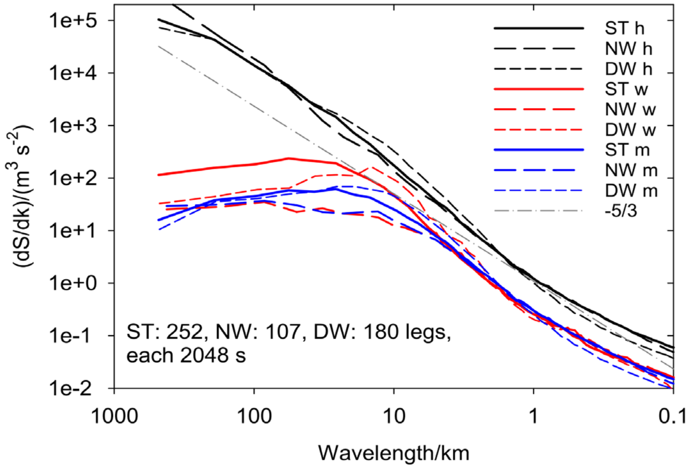
DLR + partners HALO

NSF–NCAR Gulfstream V



3 campaigns

h: horizontal
w: vertical
m: model
b: body motions

spectra +
dissipation rates

Measurements of High-Altitude Turbulence from Research Aircraft:
Energy spectra and dissipation rates from synoptic to dissipation scales

Ulrich Schumann[1)], Andreas Dörnbrack[1)],
Andreas Giez[2)], Markus Rapp[1)],
Peter Bechtold[3)], and Axel Seifert[4)]
[1)]Institute of Atmospheric Physics; [2)]Flight Experiments;
German Aerospace Center –
Deutsches Zentrum für Luft und Raumfahrt, DLR,
Oberpfaffenhofen,
[3)] ECMWF,
[4)] DWD (German Weather Service)

- DW: Deep Propagating Gravity Wave Experiment (DEEPWAVE) in 2014 (Fritts et al., 2016),
- NW: North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX) in 2016 (Schäfler et al., 2018)
- ST: Southern Hemisphere Transport, Dynamics, and Chemistry-Gravity Waves (SOUTHTRAC-GW) mission in 2019 (Rapp et al., 2021).

HALO (DLR)

NSF–NCAR Gulfstream V

Measurements of High-Altitude Turbulence from Research Aircraft

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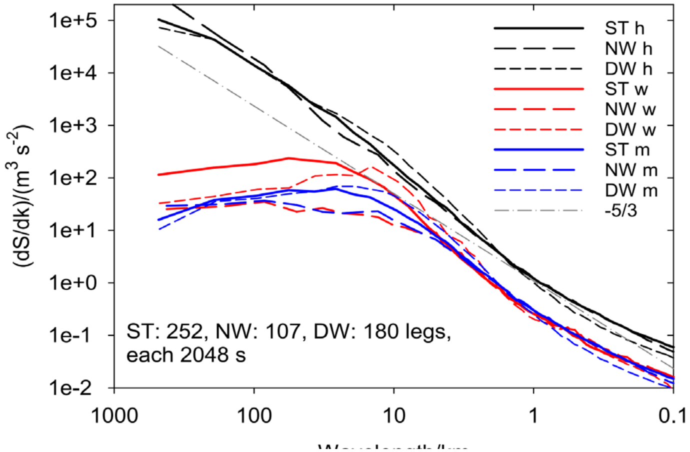
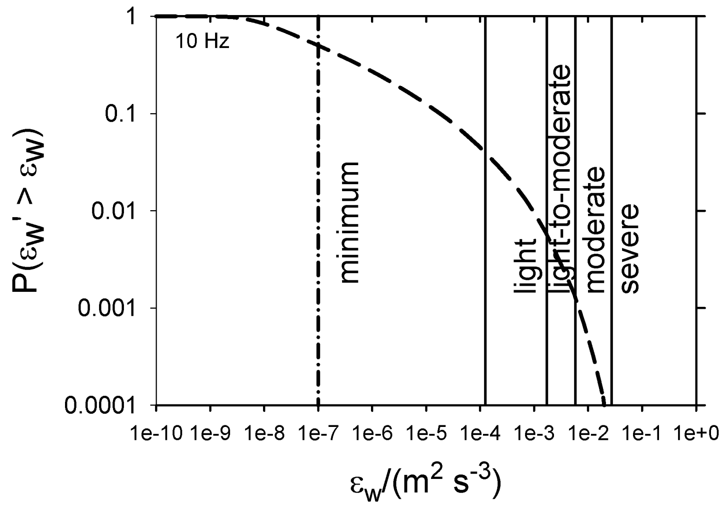




- Strong turbulence very rare
- Mostly wavy motions
- Anisotropic
- Inertial subrange for $L_O/\eta > 10$ requires $\varepsilon > \varepsilon_{MIN}$
- Non-Gaussian
- ε_w most accurate

Knowledge for Tomorrow

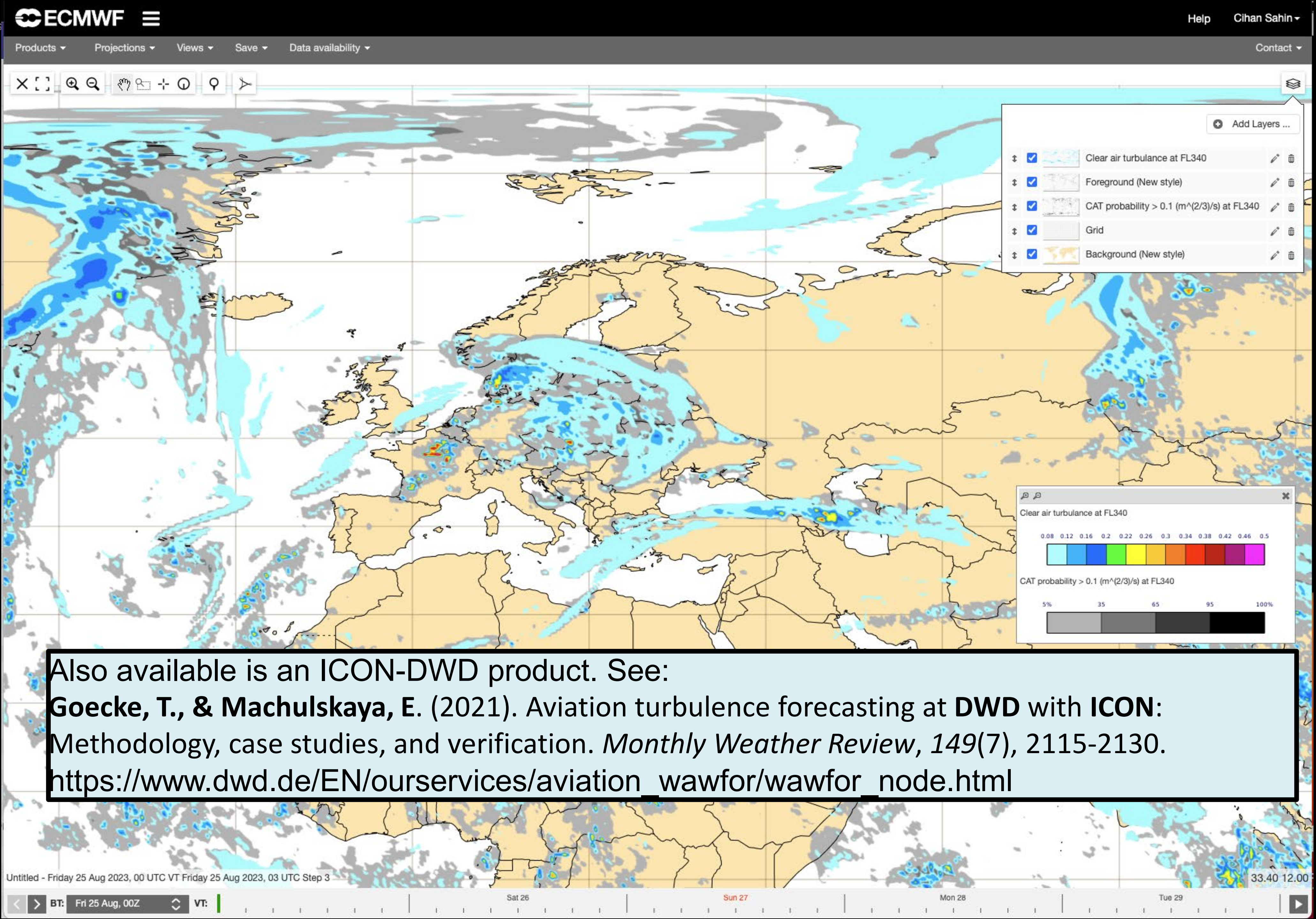
CAT at FL 340 from (brand-)new ECMWF Forecast product

provided by Peter Bechtold

New web product of Cihan Sahin, ECMWF

colors: CAT (EDR) from HRES

grey: Probability of CAT> 0.1 $m^{2/3} s^{-1}$ in 50 member ensemble



Also available is an ICON-DWD product. See:

Goecke, T., & Machulskaya, E. (2021). Aviation turbulence forecasting at **DWD** with **ICON**: Methodology, case studies, and verification. *Monthly Weather Review*, *149*(7), 2115-2130.

https://www.dwd.de/EN/ourservices/aviation_wawfor/wawfor_node.html

Aviation Climate Impact Metric prediction

⇩ Aircraft type (e.g., B77L), BADA3 or PS model

DWD
72-h-ICON FC
4 × daily

⇨

T, q, p
u, v, w
IWC,
geopot, PV
irradiances

CoCiP
EF Contrail+CO_2
Prediction

+ aCCF for NOx
and H2O

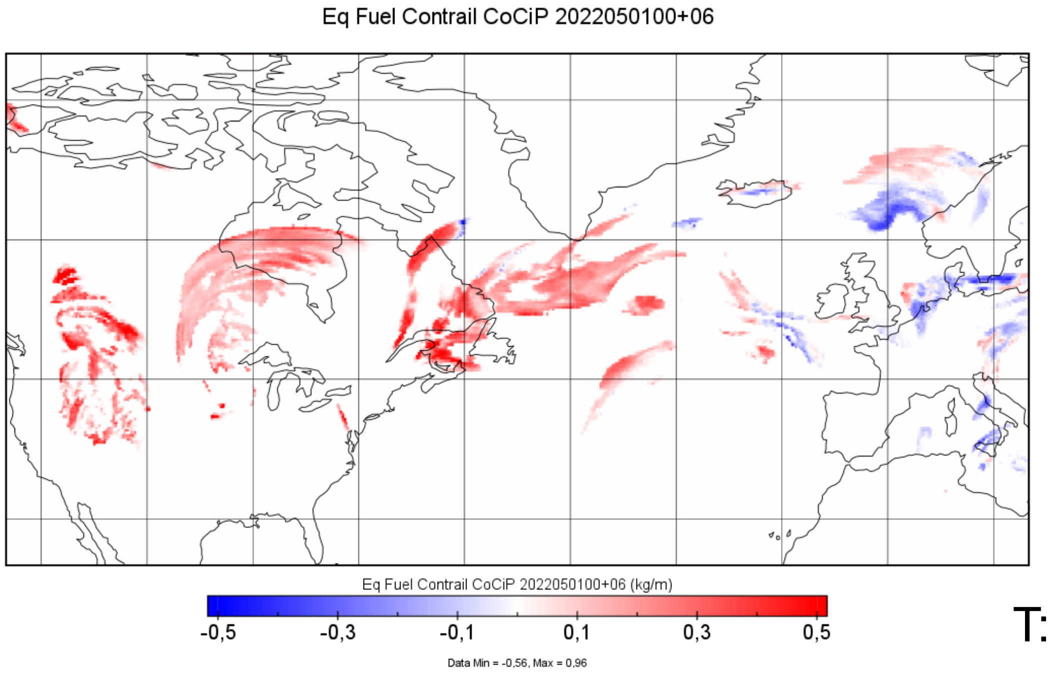
⇨

$EF_{Contrail}$
1 scalar
field per
aircraft type

Route
Optimization
(tbd)

⇨

Route
optimized for
CO_2, Contrails,
NO_x, costs,
flight time, etc.



