Winter Storms: Dropsondes Over the Pacific Ocean - ***the multifractal scaling of wind, temperature and humidity***

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06 October 2011

S J Hovde, A F Tuck, S Lovejoy & D Schertzer(2011),Vertical scaling of temperature, wind & humidity fluctuations: dropsondes from 13 km to the surface of the Pacific Ocean, *Int. J. Remote Sensing,* **32,** 5891-5918,
doi:10.1080/01431161.2011.602652

Abstract

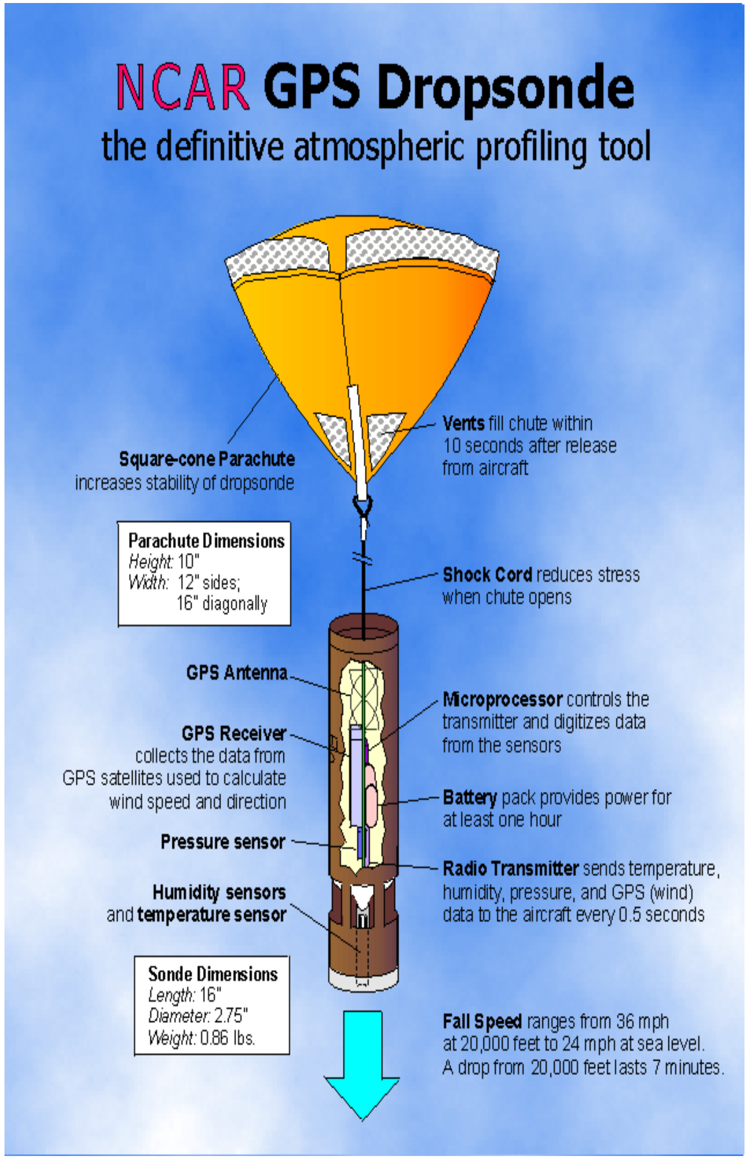
During the NOAA Winter Storms 2004-2005-2006 projects, as a result of severe flooding on the west coast of the USA, observational data were taken in the 'vertical' at 2 Hz from research dropsondes for temperature, wind speed and relative humidity during the ≈800 s it takes to reach the surface from the 13 km altitude of the National Oceanic and Atmospheric Administration (NOAA) Gulfstream 4 SP aircraft. The observations were made mainly through the depth of the troposphere above the eastern Pacific Ocean from 15˚N to 60˚N. This sizeable data set was used to characterize representatively the statistical fluctuations in the 'vertical' structure from 13 km to the surface. The fluctuations are resolved at 5-10 metres altitude, so covering up to 3 orders of magnitude of tropospheric weighting functions for passive remote sounders. Average 'vertical' statistical multifractal scaling exponents H, C_1 and α of temperature, wind speed and humidity fluctuations observed at this high resolution were computed and are available as potential generators of scale invariant summaries of the vertical structure of the marine troposphere. Current and future investigations with drone aircraft are illustrated.

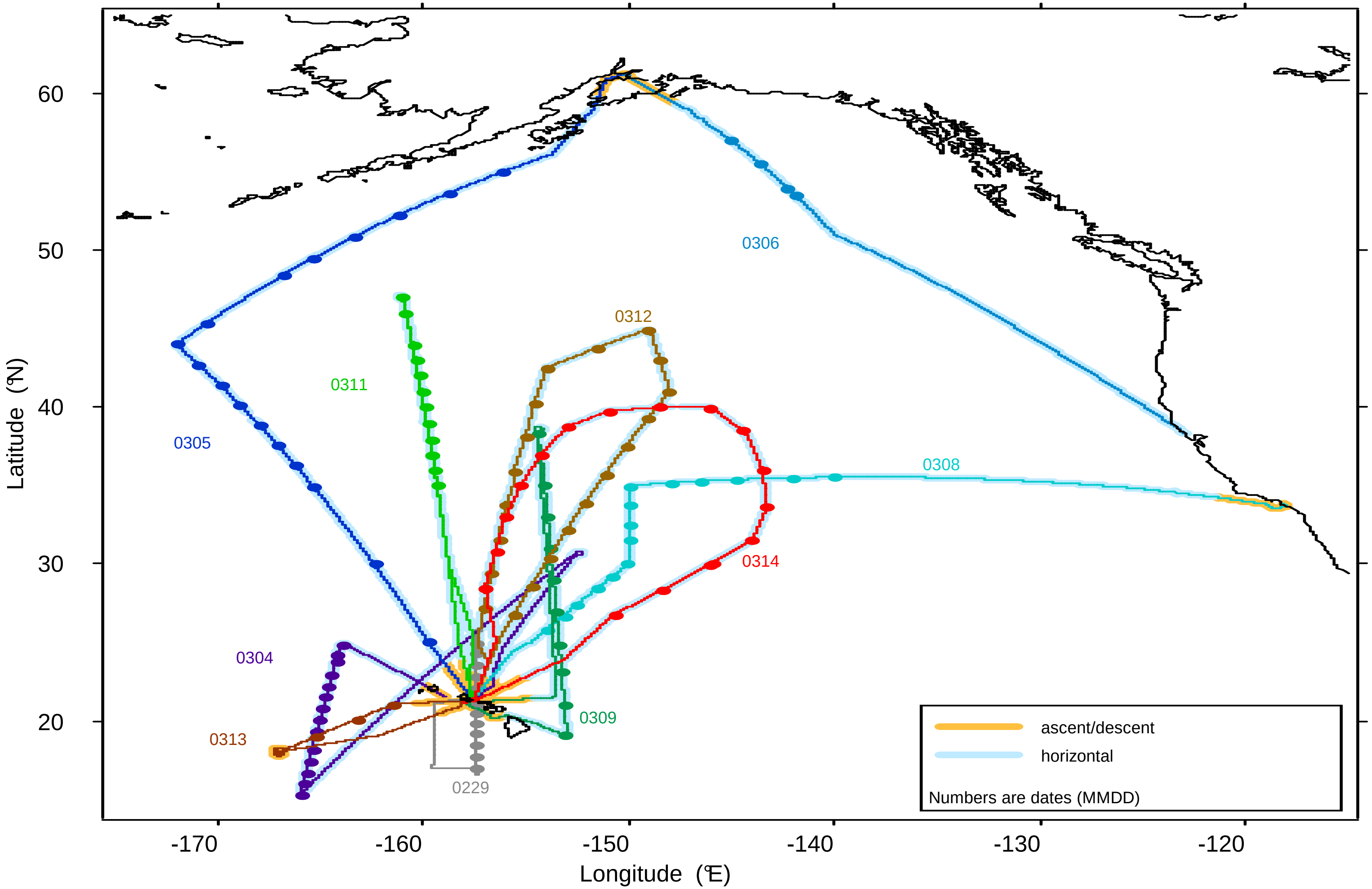
NOAA Gulfstream 4

Dropsonde

GPS Dropwindsonde Specifications

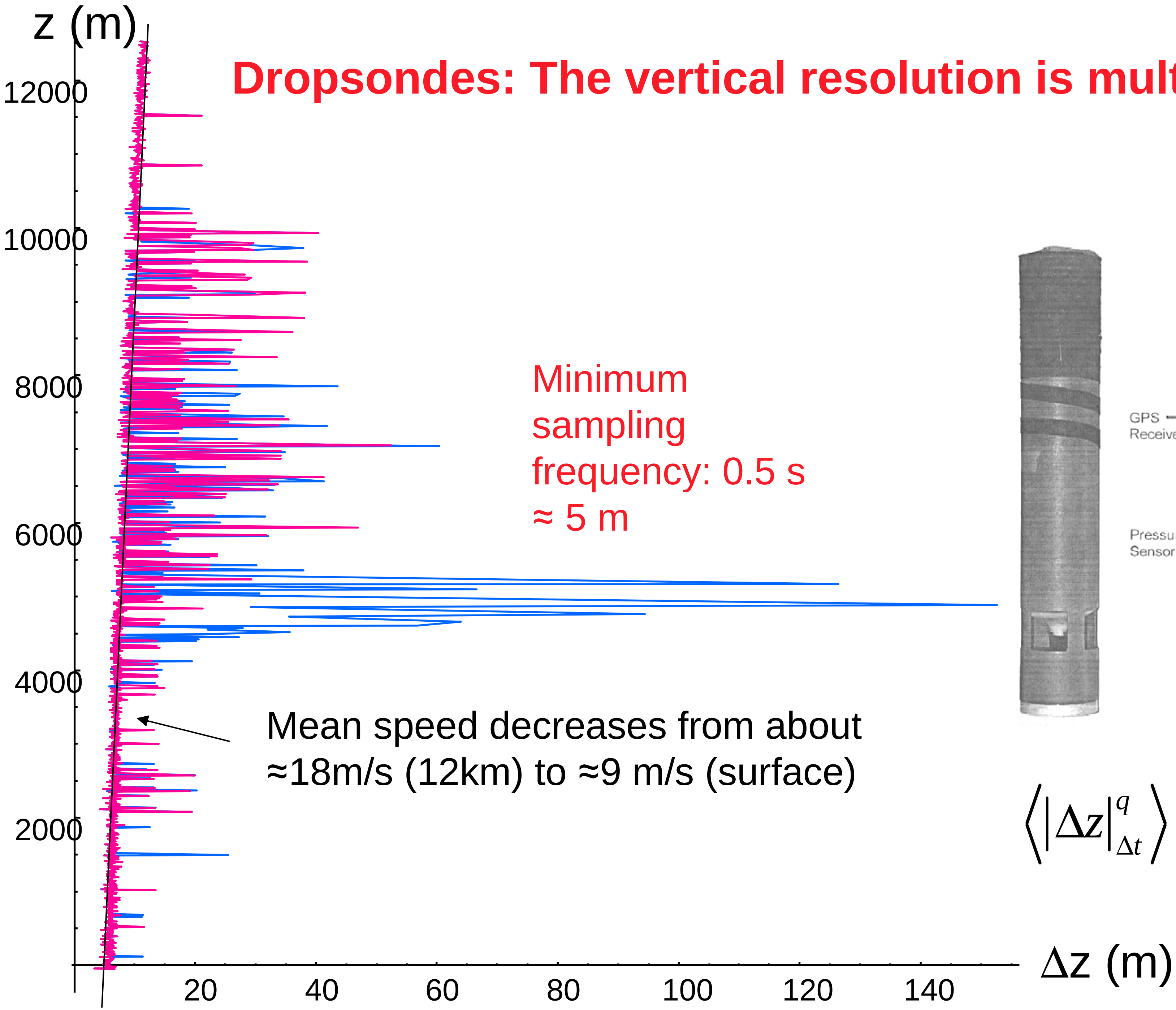
	Operate	Accuracy	Resolution	Time Const.	Typ. Error
Pressure	1060-20mb	0.5mb	0.1mb	<0.01 sec	1.0mb
Temperature	-90 to 45°C	0.2°C	0.1°C	2.5 to 3.7 s	0.2°C
Humidity	0 to 100%	2.0%	0.1%	0.1 to 10 sec	<5%
Winds	0 to 150 m/s	0.5 m/s	0.1 m/s		0.5 to 2.0ms





