Deepwave GV flux measurements: methods and uncertainties

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NCAR/EOL

Deepwave PIs: Fritts, Doyle, Eckermann, Taylor, et al.

Boulder Workshop, October 23, 24 2014

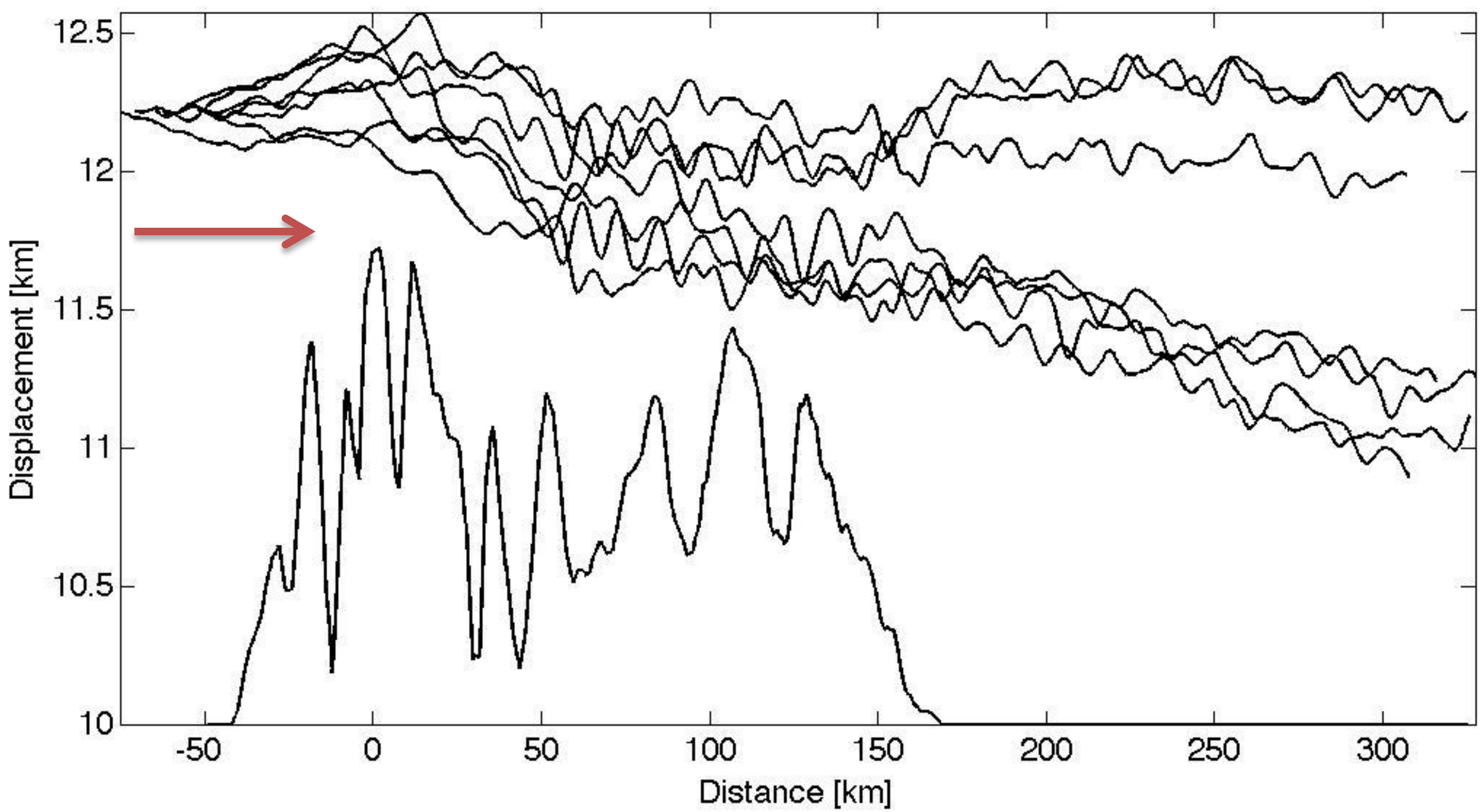
DEEPWAVE GV statistics

- Location: New Zealand and surrounding ocean
- Observing period: SH Winter; June/July 2014
- Aircraft: NSF/NCAR GV (26 flights, 180 hours)
- Typical leg: length=350km, altitude= 12.1km
- GV Survey legs
  - **Over New Zealand (97 legs; 49.1 hours)**
  - Over Ocean (157 legs; 84.3 hours)

Types of analyses

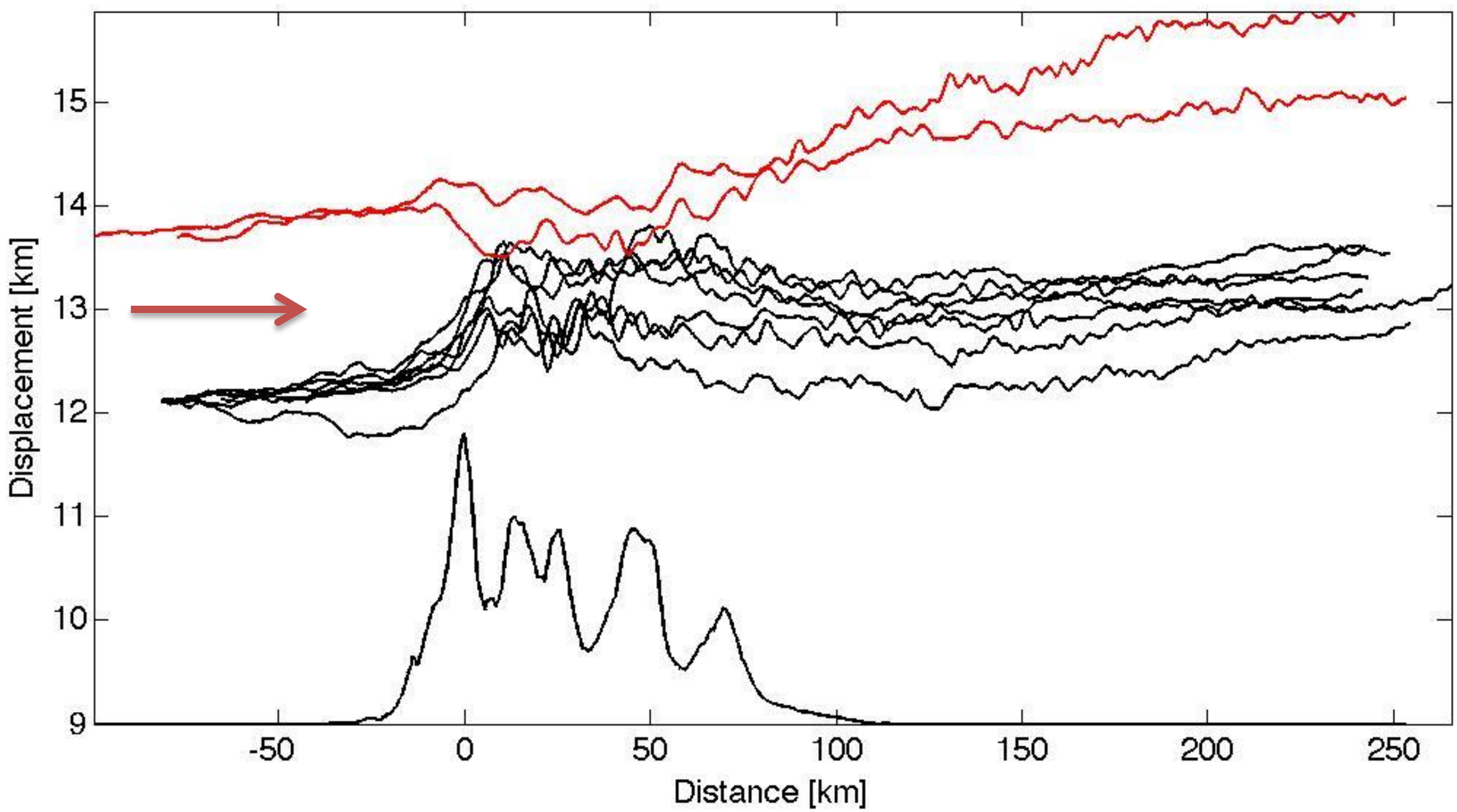
1. Vertical displacement curves
2. Flux computations
3. Transience
4. Eliassen-Palm check (Bernoulli check)
5. Direction of horizontal EF
6. Pressure analysis for Energy Flux
7. Wavelet scale analysis
8. Reverse fluxes
9. Effect of leg length

RF04: 7 legs over Mt Aspiring
Vertical displacement (estimated)