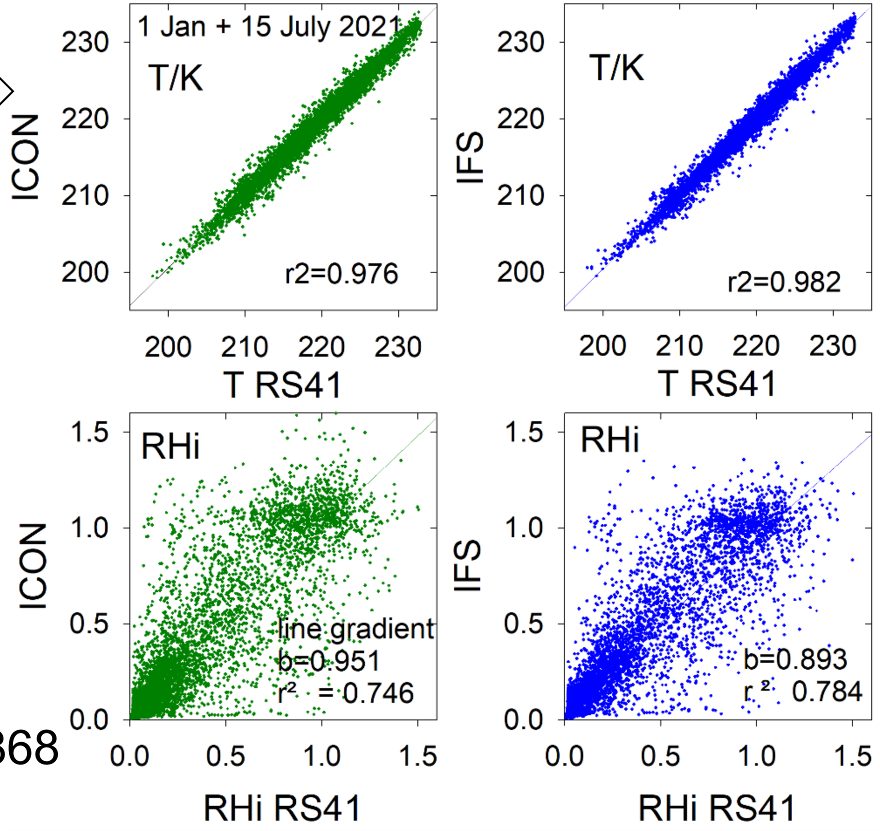
red: warming, blue: cooling contrails at FL 340

⇨

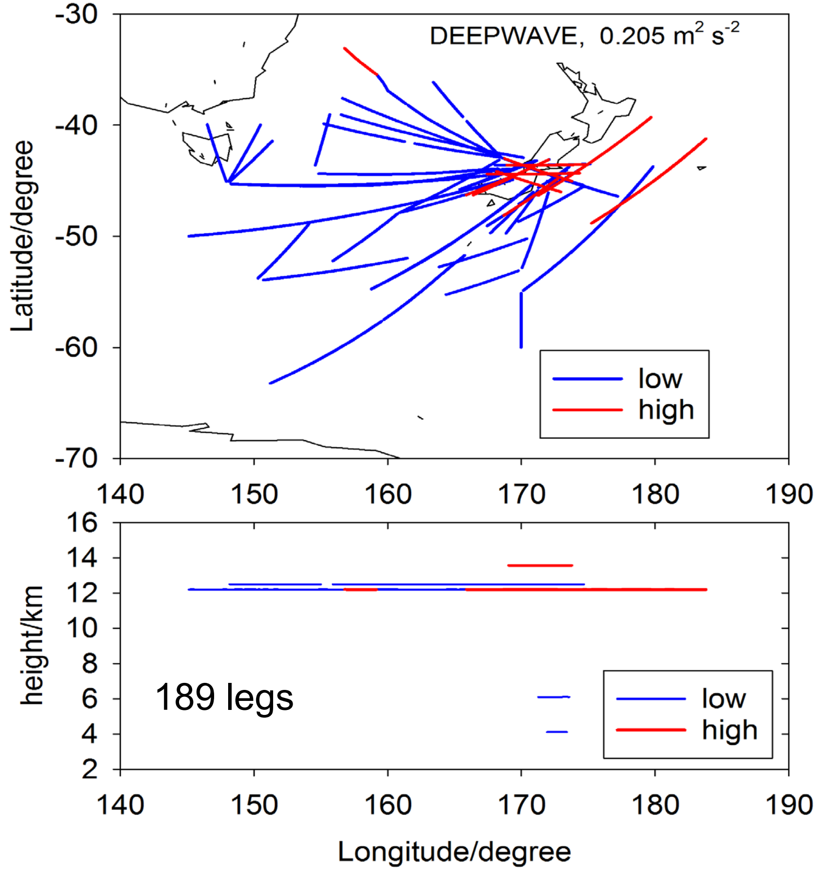
First trials of comparing IFS and new ICON (2-mom ice scheme) of Axel Seifert, DWD, to BUFR RS41 T and RHi data

T: ICON-IFS: r2=0.985

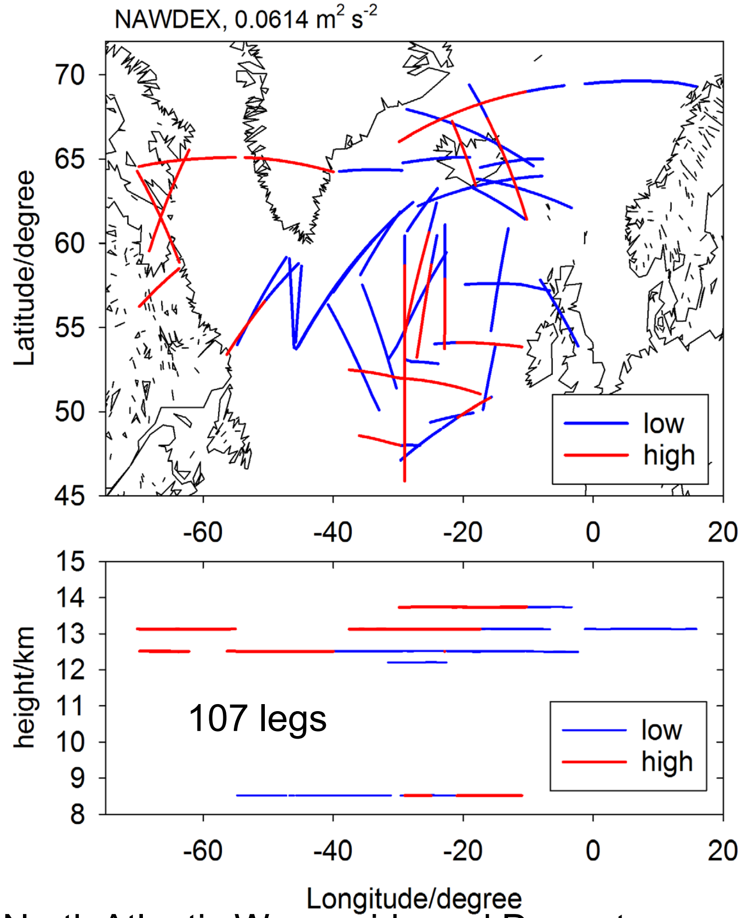
RHi: ICON-IFS, r2=0.868



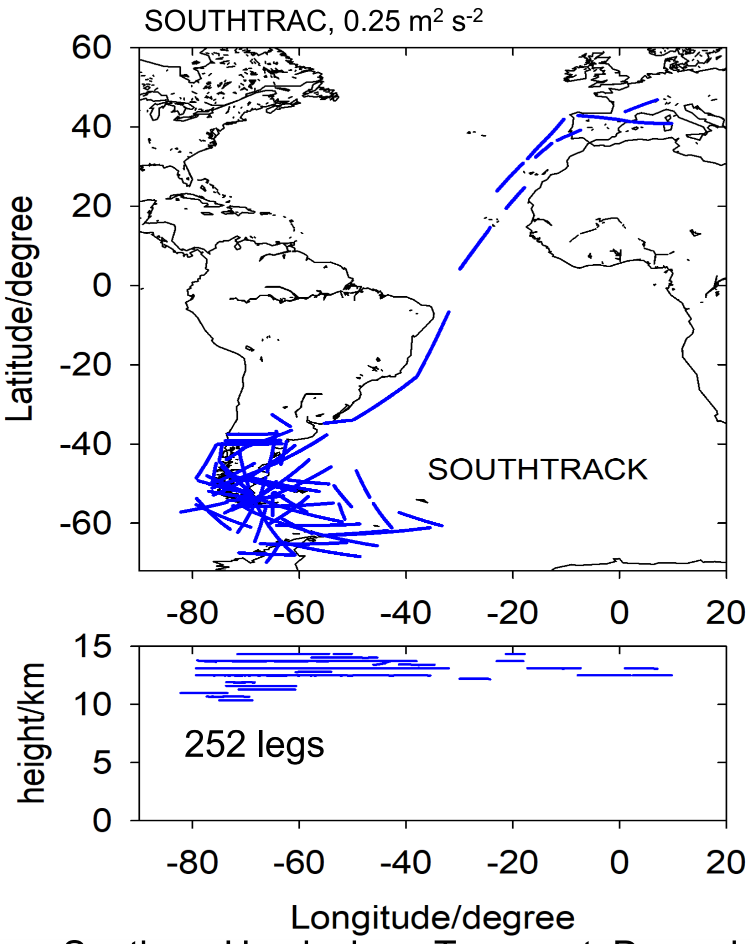
DEEPWAVE (DW, 2014), NAWDEX (NW, 2016), SOUTHTRAC (ST, 2019) for low/high dissipation rates



Deep Propagating Gravity Wave Experiment
Fritts et al. (BAMS, 2016)
Data from NSF-GV (HIAPER) NCAR EOL

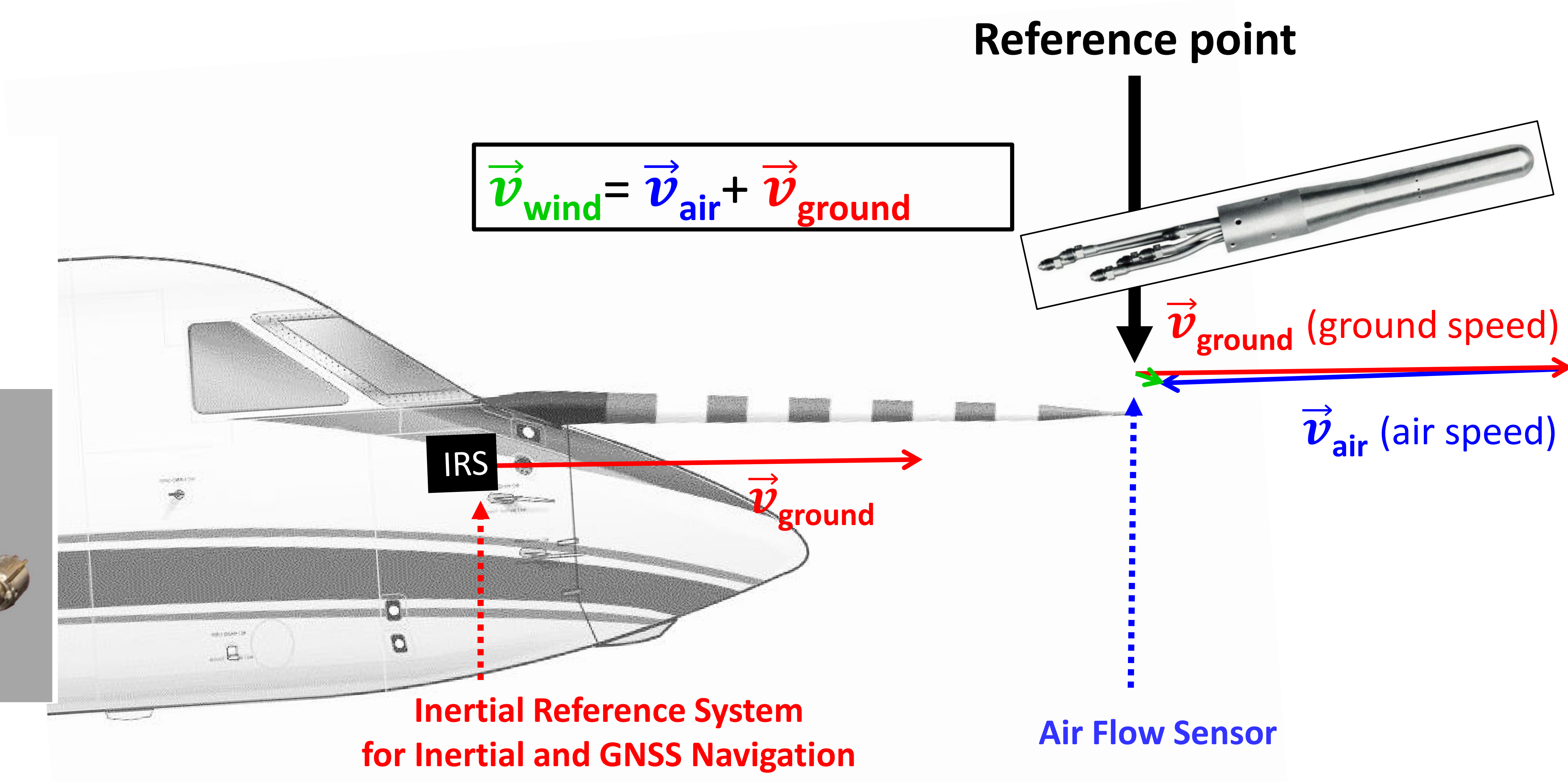


North Atlantic Waveguide and Downstream Impact Experiment
Schäfler et al. (BAMS, 2018)
Data from HALO, DLR-FX



Southern Hemisphere Transport, Dynamics, and Chemistry-Gravity Waves
Rapp et al. (BAMS, 2020)
Data from HALO, DLR-FX

Determination of the Wind Vector = air speed - ground speed on HALO with the BAHAMAS system (DLR-FX)

