May 2015 Deepwave Workshop at NCAR

Deepwave GV aircraft gravity wave statistics

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Support from the National Science Foundation

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)

NSF/NCAR Gulfstream V Research Aircraft

What’s new in Deepwave?

- Extensive lower stratosphere surveys over land and sea
- Longer legs than T-REX
- Redundant instruments
- Improved DGPS altitude
- Focus on momentum flux and horizontal and vertical energy fluxes using static pressure (corrected for geostrophic pressure gradient)
- Extensive use of wavelet analysis
- **Coincident high-altitude GW survey with remote sensing up to 90km**

Outline

- Flux Measurements: methods, redundancy and uncertainty
- Comparing land and sea
- Wave scale analysis
  - Wavelet analysis
  - High/Low Pass filters
- Wave breaking
- Rapid flux fluctuations
- Comparison with previous projects

Redundant measurements

- Pressure
  - PSXF and PS_A
- Vertical velocity
  - WIC and WI_GP
- Horizontal velocity
  - UIC, VIC and UI_GP, VI_GP
- GPS altitude
  - GGALT (OmniStar) and DGPS (ground station)

Table 2: Redundant variables from the GV in Deepwave

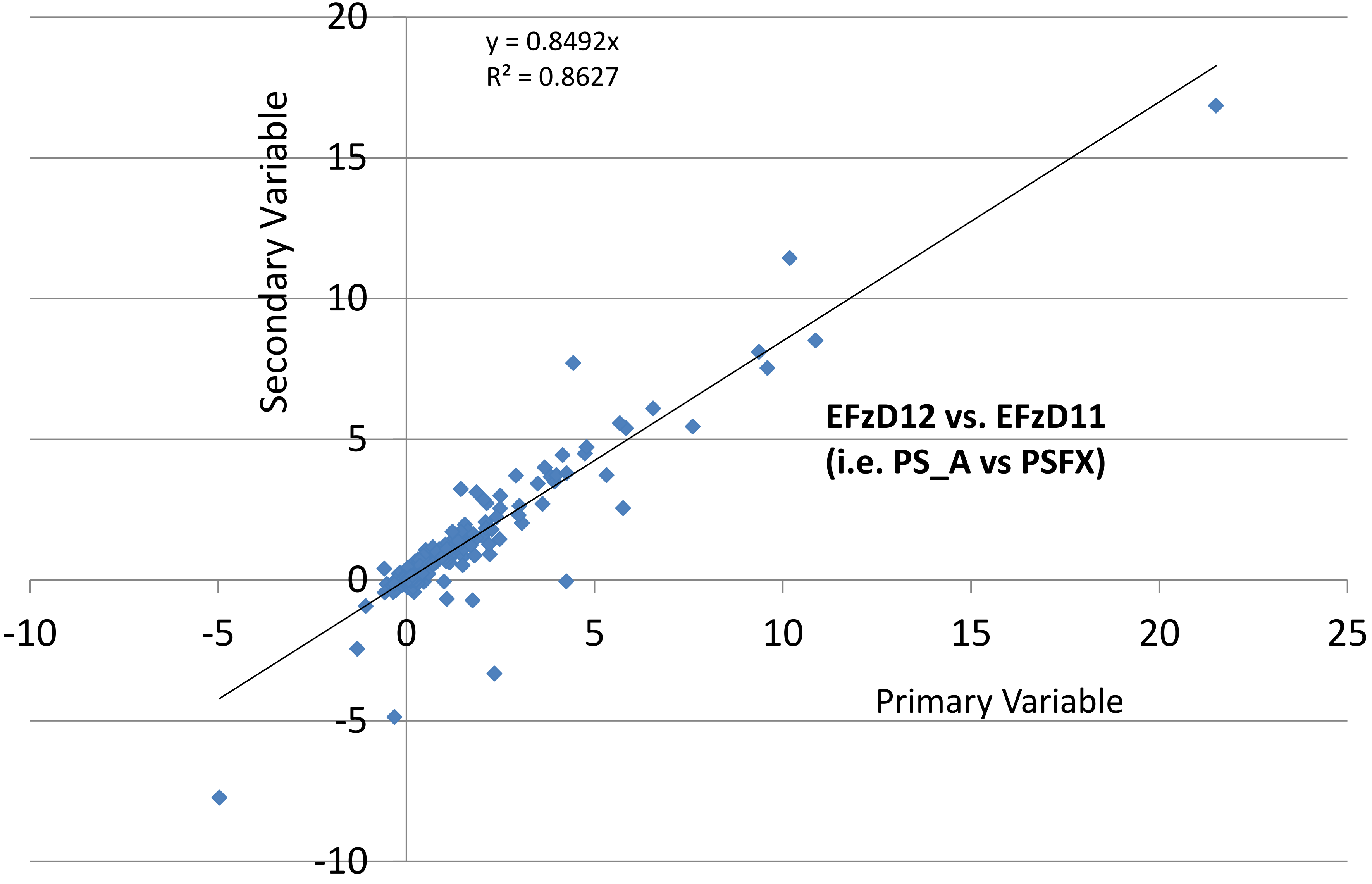
Physical Quantity	Variable 1	Variable 2	CC [slope] (Mtn only)	CC (Ocean only)	Flights with Variable 2
Static pressure	PSXF	PS_A	0.7 [0.6]	0.7	all
Vertical wind	WIC	WI_GP	0.95 [0.95]	0.85	most
Horizontal wind; eastward	UIC	U_GP	0.97 [0.95]	0.9	most
Horizontal wind; northward	VIC	VI_GP	0.97 [1.0]	0.9	most
Air temperature	ATX	ATHR1	0.995 [1.00]	0.98	all
Geometric altitude	GGALT	GGALT_DGPS	0.993 [1.0]	0.997	few

Momentum and Energy Flux calculations

The fluxes are computed from

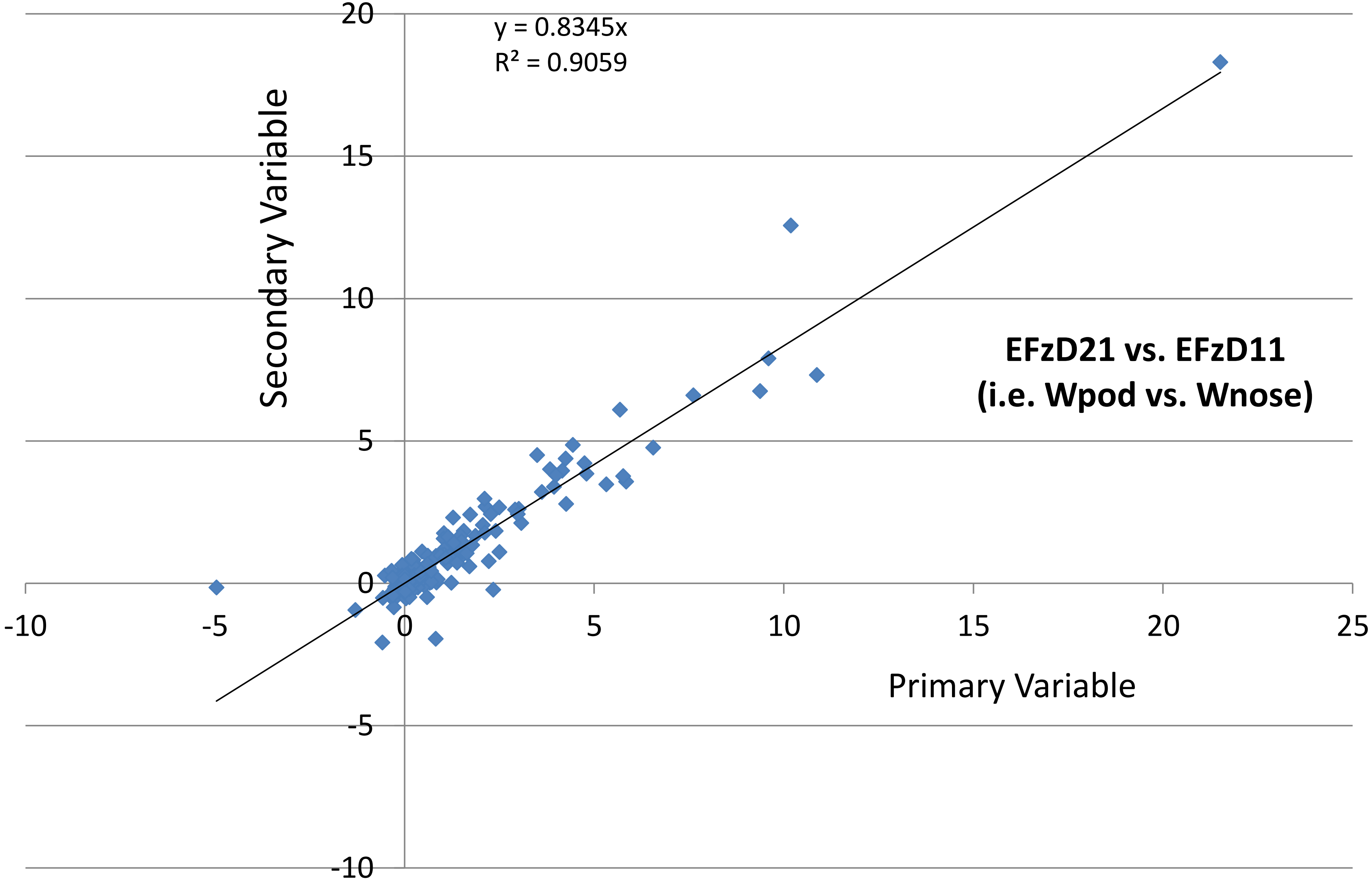
- $MFx = \bar{\rho} < u'w' >$
- $MFy = \bar{\rho} < v'w' >$
- $EFz =< P_{cg} \; w' >$
- $EFx =< P_{cg} \; u' >$
- $EFy =< P_{cg} \; v' >$
- *EFzM = -(U*MFx+V*MFy) [momentum flux scalar]*

EFz: Change pressure sensor (all data)



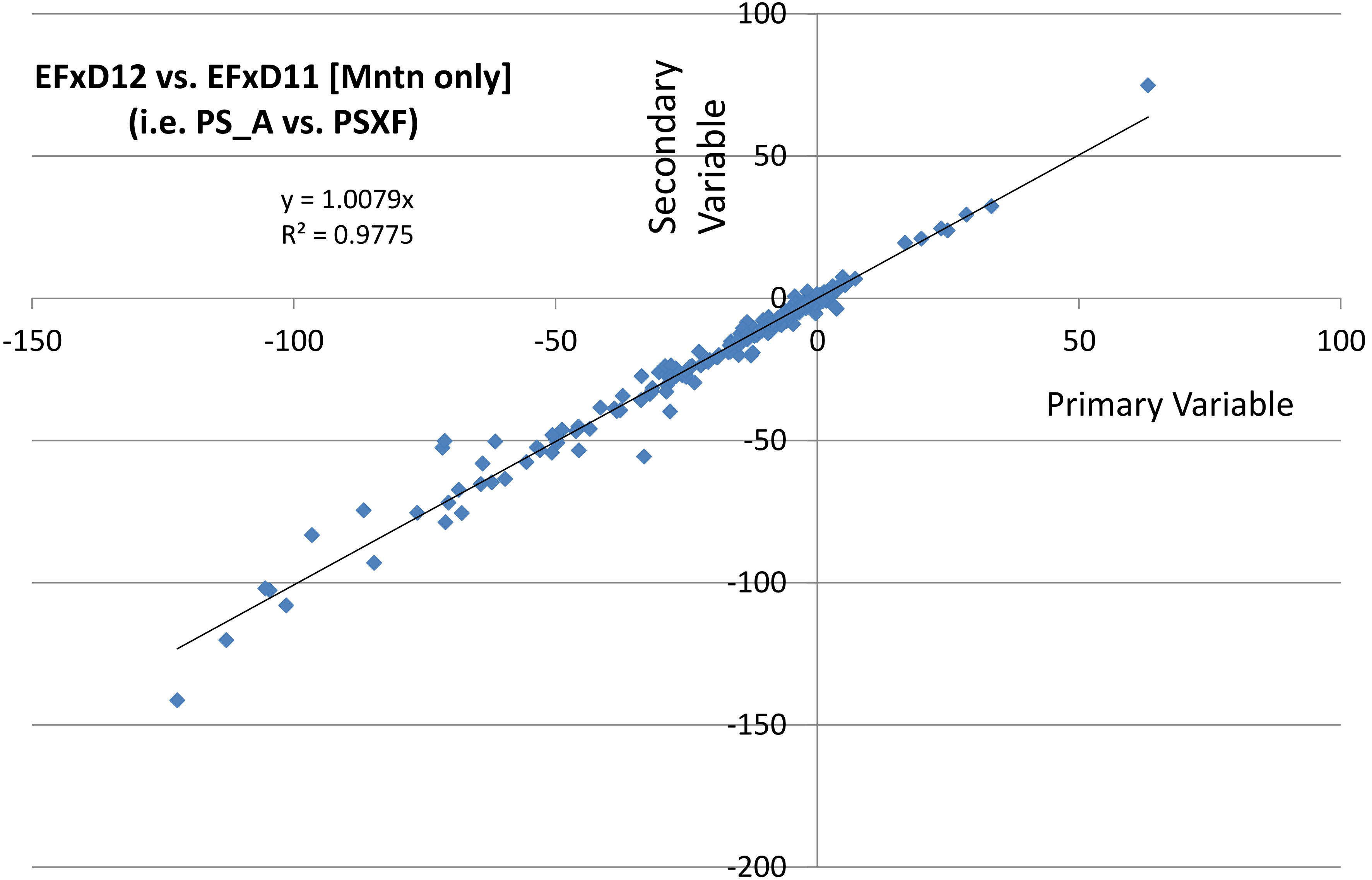
EFzD12 vs. EFzD11
(i.e. PS_A vs PSFX)

EFz: Change W sensor (all data)

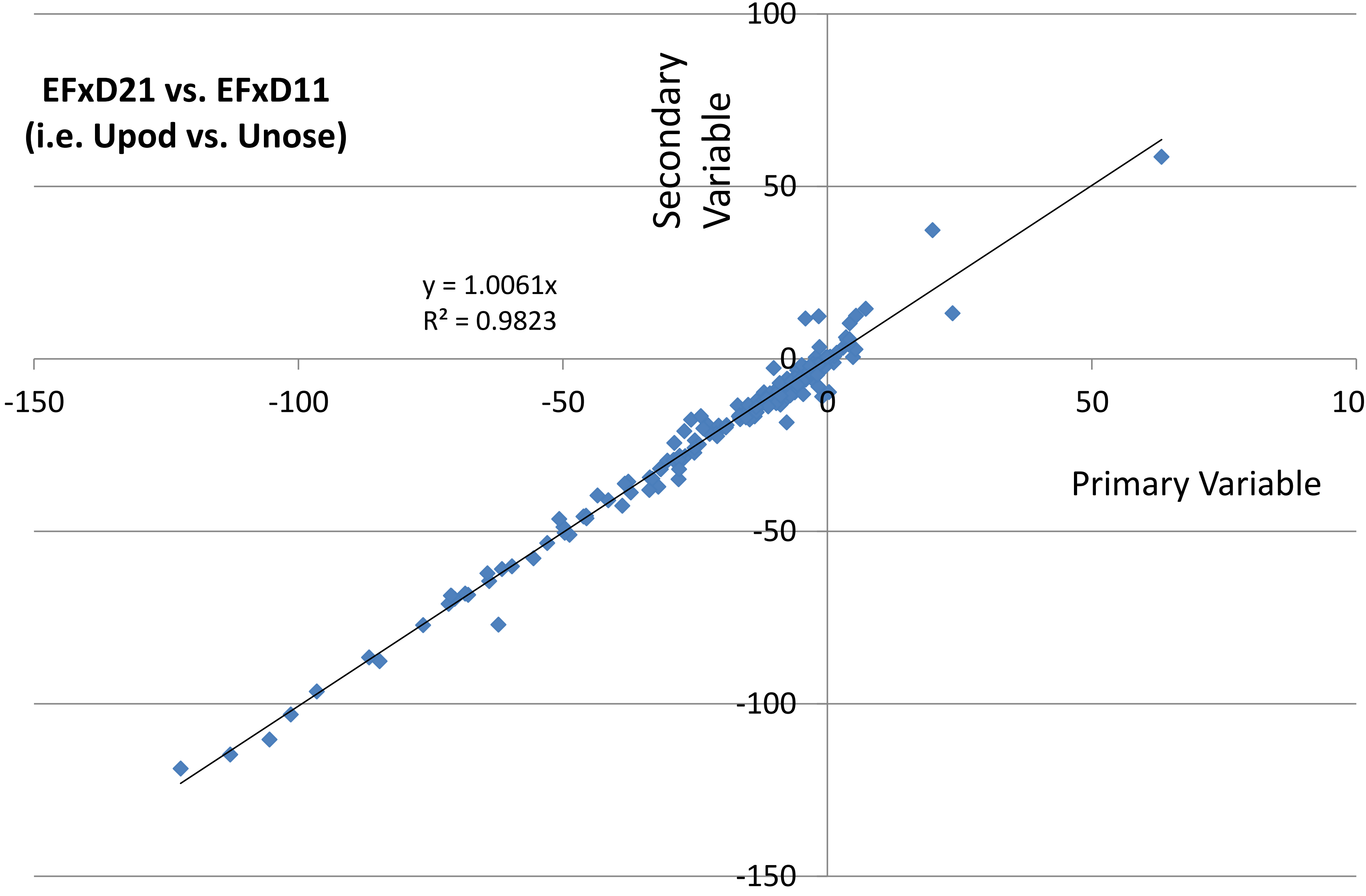


EFzD21 vs. EFzD11
(i.e. Wpod vs. Wnose)

