Aircraft effects in DEEPWAVE mountain legs?

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Aircraft effects in DEEPWAVE mountain legs?

Since ML-CIRRUS 2014, we discuss possible aircraft dynamics effects on turbulence and gravity wave spectra measurements

The evidence provided so far (e.g., from START08) was not strong enough to convince the science community that aircraft dynamics is important for gravity wave/turbulence measurements

DEEPWAVE is unique in providing high-quality gravity waves and turbulence data for many similar mountain legs

Are the variance spectra insensitive to the flight direction – as they should?

Or are there differences which could be explained by aircraft dynamics?

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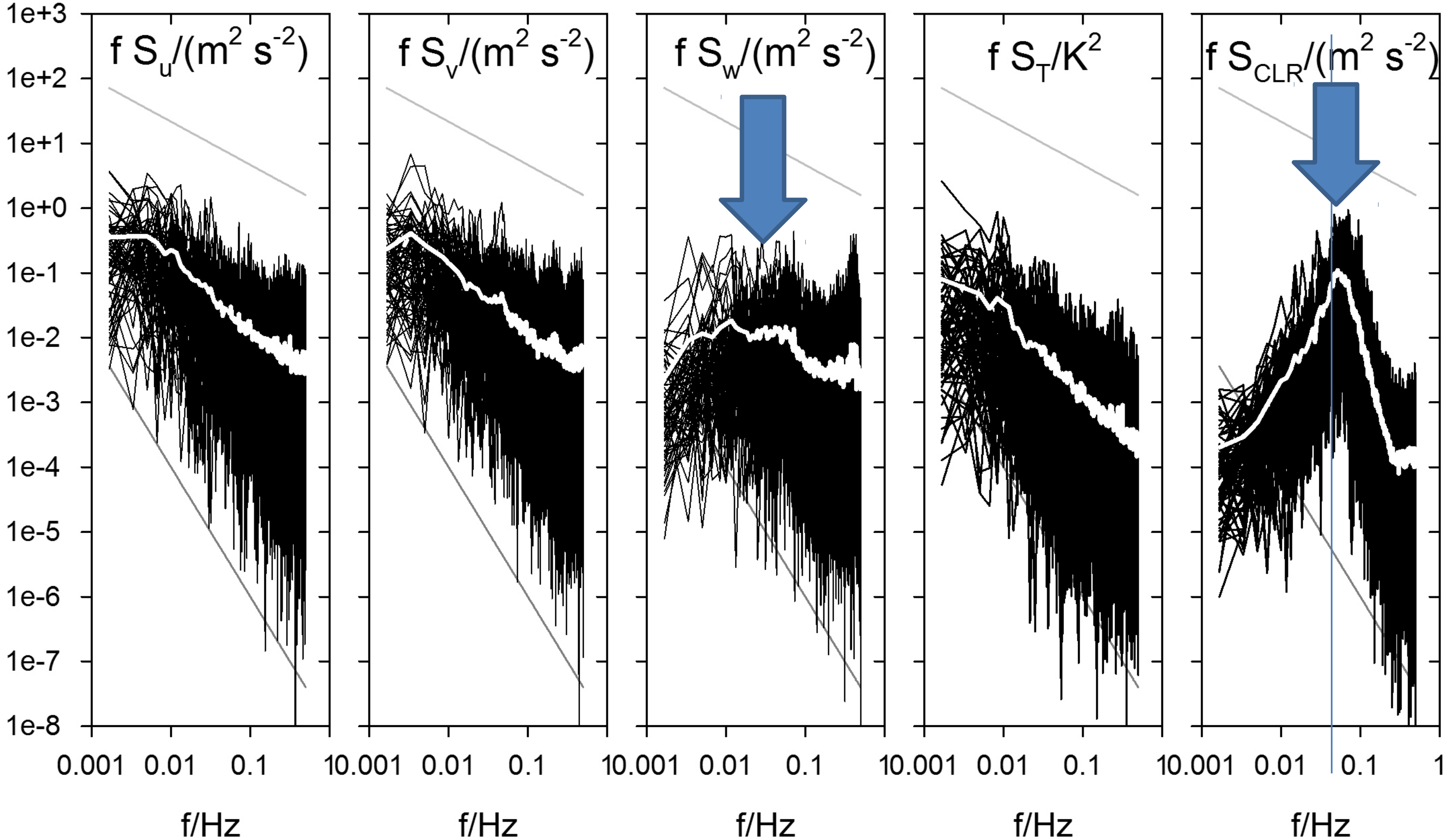
How this research started: unexplained peaks in variance spectra for HALO ML-CIRRUS 1 Hz data



Spectra of wind u, v, w, vertical aircraft body velocity ("climb rate") CLR and temperature T data vs. frequency f. From 153 constant-level flight legs, 10 min each.

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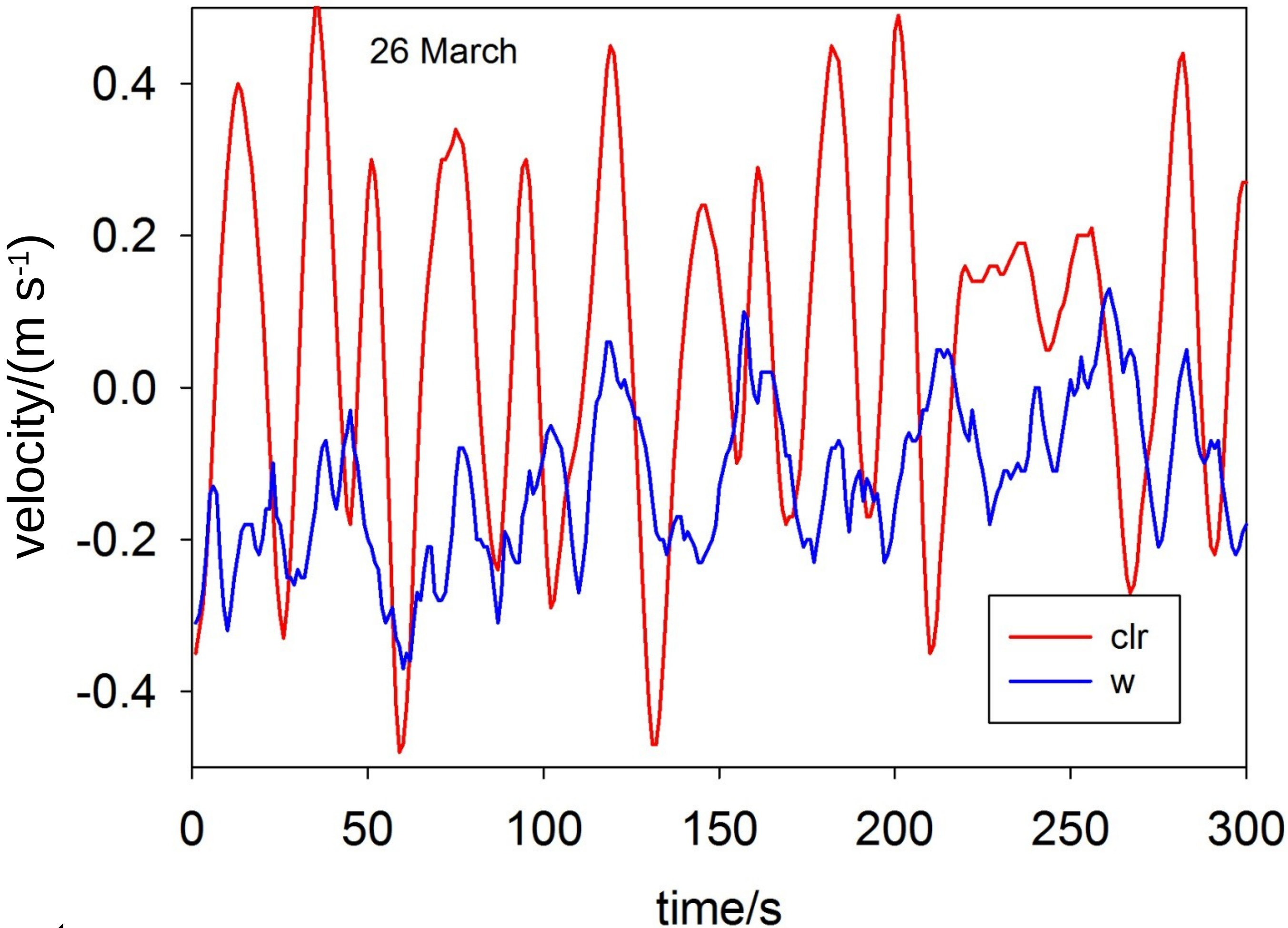
HALO upward vertical body velocity (“climb rate” clr) often larger than vertical wind *w*



Oscillation period ~20 s (~5 km)