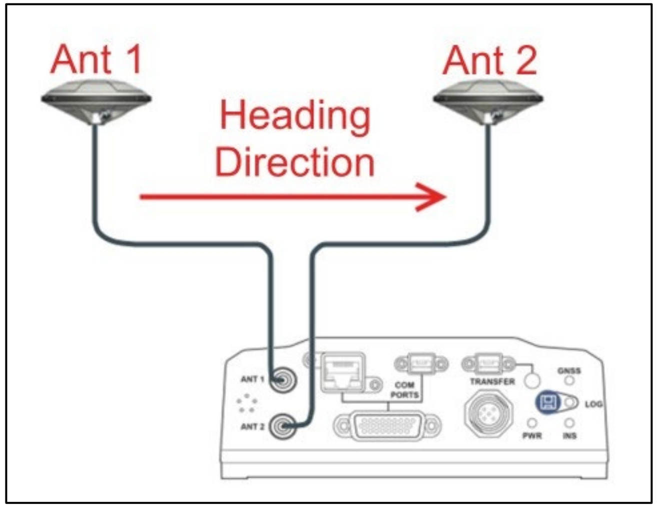


Static pressure and temperature

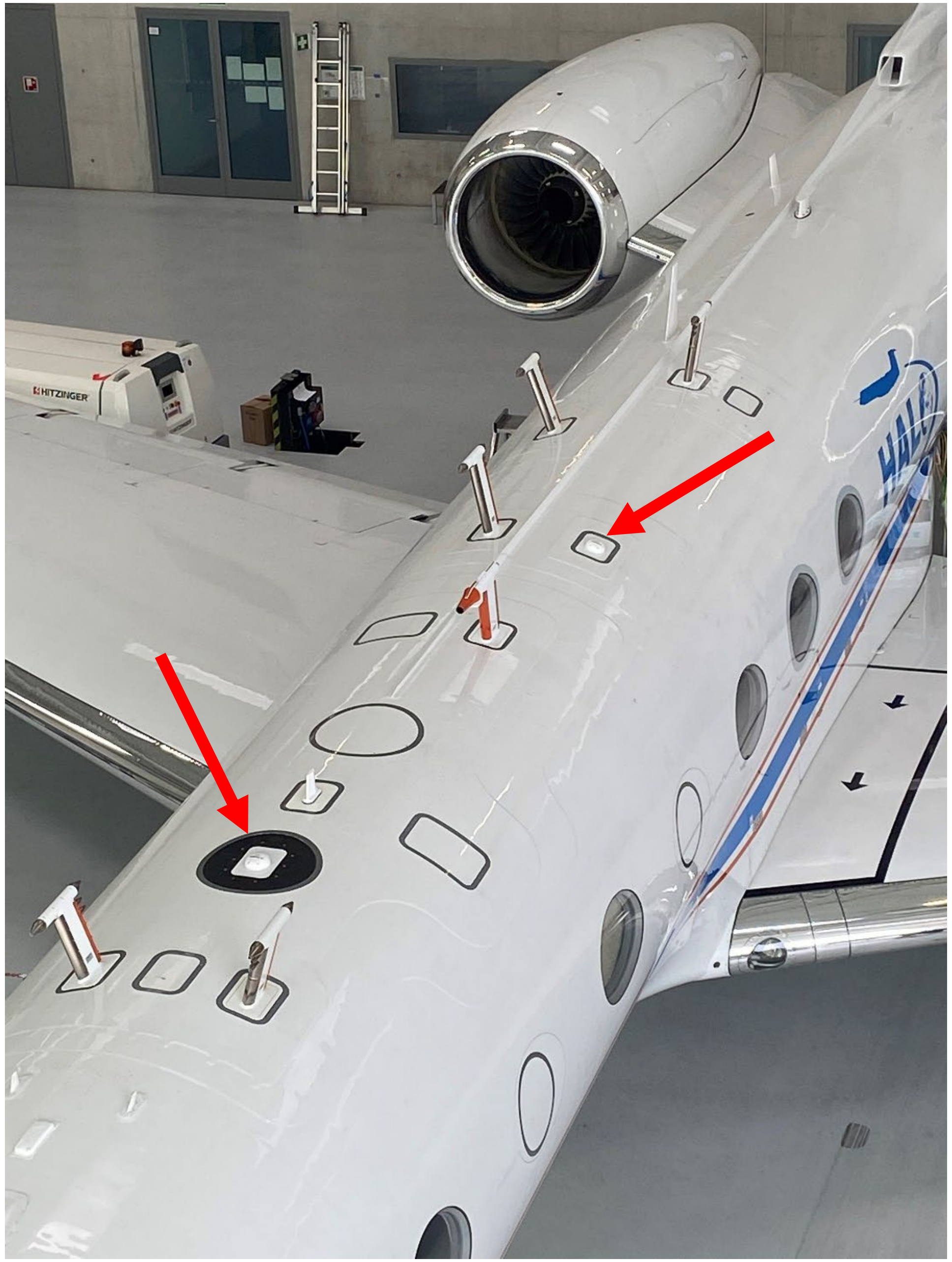
similar to Lenschow and Spyer-Duran, (1989)

New since 2022: Dual Antenna Configuration

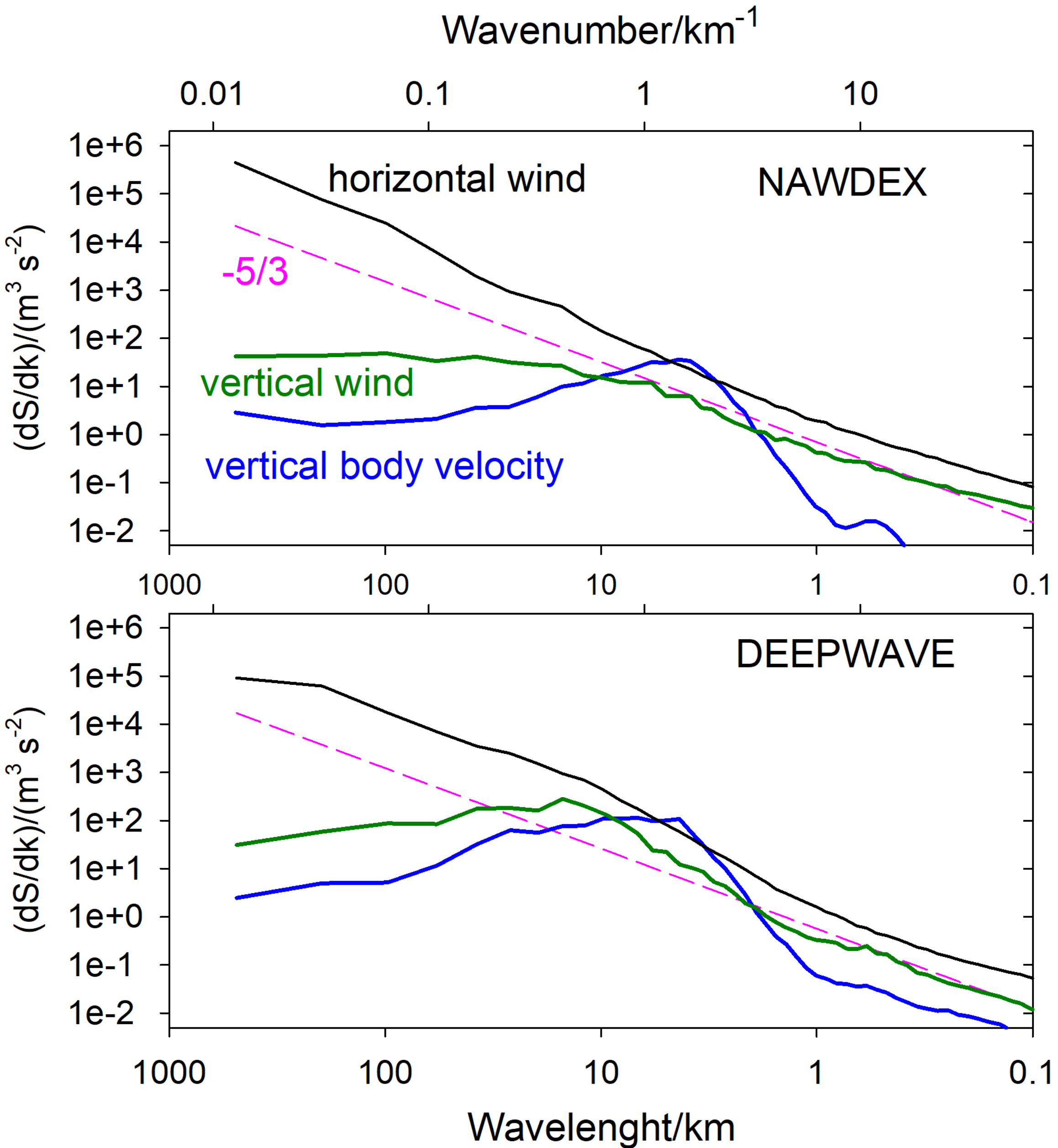
Inertial and GPS Navigation System
with a dual antenna GNSS system
for determination of low frequency
heading and pitch by using two GPS an



A.Giez, FX, 28.06.2023



Measured velocity spectra, mean over all straight 2048-s DW- and NW-legs

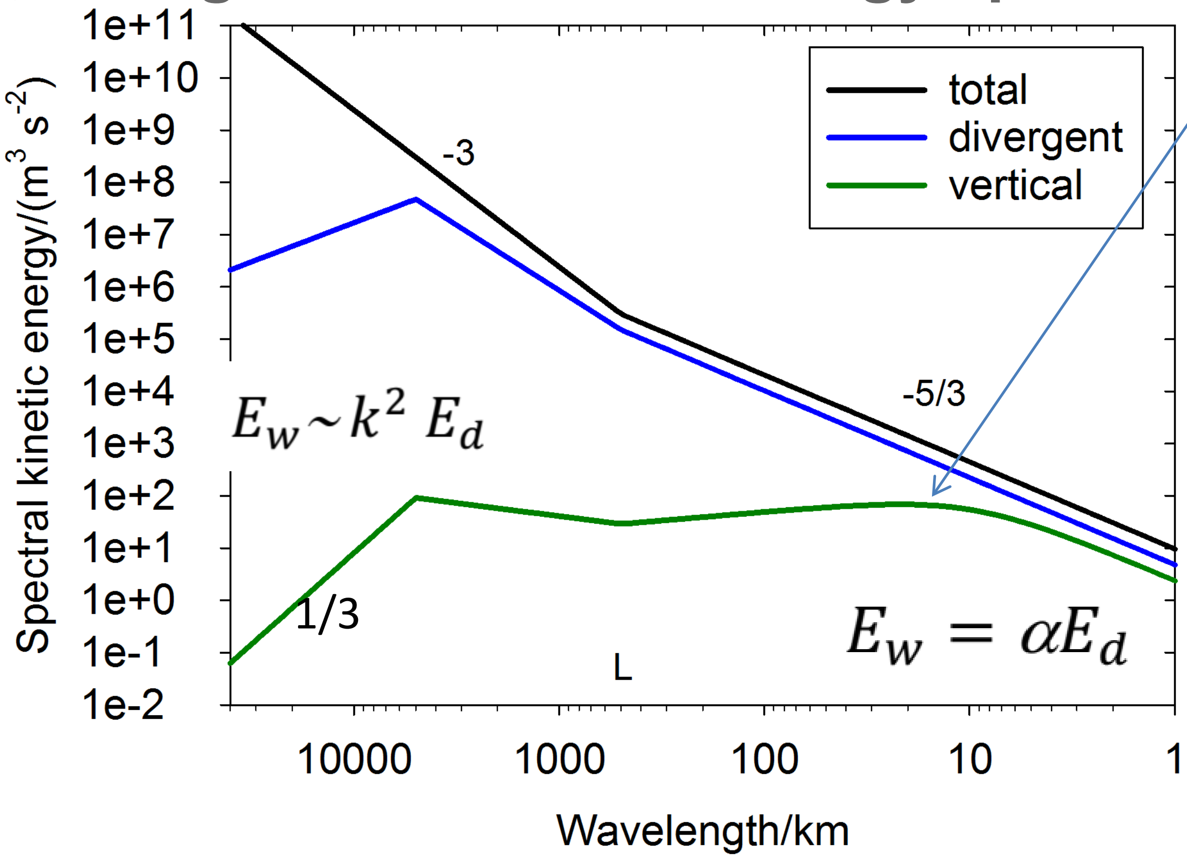


How to explain the w spectra?

Impact of vertical body motions (phugoid oscillation) on w measurement?

Schematic sketch of total, divergent and vertical energy spectra

<u>**Hypothesis:**</u>
The spectrum of vertical velocities E_w, as a function of wavenumber *k* and height *h*, is related to the spectrum of horizontal velocities E_h
1) at large scales: to E_d by continuity,
2) at small scales: to E_h by dynamics towards local isotropy



A mesoscale maximum in the w-spectrum occurs if the divergent horizontal velocity spectrum E_d has a slope flatter than -2

$$E_w(k,h) = \frac{\alpha (h_{\mathrm{eff}}\, k)^2}{\alpha + (h_{\mathrm{eff}}\, k)^2} E_d(k,h), \; h_{\mathrm{eff}} = \beta h$$

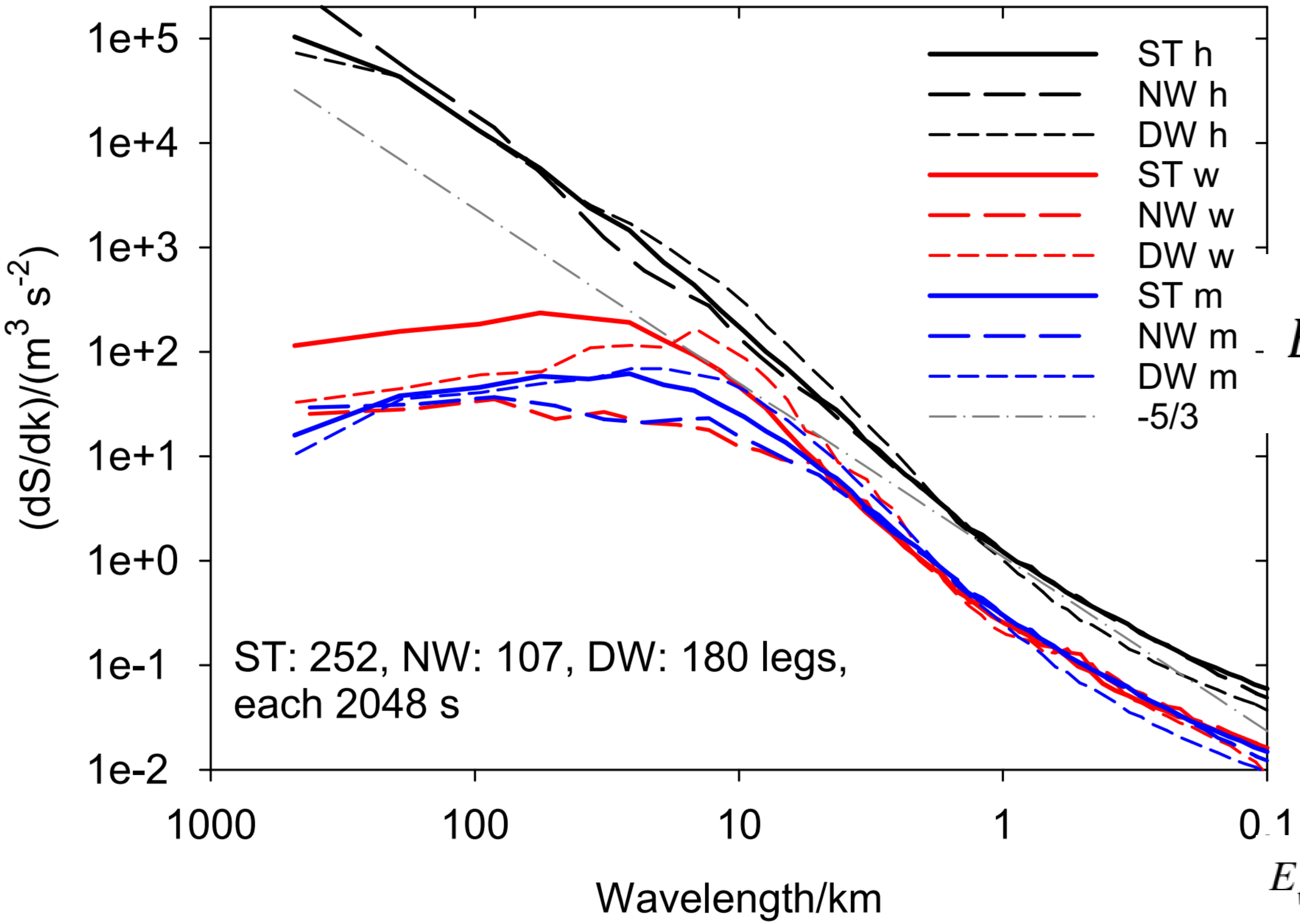
$$E_w(k,h) = (h_{\mathrm{eff}}\, k)^2 E_d(k,h), \quad hk \ll 1$$

$$E_w(k,h) = \alpha E_d(k,h) = \alpha\, d\, E_h(k,h); \quad hk \gg 1$$

h=10 km, α =1/2, β =0.11, *d*=1/2

DLR

Mean spectra of kinetic energy from 3 campaigns



"h" horizontal energy
"w" vertical energy spectra
"m" model, (Schumann, JAS, 2019)

