Vertical Fluxes of Local Structure Parameters in the Convective Boundary Layer

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“Models versus physical laws/first principles, or why models work?”
Wolfgang Pauli Institute (2-4 February, 2011)
Vienna, Austria

Overview

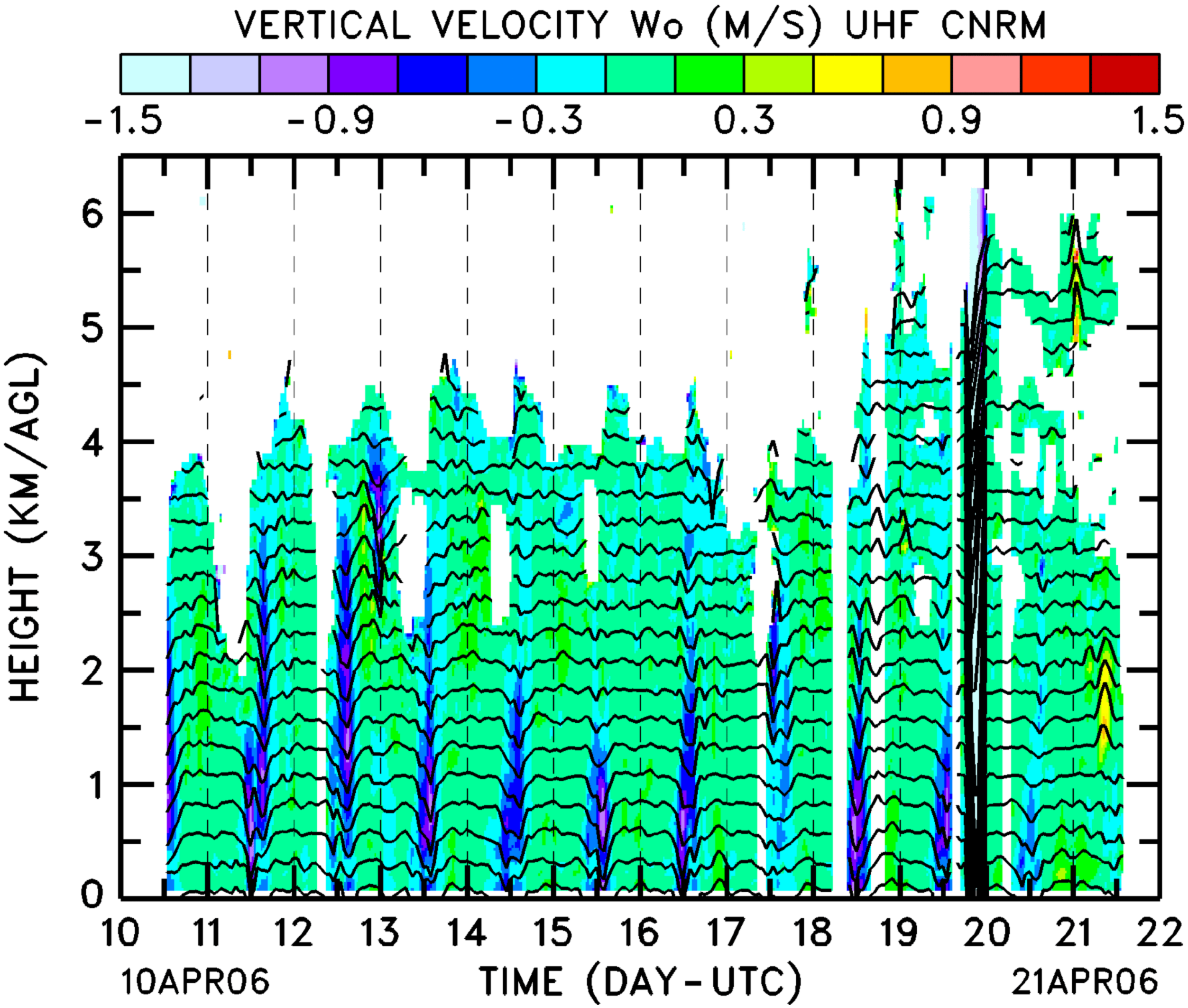
(1) Motivation: Problem and hypothesis

(2) Basic theory

(3) Observations

(5) LES [thanks to Peter Sullivan for the data!]

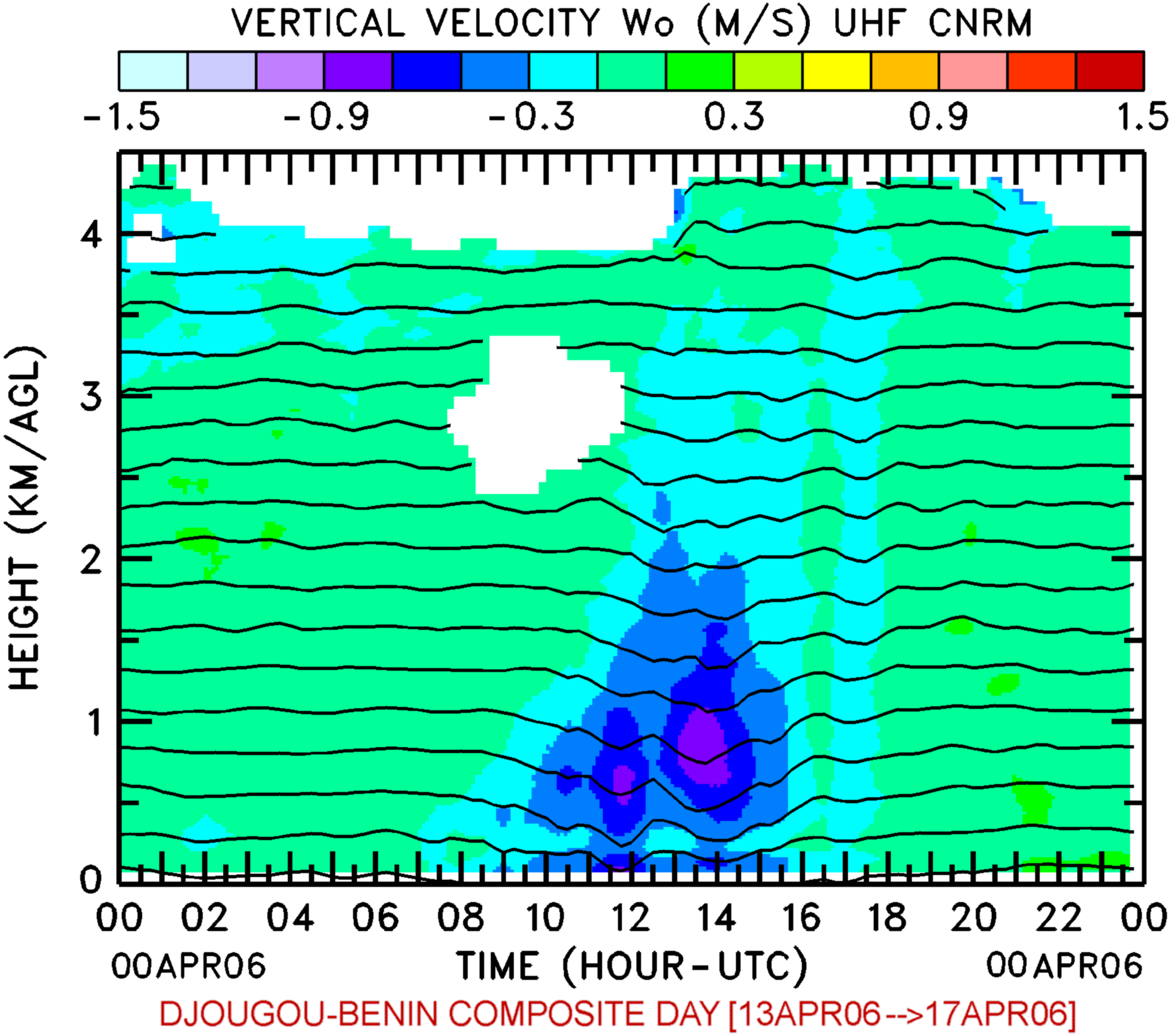
(6) Summary and conclusions



DJOUGOU UHF WIND PROFILER [low mode]

Five beams, 4 Kw: 25 min (consensus) and 150 m resolution. 2-hour running mean on the images.

