Measurements of High-Altitude Turbulence from Research Aircraft

and

Comparison with CAT indices as predicted by ECMWF's IFS

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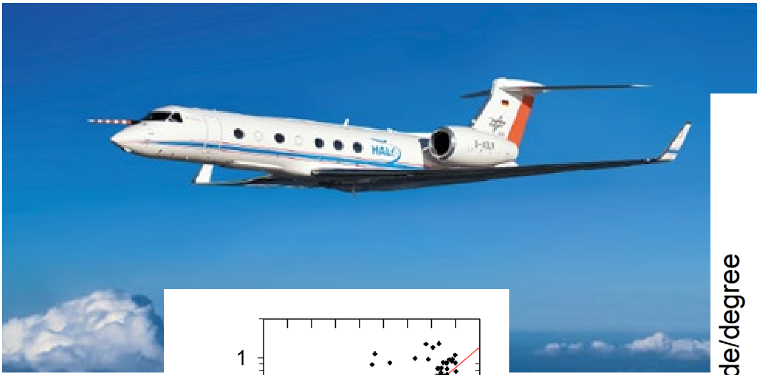
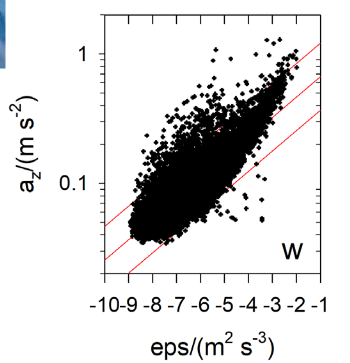
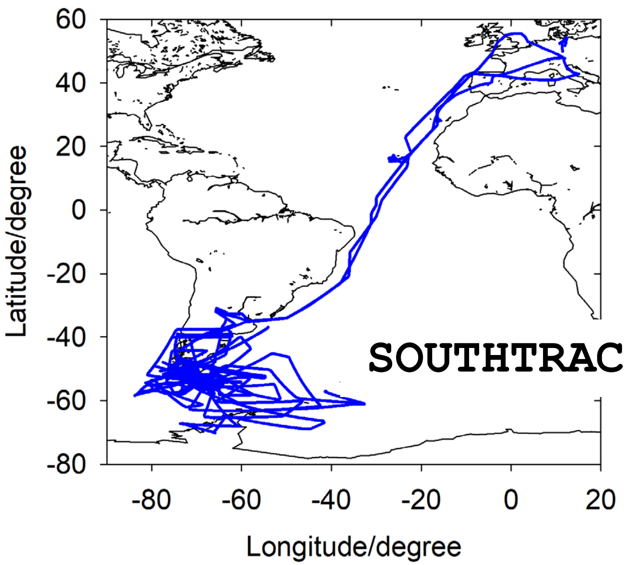
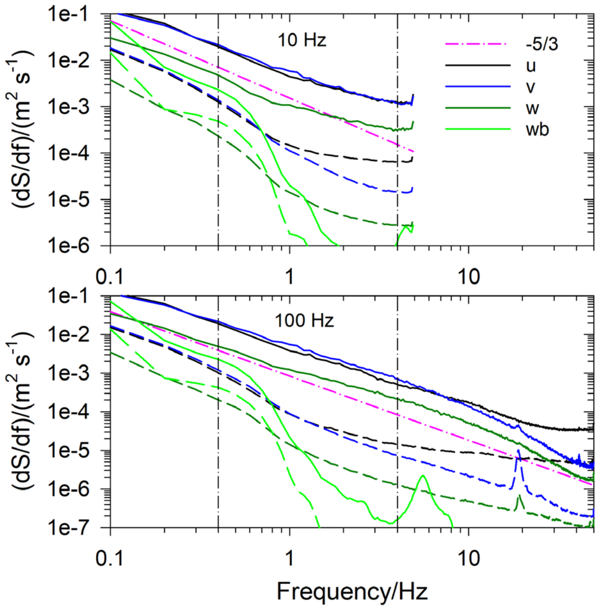
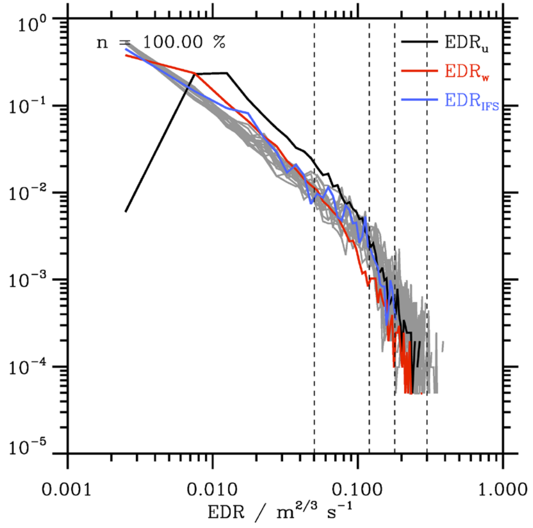