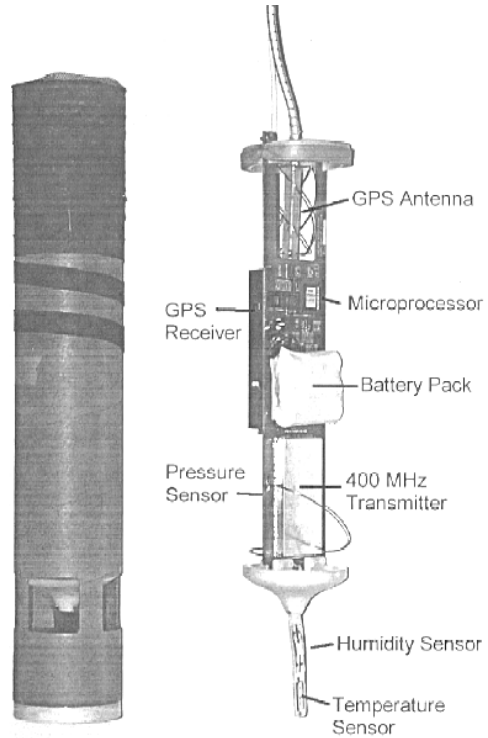
60
50
40
30
20
-170
-160
-150
-140
-130
-120
Latitude (°N)
Longitude (°E)
0306
0312
0311
0305
0308
0314
0304
0309
0313
0229
ascent/descent
horizontal
Numbers are dates (MMDD)

Dropsondes: The vertical resolution is multifractal

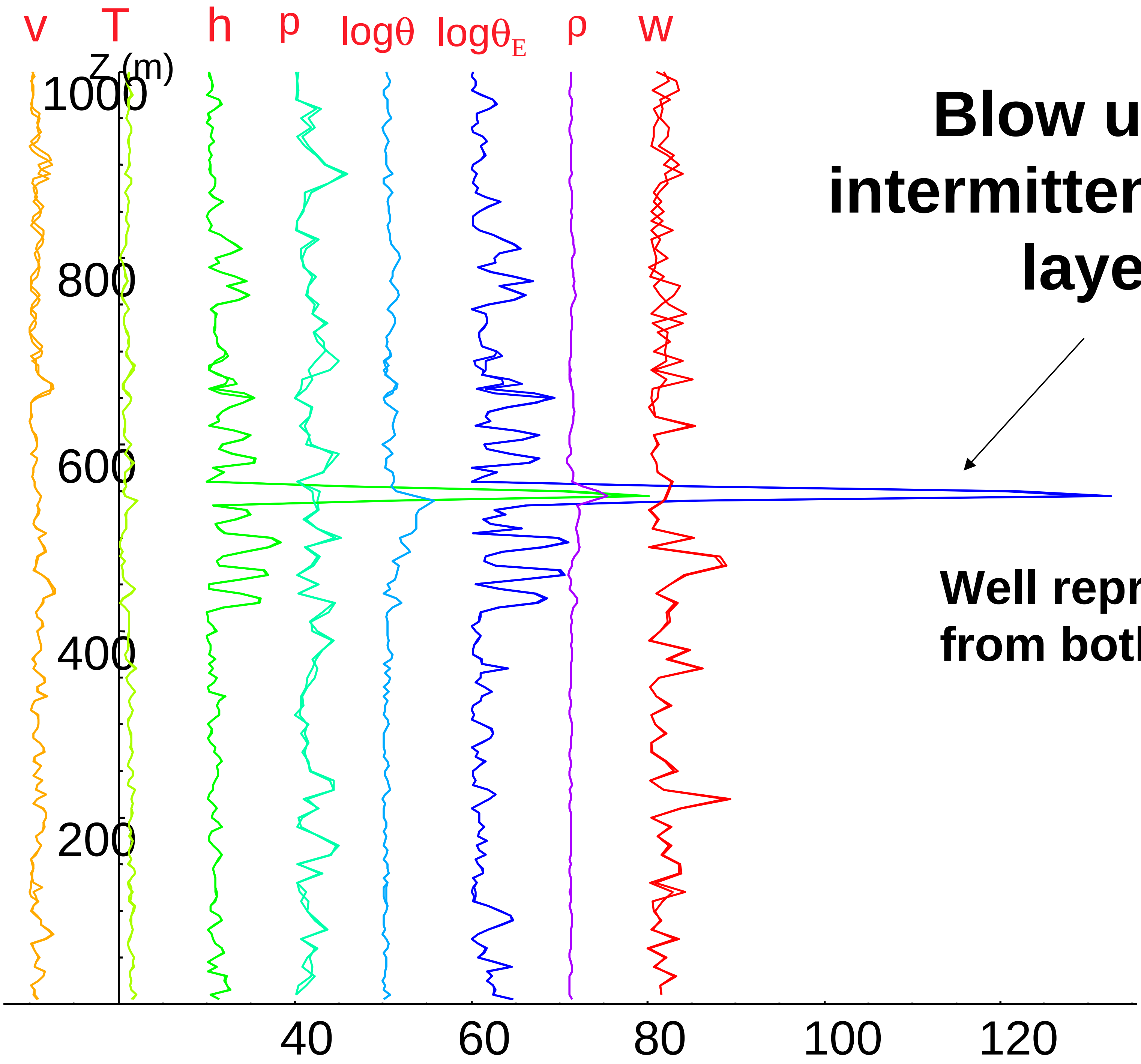


Minimum sampling frequency: 0.5 s ≈ 5 m

Mean speed decreases from about ≈18m/s (12km) to ≈9 m/s (surface)



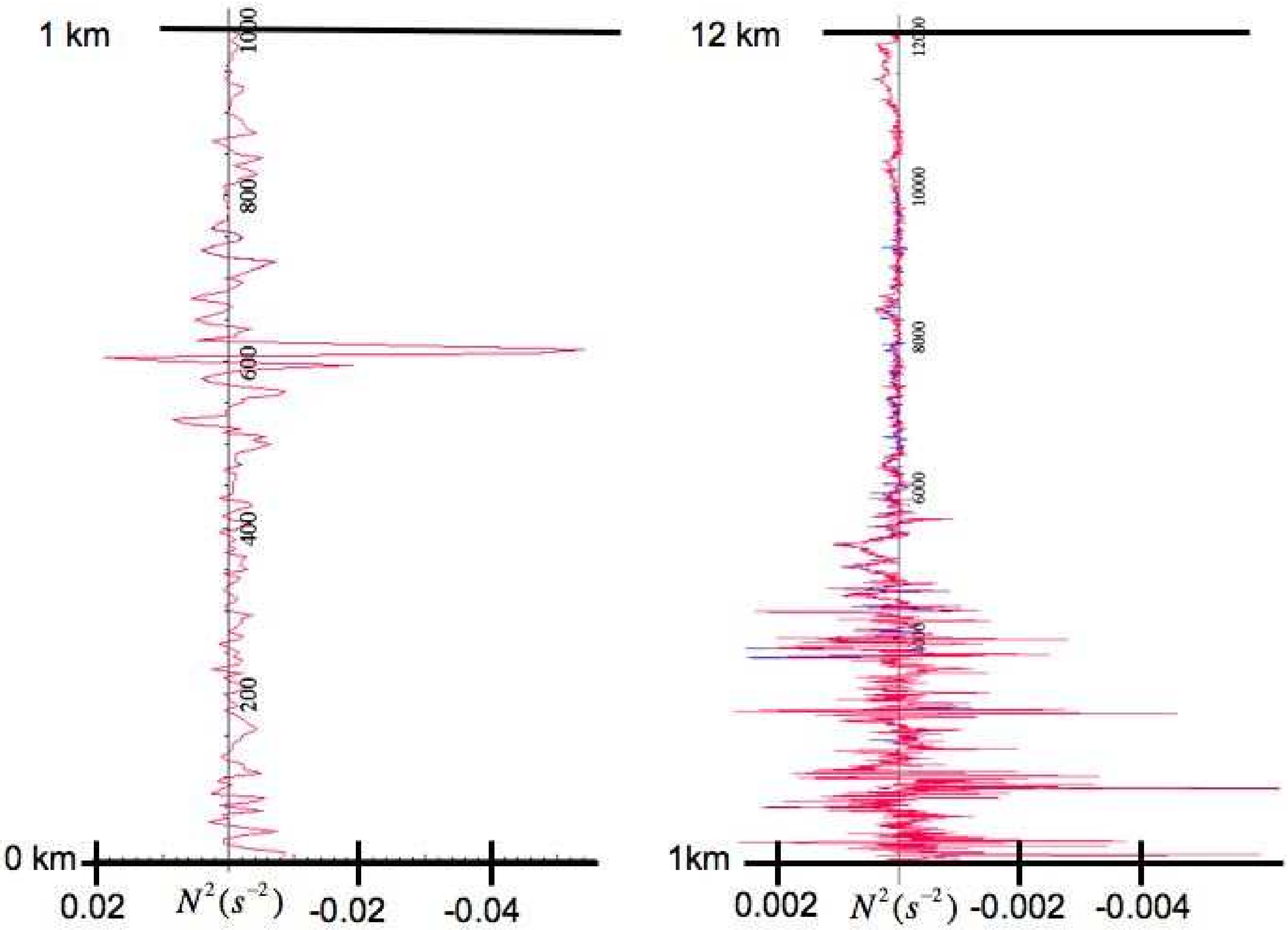
$$\left\langle \left|\Delta z\right|_{\Delta t}^{q} \right\rangle \approx \Delta t^{-\varphi(q)}$$



Blow up of intermittent lower layer

Well reproduced from both sondes

Dynamic stability: marine boundary layer, troposphere



Potential Temperature, θ

- θ is an alternative vertical coordinate in meteorology.

- It is the temperature an air element would have if it was brought adiabatically to the surface.