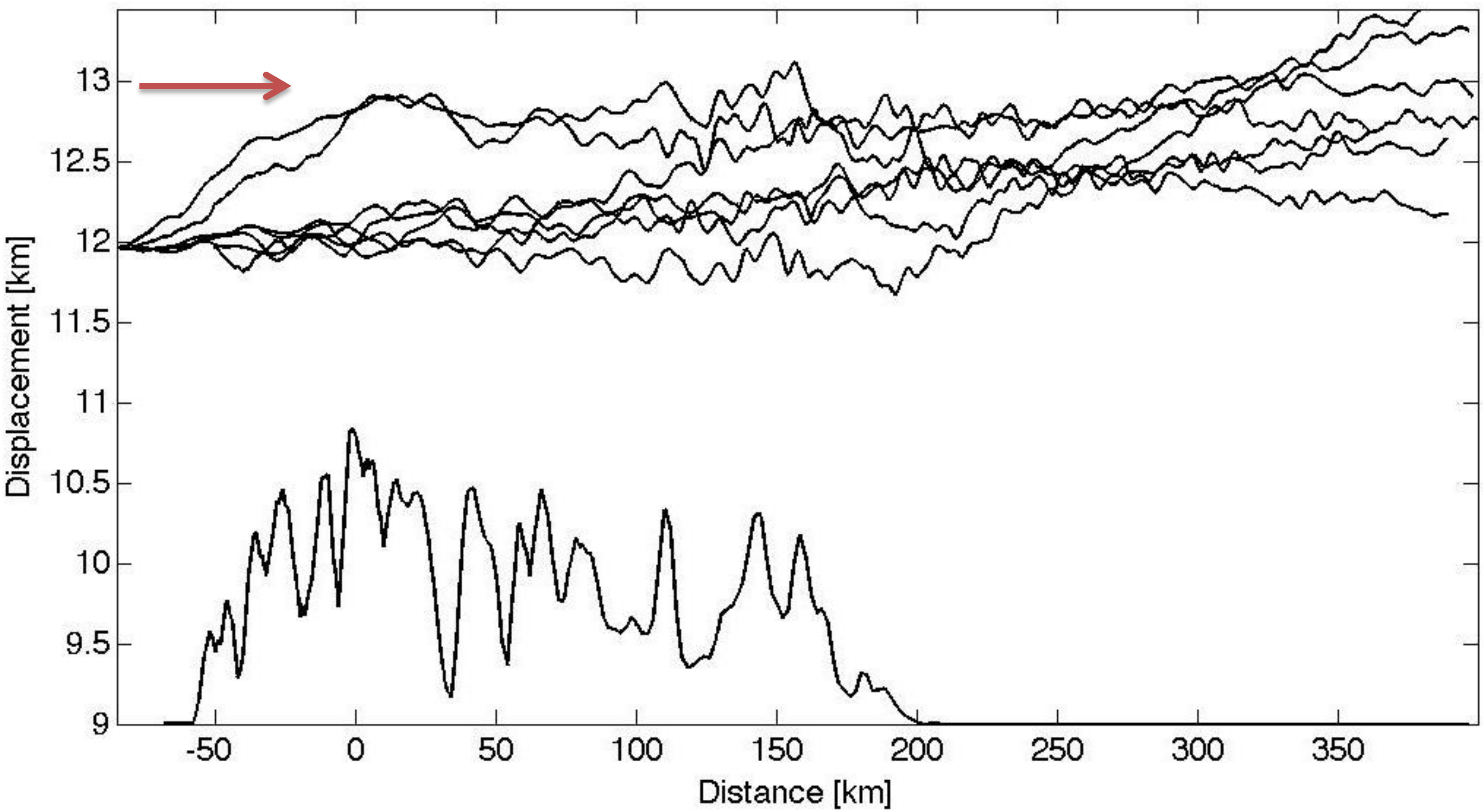
Mountain to scale but offset vertically

RF05: 9 Legs over Mt Cook
Vertical displacement

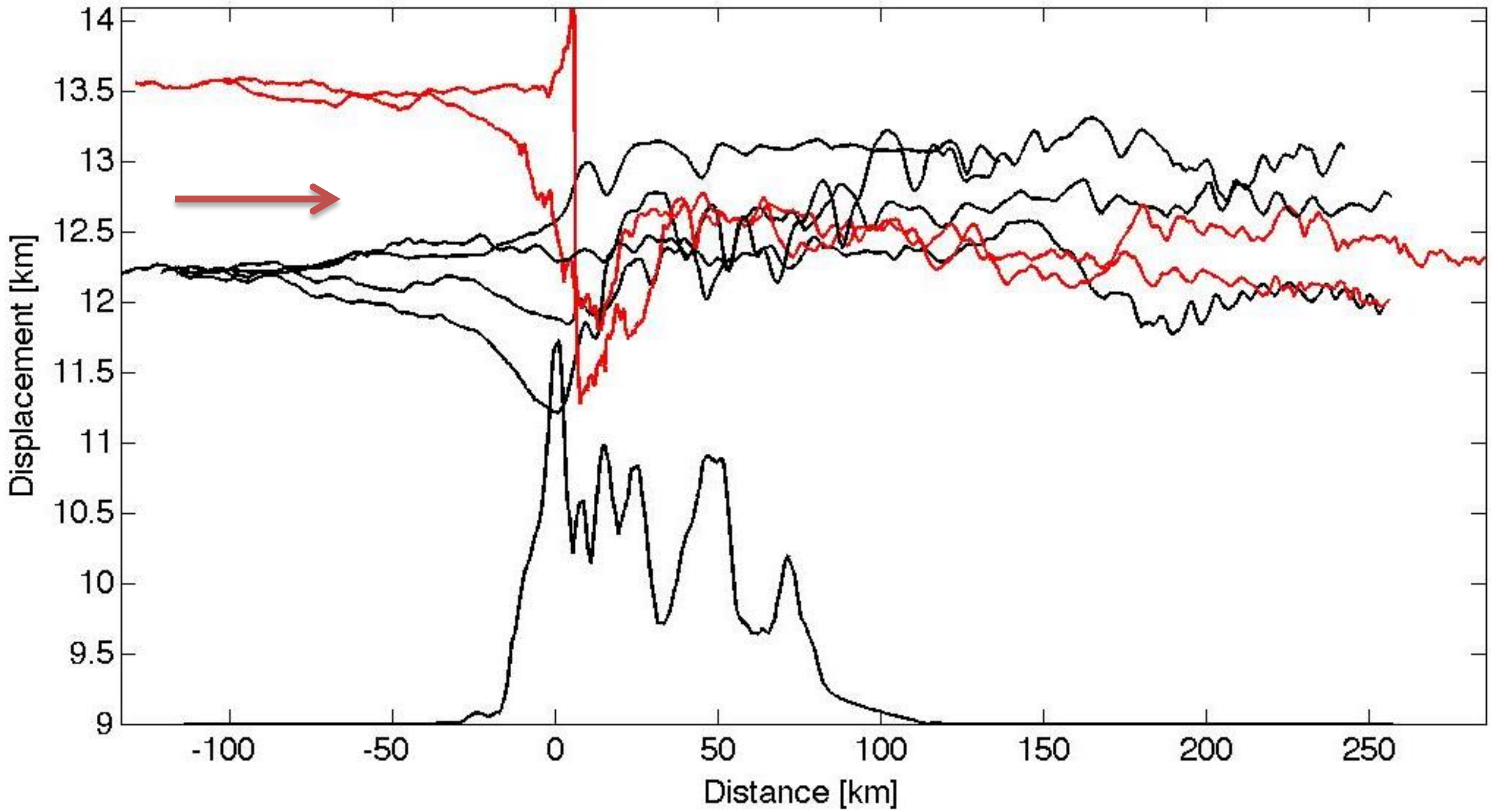


Mountain to scale but offset vertically

RF08: 7 Legs over Mt Aspiring
Vertical displacement

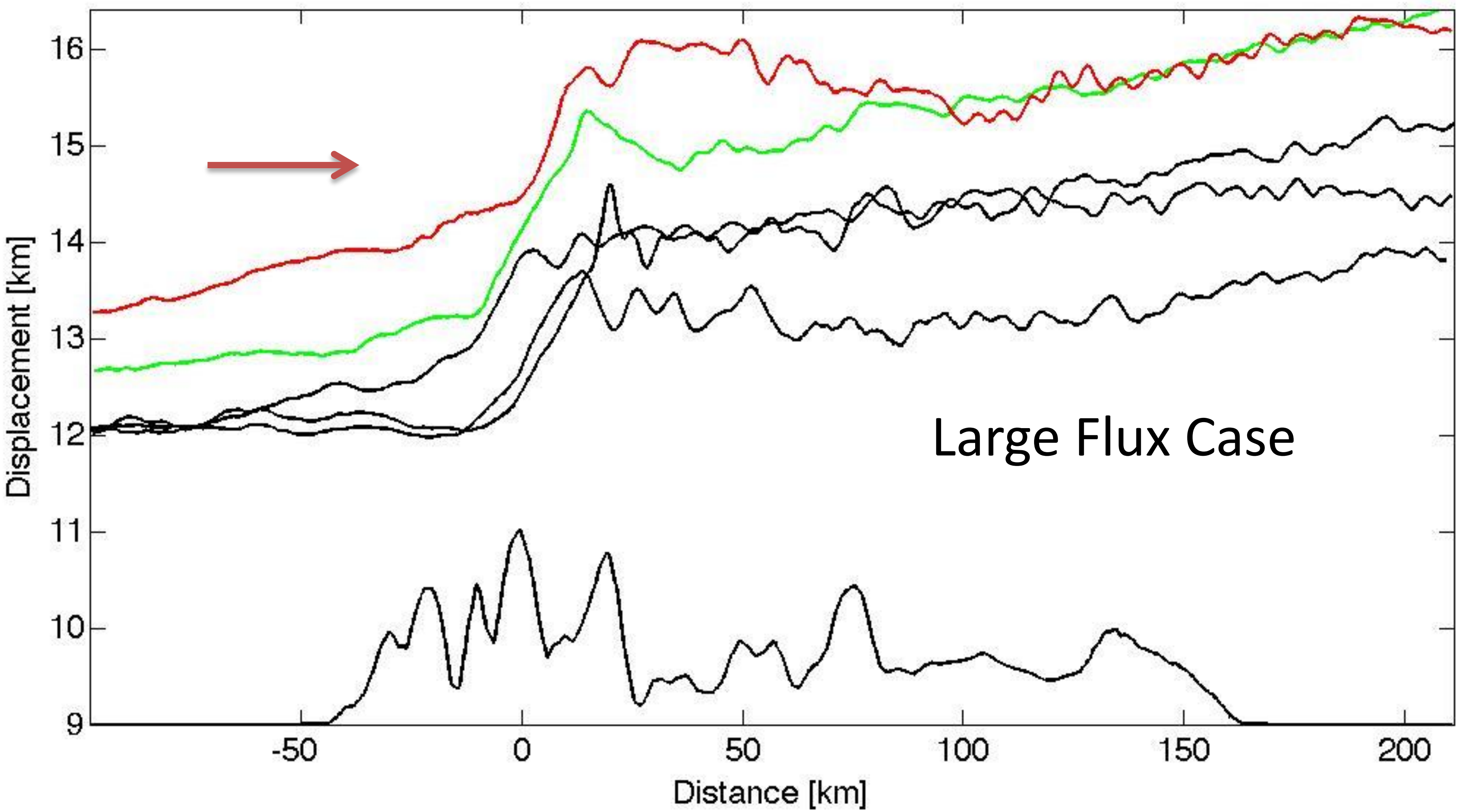


RF09: 6 legs over Mt Cook Vertical displacement

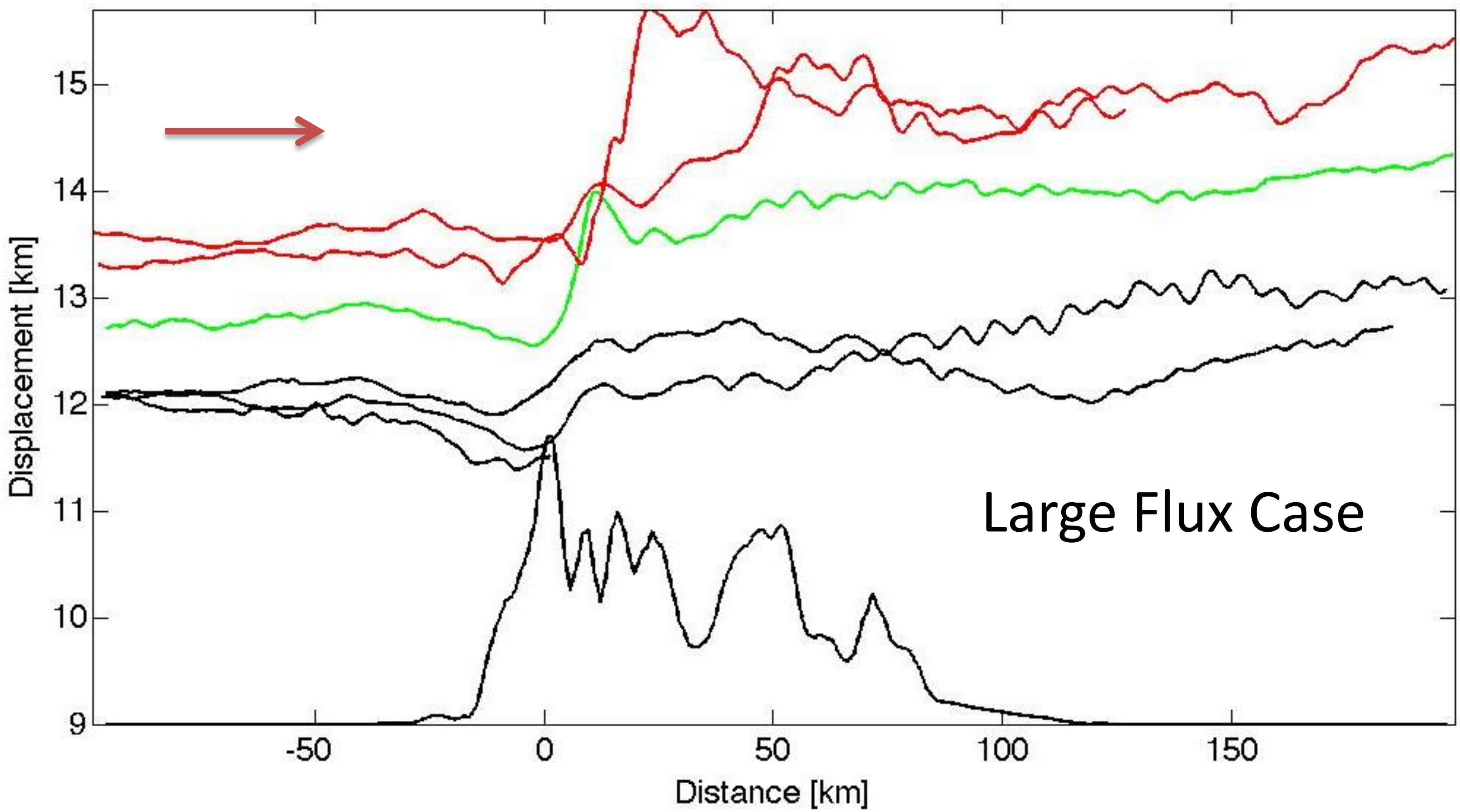


Mountain to scale but offset vertically

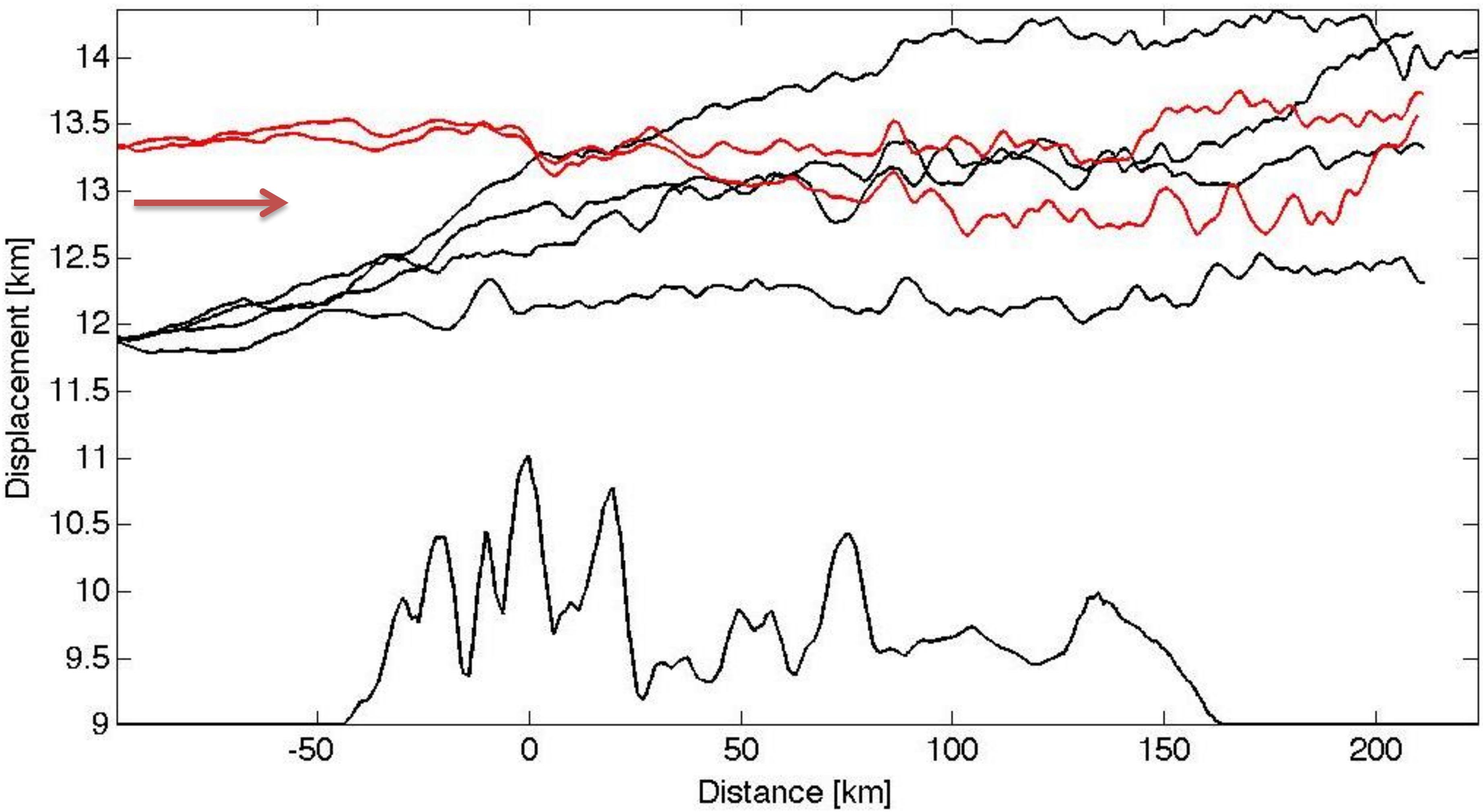
RF012: 5 legs over Mt Aspiring
Vertical displacement



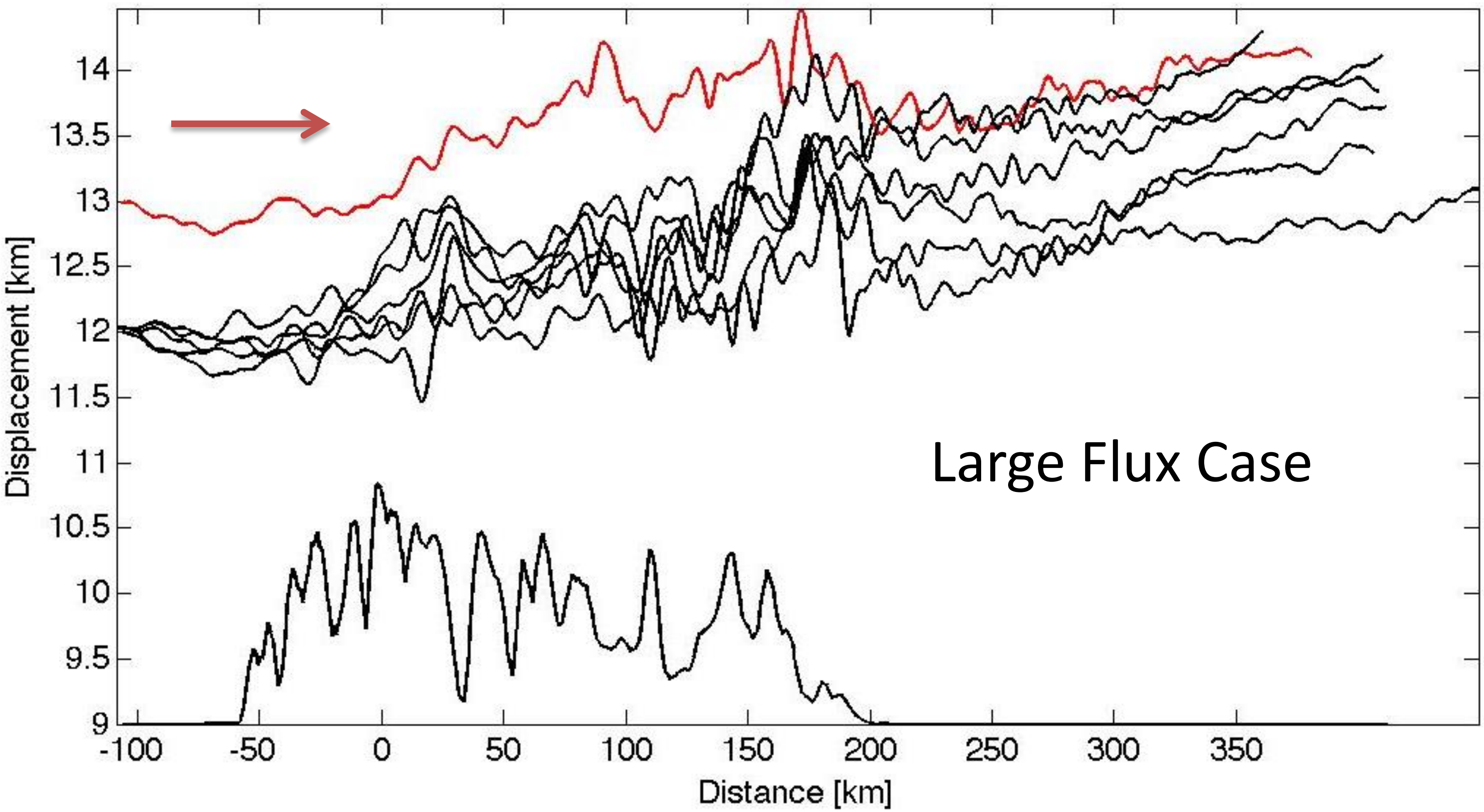
RF012: 5 legs over Mt Cook
Vertical displacement



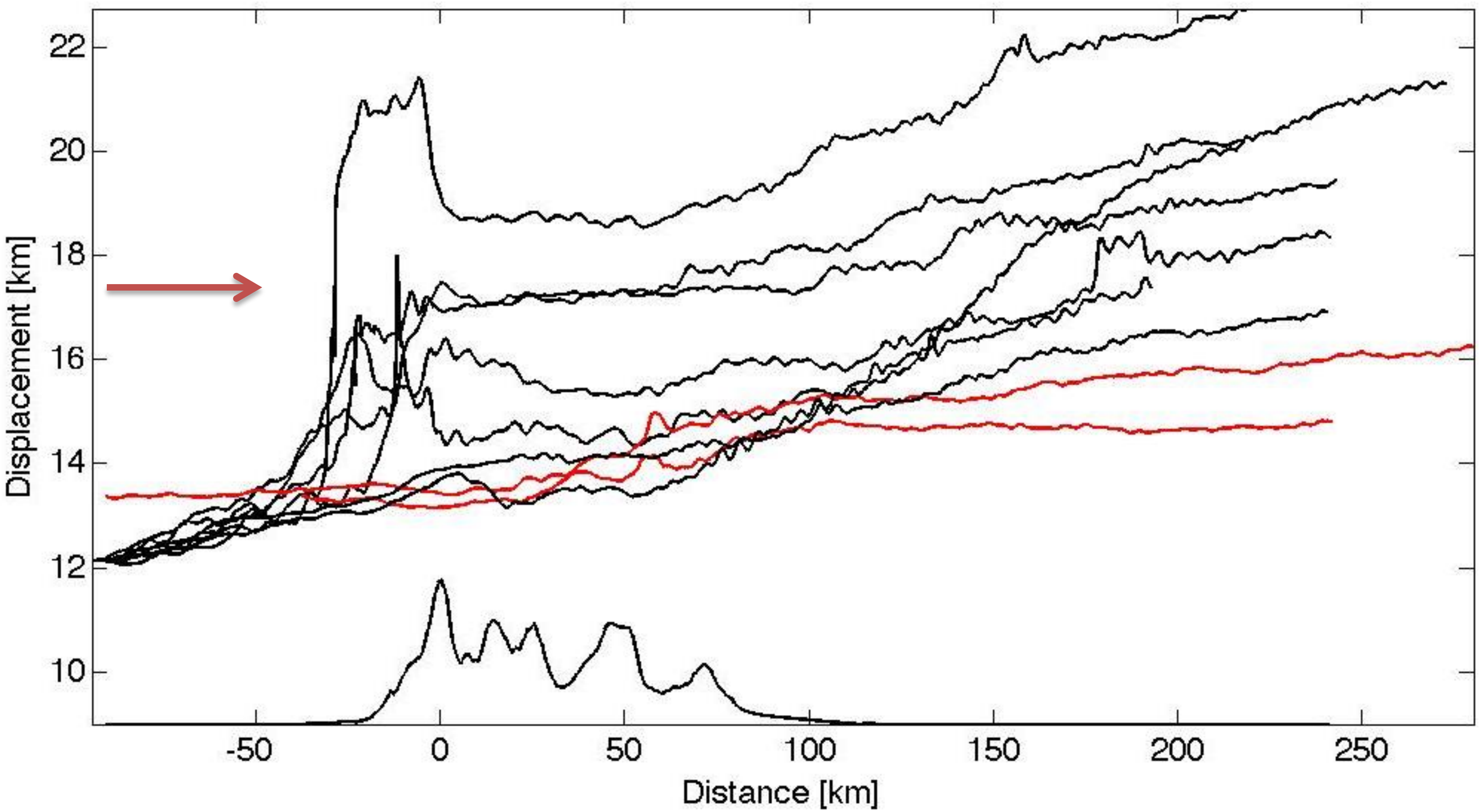
RF13: 6 Legs over Mt Aspiring
Vertical displacement



RF16: 7 Legs over Mt Aspiring
Vertical displacement



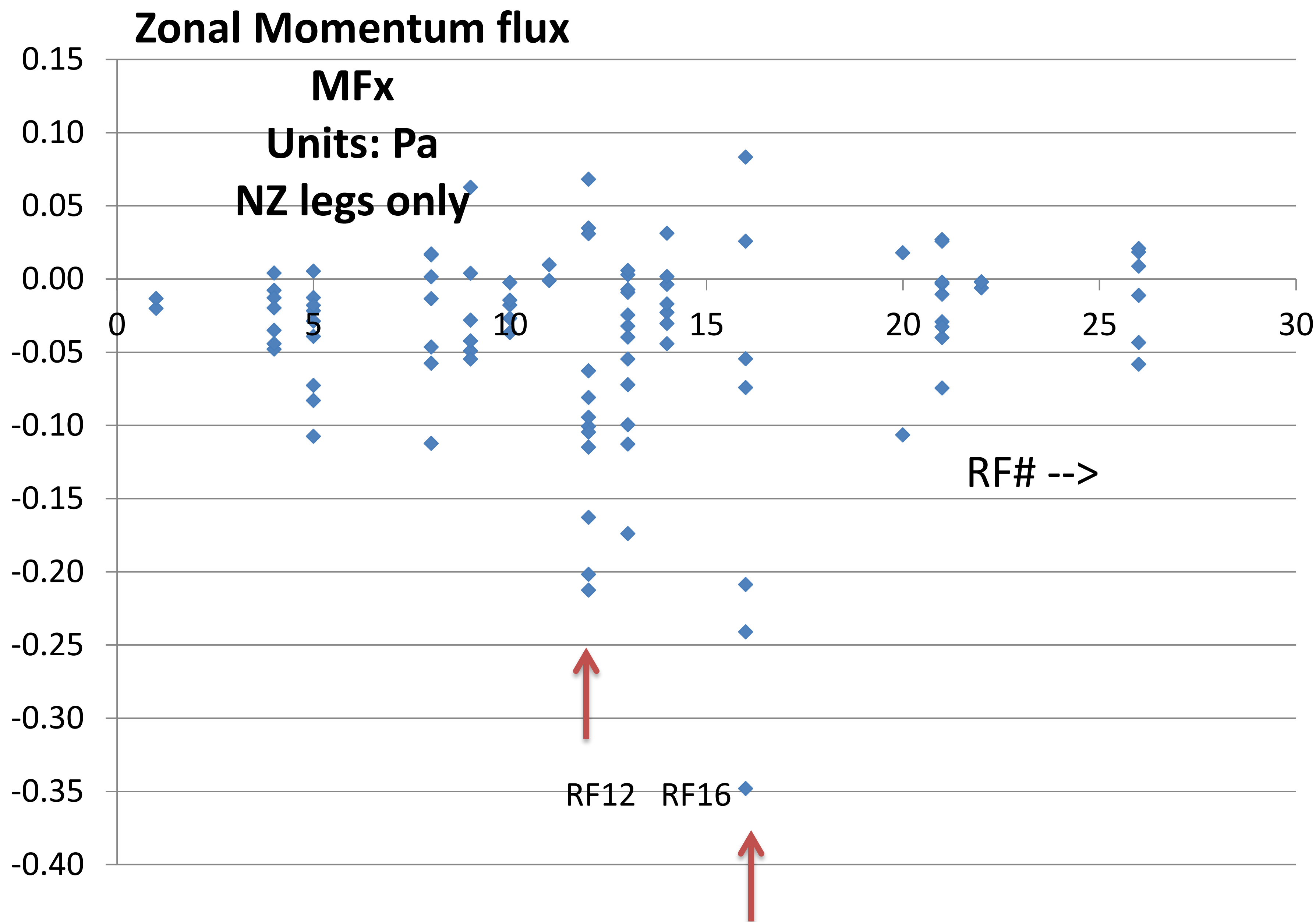
RF21: 9 Legs over Mt Cook
Vertical displacement