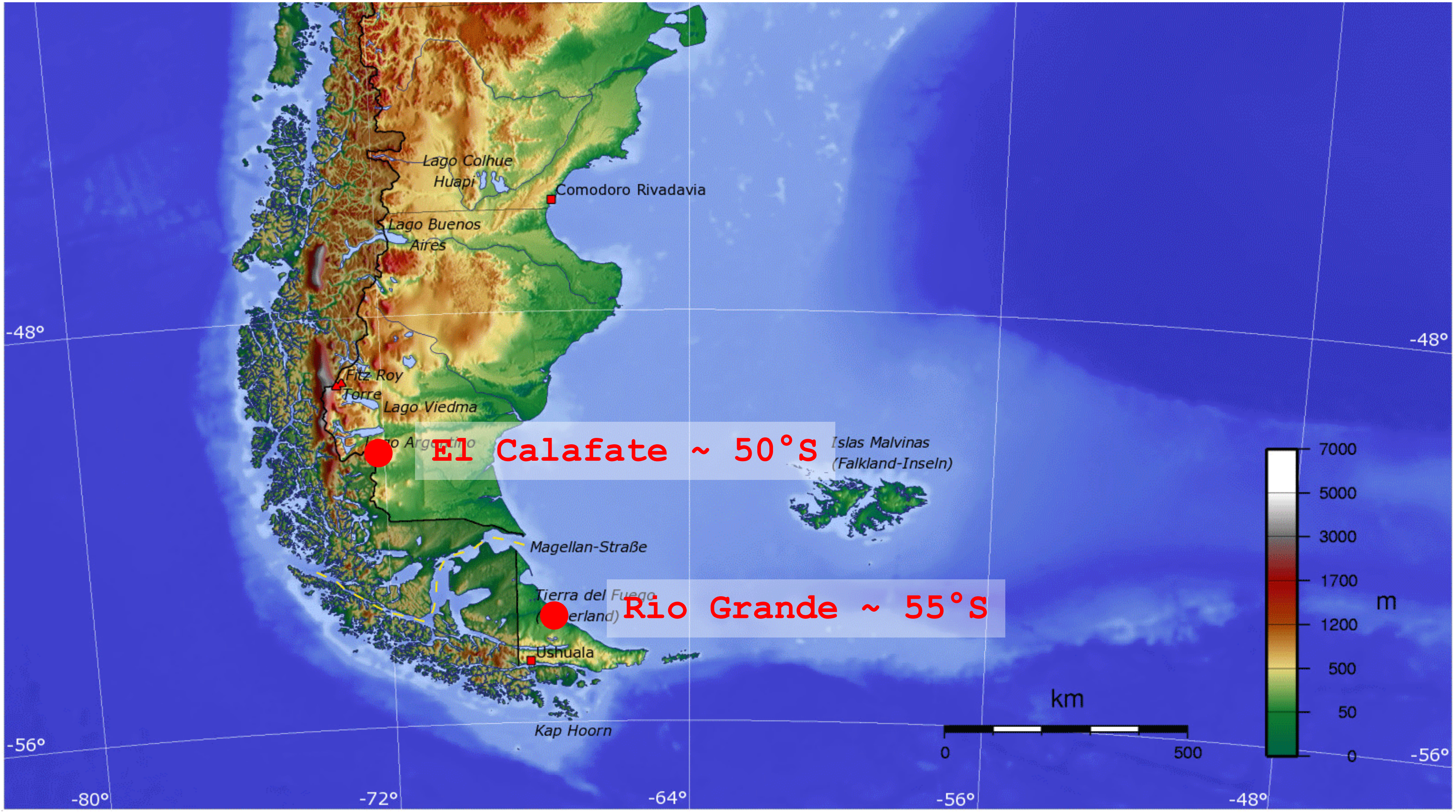




SOUTHTRAC: Southern Hemisphere Transport, Dynamics, and Chemistry

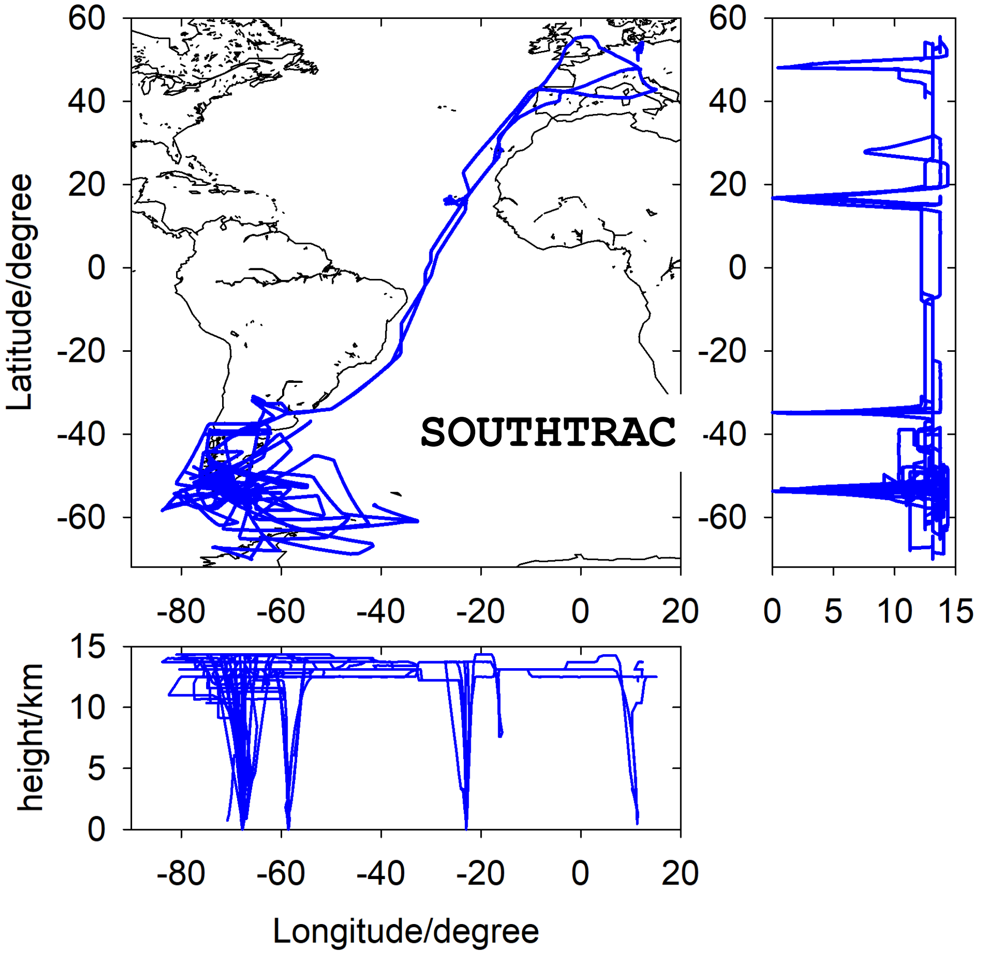
Rapp, M., B. Kaifler, A. Dörnbrack, S. Gisinger, T. Mixa, R. Reichert, N. Kaifler, S. Knobloch, R. Eckert, N. Wildmann, A. Giez, L. Krasauskas, P. Preusse, M Geldenhuys, W. Woiwode, F. Friedl-Vallon, B.-M. Sinnhuber, A. de la Torre, P. Alexander, J. L. Hormaechea, D. Janches, M. Garhammer,J. L. Chau, J. F. Conte, P. Hoor, and A. Engel, 2021: SOUTHTRAC-GW: An airborne field campaign to explore gravity wave dynamics at the world's strongest hotspot. *Bulletin of the American Meteorological Society*, **102**, E871-E893. https://journals.ametsoc.org/view/journals/bams/102/4/BAMS-D-20-0034.1.xml