from Bernard Campistron, Laboratoire d'Aerologie, Toulouse, France



from Bernard Campistron, Laboratoire d'Aerologie, Toulouse, France

Upward bias in vertical velocities observed with a sodar in the lower CBL

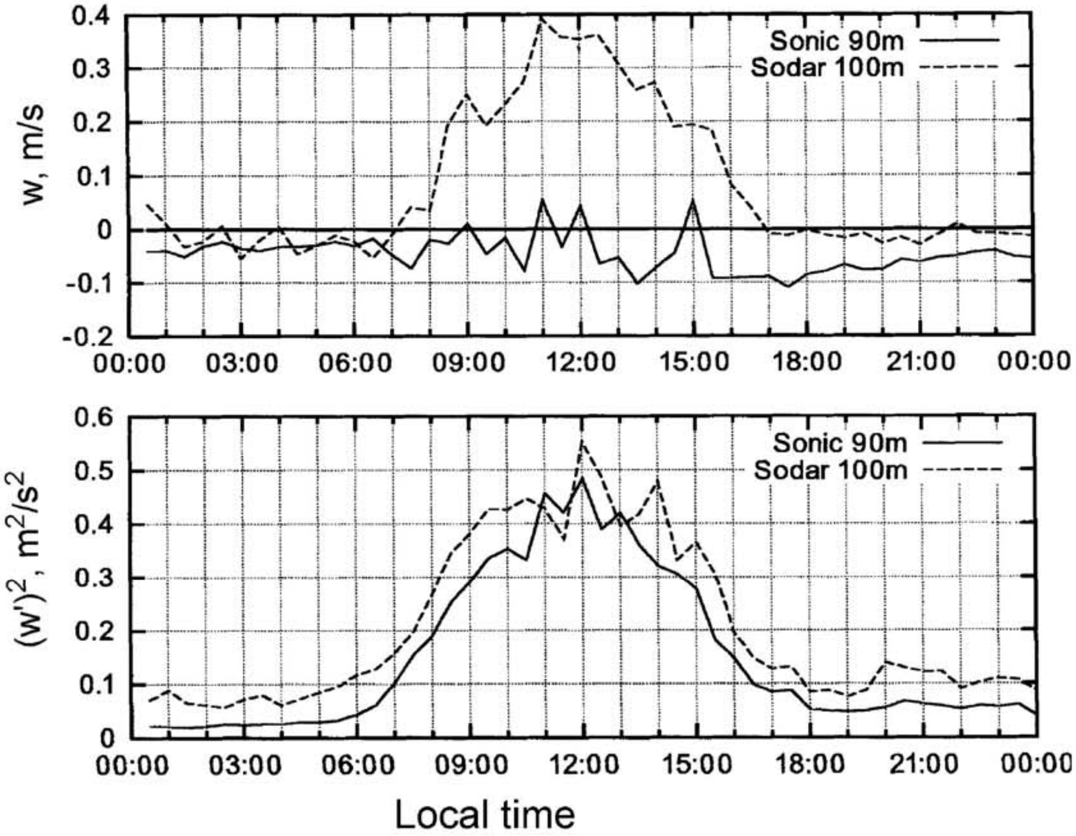


Fig. 2. Comparison of time series of w and σ_w by sonic anemometer and SODAR in convective conditions averaged over nine clear days during September 2000 at Falkenberg, Germany. A moving average of 30 min was used

Coulter, R. L., and M. A. Kallistratova, 2004: Two decades of progress in SODAR techniques […]. *Meteorol. Atmos. Phys.*, **85**, 3-19.

Motivation

Problem:

In the convective boundary layer,
vertically pointing clear-air Doppler radars and sodars
measure mean vertical velocities that are often biased
by several tens of cm/s.

Radars: downward biases.
Sodars: upward biases.

Hypothesis:

These biases are the result of "intermittency fluxes", that is,
vertical fluxes of the local clear-air reflectivity.

Basic theory of Doppler-velocity biases

For vertically pointing clear-air Doppler radars/sodars:

$$v_D = \frac{M_1}{M_0} = \frac{\langle \eta w \rangle}{\langle \eta \rangle}, \tag{1}$$

$$\eta = \langle \eta \rangle + \eta', \qquad w = \langle w \rangle + w', \tag{2}$$

where
v_D = Doppler velocity for given radar/sodar space-time sampling volume,
$w(\mathbf{x}, t)$ = local and instantaneous vertical wind velocity,
$\eta(\mathbf{x}, t)$ = local and instantaneous volume reflectivity (different for radar vs. sodar),
$\langle \cdot \rangle$ = average over radar's/sodar's space-time sampling volume.

That is,
Doppler velocities are reflectivity-weighted radial velocities of the scatterers.

Therefore,

$$v_D = \frac{\langle \eta \rangle \langle w \rangle + \langle \eta' w' \rangle}{\langle \eta \rangle} = \langle w \rangle + \Delta w, \tag{3}$$

where

$$\Delta w = \frac{\langle \eta' w' \rangle}{\langle \eta \rangle} \tag{4}$$

is the **bias** of the vertical Doppler velocity.

Note that $\langle \eta' w' \rangle$ may be interpreted as a turbulent clear-air **reflectivity flux**.

It is known that η is proportional to the refractive-index structure parameter,

$$C_n^2(\mathbf{x}) = \frac{\left\langle [n(\mathbf{x} + \mathbf{r}/2) - n(\mathbf{x} - \mathbf{r}/2)]^2 \right\rangle}{r^{2/3}}, \tag{5}$$

where n is the refractive index:

$$\eta(\mathbf{x}, t) = 0.38\, C_n^2(\mathbf{x}, t) \lambda^{-1/3}, \tag{6}$$

(Tatarskii 1961), where λ is the EM or sound wavelength.

Note that the reflectivity flux $\langle \eta' w' \rangle$ is a third-order turbulence statistic.

Microwave clear-air refractive index fluctuations:

$$n' = a_1 T' + b q', \tag{7}$$

where $a_1 = a_1(T, q, p)$ and $b = b(T, q, p)$ are known functions of the mean values of temperature T, specific humidity q and pressure p.

Microwave refractive-index structure parameter:

$$C_n^2 = a_1^2\, C_T^2 + a_1 b\, C_{Tq} + b^2\, C_q^2. \tag{8}$$

For **acoustic** propagation:

$$n' = a_2 T', \tag{9}$$

where $a_2 = a_2(T, p)$ is another known function.

Therefore, the **acoustic** refractive-index structure parameter is

$$C_n^2 = a_2^2\, C_T^2. \tag{10}$$

Now, let the structure parameters C_T^2, C_{Tq} and C_q^2 be random variables in space and time: $C_T^2 = \left\langle C_T^2 \right\rangle + \left(C_T^2\right)'$, $C_{qT}^2 = \left\langle C_{qT}^2 \right\rangle + \left(C_{qT}^2\right)'$, and $C_q^2 = \left\langle C_q^2 \right\rangle + \left(C_q^2\right)'$.

Clear-air radar bias of vertical Doppler velocity (long dwell times):

$$\Delta w = a_1^2 \frac{\left\langle \left(C_T^2\right)' w' \right\rangle}{\langle C_T^2 \rangle} + a_1 b \frac{\left\langle (C_{qT})' w' \right\rangle}{\langle C_{qT} \rangle} + b^2 \frac{\left\langle \left(C_q^2\right)' w' \right\rangle}{\left\langle C_q^2 \right\rangle}. \tag{11}$$

In the troposphere, often $|bq'| \gg |a_1 T'|$, such that the third term dominates:

$$\Delta w = \Delta w_q = b^2 \frac{\left\langle \left(C_q^2\right)' w' \right\rangle}{\left\langle C_q^2 \right\rangle}. \tag{12}$$