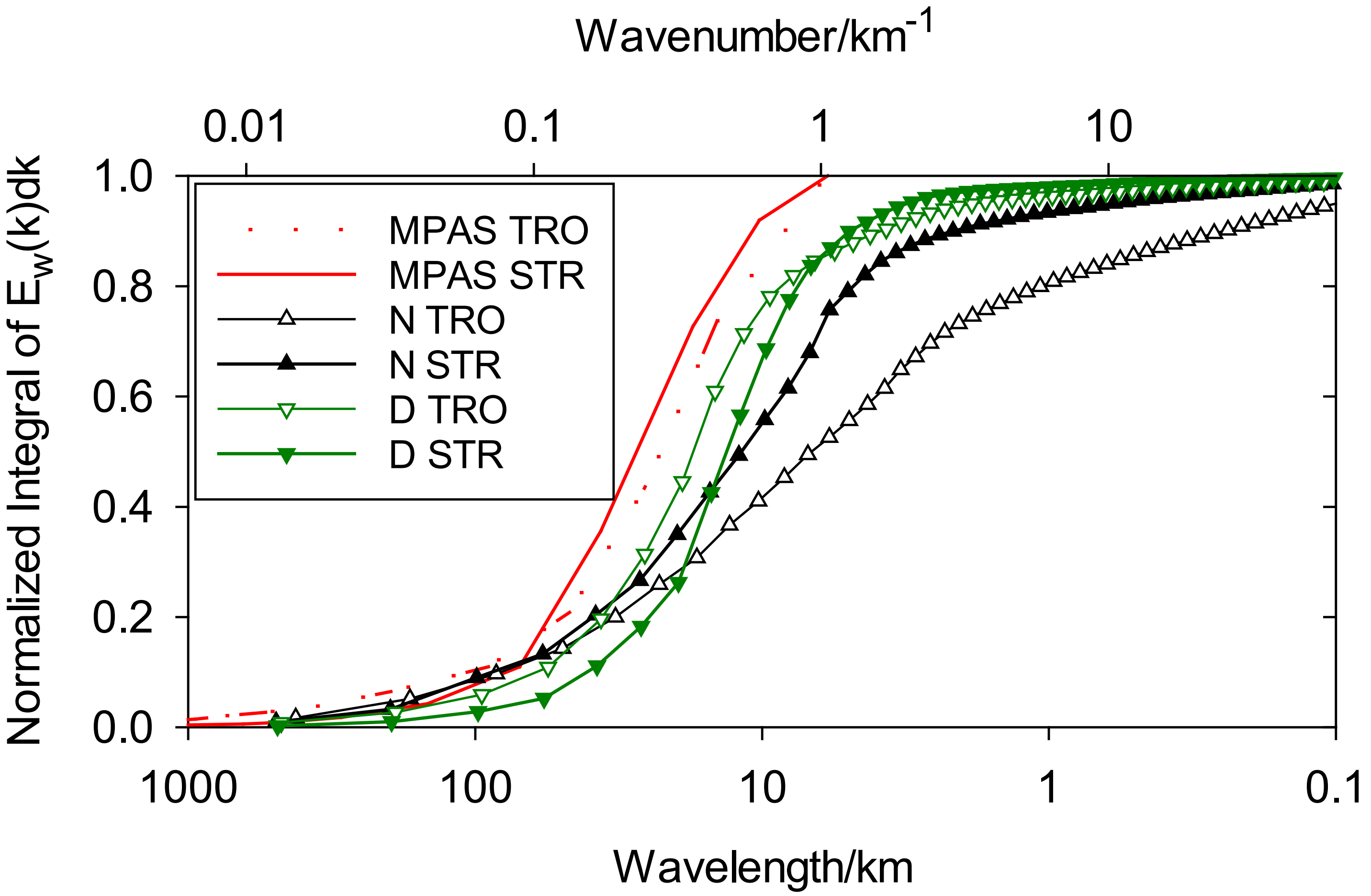
$$E_w(k,h) = \frac{\alpha (h_{\text{eff}}\, k)^2}{\alpha + (h_{\text{eff}}\, k)^2} d\, E_h(k,h),$$

$$h_{\text{eff}} = \beta h$$

$$E_w(k,h) = (h_{\text{eff}}\, k)^2 E_d(k,h), \quad hk \ll 1$$

$$E_w(k,h) = \alpha E_d(k,h) = \alpha\, d\, E_h(k,h); \quad hk \gg 1$$

Which scales contribute most to w-variance?



> 0.5 km: 90 %

> 7 km: 50 %

Dissipation rates ε from SOUTHTRAC 10 and 100 Hz data, FFT

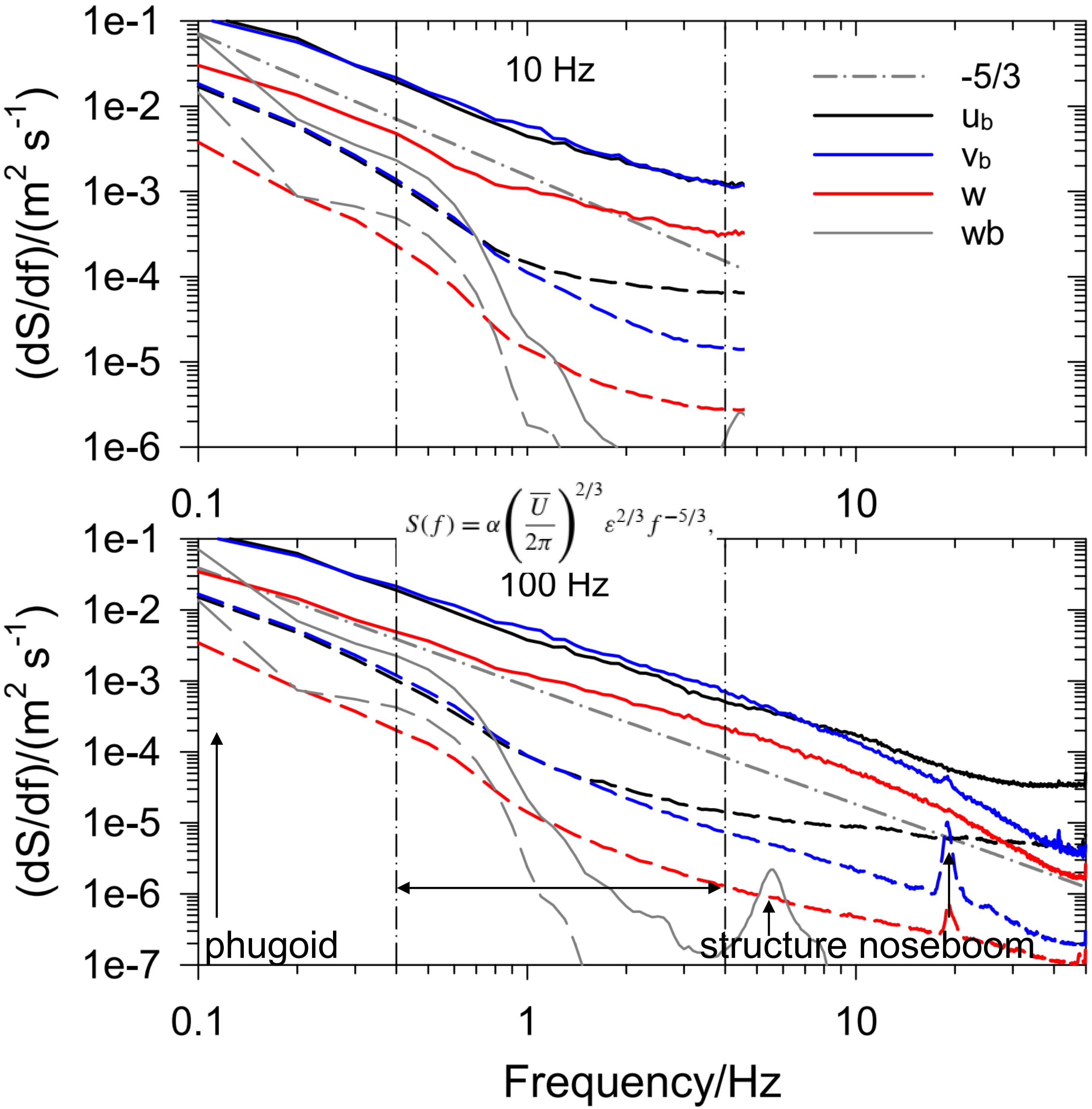
- Dissipation rate ε is computed every 5 s from 10 s-segments (100 or 1000 data points) for forward, sideward and upward velocity components -> $\varepsilon_i = (\varepsilon_u, \varepsilon_v, \varepsilon_w)$ in $m^2\ s^{-3}$
- Variance spectra computed with Tukey filter to minimize influence of aperiodicity in the data.
- Between 0.4 and 4 Hz, the spectra are fitted by a -5/3-Kolmorogrov spectrum to derive ε

$$S_i(k) = \alpha_i\ \varepsilon_i^{2/3}\ k^{-5/3}\ ,\ \alpha_i = (0{,}53,\ 0.707{,}0.707),\ k = 2\pi\ f\ /\ TAS,\ \int S_i(k)\ dk = (1/2)\ \langle u_i'^2 \rangle$$

- boundaries 0.4 Hz and 4 Hz are selected to avoid high-frequency noise (mainly from TAS for u, beta for v, alpha for w; besides noise in position and attitude data)
- Method basically as in Schumann et al. (1995), validated by comparisons to Bramberger et al. (JACM, 2020); also compared to Imazio et al. (2022, JGR)
- 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

10 and 100 Hz Frequency Spectra

as used for dissipation rate analysis



$$S_i(k) = C_i \, \varepsilon_i^{2/3} \, k^{-5/3}$$

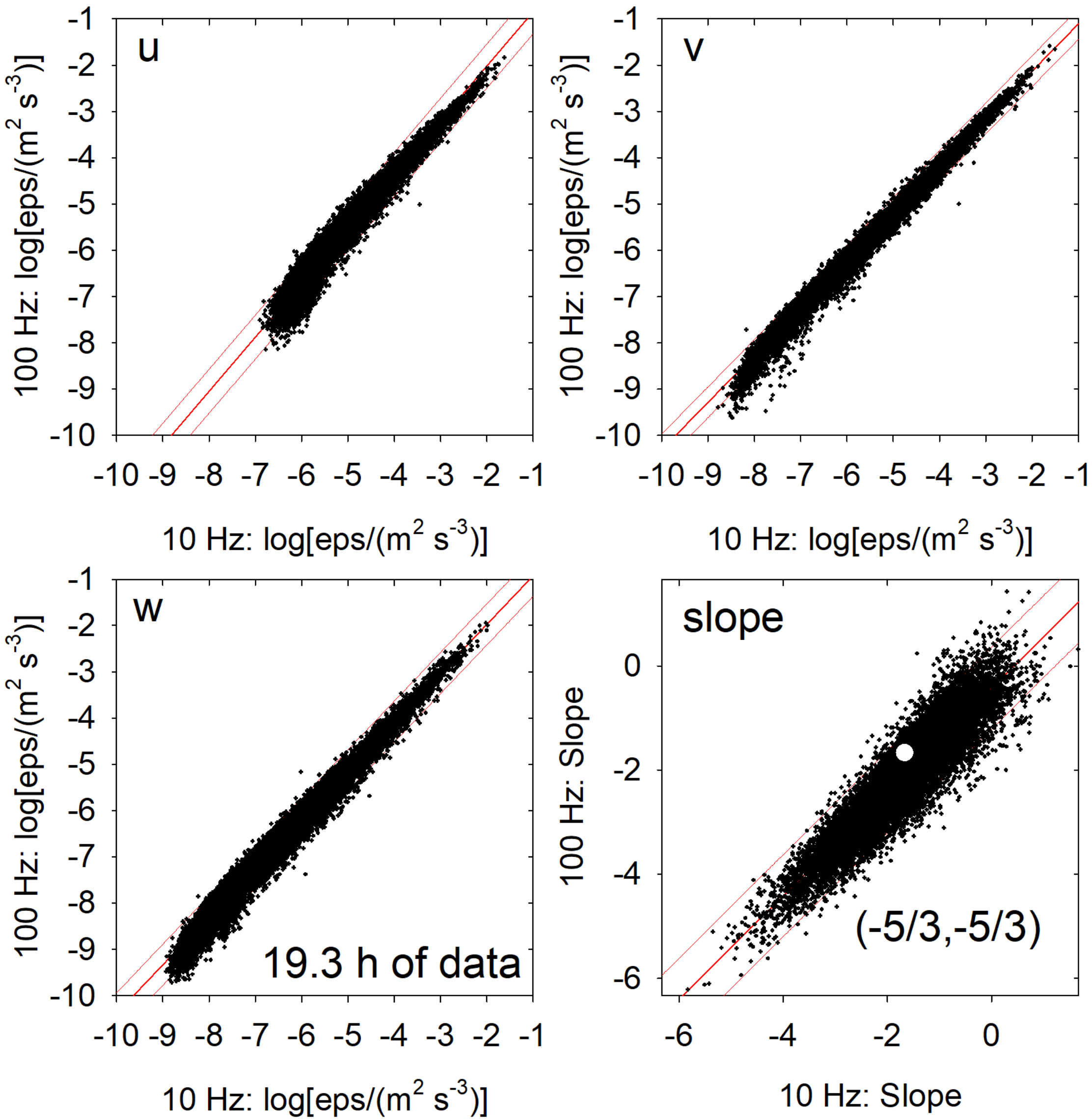
$$k = 2\pi f / TAS$$

Mean over 6921 legs

Solid : high ε
Dashed: low ε

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

DLR

Inertial range turbulence in stratified air exists only if buoyancy > inertial> viscous forces -> pdf is not log-normal (not log-Gaussian)