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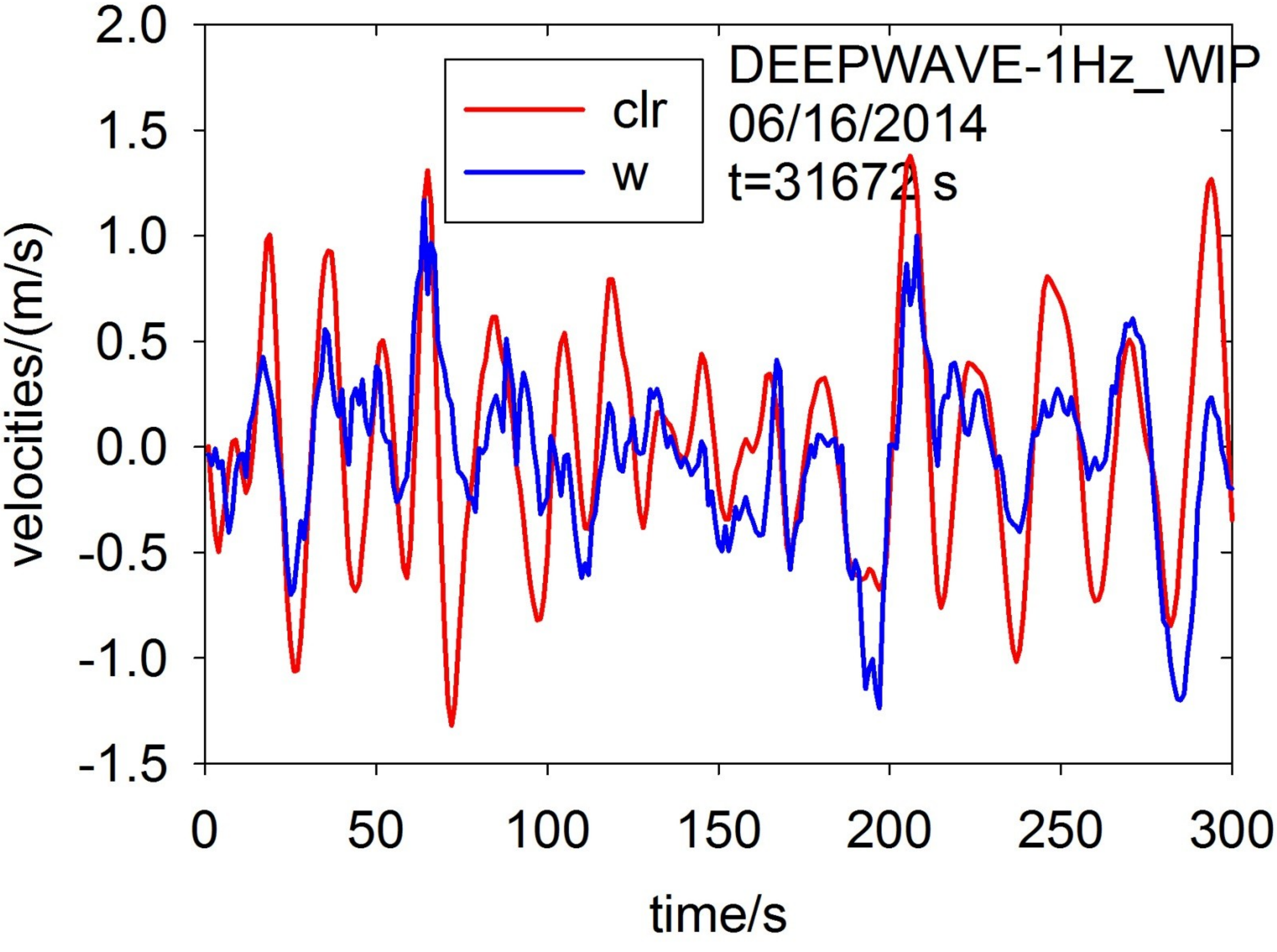
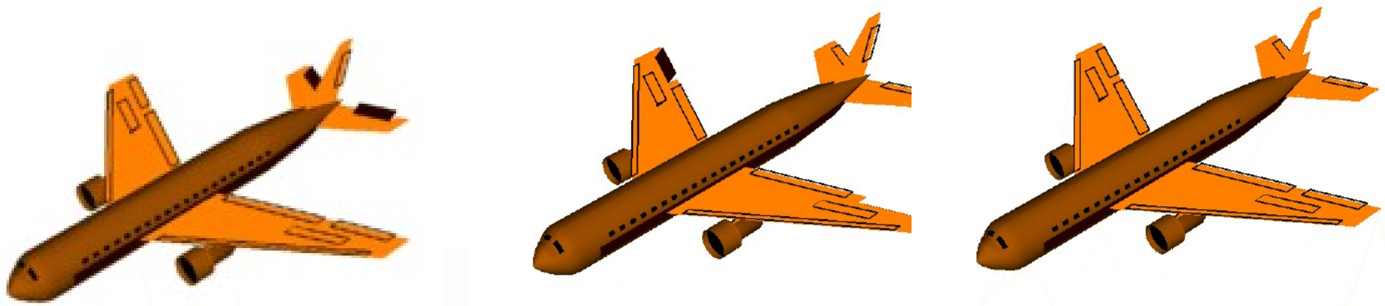
Such oscillations occur basically for all aircraft, e.g., for the NSF GV (aircraft similar to HALO, except noseboom)

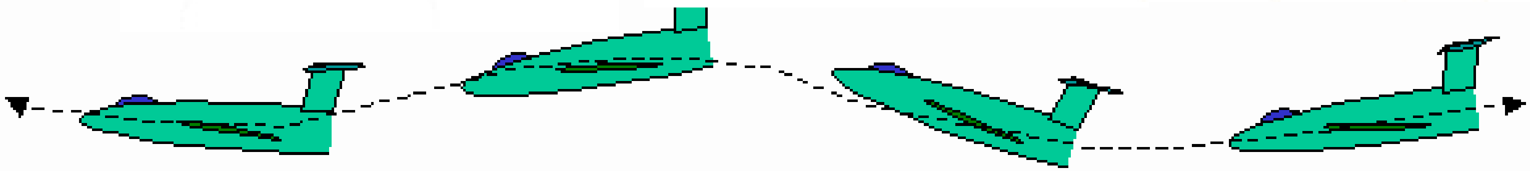


Oscillation period ~20 s (~5 km)

Aircraft Dynamics – how to explain and evaluate?

(The phugoid is a pitch mode; other modes show roll and yaw oscillations)





The phugoid frequency for low-damped airplanes ~ sqrt(2) g/(2π U) =0.01 Hz.

The observed vertical oscillation frequency is near 0.06 Hz, i.e. about 3-6 times higher higher than the phugoid mode because of drag (in particular at high Mach number) and autopilot impact

We have developed an aircraft dynamics model which simulates the aircraft response to given turbulence data. Parts of required input has to be estimated from observations.

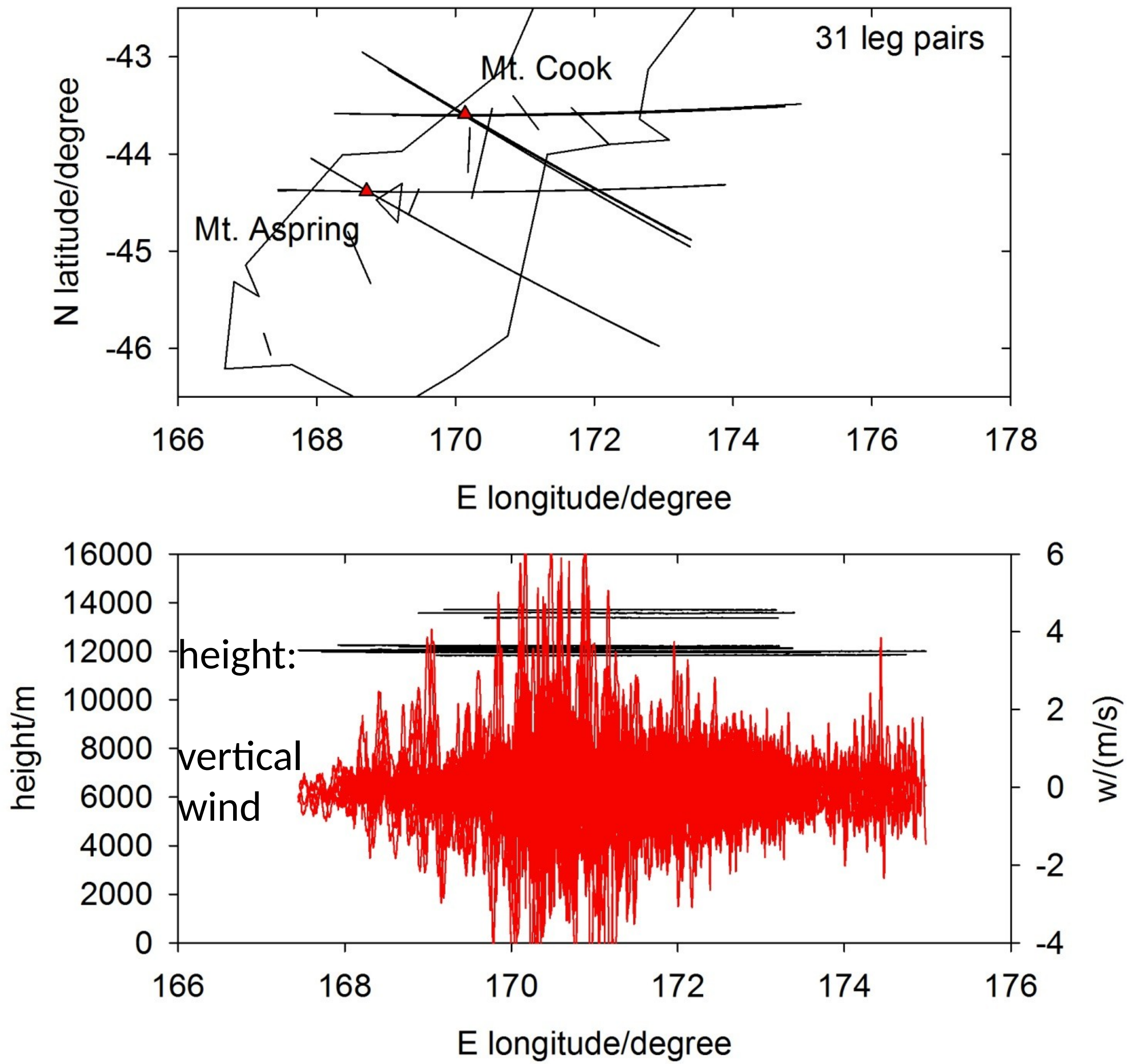
Source of figures: https://de.wikipedia.org/wiki/Roll-Nick-Gier-Winkel and https://de.wikipedia.org/wiki/Phygoide

DEEPWAVE is unique with many similar mountain legs

The variance spectra should be invariant to the flight direction,
at least under stationary conditions.