EFx: Change pressure sensor

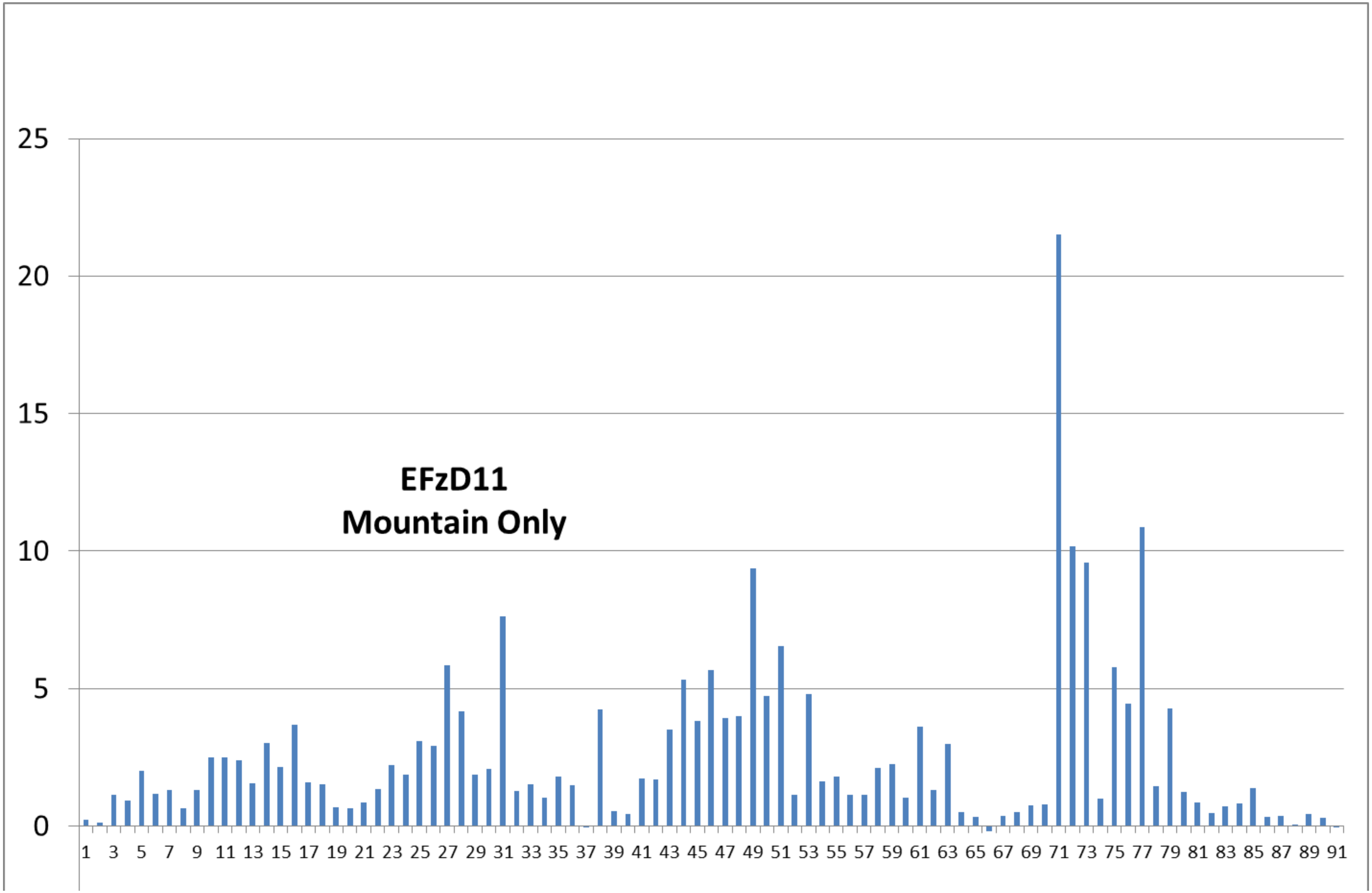


EFx: Change U,V sensor

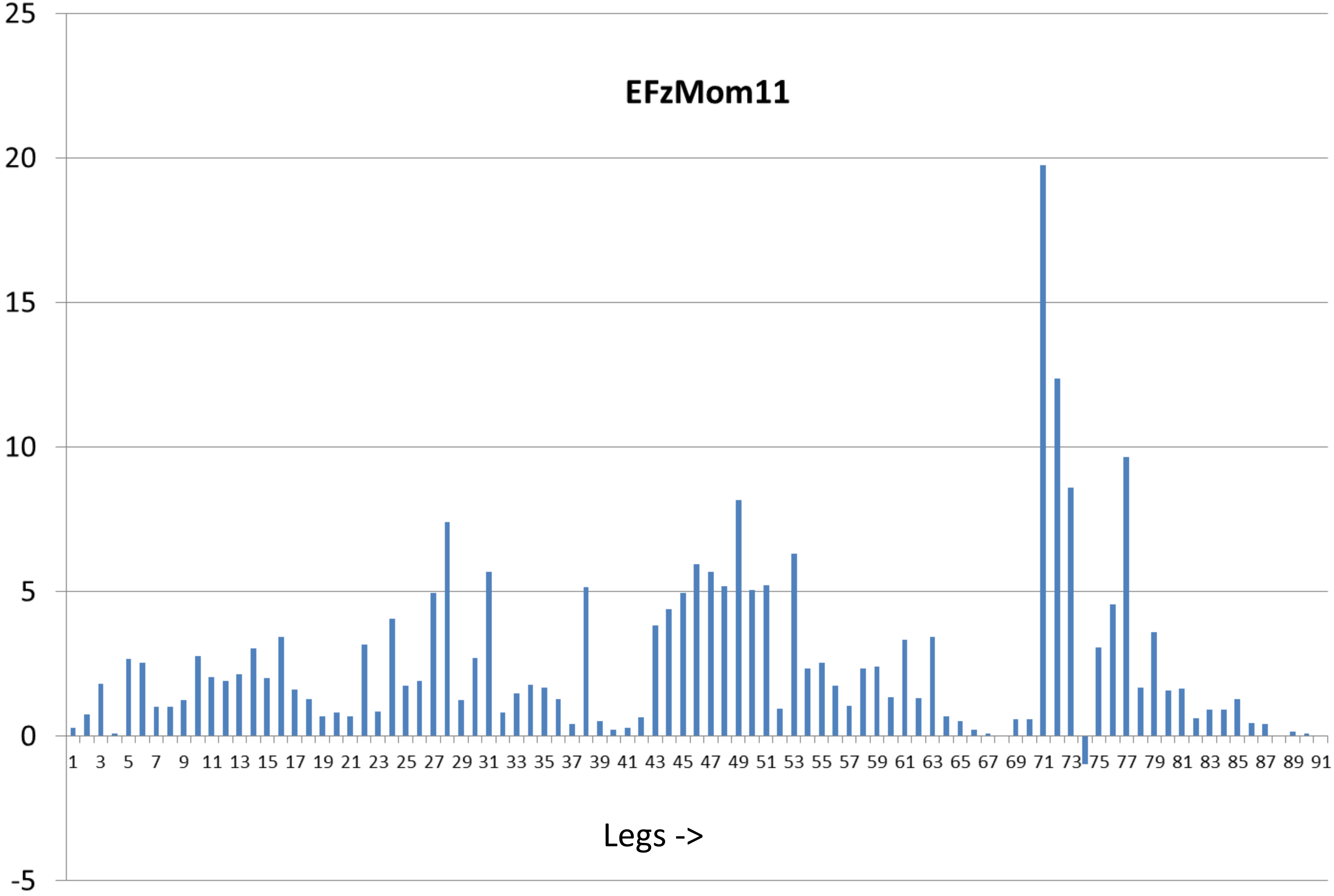


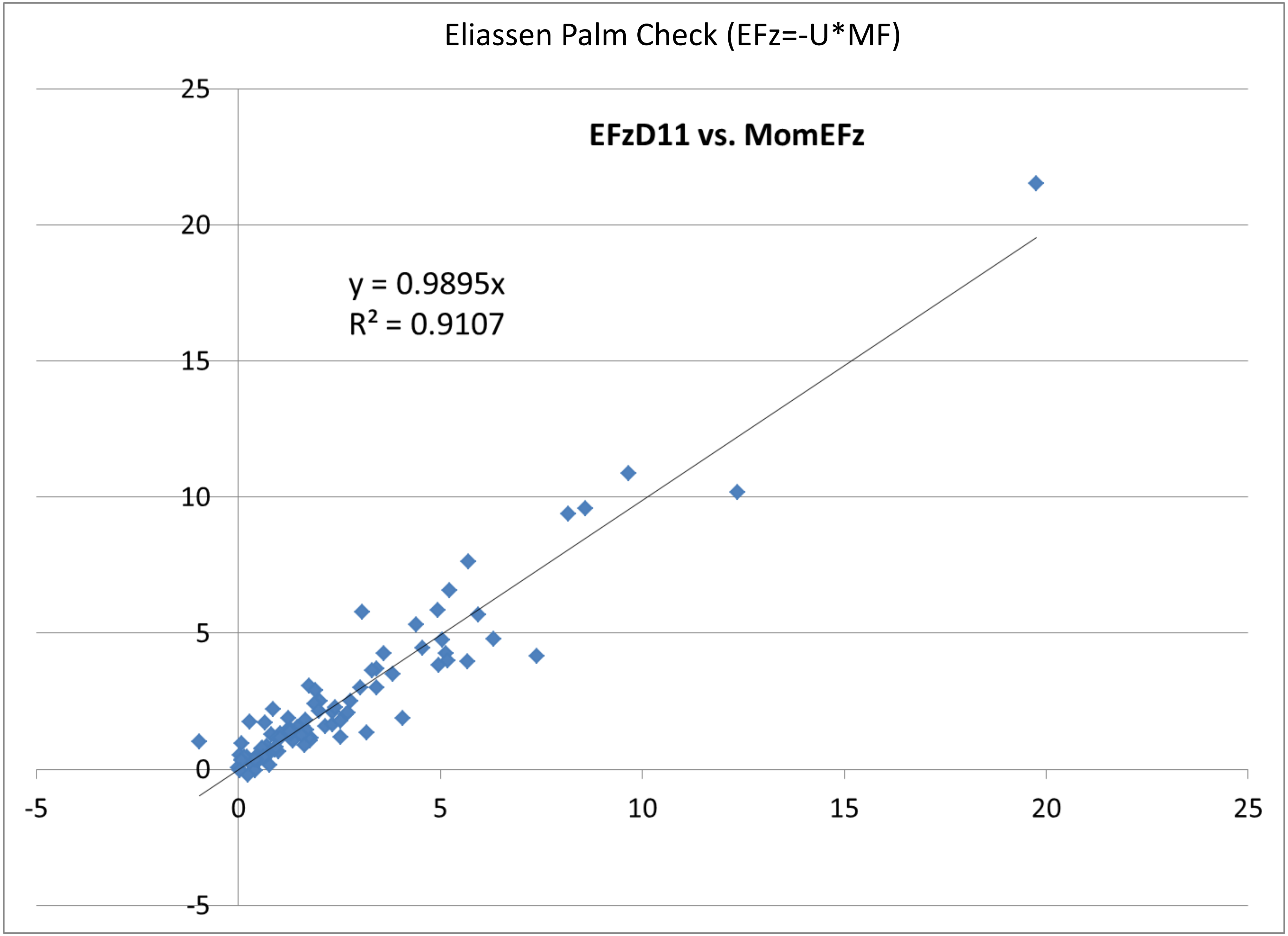
EFxD21 vs. EFxD11
(i.e. Upod vs. Unose)

Vertical Energy Flux (W/m2)

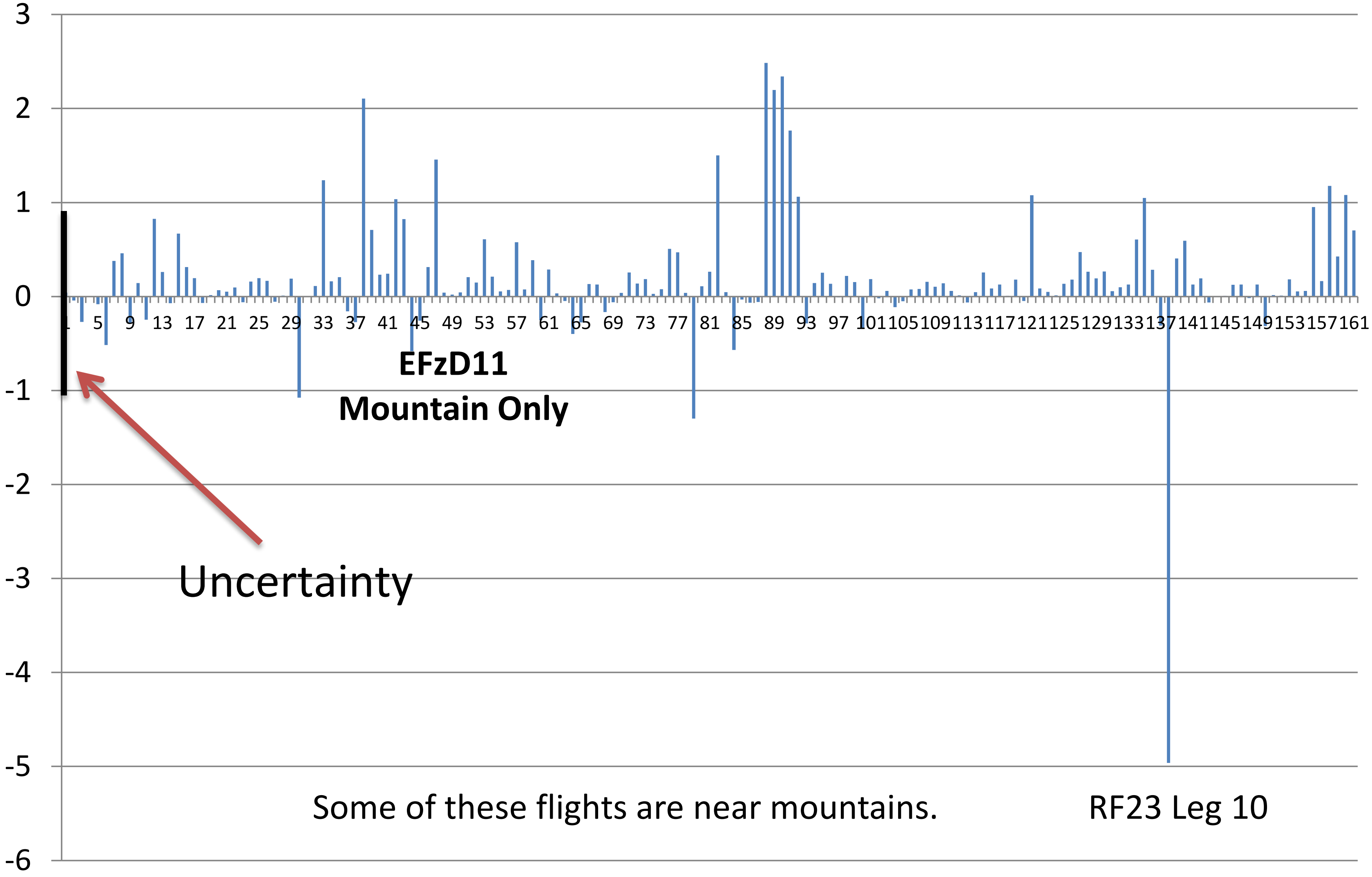


Momentum Flux (EFzMom=-U*MF; W/m2))




Eliassen Palm Check (EFz=-U*MF)
EFzD11 vs. MomEFz
y = 0.9895x
R² = 0.9107
25
20
15
10
5
0
-5
-5
0
5
10
15
20
25

Vertical energy flux (EFz): ocean only



EFzD11

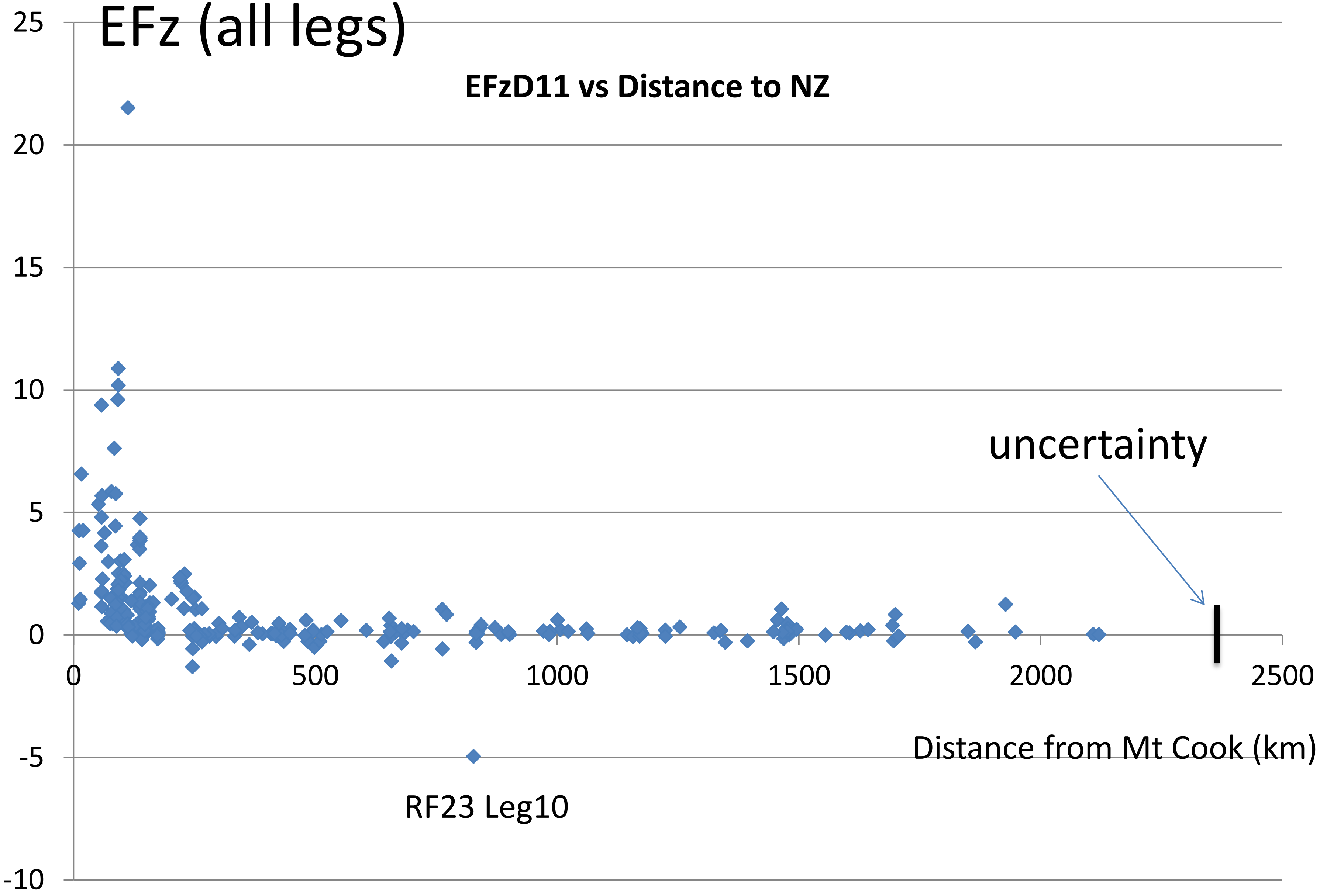
Mountain Only

Uncertainty

Some of these flights are near mountains.