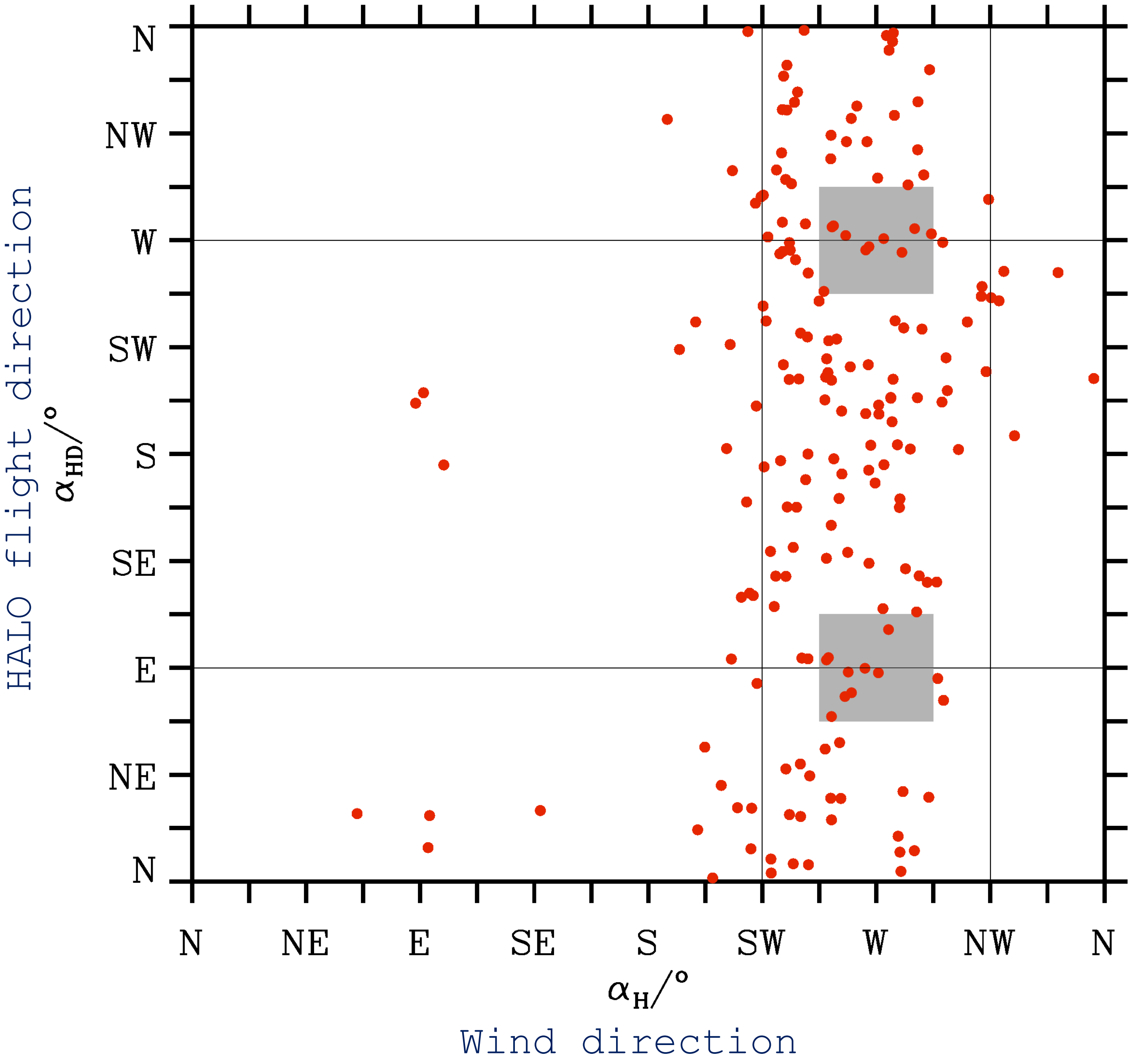
The Physical Scenery



The Aerial Scenery

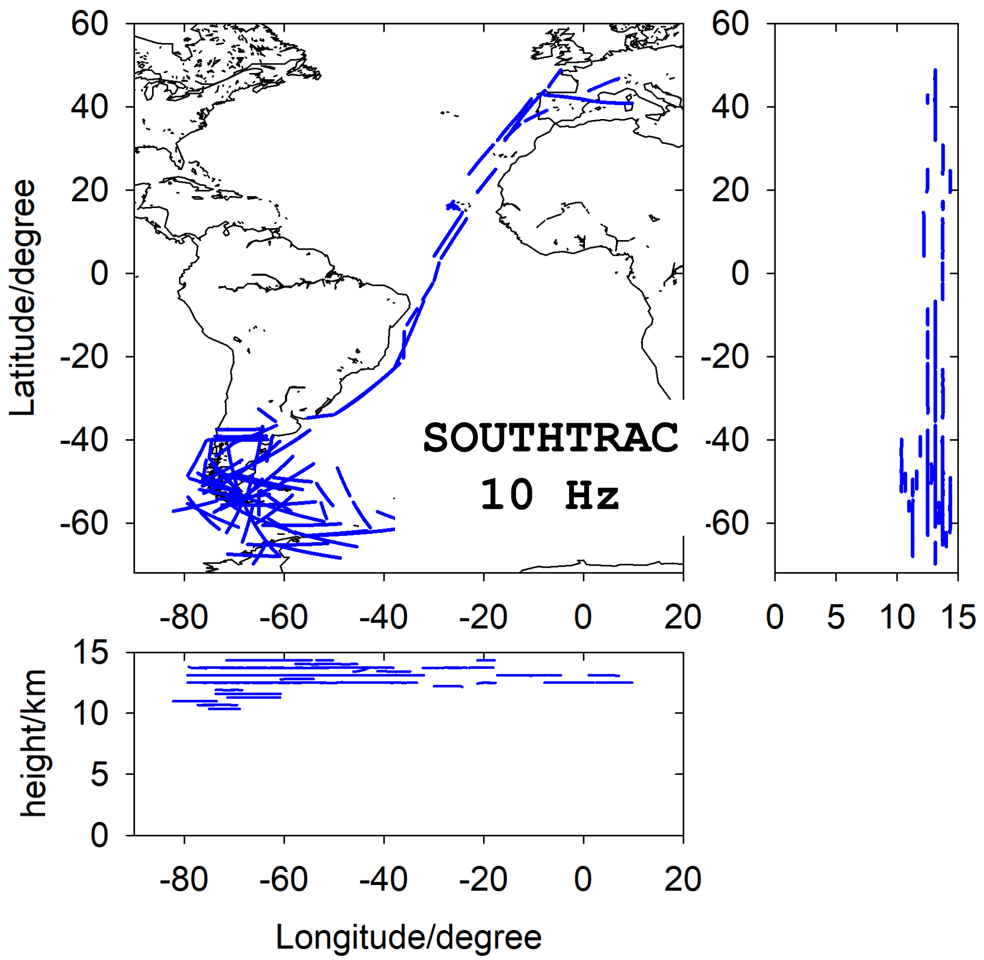
1. HALO Research Flights

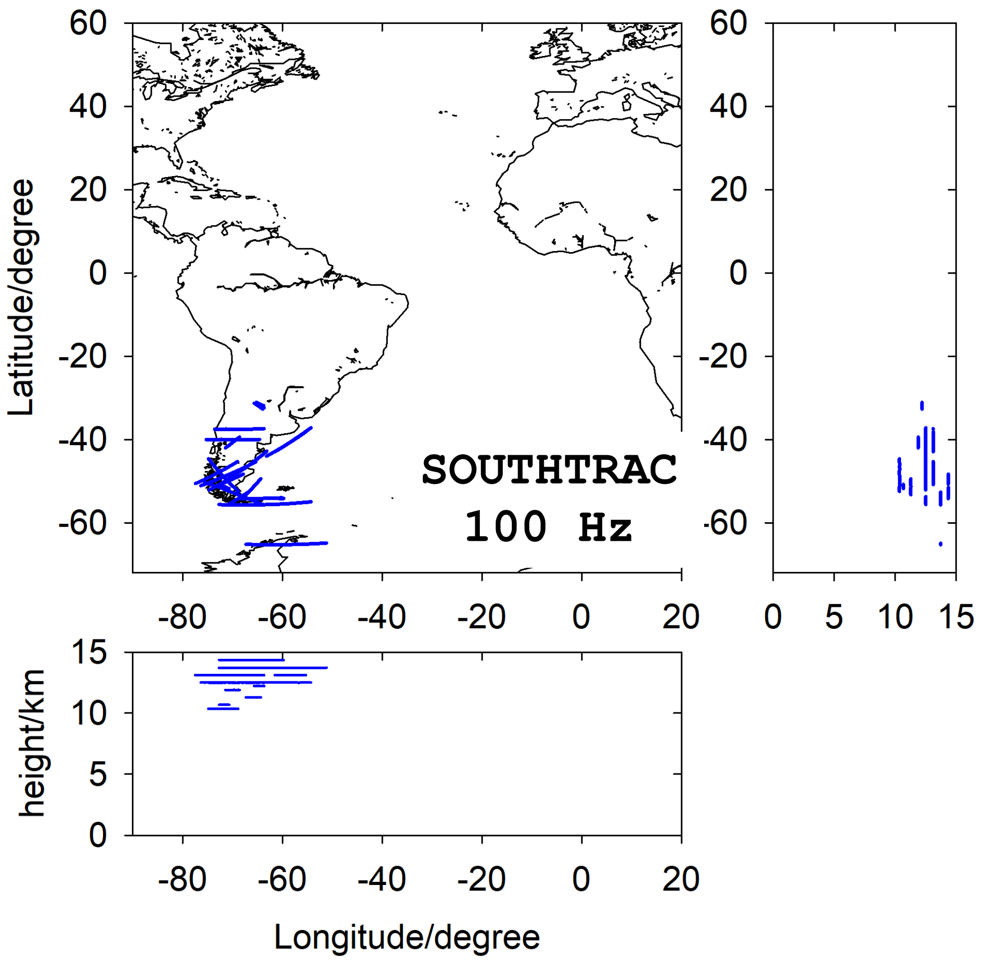




no pronounced orientation of HALO flight legs to the mean wind

1. HALO Research Flights



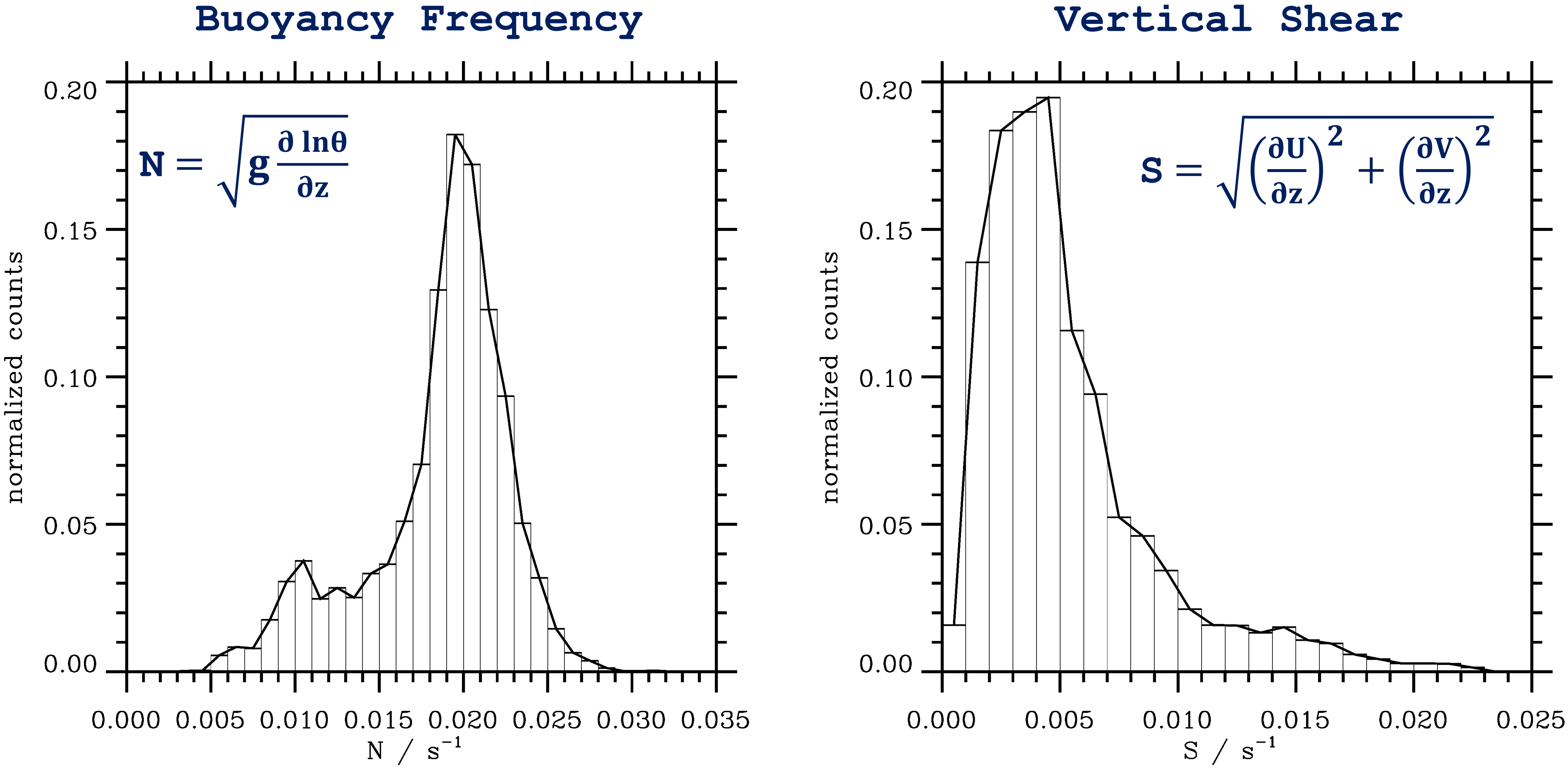


o 188 straight and level legs -> 103718 km HALO flight distance (~2.5 times the circumference of the Earth)

o 10 Hz in-situ data for 123 h flight time

100 Hz in-situ data for a subset of ~20 h

From ECMWF IFS along HALO flights:



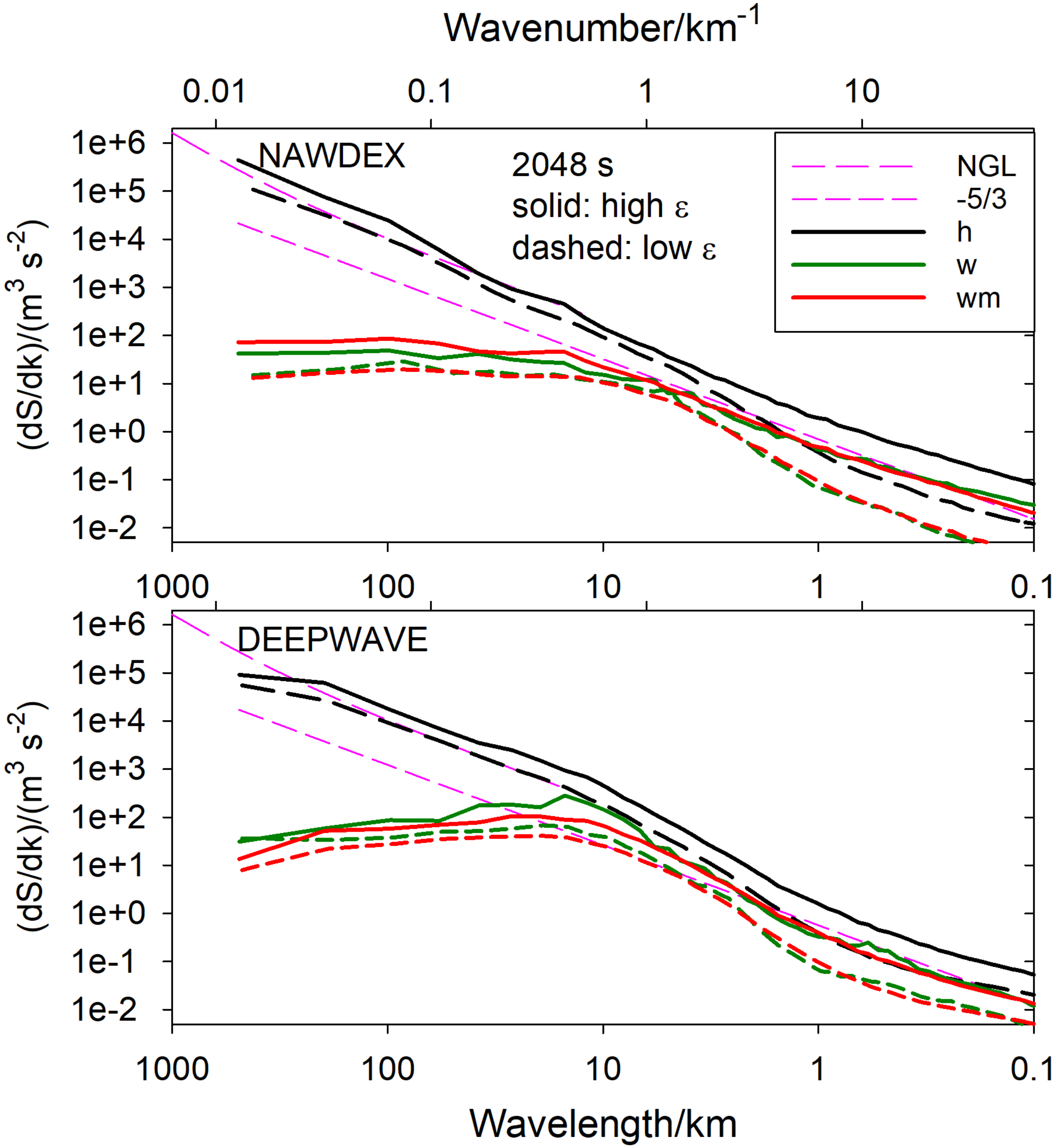
majority of flights in the lower stratosphere ($N \approx 0.02$ s^{-1}, $S < 5\cdot10^{-3}$ s^{-1})

NAWDEX/DEEPWAVE Schumann (2019):

Spectra of horizontal (h) and vertical (w) wind versus wavelength and wave number at low/high dissipation rate ε

w spectra from observation (green) compared with spectral w model wm (red)

Campaign means.



10 Hz
54/53 legs

25 Hz
89/89 legs

NGL= Naström-Gage-Lindborg (-5/3 with transition to to -3 spectrum)

5/3 = Kolmogorov inertial subrange spectrum

w model relates vertical motions to divergent motions at large scales and gravity wave and turbulent motions at smaller scales

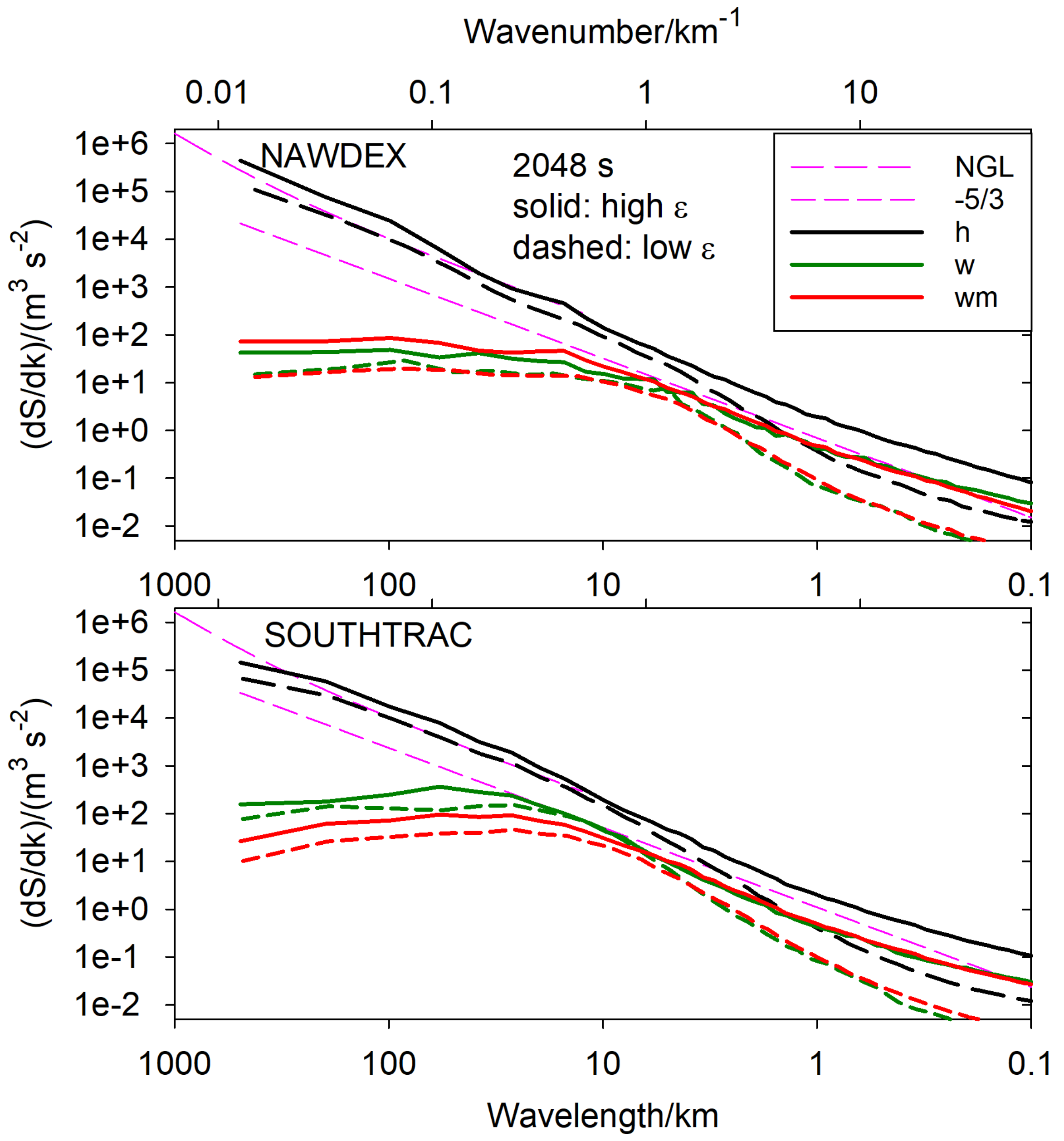
Schumann, U. (2019). The Horizontal Spectrum of Vertical Velocities near the Tropopause from Global to Gravity Wave Scales, *Journal of the Atmospheric Sciences*, ***76***(12), 3847-3862.

NAWDEX/SOUTHTRAC: New

Spectra of horizontal (h) and vertical (w) wind versus wavelength and wave number at low/high dissipation rate ε

w spectra from observation (green) compared with spectral w model wm (red)

Campaign means.



10 HZ
54/53 legs

10 Hz
126/126 legs

SOUTHTRAC:

More data than for DEEPWAVE

stronger w motions at large scales (~20 km)

w above model w_m,
- thicker layers of horizontal divergent wind?
- Similar small scale spectra