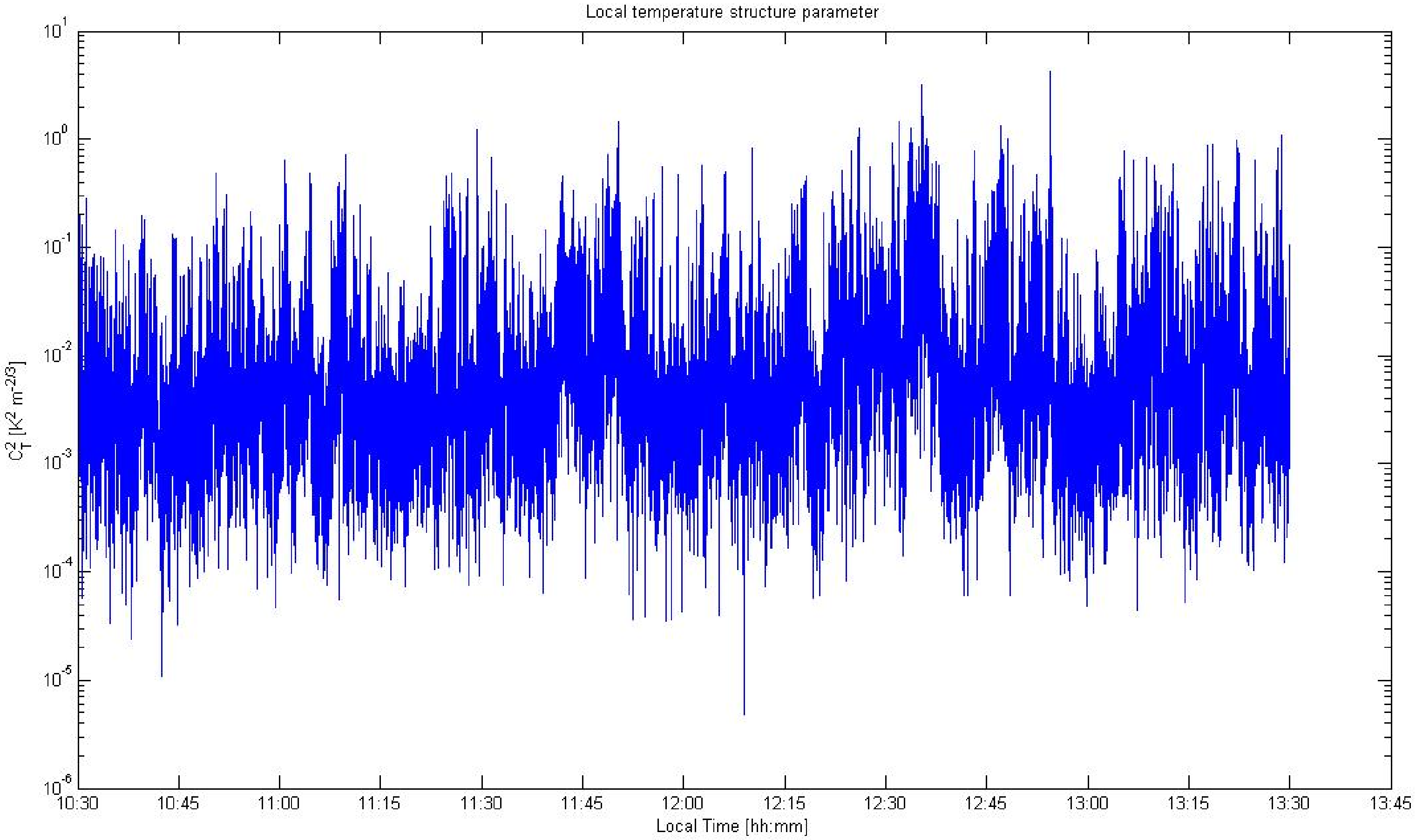
Clear-air sodar bias of vertical Doppler velocity (long dwell times):

$$\Delta w = \Delta w_T = a_2^2 \frac{\left\langle \left(C_T^2\right)' w' \right\rangle}{\langle C_T^2 \rangle}. \tag{13}$$

Mixed layer
(BAO Aug 2007)

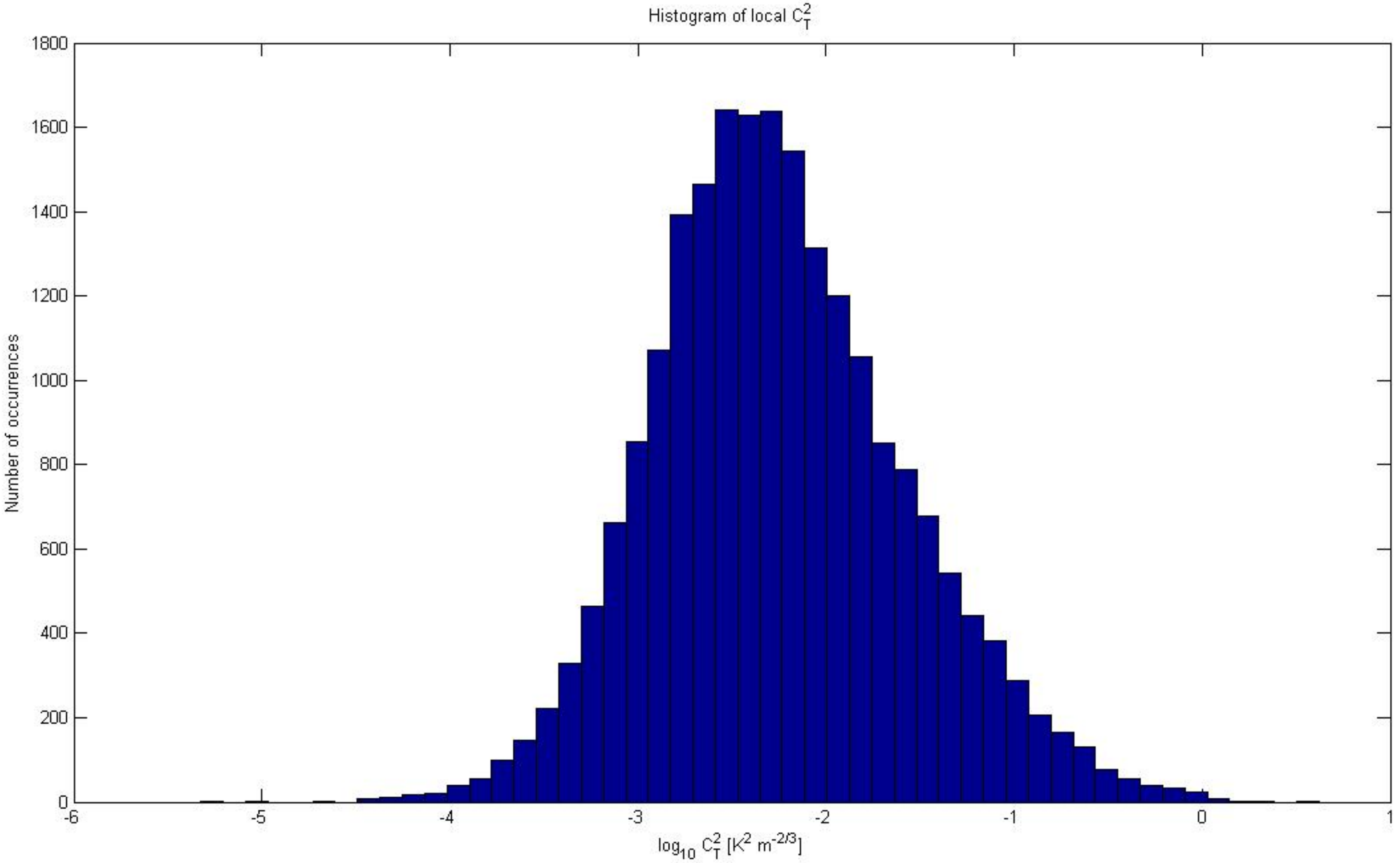
Local CT2 (time series)