$$S = C_p \ln\theta + \text{constant}$$

where S is entropy

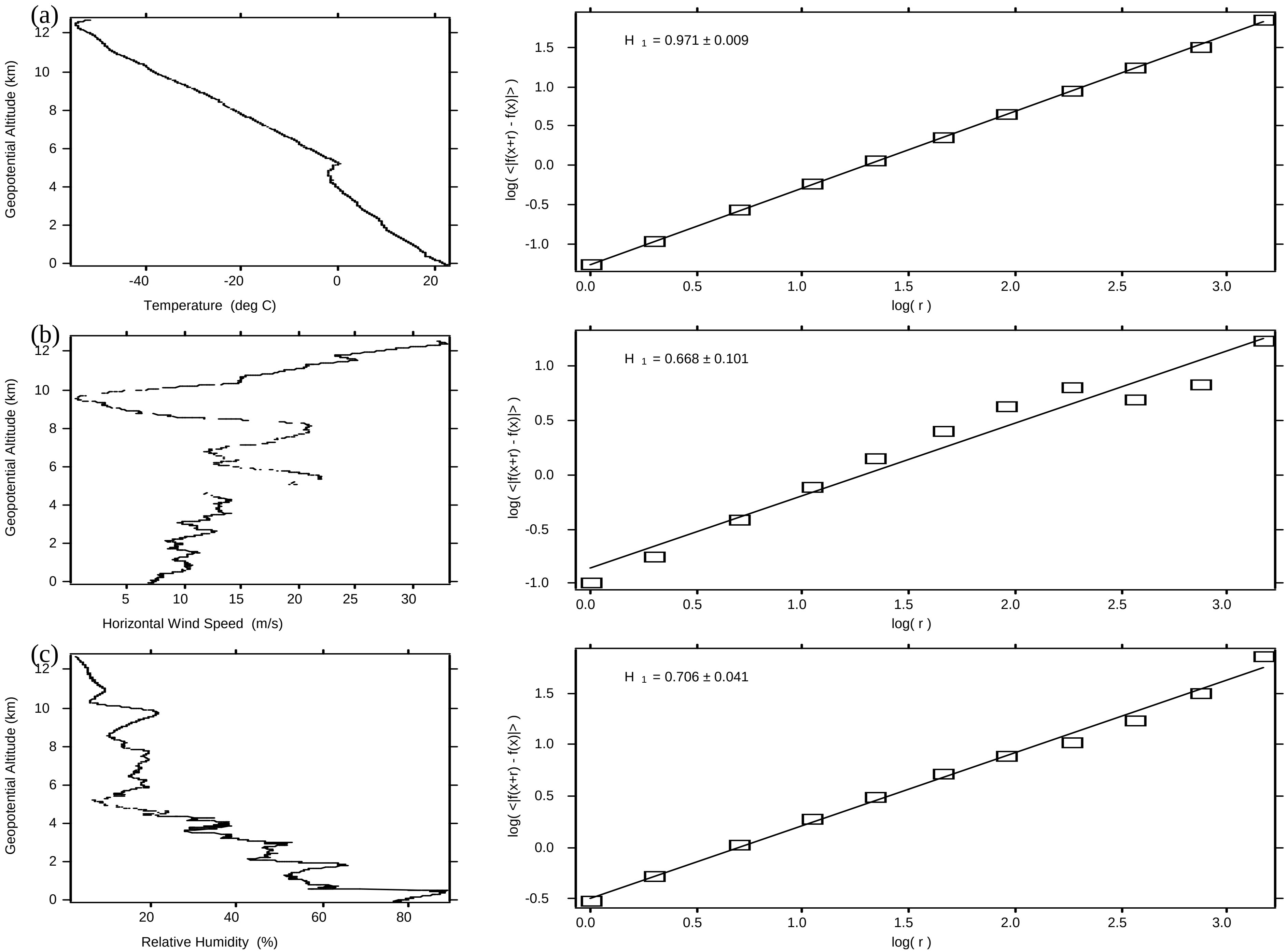
Generalised Scale Invariance: Exponents

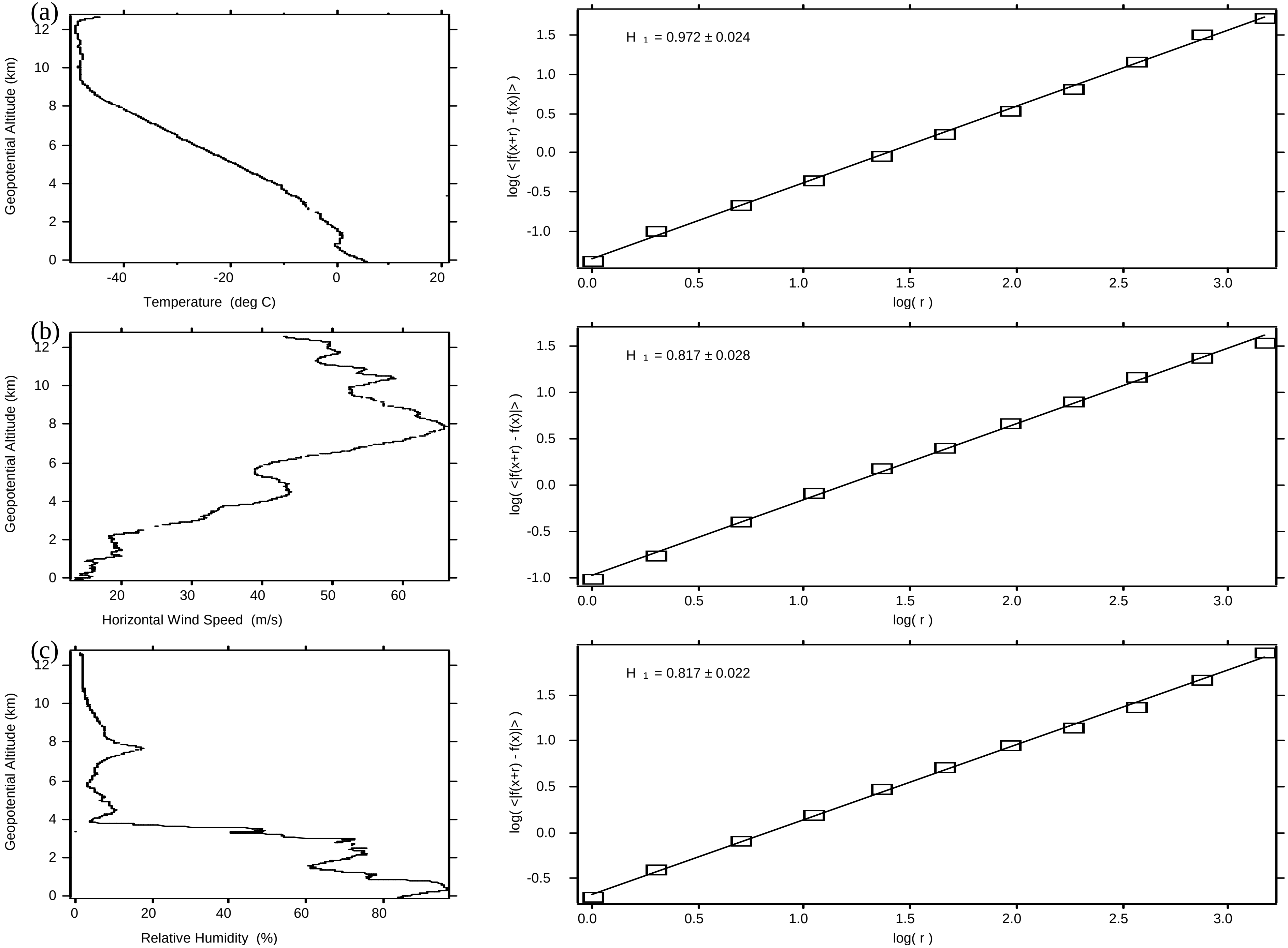
- H Hurst or conservation exponent ($0<H<1$)
- C_1 intermittency exponent ($0<C_1<1$)
- α multifractality exponent ($0<\alpha<2$)

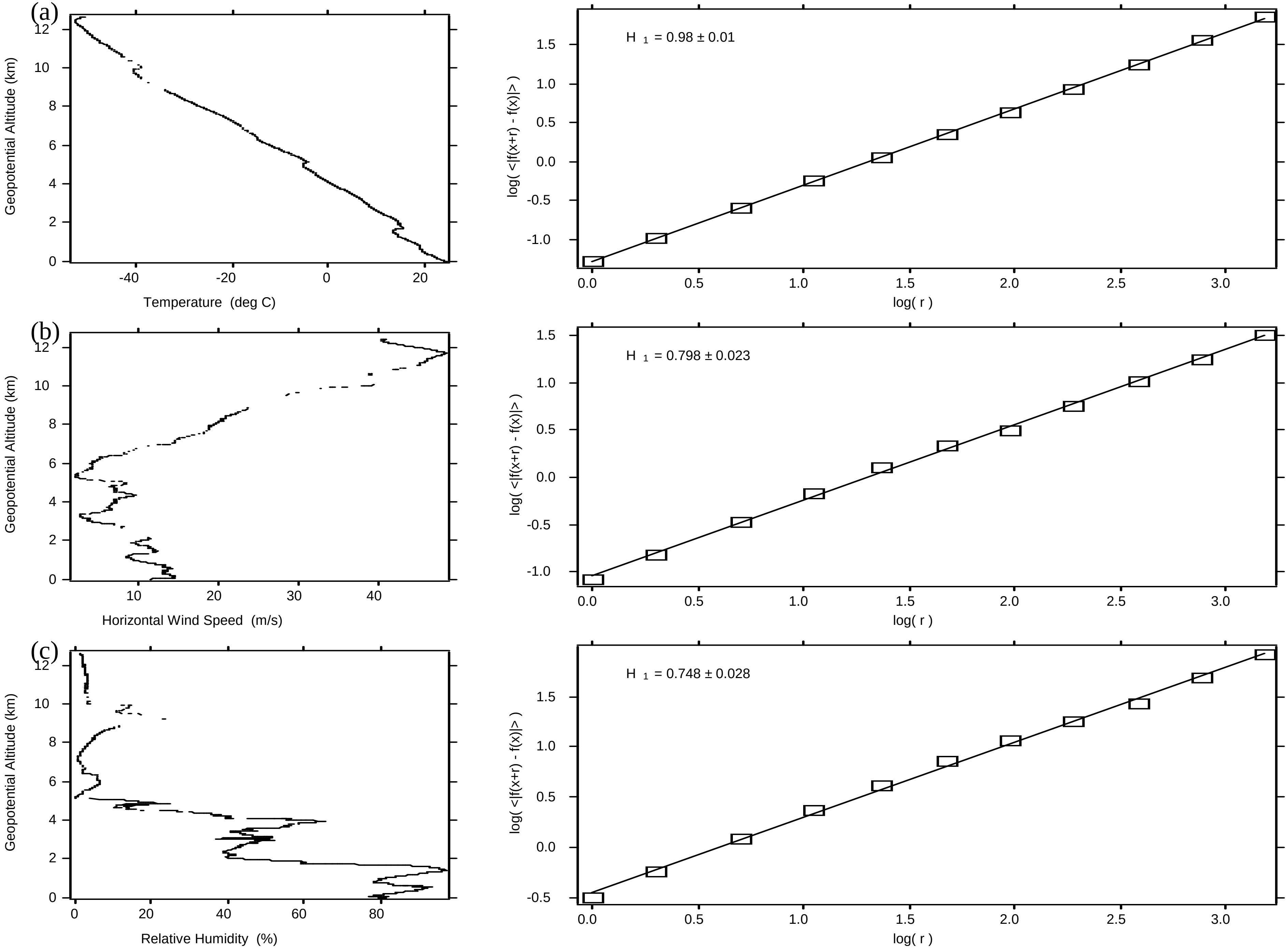
*Atmosphere has $H = 0.56$, $C_1 = 0.05$, $\alpha = 1.6$ from horizontal aircraft observations.

*Gaussian has $H = 0.5$, $C_1 = 0$, $\alpha = 2$

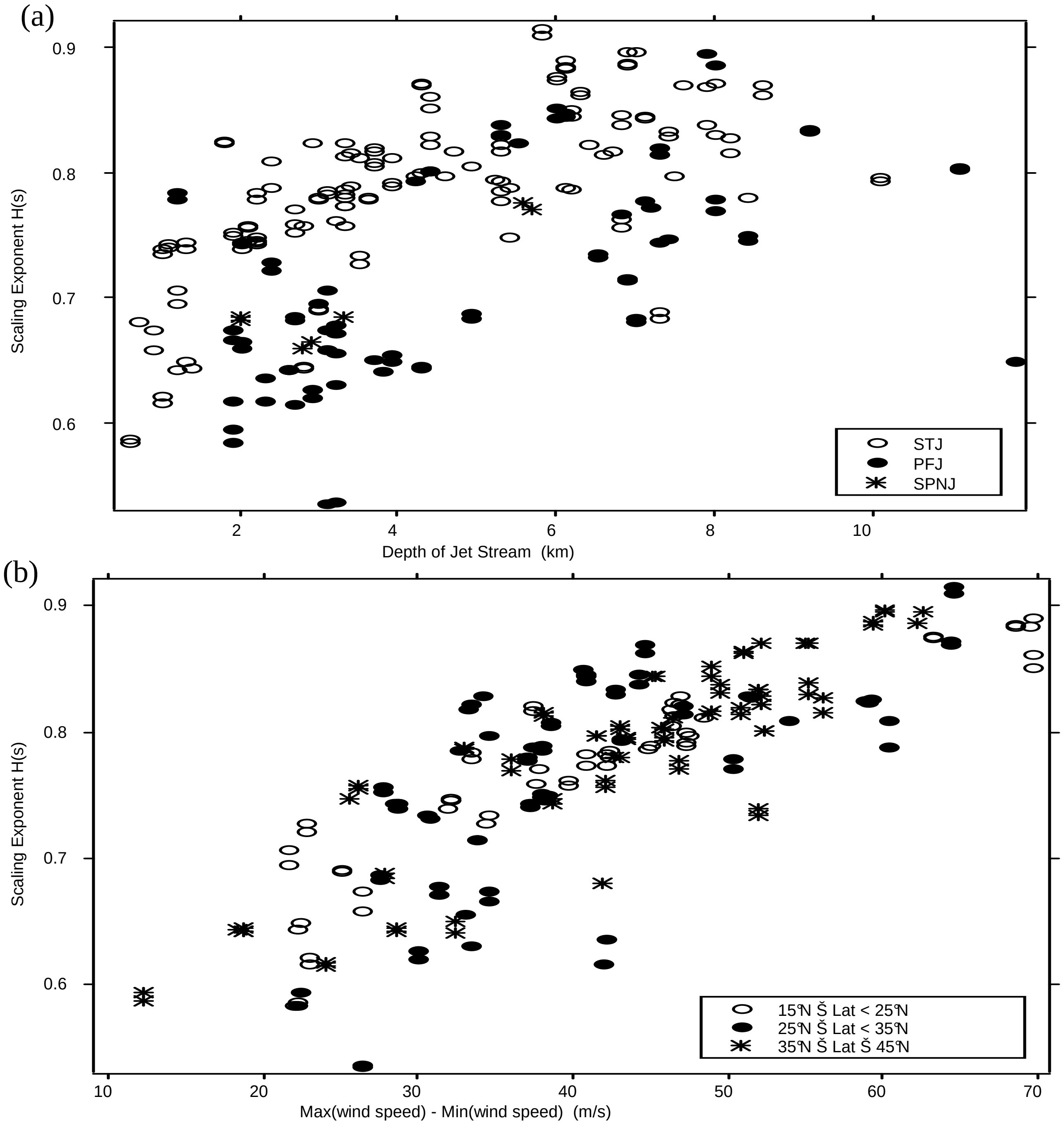
*What of the vertical scaling?