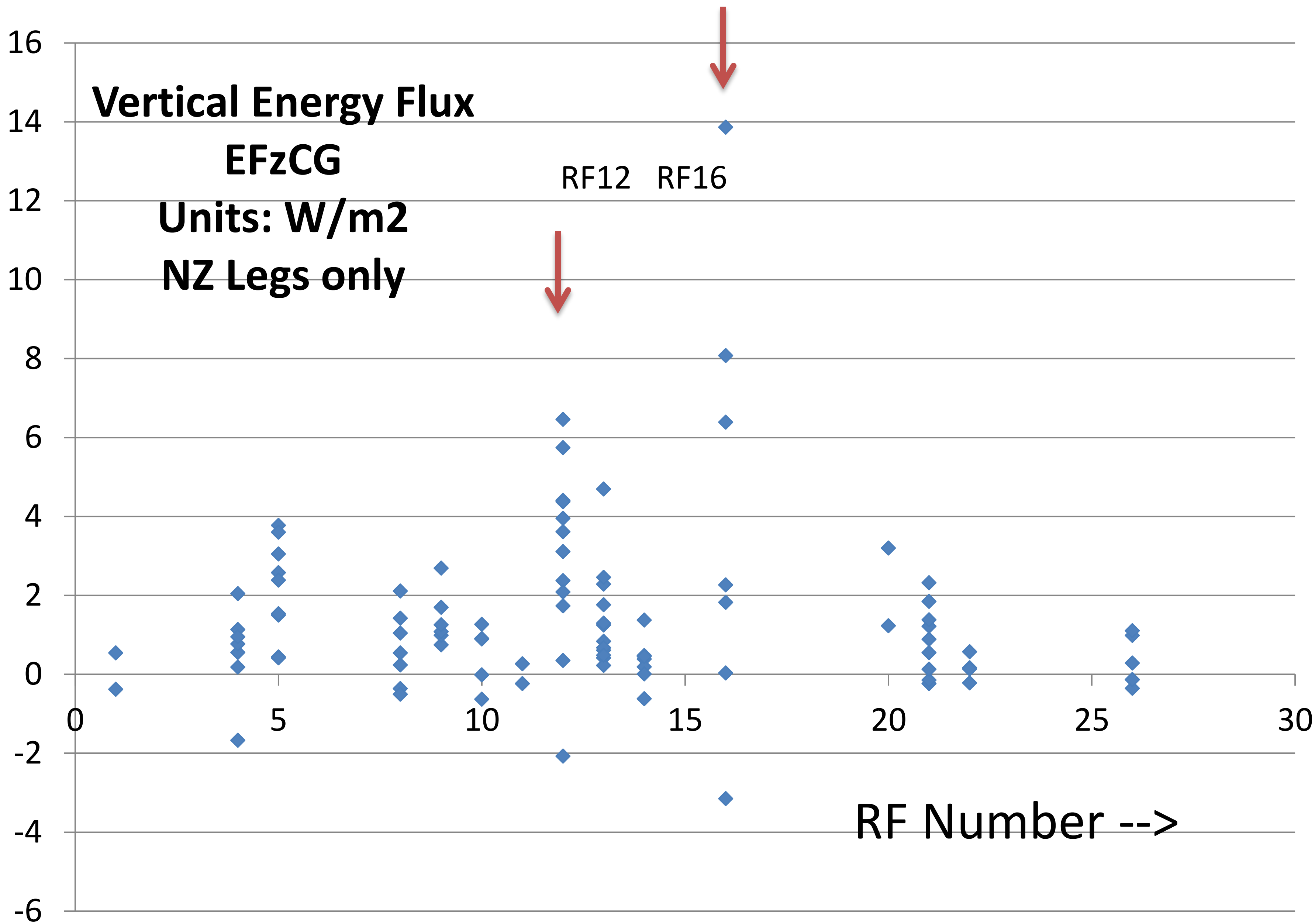


Flux calculations

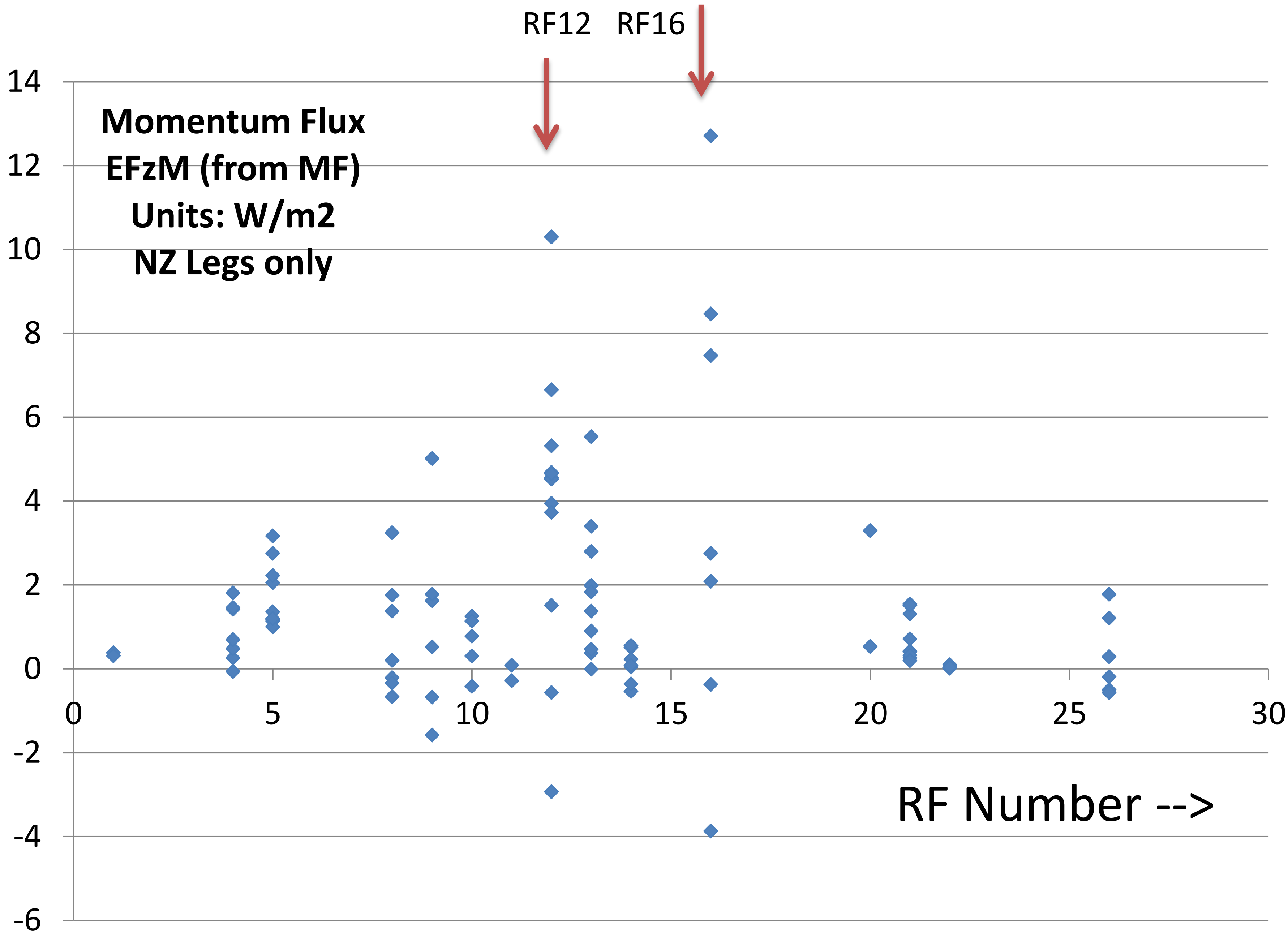
The fluxes are computed from

- $MFx = \bar{\rho} < u'w' >$
- $MFy = \bar{\rho} < v'w' >$
- $EFz =< P_{cg}\ w' >$
- $EFx =< P_{cg}\ u' >$
- $EFy =< P_{cg}\ v' >$
- *EFzM = -(U*MFx+V*MFy)*

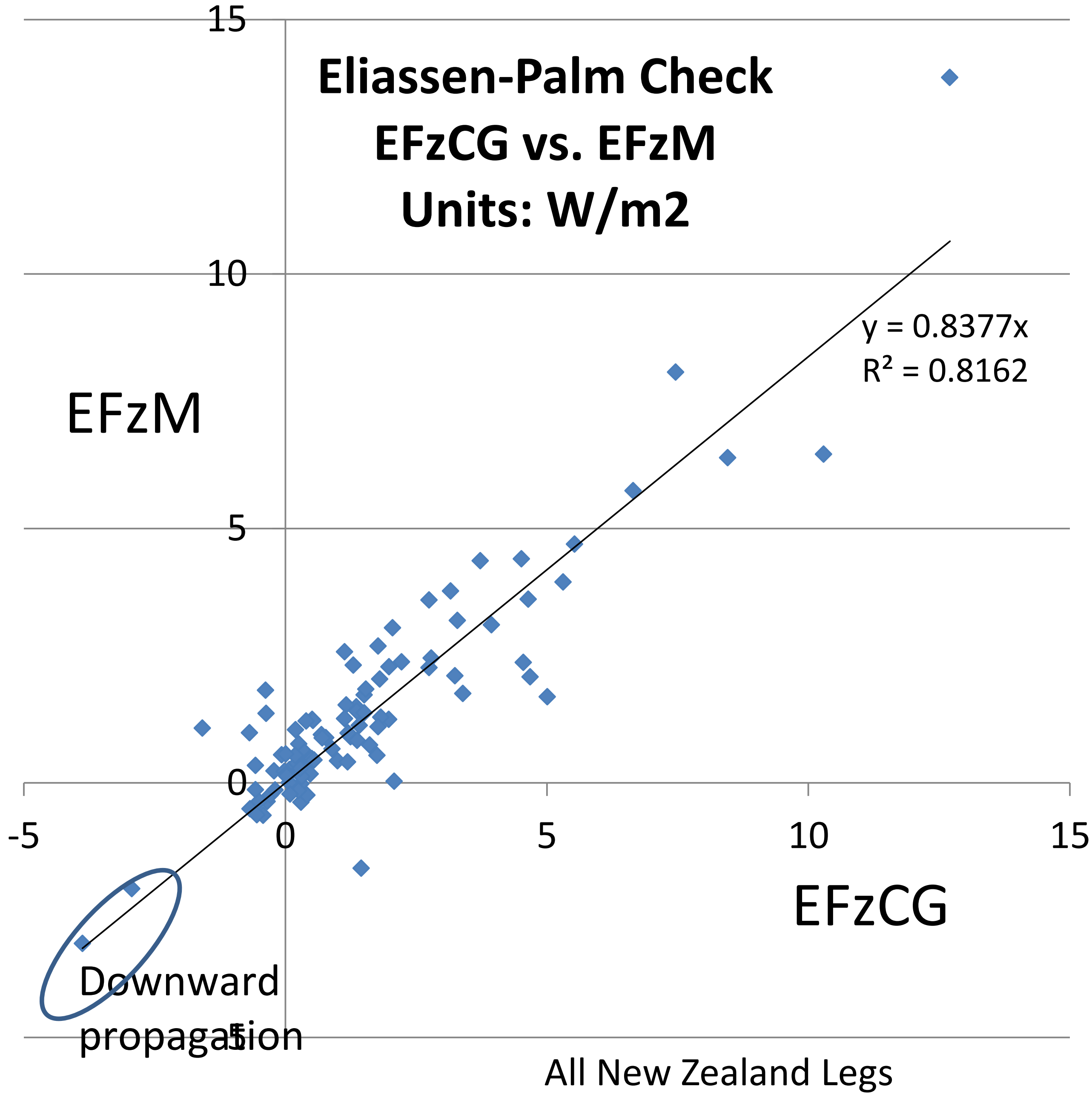

Zonal Momentum flux
MFx
Units: Pa
NZ legs only
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
0
5
10
15
20
25
30
RF# -->
RF12
RF16

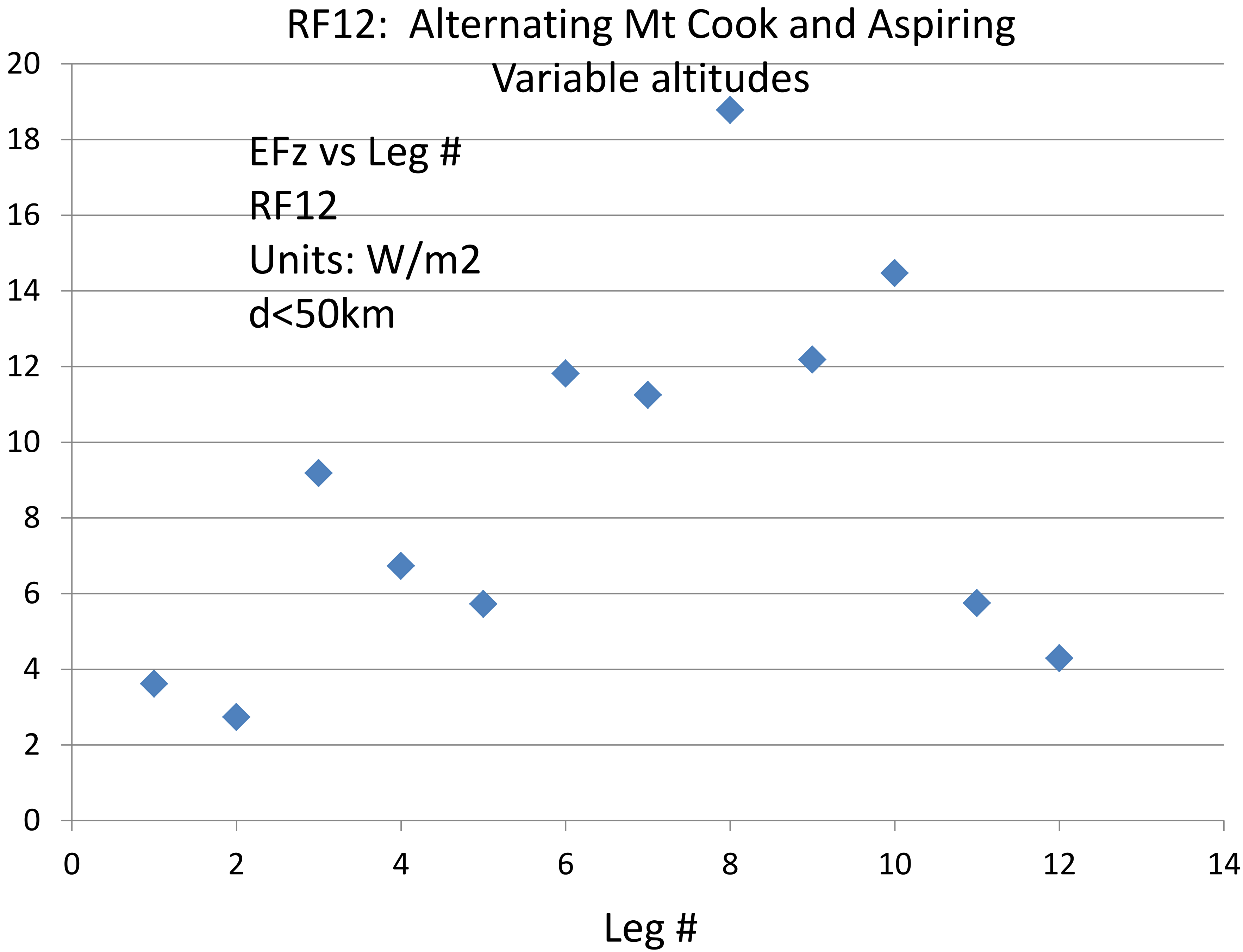


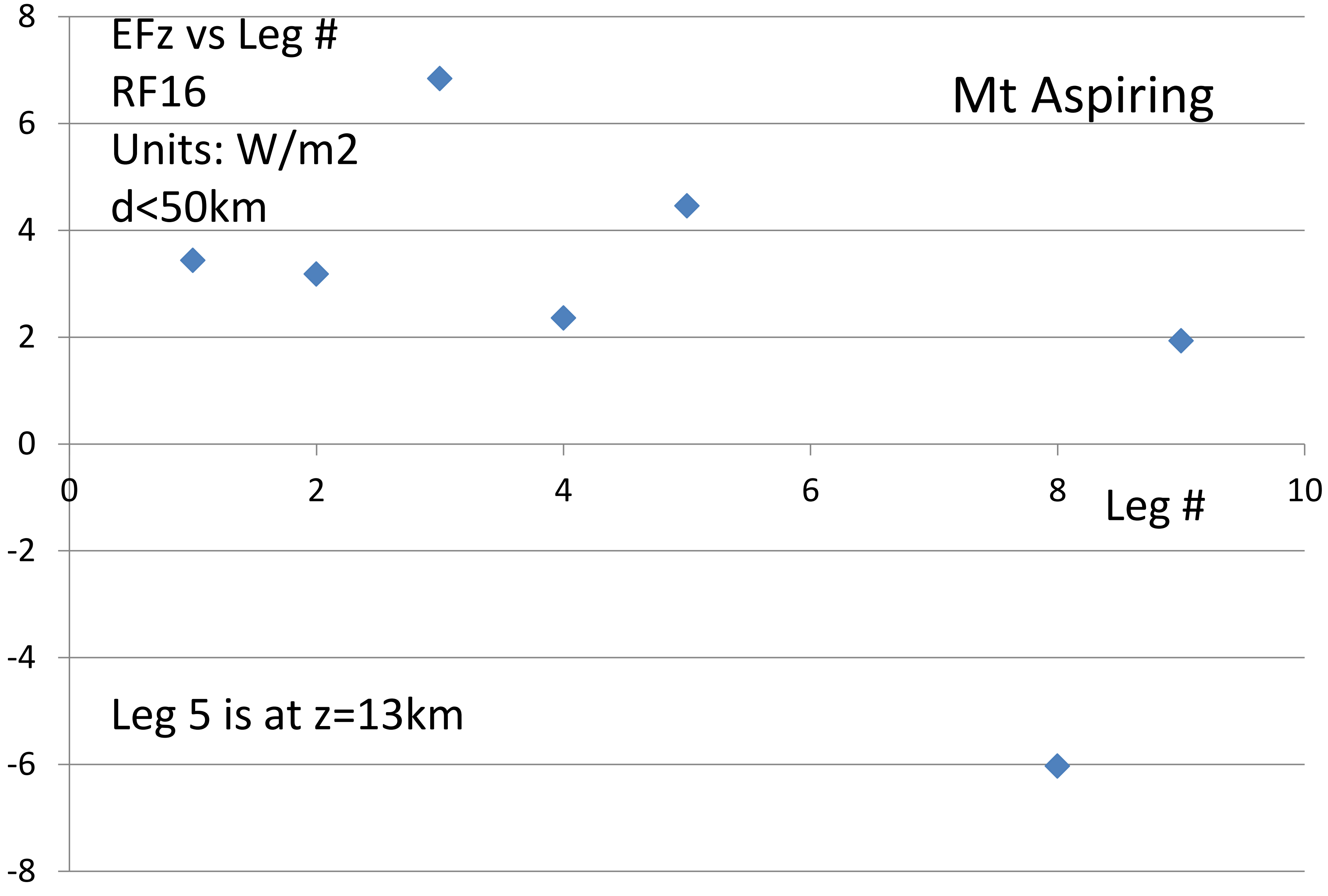
Vertical Energy Flux
EFzCG
Units: W/m2
NZ Legs only
RF12
RF16
RF Number -->
16
14
12
10
8
6
4
2
0
-2
-4
-6
0
5
10
15
20
25
30



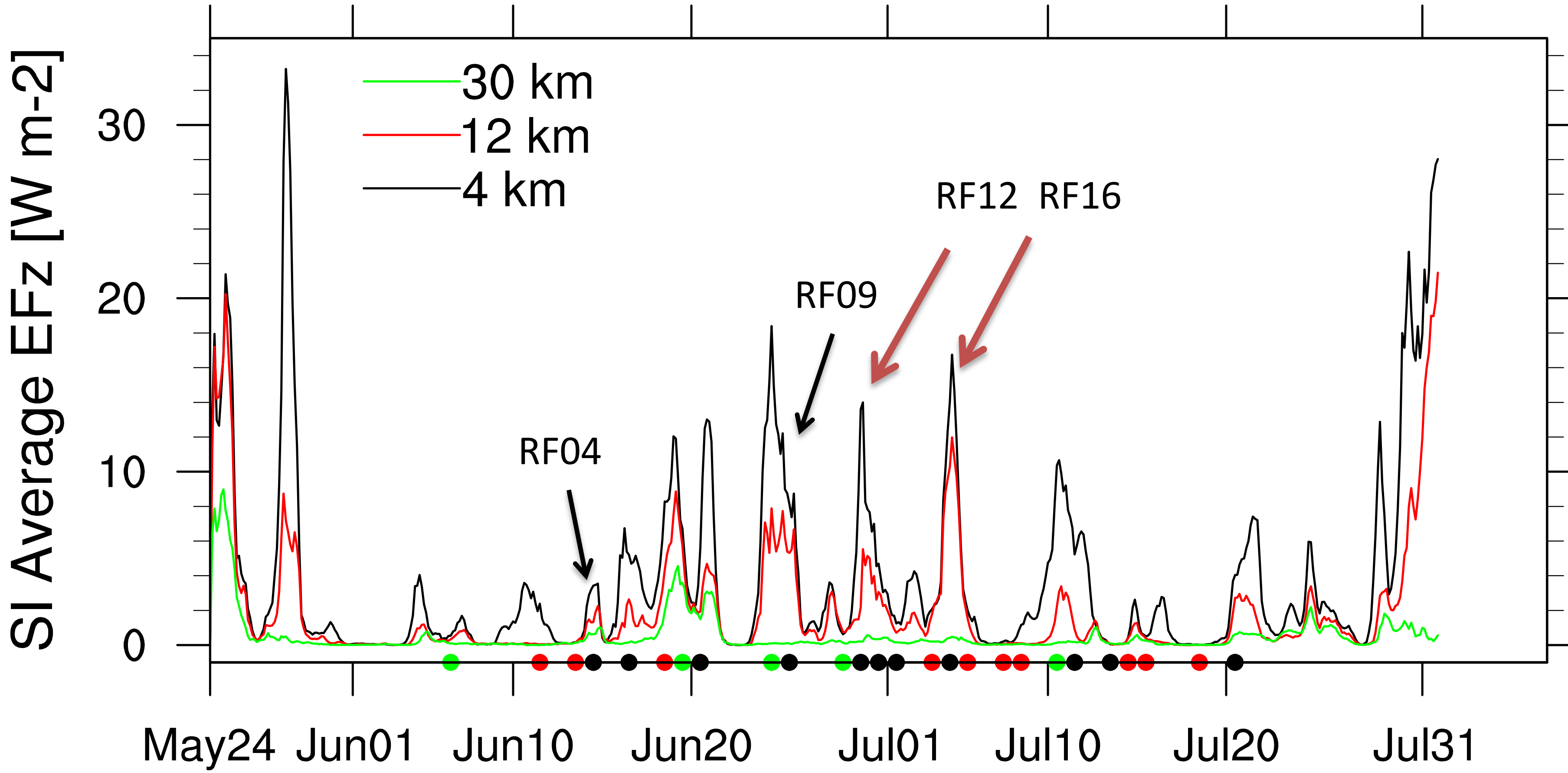
RF12
RF16
Momentum Flux
EFzM (from MF)
Units: W/m2
NZ Legs only
14
12
10
8
6
4
2
0
-2
-4
-6
0
5
10
15
20
25
30
RF Number -->