r = 4 m, z = 100 m AGL, T = 3 h



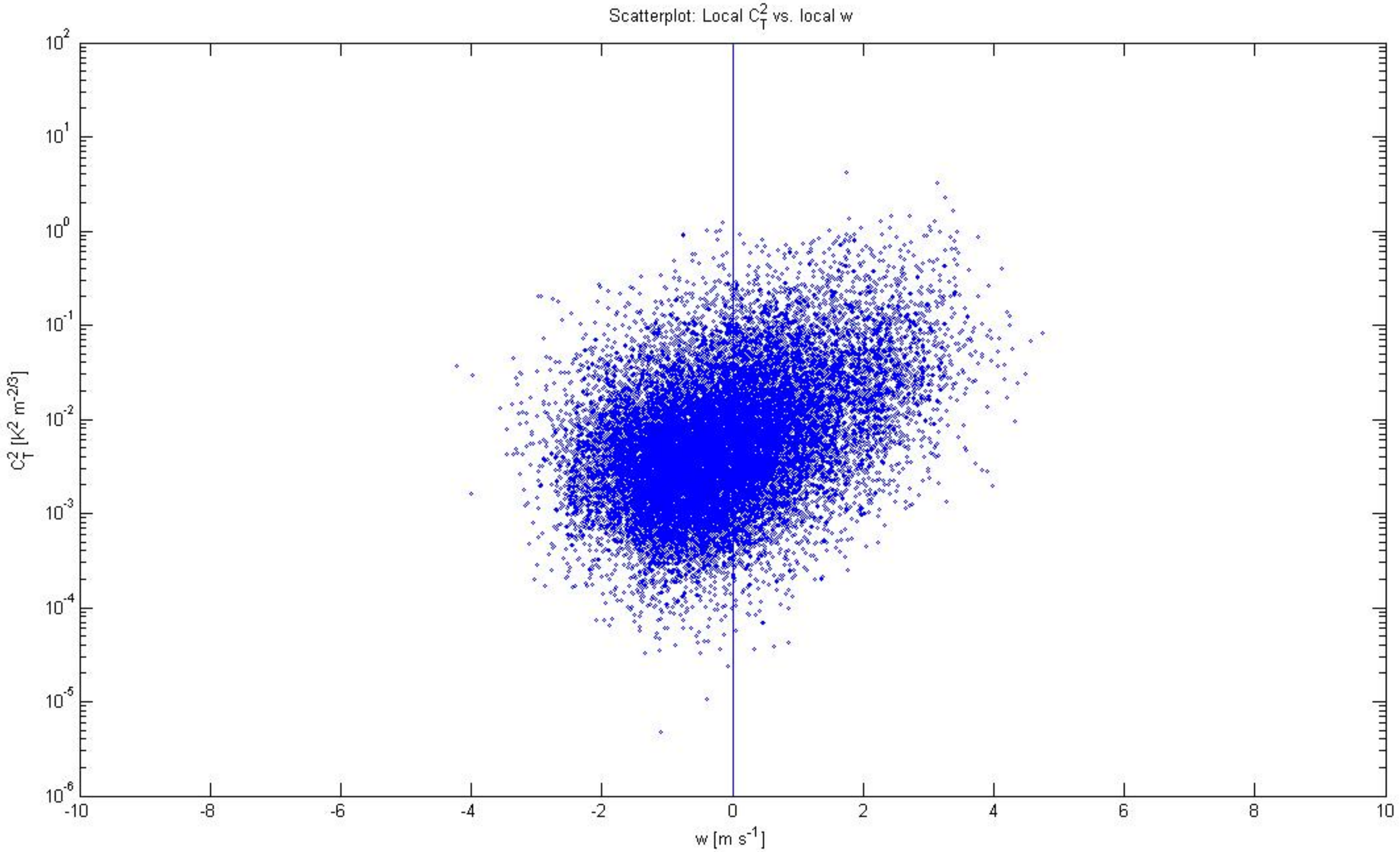
Local CT2 (histogram)

r = 4 m, z = 100 m AGL, T = 3 h

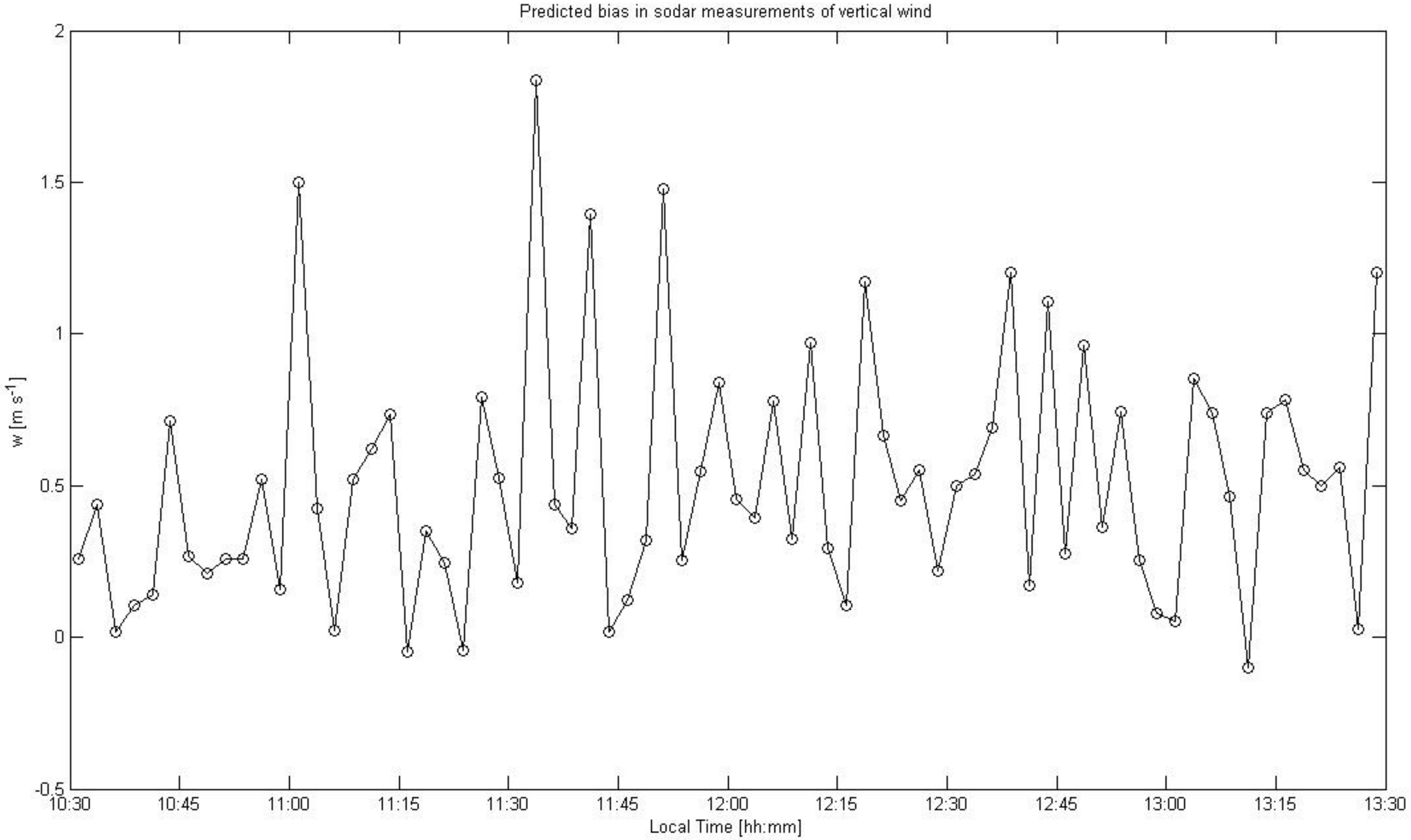


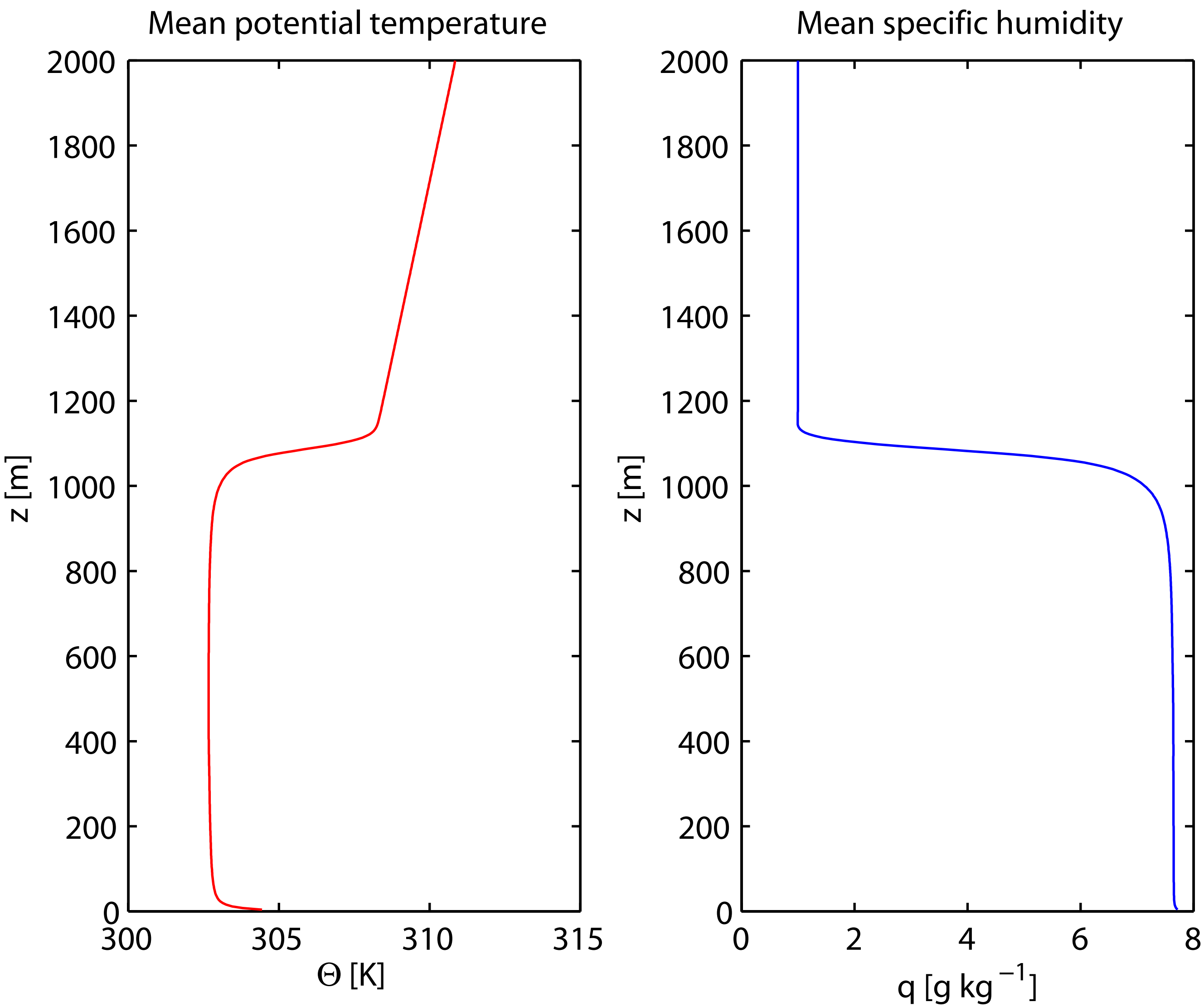
Local CT2 vs. w (scatterplot)