(a)
Geopotential Altitude (km)
Temperature (deg C)
H 1 = 0.971 ± 0.009
log(<|f(x+r) - f(x)|>)
log(r)
(b)
Geopotential Altitude (km)
Horizontal Wind Speed (m/s)
H 1 = 0.668 ± 0.101
log(<|f(x+r) - f(x)|>)
log(r)
(c)
Geopotential Altitude (km)
Relative Humidity (%)
H 1 = 0.706 ± 0.041
log(<|f(x+r) - f(x)|>)
log(r)

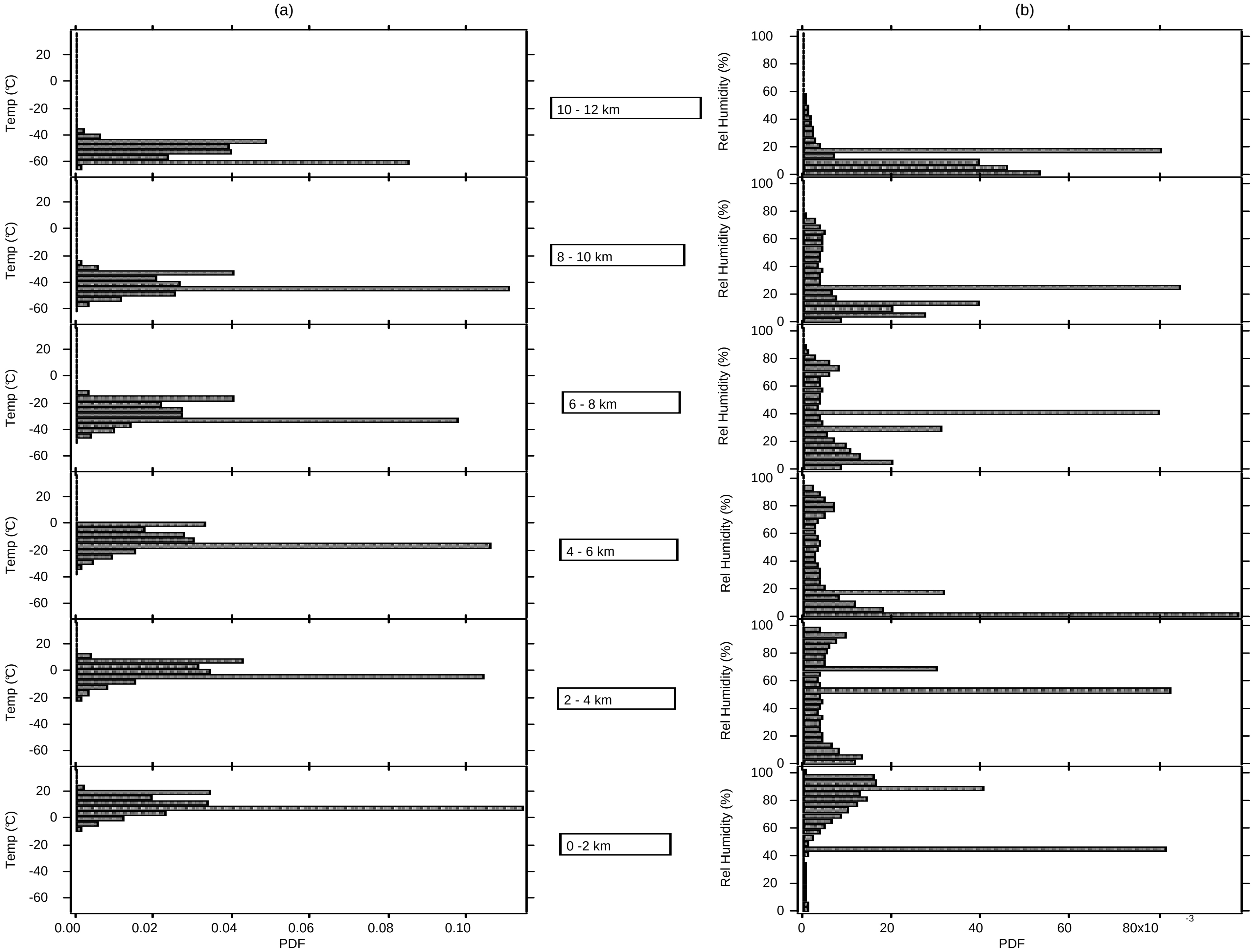

(a)
Geopotential Altitude (km)
0
2
4
6
8
10
12
-40
-20
0
20
Temperature (deg C)
H 1 = 0.972 ± 0.024
log(<|f(x+r) - f(x)|>)
-1.0
-0.5
0.0
0.5
1.0
1.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
log(r)
(b)
Geopotential Altitude (km)
20
30
40
50
60
Horizontal Wind Speed (m/s)
H 1 = 0.817 ± 0.028
log(<|f(x+r) - f(x)|>)
log(r)
(c)
Geopotential Altitude (km)
0
20
40
60
80
Relative Humidity (%)
H 1 = 0.817 ± 0.022
log(<|f(x+r) - f(x)|>)
log(r)

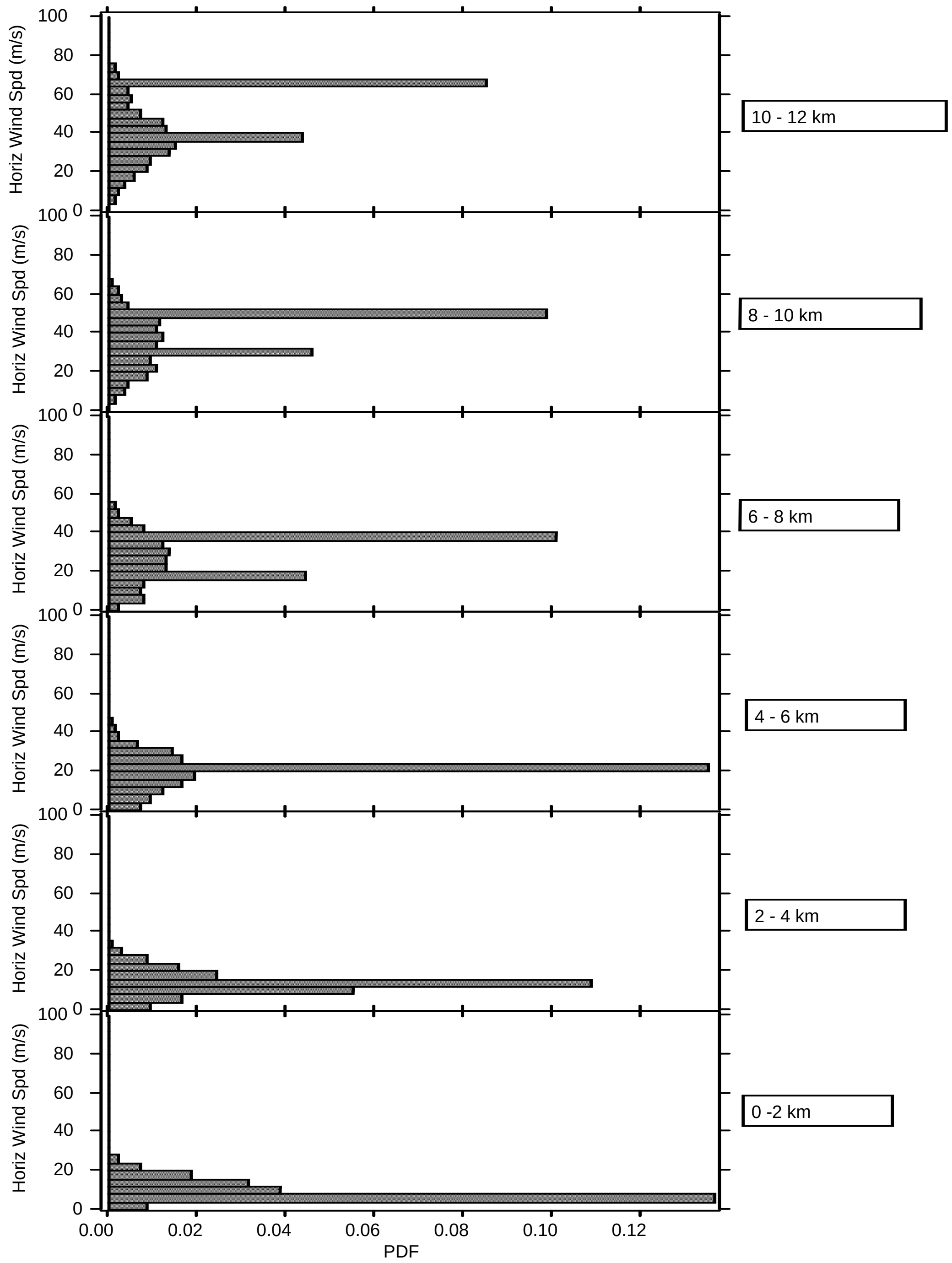


(a)
Geopotential Altitude (km)
Temperature (deg C)
H 1 = 0.98 ± 0.01
log(<|f(x+r) - f(x)|>)
log(r)
(b)
Geopotential Altitude (km)
Horizontal Wind Speed (m/s)
H 1 = 0.798 ± 0.023
log(<|f(x+r) - f(x)|>)
log(r)
(c)
Geopotential Altitude (km)
Relative Humidity (%)
H 1 = 0.748 ± 0.028
log(<|f(x+r) - f(x)|>)
log(r)



(a)
Scaling Exponent H(s)
0.9
0.8
0.7
0.6
2
4
6
8
10
Depth of Jet Stream (km)
STJ
PFJ
SPNJ
(b)
Scaling Exponent H(s)
0.9
0.8
0.7
0.6
10
20
30
40
50
60
70
Max(wind speed) - Min(wind speed) (m/s)
15°N Š Lat < 25°N
25°N Š Lat < 35°N
35°N Š Lat Š 45°N


(a)
(b)
Temp (℃)
Rel Humidity (%)
10 - 12 km
8 - 10 km
6 - 8 km
4 - 6 km
2 - 4 km
0 -2 km
PDF
0.00
0.02
0.04
0.06
0.08
0.10
0
20
40
60
80x10-3



Horiz Wind Spd (m/s)
100
80
60
40
20
0
10 - 12 km
8 - 10 km
6 - 8 km
4 - 6 km
2 - 4 km
0 -2 km
0.00
0.02
0.04
0.06
0.08
0.10
0.12
PDF