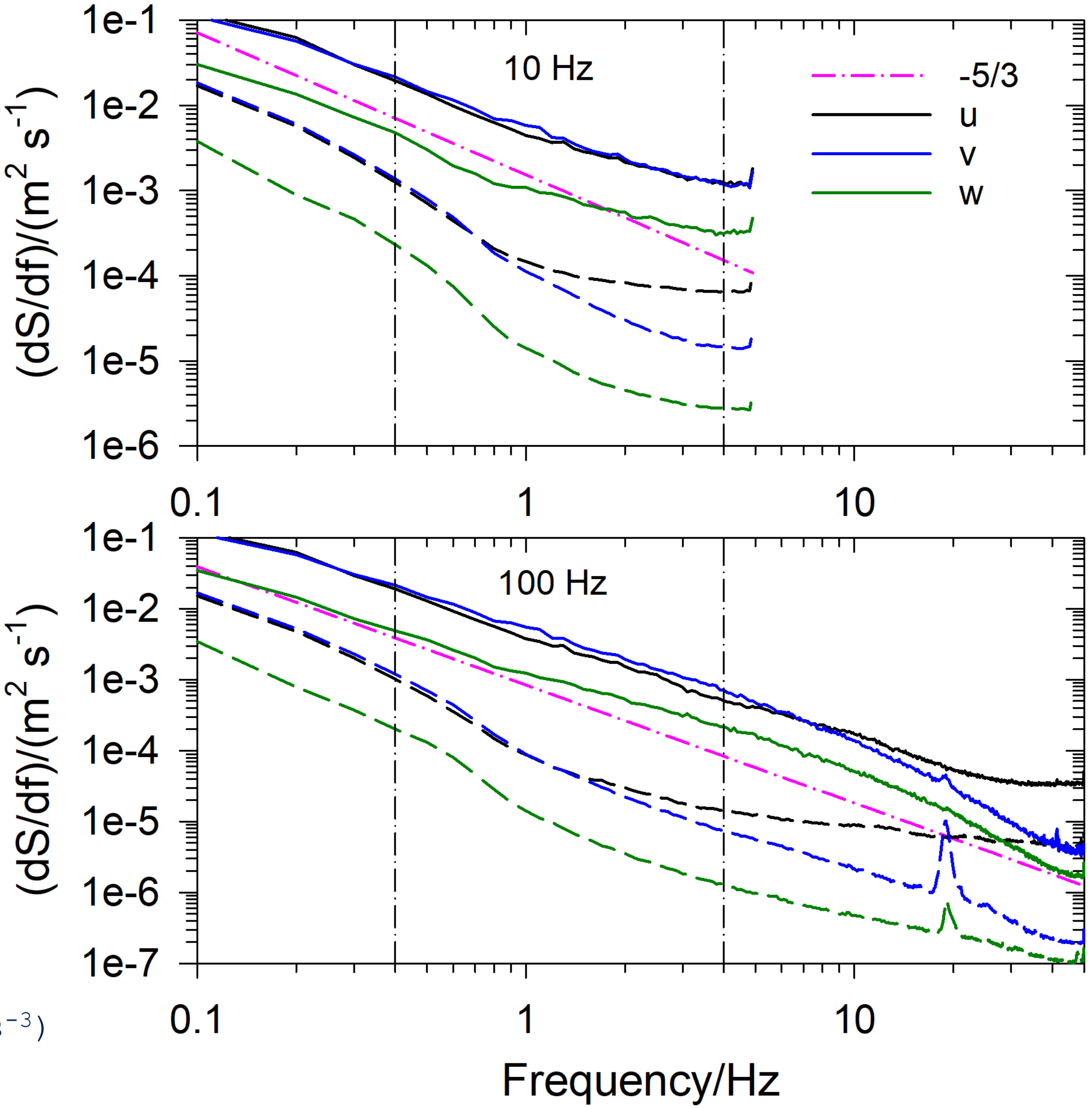
2. Analysis for all SOUTHTRAC straight and level HALO flight legs

10 and 100 Hz frequency spectra of forward, sideward and upward u,v,w, as used for computing dissipation rates $\varepsilon_u, \varepsilon_v, \varepsilon_w$

Still, even the 100 Hz measurements rarely resolve the inertial range in the sense of Ozmidov scale:

$\Delta x < L_o = (\varepsilon/N^3)^{1/2}$

Note:
L_O = 50 m (5 m) for
$\varepsilon = 0.02\ m^2\ s^{-3}$ ($0.0002\ m^2\ s^{-3}$)
and $N = 0.02\ s^{-1}$



Mean over 6921 legs

Solid : high ε
Dashed: low ε

Wind w > aircraft w_b

U-v- anisotropy at high f

20 Hz noseboom oscillation at low ε

ε From Kolmogoov spectrum fit for 0.4 – 4 Hz

$S_w(k) = (24/55)\ \alpha\ \varepsilon_w^{2/3}\ k^{-5/3}$,
$\alpha = 1.62$,
$k = 2\pi\ f\ /\ TAS$,
$\int S_w(k)\ dk = (1/2)\ \langle w'^2 \rangle$

Dissipation rates ε from SOUTHTRAC
10 Hz und 100 Hz data

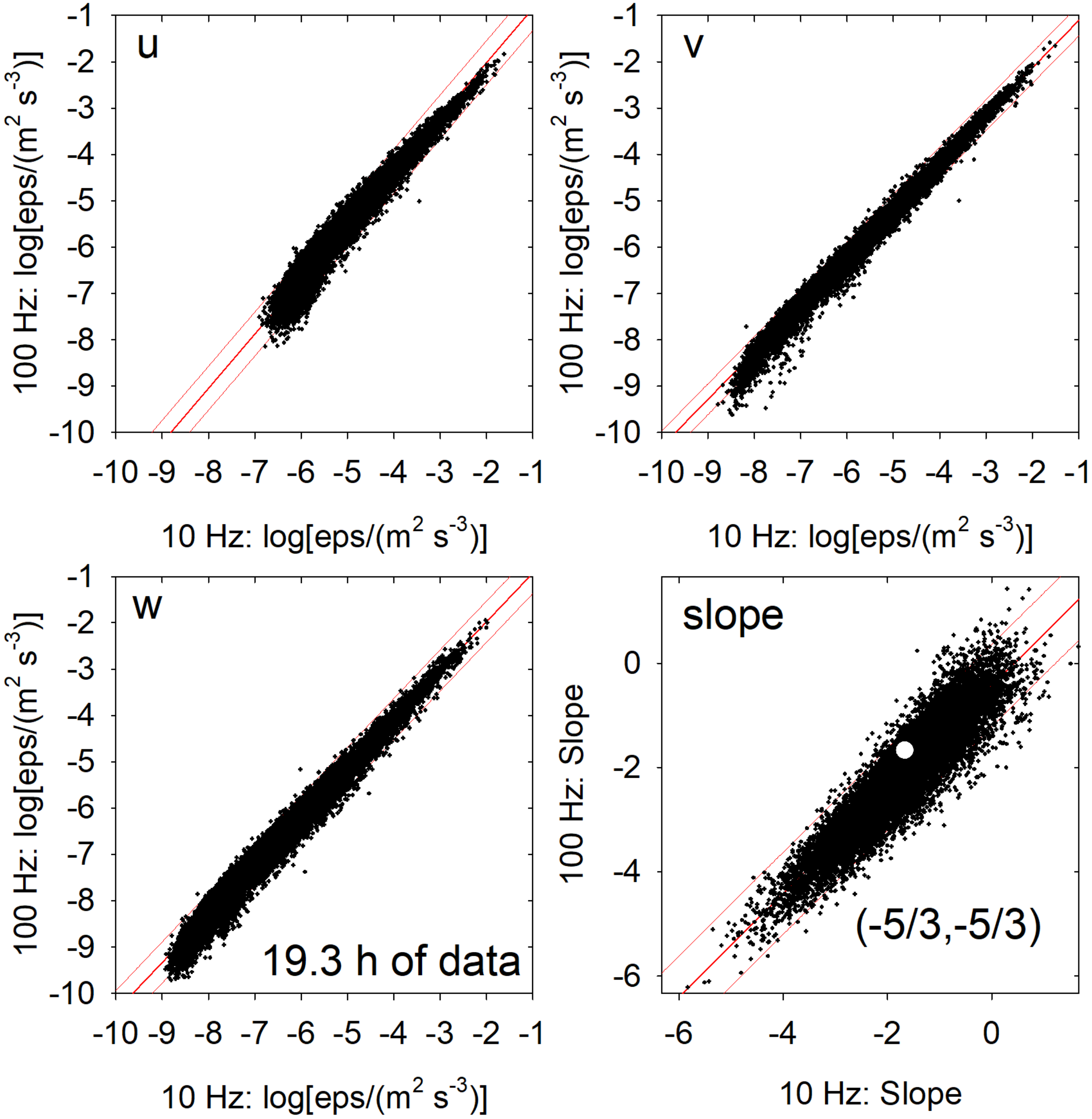
- **dissipation rate ε is computed every 5 s from 10 s-segments (100 or 1000 data points) for forward, sideward and upward velocity components -> (ε_u, ε_v, ε_w) in $m^2\ s^{-3}$**
- variance spectra computed with Tukey filter to minimize influence of aperiodicity in the data
- **between 0.4 and 4 Hz, the spectra are fitted by a -5/3-Kolmorogrov spectrum to derive ε**

$$S_w(k) = (24/55)\ \alpha\ \varepsilon_w^{2/3}\ k^{-5/3}\ ,\ \alpha = 1.62,\ k = 2\pi\ f\ /\ TAS,\ \int S_w(k)\ dk = (1/2)\ \langle w'^2 \rangle$$

- **boundaries 0.4 Hz and 4 Hz are selected to avoid high-frequency noise (mainly TAS for u, beta for v, alpha for w and from position and attitude data)**
- spectra represent mean values over 10 s or about 2.4 km leg lengths and resolves motions up to 4 Hz or 60 m flight distance
- **Method validated by comparisons to Bramberger et al. (JACM, 2020)**
- derived turbulence is highly anisotropic, for physical and for measurement reasons
- locally isotropic inertial-range turbulence occurs only in strong turbulence events.
- also computed: mean slopes of the log-log w-spectrums in the same frequency range; these slope values fluctuate between at least -4 and +1 around the -5/3 value
- **derived ε_w values vary between 10^{-10} und slightly above 10^{-3} $m^2\ s^{-3}$; EDR=$(\varepsilon_w)^{1/3}$ values reach up to 0.2 $m^{2/3}\ s^{-1}$ (moderate turbulence)**