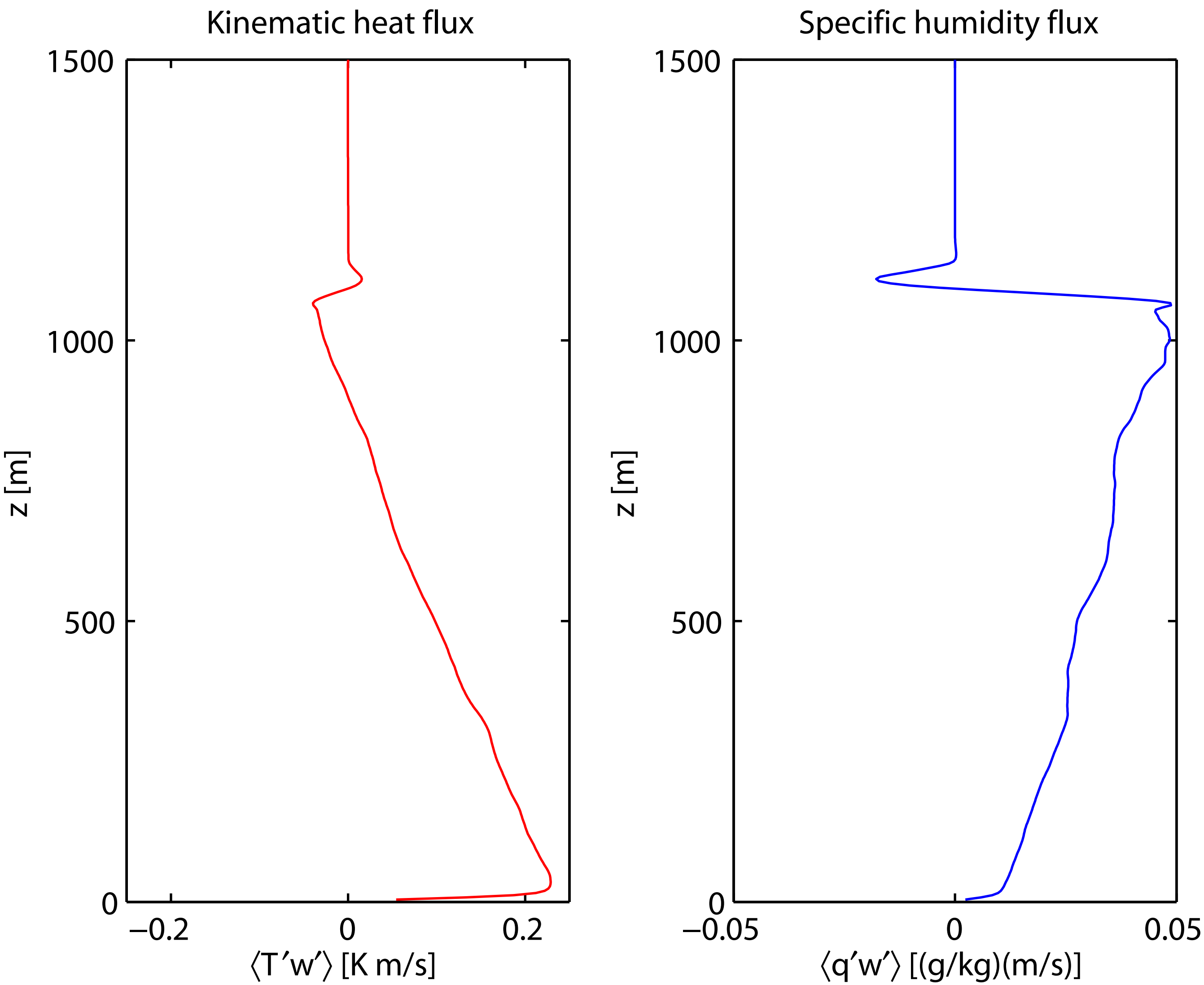
r = 4 m, z = 100 m AGL, T = 3 h

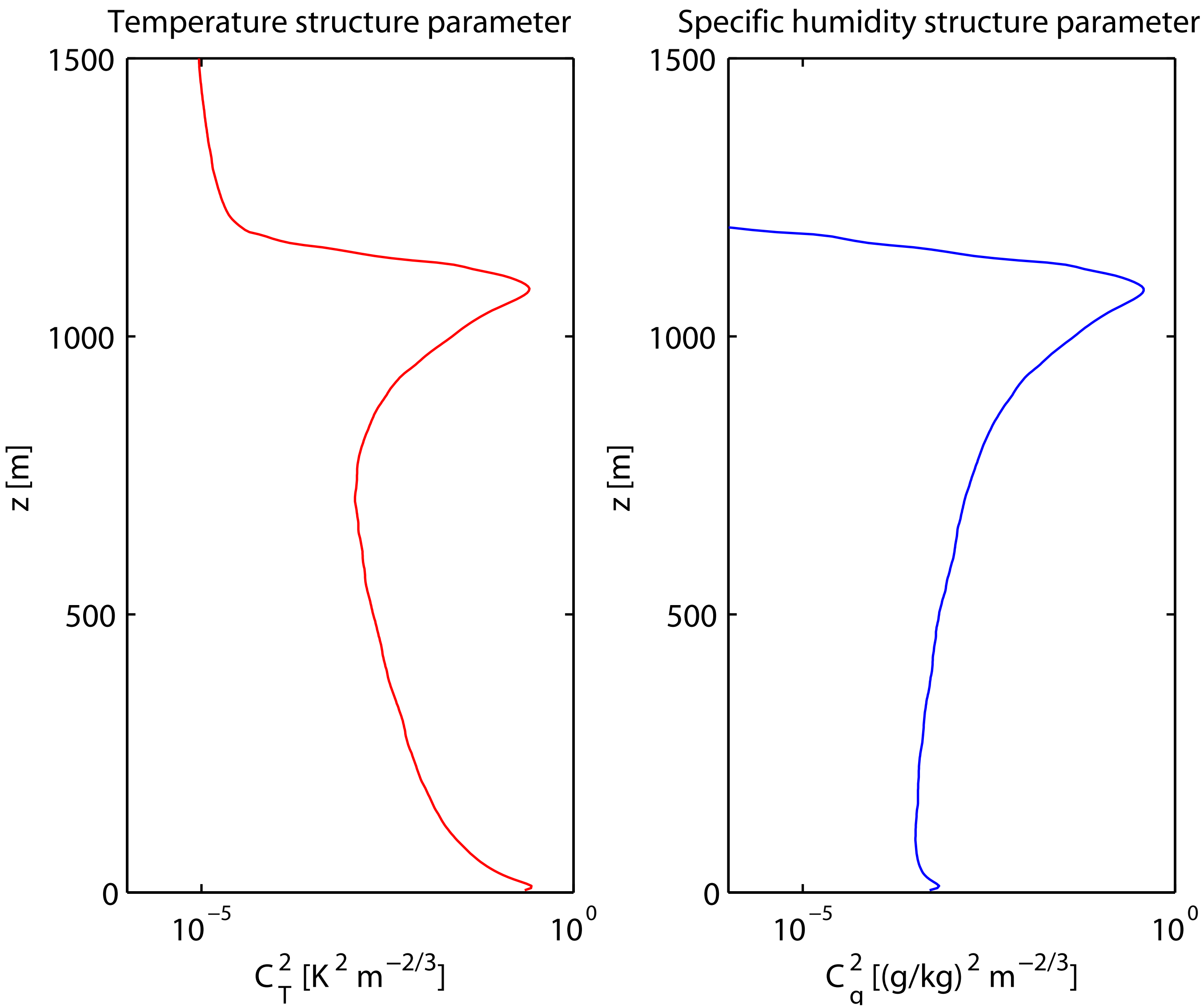


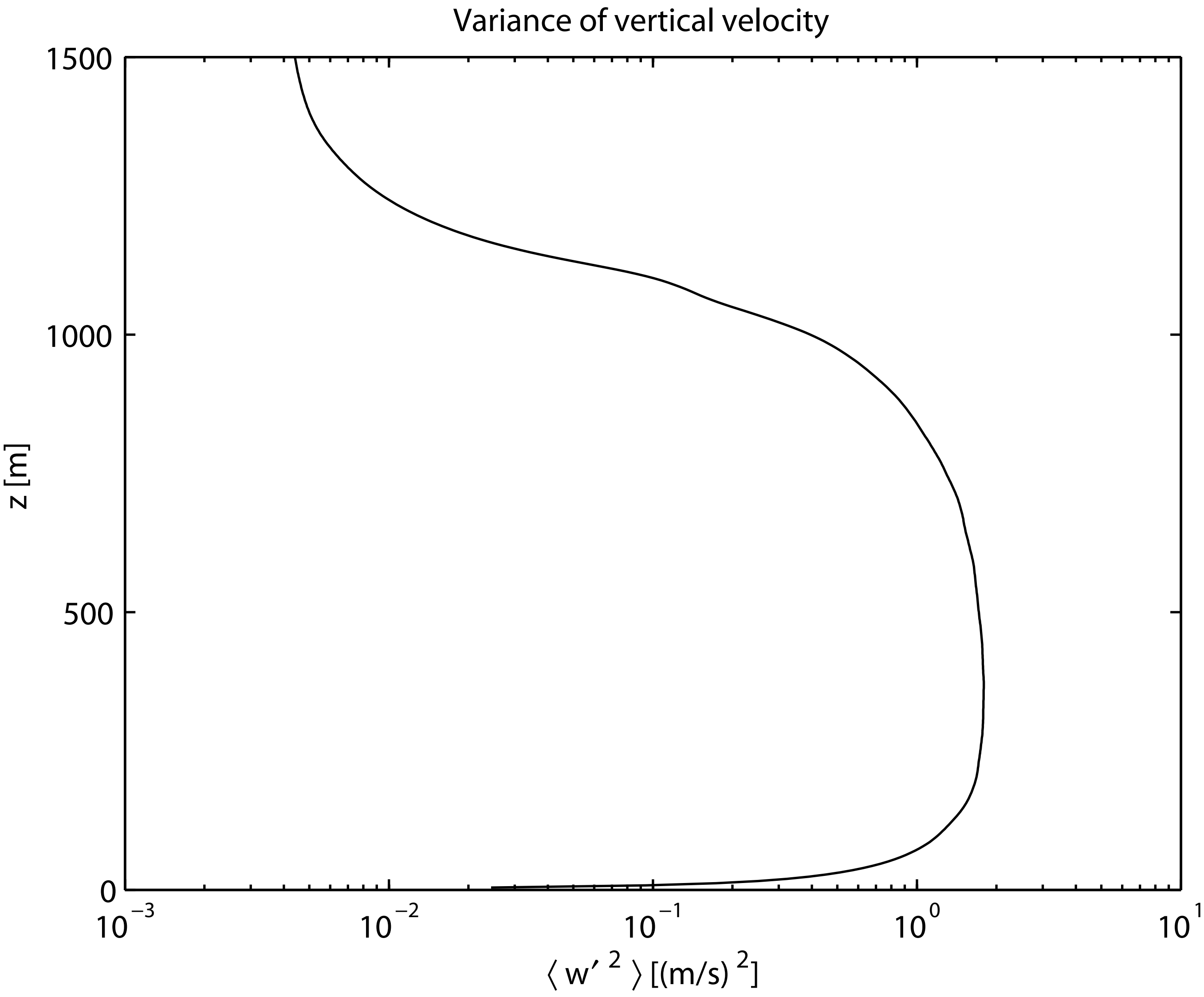
Upward w bias (due to CT2 intermittency flux)
r = 4 m, z = 100 m AGL, T = 3 h, 10-min averages