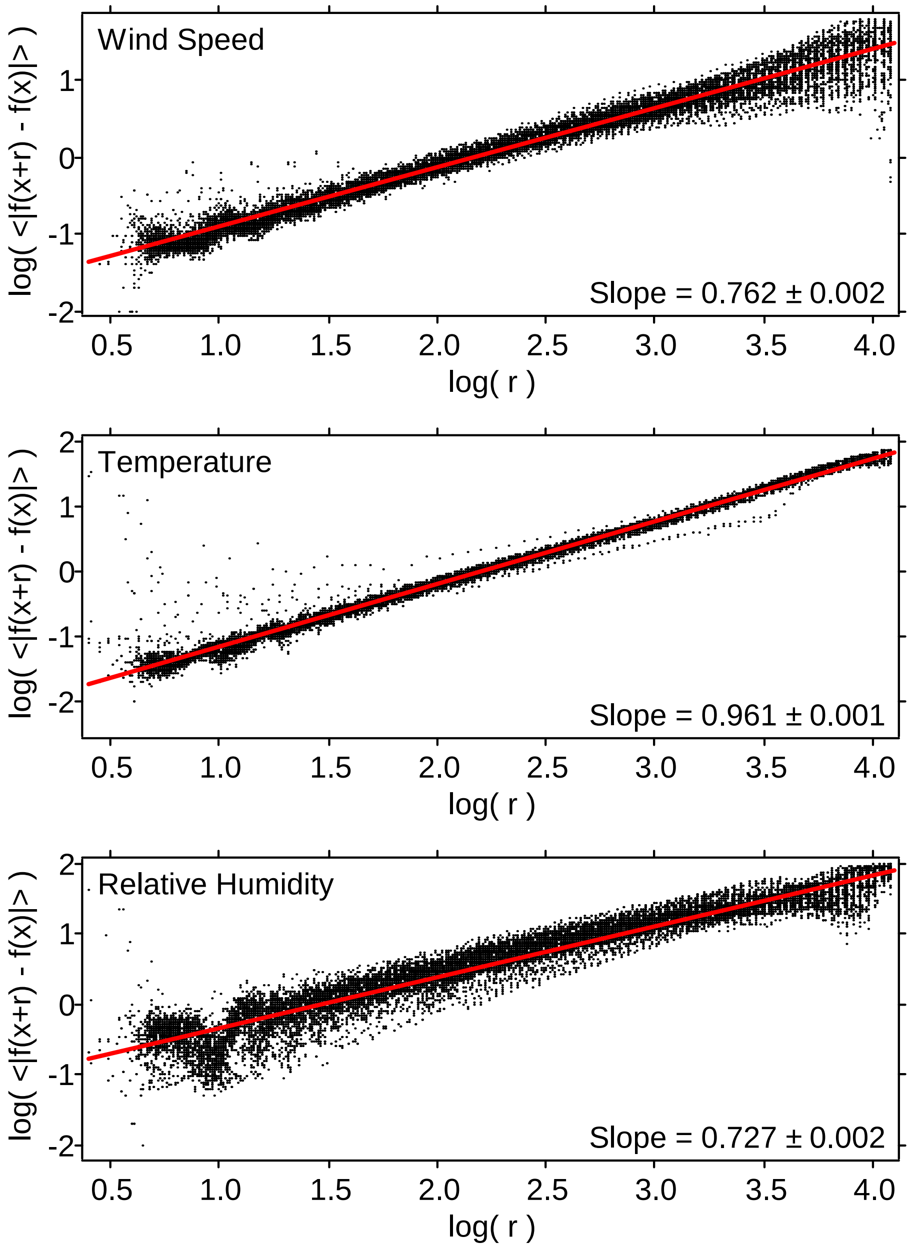
The figures to the right are *composite variograms*, created by overlaying the individual variograms computed for each dropsonde and then fitting a line to the aggregate.

While variograms typically involve variance, we use the first order structure function in order to minimize intermittency corrections and to facilitate comparison with theoretical (dimensional analysis) exponents.

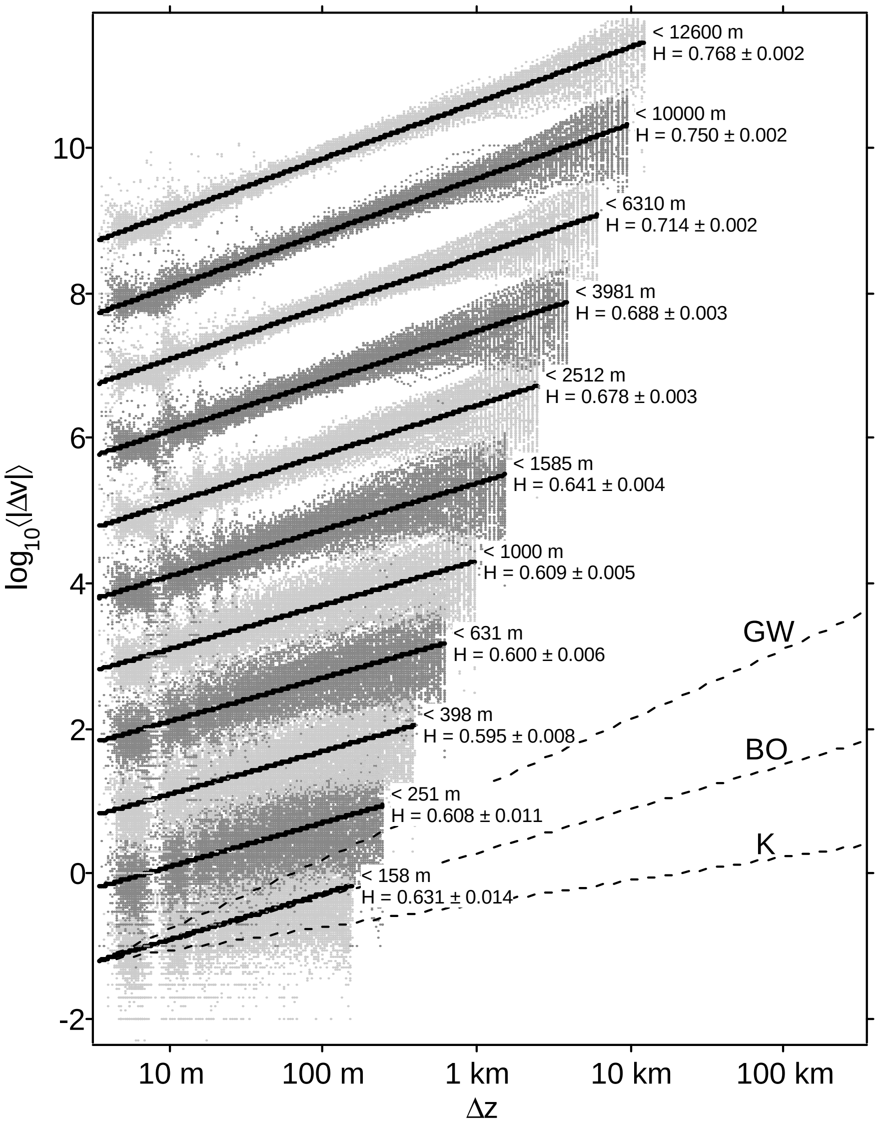
Each individual variogram contained about 100 points, and there were 235 drops that successfully measured wind speed, and 246 that measured temperature and relative humidity. Therefore the lines to the right are each fitting roughly 24,000 points. The errors are 95% confidence intervals.

The surprise is that the slope (i.e. H) for horizontal wind speed, came out appreciably higher than the Bolgiano-Obukhov theoretical value of 0.6. This indicates smoother than expected horizontal wind speed profiles. It is clear also that temperature behaves differently in the vertical than the other variables.

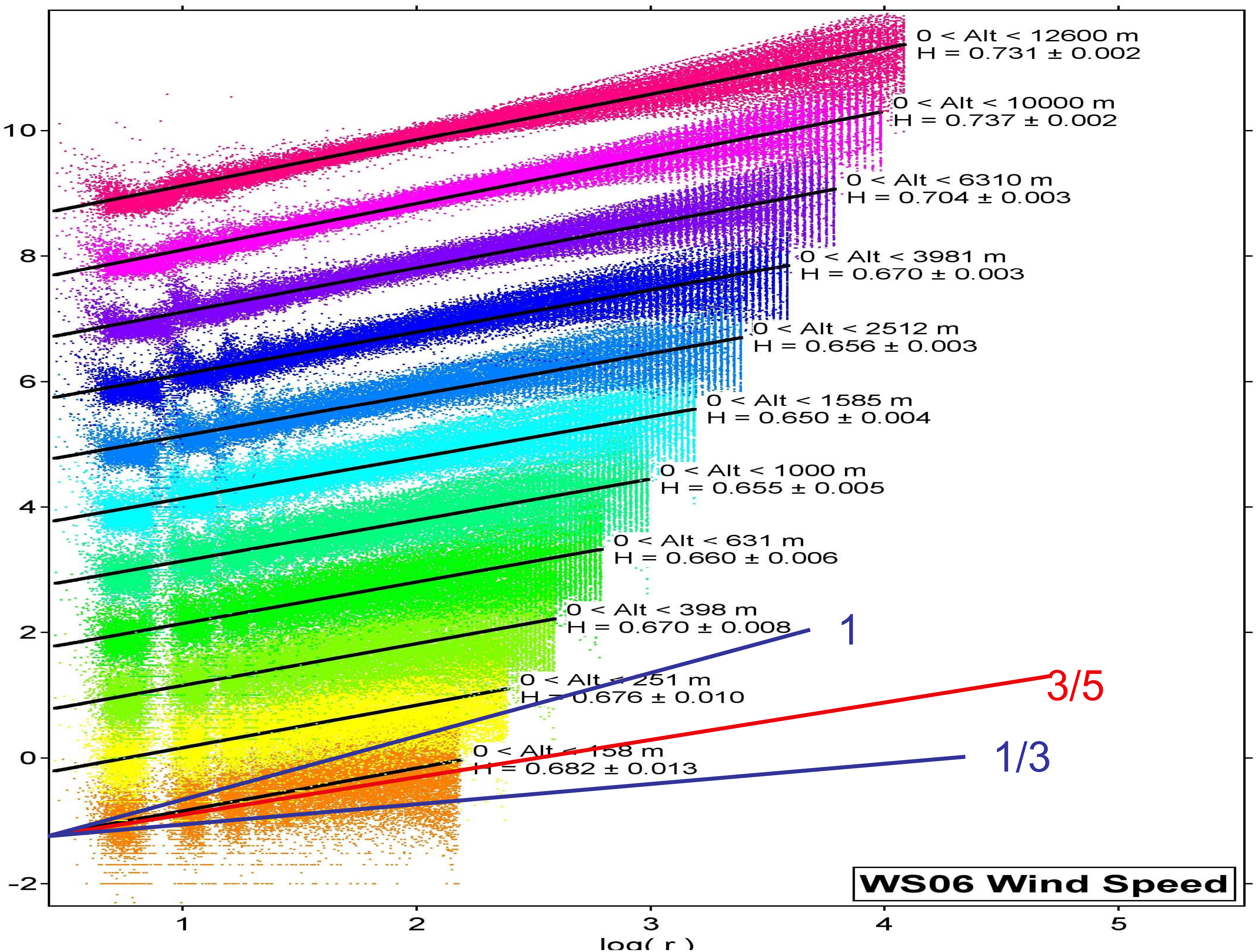
Subsequent spectral analysis has shown that the near-unity value of H for temperature is an artifact of the structure function method, which does not produce a good estimate of H when $H > 1$ or $H < 0$. For the data of 20040229, the spectral method yielded $H \approx 5/4$, again a value unique to temperature.



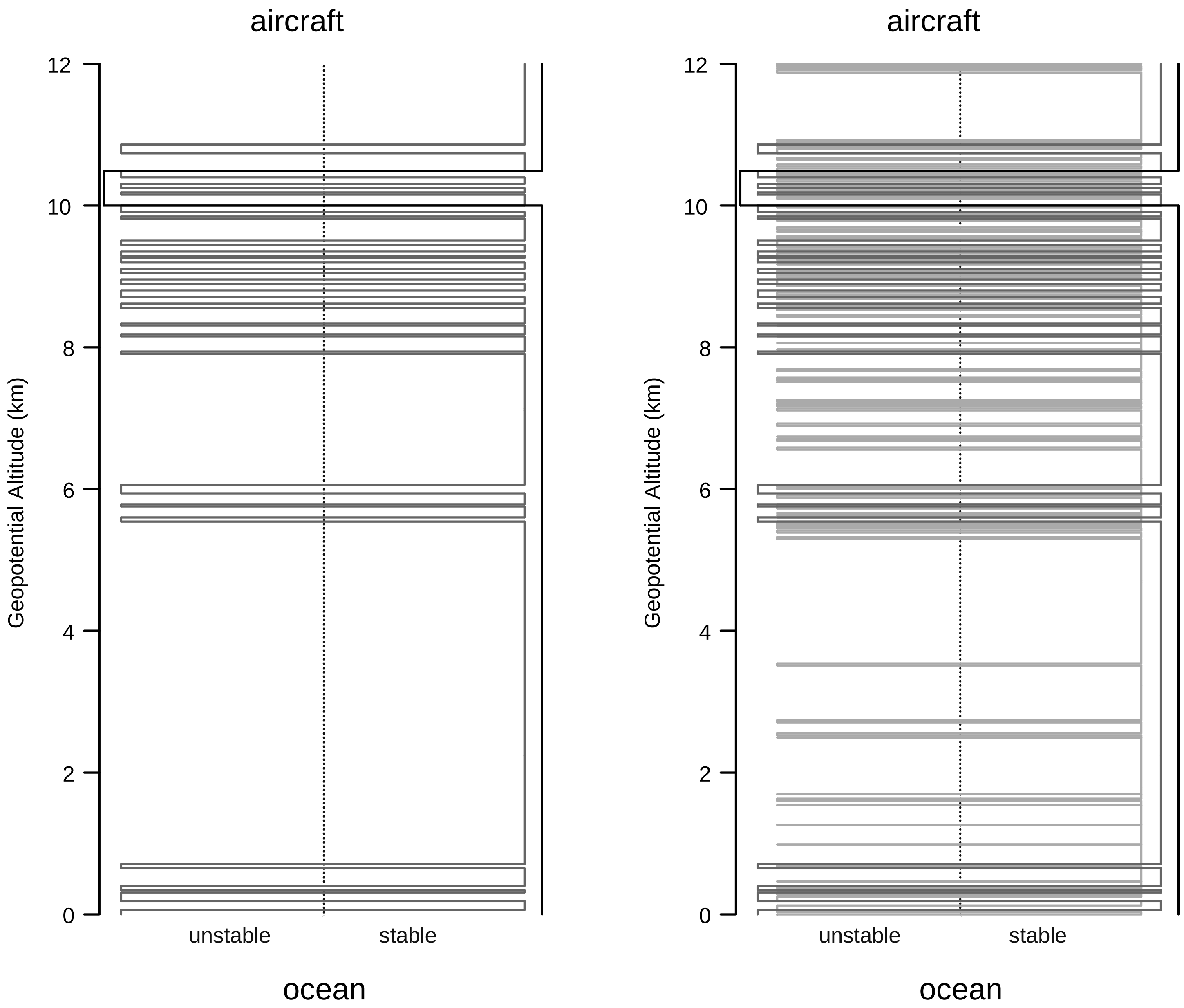
Vertical scaling of horizontal wind, 235 dropsondes, Winter Storms 2004. Scaling is not Kolmogorov or gravity wave; Bolgiano-Obukhov is close in boundary layer, but none are correct at jet altitudes.