RF23 Leg 10

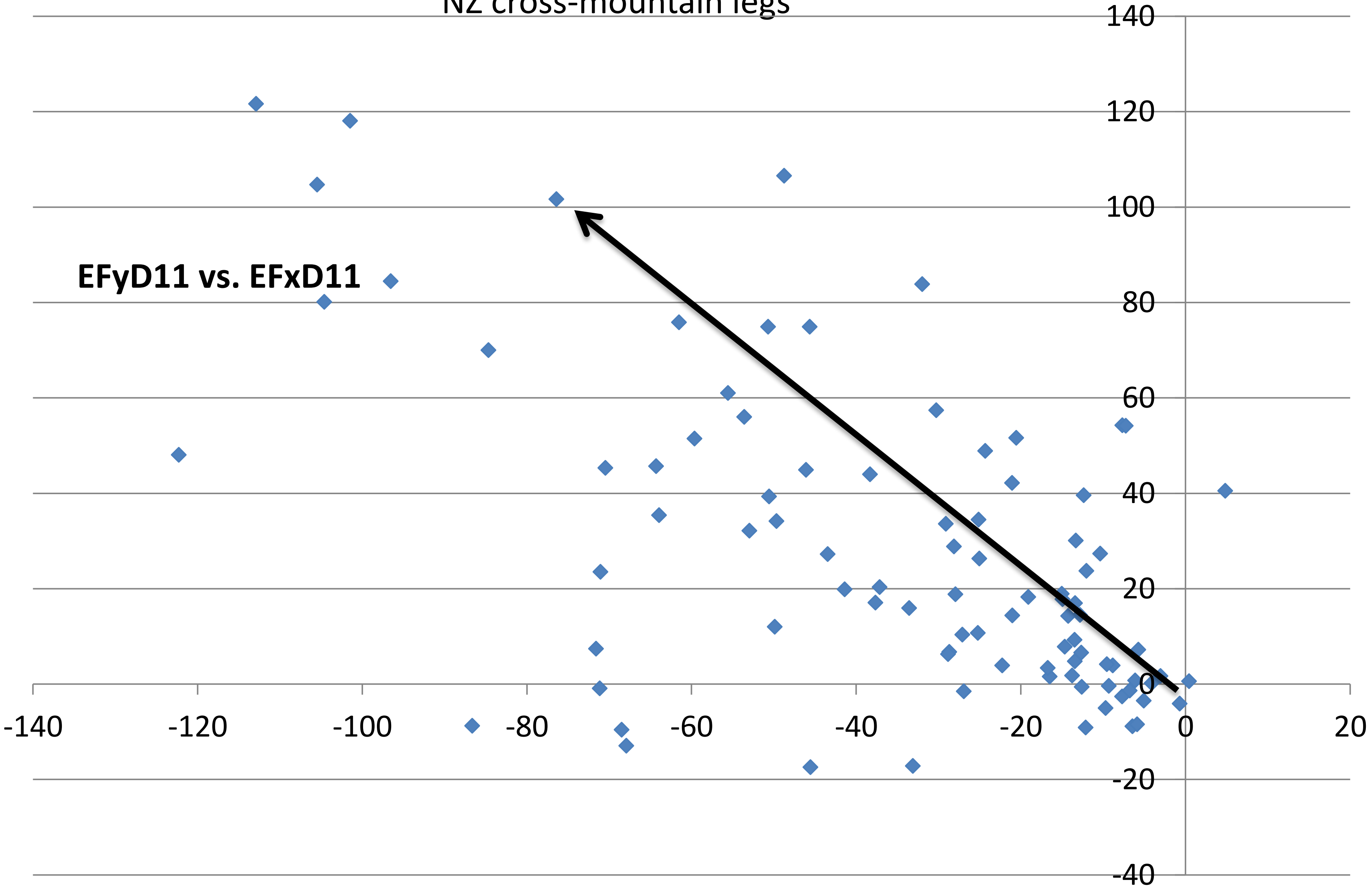
EFz (all legs)



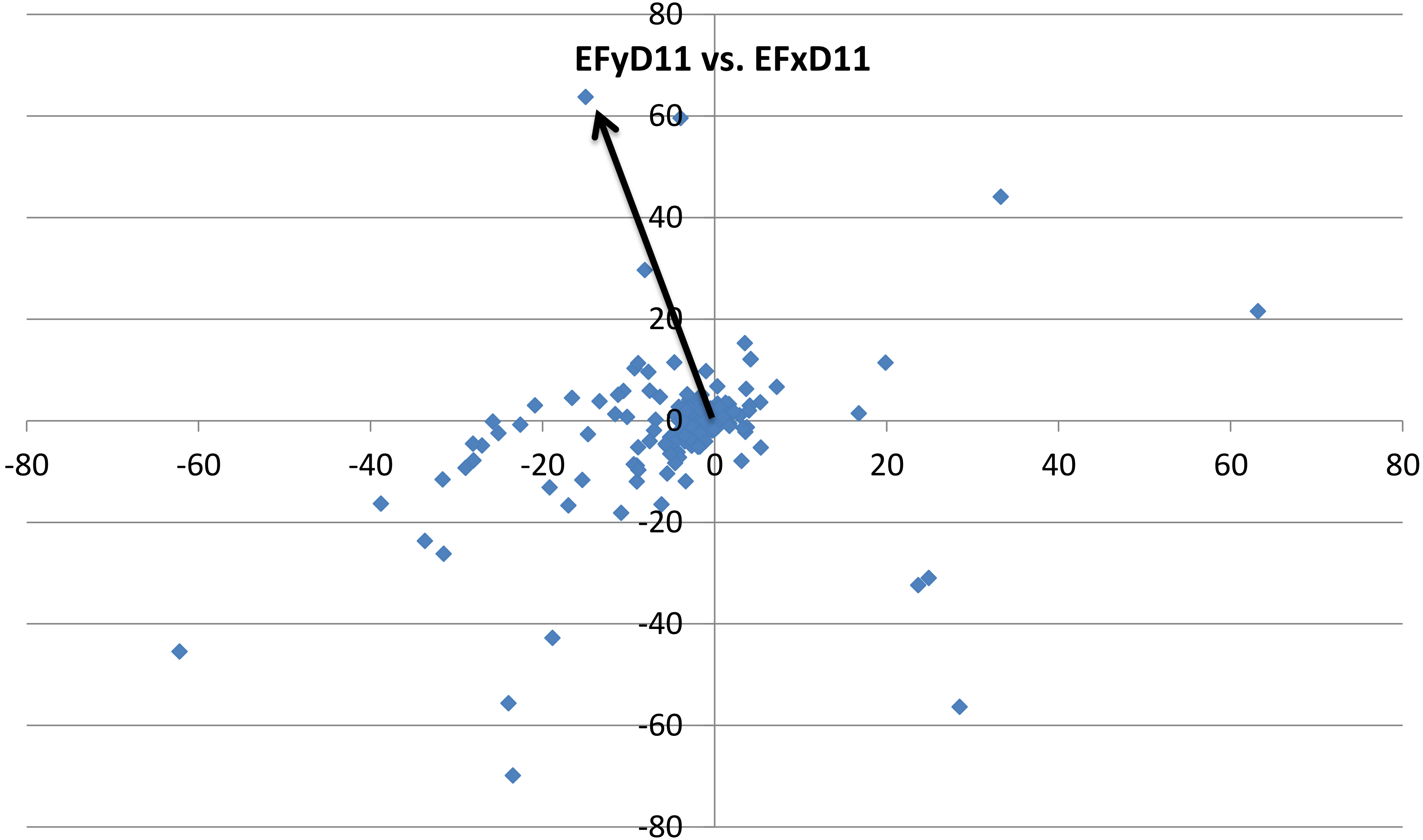
uncertainty

RF23 Leg10

Horizontal Energy Flux Vectors
NZ cross-mountain legs



Horizontal Energy Flux Vectors
Ocean and other non-NZ legs



Conclusions: Comparing Land vs Sea

- Over sea
  - Small fluxes (EFz<1W/m2); close to detection limit
  - Random horizontal EF directions
- Over New Zealand
  - Positive EFz (Max=22W/m2 in RF16)
  - Negative MFx
  - Upwind horizontal EF

Scale Analysis: Definitions “LIST”

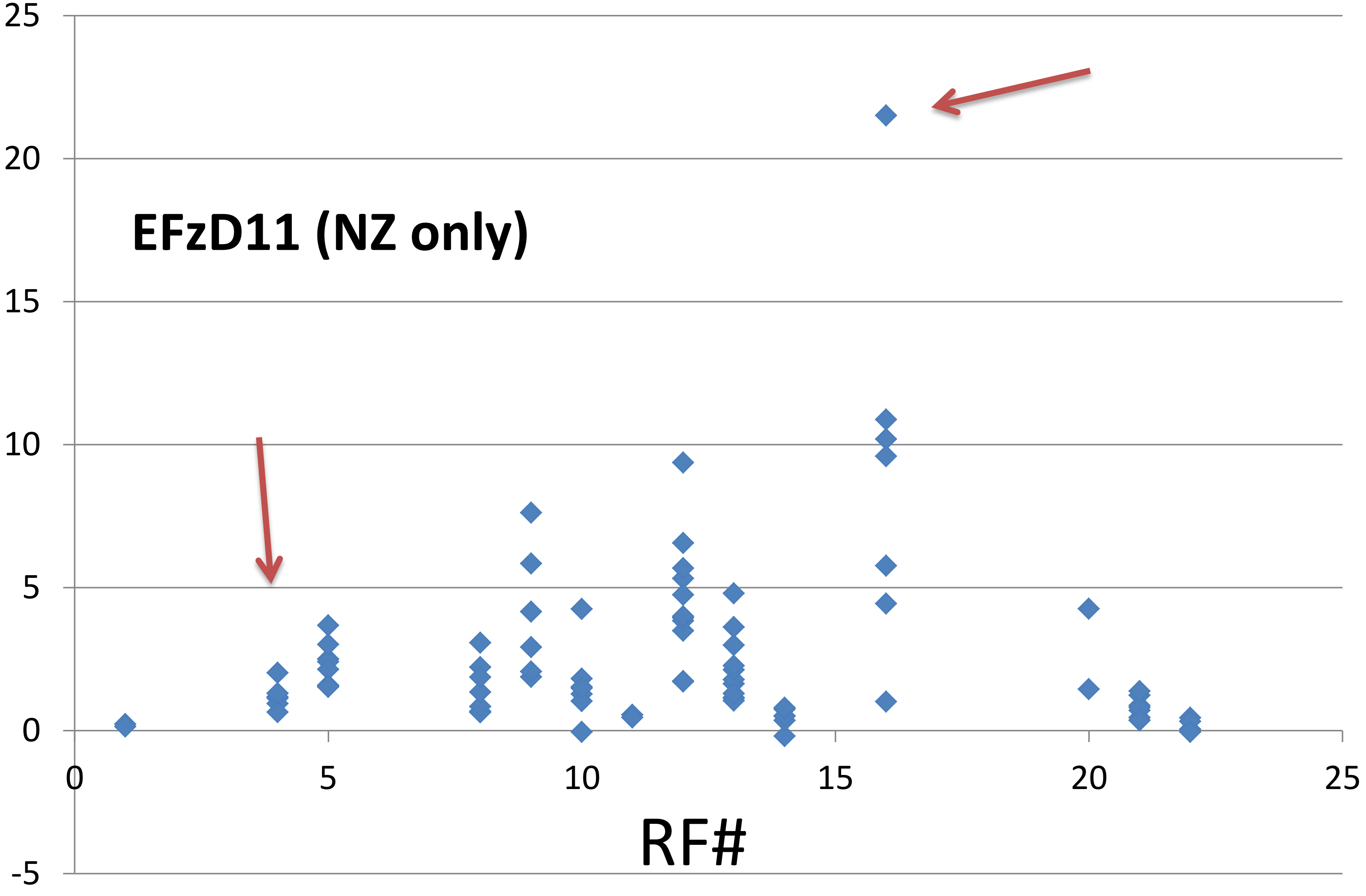
Long waves (60 to 250km)

Intermediate waves (20 to 60km)

Short waves (8 to 20km)

Turbulence with scales below 2 km

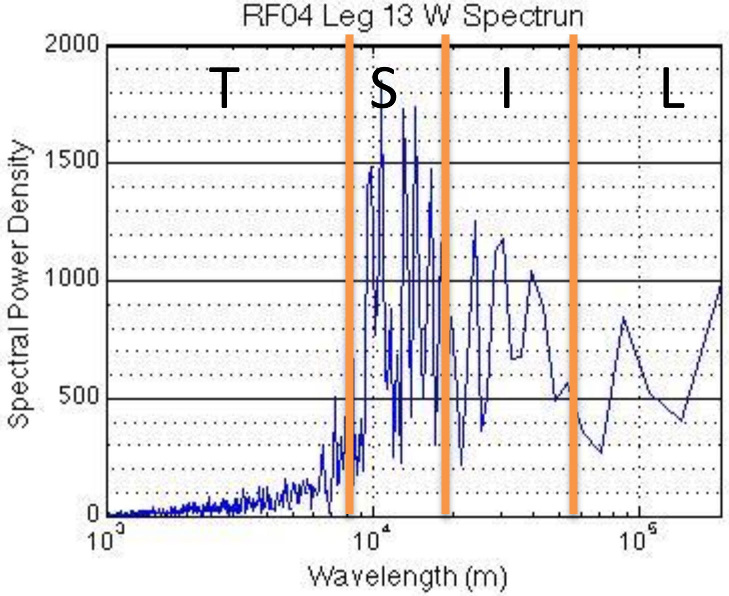
Vertical Energy Flux



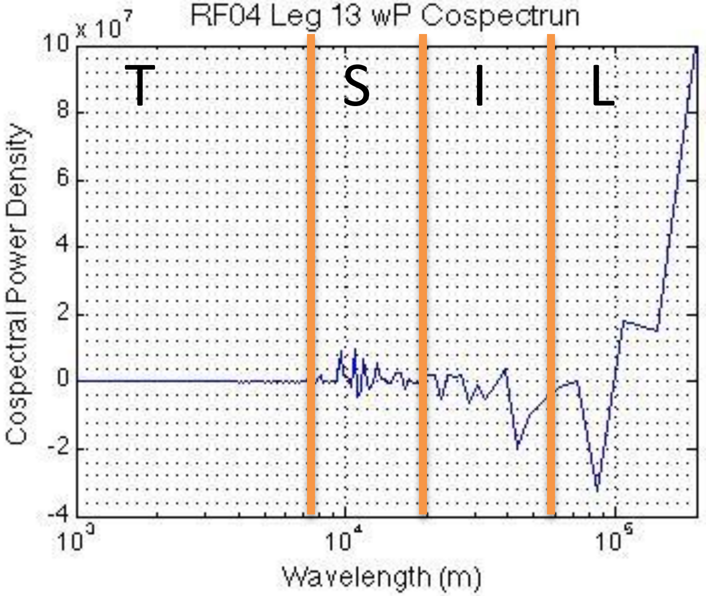
EFzD11 (NZ only)

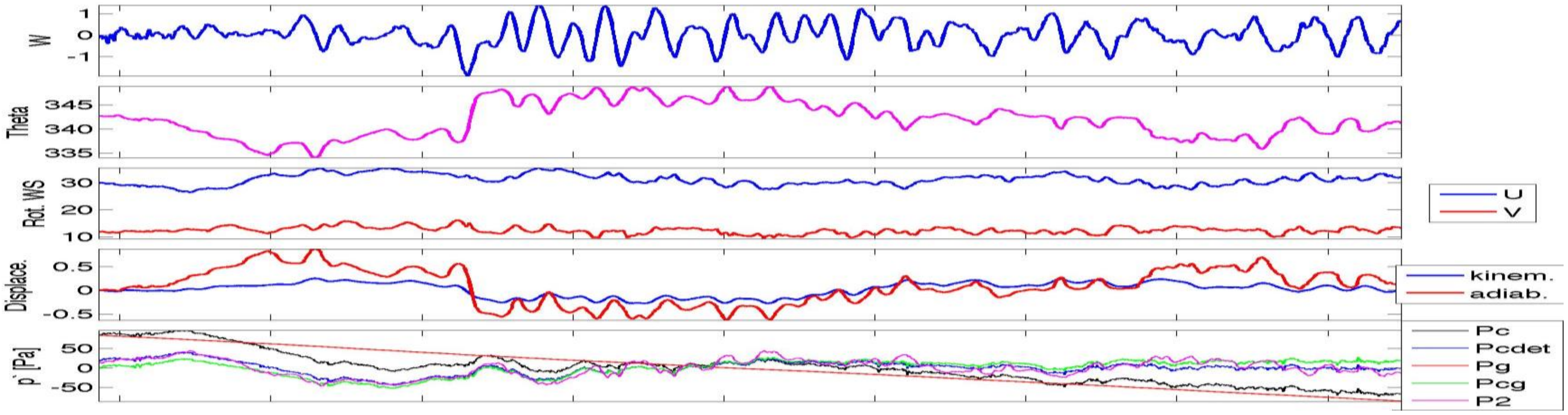
RF04 Leg 13

W-power

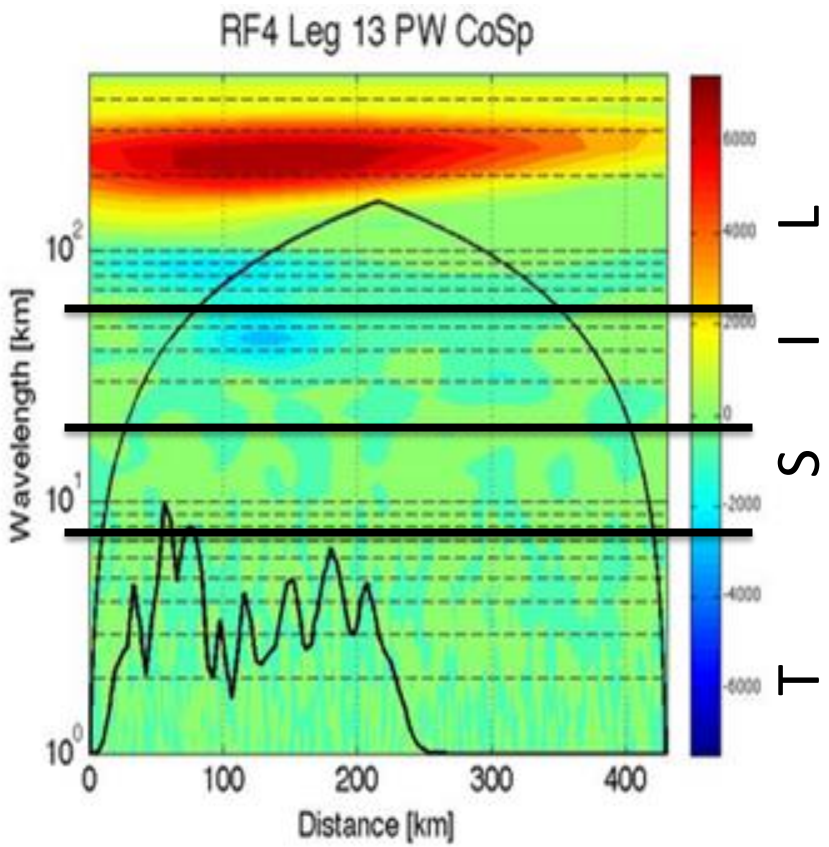


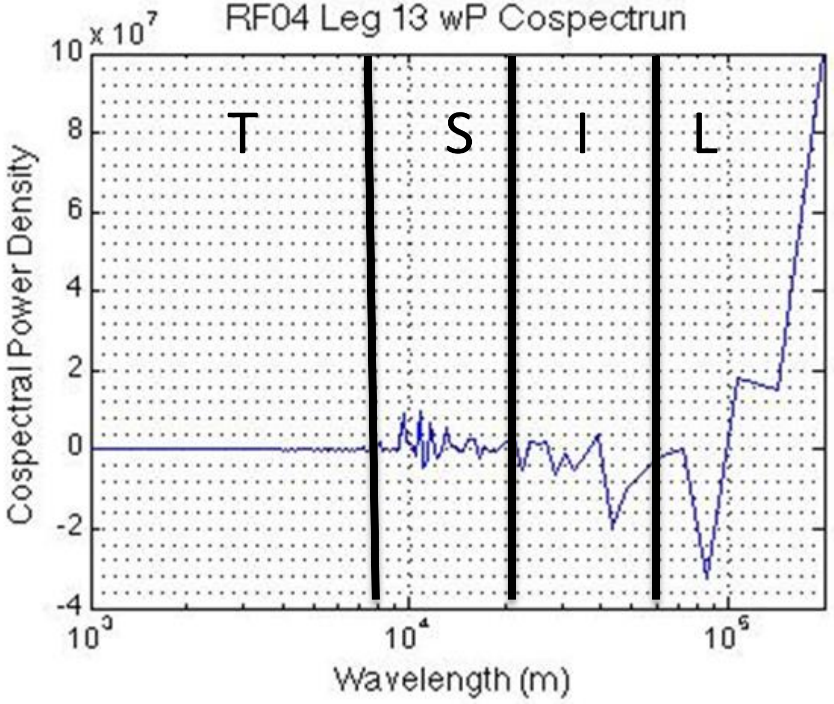
EFz=p'w'