Here, we select
31 leg pairs out of 89 mountain legs for comparison.

Data from NCAR-EOL



Example: leg pair RF08 2 & 3, w_E, w_W

leg pairs =

pair of eastward and westward legs

along same route

during same flight

from subsequent mountain traverses (Δt_{leg} < 1800 s)

in same longitude range

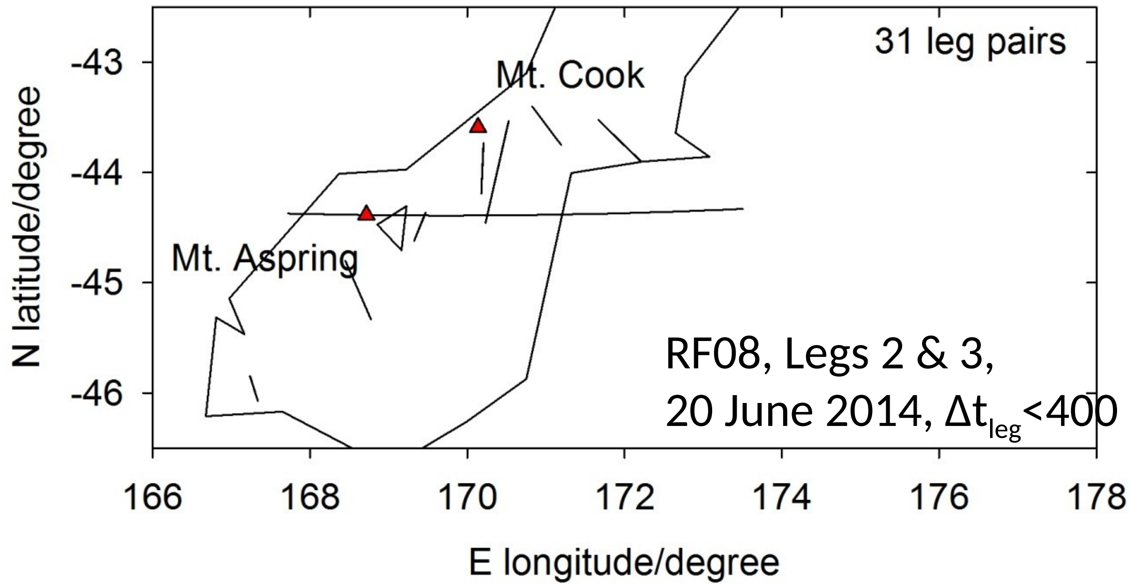
passing both coast lines

with maximum 100 m mean altitude difference

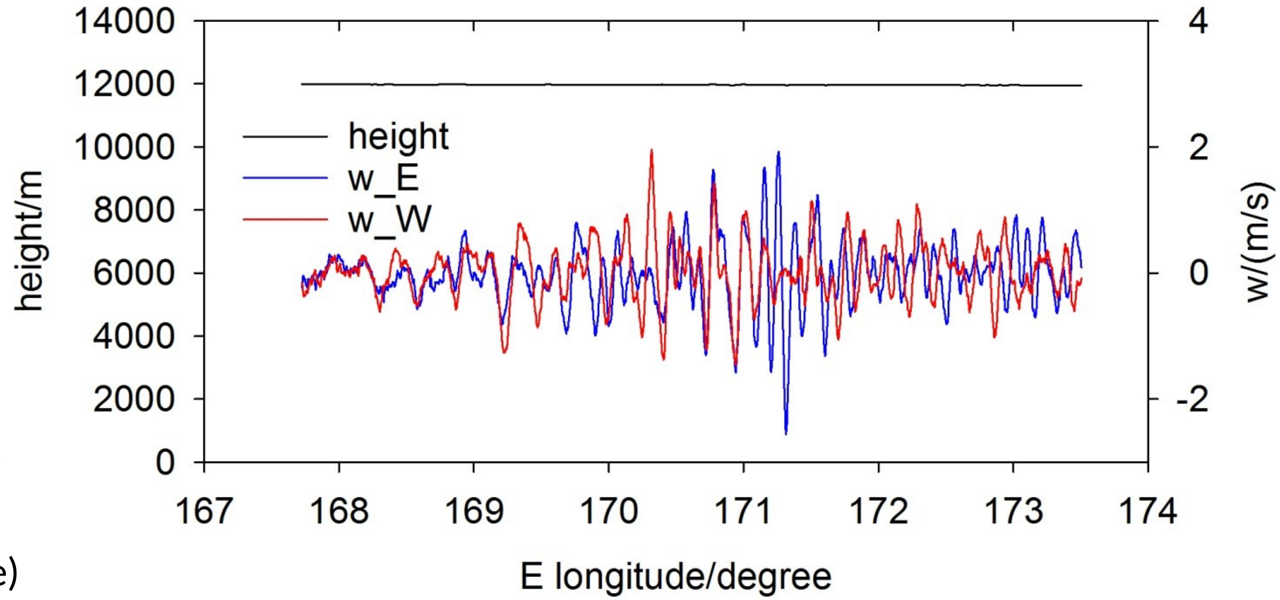
both interpolated to 3×1024 spatially equidistant grid points

analyzed with same methods

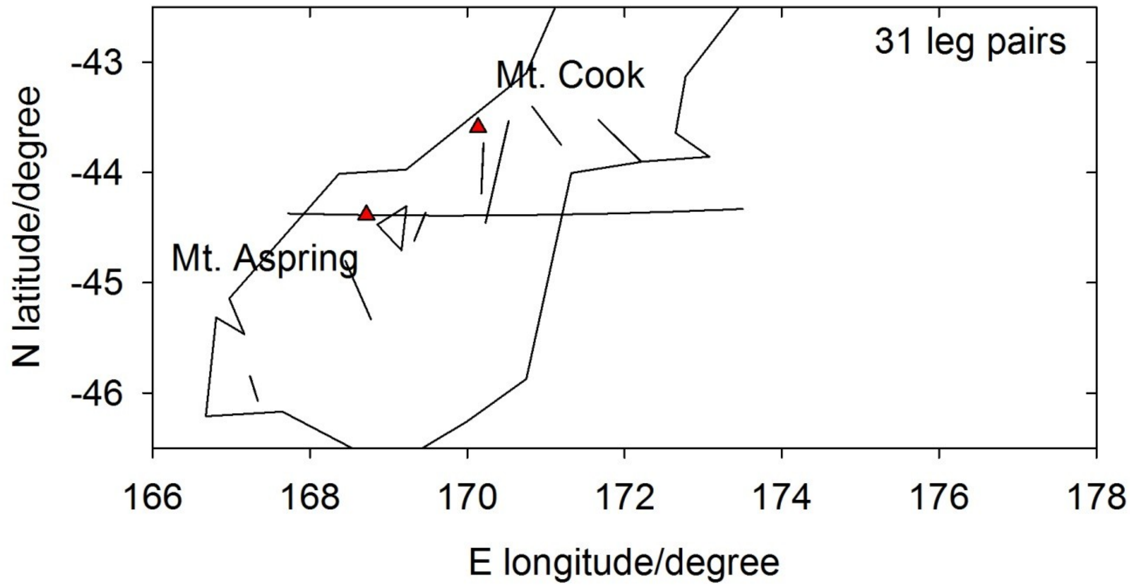
(Partly checked by comparisons with Chris Kruse)