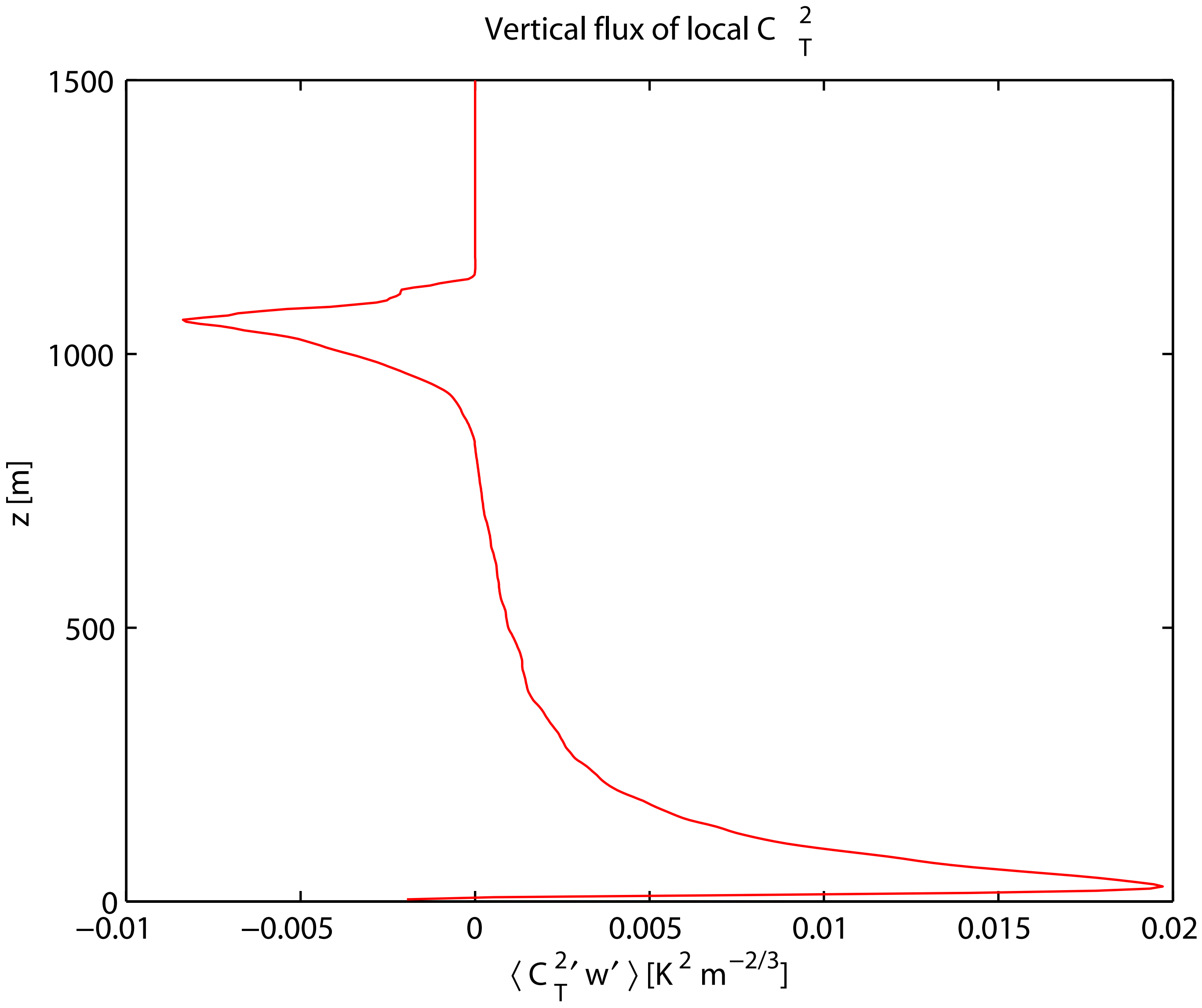


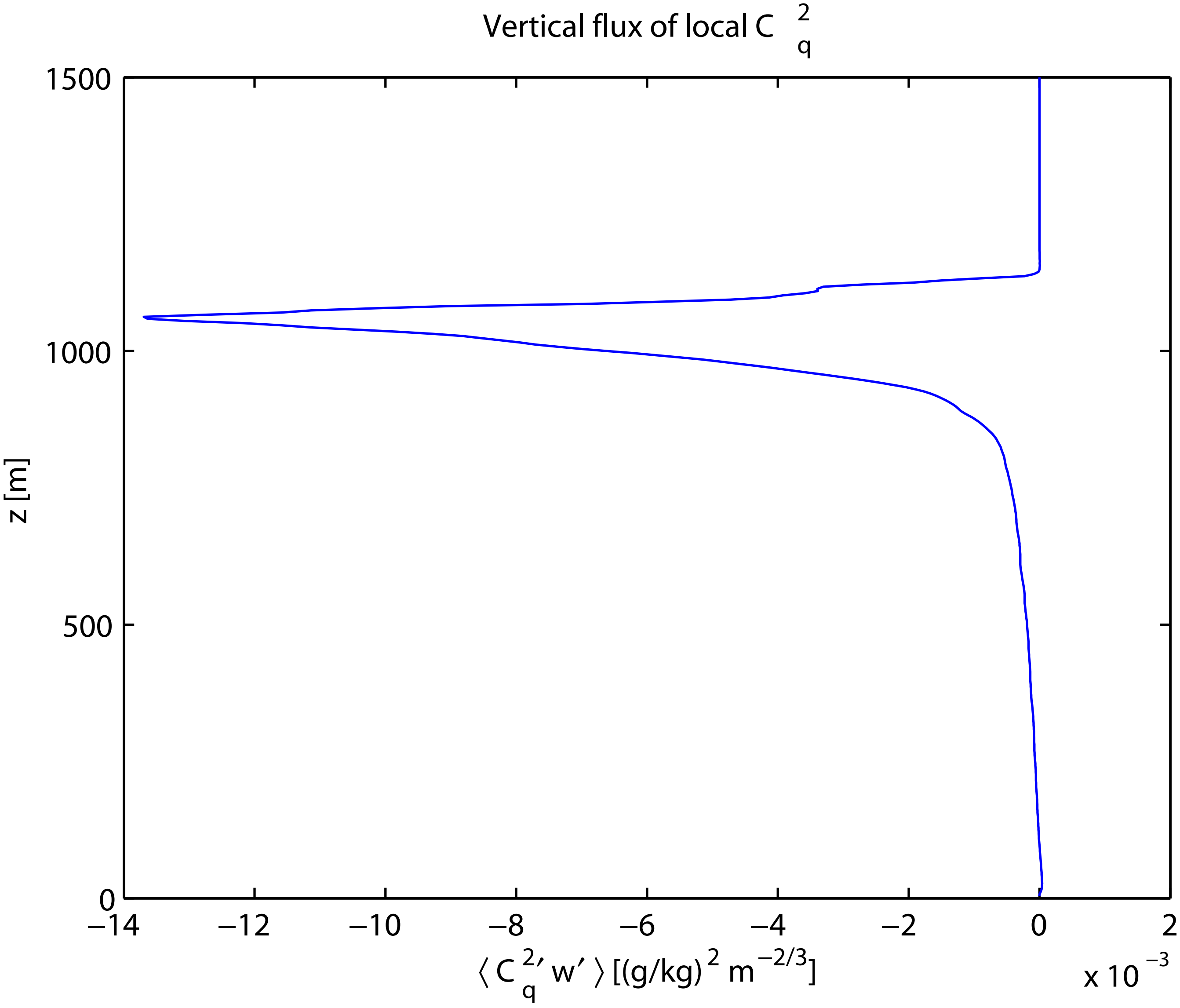

Mean potential temperature
Mean specific humidity
z [m]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
300
305
310
315
Θ [K]
0
2
4
6
8
q [g kg −1]

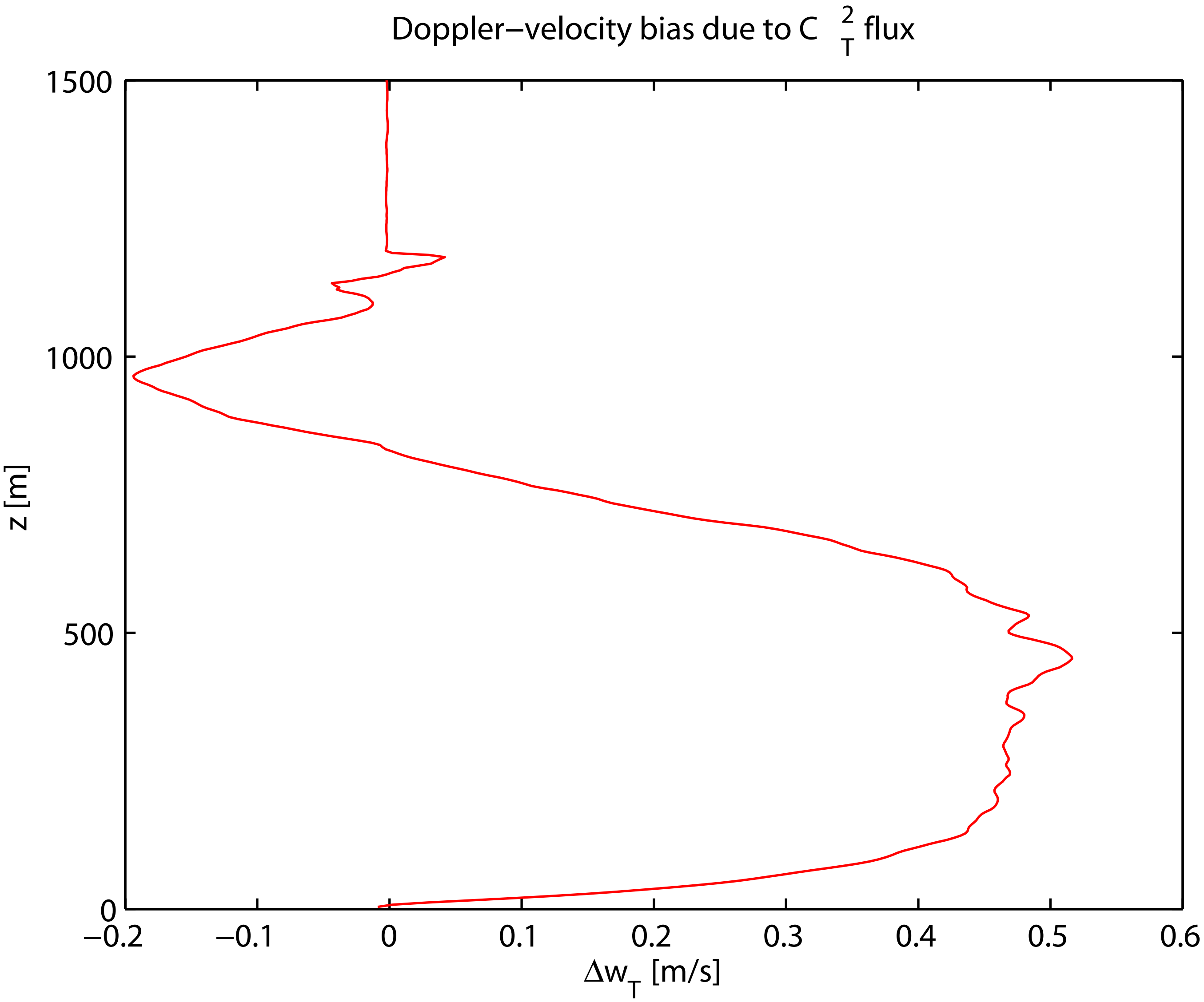

Kinematic heat flux
Specific humidity flux
1500
1000
500
0
z [m]
−0.2
0
0.2
⟨T′w′⟩ [K m/s]
1500
1000
500
0
z [m]
−0.05
0
0.05
⟨q′w′⟩ [(g/kg)(m/s)]


Temperature structure parameter
Specific humidity structure parameter
1500
1000
500
0
z [m]
10^{-5}
10^{0}
C_T^2 [K^2 $m^{-2/3}$]
C_q^2 [$(g/kg)^2$ $m^{-2/3}$]