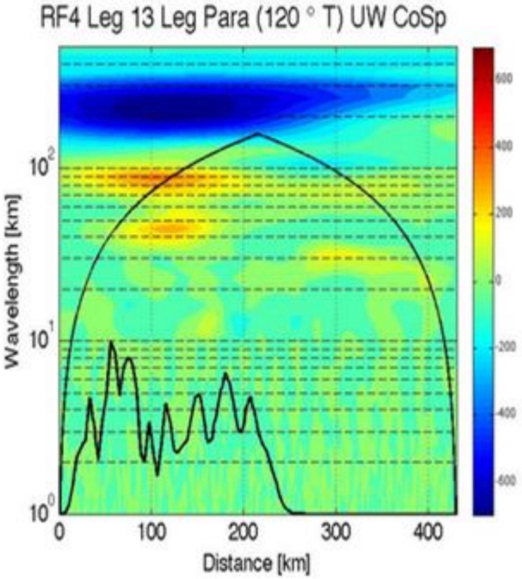
RF04 Leg 13

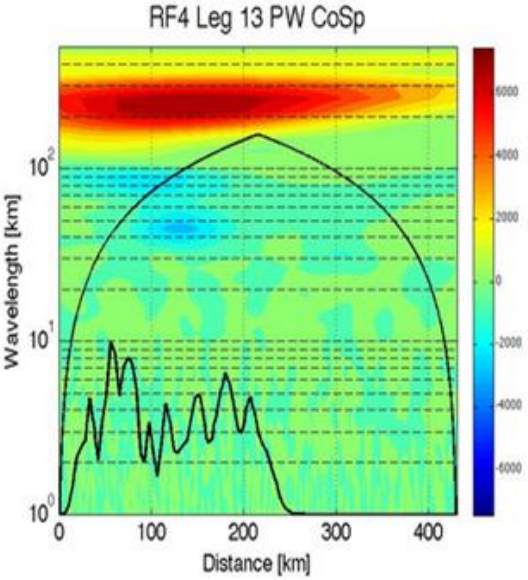


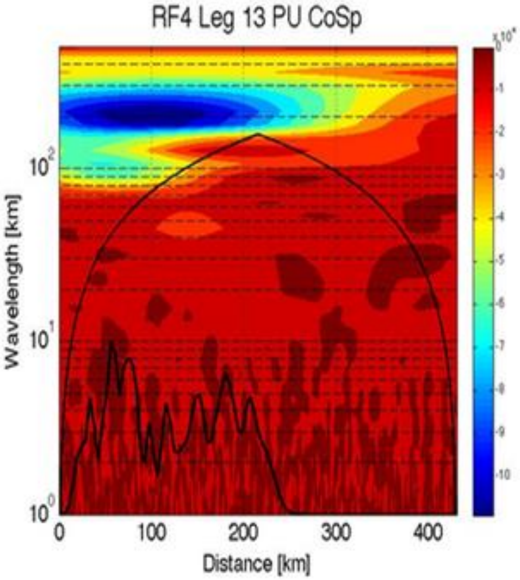


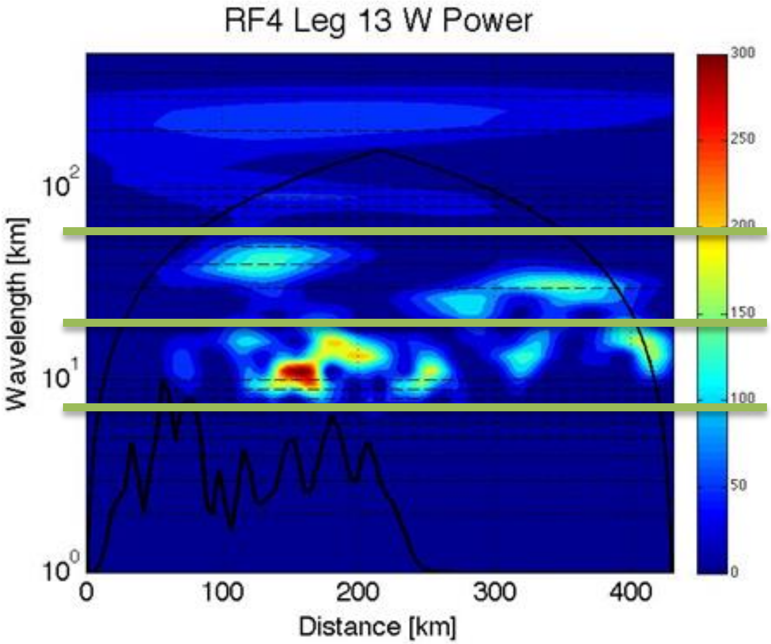
PW wavelets and spectrum

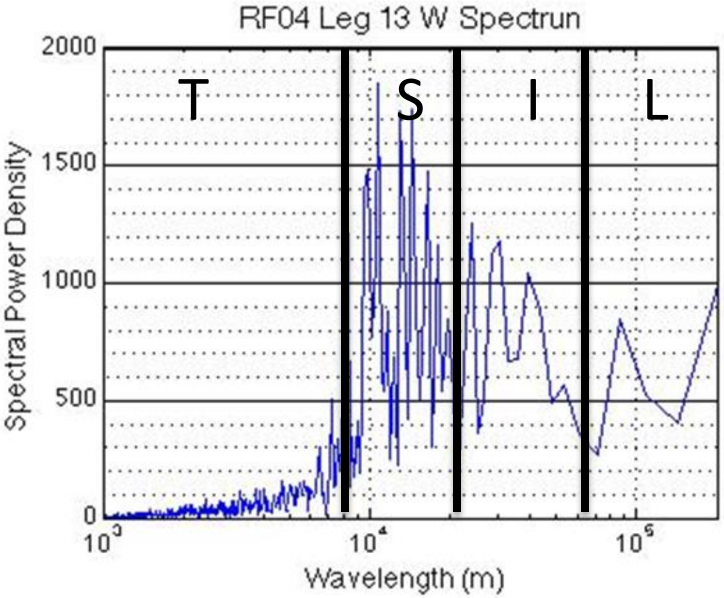
RF04 Leg 13

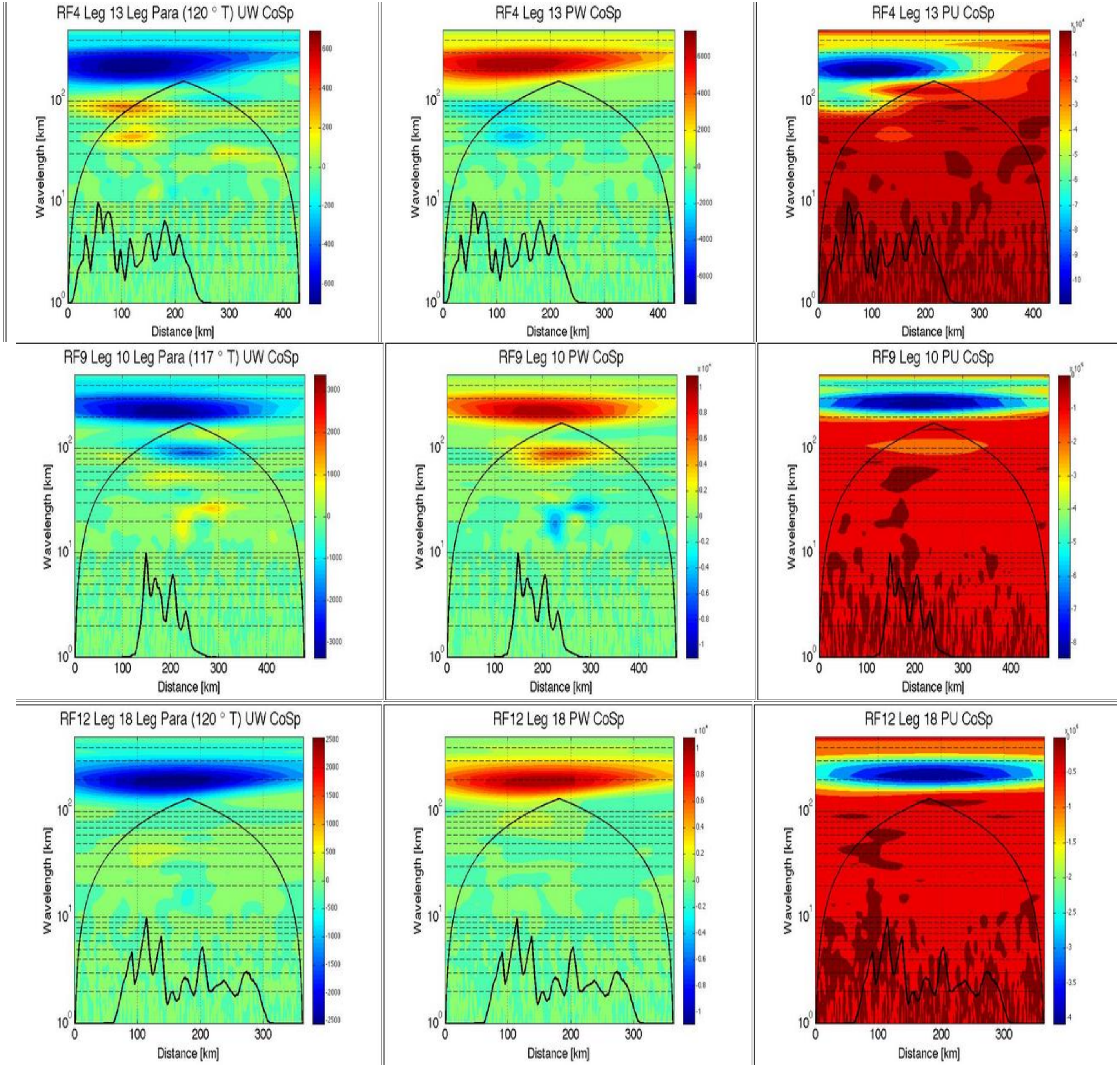

RF4 Leg 13 Leg Para (120 ° T) UW CoSp


RF4 Leg 13 PW CoSp


RF4 Leg 13 PU CoSp


RF4 Leg 13 W Power


RF04 Leg 13 W Spectrun



RF04
Leg 13

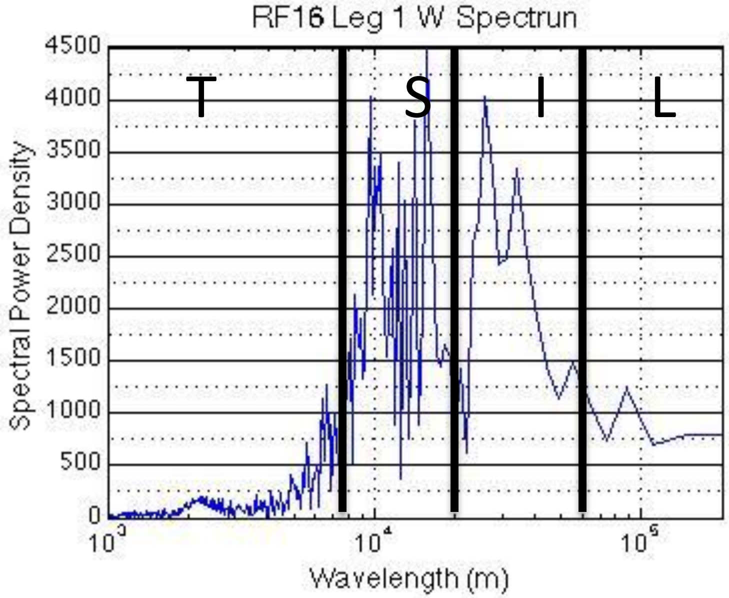
RF09
Leg 10

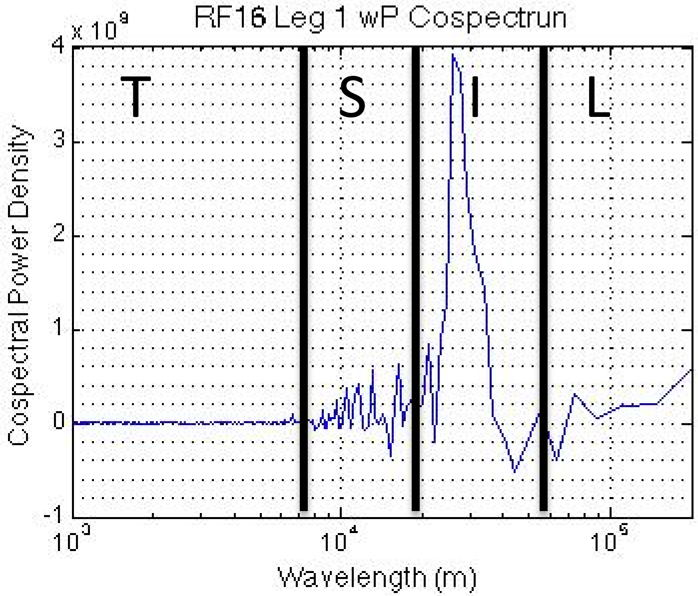
RF12
Leg 18

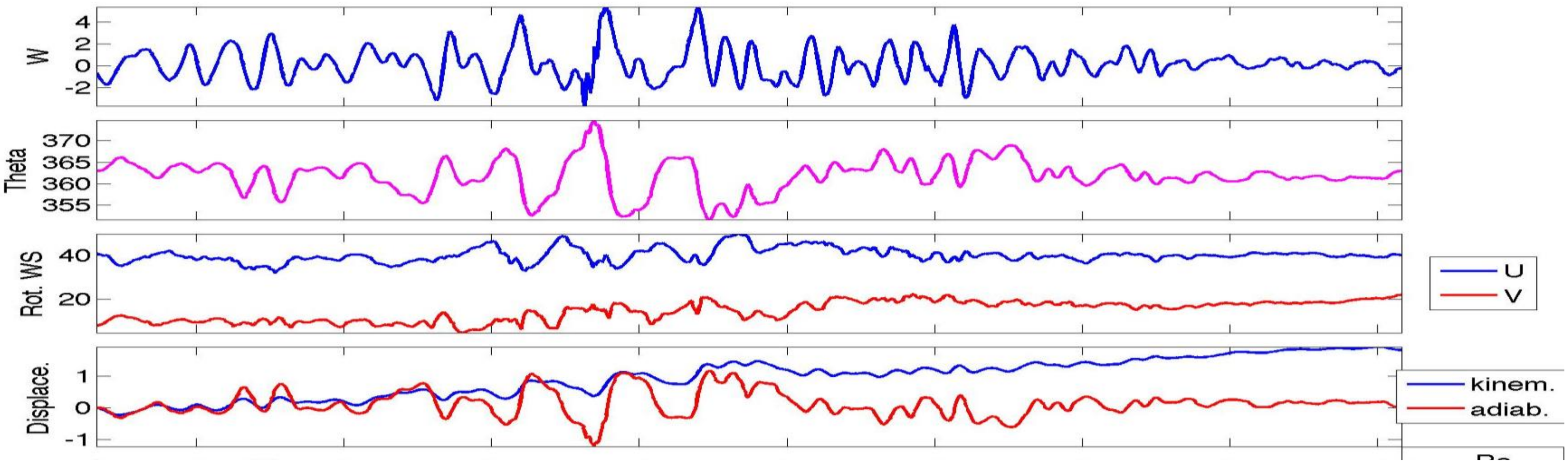
RF16 Leg 1 (extreme event)

W-power

EFz=p’w’

