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Alignment of stress, mean wind, and vertical gradient of the velocity vector

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Abstract

In many applications in the atmospheric surface layer the *turbulent-viscosity hypothesis* is applied, i.e. the stress vector can be described through the vertical gradient of velocity. In the atmospheric surface layer, where the Coriolis force and baroclinic effects are considered negligible, this is supposedly a good approximation. High resolution large-eddy simulation (LES) data show that it is indeed the case. Through analysis of WindCube lidar measurements accompanied by sonic measurements we show that this is, on the other hand, rarely the case in the real atmosphere. This might indicate that large scale mechanisms play an important role in the misalignment observed in the atmosphere. Baroclinicity is one candidate of a such, instationarity another. In this contribution we will present ongoing work: data from both a WindCube lidar, sonic anemometers and LES and discuss the results in the context of atmospheric boundary layer modeling.

The measurements are from the Danish wind turbine test sites at Høvsøre. With the WindCube lidar we are able to reach heights of 250 meters and hence capture the entire atmospheric surface layer both in terms of wind speed and the direction of the mean stress vector.

1 Introduction

We present experimental evidence of misalignment of the mean stress vector and the vertical gradient of the velocity vector. If perfectly aligned, the angle

$$\beta = \tan^{-1}(\frac{dV}{dz}/\frac{dU}{dz}) - \tan^{-1}(\langle v'w'\rangle/\langle u'w'\rangle) \quad (1)$$

should be zero. In the above equation, U and V are the two components of the mean wind (often $V = 0$ from the definition of coordinate system) and $\langle u'w'\rangle$ and $\langle u'w'\rangle$ are the two components of the mean momentum flux (Reynolds stresses). That any such alignment should exist is not clear at all, it is, however, still the main ansatz behind the *turbulent-viscosity hypothesis* (Pope, 2000), widely used in modeling of the atmospheric boundary layer.

Another interesting and much more studied quantity is the angle between the mean wind direction and the mean stress vector, defined as

$$\alpha = \tan^{-1}(V/U) - \tan^{-1}(\langle v'w'\rangle/\langle u'w'\rangle). \quad (2)$$

In the absent of the Coriolis force, which is considered to be neglected in the atmospheric surface layer, the angle, α should be zero for homogeneous surface conditions. Grachev et al. (2003) discuss the non-zero angle, observed in offshore conditions, as a result of ocean swell. In (Barnardes and Dias, 2010; Weber, 1999) the scatter around zero angle is discussed in terms of averaging and inhomogeneous surface conditions. We show in this paper, that a systematic angle exists, even for homogeneous surface conditions. Due to its fixed coordinate system, the wind lidar seem like the obvious choice of instrument and its usage in the present context is therefore the main focus of this contribution.

2 Sonic anemometer measurements at Bolund

The Bolund measurement campaign in the winter of 2007-2008 in Denmark (Berg et al., 2011) indicated that the surface fluxes (sonic measurements in 5 m and 12 m) were misaligned with the mean wind. Figure 1 shows histograms of α for upstream conditions with fetch lengths of 800 m and 7 km. The measurements (12 m above sea level) are carried out on an offshore platform in a shallow water fjord and should therefore not be influenced by swell as discussed in Grachev et al. (2003). The mean value of α is $15°$ and $21°$ for the two fetch classes, respectively. The variance is, however, much larger for the shorter fetch, as expected, due to inhomogeneous conditions and accompanying high turbulence levels onshore. The sign of α is in agreement with an ABL Ekman spiral in the northern hemisphere (the wind vector is to the right of the momentum flux vector), although the value is much

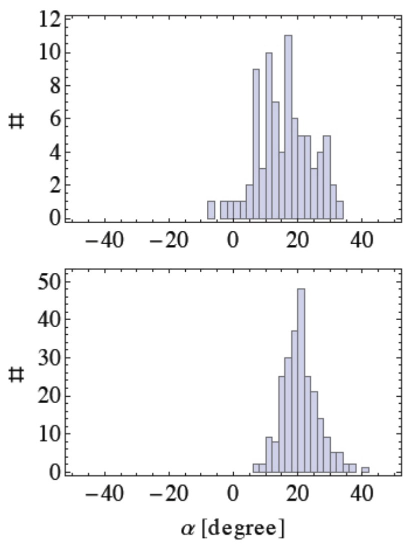

Figure 1: Histogram of α measured at Bolund. *Top:* Short fetch, 800 m. *Bottom:* Long fetch, 7 km. . We have used 30-min averages of momentum flux and wind speed in neutral/near-neutral conditions.

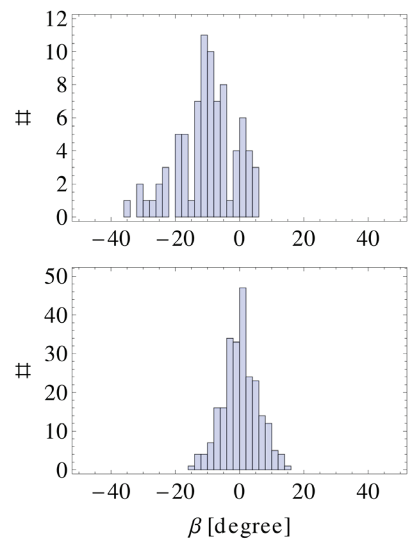

Figure 2: Histogram of the angle, β, measured at Bolund. *Top:* Short fetch, 800 m. *Bottom:* Long fetch, 7 km. . We have used 30-min averages of momentum flux and wind speed in neutral/near-neutral conditions.

higher than we would expect taking the low measurement height (12 m) into account.