Stratification is characterized by the Brunt-Väisälä frequency

$$N = \sqrt{\frac{g}{\Theta}\frac{\partial \Theta}{\partial z}}$$

Characteristic scales are the

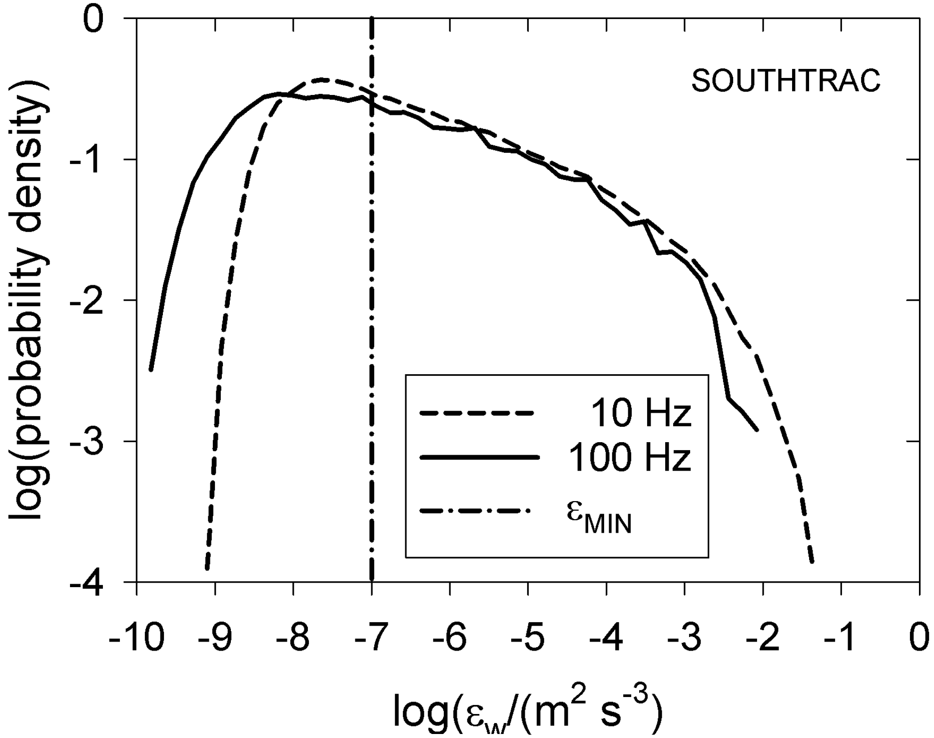
Ozmidov for similar inertial/buoyancy forces

$$L_O = \left(\frac{\epsilon}{N^3}\right)^{1/2}$$

and the

Kolmogorov scales for similar inertial/viscous forces

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$$



L_O/η > 10 requires $\varepsilon > \varepsilon_{MIN}$, with

$$\epsilon_{MIN} = \left(\frac{L_O}{\eta}\right)^{4/3} \nu N^2 \approx 21.5\, \nu N^2$$

$$L_O/\eta = 10$$

See also Lübken (1997), Rapp et al. (2004)

Inertial range turbulence in stratified air exists only if buoyancy > inertial> viscous forces. Same in linear PDF scale

Stratification is characterized by the Brunt-Väisälä frequency

$$N = \sqrt{\frac{g}{\Theta}\frac{\partial\Theta}{\partial z}}$$

Characteristic scales are the

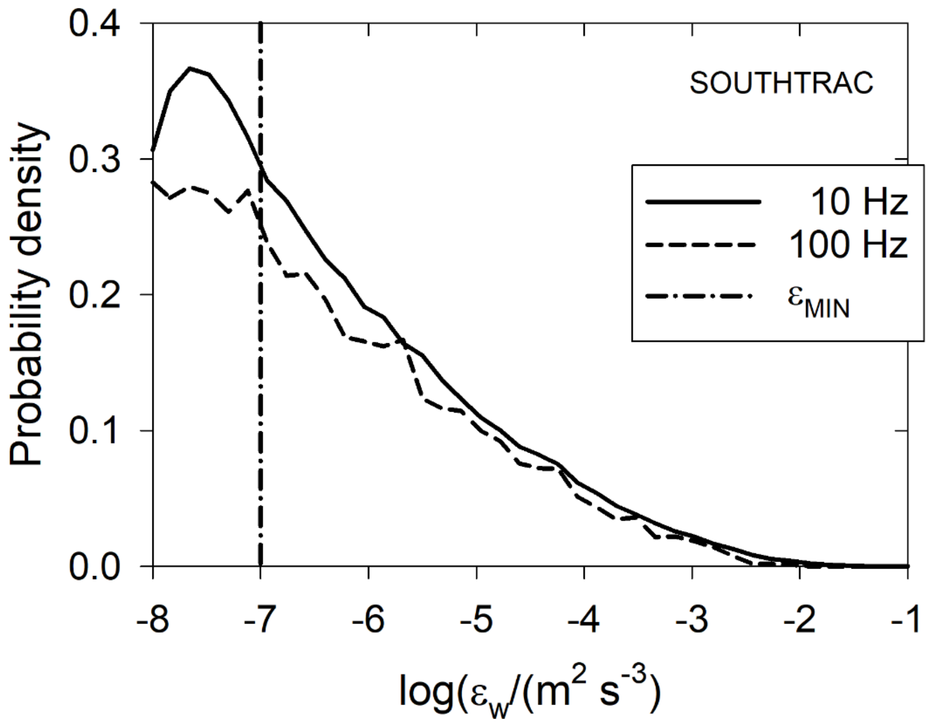
Ozmidov for similar inertial/buoyancy forces

$$L_O = \left(\frac{\epsilon}{N^3}\right)^{1/2}$$

and the

Kolmogorov scales for similar inertial/viscous forces

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$$



$L_O/\eta > 10$ requires $\varepsilon > \varepsilon_{MIN}$, with

$$\epsilon_{MIN} = \left(\frac{L_O}{\eta}\right)^{4/3} \nu N^2 \approx 21.5\, \nu N^2$$

$$L_O/\eta = 10$$

See also Lübken (1997), Rapp et al. (2004)

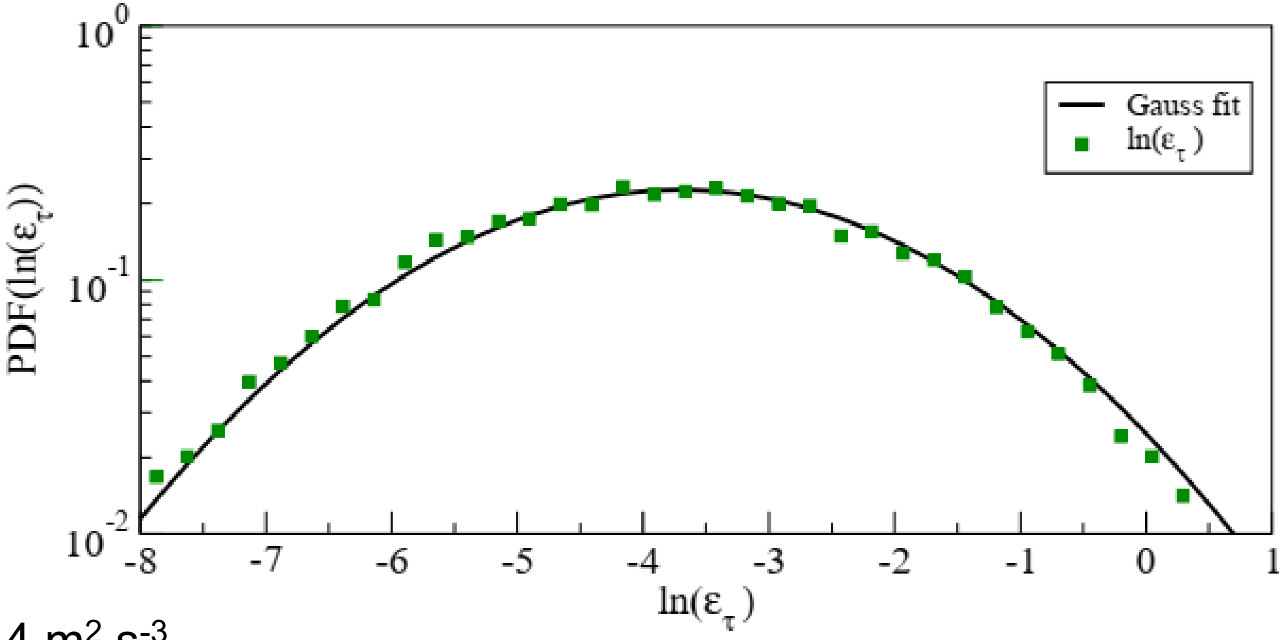
Comparison to literature:

log-normal pdfs expected for intermittency [*Kolmogorov*, 1962; *Obukhov*, 1962; *Van Atta and Chen*, 1970; Merceret, 1976; *Nastrom and Gage*, 1985; Mandelbrot, 1991; Frisch, 1996; *Frehlich and Sharman*, 2004; *Frehlich et al.*, 2004]

-> log normal if stratification effects are small

High-resolution measurement of ... turbulence at a mountain top station

by H. Siebert, R. A. Shaw, J. Ditas, T. Schmeissner, S. P. Malinowski, E. Bodenschatz, and H. Xu; AMT, 2015



≈3.E-4 $m^2\ s^{-3}$

Figure 7. Probability density function (PDF) of $\ln(\varepsilon_\tau)$ with $\tau = 0.1$ s estimated from the same data as in Fig. 4. A Gaussian distribution is plotted as a reference.

Comparison to literature:

Estimate of Turbulent Energy Dissipation Rate From the VHF Radar and Radiosonde Observations in the Antarctic by Kohma, Sato, Tomikawa, Nishimura and Sato (JGR, 2018)

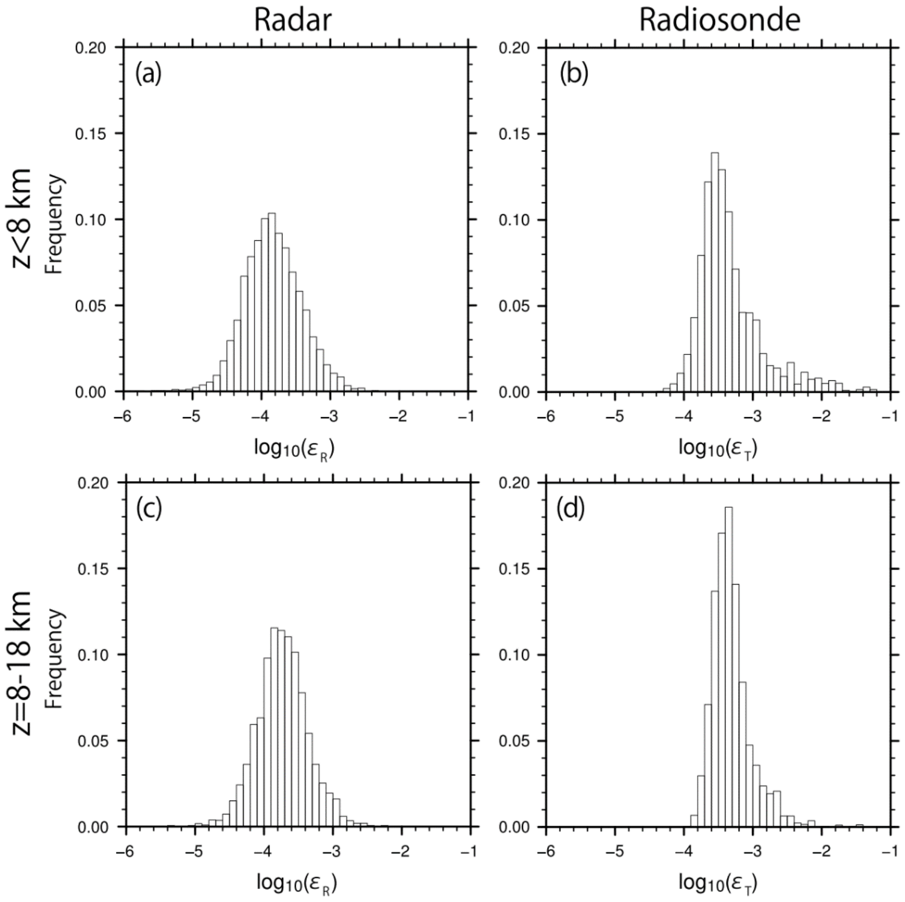
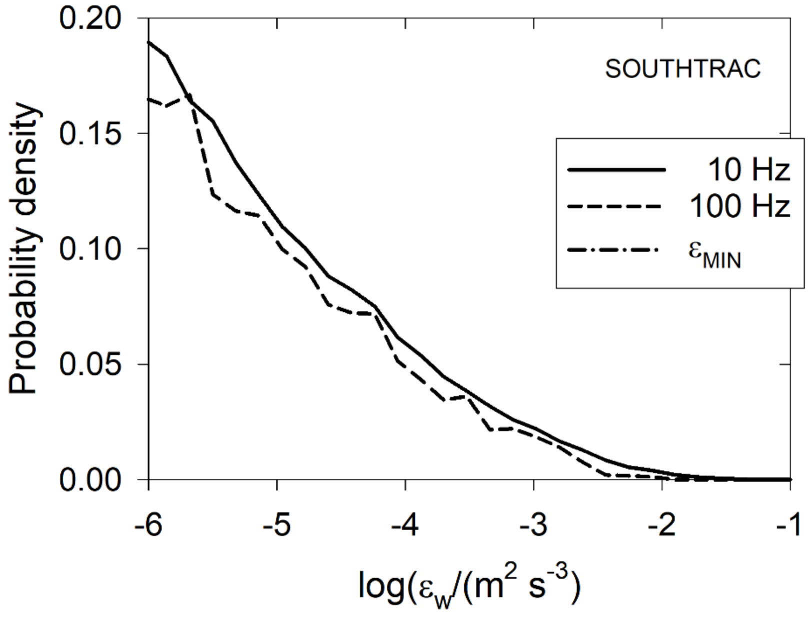


Figure 4. Normalized histograms of ε estimated from (a) radar and (b) radiosondes in the altitude below 8 km. (c, d) The same as Figures 4a and 4b but for altitudes of 8 to 19 km.