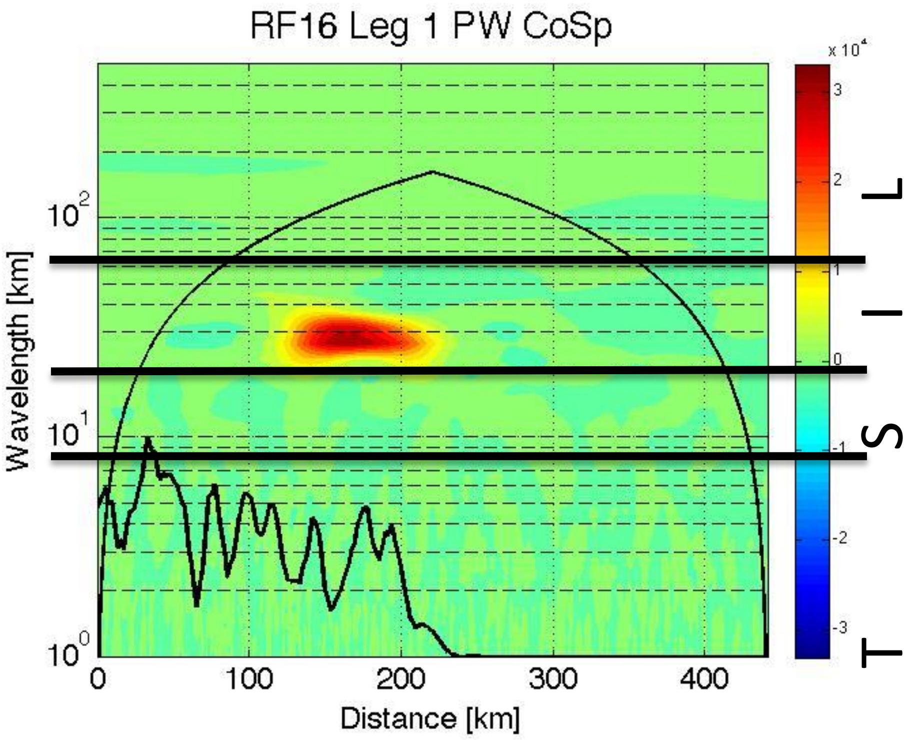




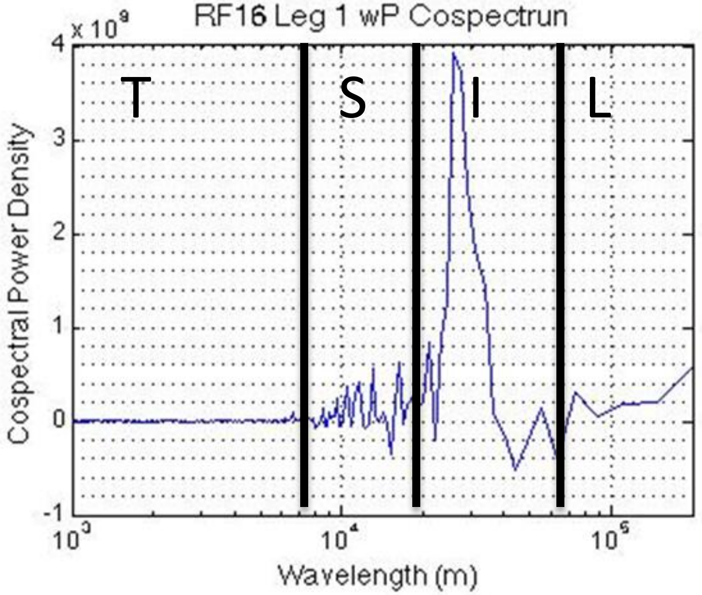


RF16 Leg 1 (extreme event)

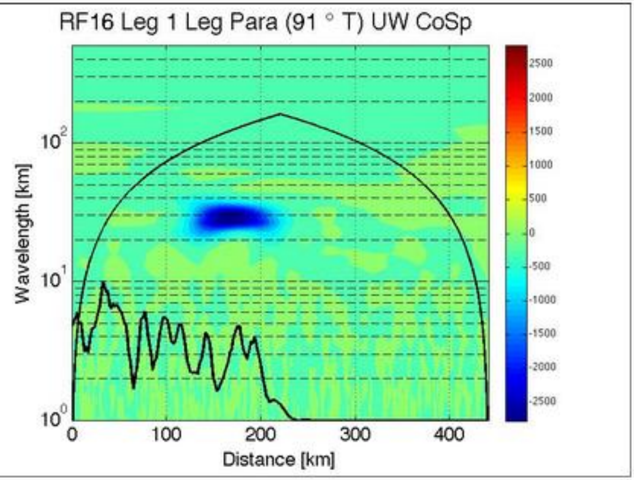
PW Wavelet

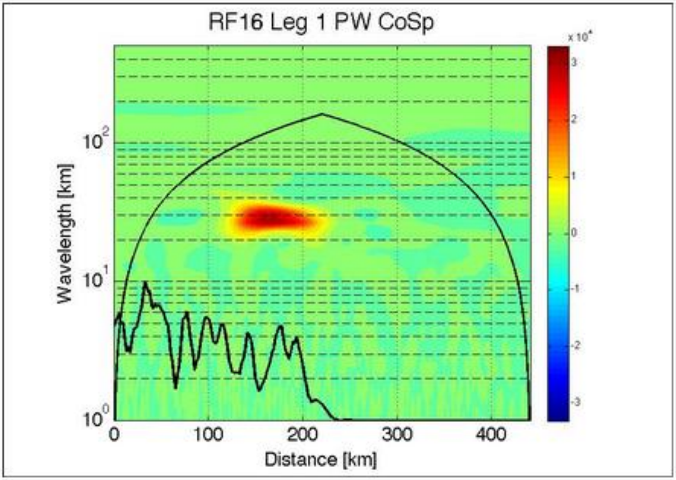


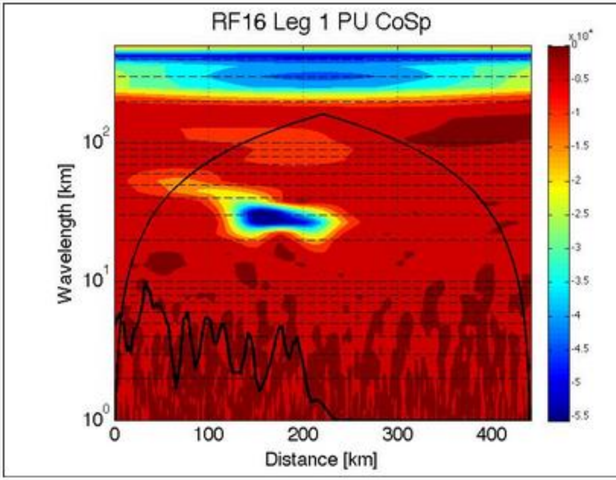
PW spectrum

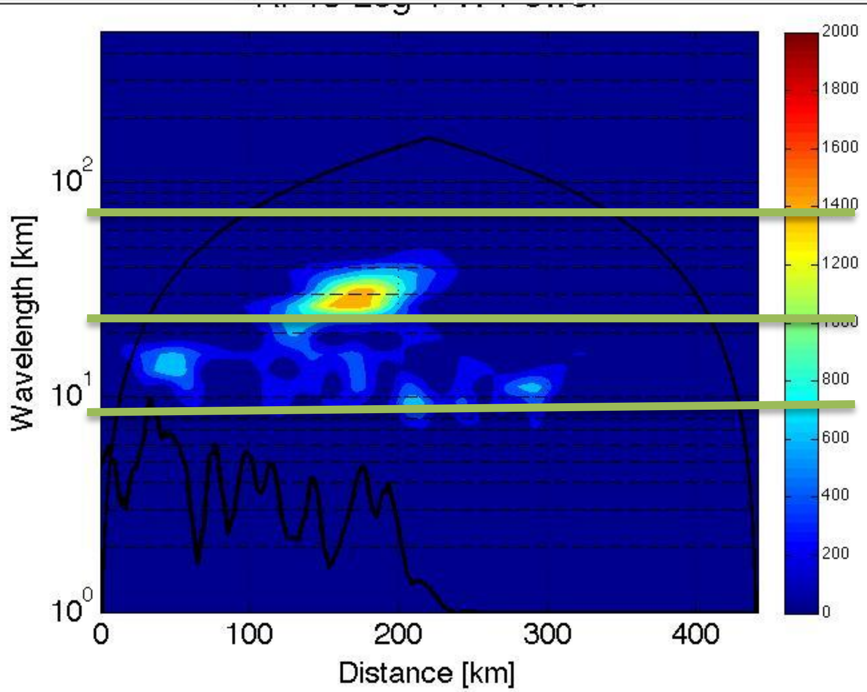


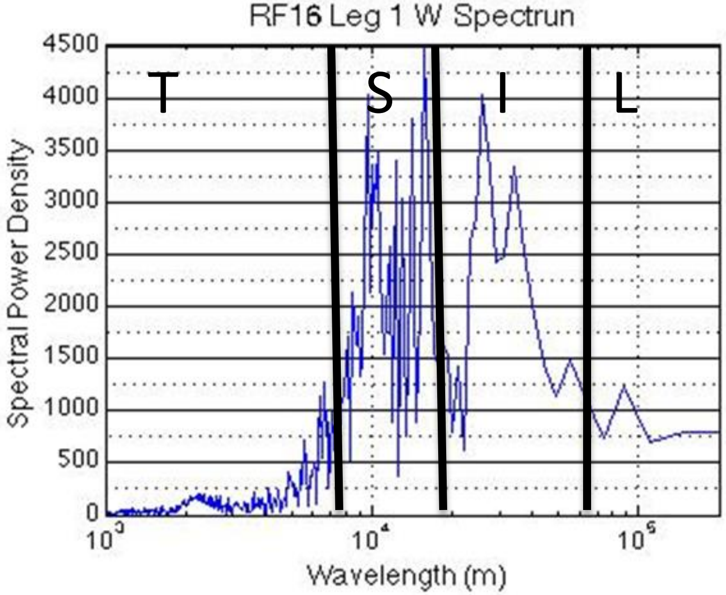
RF16 Leg 1 (extreme event)









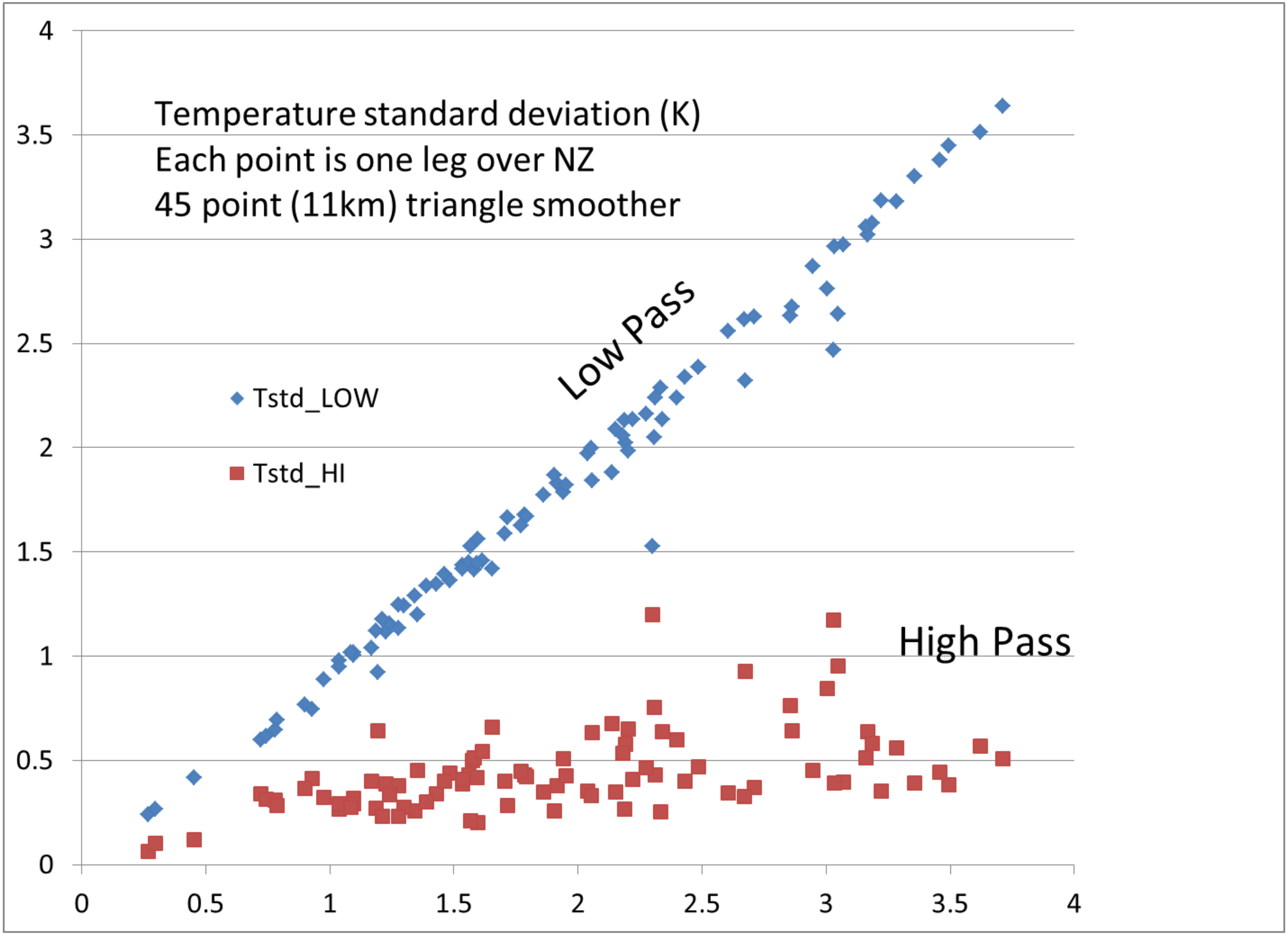


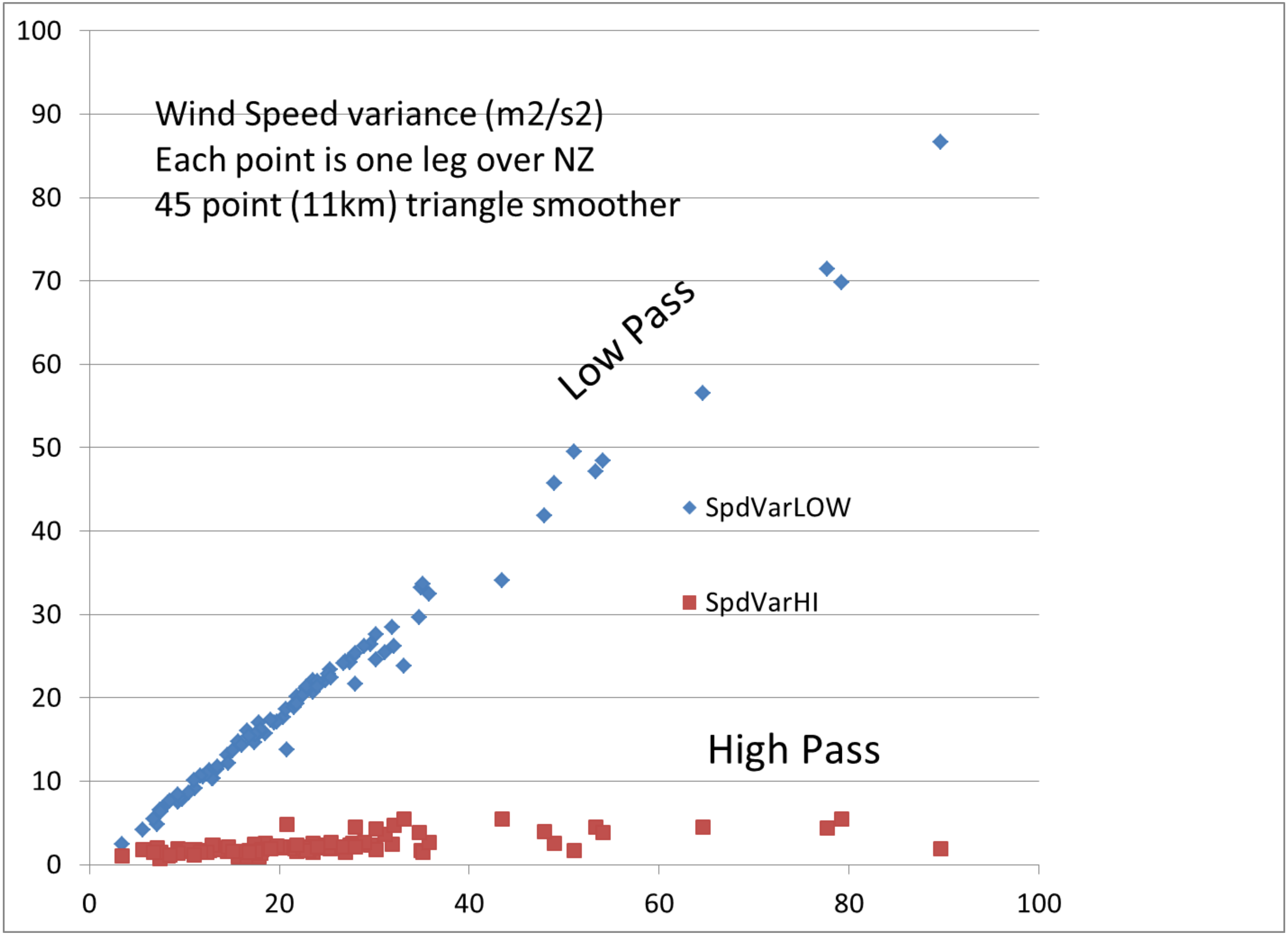
Two cases

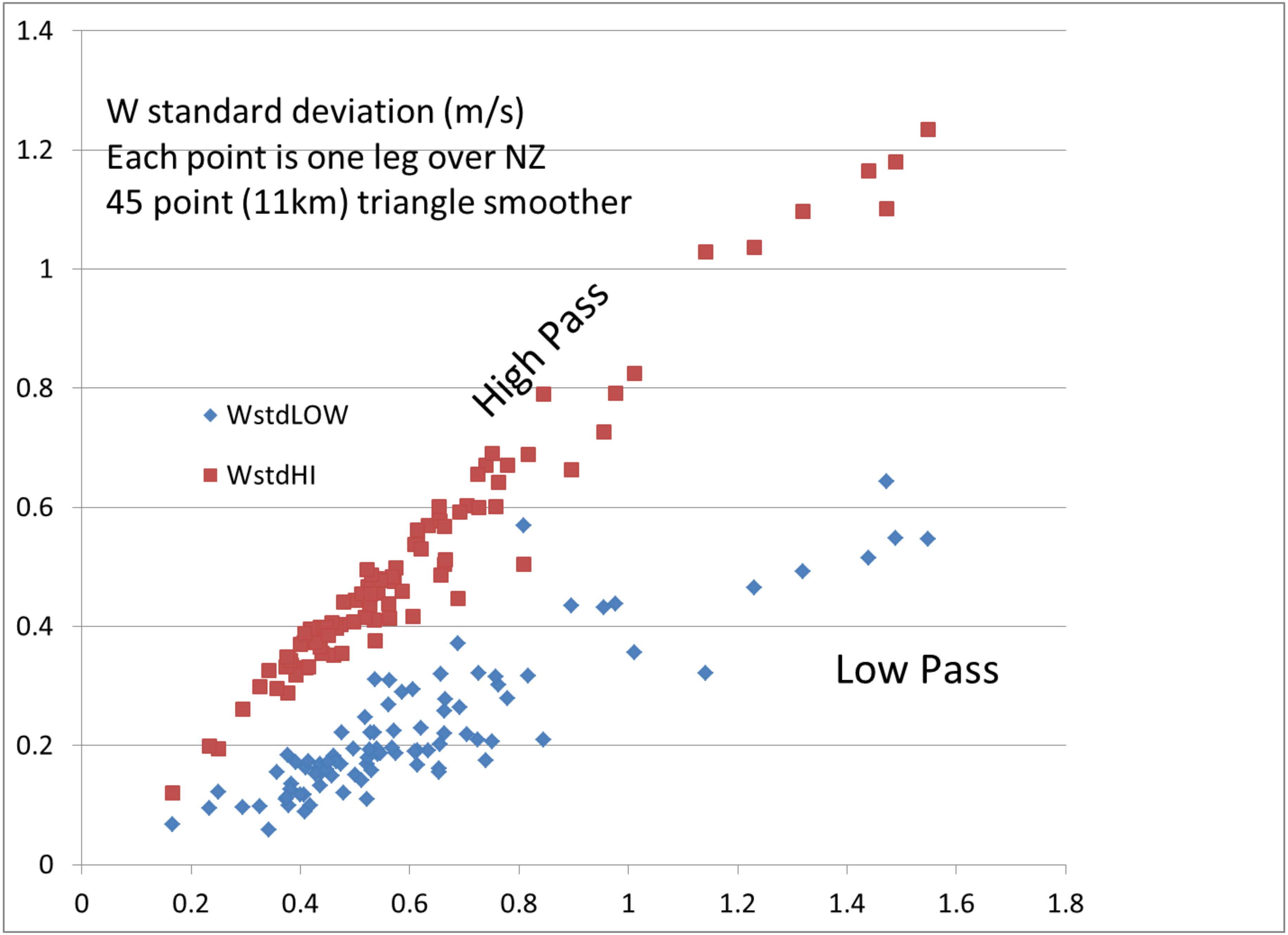
- RF04
    - Weak deep case (EFz = 1 to 3 W/m2)
    - Dominant flux-carrying long wave (L=200km)
    - Weak downward intermediate wave
    - Lots of short wave energy in w-power
    - No turbulence
- RF16
    - Extreme and variable case (EFz= 1 to 22W/m2)
    - Little long wave energy
    - Dominant flux-carrying intermediate wave (L=30km)
    - Lots of short wave energy in w-power
    - No turbulence

