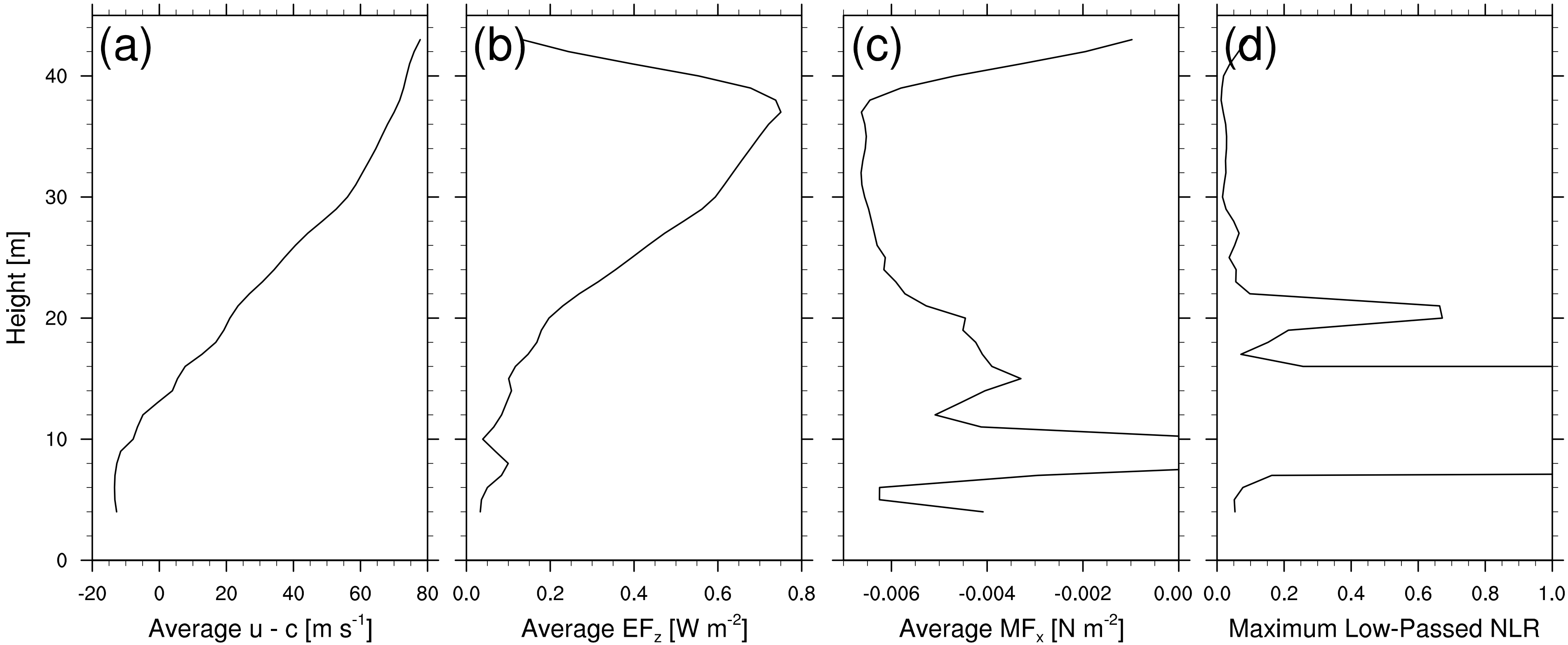


20 W m-2
44°S
46°S
48°S
50°S
52°S
54°S
150°E
154°E
158°E
162°E
166°E
T' [K]
-3
-2.5
-2
-1.5
-1
-.5
0
.5
1
1.5
2
2.5
3

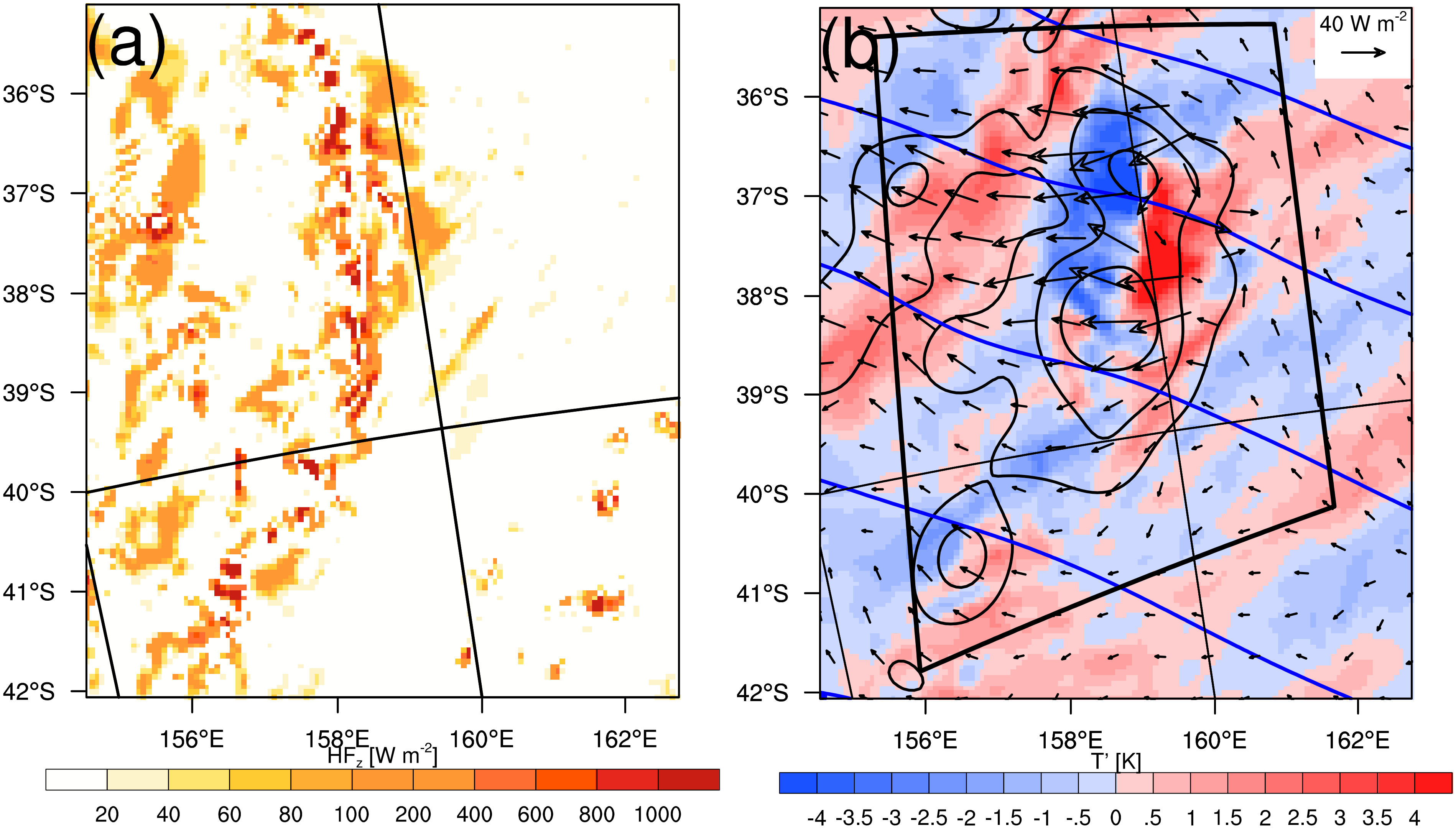

(a)
(b)