HALO



-> strong differences

Further Comparison to literature:

Characterizations of tropospheric turbulence and stability layers from aircraft observations (JGR, 2003)

John Y. N. Cho[1] and Reginald E. Newell

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Bruce E. Anderson, John D. W. Barrick, and K. Lee Thornhill

NASA Langley Research Center, Hampton, Virginia, USA

Received 2 August 2002; revised 12 December 2002; accepted 23 December 2002; published 26 August 2003.

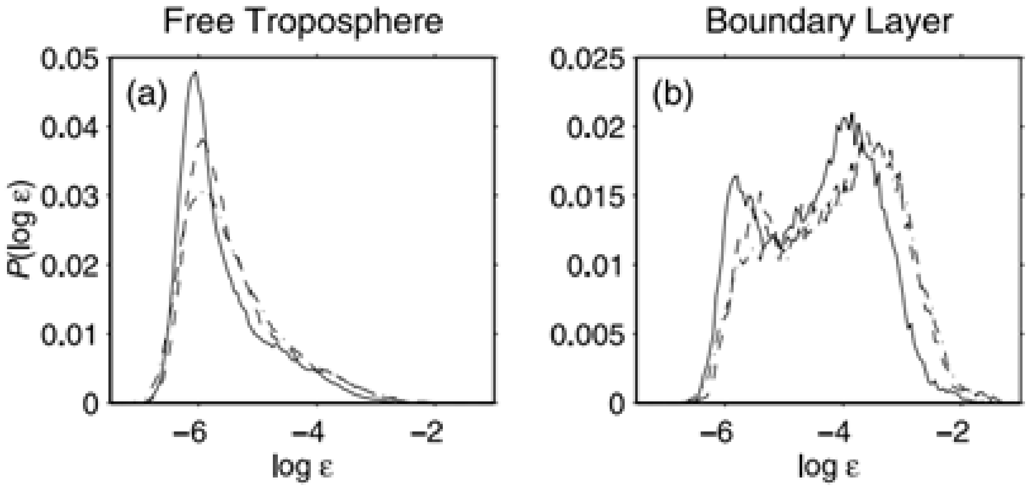
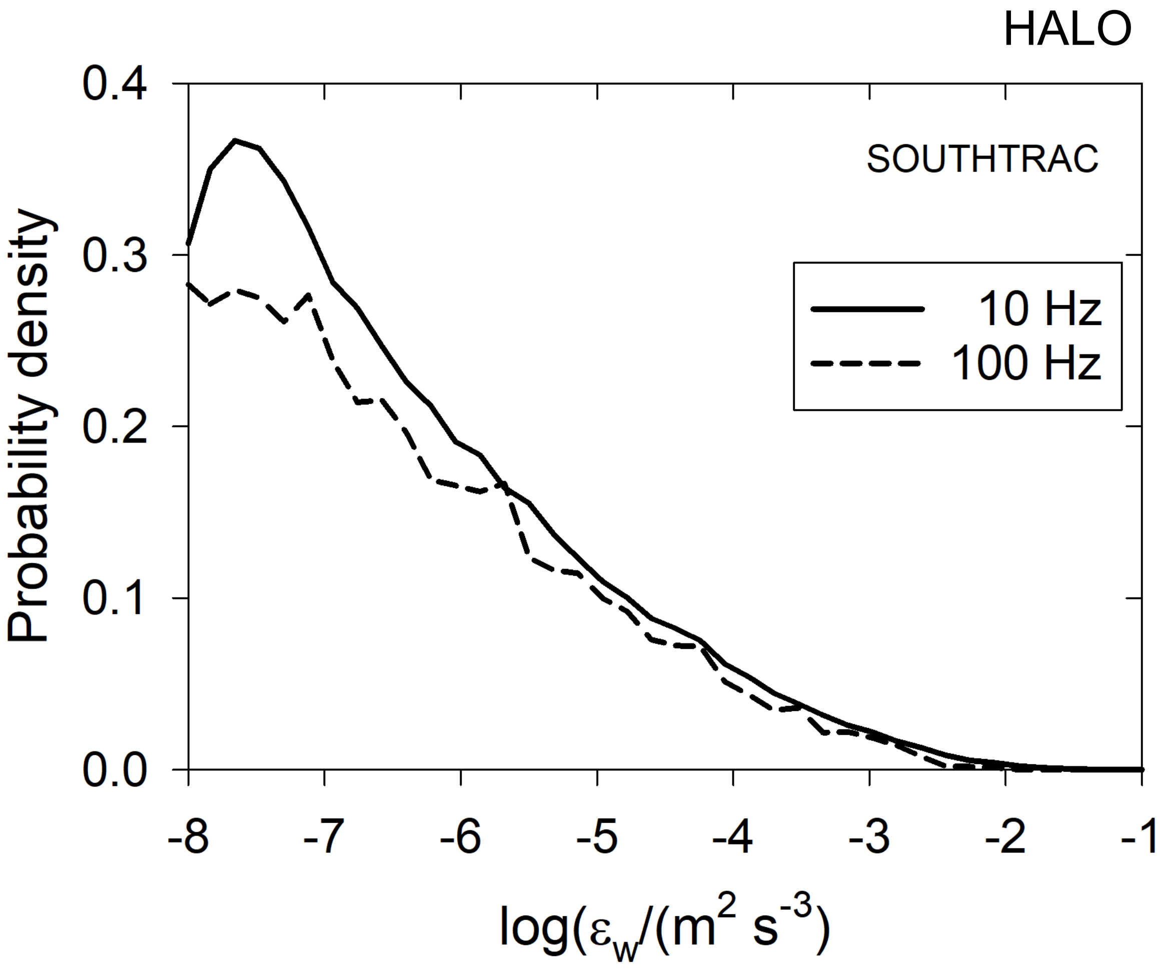


Figure 4. PDFs of log ϵ and log I for Δt = 0.05 s (solid), 0.25 s (dashed), and 0.5 s (dash-dotted).



Further Comparison to literature:

NOVEMBER 2017 PODGLAJI

Small-Scale Wind Fluctuations in the Tropical Tropopause Layer from Aircraft Measurements: Occurrence, Nature, and Impact on Vertical Mixing

AURÉLIEN PODGLAJEN,[a] T. PAUL BUI,[b] JONATHAN M. DEAN-DAY,[b] LEONHARD PFISTER,[b] ERIC J. JENSEN,[b] M. JOAN ALEXANDER,[c] ALBERT HERTZOG,[d] BERND KÄRCHER,[e] RIWAL PLOUGONVEN,[f] AND WILLIAM J. RANDEL[g]

JAS (2017)

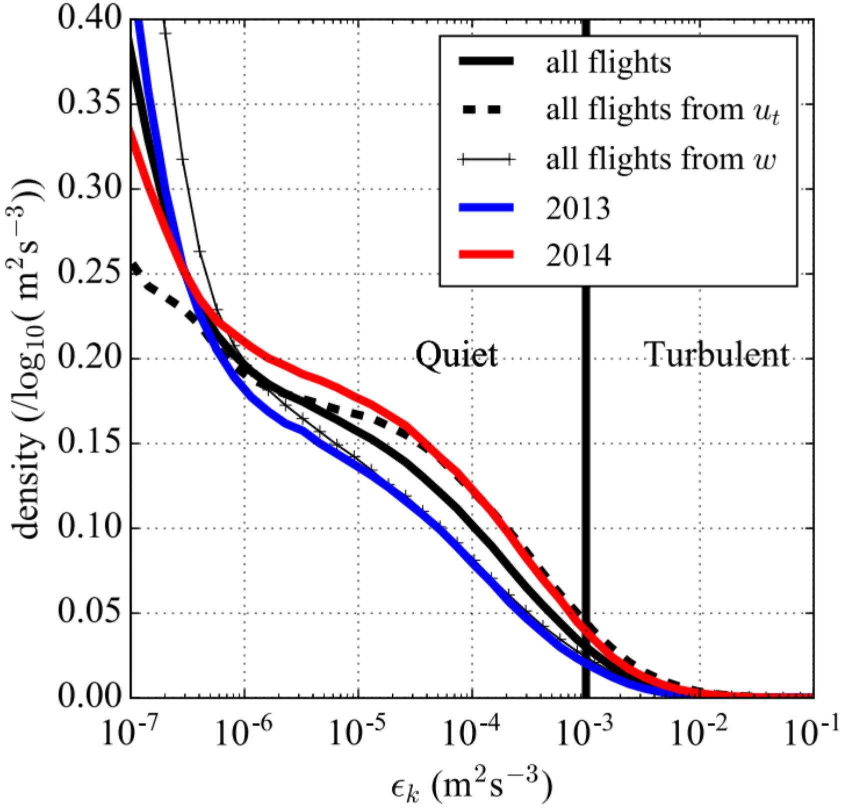
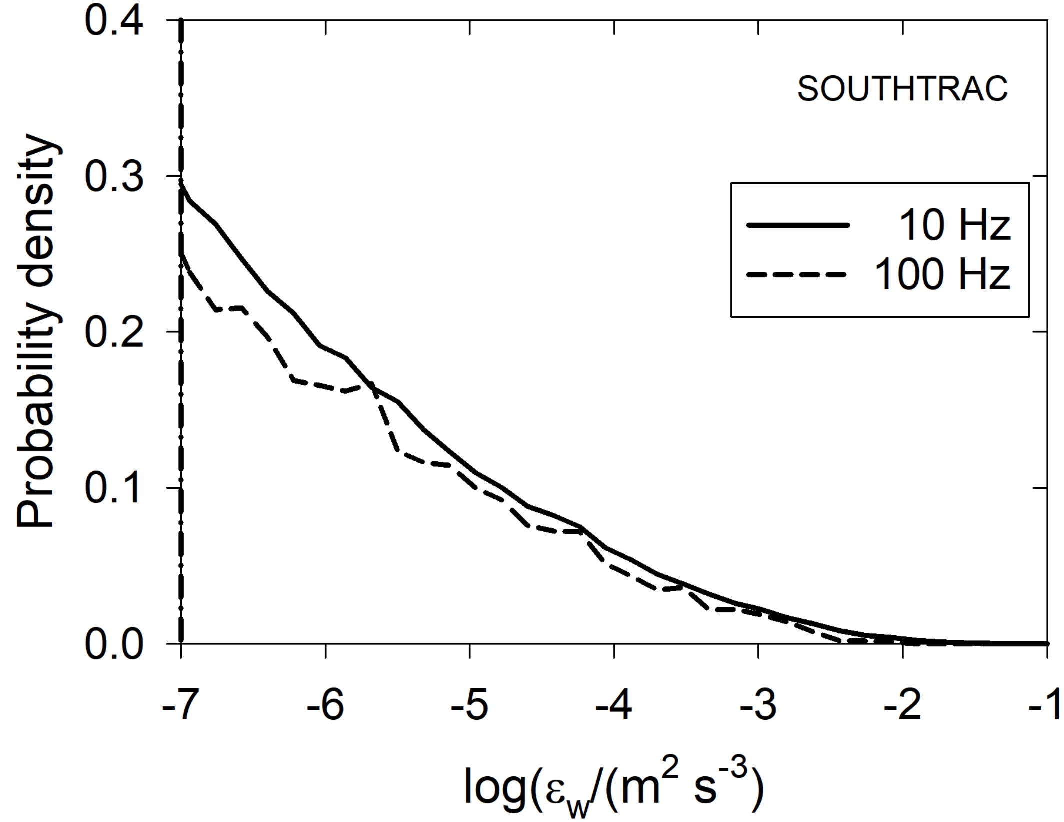


FIG. 6. PDF of ε_k for all ATTREX flights estimated from u_t only (dashed black line) and from w only (crosses) or using Eq. (3) (continuous black line), 2013 eastern Pacific flights (blue line), and 2014 western Pacific flights (red line). The vertical black line shows the threshold chosen to select occurrence of active events. Only the values above the estimated noise level ($\sim 1 \times 10^{-7}\,m^2\,s^{-3}$) are shown.

ATTREX,
Global Hawk,
20 Hz

HALO



Comparison to Literature: Turbulence in the tropopause region: inertial range? Local isotropy?