RF08, Legs 2 & 3,
20 June 2014, Δt_{leg}<400 s

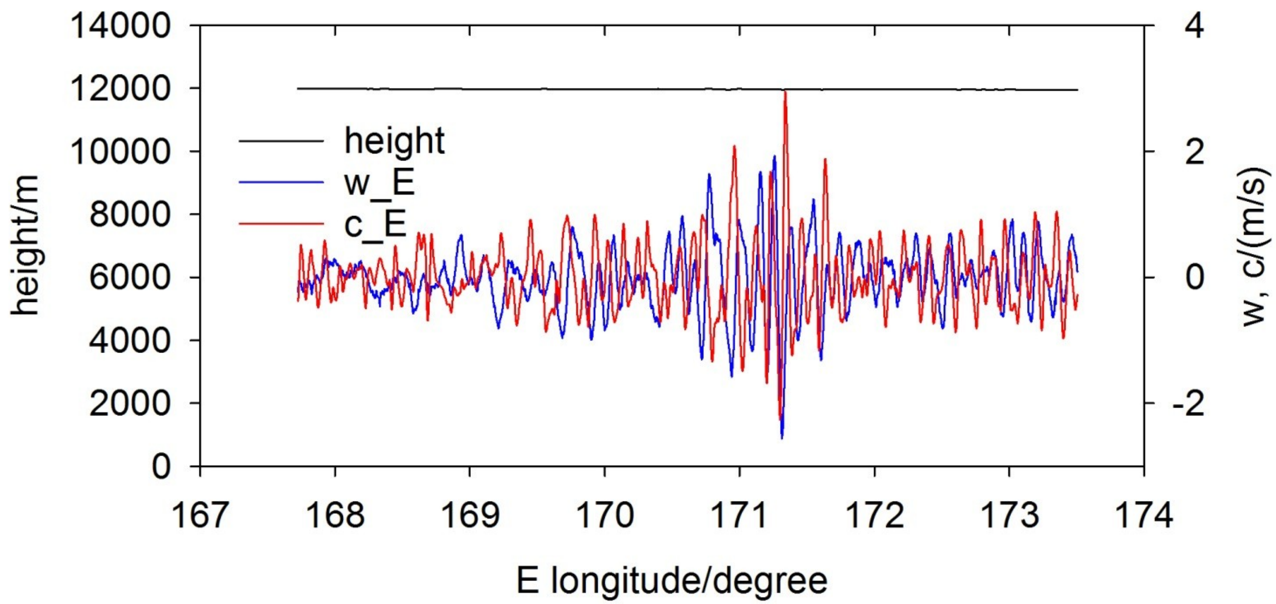


Example: leg pair RF08 2 & 3, w_E, c_E



now with
w and c
for same leg
(eastward)

var(c) > var(w)



Variance spectra for all pairs of E- and W-bound flight legs, first for vertical aircraft body velocity c in m/s

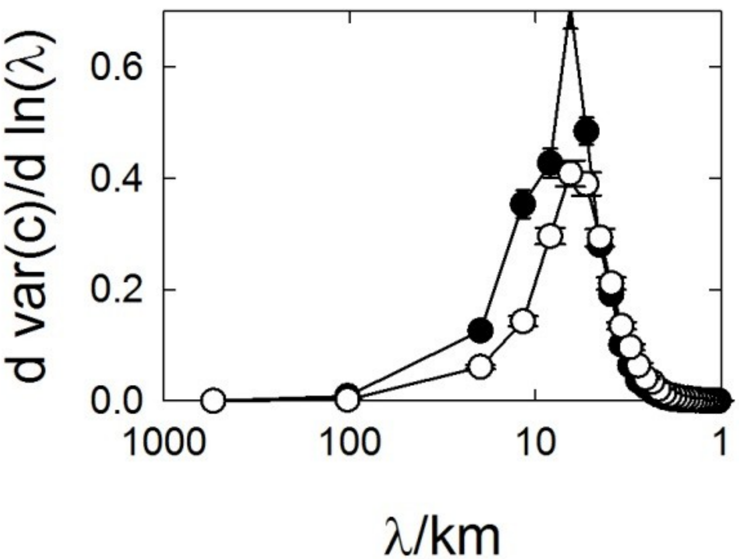
full symbols: eastward flights (with wind)

open symbols: westward flights (against wind)

the spectra are binned in wavelength intervals with equal number of discrete wavenumbers per bin (60 bins)

var(y) =variance spectrum of y in units of m/s, K, or Pa

per change in natural logarithm (ln) of wavelength λ



Here we see, as expected, significant differences for different flight directions:

Strong peak in vertical aircraft velocity variance in (m^2 s^{-2})
$var(c)_E > var(c)_W$
at 6 to 15 km wavelengths

higher c because of higher speed over “rough terrain”

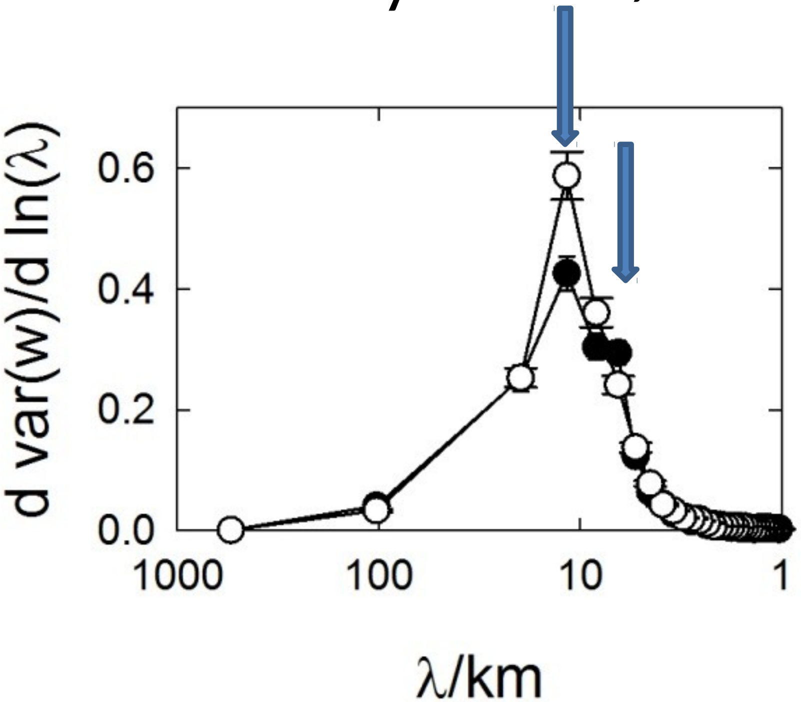
Same for vertical velocity w in m/s?

Here, error bars = expected uncertainty of the mean values based on standard deviation σ of leg to leg variance and n (here, n=31 legs) for Gaussian statistics, error= σ/sqrt(n-1).

Non-overlap of error bars is the minimum required for a significance test

As before:
full symbols: eastward flights (with wind)

open symbols: westward flights (against wind)



similar magnitude for w as for c, but wider spectrum.
Again, we see E-W differences (unexpected):
$var(w)_E > var(w)_W$ at 5 to 10 km wavelengths;
surprisingly:
opposite ordering at 10 to 15 km wavelengths;

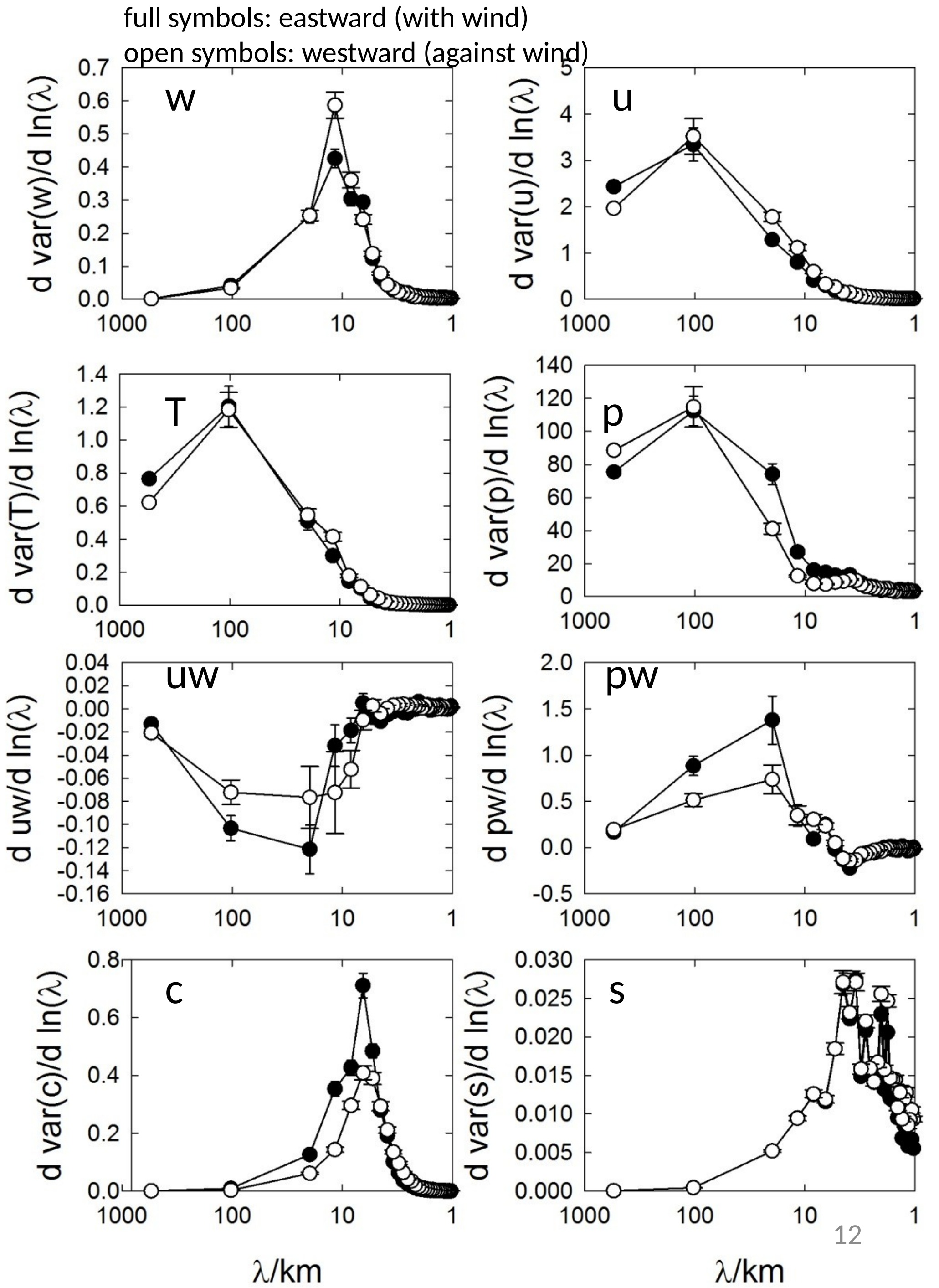
No difference detectable at longer wavelengths