WS 2004


0 < Alt < 12600 m
H = 0.731 ± 0.002
0 < Alt < 10000 m
H = 0.737 ± 0.002
0 < Alt < 6310 m
H = 0.704 ± 0.003
0 < Alt < 3981 m
H = 0.670 ± 0.003
0 < Alt < 2512 m
H = 0.656 ± 0.003
0 < Alt < 1585 m
H = 0.650 ± 0.004
0 < Alt < 1000 m
H = 0.655 ± 0.005
0 < Alt < 631 m
H = 0.660 ± 0.006
0 < Alt < 398 m
H = 0.670 ± 0.008
0 < Alt < 251 m
H = 0.676 ± 0.010
0 < Alt < 158 m
H = 0.682 ± 0.013
1
3/5
1/3
WS06 Wind Speed
log(r)

Dynamical stability [Ri>0.25] at 500 & 150 m(left),50 & 10 m(right)
Dropsonde (25˚N,157˚W) on 20040229. The ‘Russian doll’ structure.



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decompressor
are needed to see this picture.

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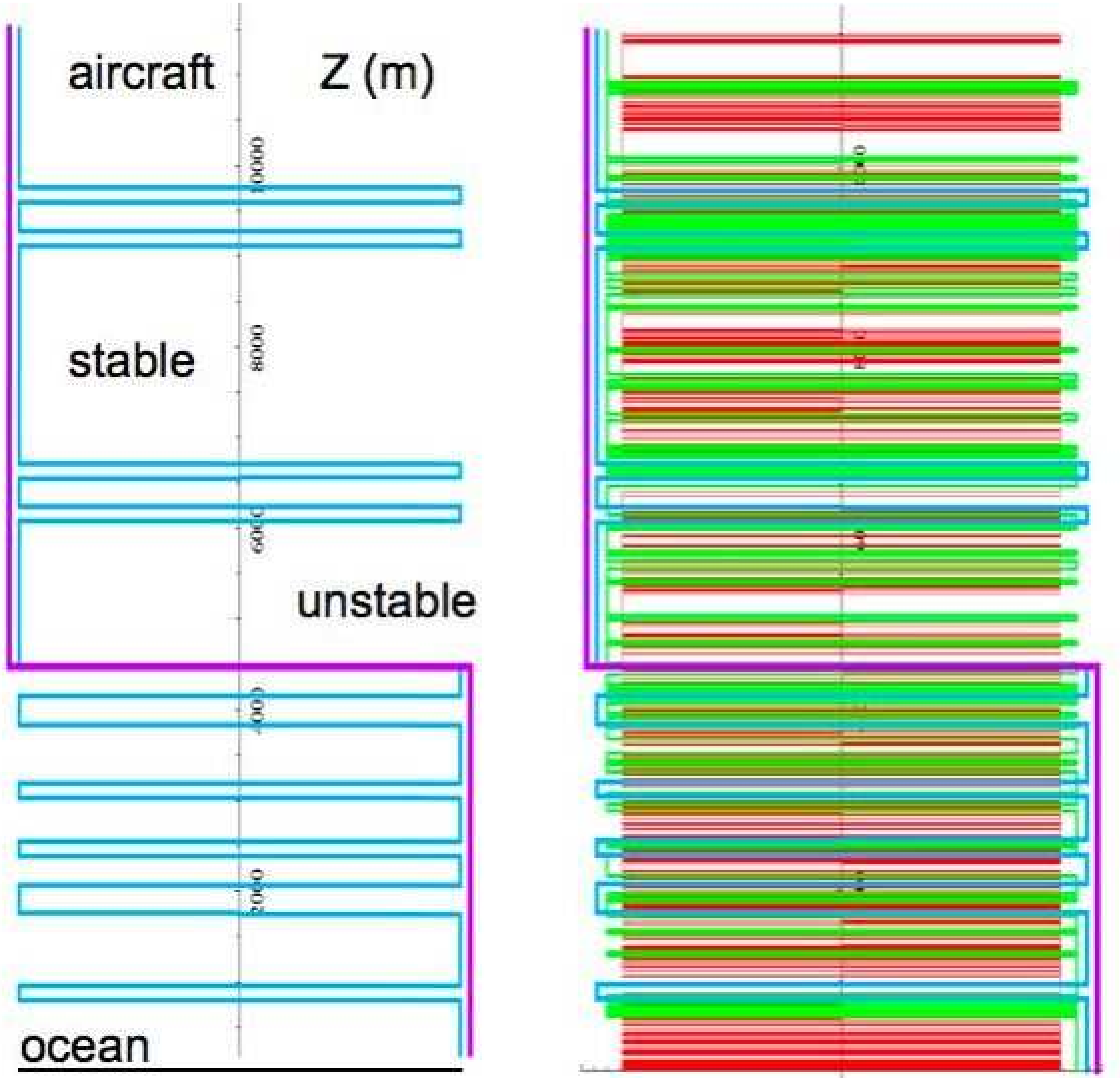
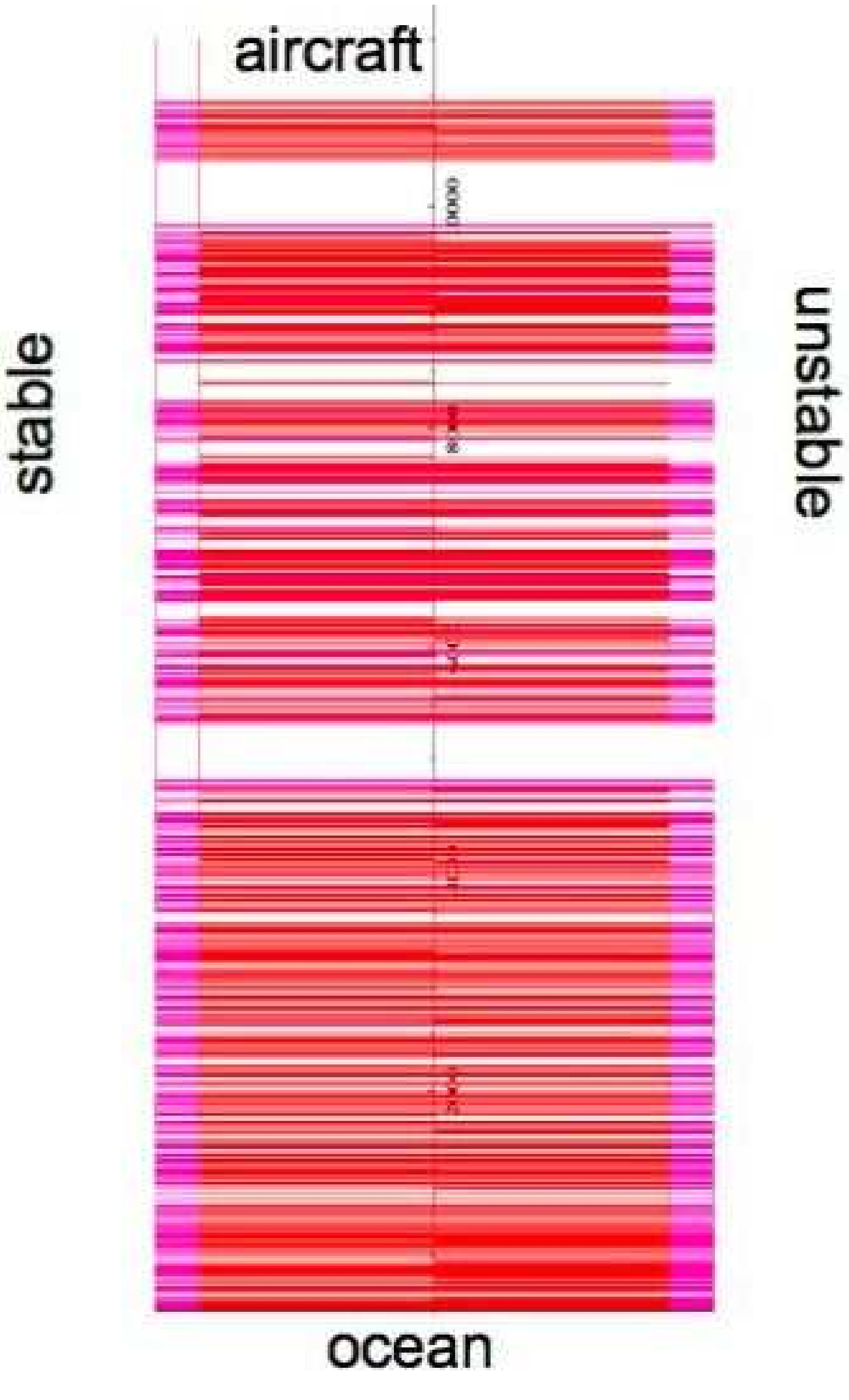
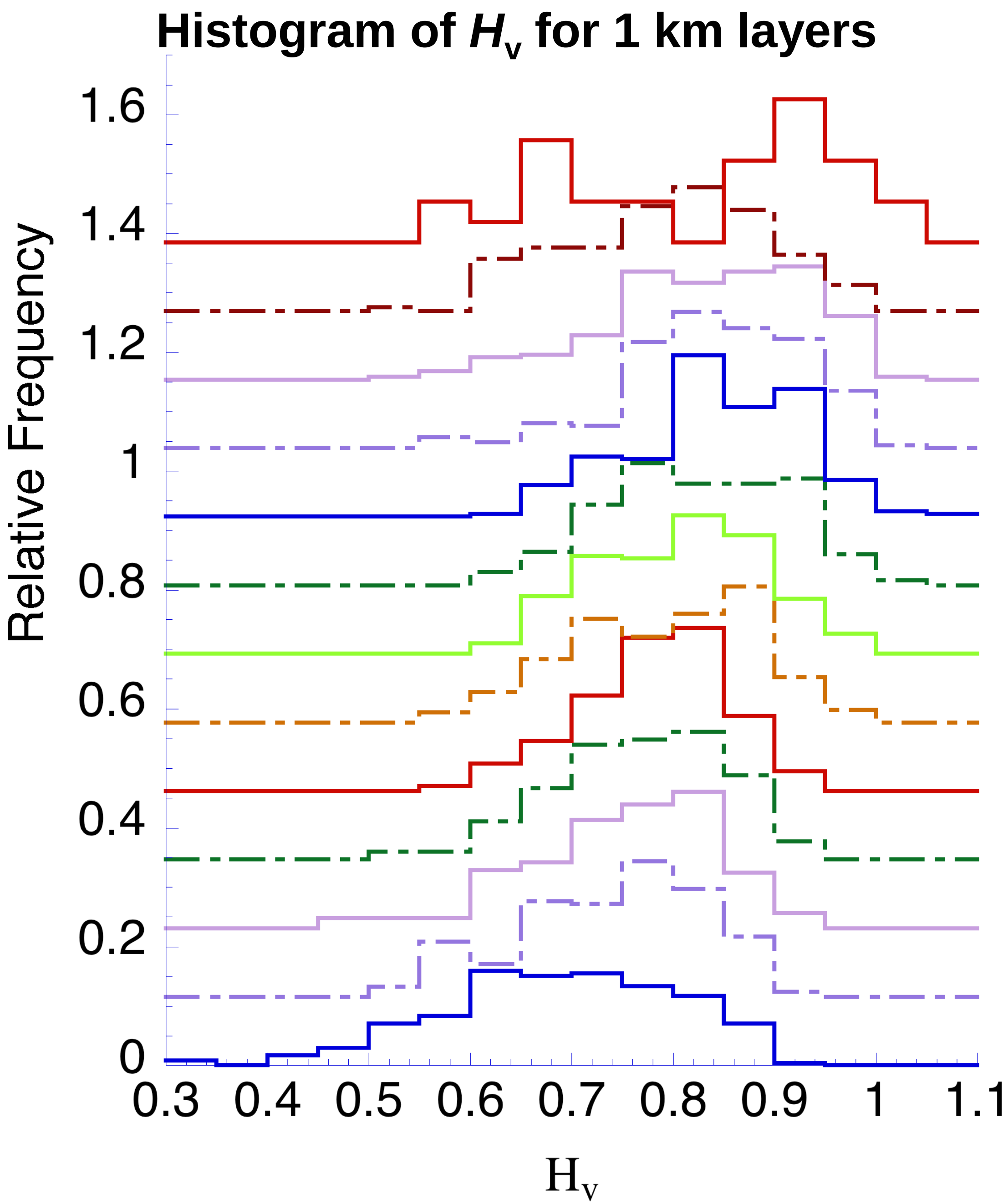
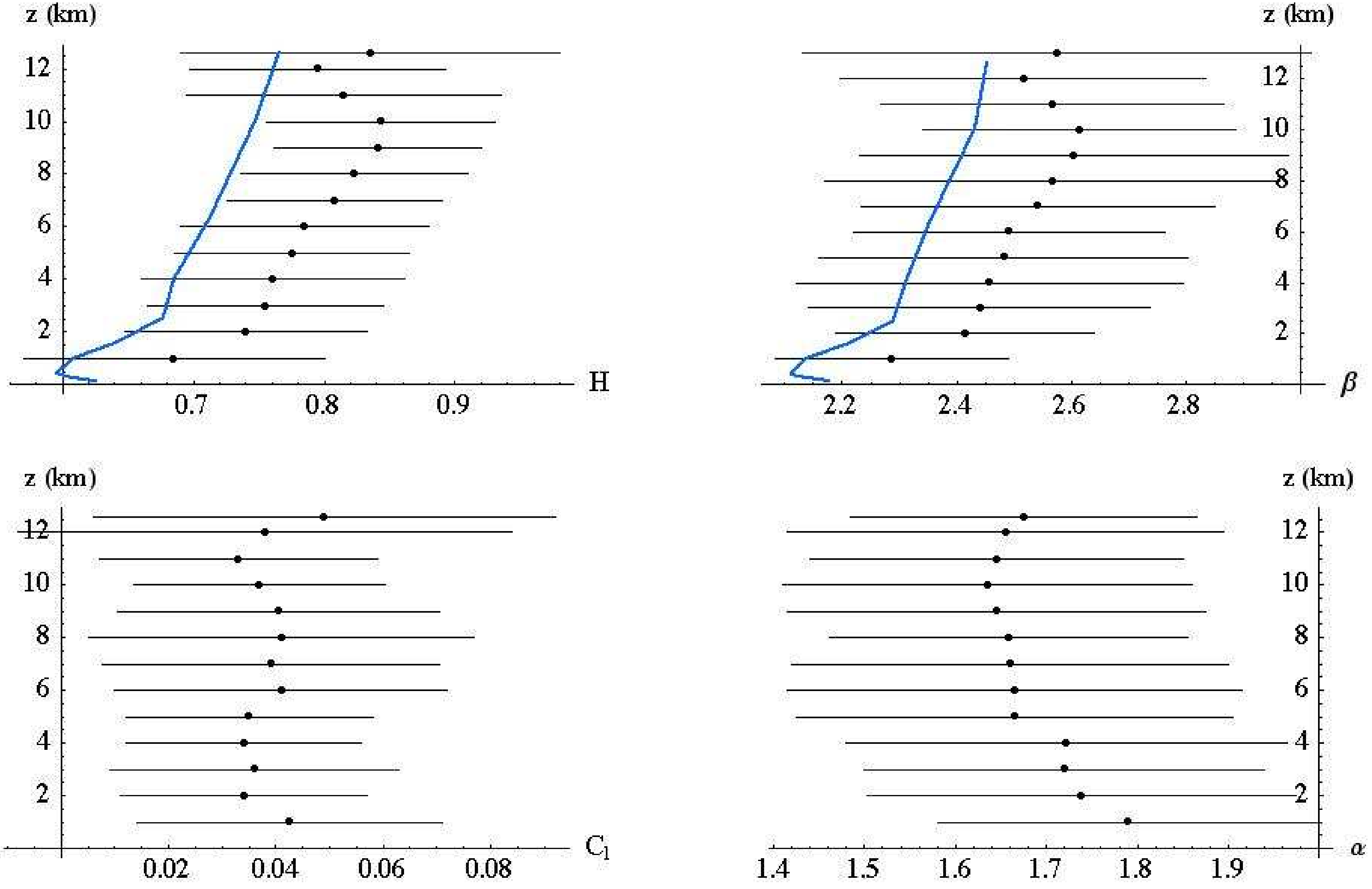