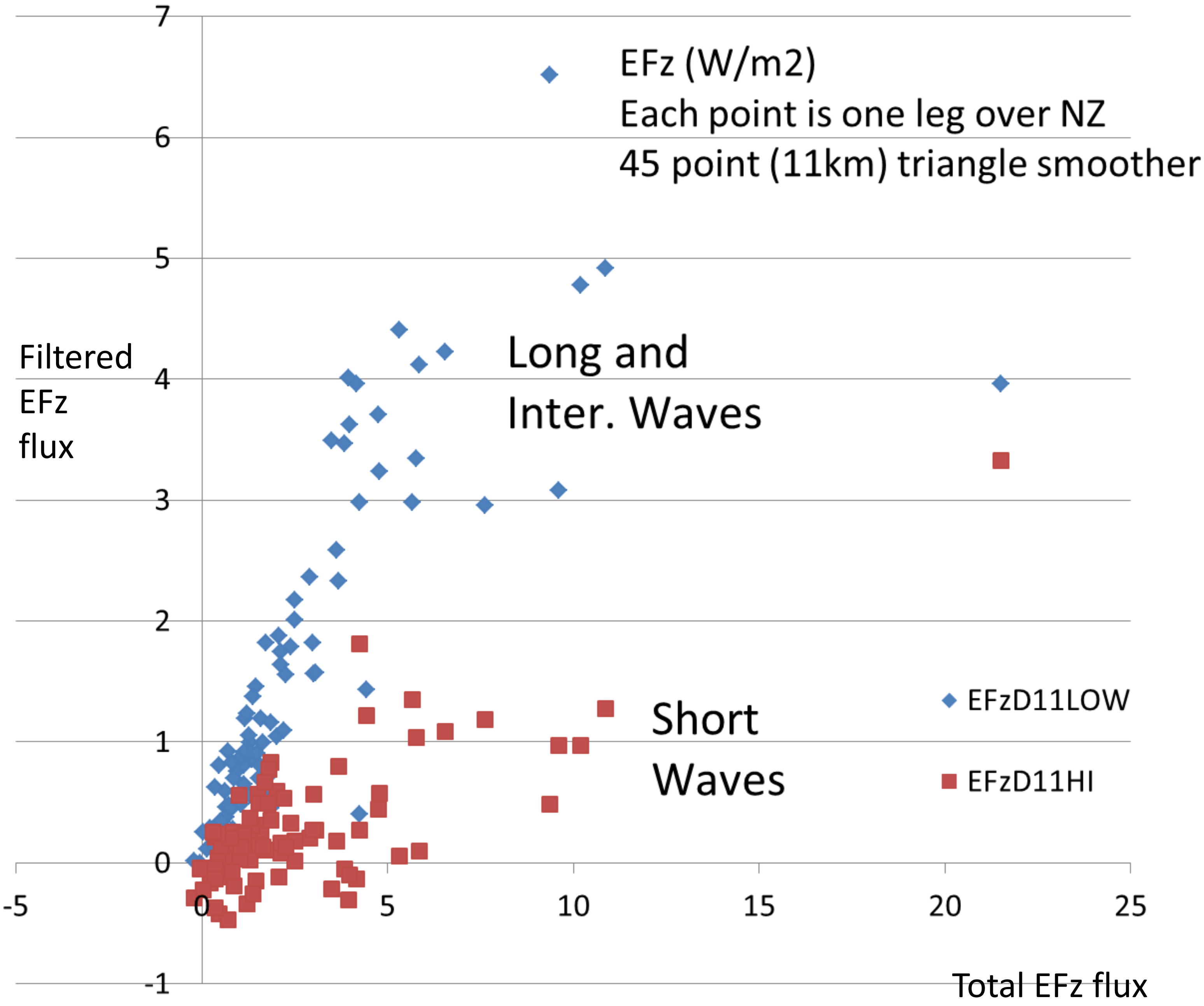
High and low pass filtering

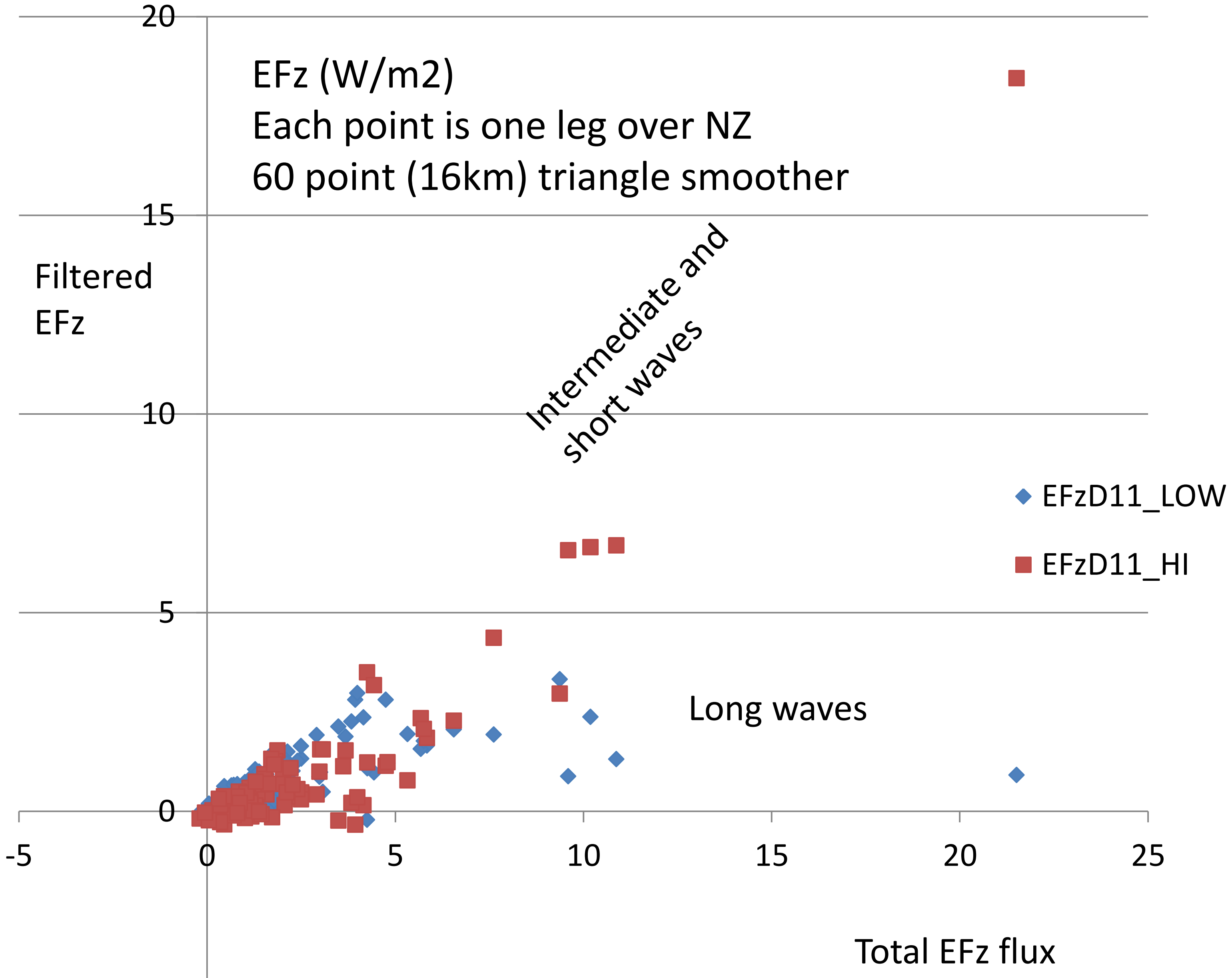
- Use spatial filtering to learn more about waves of different scales
- Low pass filter with a 125 point (30km), 60 point (14.4km) and 45 point (11km) triangular smoother
- $S = S_{HP} + S_{LP}$
- HP kills long waves; LP kills short waves
- Decreasing filter width from 125 to 45 points shifts the cutoff to shorter wavelength and pushes more data into the Low Pass category.


Temperature standard deviation (K)
Each point is one leg over NZ
45 point (11km) triangle smoother
Low Pass
High Pass
◆ Tstd_LOW
■ Tstd_HI
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4

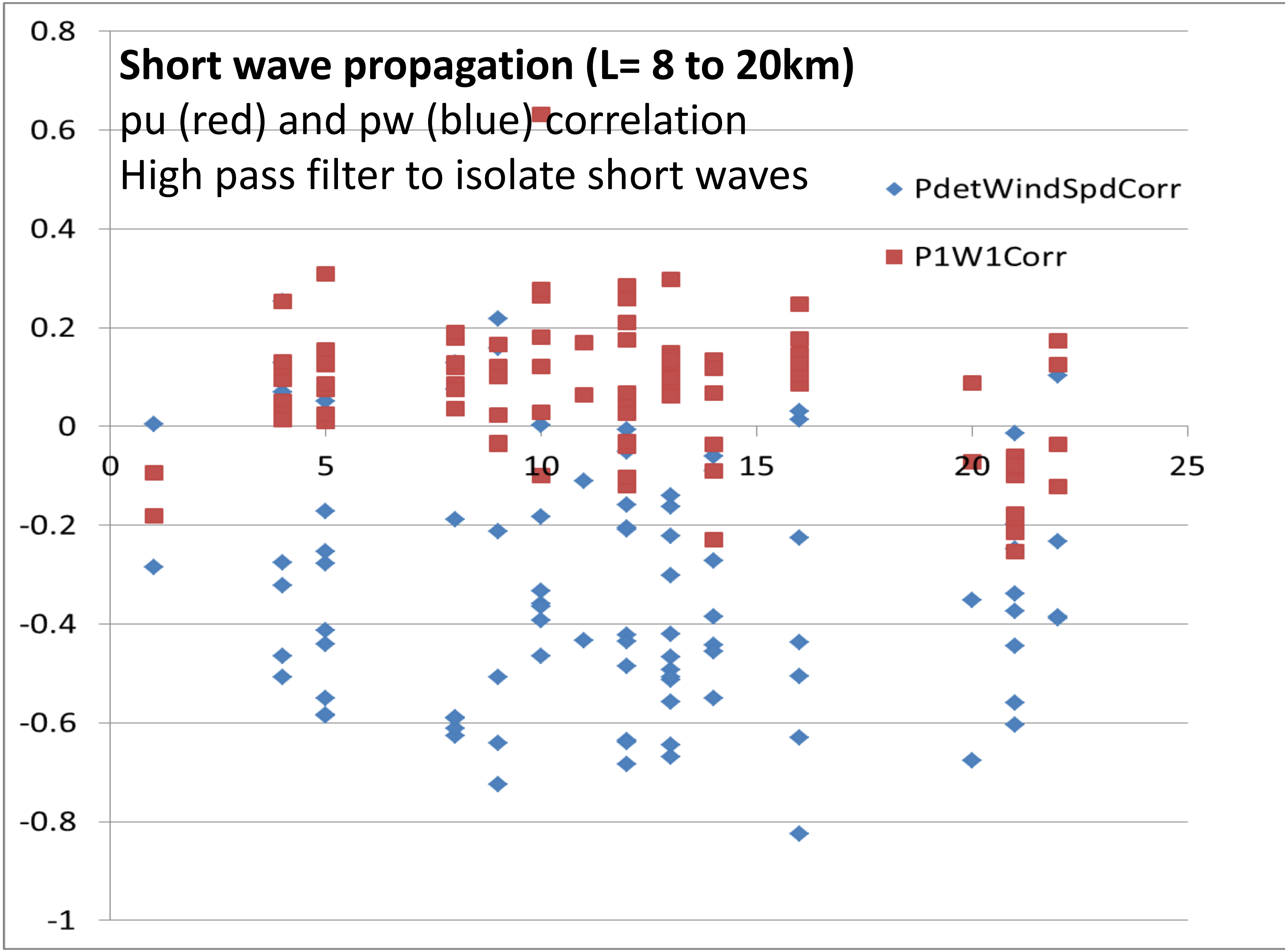

Wind Speed variance (m2/s2)
Each point is one leg over NZ
45 point (11km) triangle smoother
Low Pass
High Pass
◆ SpdVarLOW
■ SpdVarHI
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100


W standard deviation (m/s)
Each point is one leg over NZ
45 point (11km) triangle smoother
High Pass
Low Pass
◆ WstdLOW
■ WstdHI
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


EFz (W/m2)
Each point is one leg over NZ
45 point (11km) triangle smoother
Long and
Inter. Waves
Short
Waves
◆ EFzD11LOW
■ EFzD11HI
Filtered
EFz
flux
Total EFz flux
7
6
5
4
3
2
1
0
-1
-5
0
5
10
15
20
25



EFz (W/m2)
Each point is one leg over NZ
60 point (16km) triangle smoother

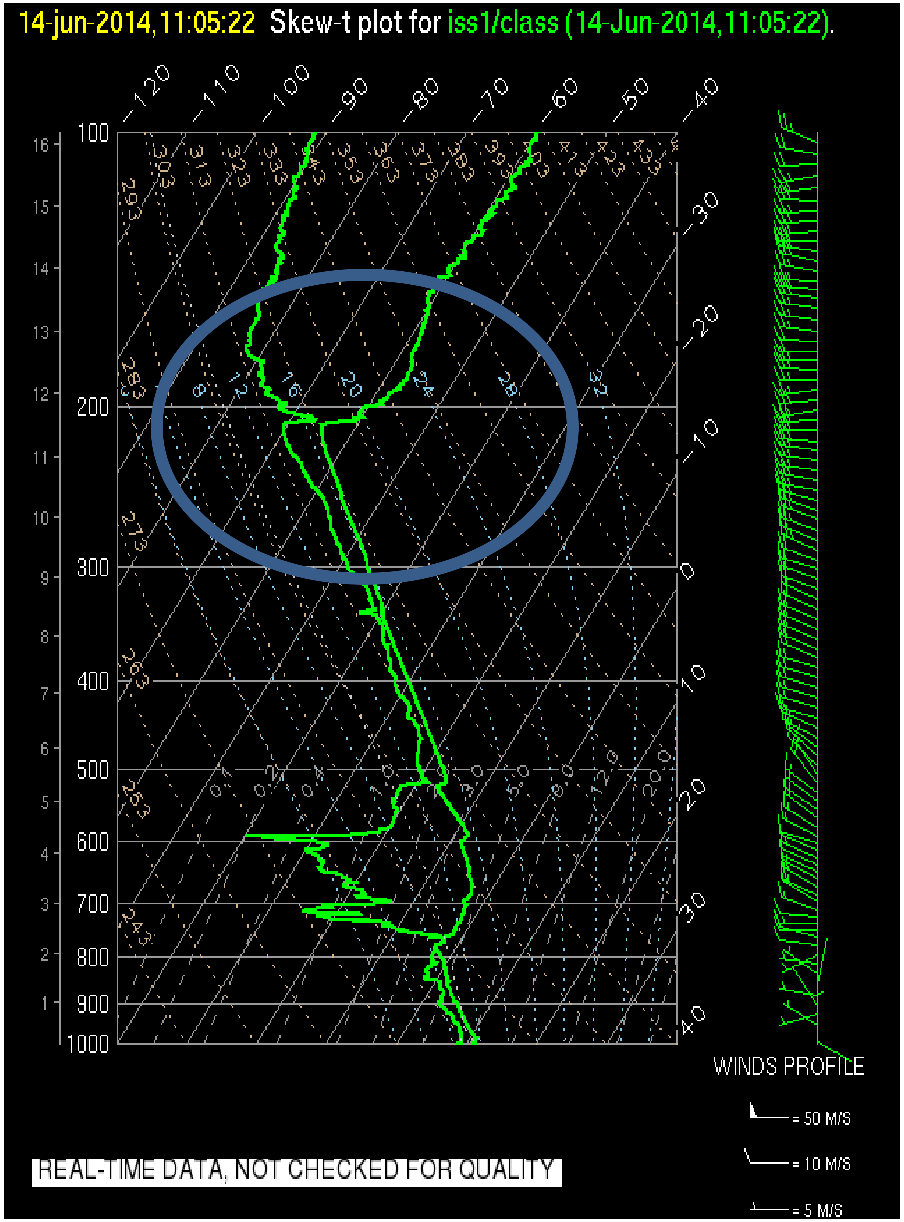


Short wave propagation (L= 8 to 20km)