Similar findings for further data

Differences (with debatable significance) occur in most of them

w = vertical velocity/(m/s)
u= inflight velocity/(m/s)
T = temperature/K
p= pressure/Pa
c= vertical body velocity/(m/s)
s = terrain slope/(m/m)

U sign changed for westward flights



Differences are more pronounced for strong winds:

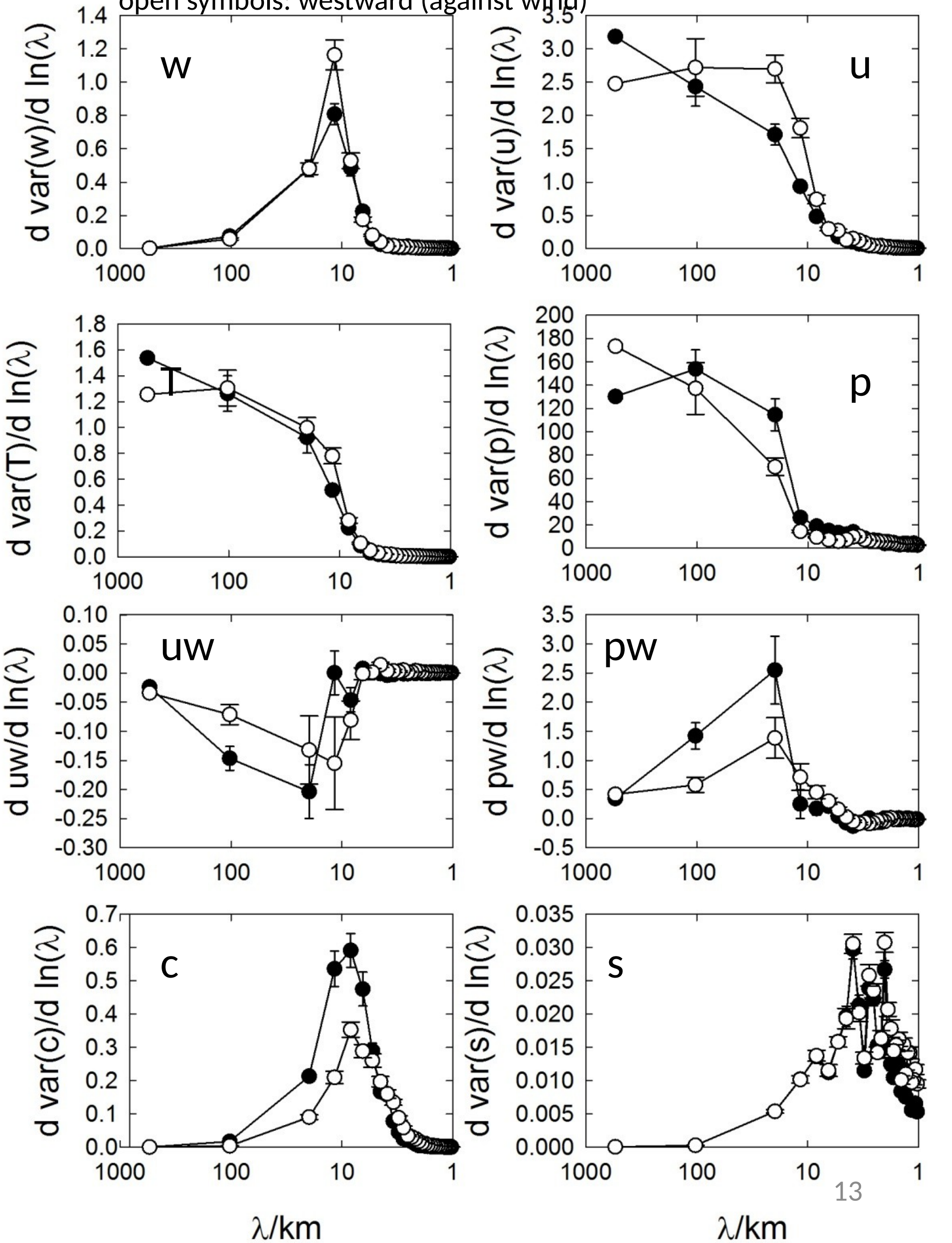
ΔGS/GS > 0.12
(14 of the 31 leg pairs)

again:
w is smaller on W-legs.

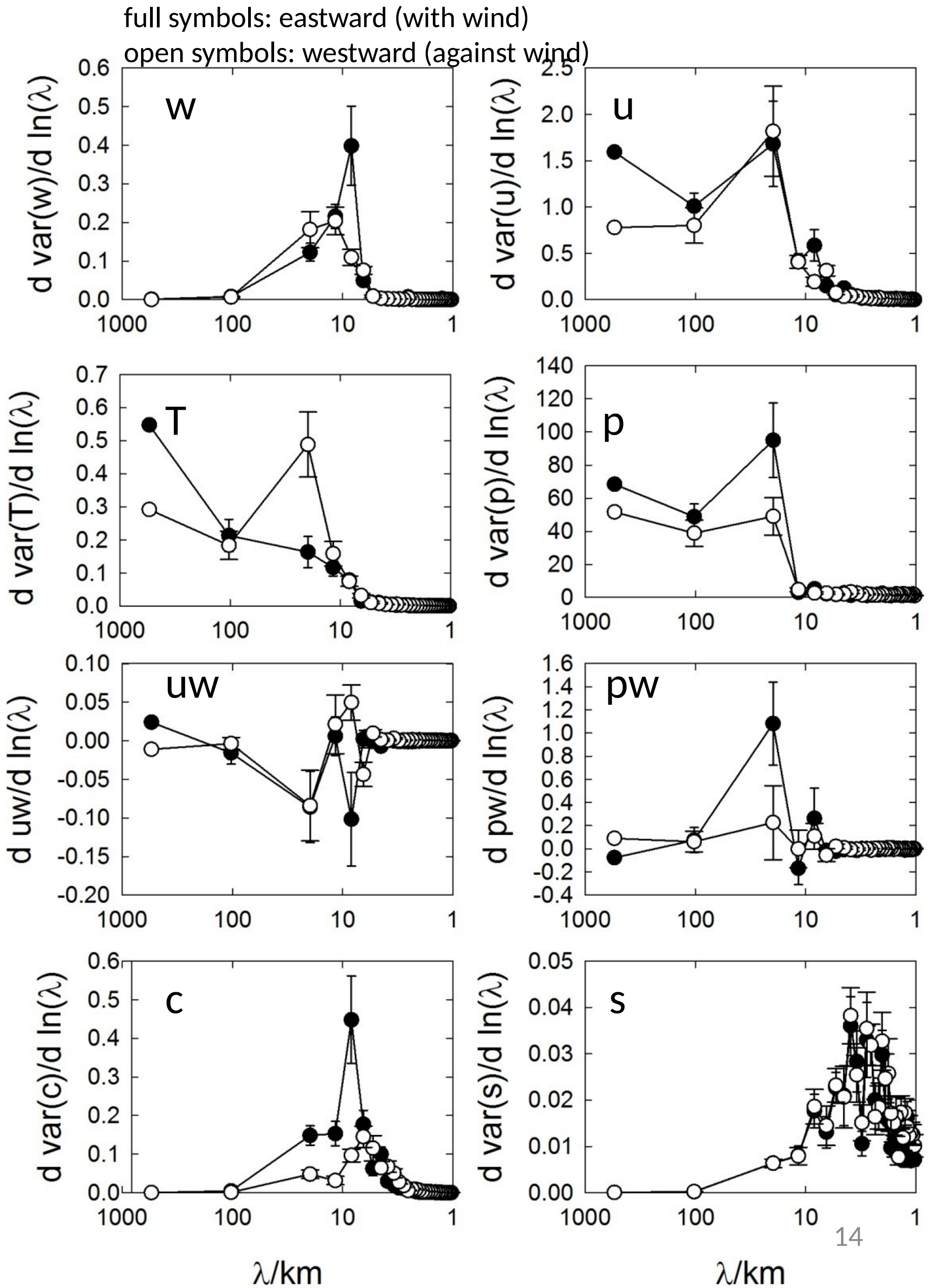
p, and c are larger on W-legs than on E-legs

Large differences also in u and
co-variances (fluxes)

full symbols: eastward (with wind)
open symbols: westward (against wind)



Single leg pair with smallest time delay and strong wind (ΔGS/GS>0.12, RF08, legs 2 & 3)

