Karlsruhe Institute of Technology

Institute of Meteorology and Climate Research, Department of Atmospheric Environmental Research (IMK-IFU)
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Stable internal boundary layer at FINO1

Measurements and Numerical Simulations during May 4-11, 2006

Richard Foreman (richard.foreman@kit.edu) & Stefan Emeis

1. Introduction

A stable boundary layer occurs when the air density is stratified such that the cooler, denser air lies beneath warmer, lighter air. In these layers, the intensity of turbulent vertical motions are damped by opposing buoyancy forces, resulting in reduced levels of turbulence and greater wind shear. An internal boundary layer forms at surface roughness and/or temperature discontinuities such as that found along coastlines. While the effects of a roughness discontinuity can persist for fetches of O(10 km), the effects of temperature discontinuities can persist for O(100 km), such as that which can occur at the FINO1 platform in the North Sea, positioned about 60 km north and 150 km west of the German mainland as illustrated (⊗) in **Figure 1** (left).

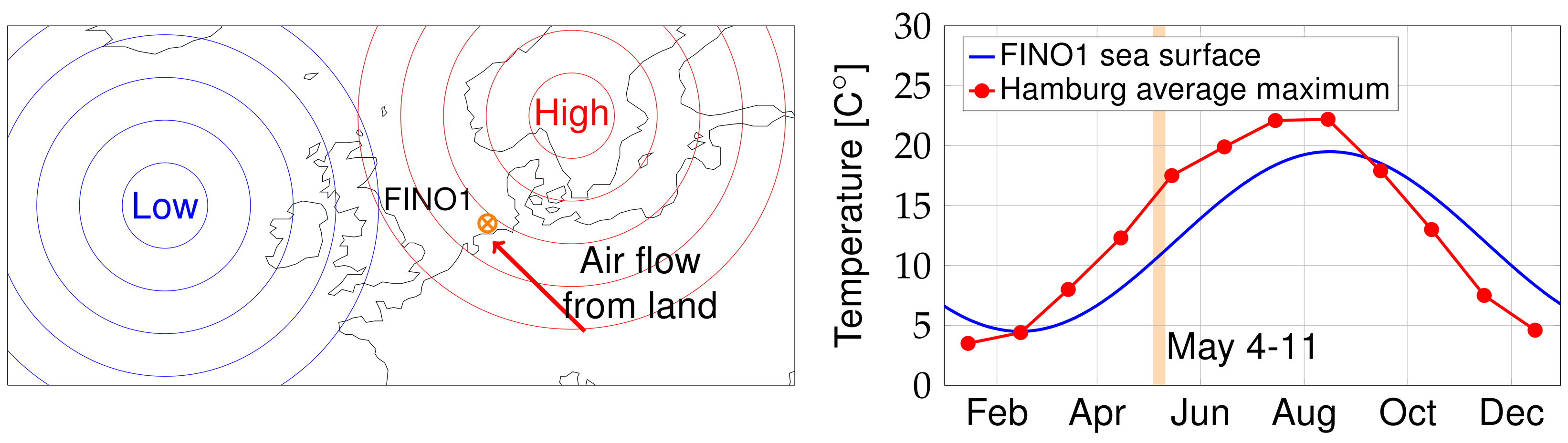

Figure 1: *Left: Rough positions of the high and low surface pressure areas relative to the FINO1 platform (⊗) between the 4th and 11th of May 2006 bringing warmer & drier continental air over the cooler North Sea. Right: Idealised sea surface temperature at FINO1 throughout the year (—) in comparison with average daily maximum temperatures in Hamburg (-•-). Highlighted ( ) is the period May 4-11, on average the period of greatest differential between the sea surface and land temperature.*

Figure 1 (right) shows a typical yearly sea surface temperature cycle at FINO1 (—) in comparison with the average monthly temperature maximum in Hamburg (-•-). Given a favourable synoptic weather situation during the warming months of spring and early summer, such as that illustrated in **Figure 1** (left), it is possible that a stable internal boundary layer will be detected by the FINO1 platform. **Figure 1** (left) shows counter- and clockwise rotating low and high pressure systems located west of Ireland and over Scandinavia, respectively, acting to move the warmer, dryer continental air over the relatively cooler North Sea such as which occurred at FINO1 during the days 4-11 of May, 2006.

2. May 4-11, 2006 - Measurements

In the spring and early summer of 2006, Europe experienced above average temperatures after an unusually cold winter. For example, a time series of 100 m (-•-) and sea surface temperatures (SST, —) during May 5-11, 2006 are displayed in **Figure 2** showing both the large temperature gradient between the sea surface and 100 m above, as well as the diurnal oscillation in 100 m temperature, a phenomena not usually witnessed in most offshore time series. The highly stably stratified nature of this period is demonstrated by the large temperature gradients, particularly during the day reaching O(10°C) – a neutral layer on the other hand would have a gradient of about 1°C.