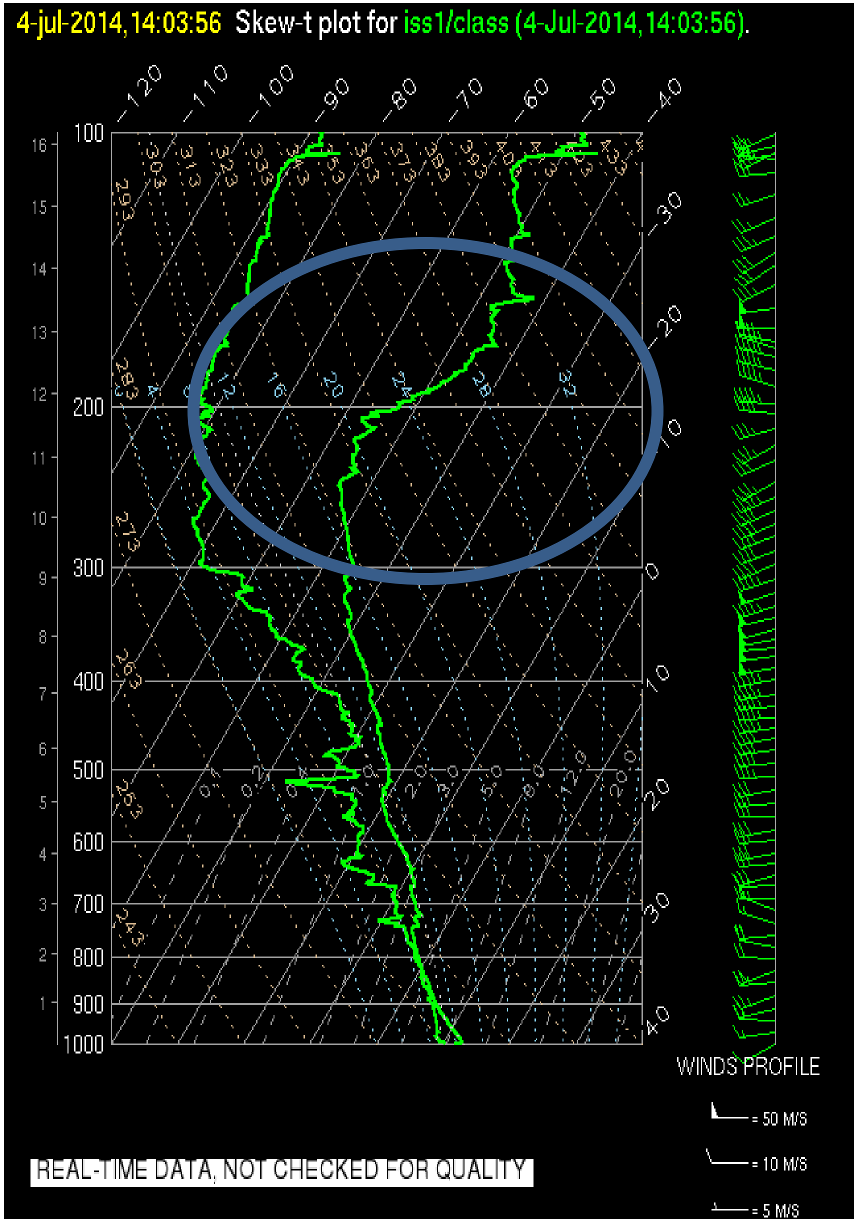
pu (red) and pw (blue) correlation

High pass filter to isolate short waves

Ducted waves in the tropopause inversion layer (TIL)



14-jun-2014,11:05:22 Skew-t plot for iss1/class (14-Jun-2014,11:05:22).



4-jul-2014,14:03:56 Skew-t plot for iss1/class (4-Jul-2014,14:03:56).

Filtering results

- Long (60 to 250km) and intermediate (20 to 60km) waves:
  - dominate Var(T’) , Var(u’) , Var(v’)
  - dominate fluxes
  - strongest cases use the intermediate waves
- Short waves (8 to 20km):
  - dominate Var(w’)
  - Ducted “lee” waves propagating upwind
  - small vertical fluxes

Wave breaking events in Deepwave

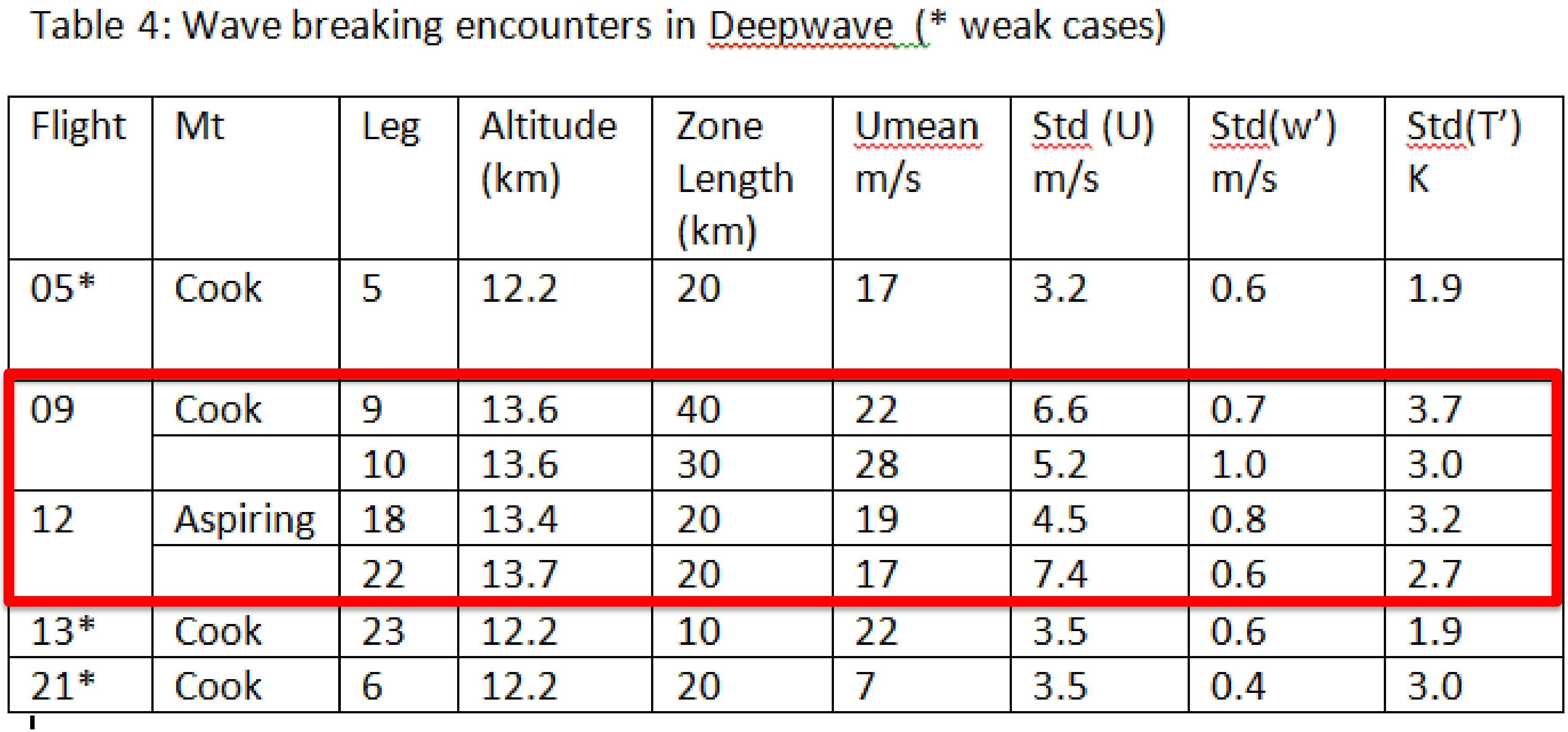


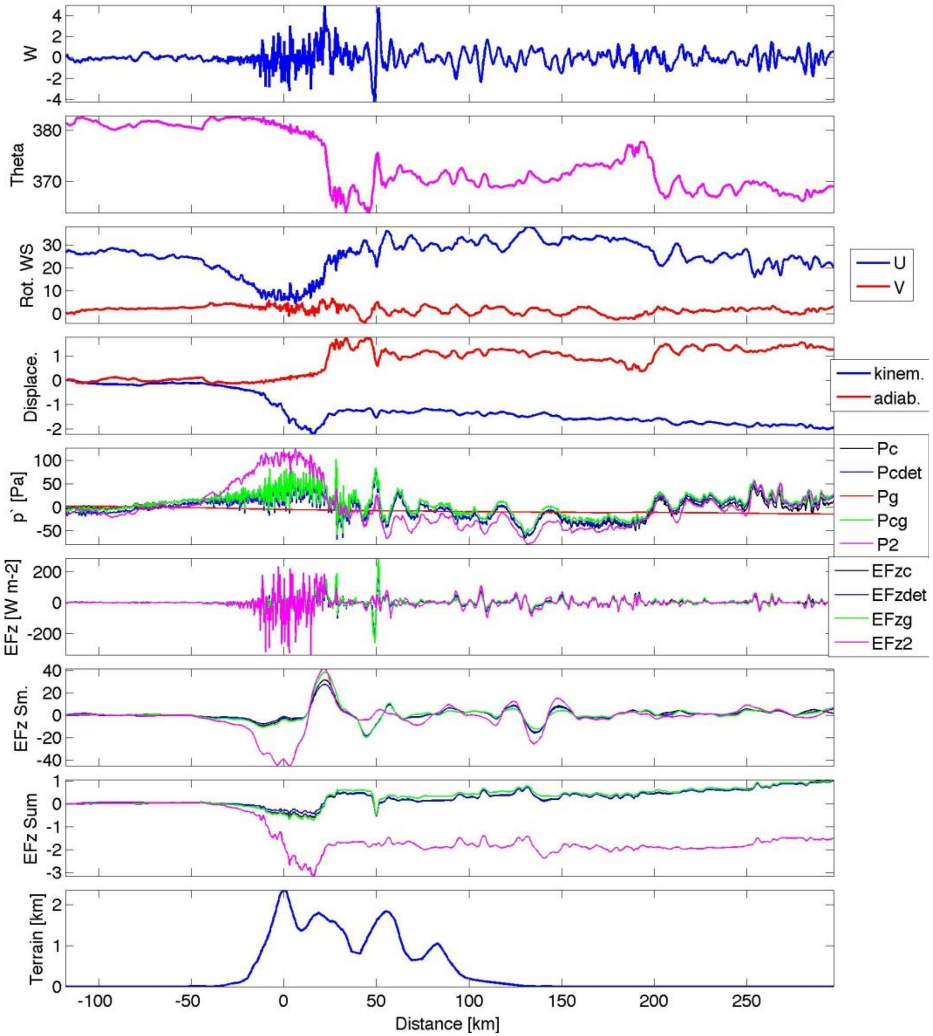
Table 4: Wave breaking encounters in Deepwave (* weak cases)

Flight	Mt	Leg	Altitude (km)	Zone Length (km)	Umean m/s	Std (U) m/s	Std(w') m/s	Std(T') K
05*	Cook	5	12.2	20	17	3.2	0.6	1.9
09	Cook	9	13.6	40	22	6.6	0.7	3.7
		10	13.6	30	28	5.2	1.0	3.0
12	Aspiring	18	13.4	20	19	4.5	0.8	3.2
		22	13.7	20	17	7.4	0.6	2.7
13*	Cook	23	12.2	10	22	3.5	0.6	1.9
21*	Cook	6	12.2	20	7	3.5	0.4	3.0

No flight level wavebreaking in RF16; extreme case

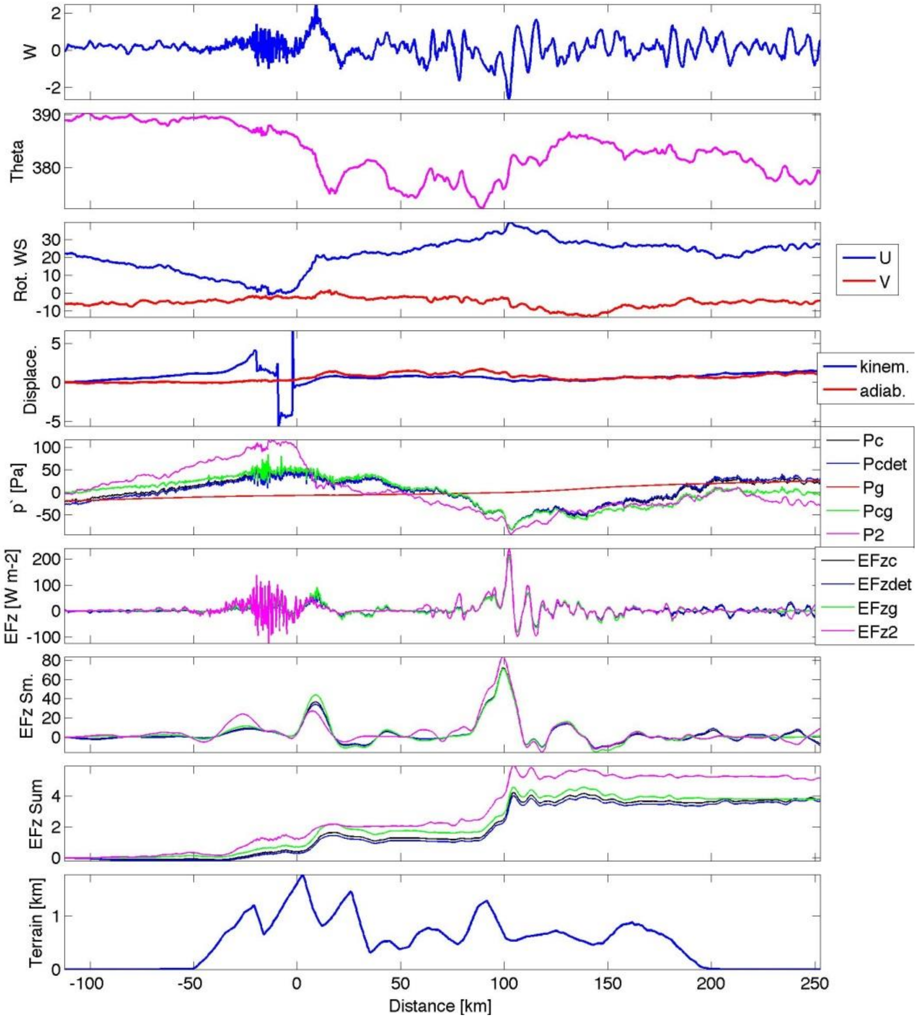
RF09 Leg 9, Type = mce, Z = 13577 [m], Course = 121 [degT]

RF09: Mt Cook



RF12 Leg 22, Type = maw, Z = 13573 [m], Course = 120 [degT]

RF12: Mt Aspiring



Two examples of flow stagnation and wave breaking

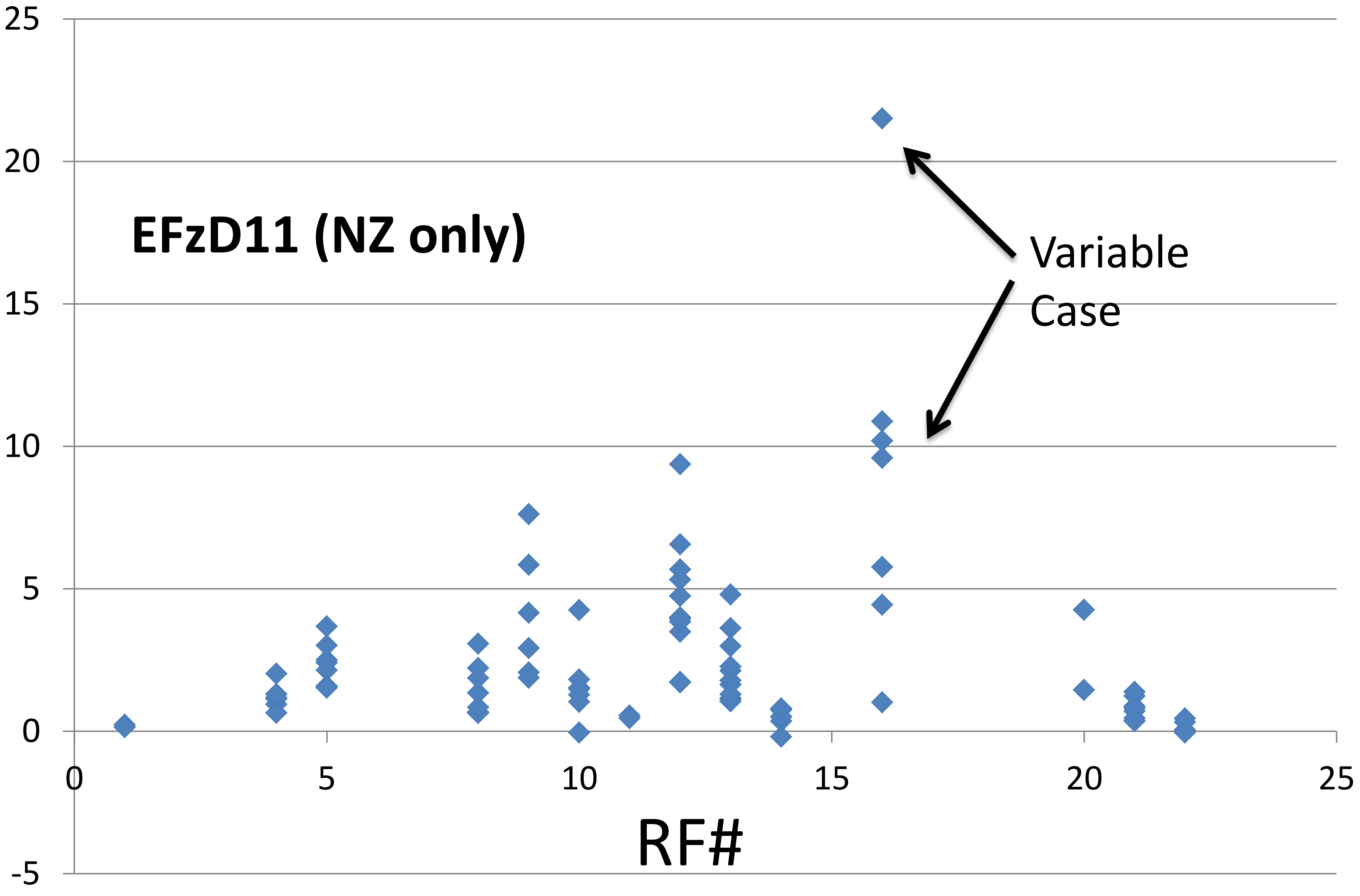
Wave breaking: strong cases

- Both mountains: RF9 and RF12
- Aircraft ascends to 13km
- Flow stagnation
- Turbulent patch: 20 to 40 km
- Updraft and temperature drop