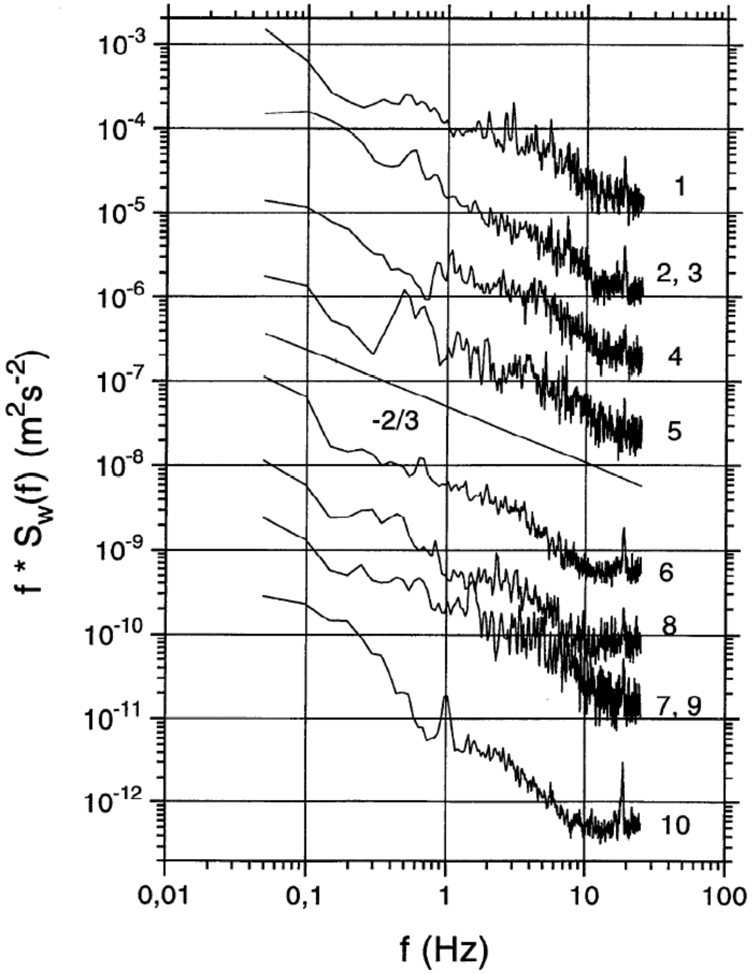
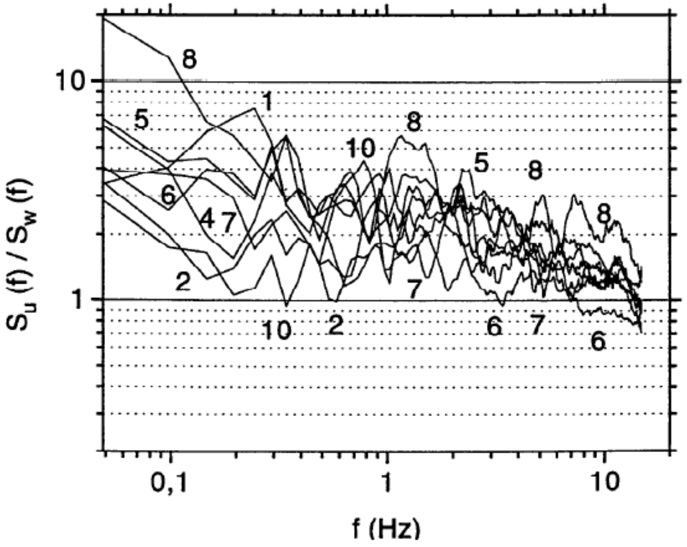


Figure 12. Spectral density function $M(f) = fS_w(f)$ (non-filtered) of vertical velocity fluctuations versus frequency f. The numbers refer to the peaks within the respective flight segments as in Figure 11. To separate the curves, $M(f)$ has been reduced before plotting by a factor 1 (for 1), 10 (for 2, 3), 100 (for 4), etc.



Number	ε, 10^{-8} m² s⁻³	L_O, m	η, m
1	7.9 ± 0.7	0.12	0.02
2	5.7 ± 1.4	0.10	0.03
3	5.7 ± 1.4	0.10	0.03
4	10 ± 2.0	0.12	0.03
5	16 ± 3.0	0.15	0.02
6	1.4 ± 0.5	0.06	0.04
7	1.7 ± 0.5	0.06	0.04
8	10 ± 2.0	0.14	0.03
9	10 ± 2.0	0.14	0.03
10	1.1 ± 0.2	0.04	0.05

UTLS North Atlantic mid latitudes POLINAT, Falcon

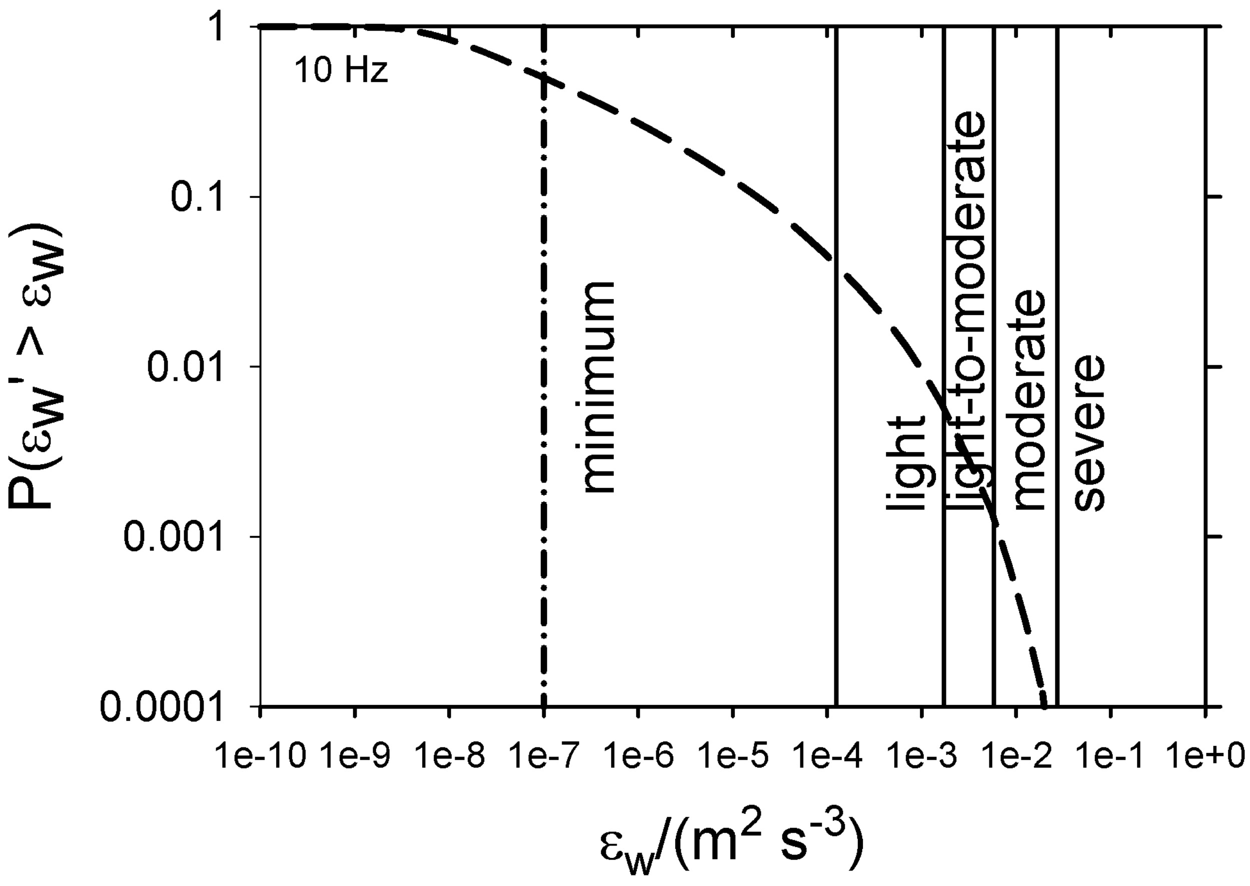
Schumann, Konopka, Baumann et al. (JGR, 1995)

$$L_O = \left(\frac{\epsilon}{N^3}\right)^{1/2}$$

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$$

DLR

Severe turbulence occurs very rarely. Even moderate turbulence occurred in only < 0.1 % of all 10-s SOUTHTRAC flight legs



		ε	EDR= $\varepsilon^{1/3}$
unit:		$m^2\ s^{-3}$	$m^{2/3}\ s^{-1}$
minimum	<	1.e-7	0.005
light	>	0.000125	0.05
light-to-moderate	>	0.001728	0.12
moderate	>	0.005832	0.18
moderate-to-severe	>	0.027	0.3

higher limit values used elsewhere (Sharman et al., 2014, pers. comm. 2023):
EDR=0.10, 0.3, 0.5 $m^{2/3}s^{-1}$ (ICAO, 2001)
EDR=0.15,0.22,0.34 $m^{2/3}s^{-1}$ (Sharman, 2023)
for “light”, “moderate”, “severe”, resp.

For more details see:

DECEMBER 2019 SCHUMANN 3847

The Horizontal Spectrum of Vertical Velocities near the Tropopause from Global to Gravity Wave Scales

ULRICH SCHUMANN

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

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JGR Atmospheres

RESEARCH ARTICLE
10.1029/2022JD036654

Special Section:
SOUTHTRAC-GW: An airborne field campaign to explore gravity wave dynamics at the world's strongest hotspot

High-Resolution Aircraft Observations of Turbulence and Waves in the Free Atmosphere and Comparison With Global Model Predictions

Andreas Dörnbrack[1], Peter Bechtold[2], and Ulrich Schumann[1]

[1]DLR Oberpfaffenhofen, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, [2]ECMWF, Reading, UK, Bologna, Italy, Bonn, Germany

Conclusions

- The BAHAMAS system on HALO provides reliable energy spectra and dissipation estimates
- The vertical wind (w) spectra are related to kinetic energy of divergent motions (d) at large scales by continuity and to total horizontal energy (h) at small scales
- In the stably stratified atmosphere near the tropopause, dissipation is anisotropic and not log-normal distributed.
- The Kolmogorov model provides reliable dissipation rate for $\varepsilon > \varepsilon_{MIN} \sim 1.e\text{-}7\ m^2\ s^{-3}$ only
- **Strong turbulence occurs very rarely.** Even moderate turbulence occurred in only 0.1% of al SOUTHTRAC 10-s flight legs
- Instead we have **mainly anisotropic wavy motions without inertial-range turbulence**
- Comparison to literature shows reasonable agreement with previous research aircraft results
- The set of derived ε_w values is available and is a valid measure for “clear air turbulence”
- Next: relate ice supersaturation (Rhi>1) to turbulence, stratification shear etc. using high resolution radiosonde data (BUFR) data. Mainly RS41?

Reserve slides

Dissipation rates ε from spectra or structure function

- Both spectra and structure functions useful to identify scaling laws
- Spectra provide more accurate results than structure functions, at least for turbulence in stratified air masses

Dissipation rates ε from SOUTHTRAC 10 Hz data - Structure Function

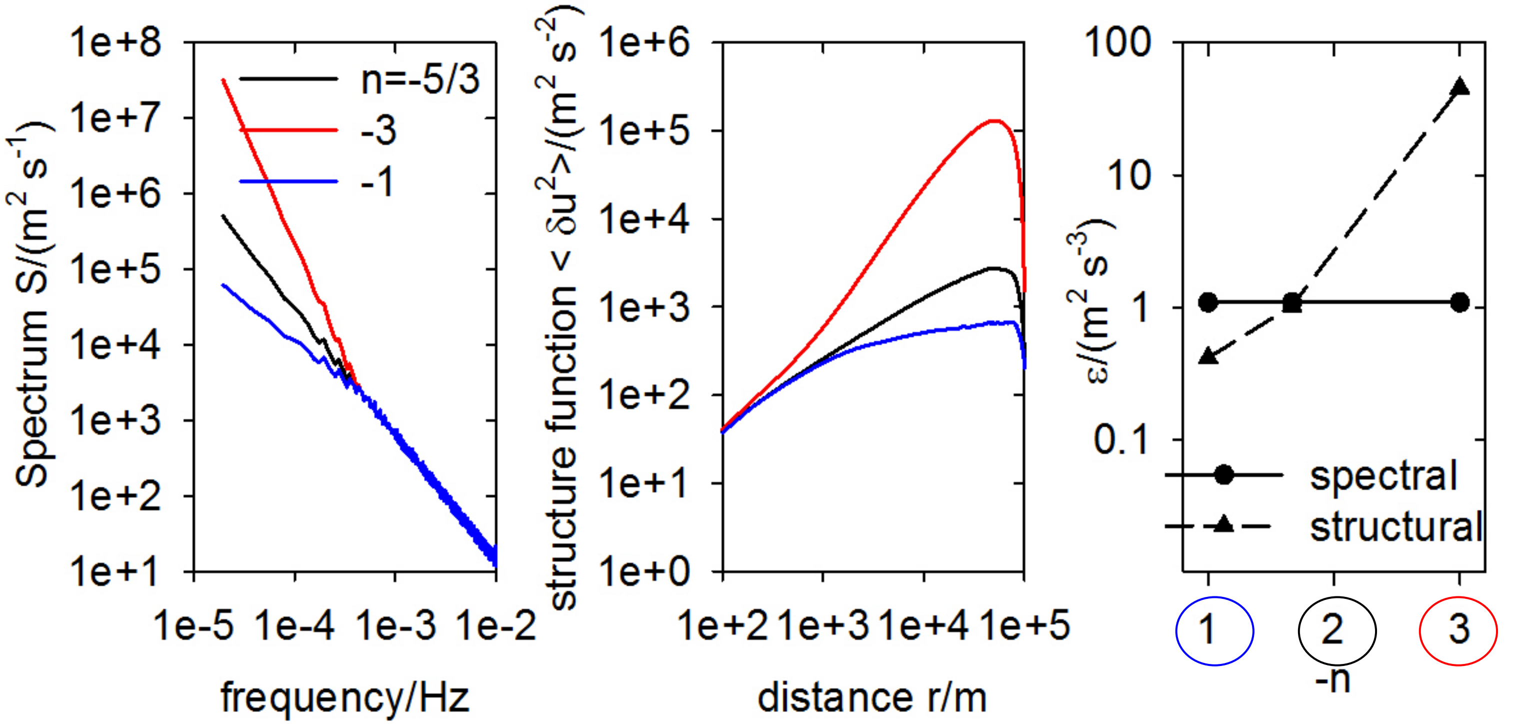
- See Frehlich and Sharman (MWR, 2004)
- dissipation rate ε is computed every 5 s from 10 s-segments (100 data points) for forward, sideward and upward velocity components -> (ε_u, ε_v, ε_w) in $m^2\ s^{-3}$
- Structure function computed from the definition

$$D_u(s) = \langle u'(x+s)u'(x) \rangle = C_K\ \varepsilon^{2/3}\ s^{2/3}\ ,\ C_K = (2,\ 8/3,\ 8/3) \text{ fur } u,\ v,\ w$$

- Which requires a double loop (s, and time) and hence more computer time than computing spectra
- and approximated by the Kolmogorov law:

- Evaluated for smallest distance s = TAS* Δt

Dissipation rates from turbulence structure-functions and (1-d) variance spectra with spectral slopes between -1 and -3.