aircraft
Z (m)
10000
stable
8000
6000
unstable
4000
2000
ocean


aircraft
stable
unstable
ocean

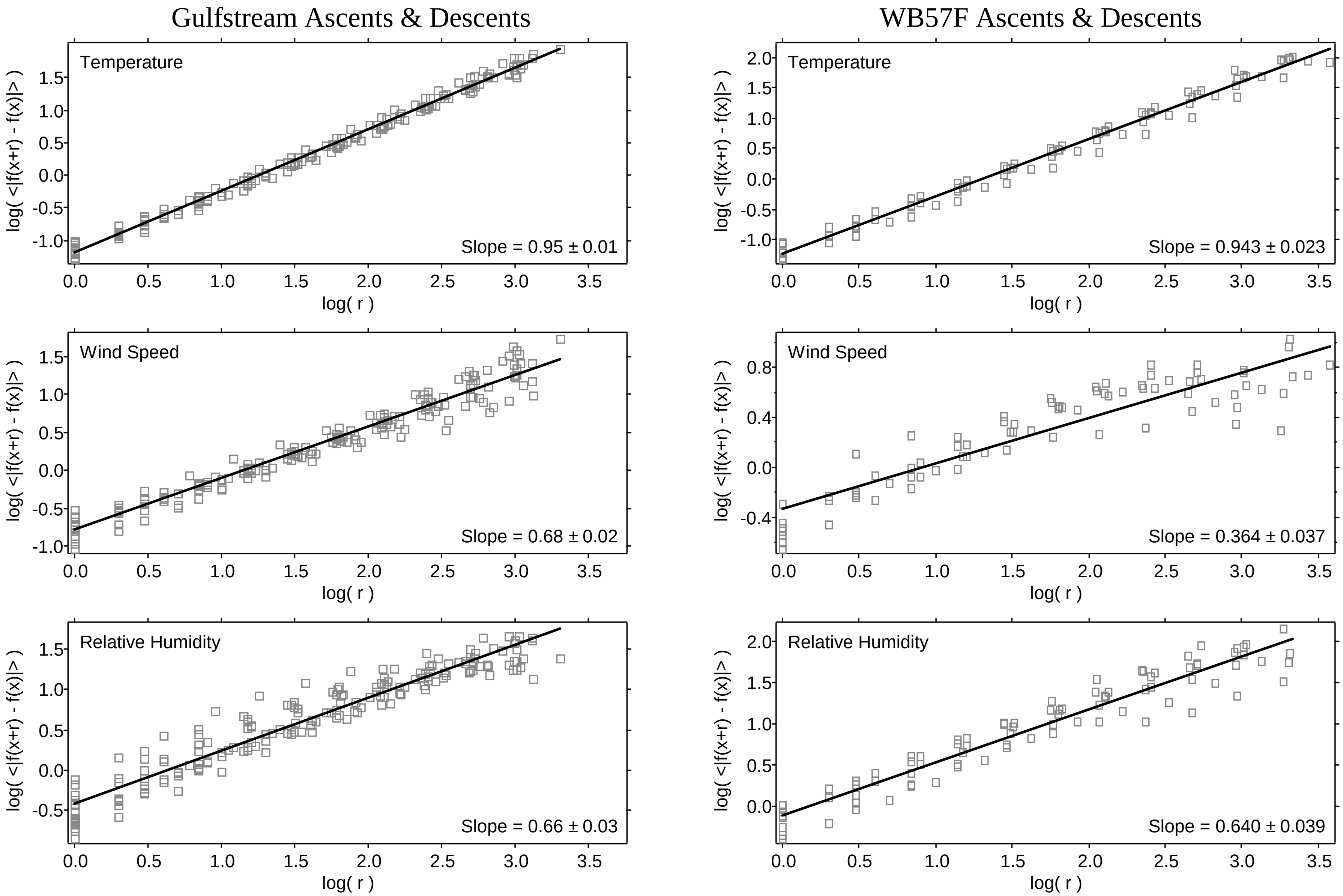

Histogram of H_v for 1 km layers
Relative Frequency
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
H_v

Velocity scaling exponents H, β, C_1 and α

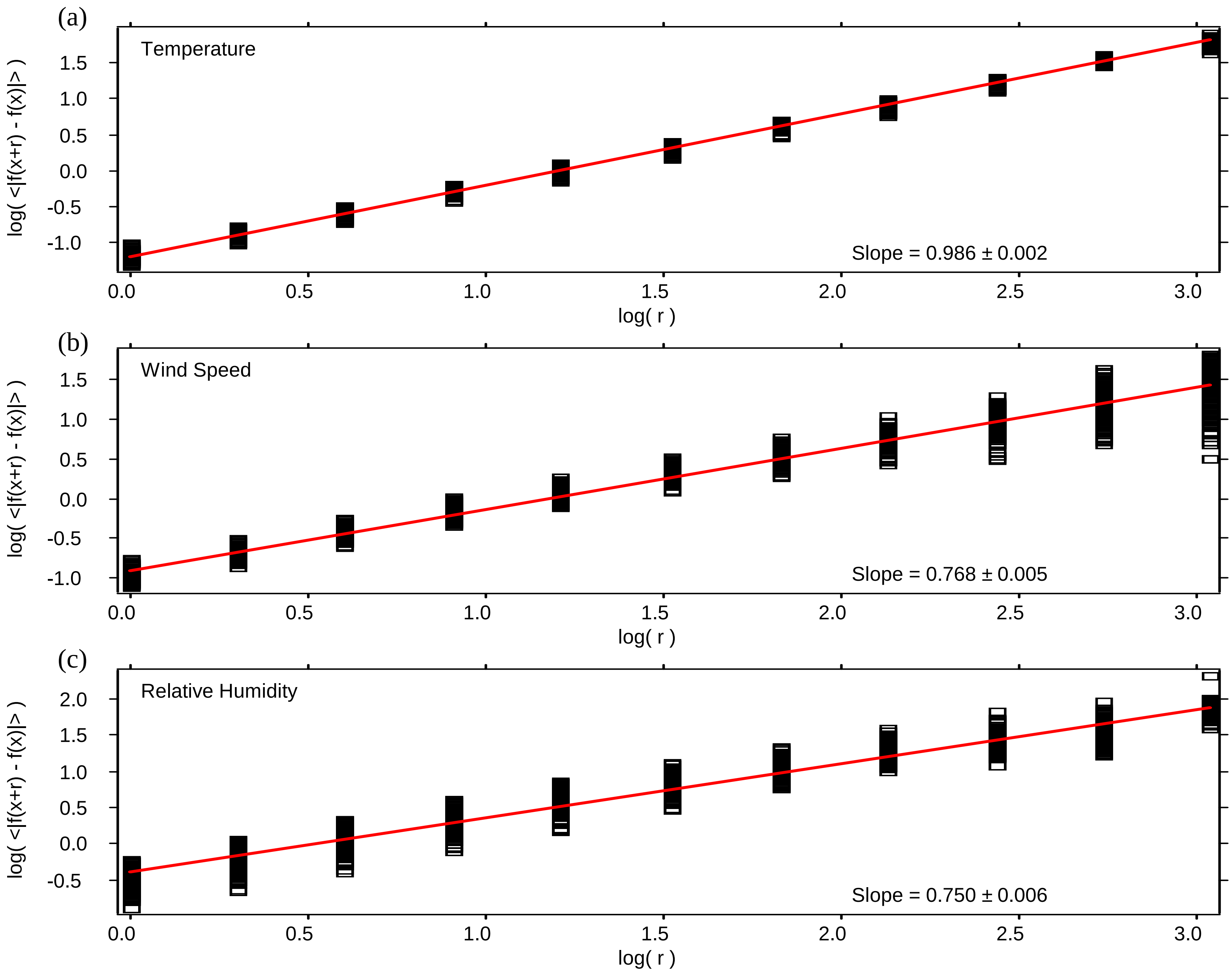



26

Aircraft ascents and descents,Jan-Mar 2004,10˚- 60˚N,84˚- 158˚W



Variogram, all 261 dropsondes during the mission



Scaling from G4 in Winter Storms 2004

	Dropsond	Vertical Aircraft Segments	Horizontal Aircraft Segments
Temperat	0.986±0.002	0.95±0.02	0.52±0.02
Wind Speed	0.768±0.005	0.68±0.02	0.56±0.02
Relative Humidity	0.750±0.006	0.66±0.03	0.45±0.03

Vertical & horizontal exponents are different; no isotropy!