Rapid flux fluctuations

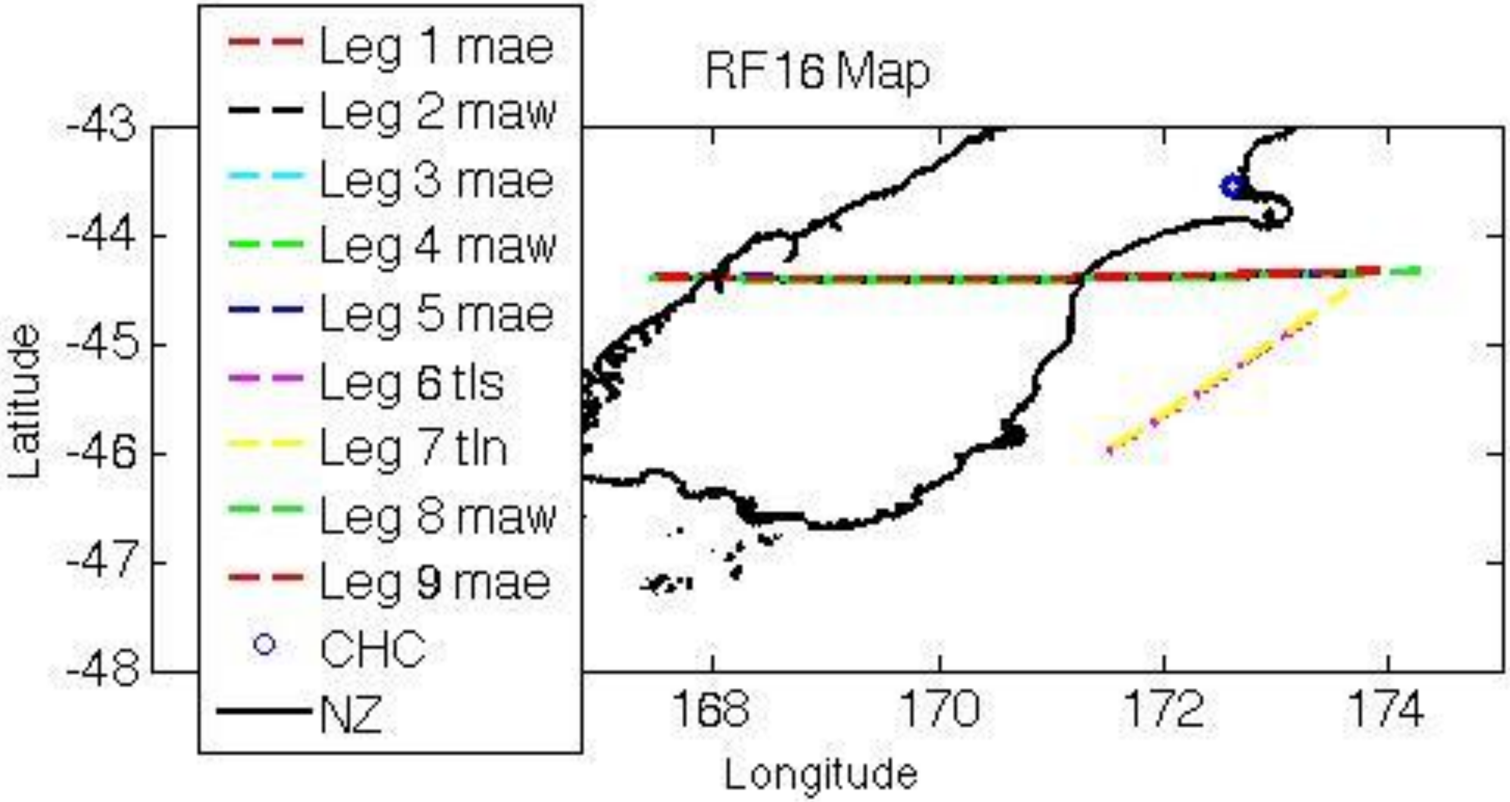
- Vertical fluxes can fluctuate from leg to leg
- Good example: RF16 extreme case
- Recall: This case is dominated by intermediate waves

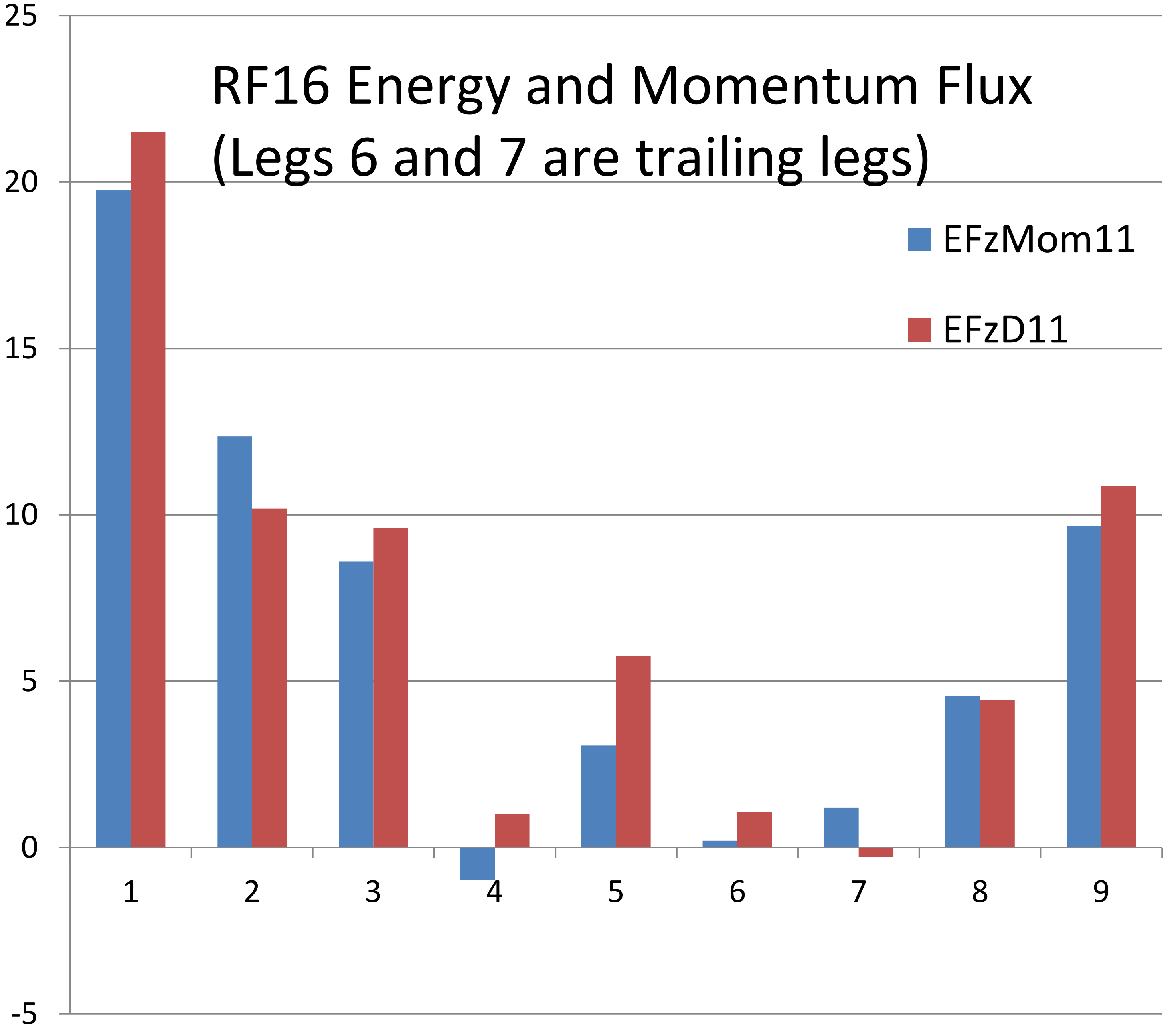
Vertical Energy Flux



EFzD11 (NZ only)

Variable Case


RF16 Map
Leg 1 mae
Leg 2 maw
Leg 3 mae
Leg 4 maw
Leg 5 mae
Leg 6 tls
Leg 7 tln
Leg 8 maw
Leg 9 mae
CHC
NZ
Latitude
-43
-44
-45
-46
-47
-48
168
170
172
174
Longitude



RF16 Energy and Momentum Flux
(Legs 6 and 7 are trailing legs)

Comparison with other projects: MFx at 12km

- Front Range: Lilly &Kennedy (1973)
  - MFx= -0.4 Pa; L=50km
- Pyrenees: Hoinka (1984)
  - MFx= -0.2Pa; L=40km
- Sierras: Smith et al. (2008) (leg = 150km)
  - MFx= -1.0 Pa; L=30km
- Southern Alps: Deepwave
  - MFx= -0.5Pa (max); L=30 to 200km

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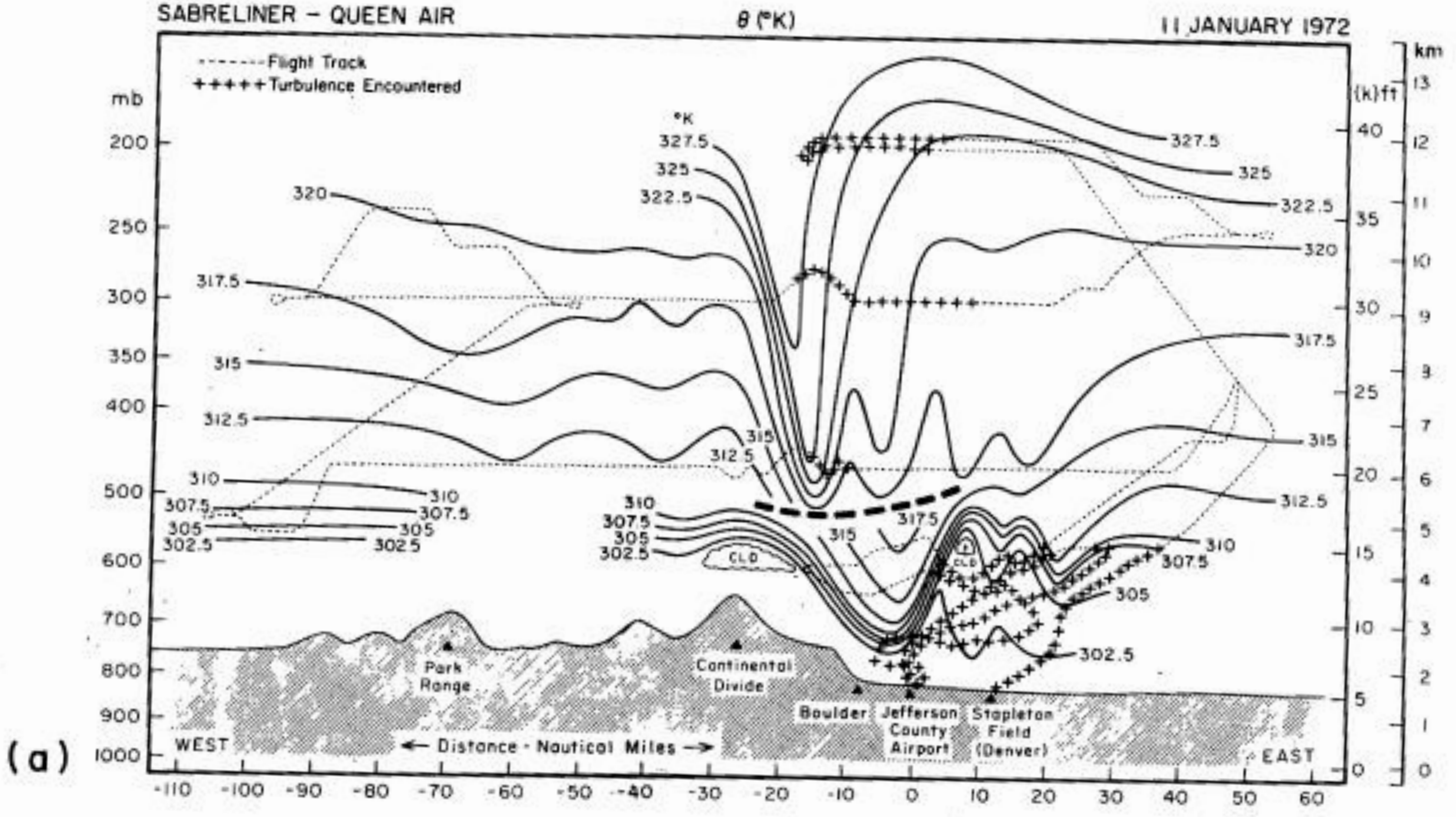


At 12 km: incomplete leg

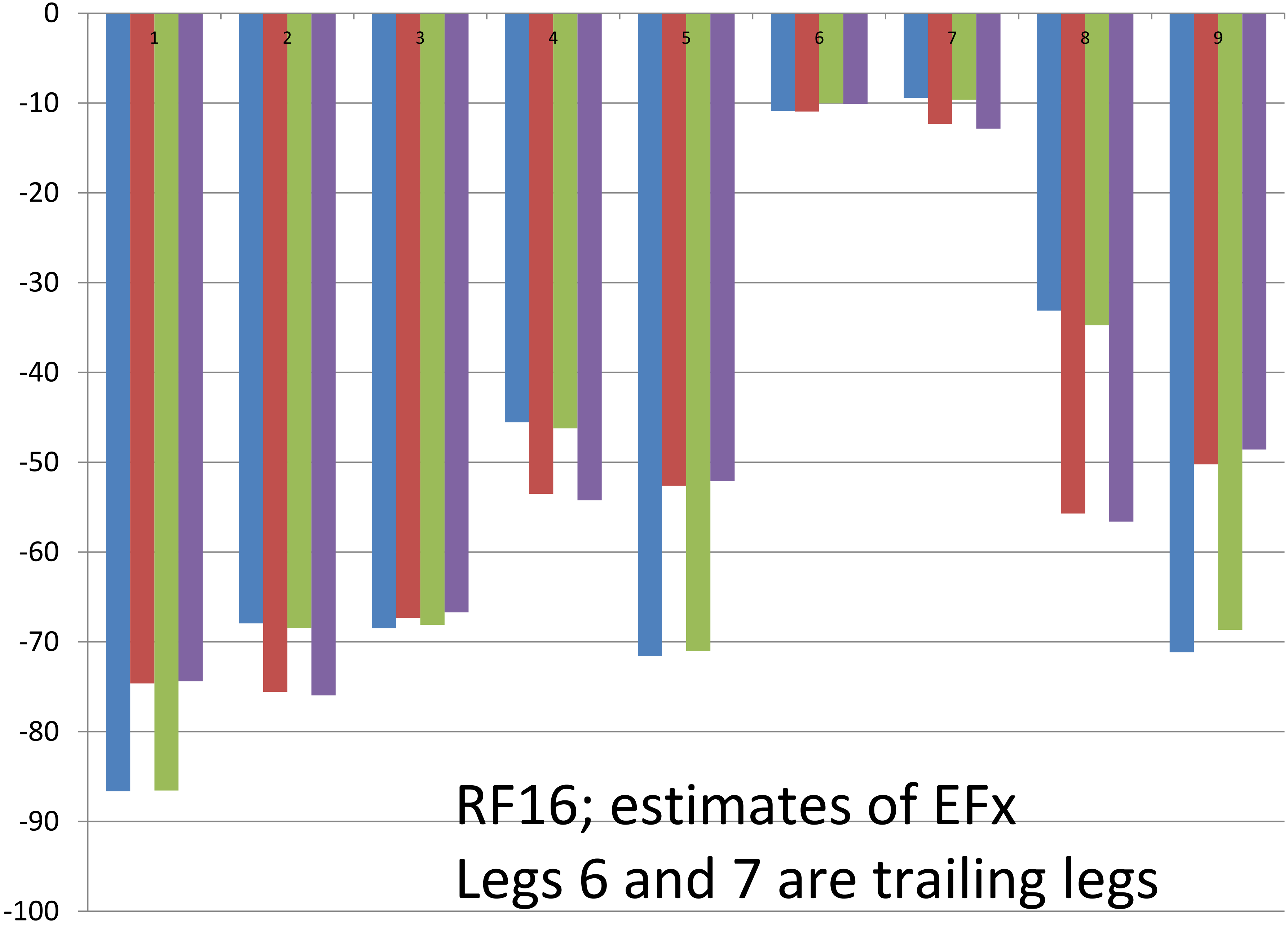
At 6 km: cancelling wave and turbulent MFx

Summary of GV gravity wave statistics

- Flux uncertainty:
  - EFz: 1W/m2 (20%) [similar for MF]
  - EFx,y: 3W/m2 (10%)
  - New calibrations and geostrophic detrending has improved fluxes
- Land versus Ocean
  - Land: EFz all positive (1 to 22W/m2); MFx all negative; EFxy upwind
  - Ocean: mostly below detection threshold; EF random direction
- Scale analysis:
  - Long waves: most common mountain wave structure
  - Inter. waves: variable flux contribution; strong events use intermediate scale waves
  - Short waves: dominate w-power, ducted secondary waves on TIL
- Breaking waves and Turbulence: strong cases 2 RFs, 4 legs
- Rapid flux changes in large event (RF16)
- Previous studies: similar fluxes, ducted waves, shorter flux-carrying waves

Future work

- Complete current manuscript on GV flux statistics (i.e. “LIST”)
- Investigate switch from long to intermediate flux-carrying waves
- Investigate short wave physics (generation?)
- Investigate flux fluctuations (RF9,12,16, DLR?)
- Compare observations with WRF model runs
- Use GV flight level data in collaboration with Remote Sensing groups



RF16; estimates of EFx

Legs 6 and 7 are trailing legs

Conclusions regarding: redundancy and uncertainty

- U,V and GGALT are accurately measured and errors do not degrade fluxes
- uncertainties in P and W impact fluxes
- PXSF and WIC give the best EP check
- All NZ EFz values are positive in the new data
- Uncertainty in EFz or EFzMom is about 1W/m2 (20%)
- Uncertainty in EFx, EFy is about 3W/m2 (10%). First project to use this flux.