Results from analytical integrals an numerical simulations agree

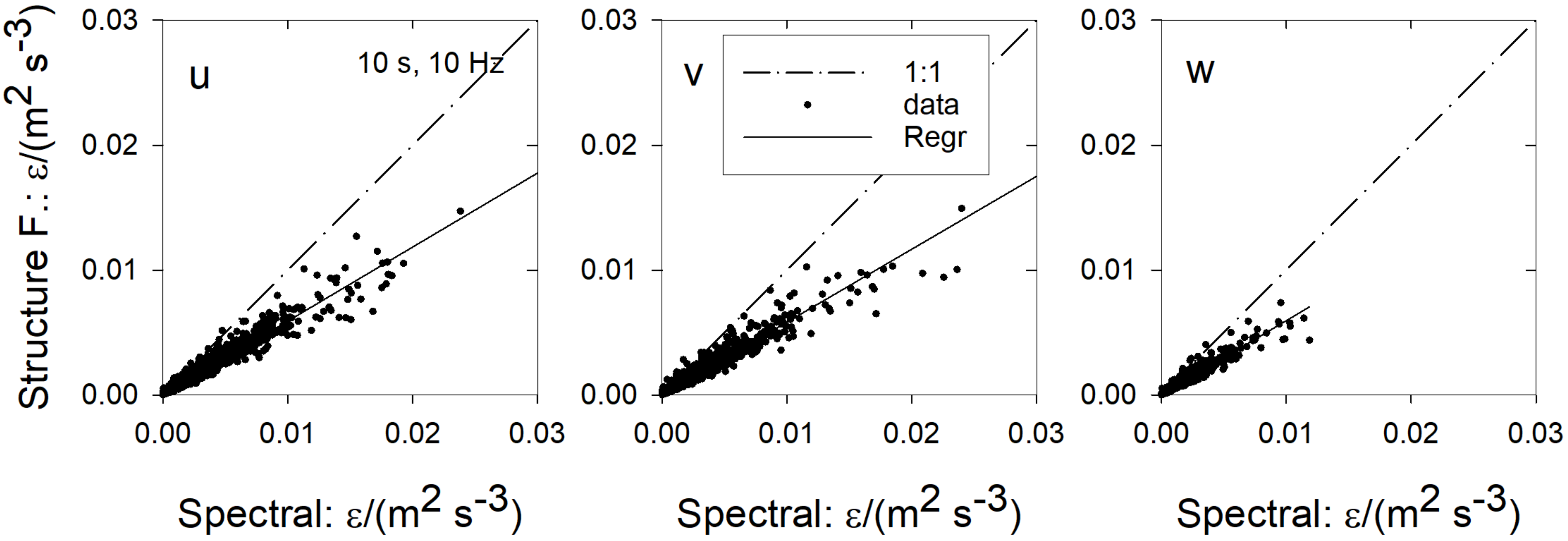
Kolmogorov(1941):

$$E(k) = \alpha \varepsilon^{2/3} k^{-5/3} \qquad S(r) = c \varepsilon^{2/3} r^{2/3} \qquad c = (3/2)\Gamma(1/3)\alpha$$

-> Spectra are better suited for dissipation analysis

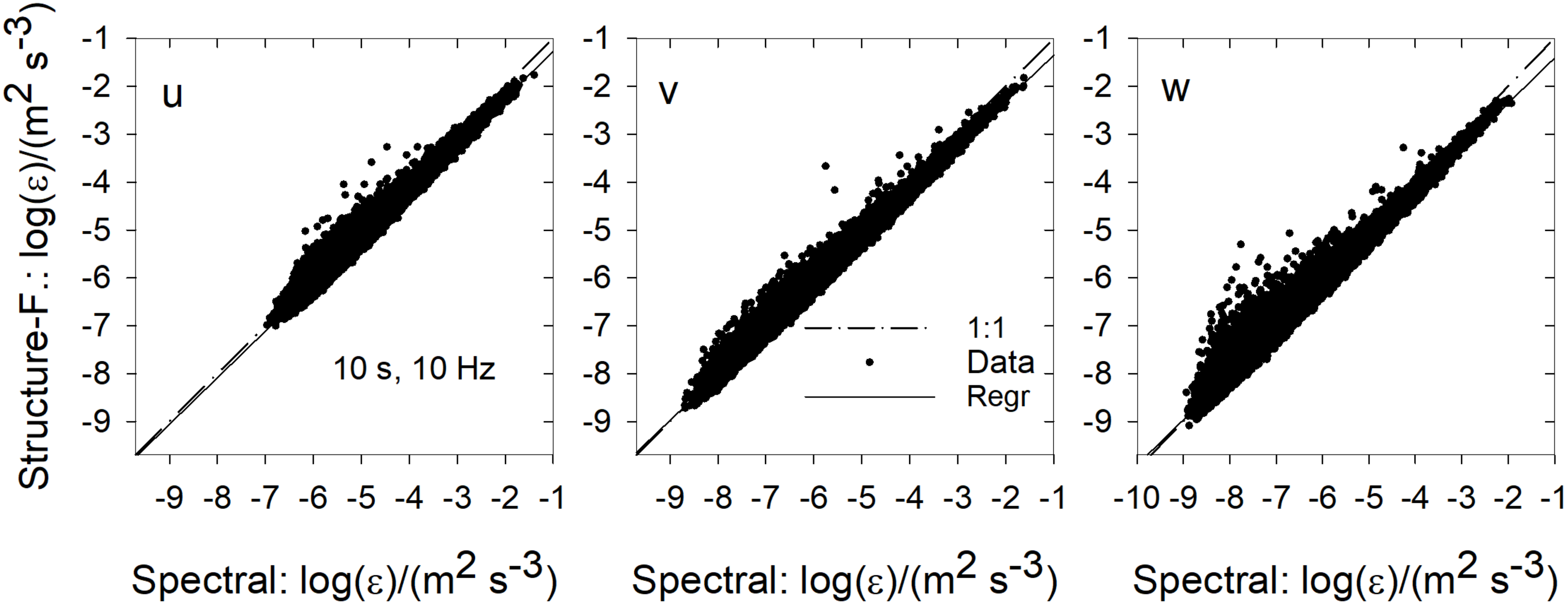
SOUTHTRACK: Dissipation rates from spectral and structure function analysis

10-s segments - Linear scales:



SOUTHTRACK: Dissipation rates from spectral and structure function analysis

10-s segments - Logarithmic scales:



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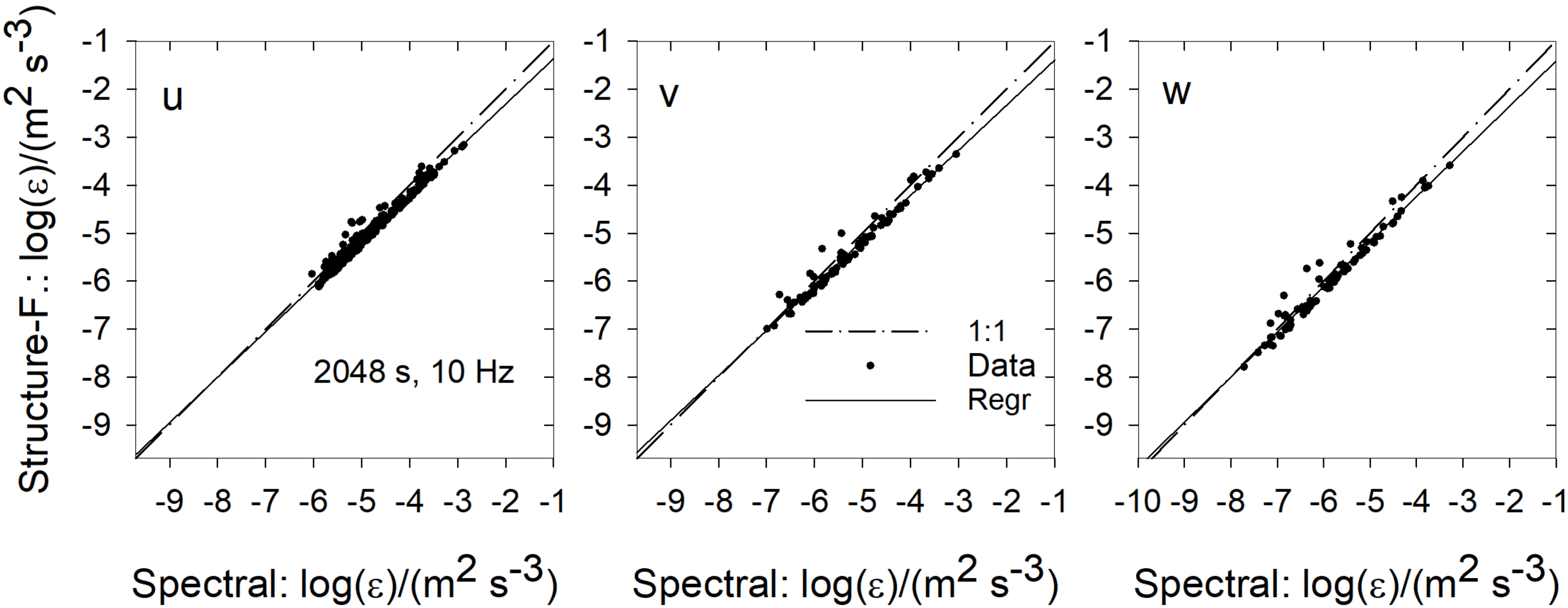
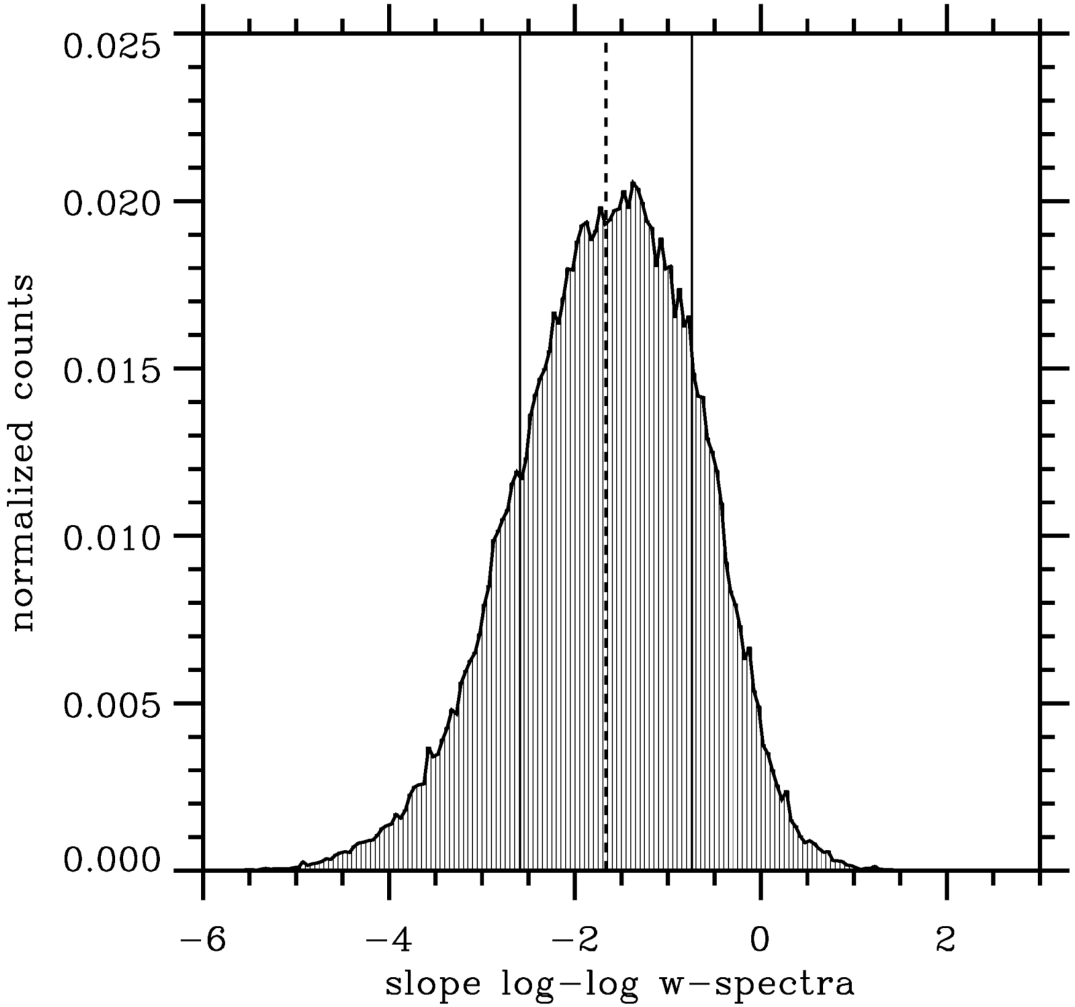
SOUTHTRACK: Dissipation rates from spectral and structure function analysis

2048-s segments - logarithmic scales:



Spectra of 10-s flight segments reflect a steady inertial subrange in the mean only: bursts and decaying turbulence instead



mean slope = $-\frac{5}{3} \pm 0.92$

derived turbulence is nonsteady and highly anisotropic;

i.e. assumption of locally isotropic inertial-range turbulence is a hardly satisfied, rough approximation and valid in large-ensemble averages only.

There are atmospheric regions where turbulence is in its stationary state and regions where turbulence decays in time or, on the contrary, becomes stronger (WACŁAWCZYK et al., JAS 2019).

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