Eliassen-Palm Check
EFzCG vs. EFzM
Units: W/m2
y = 0.8377x
R² = 0.8162
EFzM
EFzCG
15
10
5
0
-5
-5
0
5
10
15
Downward
propagation
All New Zealand Legs


RF12: Alternating Mt Cook and Aspiring
Variable altitudes
EFz vs Leg #
RF12
Units: W/m2
d<50km
20
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
Leg #


EFz vs Leg #
RF16
Units: W/m2
d<50km
Mt Aspiring
Leg 5 is at z=13km
Leg #
8
6
4
2
0
-2
-4
-6
-8
0
2
4
6
8
10

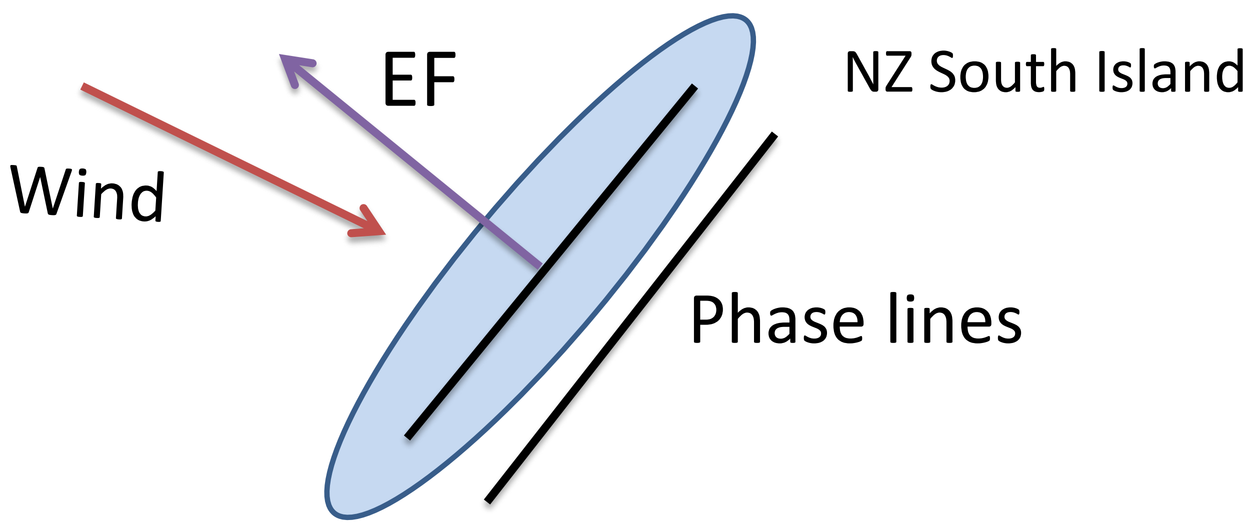
Yale WRF Long Run
SI Averaged EFz



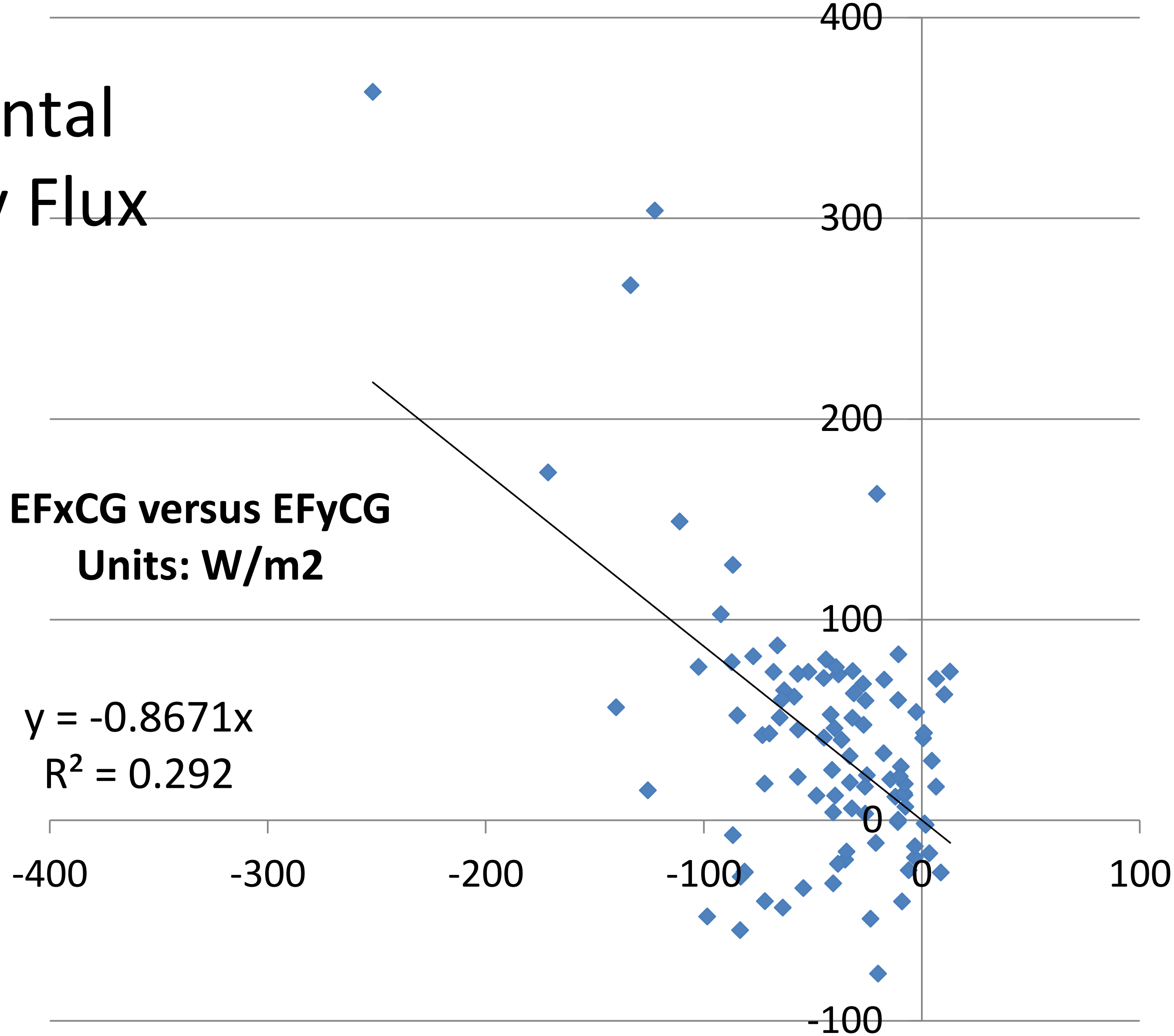
SI Flights !SI Flights Combination

Horizontal energy flux direction

- The horizontal energy flux (EFx, EFy) vectors should be acting against the mean flow .



Horizontal Energy Flux



Pressure analysis

- Error analysis for EF
- Correcting for aircraft altitude and the Coriolis force
- Redundant static pressure

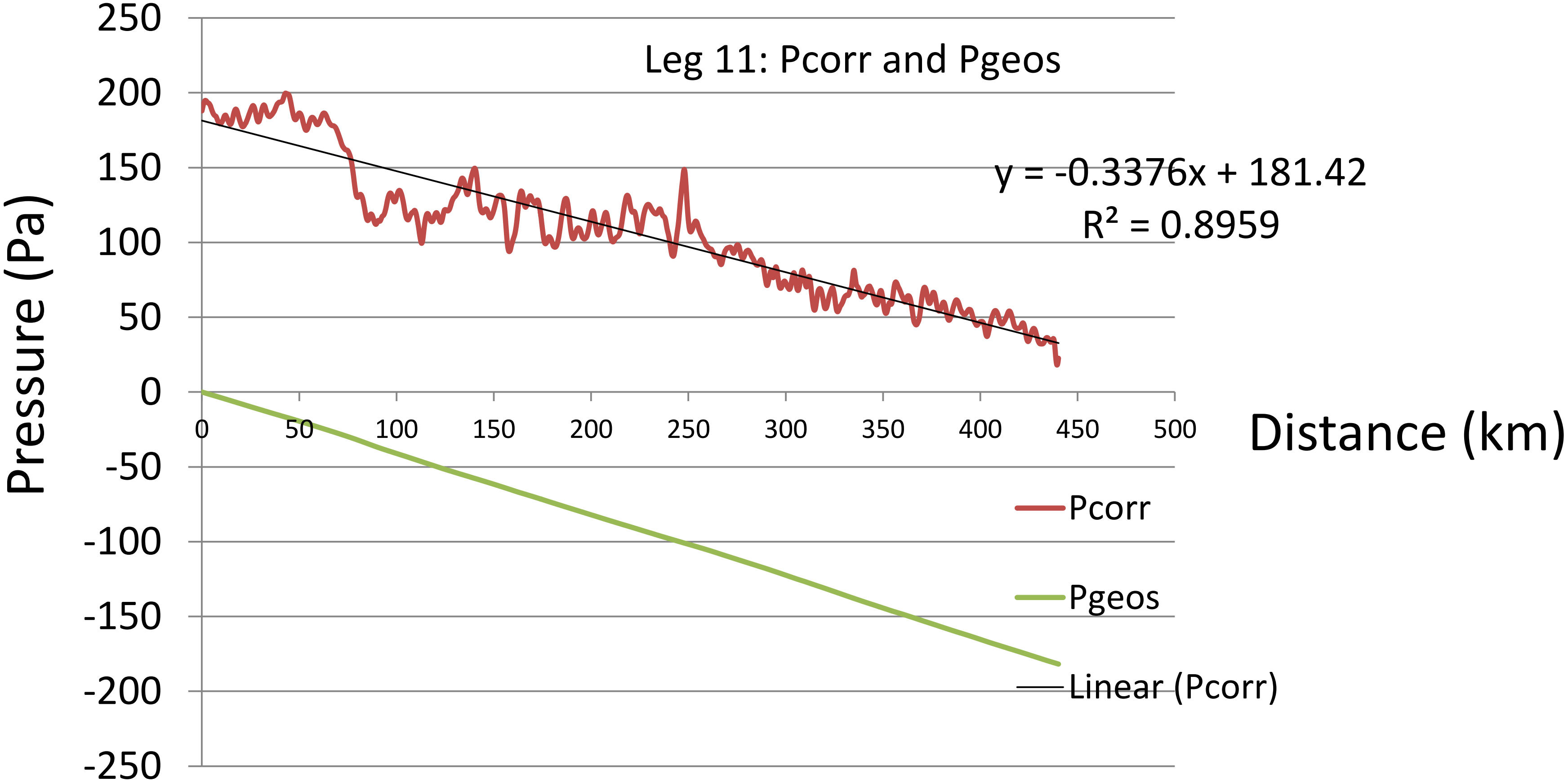
Error estimates for EFz=<p'w'>

- Assume a reference case with w'=1m/s and p'=10Pa so EFz=10 W/m2
- A typical error in Pstatic is p'= 0.1hPa=10Pa
  - (100% error in EFz)
- A typical error in altitude is 1 meter, giving a pressure error of (0.31)(9.81)(1)=3 Pa
  - (30% error in EFz)
- A typical error in W is 0.2m/s.
  - (20% error in EFz)

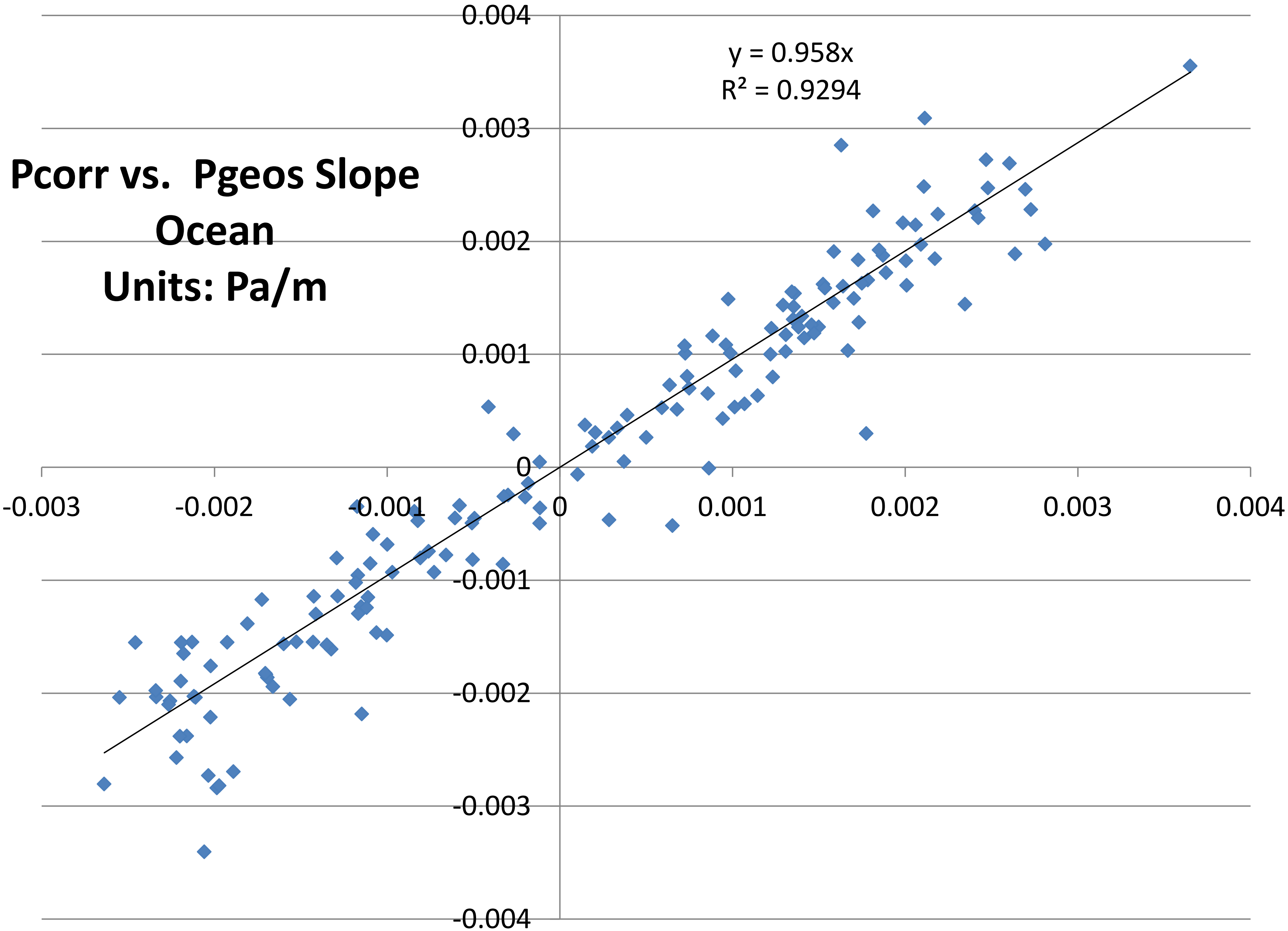
Corrected pressure

- Pstatic is fuselage static pressure corrected for airflow effects
- Pcg is the static pressure, corrected for altitude fluctuation and the geostrophic pressure gradient
- $Pcorr(x) = Pstatic' + \bar{\rho}g(GGalt')$
- $P_{GEOS}(x) = \bar{\rho}2(0.0000727)\int_0^x \sin(\varphi)\, U_{CT}dx$
- $Pcg(x) = Pcorr(x) - P_{GOES}(x)$

RF04 Leg 11



Leg 11: Pcorr and Pgeos
y = -0.3376x + 181.42
R² = 0.8959
Pressure (Pa)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
50
100
150
200
250
300
350
400
450
500
Distance (km)
Pcorr
Pgeos
Linear (Pcorr)

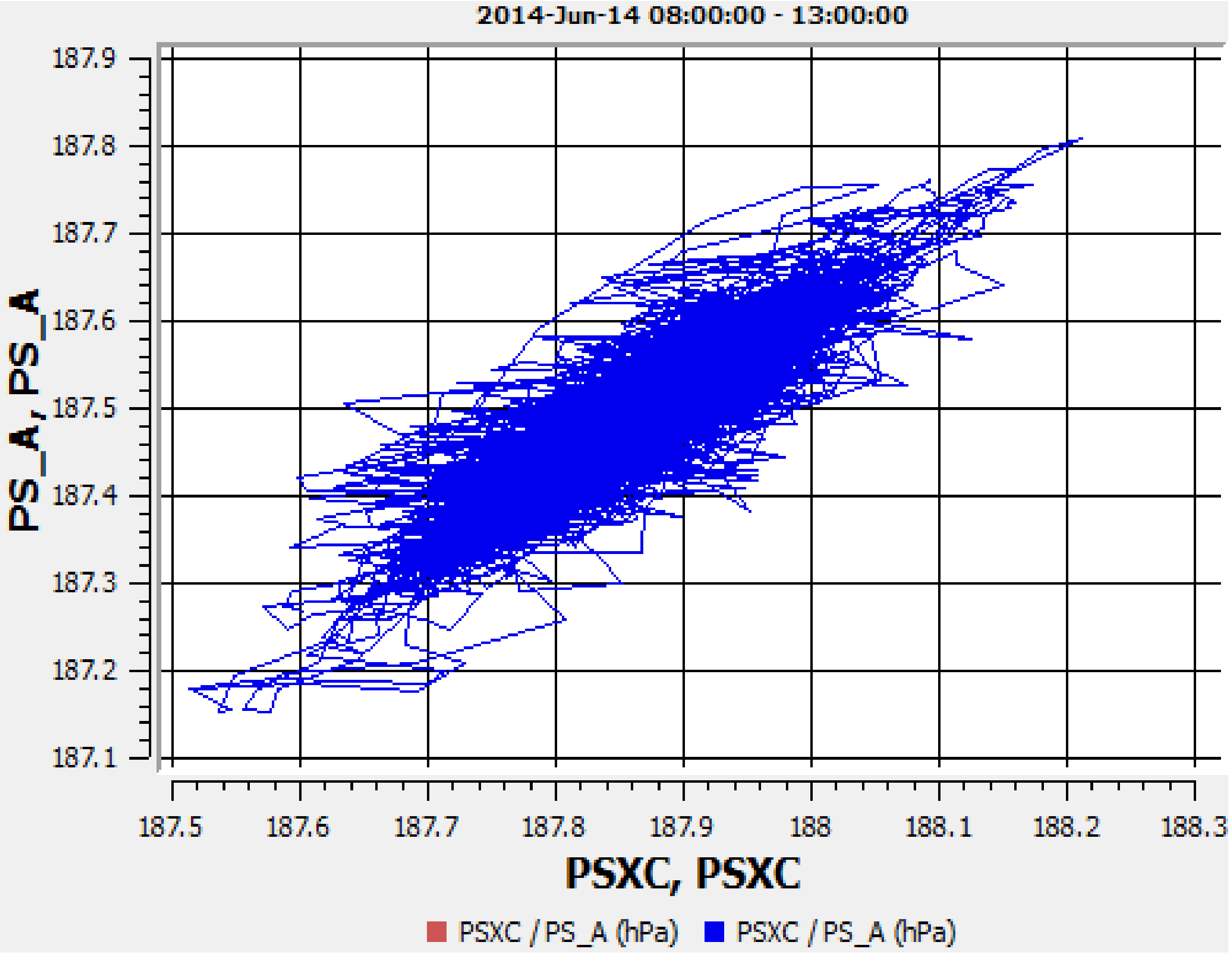


Pcorr vs. Pgeos Slope
Ocean
Units: Pa/m
y = 0.958x
R² = 0.9294
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.003
-0.002
-0.001
0
0.001
0.002
0.003
0.004