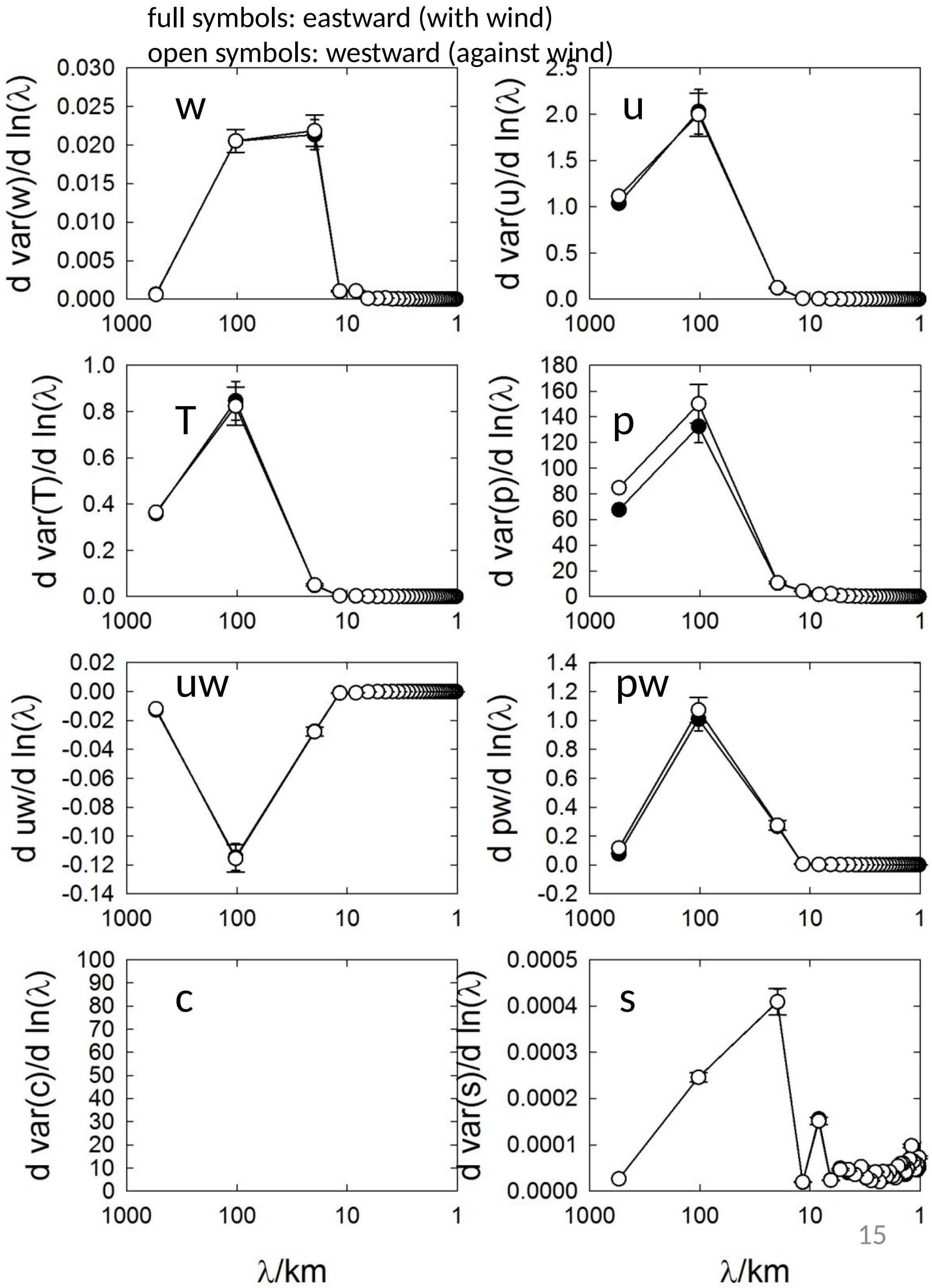


c and w are both enhanced at wavelengths near 8 km, but w is reduced at 20 km

Large differences for T, p, and fluxes (non-stationary?)

Large scale variability apparently low

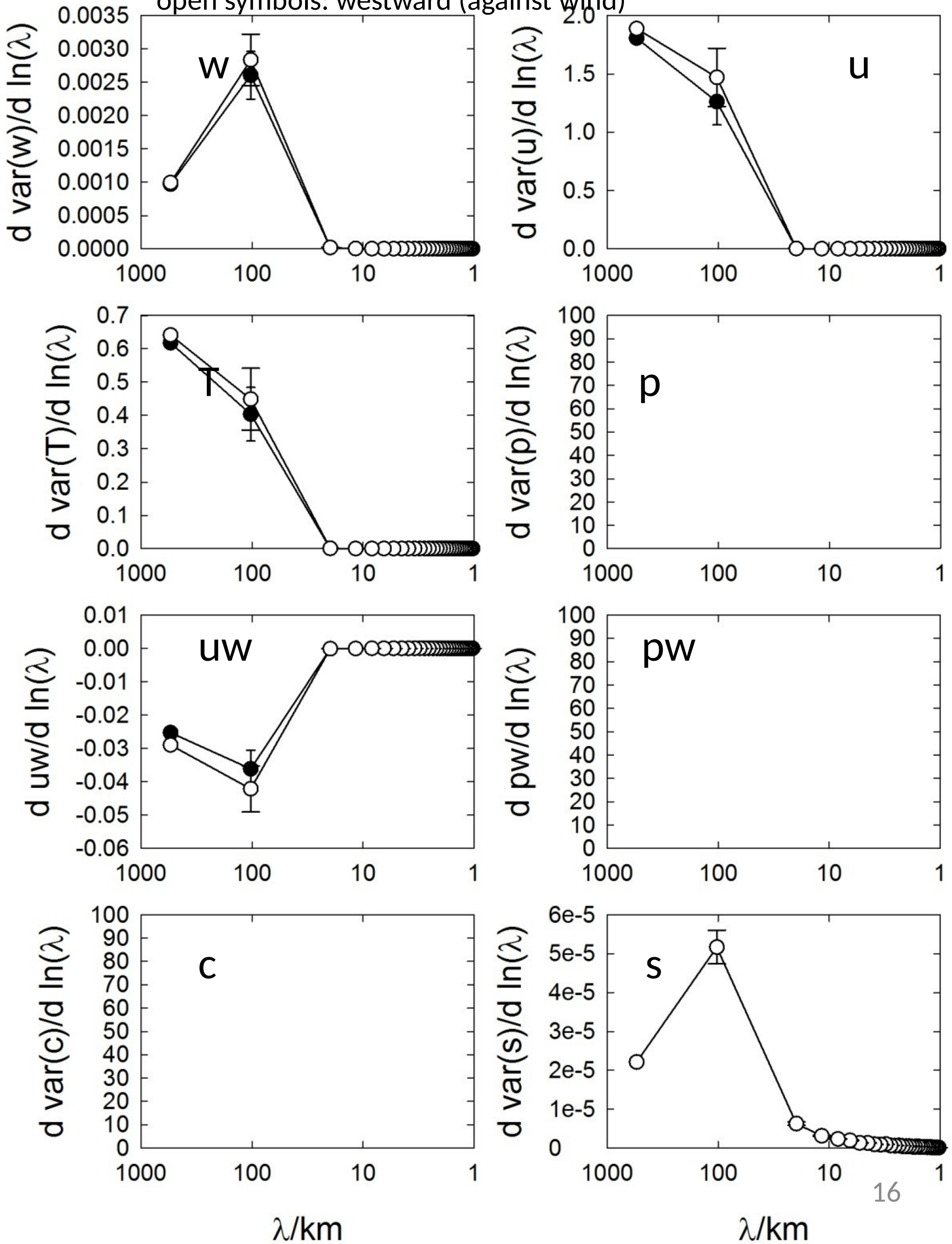
from 6-km WRF



data from Chris Kruse

Similar for ECMWF with even coarser spatial resolution

full symbols: eastward (with wind)
open symbols: westward (against wind)



The data show **very** similar results for E and W legs.

data from Andreas Dörnbrack

How significant are the (non-Gaussian) statistics?
For this purpose, we look to mean variances:
integrals over λ intervals

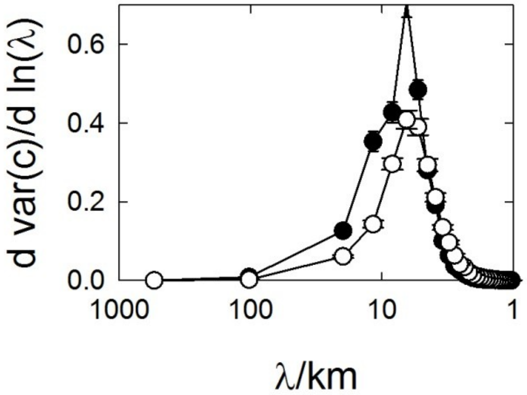
$\Delta y/y = (y_E - y_W)/(y_E + y_W)$

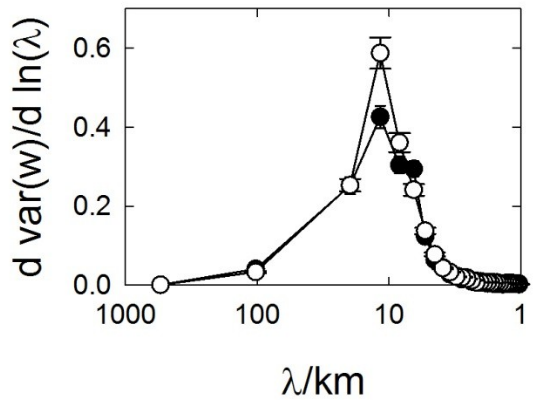
here for
c = vertical body velocity
and
w = vertical air velocity

apparently:

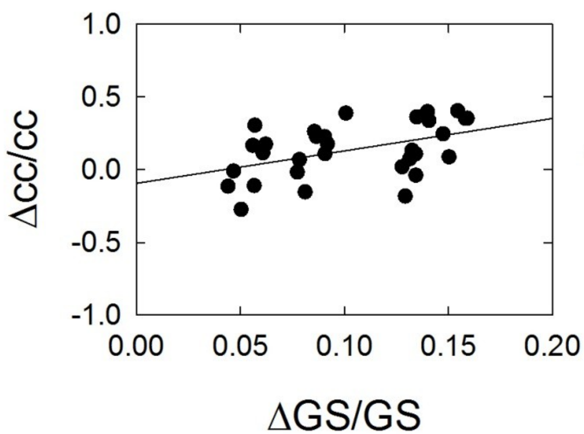
Trend for c.