We have also calculated the angle, β, where the gradient wind speed vector is calculated as a finite difference between the two heights, 5 m and 12 m. The result is presented in Figure 2. For the short fetch, the mean of β equals -10° while it is zero for the long fetch as assumed by the *turbulent-viscosity hypothesis*. Again the variance is largest in the short fetch case.

3 Lidar measurements at Høvsøre

The Bolund measurements were done with sonic anemometers close to the surface. The ultimate goal would be to monitor the behavior throughout the ABL: for which sonic anemometers seem inadequate due to the tall masts needed and alignment issues. We therefore turn to pulsed lidars, more specifically WindCube from the French company Leosphere, which have shown to successfully measure turbulent fluxes in the streamwise direction by using a two beam technique (Mann et al., 2010): the authors furthermore find from theoretical considerations that for heights above approximately 50 m, the constant systematic error on measuring $\langle u'w' \rangle$ is approximately 20%. In this paper the transverse component, $\langle v'w' \rangle$, is of equally importance, in principle, if the error on $\langle u'w' \rangle$ is of similar size - we might expect the angles, α and β to be unbiased by the filtering of the WindCube measurements. We use the technique described in Mann et al. (2010) for estimation for both the streamwise and the transverse component of momentum flux and apply the same quality criterion.

We now look at simultaneous measurements from a sonic anemometer and the WindCube at the Danish test site for large wind turbines at Høvsøre (see Peña (2009) for a site description of Høvsøre). As shown in Figure 3, where we present measurements of the angle, α, this is unfortunately not fully the case for all three different stability cases: for neutral stratification the slope of the best linear fit is just above 0.7, while it is much lower in the stable and unstable case. We would expect the best correlation in the unstable case, due to more similar turbulent integral length scales in the streamwise and transverse directions. This is, however, not observed. It turns out (not shown) that the transverse component, $\langle v'w' \rangle$, is worse correlated between the sonic anemometer and the lidar than $\langle u'w' \rangle$; even the slightest random error in the sonic measurements, for example due to flow distortion from the mast, can alter the correlation. Further studies should look into this. For the time being we will move on and look at WindCube measurements all the way through the surface layer.

In Figure 4 we present vertical profiles of the angles, α, β and γ, from measurements with a WindCube at Høvsøre. γ is the wind veer angle and is thus an indicator of the atmospheric Ekman spiral. Only wind speeds higher than 7 m s^{-1} are shown. Looking first at the blue curves representing, α, the largest values are observed for the stable case (top panel) in agreement with the low height of the ABL and hence an intensification of the Ekman spiral; the two angles, α and γ also seems to follow the same trend (in all three stability cases). The unsta-

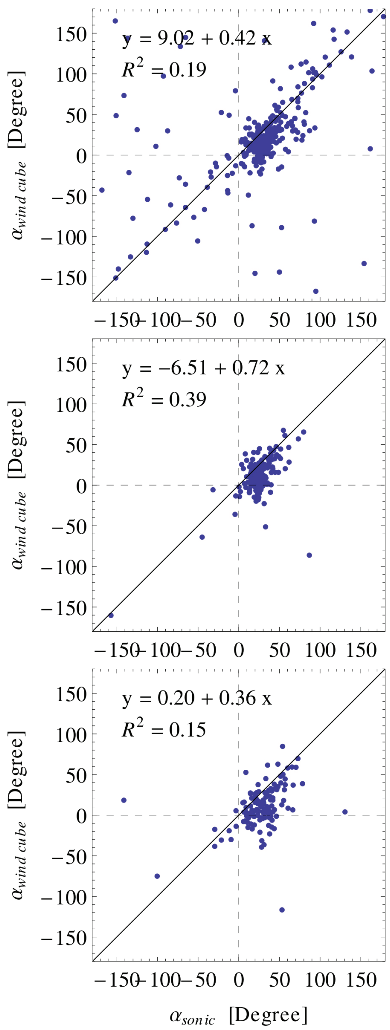

Figure 3: Sonic anemometers vs. WindCube for measurements of the angle, α, at Høvsøre in 100 m in Easterly wind for various stratification: *Top:* Stable. *Middle:* Neutral. *Bottom:* Unstable. We have used 30-min averages of momentum flux and wind speed.