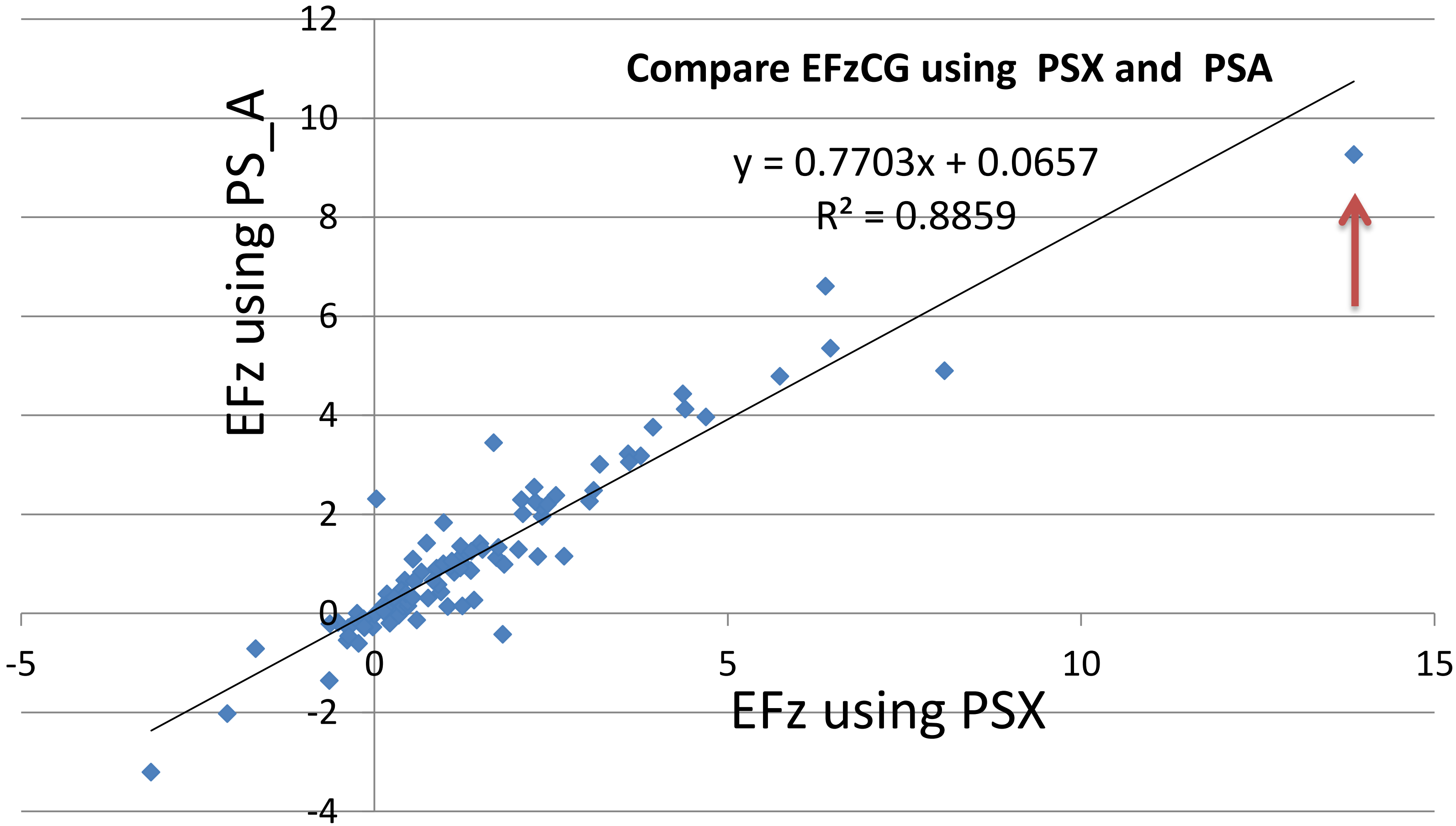
Instrument Redundancy

- In the Preliminary Deepwave data set, the only useful redundant measurement is static pressure (PSXC and PS_A).
- In the final data set, with the gust pod recalibrated, we hope to have an additional u,v,w,p data set and a new DGPS data set for two flights

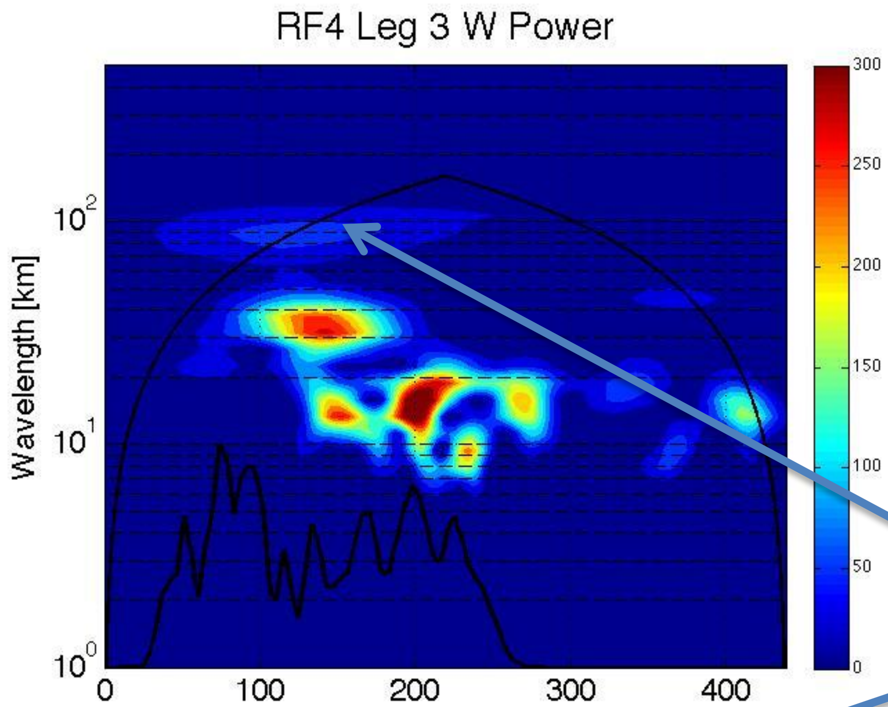
Redundant static pressure (RF04) Uncertainty=10Pa



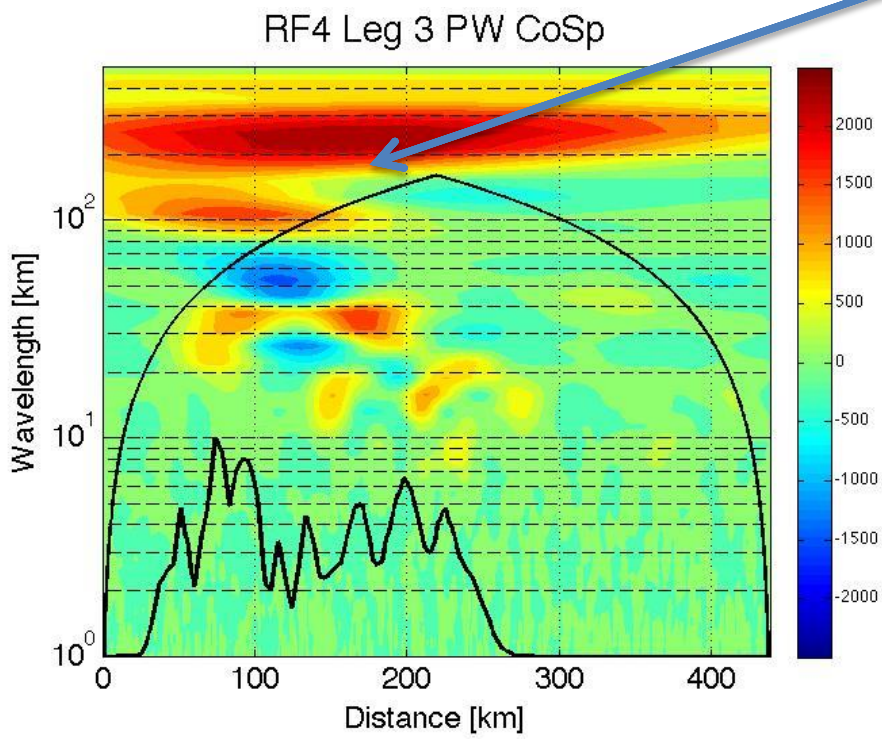
Vertical Energy flux:
two different pressure sensors (PSX and PS_A)

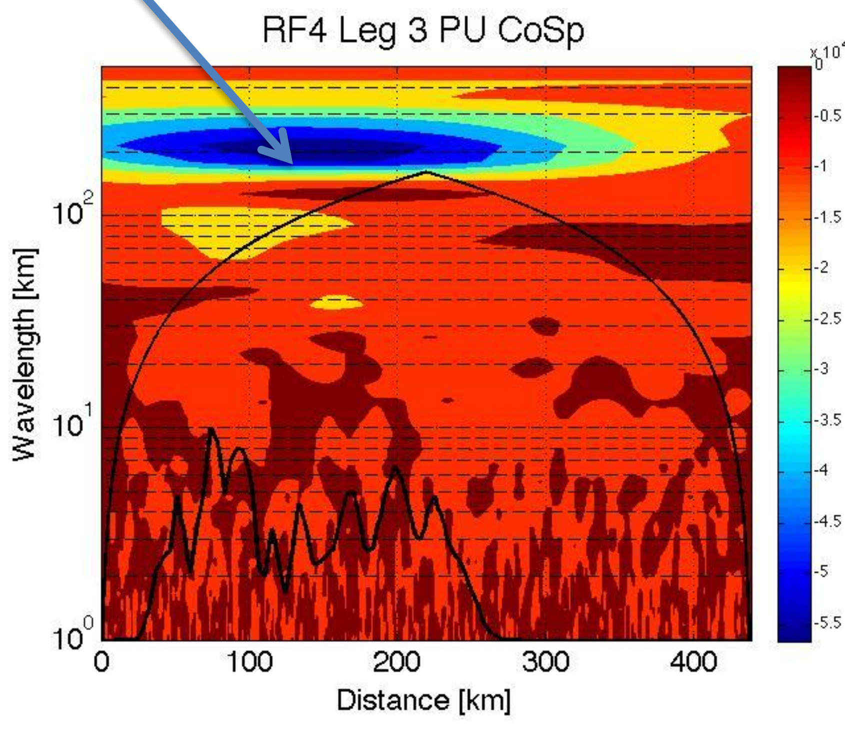


Wavelet Scale Analysis of RF04; Leg 3 @z=12.2km



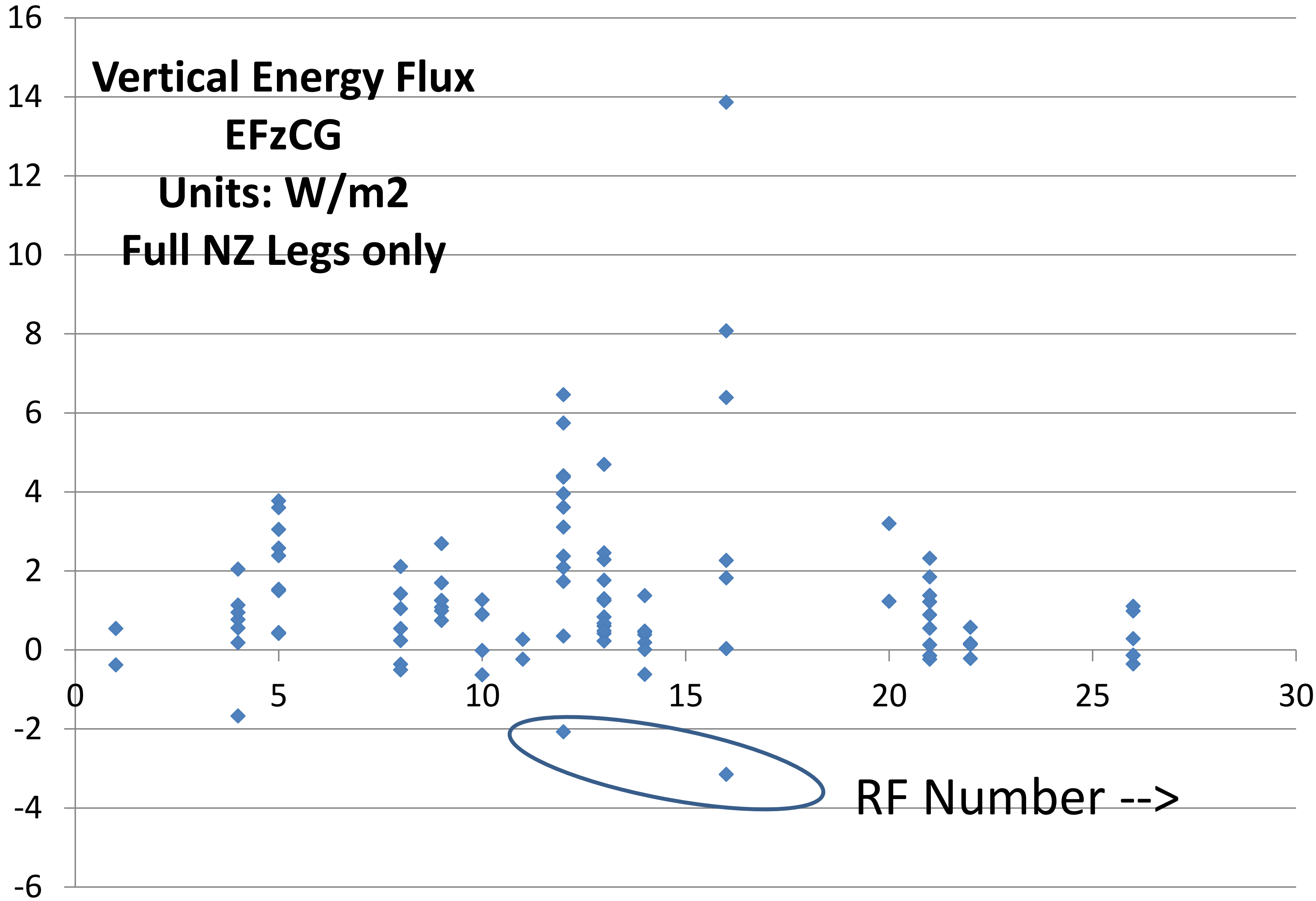
Flux-carrying Waves



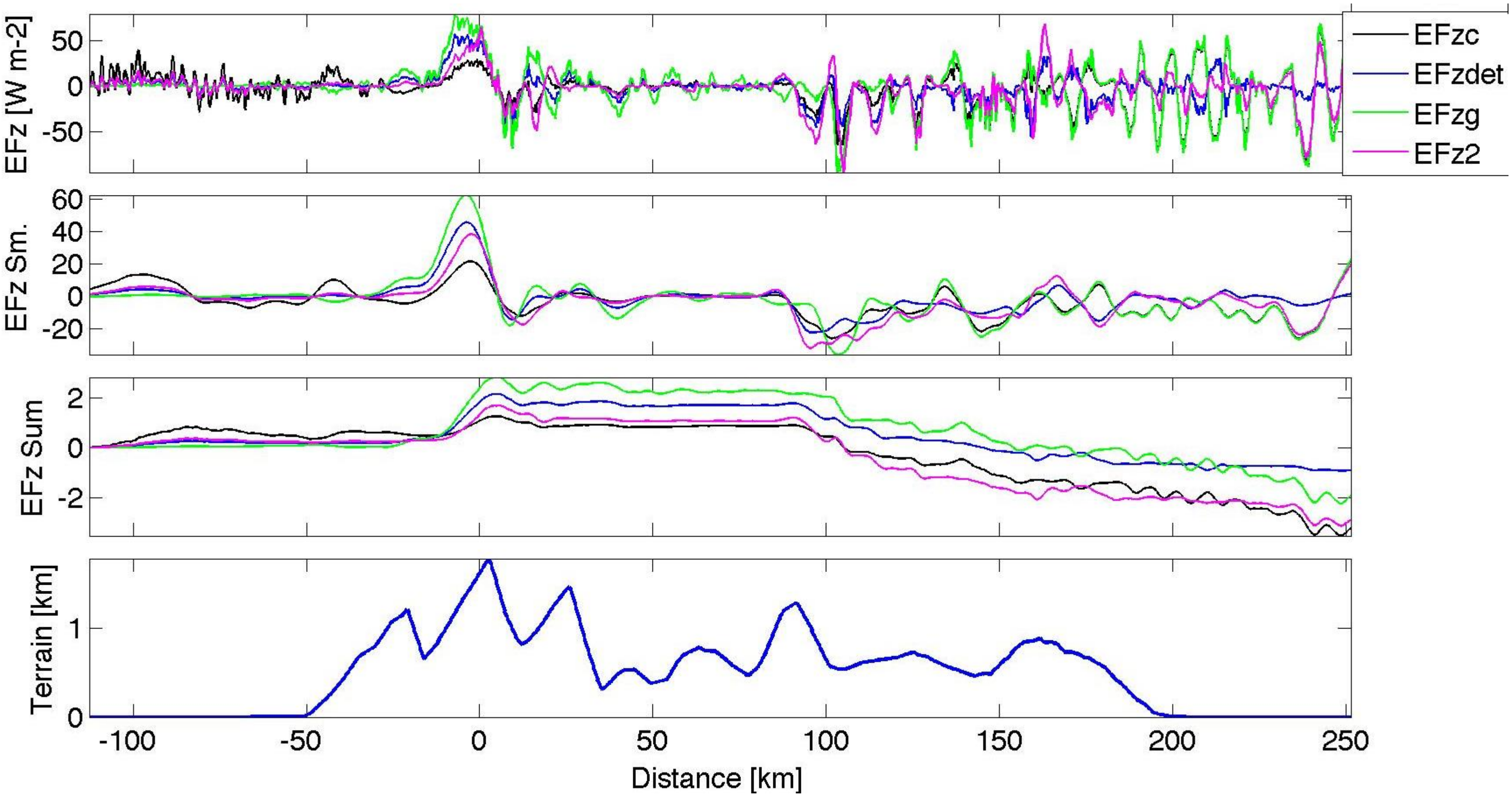


Negative Energy Flux EFz

- A few legs with negative EFz are seen
- These fluxes still fall on the E-P line
- Mostly caused by downward wave beams over the east end of Mt Aspiring