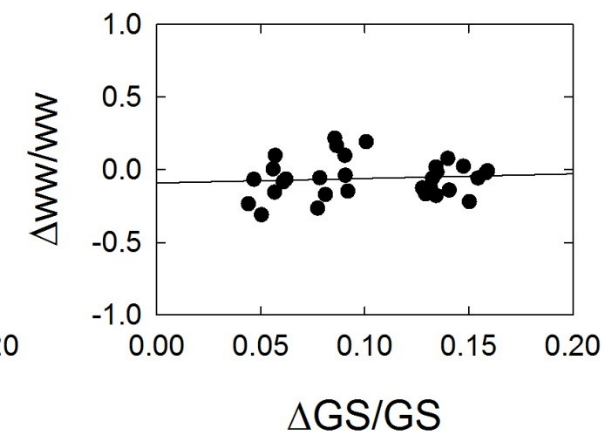
In spite of spectral peak, no trend (!) for w
in this broadband average





Here, integral over the whole spectrum,
λ_{max} =540 km to λ_{min}= 0.5 km





NSF GV short-wavelength range:
λ_{max} =10 km, λ_{min}=2 km

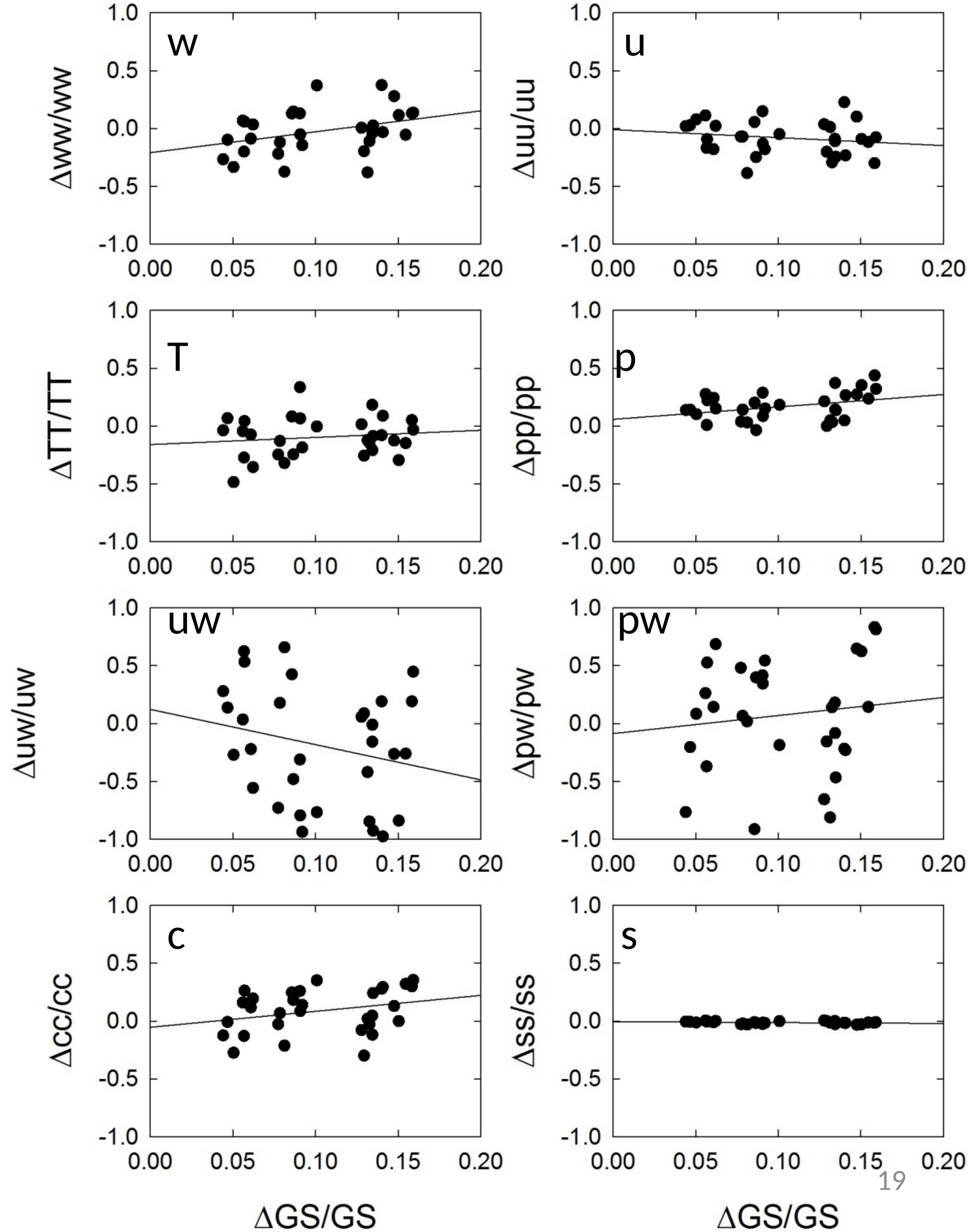
$\Delta y/y = (y_E - y_W)/(y_E + y_W)$

y=

w = vertical velocity/(m/s)
u= inflight velocity/(m/s)
T = temperature/K
p= pressure/Pa
c= vertical body velocity/(m/s)
s = terrain slope/(m/m)

var(y) =variance spectrum of y
uw = co-spectrum of uw

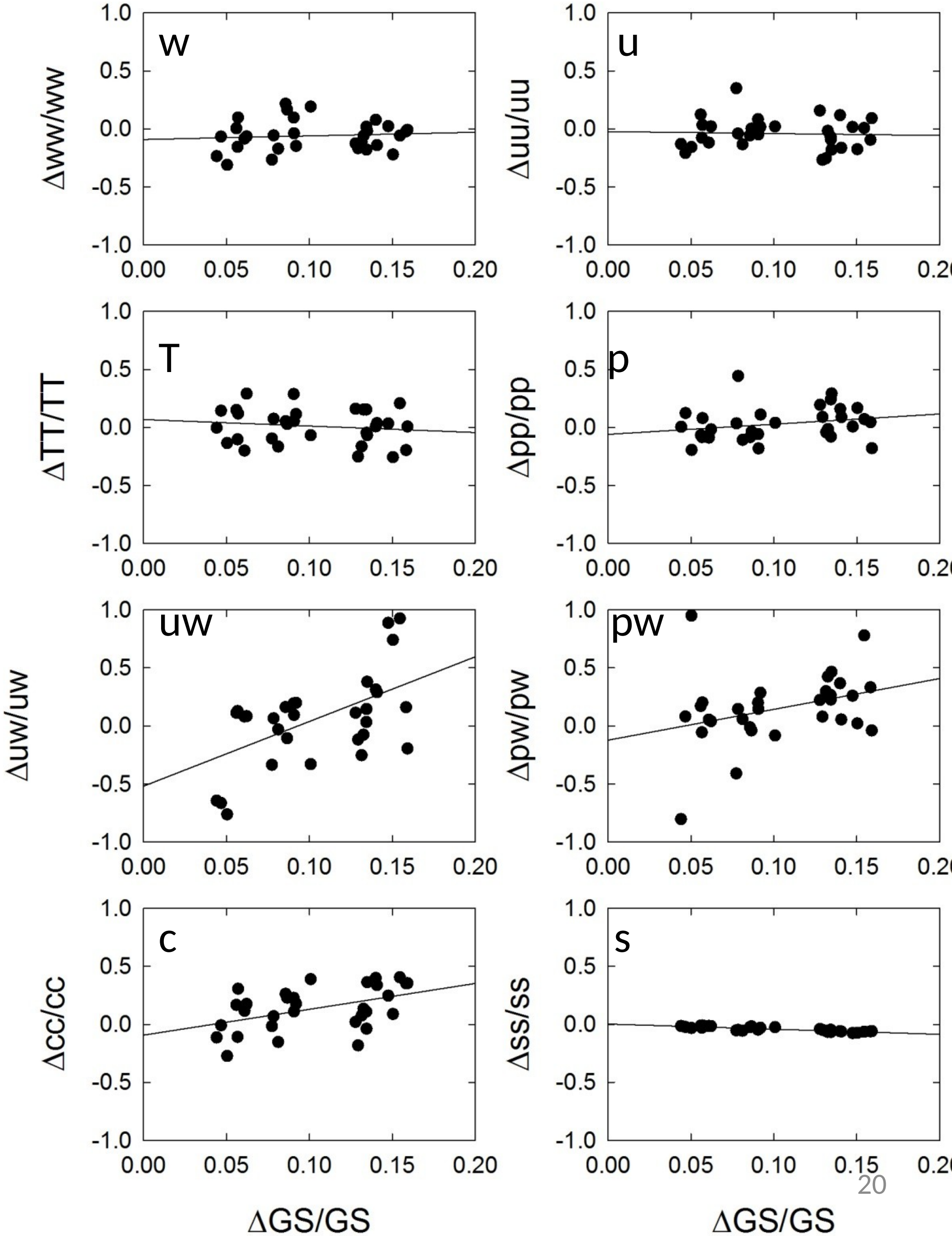
We see weak trends for c, w and p



Again, broad band variances
NSF GV

λ_{max} = 540 km

λ_{min}= 0.5 km



Here the data appear to show hardly any trend,
except:
cc and perhaps some flux cases (non-stationary?)