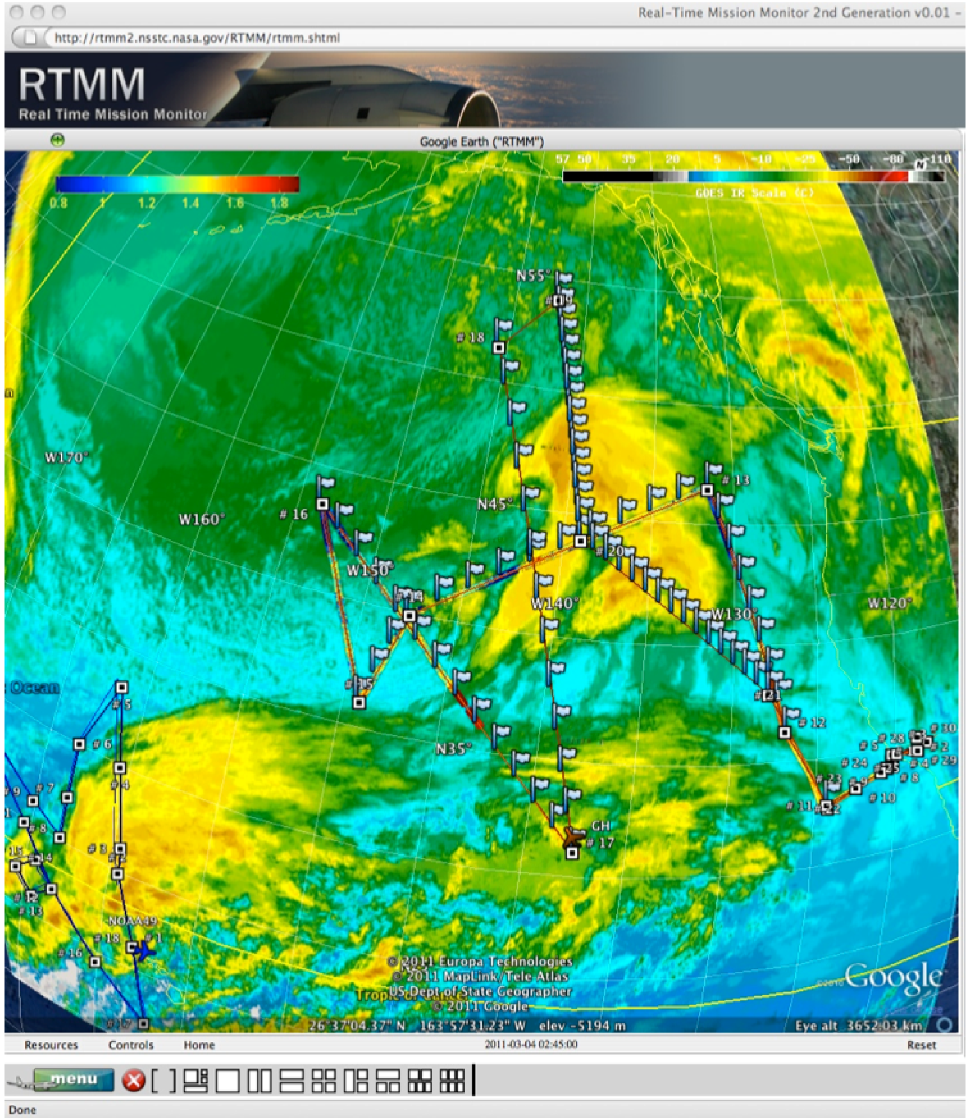
Co-dimensions of vertical stability criteria

CRITERION	**CO-DIMENSION**
$N^2(\theta) = g\partial\log\theta/\partial z$ Brunt-Väisälä (dry)	0.36 ± 0.06
$Ri = N^2(\theta)\,[\partial v/\partial z]^{-2}$ Richardson Number	0.22 ± 0.04
$N^2(\theta_w) = \partial\theta_w/\partial z$ Moist static stability	0.15 ± 0.02

Water - via its latent heat entropy - makes a big difference to atmospheric stability *on all scales.*

NASA Global Hawk drone aircraft

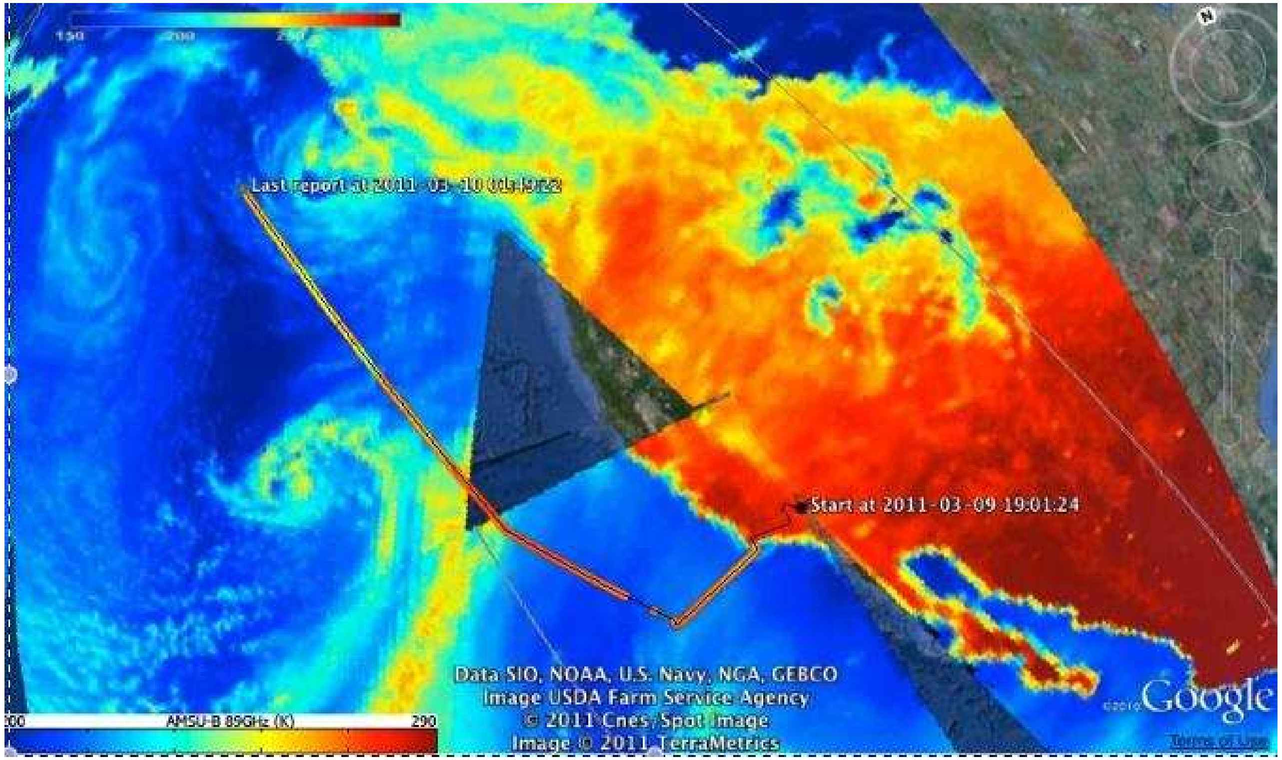
1 000 kg to 19 km altitude for 28 hours at 175 m/s



Feb-Mar 2011

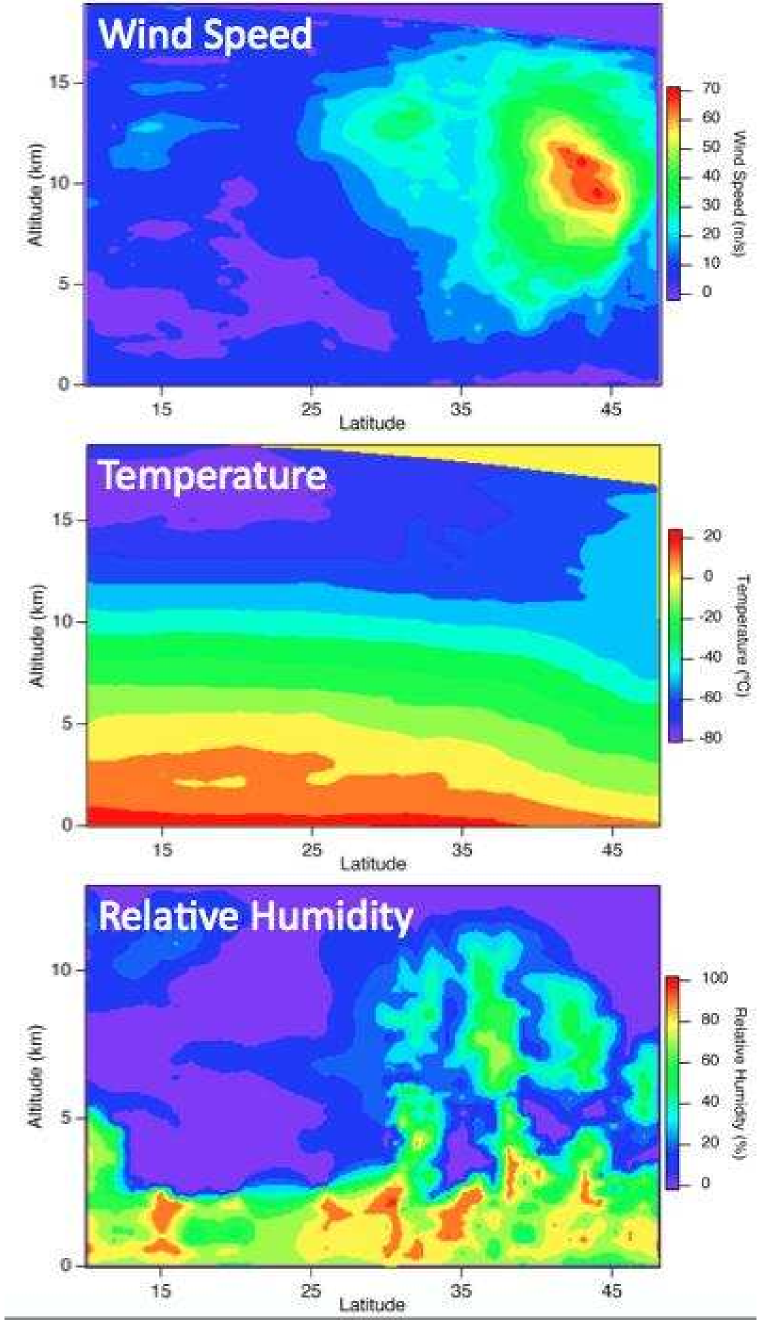
GH: 24 000 km, 70 sondes from 19 km in 30 hours
G4: 7 000 km, 16 sondes from 13 km in 7 hours

Brightness temperature 89.5 GHz from AMSU-B



See: F M Ralph et al. Flooding on California's Russian River: rôle of atmospheric rivers, *Geophys Res Lett* 33, L13801, (2006)

HAMSR on Global Hawk



SUMMARY

* GPS dropsondes are very effective at observing the vertical structure of wind, temperature and humidity. They improved forecasts of flooding on the California coast.

* Variables do not follow Gaussian statistics. They show statistical multifractal scale invariance.
*No monolithic stable layers; no isotropic turbulence.
*Jet streams alter scaling exponent *H* , horiz & vert*.*

* Atmospheric moisture greatly affects vertical scaling, and is highly concentrated in so-called “atmospheric rivers”.

* Drone aircraft are showing a large improvement in capability.