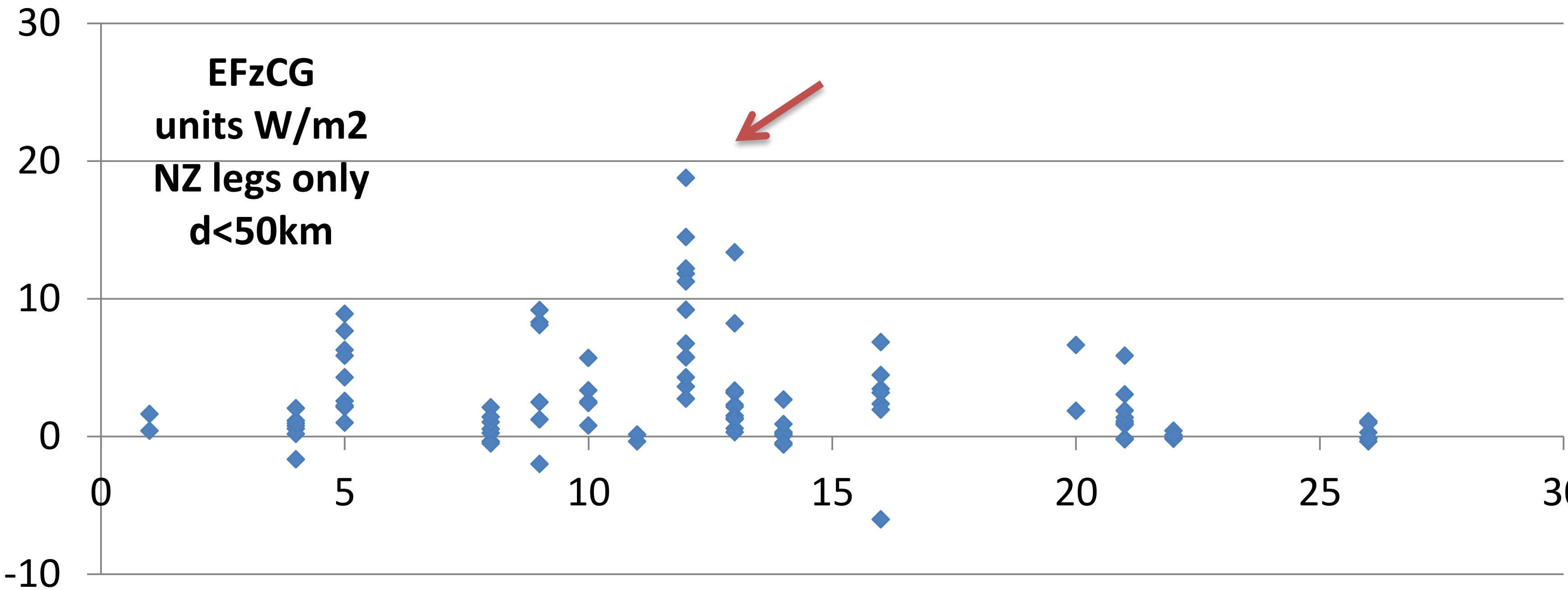

Vertical Energy Flux
EFzCG
Units: W/m2
Full NZ Legs only
RF Number -->
16
14
12
10
8
6
4
2
0
-2
-4
-6
0
5
10
15
20
25
30

RF12 Leg 1: EFz ~ -3W/m2

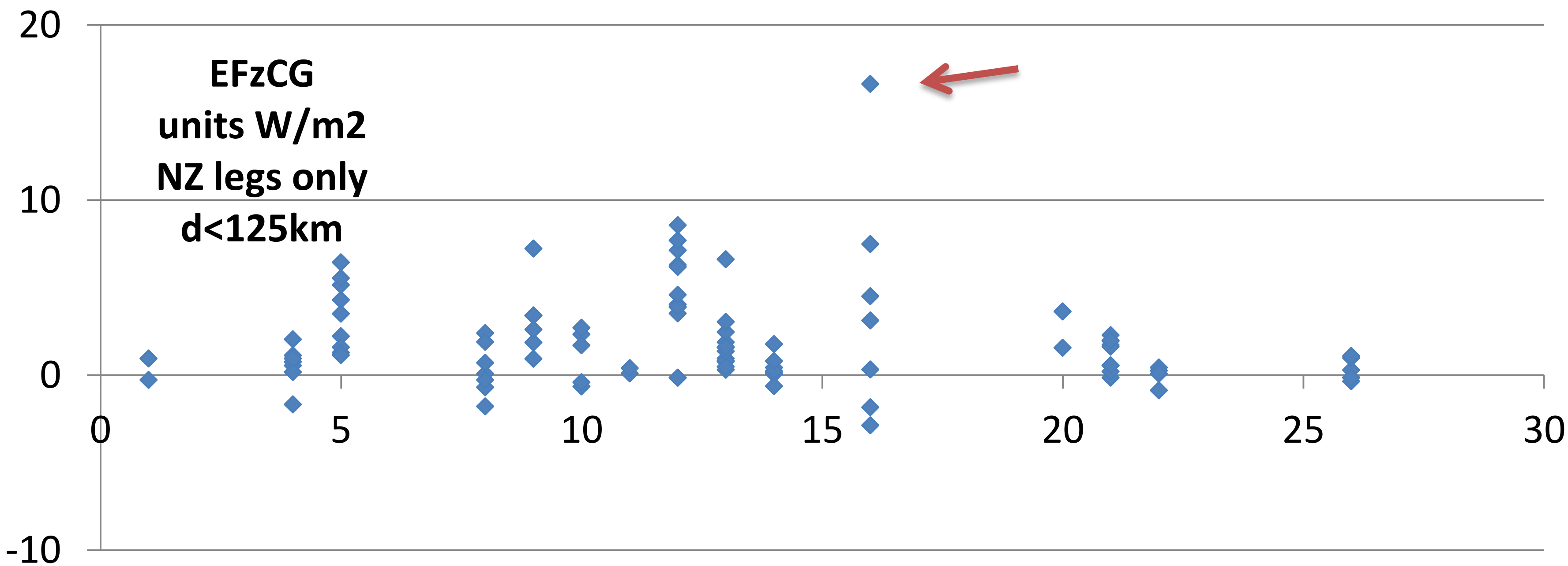


Sensitivity to leg length

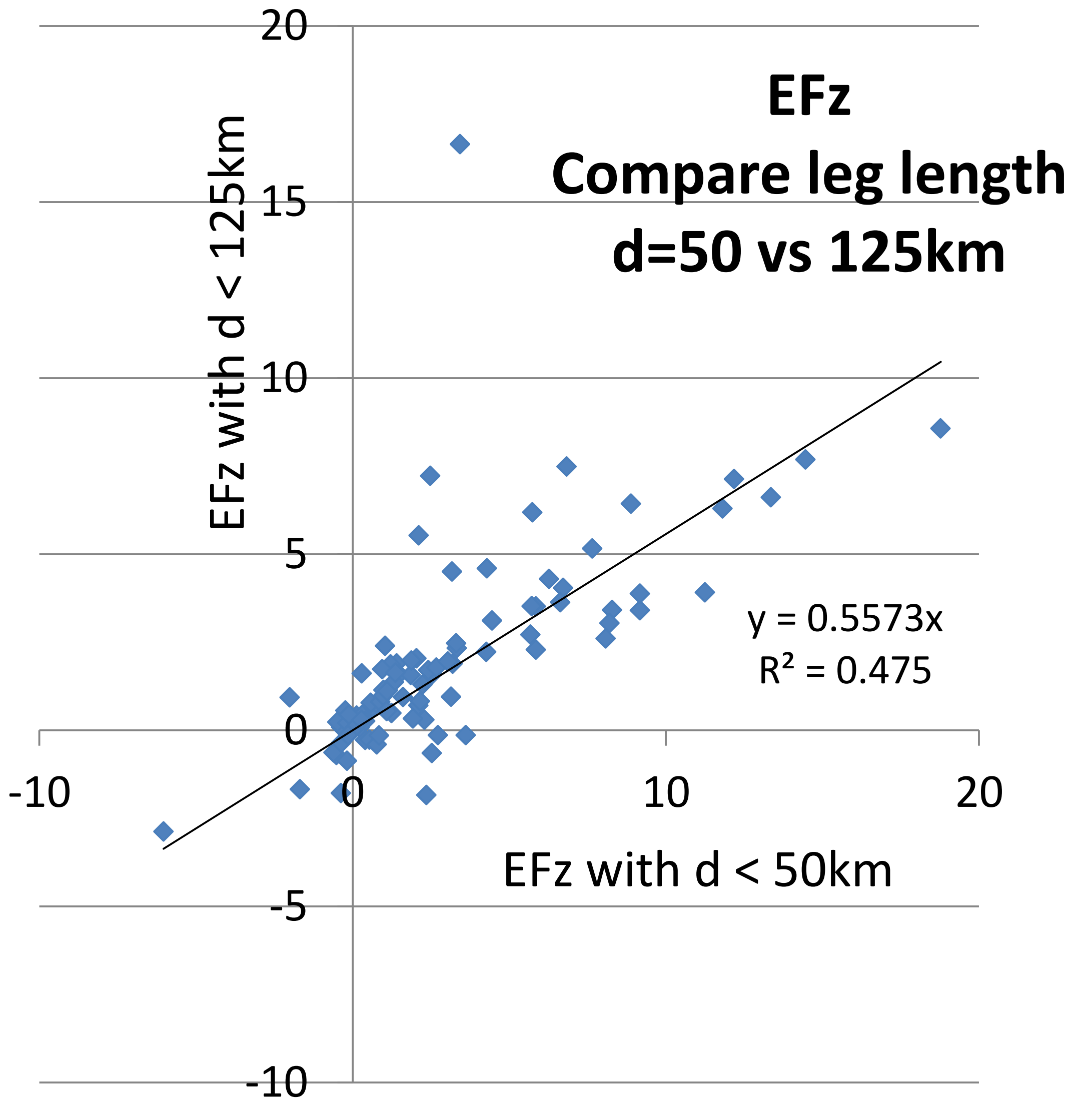
- Compute fluxes only for distance from mountain peak < d
- Compare d=50km and d=125km
- Maximum flux legs change with d
- Average flux values are less on the longer legs



EFzCG
units W/m2
NZ legs only
d<50km
30
20
10
0
-10
0
5
10
15
20
25
30



EFzCG
units W/m2
NZ legs only
d<125km
20
10
0
-10
0
5
10
15
20
25
30



EFz
Compare leg length
d=50 vs 125km
EFz with d < 125km
EFz with d < 50km
y = 0.5573x
R² = 0.475
20
15
10
5
0
-5
-10
-10
0
10
20

Conclusions I

- Energy and Momentum fluxes are very transient within flights. Strong wave days have the largest flux variance and reversed fluxes.
- Observed momentum and energy fluxes satisfy the Eliassen-Palm condition: EFz=EFzM.
- Energy fluxes are sensitive (e.g. +/-20%) to static pressure sensor error.

Conclusions II

- Horizontal energy flux direction is mostly
 NW-ward; upwind and perpendicular to the NZ terrain.
- Almost every case has vertical velocities dominated by short waves with wavelength from 8 to 12km. These waves carry little flux.
- Dominant flux-carrying waves have wavelength from 70 to 250km

Conclusions III

- Flux values are sensitive to leg length. Flux density is greatest near the mountain peaks. Average flux decreases with integration leg length.
- Aircraft flux measurements in Deepwave have uncertainties of 30% or larger due to:
  - Lack of redundant sensors (so far?)
  - Large Unsteadiness
  - Sensitivity to leg length

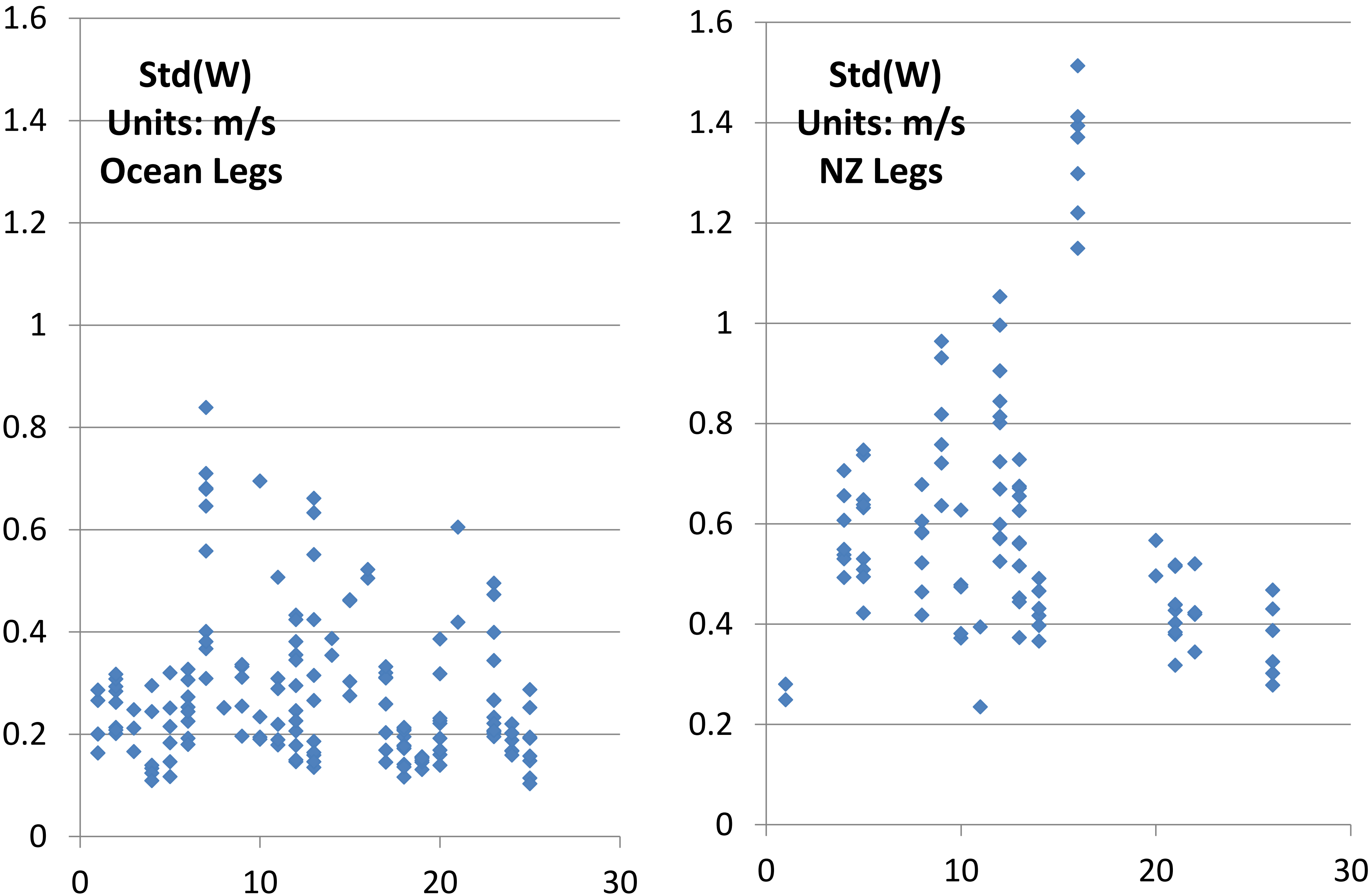
Yale Deepwave Priority Research

- Mountain wave transience
- Wave generation and the ABL
- Wave dissipation in the stratosphere
- Wave diagnostics from model output
- Flux error estimates, redundant measurements
- Trapped waves
- Moist processes; convection
- Downward propagating waves

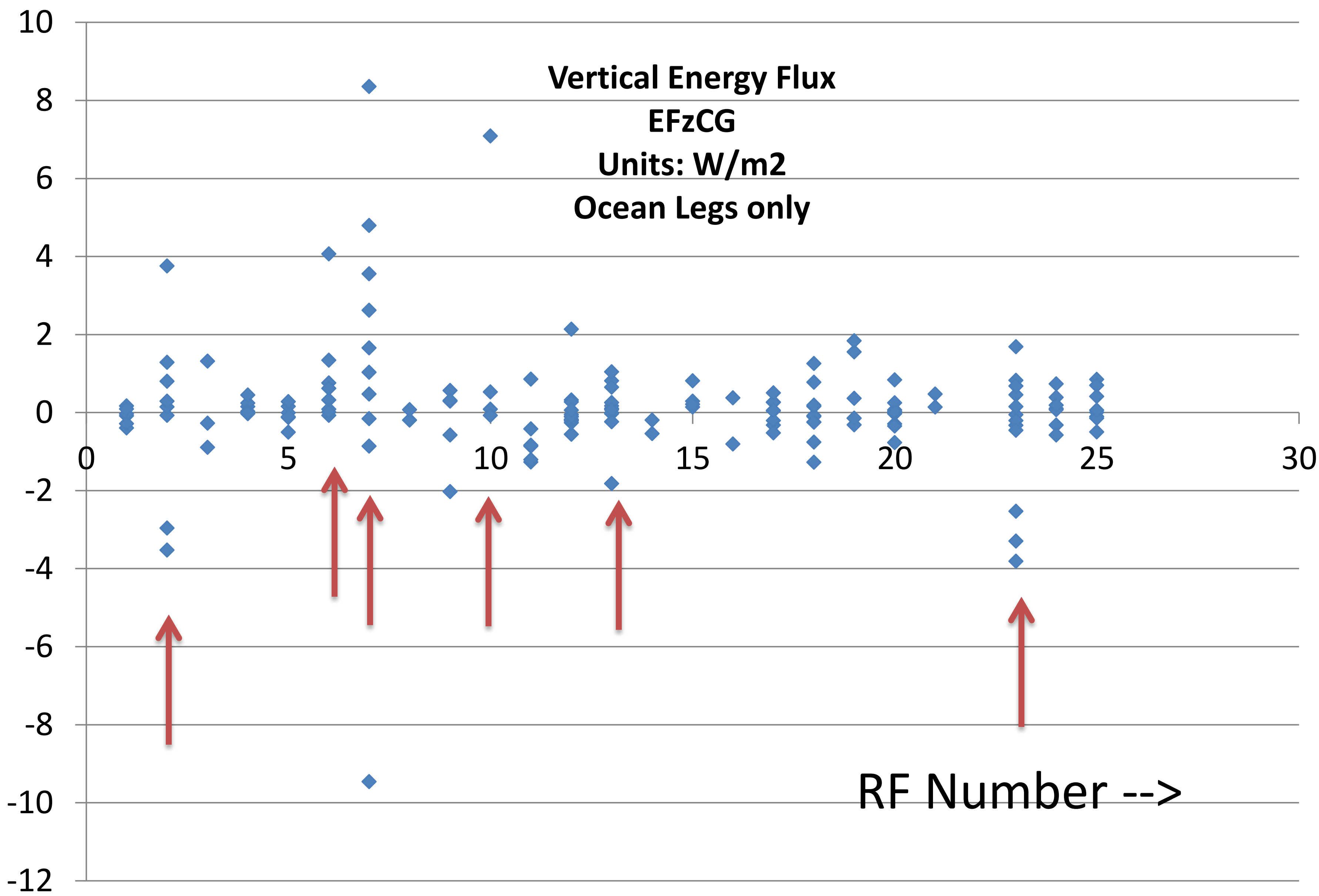
The End

Conclusions IV

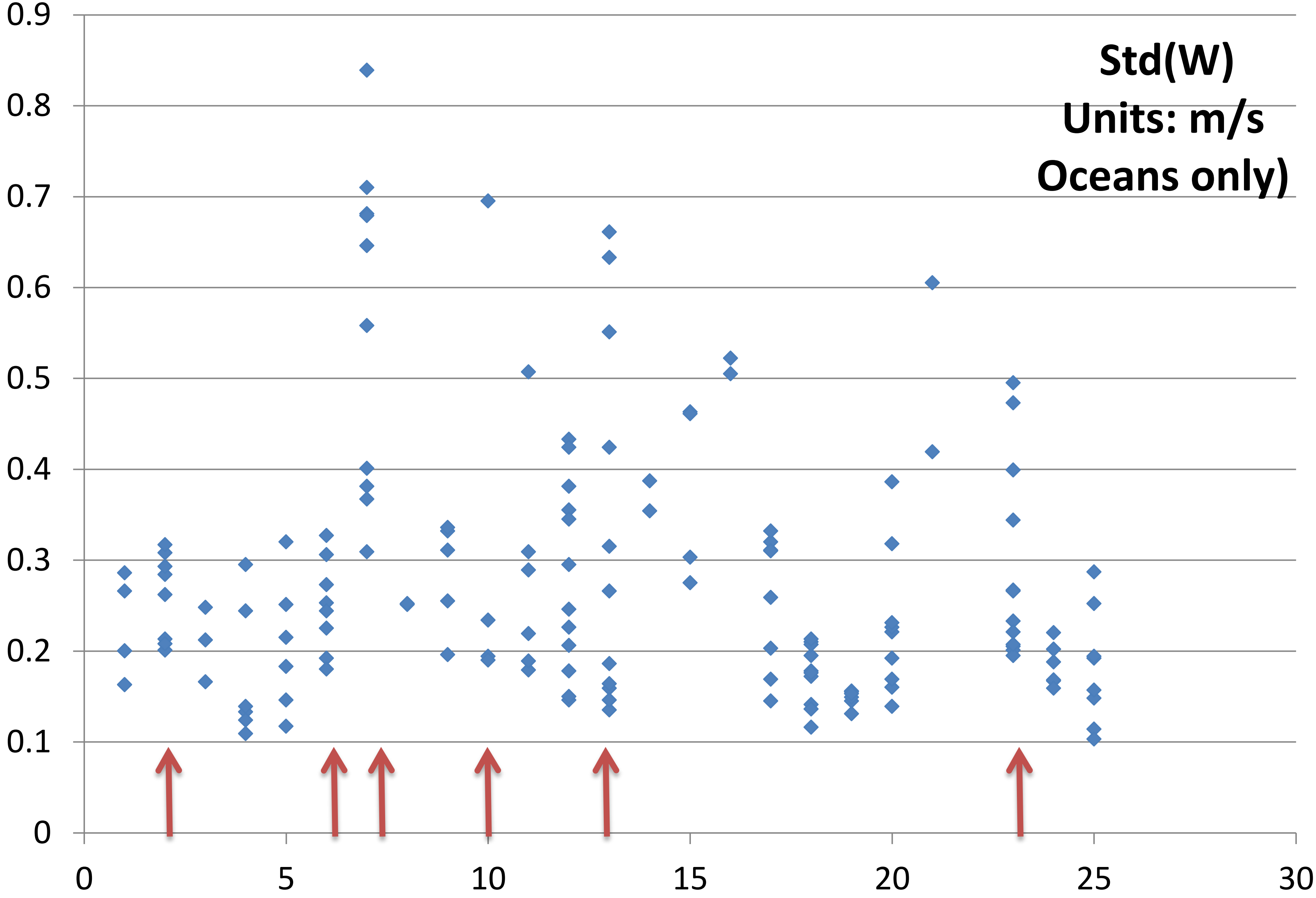
- South Island area is approximately 160,000km2, so EFz=10W/m2 gives 1.6 TeraWatts
- WRF and GV flux values are in rough agreement
- WRF-based deep cases on June 19-21
  - RF07: Not flown over NZ
  - RF08: Weak waves over Mt Aspiring