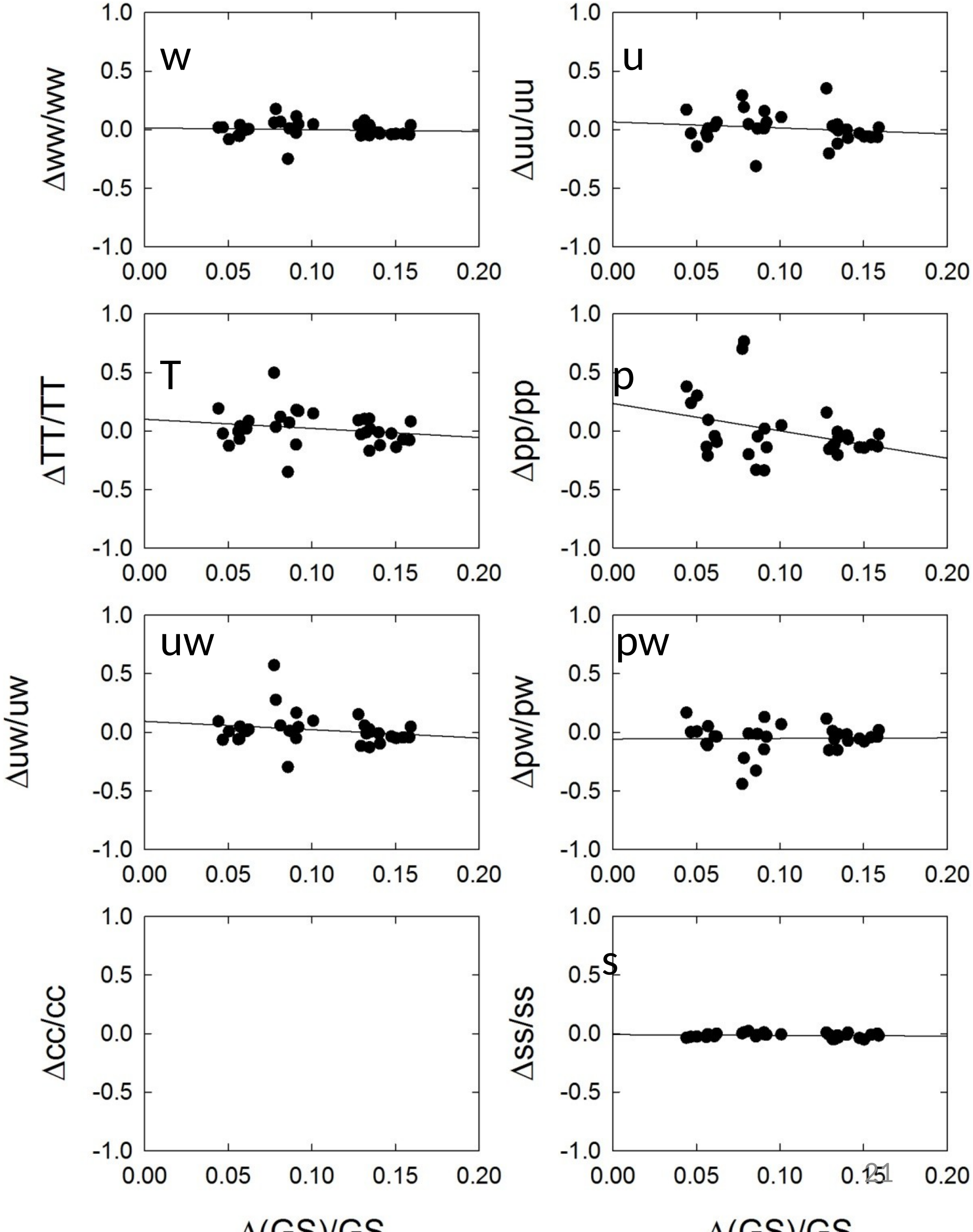
for comparisons:

WRF

λ_{max} =540 km

λ_{min} = 0.5 km

the synoptic variability is small

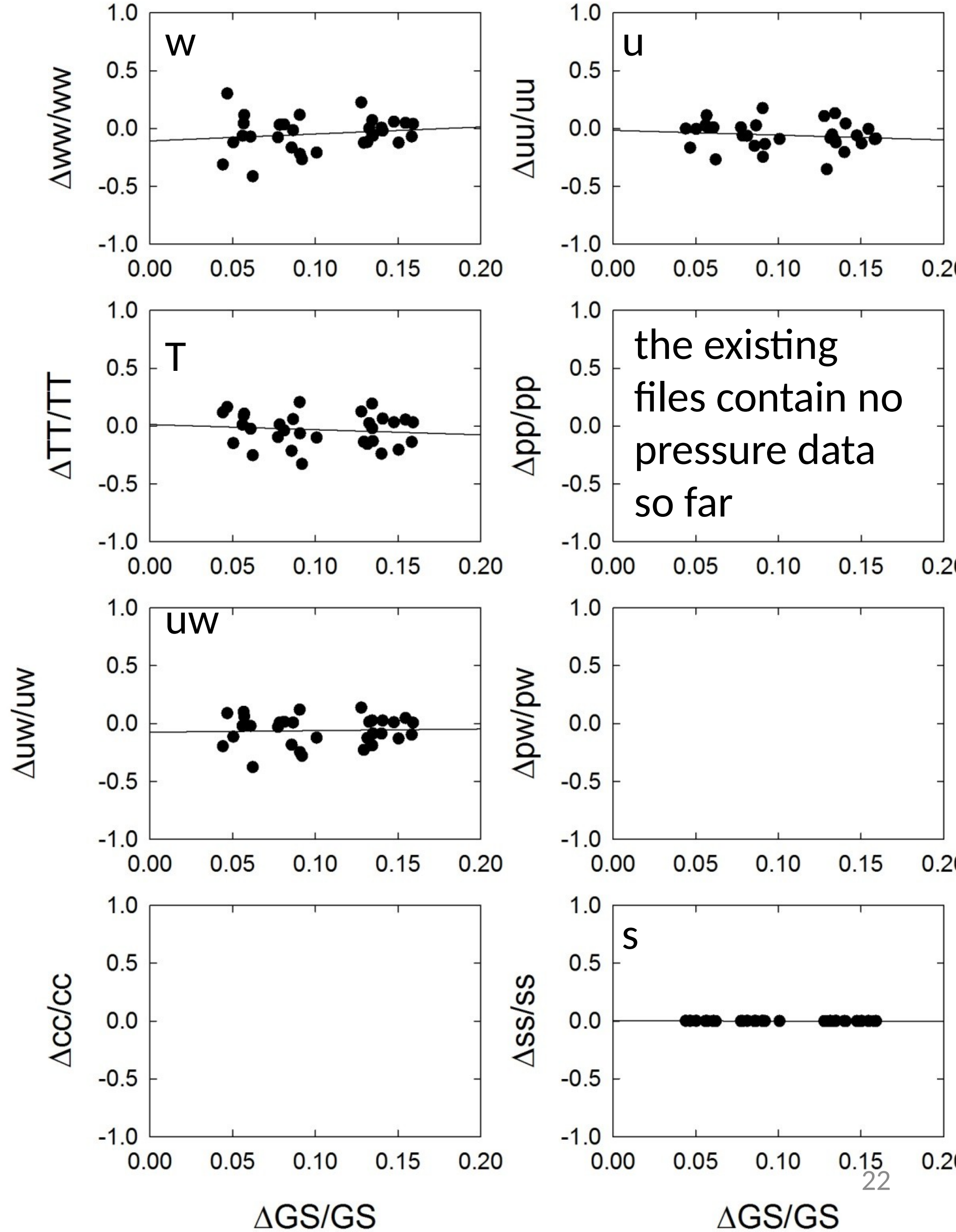


ECMWF

λ_{max} = 540 km

λ_{min} = 0.5 km

the synoptic variability is small



Conclusions

- Strong aircraft dynamics obvious at 5 – 10 km wavelengths
- Aircraft dynamics stronger on E legs than on W legs (as to be expected)
- Vertical velocity $var(w)_E$ larger at short, but smaller at intermediate wavelengths!
- u and p appear to be sensitive to flight direction also
- Statistical significance is limited because of large variability
- In the broadband integral, the aircraft effects are small compared to variabilty
- The general consistency of the analysis allows for some tentative conclusions:
- Aircraft dynamics explains parts of the W-E leg differences
- Flux changes are surprisingly large, possibly from non-stationarity(?)
- Further research is needed for understanding (aerodynamics, autopilot etc.)
- Improved measurement analysis methods and better technology are needed to avoid/correct aircraft disturbances in airborne measurements
- The community should face the fact that aircraft dynamics have to be considered for correct analysis of airborne measurements
- The DEEPWAVE data are very useful for this research
- Thank you to many of you.

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