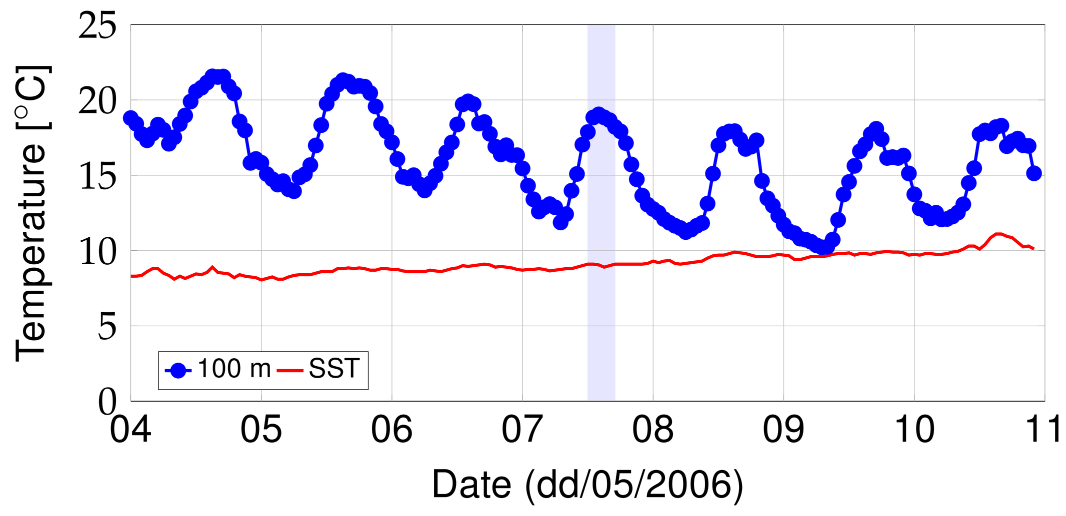

Figure 2: *Time series of the temperature measured at 100 m above the sea surface at FINO1 and the sea surface temperature (SST) during May 4-11, 2006. Highlighted ( ) is the period during the 7th corresponding with the wind speed profile displayed below in **Figure 4**.*

The temperature gradient alone is however not enough to classify the stability which needs to further include information about the wind speed. One measure of stability is the bulk Richardson number and is defined as

$$R_b = z\frac{g}{\theta}\frac{\Delta\theta_s}{U^2}, \tag{1}$$

where z [m] is the height above ground, g [ms^{-2}] is the acceleration due to gravity, θ [K] is the average temperature within the layer of interest, $\Delta\theta_s$ [K] is the temperature difference between the sea surface and height, z and U [ms^{-1}] is the mean wind speed. Physically, a Richardson number is a ratio of turbulence produced by buoyancy to that produced by friction as the flow moves over the land or sea surface.

At some critical Richardson number, the forces of buoyancy overwhelm the forces of surface friction such that the influence of the surface roughness on the flow above becomes practically negligible. In such a scenario, we would expect that the surface drag coefficient, defined as

$$C_D = \left(\frac{u_*}{U}\right)^2 \tag{2}$$

would tend towards a magnitude of zero. Here, u_* [ms^{-1}] is the friction velocity. The bulk Richardson number (-•-) and drag coefficient (-■-) are displayed in **Figure 3** for between May 6-10 where there is a clear negative correlation between these two numbers. The critical Richardson number is approached, that is when $C_D \to 0$, when $R_b \to 0.15$ (more or less).