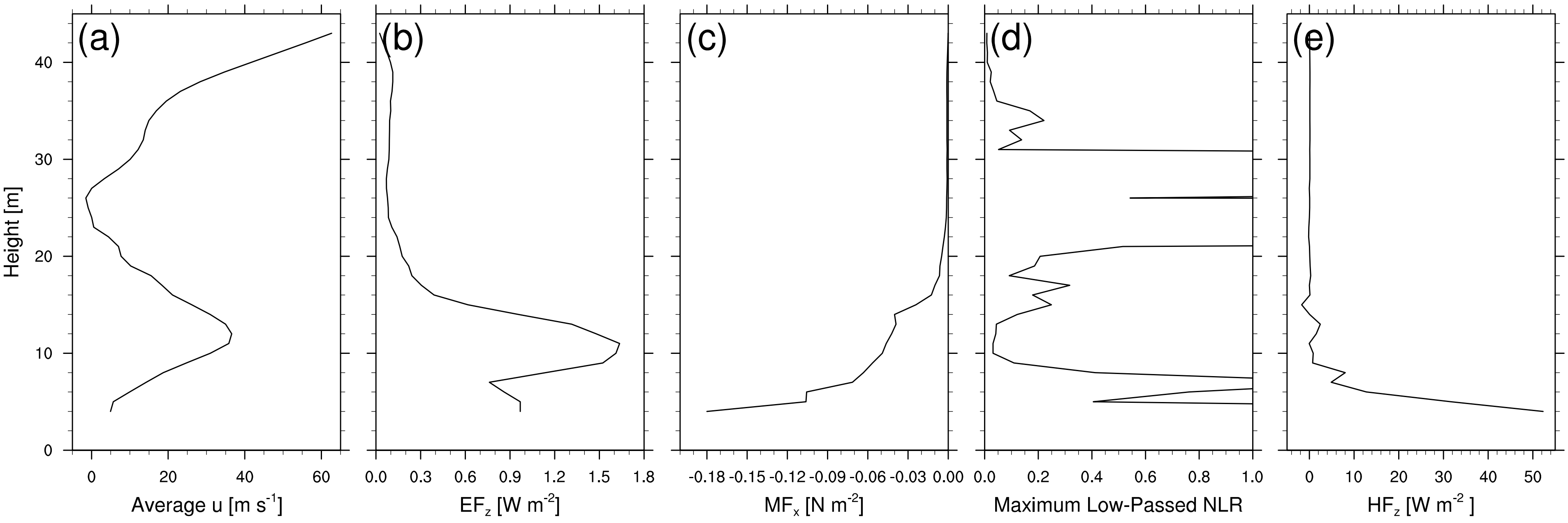
45
40
35
30
25
20
15
10
5
0
Height [km]
80
60
40
20
20
158
158
159
159
160
160
161
161
162
162
Longitude [degE]
ρ^1/2w [kg^1/2 m^-1/2 s^-1]
-.2
-.16
-.12
-.08
-.04
-.0
.04
.08
.12
.16
.2