Comparison 10 Hz – 100 Hz: Correlations

Based on all coincident 100 Hz and 10 Hz legs



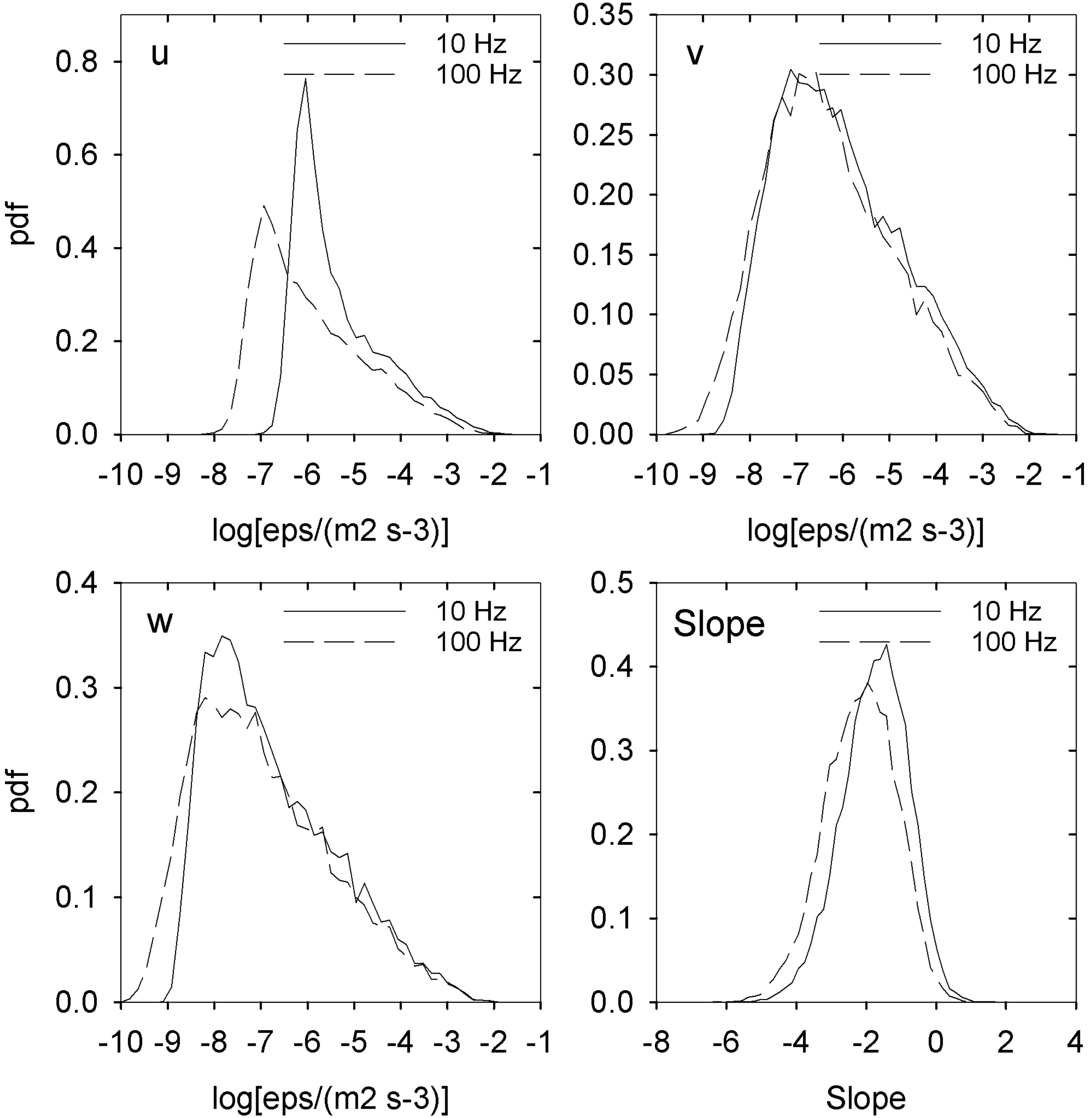
Dissipation rates:
ε_u limited by TAS
ε_v limited by beta
ε_w limited by alpha

Best resolution for dissipation rate ε from w

w-spectral slope often deviating from Kolmogorov's -5/3, mainly because of local non-equilibrium

Comparison 10 Hz – 100 Hz: Correlations

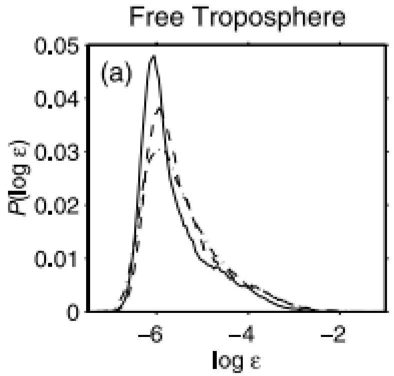
For all coincident 100 Hz and 10 Hz legs



best agreement for dissipation rate ε from w-spectra

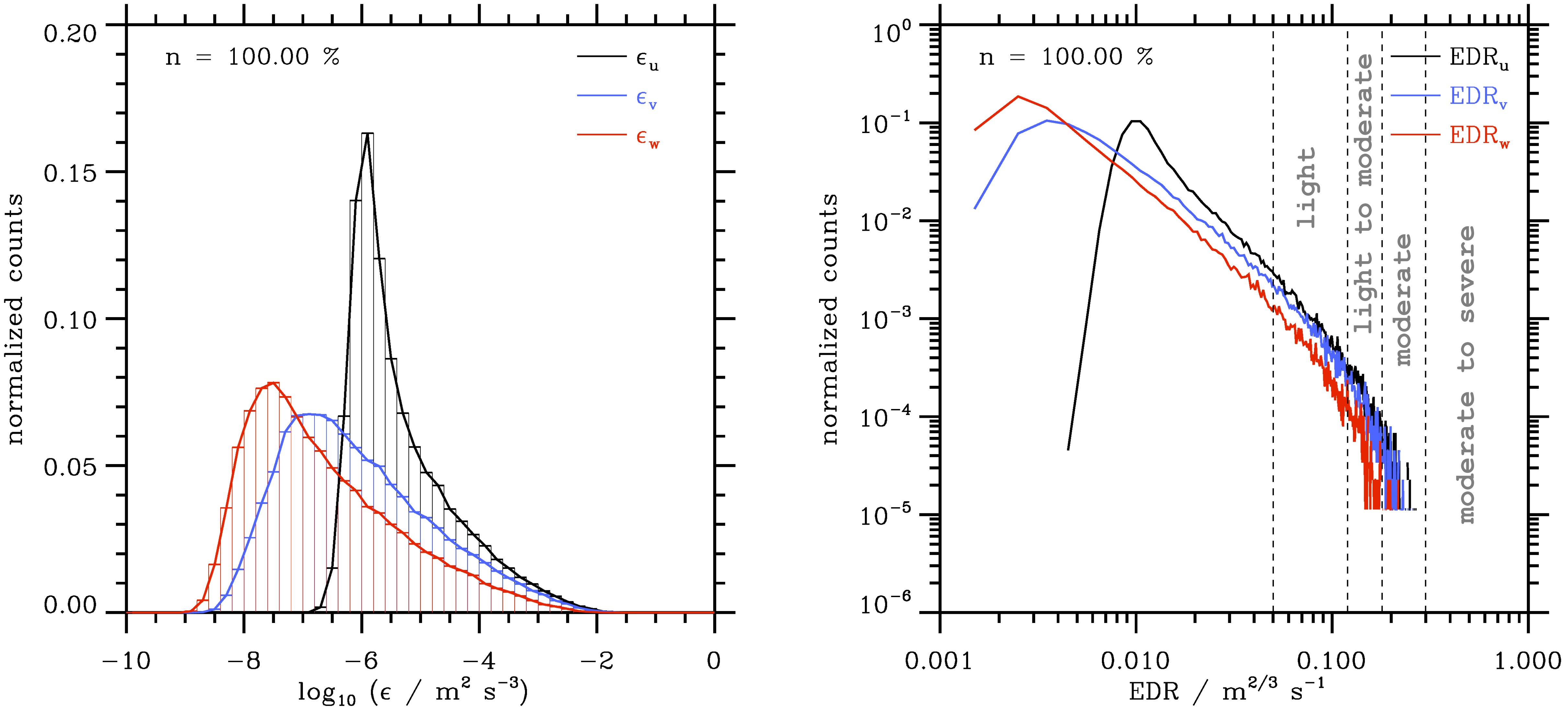
w-spectral slope often deviating from Kolmogorov’s -5/3: better for 100 Hz data due to less measurement noise

Resolves lower eps than most previous studies(e.g., Cho, Newell et al., JGR, 2003:)



Overall: ε_w provides most reliable dissipation rate estimate

Observed probability density functions of eddy dissipation rates ε_i and $EDR_i = (\varepsilon_i)^{1/3}$



0.05 < EDR < 0.12: light
0.12 < EDR < 0.18: light to moderate
0.18 < EDR < 0.30: moderate
EDR > 0.30: moderate to severe

88340 ε_i and EDR values are used for the normalization of the observed probability density functions.