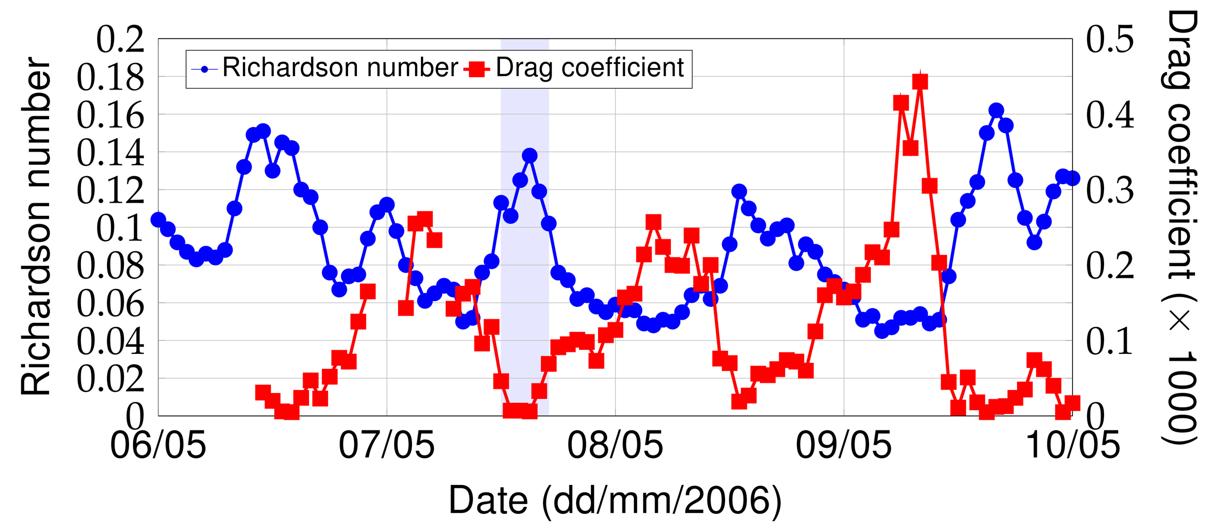

Figure 3: *Time series of the Richardson number and drag coefficient calculated according to eq. (1) and (2), respectively from May 6-10, 2006 at FINO1. Highlighted ( ) is the period during the 7th corresponding with the wind speed profile displayed below in **Figure 4**.*

3. May 4-11, 2006 - Numerical Simulations

The discussion above has relevance for the numerical simulation of stable internal boundary layers. Take for example the Weather Research and Forecasting (WRF) model [1] within which contains a number of different parametrizations for turbulence and mixing within the planetary boundary layer. One of those boundary layer parametrizations in the WRF model (and indeed in most models) is based on the classic Mellor-Yamada [2] methodology, whose implementation within WRF (called the Mellor-Yamada-Janjić parametrization) results in a critical Richardson number of 0.51 which is far above what the measurements suggest in **Figure 3** is a realistic value.

Instead, changing the critical Richardson number to 0.15 (see [3]) produces less mixing and hence more shear in wind speed profiles as displayed in **Figure 4** (left). A direct comparison with FINO1 wind speeds in **Figure 4** (middle & right) show an **improved calculation of wind speed** using our changes ("New") compared with the existing model ("Old") during May 4-11, 2006.

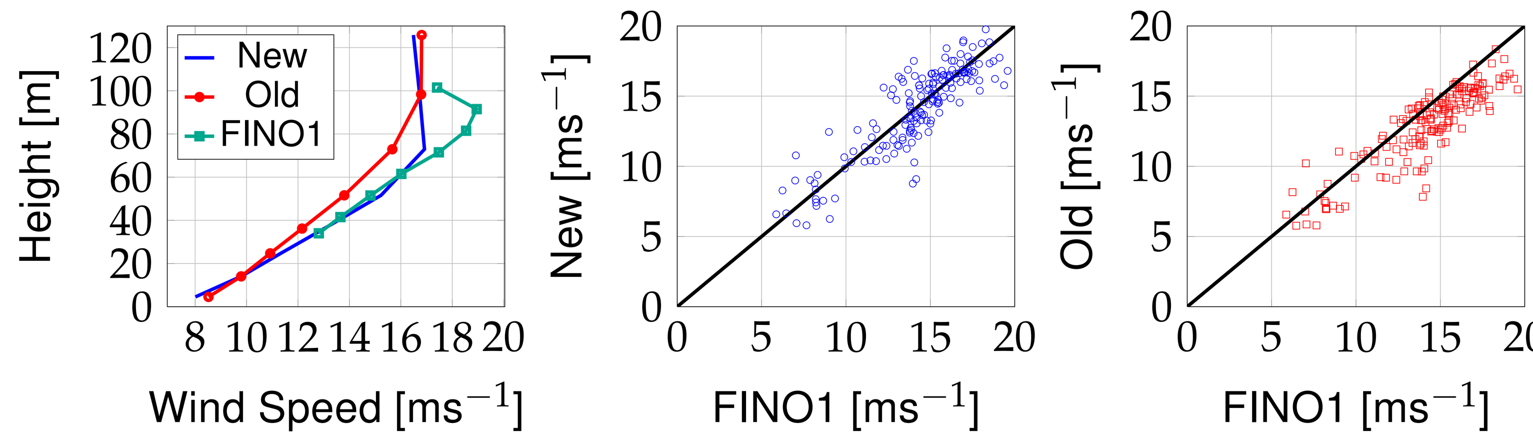

Figure 4: *Left: Measured average wind profiles during a period of the 7th May 2006 at FINO1 (see the shaded area in **Figures 2** and **3**) using a lower critical Richardson number (0.15) compared with that in the standard model (0.51). These are labelled as "New" and "Old", respectively in the legend. Middle: Direct comparison with the FINO1 measurements using the "New" modelled wind speed. Right: The same as middle except "Old" is compared with the FINO1 measurements.*

References

[1] W.C. Skamarock, A Description of the Advanced Research WRF Version 3. Tech. rep., National Center for Atmospheric Research (2008)

[2] G.L. Mellor, T. Yamada, Rev. Geophys. Space Phys. **20**, 851 (1982)

[3] R.J. Foreman, S. Emeis, Boundary-Layer Meteorol. (2012). In Press.

Acknowledgements

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