Std(W)
Units: m/s
Ocean Legs
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
Std(W)
Units: m/s
NZ Legs
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30



Vertical Energy Flux
EFzCG
Units: W/m2
Ocean Legs only
RF Number -->
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0
5
10
15
20
25
30


Std(W)
Units: m/s
Oceans only)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30

Significant “Ocean” vertical velocity or fluxes

- RF02: Tasmania
- RF06: Tasmania
- RF07: NZ box pattern (Bad WIC)
- RF10: Trailing wave leg near NZ
- RF13: Trailing wave leg near NZ
- RF23: Macquarie and Auckland Islands

Outline

- Deepwave GV flight level data set
- Momentum and Energy Flux statistics
- Pressure corrections for energy flux
  - Error analysis
  - The constant P assumption
  - Coriolis correction
  - Redundant pressure sensor
- Trapped waves and dominant scales
- Downgoing waves
- Effect of leg length
- WRF comparison
- Ocean versus NZ legs

Types of flux measurements

- Momentum flux
  - Traditional mountain wave quantity
  - Impacts large scale flow
  - Need gust-probe wind field only
  - Constant with height in steady, linear, non-dissipative flow
  - (not wave specific)
- Energy flux
  - New diagnostic quantity
  - Better physical interpretation in unsteady flows
  - Wave specific
  - (needs static pressure)

Motivations for flux measurements

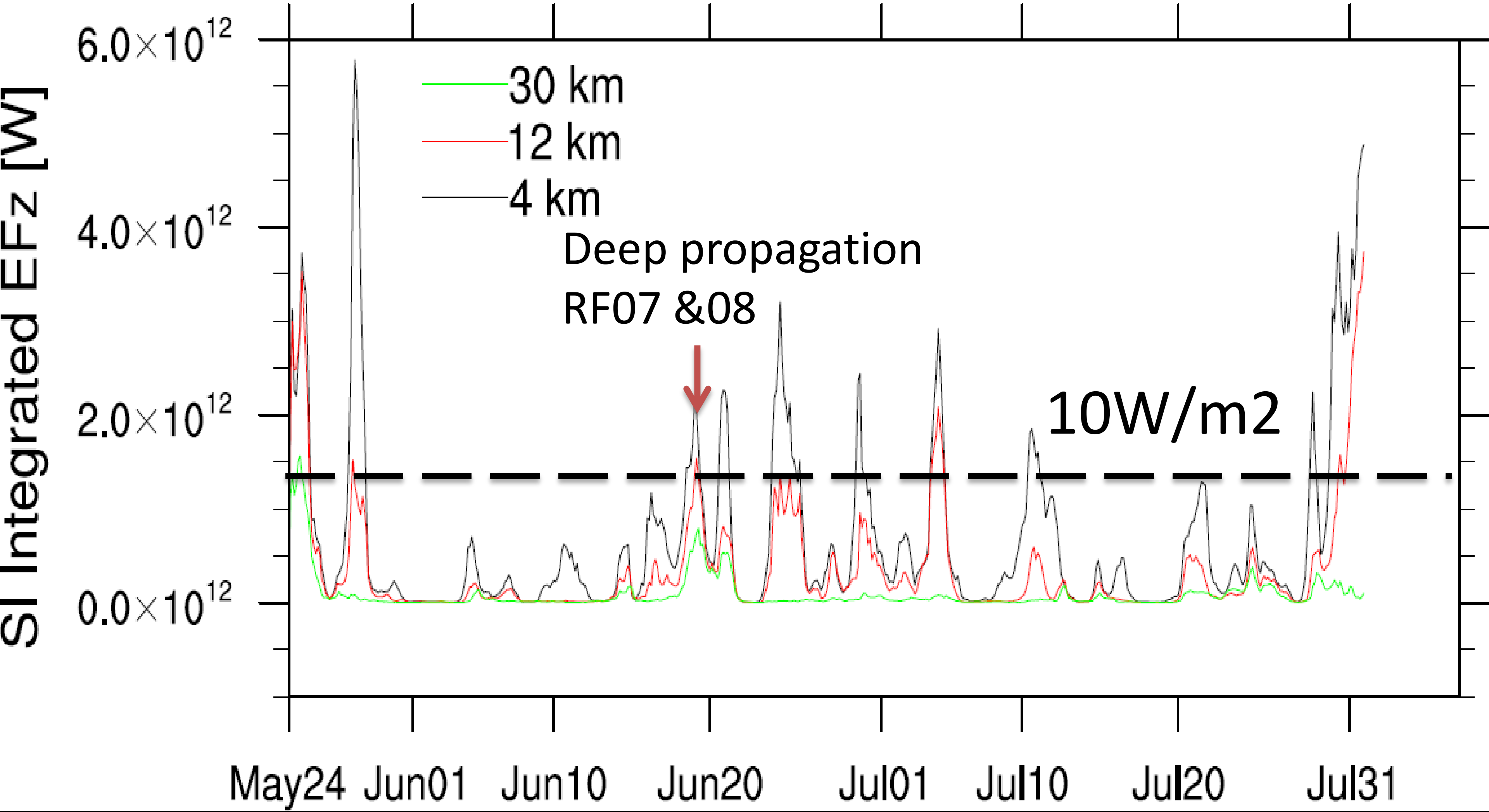
- Statistics for global models
- Compare with GW parametrizations
- Compare with hi-res models
- Compare with remote sensing wave data
- Examine the physics of GW


Cape Farewell
Farewell Spit
GOLDEN BAY
Collingwood
D' URVILLE ISLAND
Takaka
TASMAN BAY
KARAMEA BIGHT
Motueka
COOK STRAIT
Karamea
Havelock
Picton
Richmond
NELSON
Little Wanganui
Wakefield
Blenheim
Granity
Westport
Cape Foulwind
Murchison
Seddon
Inangahua
St Arnaud
Tapuae-o-Uenuku
2885
Punakaiki
Reefton
Clarence
Clarence River
Lewis Pass
Runanga
Greymouth
Hanmer Springs
Kaikoura
Kaikoura Peninsula
Kumara
Waiau
Hokitika
Culverden
Cheviot
Waiau River
Otira
Hawarden
Arthurs Pass
Ross
SOUTHERN ALPS
Amberley
Harihari
Rangiora
Whataroa
Springfield
PEGASUS BAY
Porters Pass
Kaiapoi
Franz Josef Glacier/Waiau
Waimakariri River
Fox Glacier
Darfield
CHRISTCHURCH
Aoraki/Mt Cook
3754
Lyttelton
Mt Somers
Methven
BANKS PENINSULA
Aoraki/Mount Cook
Lincoln
Akaroa
Haast River
Haast
Lake Tekapo
Leeston
Ashburton
Rakaia River
Jackson Head
Lake Pukaki
Geraldine
Hinds
Ashburton River/Haratere
Haast Pass/Tioripatea
Lake Tekapo
Fairlie
Temuka
CANTERBURY BIGHT
Lake Ohau
Twizel
Rangitata River
Makarora
Awarua Point
Lake Wanaka
Lake Hawea
Timaru
Mt Aspiring/Tititea
3027
Omarama
Milford Sound/Piopiotahi
Lindis Pass
Milford Sound
Waimate
Wanaka
Kurow
Homer Tunnel
Glenorchy
Tarras
George Sound
Arrowtown
Waitaki River
Queenstown
Cromwell
Oamaru
Ranfurly
Maheno
Lake Te Anau
Lake Wakatipu
Alexandra
Hampden
Doubtful Sound/Patea
Kingston
Te Anau
Middlemarch
Palmerston
Dagg Sound
Doubtful Sound
Roxburgh
Waikouaiti
Manapouri
Secretary I
Mossburn
Port Chalmers
Lake Manapouri
Lumsden
Dusky Sound
Mosgiel
OTAGO PENINSULA
Ohai
Tapanui
Lawrence
DUNEDIN
Nightcaps
Gore
Winton
Clinton
Tuatapere
Mataura
Balclutha
Kaitangata
Riverton/Aparima
Clutha River
Owaka
INVERCARGILL
FOVEAUX STRAIT
Bluff
Chaslands Mistake
Solander I
Ruapuke I
Codfish
Halfmoon Bay (Oban)
Stewart Island/Rakiura
South Cape/Whiore

Internal data checks

- Vertical displacement
  - Vertical velocity
  - Potential temperature
- Pressure
  - Static P corrected for altitude and Coriolis force
  - Bernoulli equation using wind speed
- Energy flux (EP relationship)
  - EFz = <p’w’>
  - EFz2 = -U*MFx-V*Mfy
- Mean W over the sea
- EF and MF direction

WRF "Long Run"

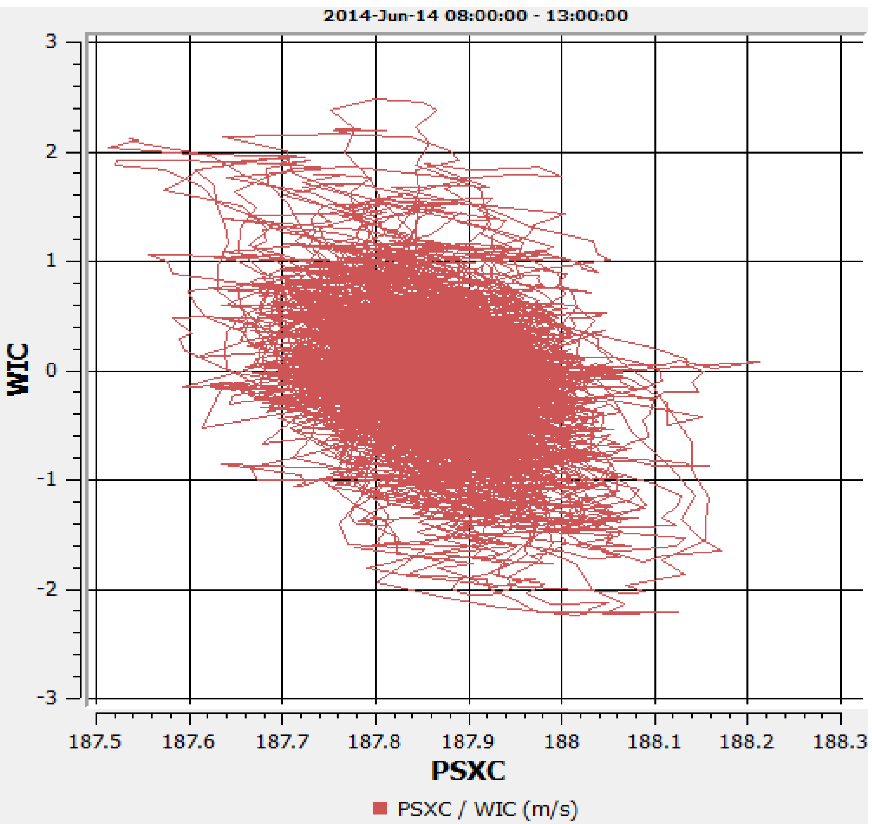


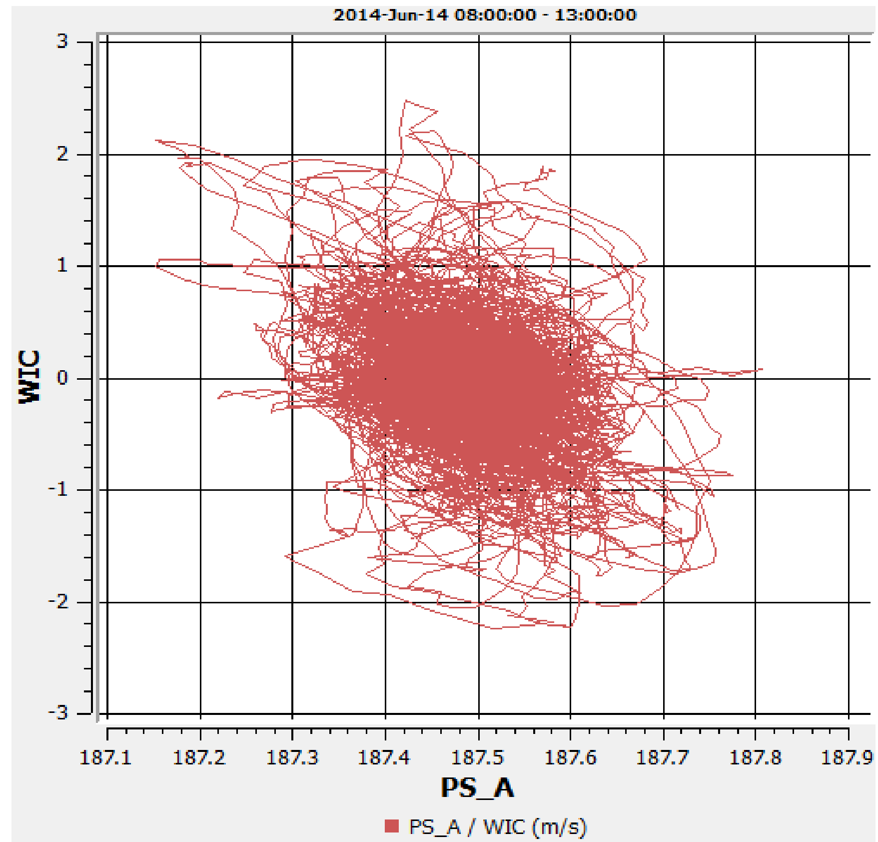
SI Integrated EFz [W]
6.0×10^12
4.0×10^12
2.0×10^12
0.0×10^12
30 km
12 km
4 km
Deep propagation
RF07 &08
10W/m2
May24
Jun01
Jun10
Jun20
Jul01
Jul10
Jul20
Jul31

Results of setting Pstatic’=0

- One potentially reasonable assumption is to set the static pressure perturbation equal to zero. This is the assumption that the aircraft maintains itself on a constant pressure surface. However:
- This assumption leads to a large negative bias in the vertical energy flux EFz=<p’w’>, because of a systematic negative correlation between Pstatic and WIC. This is due to the aircraft altitude responding to vertical air motion.