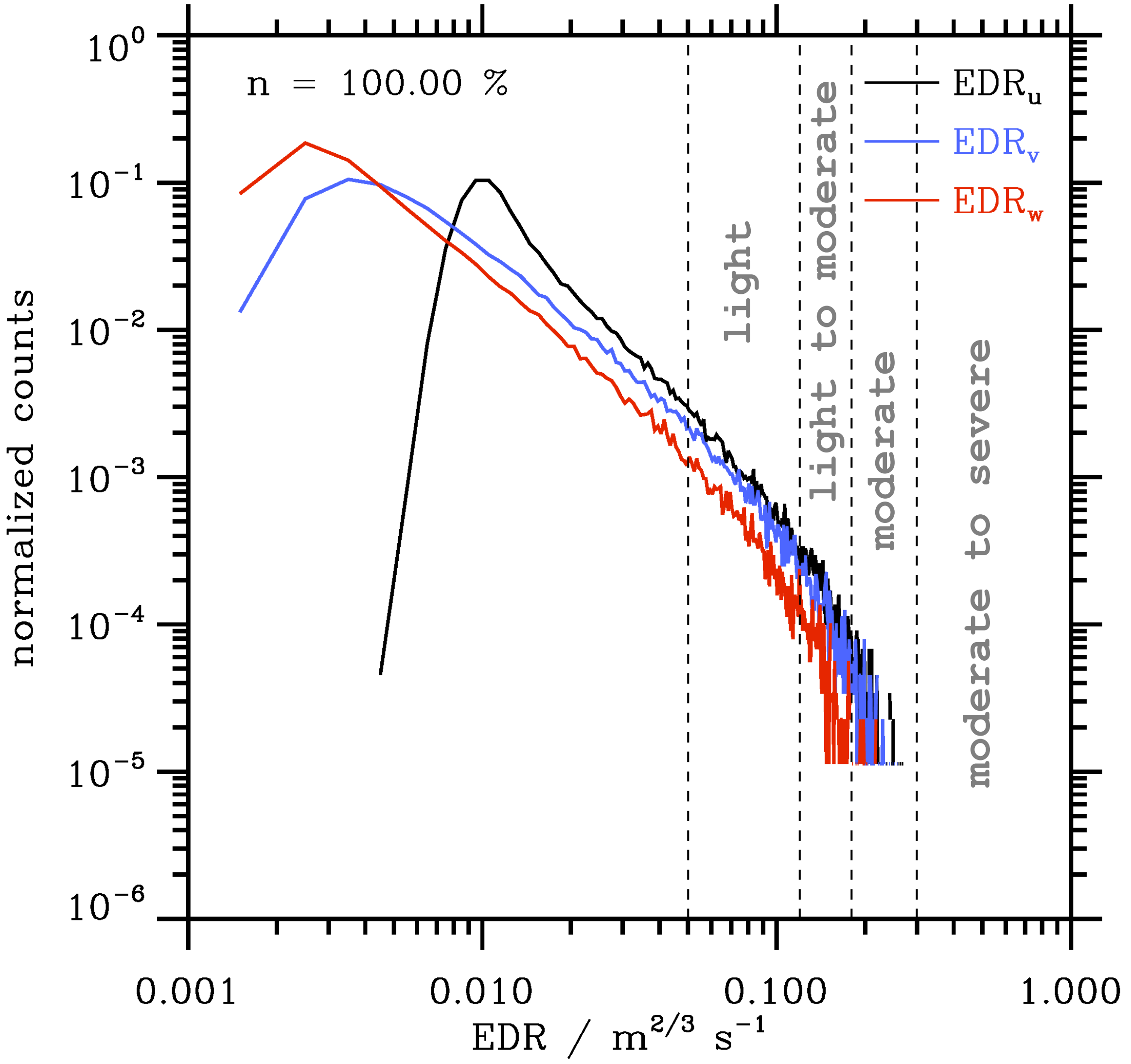
Observed probability density functions of eddy dissipation rates ε_i and $EDR_i = (\varepsilon_i)^{1/3}$

How likely is high turbulence?

From 10 Hz data:

$P(\varepsilon_w > 0.01\ m^2\ s^{-3}) < 10^{-3}$

- **probability to encounter moderate turbulence is below 10^{-3}**
- **90% of flight time at $\varepsilon_w < 10^{-5}\ m^2\ s^{-3}$ ($EDR_w < 0.02$)**



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3. CAT indices as computed in the IFS

- IFS has no SGS scheme for TKE; therefore, three diagnostic predictors have been included to obtain a measure of the EDR

(1) positive definite **Ellrod1** index

$$\text{Ellrod1} = S \cdot \left[\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 \right]^{1/2}$$

(2) subgrid contribution from the drag by breaking convectively generated gravity waves (**GWD**)

-> scale ε from the non-orographic gravity wave scheme (assuming a globally uniform departure wave spectrum) with the normalized vertically integrated convective heating between 500 hPa and the cloud top.

(3) total turbulent dissipation (**DISS**)

-> derived from IFS physical tendencies for horizontal momentum including contributions from the vertical diffusion scheme (due to turbulent mixing, orographic wave drag and orographic blocking)and convective momentum transport

Bechtold, P., M. Bramberger, A. Dörnbrack, L. Isaksen, M. Leutbecher, 2021: Experimenting with a clear air turbulence (CAT) index from the IFS. ECMWF Technical Memorandum 874. https://doi.org/10.21957/4l34tqljm

3. CAT indices as computed in the IFS

Validated GTG[§]-Approach:

$$CAT1 = 0.7 \cdot Ellrod1^* + GWD^*$$

$$CAT2 = 0.66 \cdot DISS^* + GWD^*$$

$$CAT12 = 0.5 \cdot (CAT1 + CAT2)$$

$()^*$ = after EDR projection

[§]Sharman, R., Tebaldi, C., Wiener, G., & Wolff, J., 2006: An Integrated Approach to Mid- and Upper-Level Turbulence Forecasting, *Weather and Forecasting*, **21**(3), 268-287.

Bechtold, P., M. Bramberger, A. Dörnbrack, L. Isaksen, M. Leutbecher, 2021: Experimenting with a clear air turbulence (CAT) index from the IFS. *ECMWF Technical Memorandum* **874**. https://doi.org/10.21957/4l34tqljm

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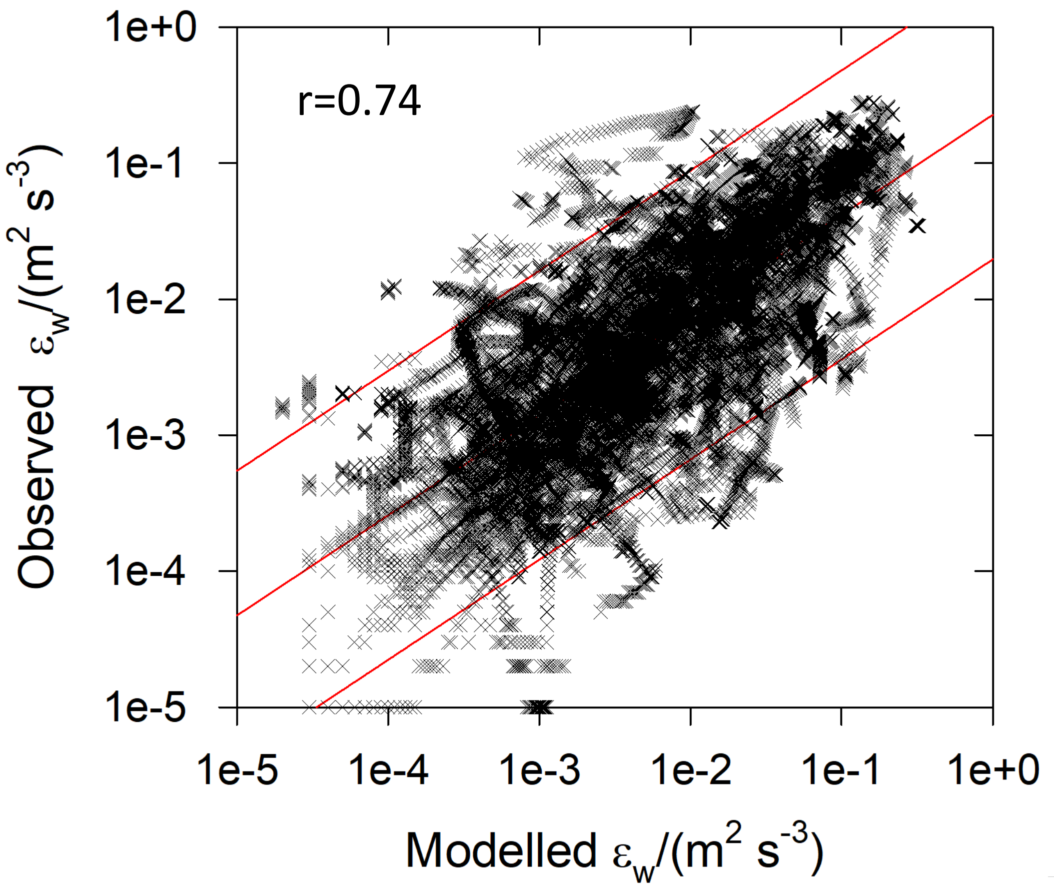
4. Comparision of SOUTHTRAC EDRs with IFS predictions

- computed EDR values from the IFS runs exist
  - every hour t_{IFS} for all the flight days in Sep/Oct/Nov 2019
  - for 15 ensemble members initialized differently
  - are interpolated onto the lat/lon positions of the HALO observations