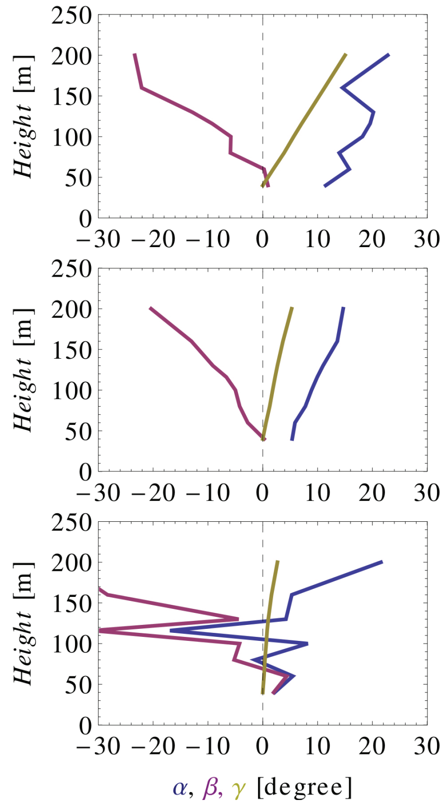

Figure 4: Vertical profiles of the angles, α (blue) and β (purple) and γ (yellow), measured at Høvsøre with WindCube in Easterly wind. *Top:* Stable. *Middle:* Neutral. *Bottom:* Unstable. We have used 30-min averages of momentum flux and wind speed.

ble profile is rather noisy, but still the trend seems to be consist of positive values of β. The angles in the neutral case are all lower than in the Bolund case, even at 250 m. The wind direction is easterly, which mean that the upstream conditions are fairly homogeneous, even far upstream. We are, however, close (approximately 2 km) to the west coast of Jylland (Danish main peninsula) and large horizontal temperature gradients inducing baroclinicity could potentially add complexity to the larger scales (meso-scales) and hence alter the observations.

The purple curves represent the angle, β. For all three stability classes it is close to zero at 40 m in agreement with the long fetch measurements from Bolund. It then grows close to linearly with height. The growth is largest in the stable case (again the unstable case is very noisy). This is in contrast with the *turbulent-viscosity hypothesis*. In wind energy siting applications the hypothesis is the basis of the state-of-the art numerical models (most often using K-ϵ closure). Whether the misalignment documented here has any practical importance the future will tell.

For the low wind speed cases (winds smaller than 7 m s^{-1}) the trends observed in the angles, α, β and γ are amplified, i.e. larger angles as we move up in the atmosphere (not shown).

The same results were obtained from pure sonic anemometer measurements at the meteorological mast at Høvsøre, so the non-perfect correlations presented in Figure 3 cannot explain the findings.

4 LES

In order to study the angles, α and β, under more controlled settings, we use high resolution LES. The pseudospectral LES code of Sullivan and Patton (2011) simulates the ABL over flat, homogeneous terrain, with high temporal and spatial resolution. A database containing

LES results from this code has been established, for different ABL states and surface conditions. In Figure 5 we

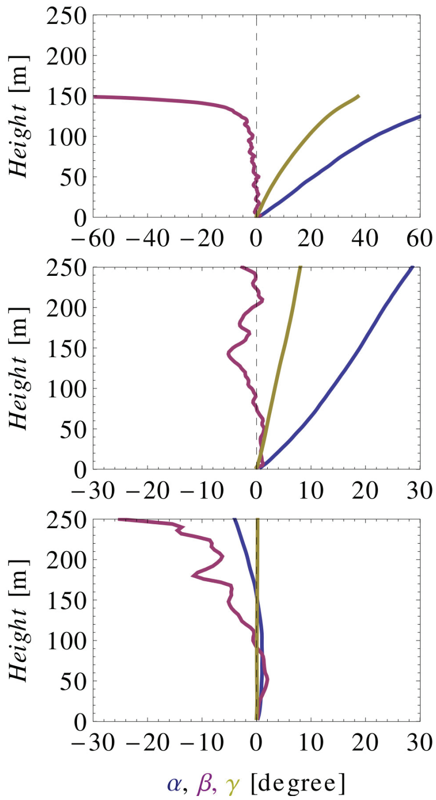

Figure 5: Vertical profiles of the angles, α (blue) and β (purple) and γ (yellow) from LES. *Top:* Stable. *Middle:* Neutral. *Bottom:* Unstable.

present the LES data. The Figure is constructed in the same way as Figure 4. Besides the exact numbers (the LES stable case is a low wind speed case with a ABL height of 150 m), the main difference from the WindCube data presented in Figure 4 at Høvsøre is the zero angle obtained for β throughout the surface layer. I.e. the momentum flux and the vertical gradient of the velocity vector is aligned.

5 Final comments

From comparing the measurements from Bolund, Høvsøre and the LES data one thing is certain: we need a theory including more than just the local micro scales. LES is in many ways the logical starting point, since they only include the micro scales. Setting appropriate boundary conditions, for example a horizontal temperature gradient to mimic meso-scale effects, in future LES might seem like a way to go. We should also study other sites with different geography, how does the growth of numerous internal boundary layers affect the transverse momentum flux? The new Danish site of Østerild will be explored in the near future.

Besides sonic anemometers and WindCube lidar we will also try to use the continuous-wave lidar, ZephIR from QinetiQ (Natural Power). Its problem with measuring in the transverse direction should, however, be addressed before any reliable estimate of the momentum flux vector can be obtained.

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