RF04: Raw Pstatic vs WIC
CC~ -0.4

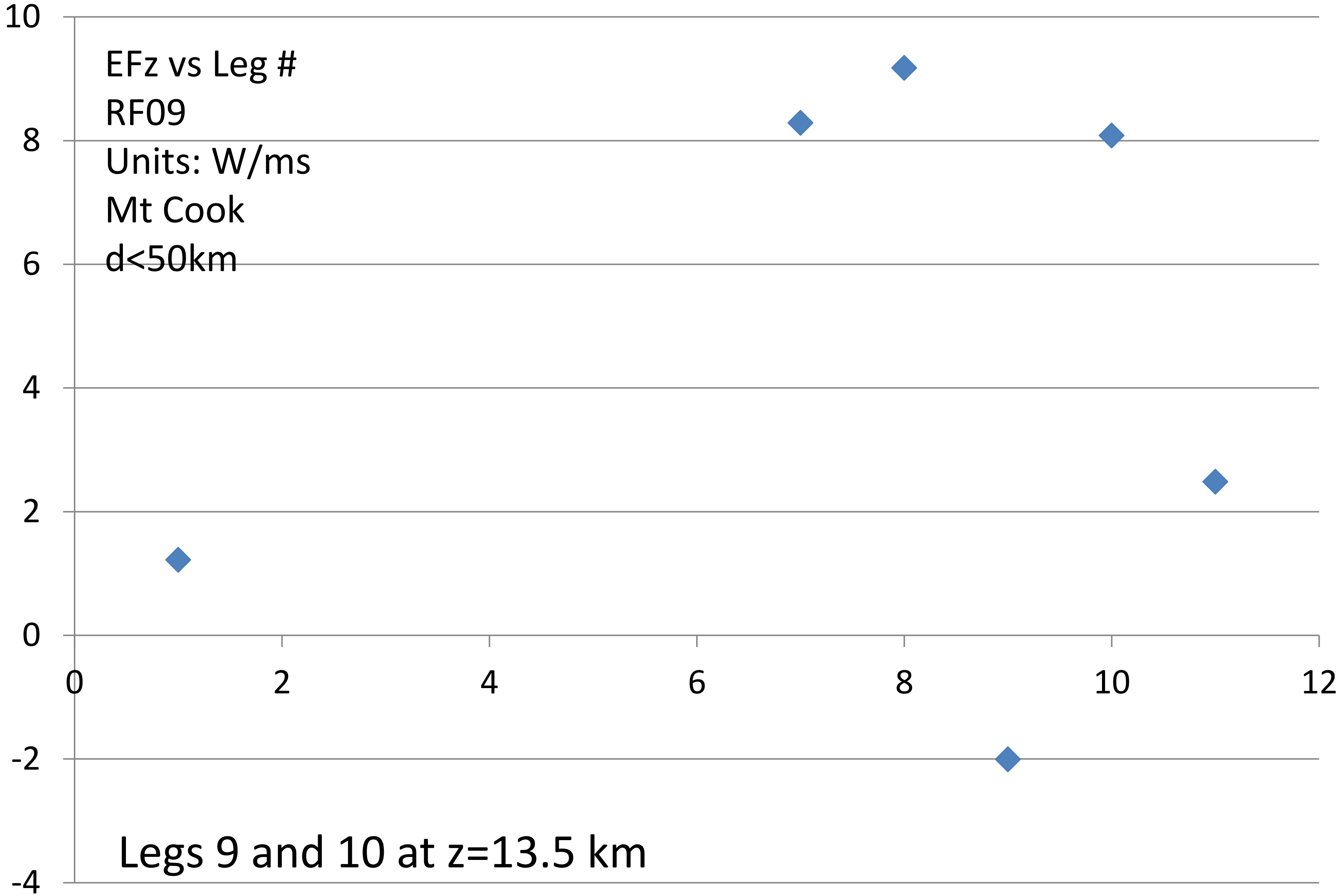




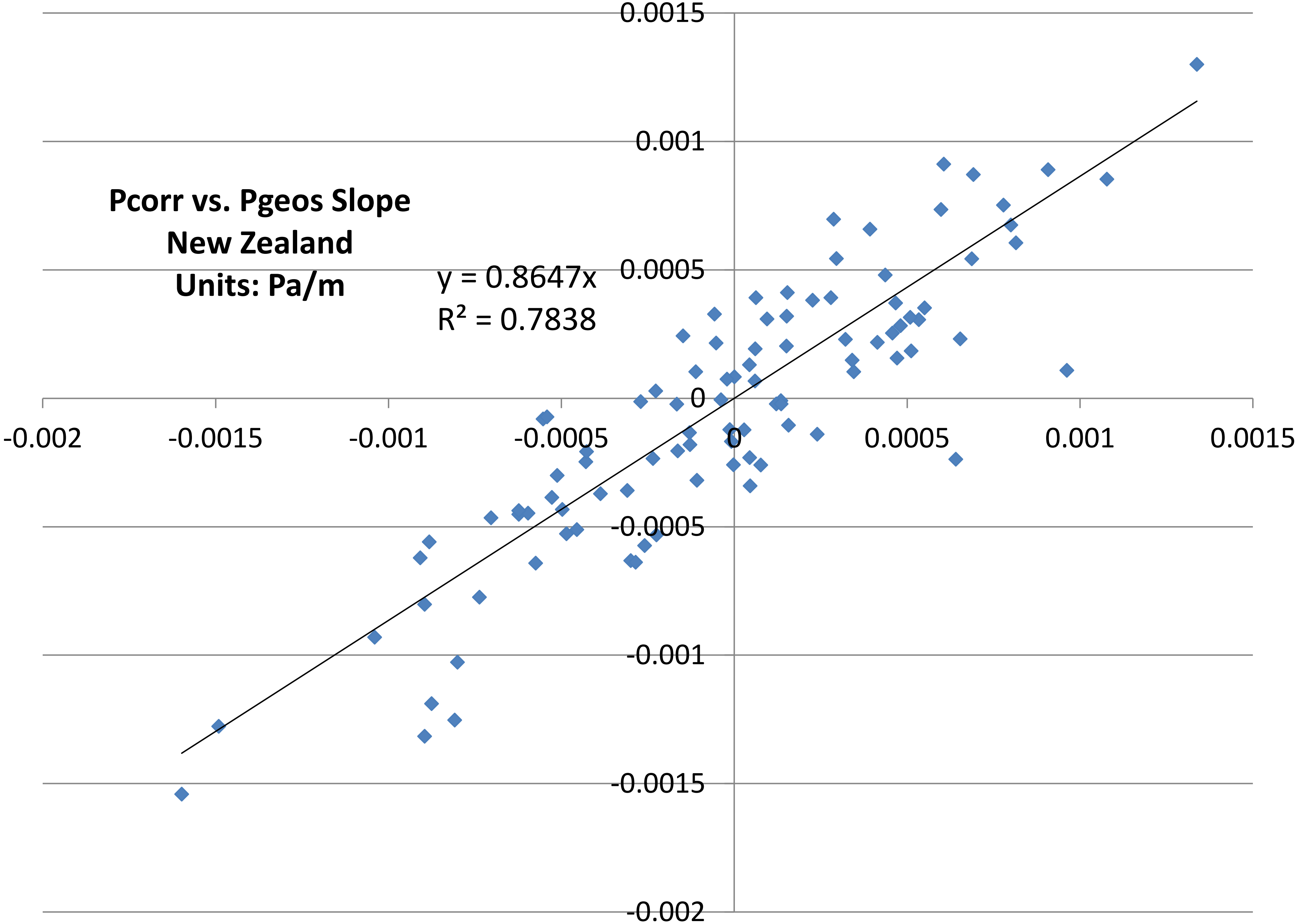
Aircraft leaves the constant pressure surface by +/- 0.2 hPa

Instrument Redundancy

- Momentum and Energy Fluxes require: u,v,w,p,z
- In the Preliminary Deepwave data set, the only useful redundant measurement is static pressure (PSXC and PS_A). For u,v,w,z we have only: UIC, VIC, WIC from the nose cone and GGALT from Omnistar.
- In the final data set, with the gust pod recalibrated, we hope to have an additional u,v,w,p data set
- It seems as if the Omnistar satellite DGPS will give z=+-20cm accuracy for altitude (z). For two flights, we will have redundancy from the ground station DGPS.

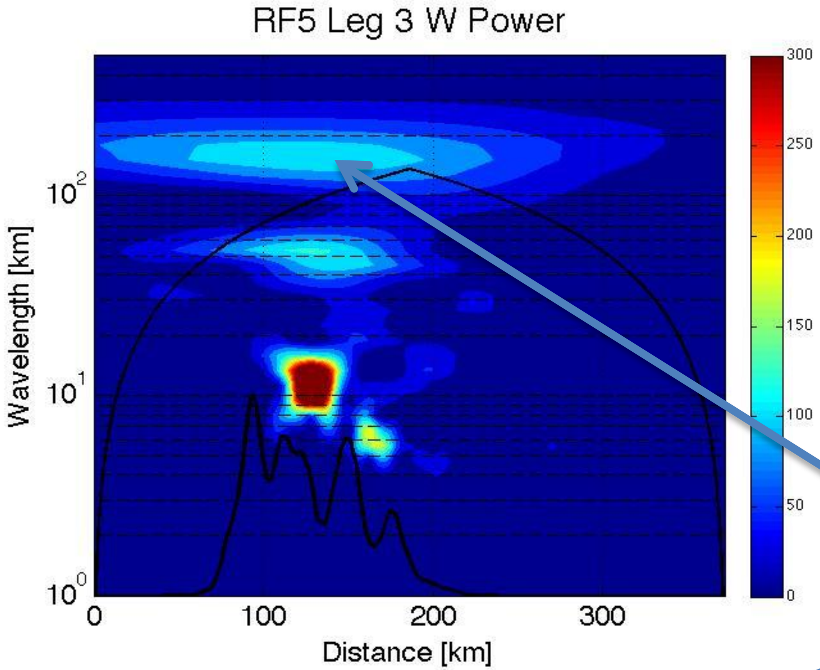


EFz vs Leg #
RF09
Units: W/ms
Mt Cook
d<50km
Legs 9 and 10 at z=13.5 km
10
8
6
4
2
0
-2
-4
0
2
4
6
8
10
12

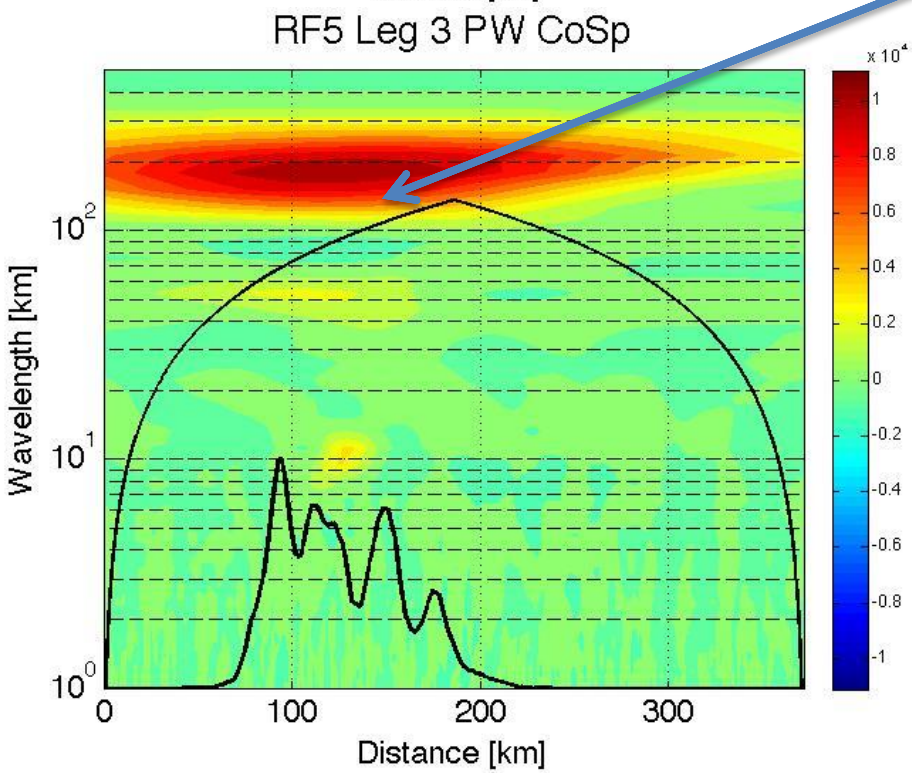


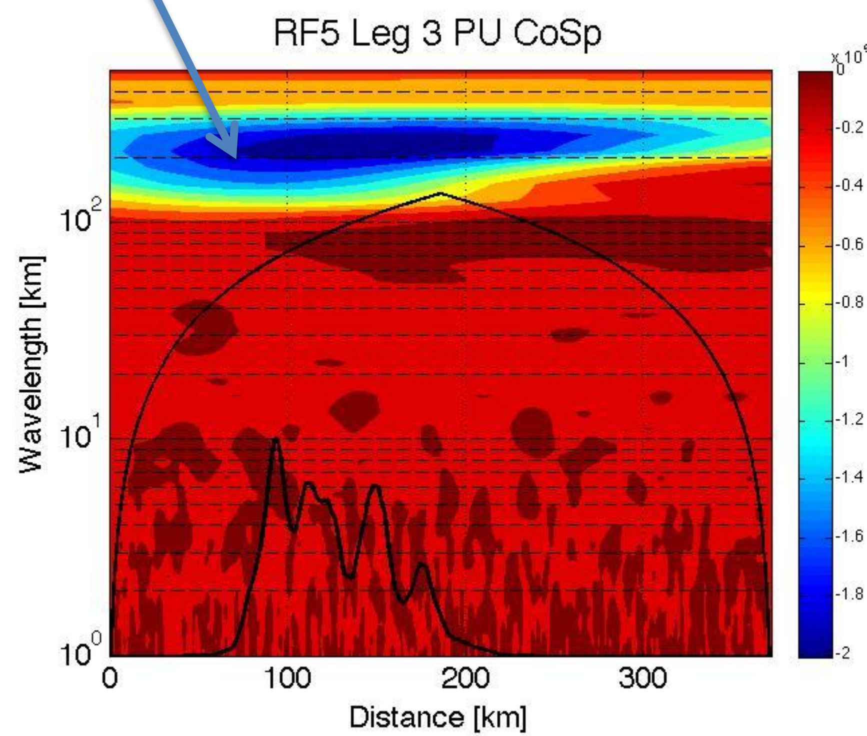
Pcorr vs. Pgeos Slope
New Zealand
Units: Pa/m
y = 0.8647x
R^2 = 0.7838
0.0015
0.001
0.0005
0
-0.0005
-0.001
-0.0015
-0.002
-0.002
-0.0015
-0.001
-0.0005
0
0.0005
0.001
0.0015

Wavelet Analysis of RF05; Leg 3 @z=12.2km

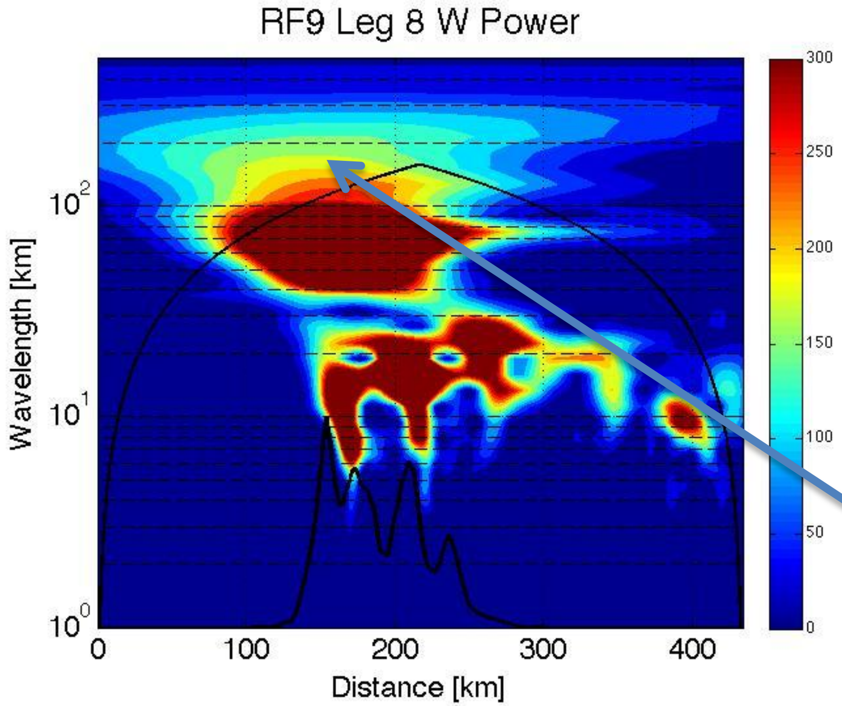


Flux-carrying Waves

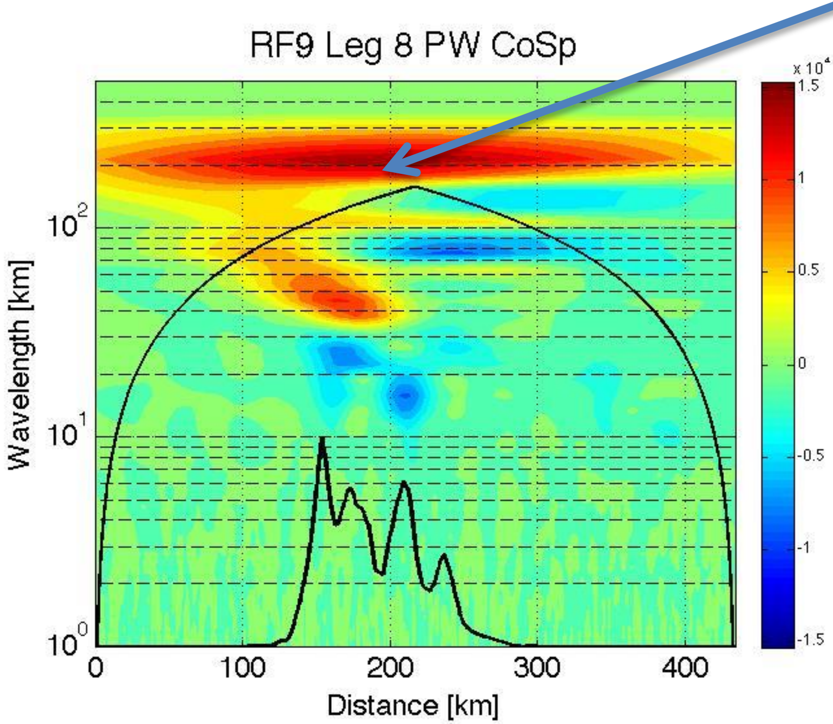


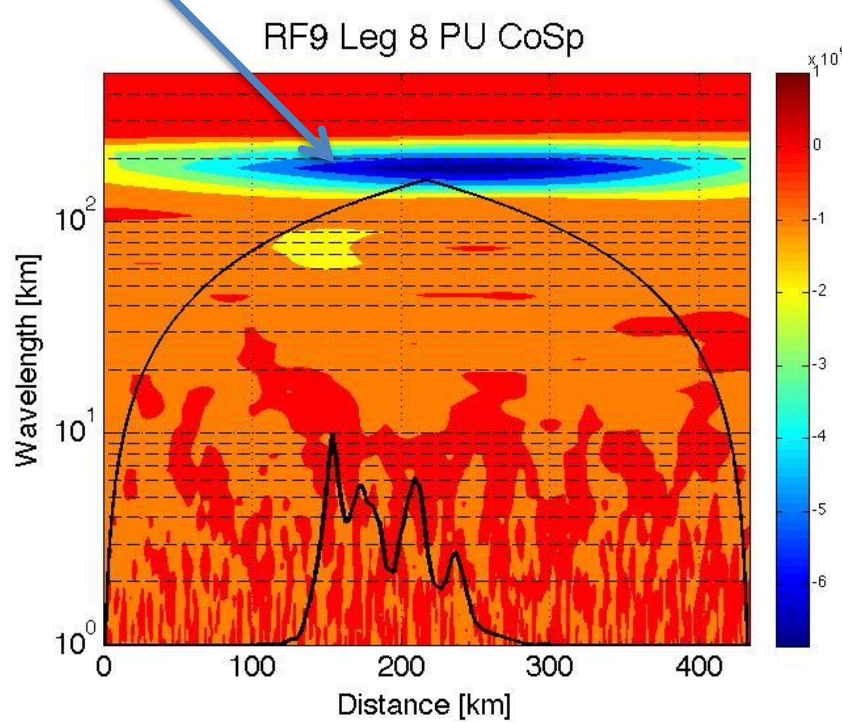


Wavelet Analysis of RF09; Leg 8 @z=12.2km

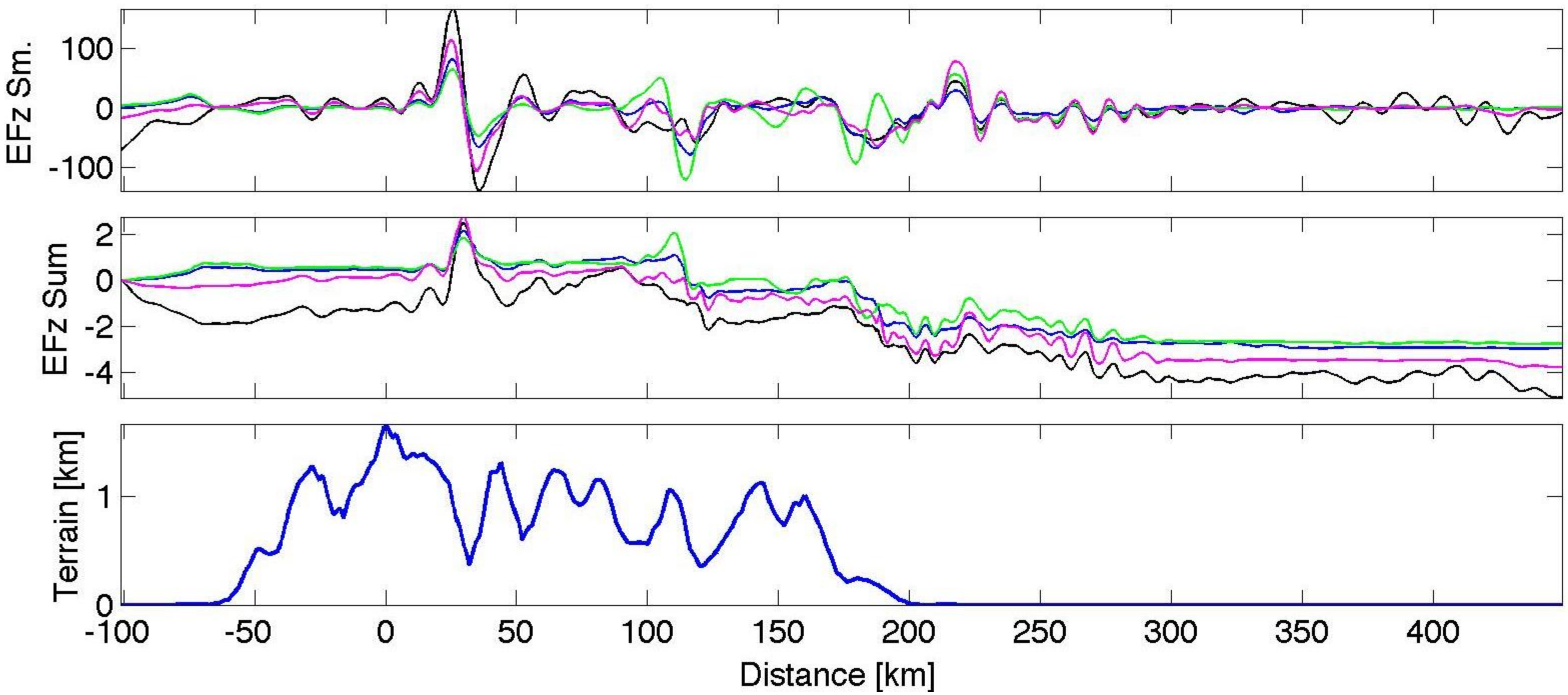


Flux-carrying Waves





RF16 Leg 4: EFz ~-4W/m2



Results of pressure redundancy test (PSX->PSA)

- Reduces EFz by 23%
- Degrades EP-check slightly
- Maintains qualitative checks
  - EFhor direction
  - Ranking flights by energy flux
- PSX is probably better than PSA