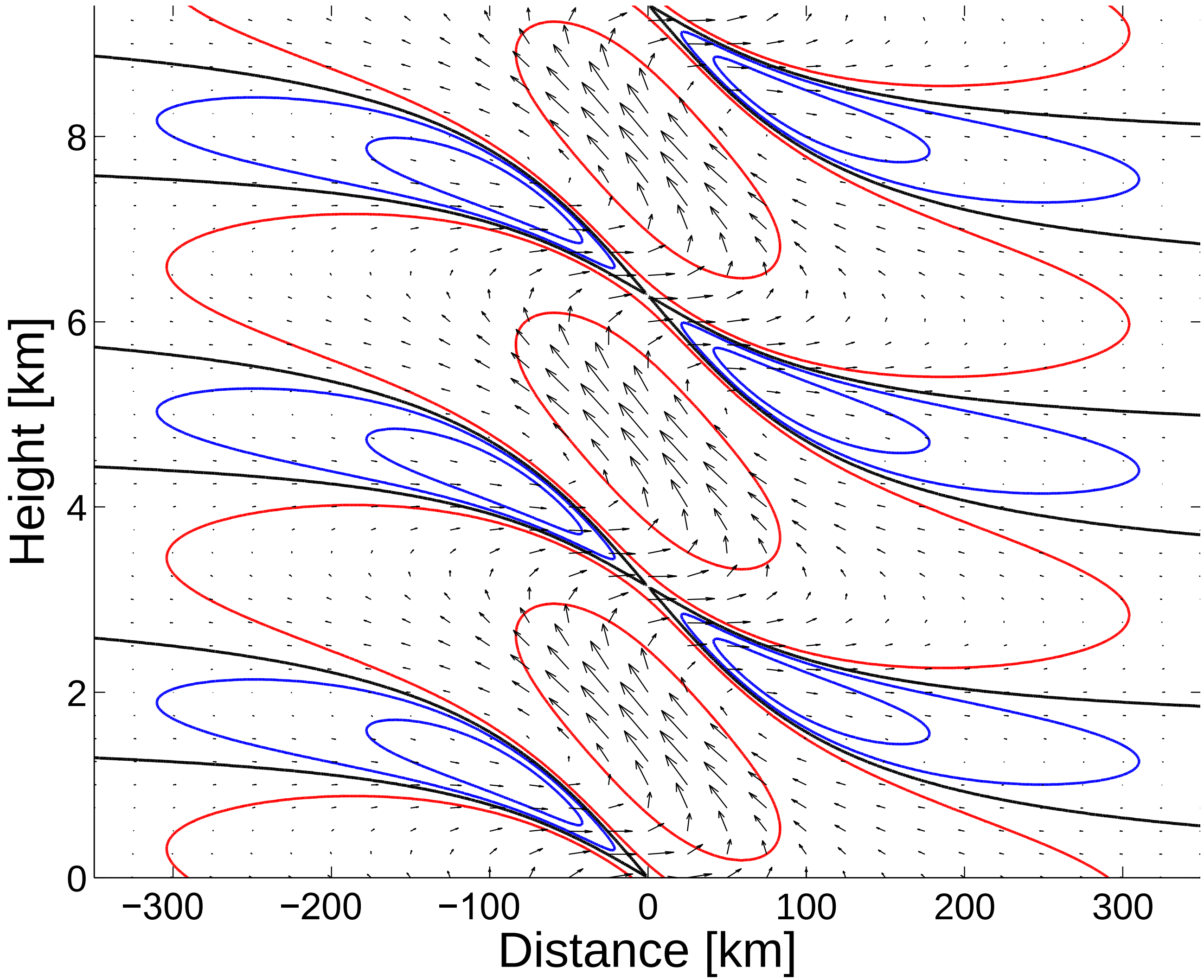
(a)
(b)
(c)
(d)
Height [m]
0
10
20
30
40
-20
0
20
40
60
80
Average u - c [m s^{-1}]
0.0
0.2
0.4
0.6
0.8
Average EF_z [W m^{-2}]
-0.006
-0.004
-0.002
0.00
Average MF_x [N m^{-2}]
0.0
0.2
0.4
0.6
0.8
1.0
Maximum Low-Passed NLR



(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
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]
Average u [m s^{-1}]
EF$_z$ [W m^{-2}]
MF$_x$ [N m^{-2}]
Maximum Low-Passed NLR
HF$_z$ [W m^{-2}]



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