Abstract
Wind lidar measurements of mean wind speed profiles are compared to WRF model simulations (Skamarock et al., 2008) up to 600 m at a flat coastal site. Two 15-day periods in the autumn of 2010 are modelled using 2 different planetary boundary layer (PBL) schemes (MYNN and YSU) and 2 different vertical resolutions. In general the modelled profiles are less sheared compared to WRF model simulations (Skamarock et al., 2008) up to 500 m. Wind lidar measurements of mean wind speed profiles are compared with long-range WRF hindcasts (produced once per day) on a 2 km grid domain (red box figure 8). The mean dimensionless wind profile for September is shown (left). When the WRF wind profile is normalized with the measured friction velocity at 10 m (black curves) the agreement is good near the surface, but shows a negative bias higher up in the PBL, except for the MYNN scheme with 41 levels. Normalizing with \( u_z \) from WRF shifts the curves to the left due to the high roughness in WRF (red curves). Below, profiles are shown from the forecast run (first panel) and the analysis run for different atmospheric stability (other panels). Increasing the resolution does not seem to improve agreement in stable conditions, whereas it does for October (not shown). The profile of YSU performs a bit better in stable conditions.

Methods
The parameters of interest in this study are the profile of the wind speed \( U \) and the friction velocity \( u_z \). Wind speeds are measured up to a height of 600 m with a Leosphere Windcube 70, which shows excellent agreement with the cup anemometer (Floors et al., 2011). \( u_z \) is both measured at 10 m \((u_z)\) and estimated \((u_z)\) from the lowest available level of \( U \) using the logarithmic wind profile equation

\[
\frac{u_*}{u_z} = \frac{0.016}{z} \quad \text{where} \quad z > 0.016 \text{m is the observed roughness length. In WRF } z_u = 0.15. \text{ For plotting profiles, each } U \text{ profile is normalized with } u_z \text{ from a sonic anemometer at } 10 \text{ m and then all profiles are averaged.}
\]

To see in which regime the boundary layer parametrizations have most difficulties, the atmospheric stability is determined according to the measured Obukhov length \( L \) at 10 m. For each stability class the number of profiles is given in the table below.

<table>
<thead>
<tr>
<th>Stability Class</th>
<th>Number of Profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>30</td>
</tr>
<tr>
<td>Neutral</td>
<td>30</td>
</tr>
<tr>
<td>Unstable</td>
<td>30</td>
</tr>
</tbody>
</table>

WRF runs are in forecast mode (restated every 24 hours with 3 hourly boundary conditions from GFS reanalysis) on a 2 km grid domain (red box figure above). The NOAH land surface scheme and Thompson microphysics scheme are used. Wind profiles were classified as a low level jet (LLJ) when the fall-off above the wind maximum is more than 2 m s\(^{-1}\) and 25% (Baas et al., 2009).

Summary statistics
Linear regression with slope and \( R^2 \) (in brackets) between the measured \( U \) and \( u_z \) at Høvsøre and from WRF runs.

<table>
<thead>
<tr>
<th>Month</th>
<th>YSU</th>
<th>MYNN 3.2</th>
<th>MYNN 41</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>1.1 (0.89)</td>
<td>1.05 (0.85)</td>
<td>1.05 (0.85)</td>
</tr>
<tr>
<td>October</td>
<td>1.01 (0.95)</td>
<td>0.98 (0.96)</td>
<td>0.98 (0.96)</td>
</tr>
</tbody>
</table>

Two boundary layer parameterizations are used:
- The Yonsei University (YSU, first order) closures have non-local vertical diffusivity with explicit entrainment layer and parabolic \( K_z \) profile (Hong et al., 2006).
- Mellor-Yamada Nakanishi Niino (MYNN, level 2.5 closure) has one prognostic equation for TKE and an updated stability formulation and mass-length scale (Nakanishi & Niino, 2009).

WRF is run in forecast mode (restated every 24 hours with 3 hourly GFS global forecast data as boundary conditions) and to climate mode (started once with 6 hourly boundary conditions from GFS reanalysis) on a 2 km grid domain (red box figure above). The NOAH land surface scheme and Thompson microphysics scheme are used. Wind profiles were classified as a low level jet (LLJ) when the fall-off above the wind maximum is more than 2 m s\(^{-1}\) and 25% (Baas et al., 2009).

Results
The mean dimensionless wind profile for September is shown (left). When the WRF wind profile is normalized with the measured friction velocity at 10 m (black curves) the agreement is good near the surface, but shows a negative bias higher up in the PBL, except for the MYNN scheme with 41 levels. Normalizing with \( u_z \) from WRF shifts the curves to the left due to the high roughness in WRF (red curves). Below, profiles are shown from the forecast run (first panel) and the analysis run for different atmospheric stability (other panels). Increasing the resolution does not seem to improve agreement in stable conditions, whereas it does for October (not shown). The profile of YSU performs a bit better in stable conditions.

Discussion
Both schemes model the wind profile relatively well in the surface layer, although YSU tends to over predict surface winds. However, both schemes show a 10% negative bias at larger heights, which is not improved when using a higher resolution. The bias might partly be induced by the too high roughness in WRF which shows a micro scale approach is needed when comparing observations with WRF. Since the footprint area of a wind profile increases with height, one might expect that local roughness effects become less important and agreement would improve higher up. This is not observed and might point to either poorly modelled mixing at larger heights or a bias in PBL height. Both schemes do not model the LLJ properly, which explains the under estimation in stable conditions. This introduces errors in the \( k \) parameter of the Weibull distribution between 100 and 300 m. A limitation of this study is that the YSU and MYNN scheme cannot be compared directly here because YSU is run in forecast mode. However, similar conclusions are found for a direct comparison between MYNN and YSU in the same mode.

References