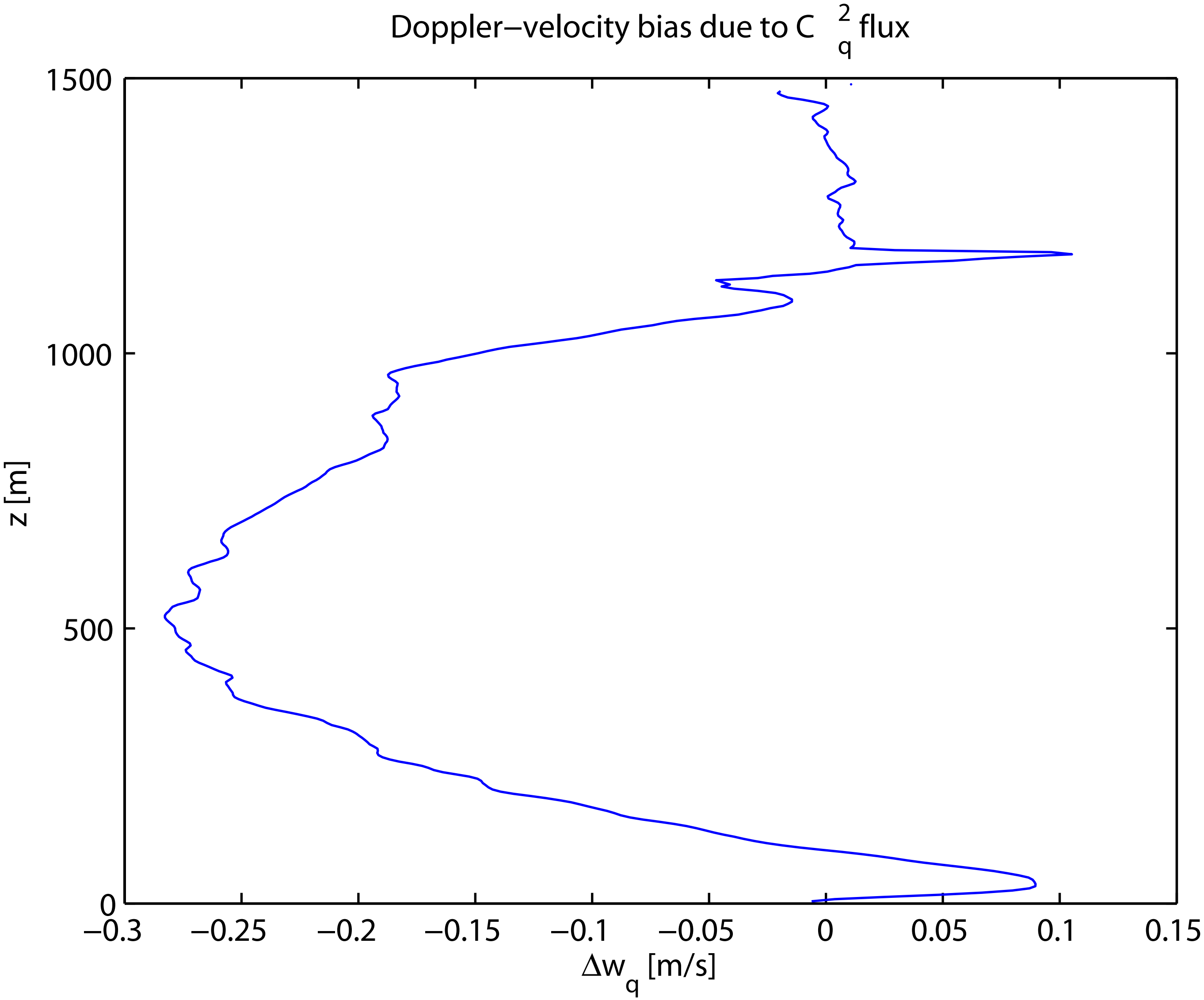

Variance of vertical velocity
1500
1000
500
0
z [m]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$\langle w'^2 \rangle$ [(m/s)^2]

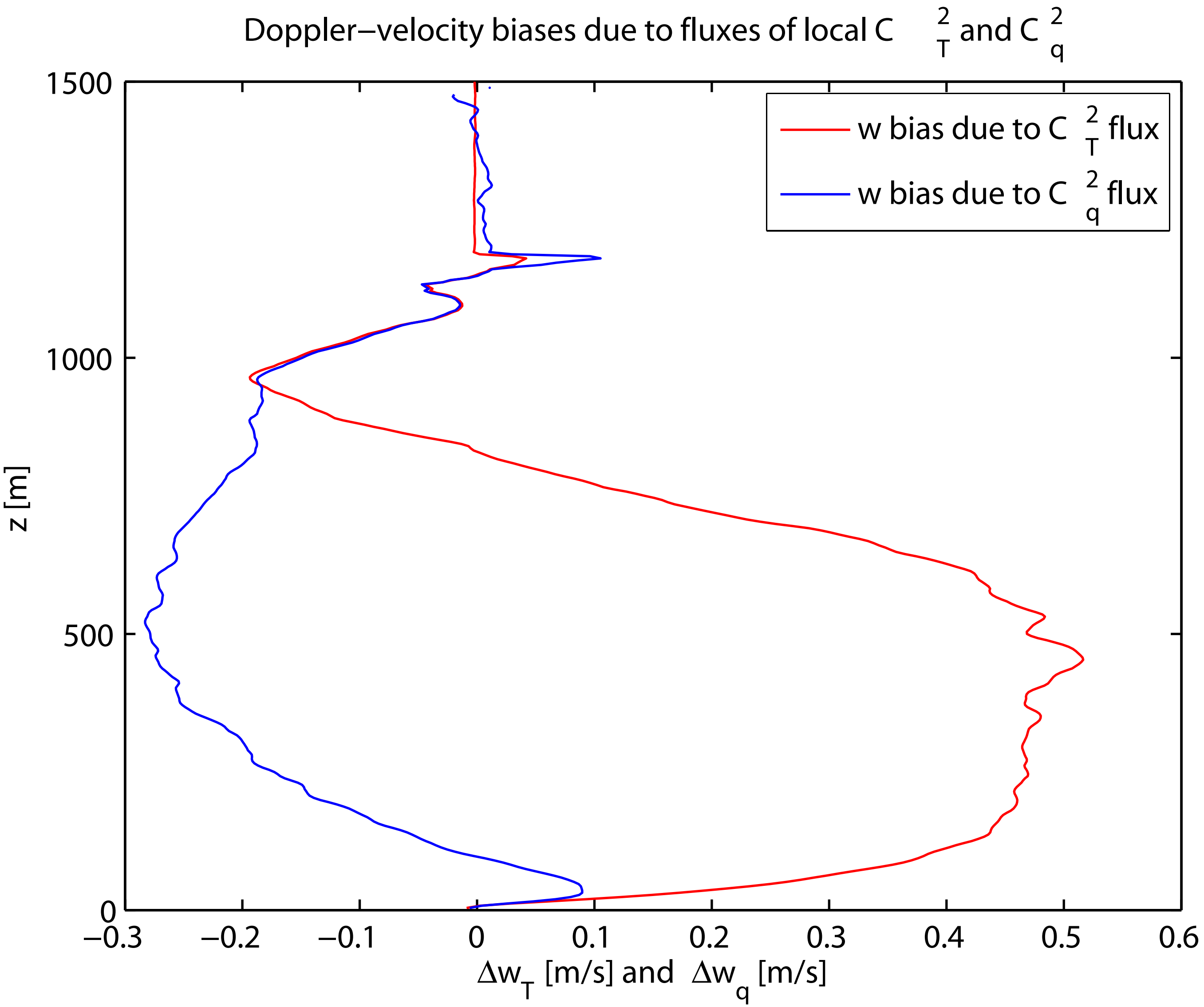

Vertical flux of local C_T^2
1500
1000
500
0
z [m]
−0.01
−0.005
0
0.005
0.01
0.015
0.02
$\langle C_T^{2\prime} w' \rangle$ [K^2 m$^{-2/3}$]


Vertical flux of local C_q^2
1500
1000
500
0
z [m]
−14
−12
−10
−8
−6
−4
−2
0
2
$\langle C_q^{2\prime} w' \rangle$ [(g/kg)^2 m$^{-2/3}$]
x 10^{-3}



Doppler−velocity bias due to C_T^2 flux
1500
1000
500
0
z [m]
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
Δw_T [m/s]


Doppler−velocity bias due to C_q^2 flux
1500
1000
500
0
z [m]
−0.3
−0.25
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
Δw_q [m/s]


Doppler−velocity biases due to fluxes of local C_T^2 and C_q^2
w bias due to C_T^2 flux
w bias due to C_q^2 flux
z [m]
1500
1000
500
0
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
Δw_T [m/s] and Δw_q [m/s]

Summary and Conclusions

The in-situ turbulence data (sonics) confirm the hypothesized correlation between CT2 and w.

The LES data confirm the hypothesized correlation (1) between (1) CT2 and w and (2) between Cq2 and w.

In-situ observations and LES data confirm the hypothesis that Doppler velocity biases can be qualitatively and quantitatively explained by reflectivity fluxes (or “intermittency fluxes”).

Conclusions

For more than 10 years, researchers have reported upward biases in Doppler sodar w observations and downward biases in clear-air Doppler radar w observations (magnitude tens of cm/s).

These observations can be explained by
(1) surface-driven upward fluxes of CT2
(2) entrainment-driven downward fluxes of Cq2.

In the future, measurements of the “biases” could be used to measure additional CBL statistics.