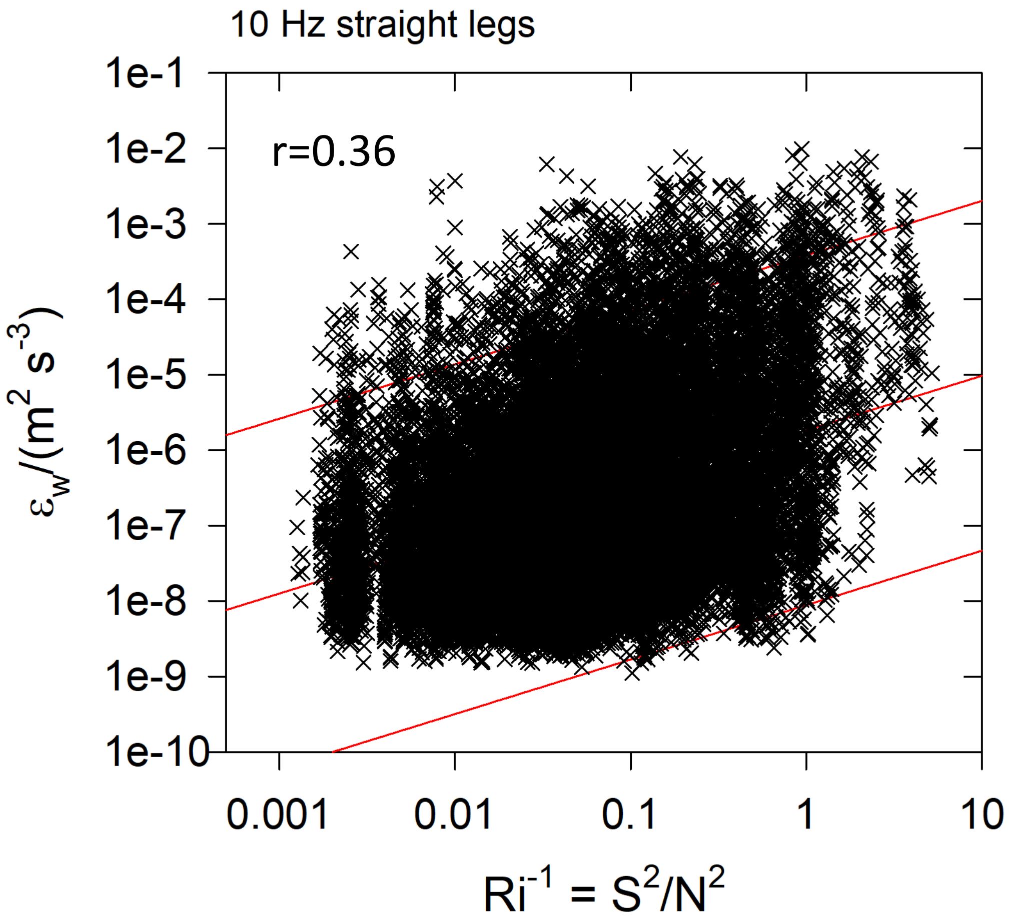
- observed EDR values are compared with IFS values at t_{IFS} at the location of the observations if
  - they fall into a time window $t_{IFS} \pm 15$ min, and
  - they deviate less than 160 m in altitude ($\Delta z_{IFS} \approx 300$ m)

- results in a data reduction from 120000 values to 24000 (1/5)

4. Comparision of SOUTHTRAC EDRs with IFS predictions & Ri^{-1}

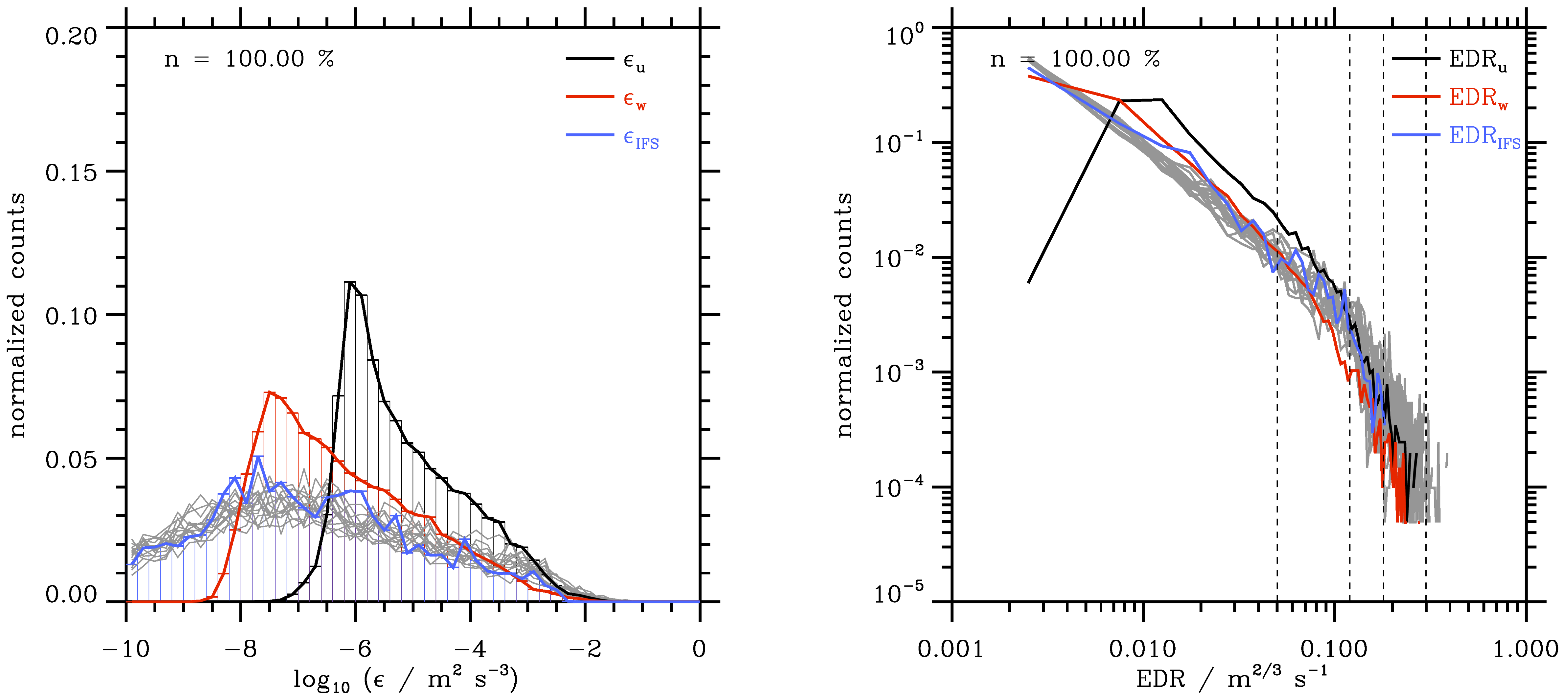


HALO ε_w vs IFS ε_w



HALO ε_w vs IFS $Ri^{-1} = S^2/N^2$

4. Comparision of SOUTHTRAC EDRs with IFS predictions



Model covers a wider range of ε than measurements - covers low and high ε events

4. Comparision of SOUTHTRAC EDRs with IFS predictions

EDR parameter	Corr HRES Jan–Mar	MAE HRES Jan–Mar	Corr HRES 1–14 Jan	Corr ENS 1–14 Jan	MAE HRES 1–14 Jan	CRPS ENS 1–14 Jan
CAT1	0.33	0.050	0.33	0.38	0.049	0.030
CAT2	0.30	0.057	0.32	0.37	0.054	0.034
CAT12	0.35	0.045	0.36	0.40	0.049	0.029

TABLE 1 Verification of different EDR parameters against observations for the high-resolution forecasts (HRES - grid spacing of about 9 km) for January–March 2019 and for HRES and the ensemble forecasts (ENS - grid spacing of about 18 km) for the period 1–14 January 2019. Verification statistics are correlation (Corr), mean absolute error (MAE) and continuous ranked probability score (CRPS).

Correlations: **SOUTHTRAC HALO Data**

- Ensemble mean EDR_{IFS} versus EDR_u = 0.339
- Ensemble mean EDR_{IFS} versus EDR_w = 0.394

Continous ranked probability score (CRPS)

- Ensemble mean EDR_{IFS} versus EDR_u = 0.0187 $m^{2/3}$ s^{-1}
- Ensemble mean EDR_{IFS} versus EDR_w = 0.0113 $m^{2/3}$ s^{-1}

5. Conclusions

- extensive data set with many straight legs, for zero to moderate turbulence
- mean wind spectra of SOUTHTRAC between NAWDEX and DEEPWAVE: rather strong vertical wind, likely from gravity waves
- 10-Hz and 100-Hz BAHAMAS data are fully consistent; Kolmogorov range ($\Delta x < L_o$) for $\varepsilon > 10^{-4}$ m^2 s^{-3}
- $\varepsilon_w < \varepsilon_v < \varepsilon_u$, because of anisotropic turbulence and measurements; best representation of turbulence: ε_w (upper bound for small ε)
- 99.9% of the atmosphere at HALO flight levels is close to zero turbulent dissipation ($\varepsilon < 10^{-6}$ m^2 s^{-3}); moderate turbulence is a rare event (P< 0.001)
- PDF dependence on N, S, and z_{terr} suggests higher level of turbulence for large S and almost no variation with N and z_{terr} -> local shear main generator of turbulence
- ensemble EDR_{IFS} agrees better with observed ε_w than with observed ε_u; higher scores for ensemble prediction system
- IFS correlations with HALO data and other statistical measures are comparable (even slightly better) to the NOAA/MADIS dataset used previously
- IFS predictions are better than a simple correlation with Ri^{-1}
- the derived ε_w is an available and a valid measure for “clear air turbulence” – valuable data set to compare with predictions from other NWP results. Tbd: Comparisons with GTG (Sharman et al., 2006)