LUND UNIVERSITY
Faculty of Science

Nocturnal jets in Skåne:

an analysis of data from Hyltemossa research tower

Tove Fast

Thesis submitted for the degree of Bachelor of Science
Project duration: 05 months

Supervised by Elna Heimdal Nilsson and Thomas Holst

Department of Physics
Division of Combustion Physics
May 2019

(This page is intentionally left empty)

Acknowledgements

ICOS Sweden and Swedish Research Council (SRC) - thank you for providing data.
Thomas Holst and Elna Heimdal Nilsson - thank you for supervising this project.
Joel Lundqvist - thank you for your support and for many good discussion throughout the years.

My friends and family - thank you for your support.

Abstract

A nocturnal jet is a low level air jet that is often seen at an altitude below 500 m during night time conditions. It can reach wind speeds of storm force and is thus of importance for aviation and also for transport of e.g. moisture and pollutants in the lower troposphere. By comparing wind speed measurements at 150 m at Hyltemossa research station (measured by ICOS Sweden) to the logarithmic wind profile and the power law wind profile for different times of the day and different time periods, no large deviations that could indicate a nocturnal jet were found. The temperature profile for the times where the largest deviations occurred where analysed and showed either that that the temperature inversions reached higher than 150 m, or in one case, that the lower most part of the troposphere was unstable. The analysis of the root mean square errors showed that the logarithmic wind profile described the lower troposphere better than the power law wind profile. However, both theories are based on simplifications of a complicated system.

Abberations

GHG - GreenHouse Gas
LLJ - Low Level Jet
PBL - Planetary Boundary Layer
PGF - Pressure Gradient Force
RMSE - Root Mean Square Error
WS - Wind Speed

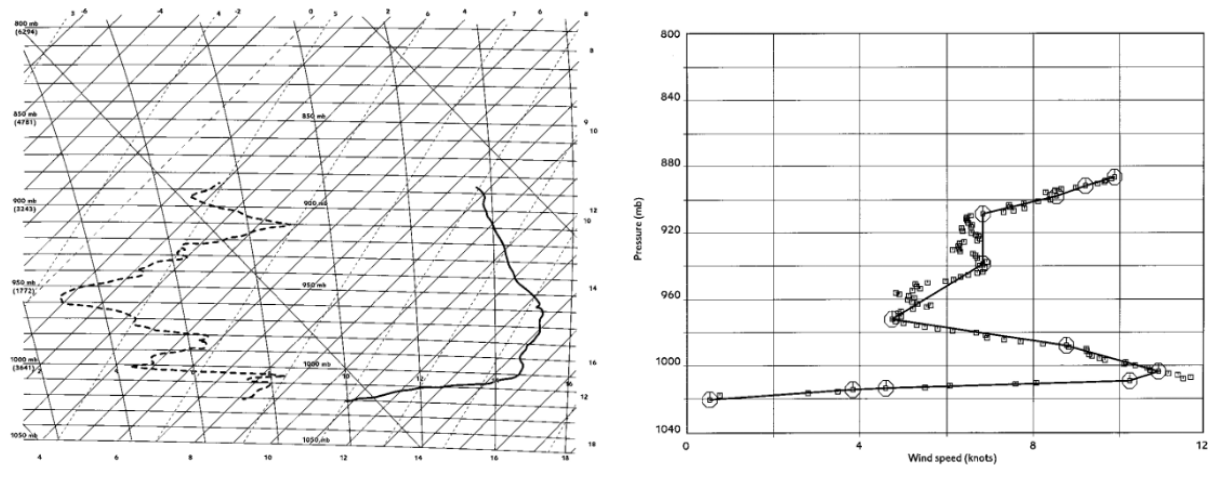
u - wind speed in West-East direction
v - wind speed in North-South direction
w - wind speed in the vertical direction

Contents

1 Introduction

An atmospheric jet is a narrow stream of air with high wind speeds and a strong vertical shear. There are several types of jets, which differs in terms of location, mechanisms of formation and strength (Davis, 2000). The aim of this thesis is to analyse wind speed and temperature data provided by ICOS Sweden and Swedish Research council (SRC), from Hyltemossa research station, to find the occurrence of a certain low level jet: the nocturnal jet. The low level jets have the characteristics of being located at low altitudes (Ahrens, 2009). There are several types of low level jets, but this thesis will only cover the nocturnal jet.

The nocturnal jet is a boundary-layer jet, i.e. it appears in the lowest part of the troposphere in the layer where friction is non-negligible. The diurnal pattern of the frictional force is the main factor for the development for the jet (Holton, 1967). The planetary boundary layer (PBL) experience a strong diurnal pattern. As the sun rise, the radiation immediately starts to heat the surface. This creates turbulence and mixing which increases the friction in the layer (Stull, 2017). As the sun set, the net radiation is outgoing. This can, during a cloud free night create a stable atmosphere, an atmosphere where the temperature is either increasing or being constant with height (Stull, 2017), which is called a nocturnal inversion.



(a) Temperature profile **(b)** Wind profile

Figure 1: Temperature and wind speed profile from a sounding at 07:15 UTC the 16th of September 1996 in Cardington, UK. **a)** Shows the temperature (solid) and the dew point temperature (dashed). It shows a temperature inversion up to ~1000 mbar. **b)** Shows the wind speed profile of a nocturnal jet. The highest wind speeds are found at ~1000 mbar. Source: Fig. 3 in Davies et al., 2000.

During such a night the heat flux is from the Earth's surface to the atmosphere. This results in a cold layer below, the nocturnal boundary layer, which has experienced radiational cooling, and a warm layer above (Singh, McNider, & Lin, 1993). As the fluxes continues, a de-coupling could occur that would allow the air in the upper level to flow freely, as friction no longer act on this layer. (Davis, 2000). The maximum wind speed of the nocturnal jet is usually observed at the top of the nocturnal inversion (Frisch, Orr, & Martner, 1992), in the warm layer. This can be seen in Fig. 1.

The nocturnal jet can occur at only a few hundreds of metres height (Ahrens, 2009), depending on the thickness of the cold layer. This makes the knowledge of these jets highly relevant when it comes to aviation as well as for the spread of pollutants.(Davis, 2000) The strong vertical shear that is associated with the nocturnal jet can lead to complications for small airplanes and balloons and the low altitude allows the jet to transport substances that are emitted from, for example, a factory. As Hyltemossa research station is located close to a military location with a small airport, knowledge about nocturnal jets in the area are highly relevant.

To be able to analyse the occurrence of nocturnal jets in this thesis, data provided by ICOS sweden will be used. The data contains information about temperature and wind speeds measured at fourteen and three different heights respectively.

The analysis will be made in two steps. First the wind speeds will be analysed in two ways; by assuming a logarithmic wind profile, and by assuming a wind power law profile. The two lowest measurement points will be used to calculate the theoretical wind profiles and the highest measurement point can then be compared to the calculated values. The wind speed differences will be plotted against the temperature difference between 30 and 70 m and a correlation coefficient will be calculated to see if any correlation can be found.

For the largest deviation from the theoretical values, a further analysis will be made with temperature profiles. Using the temperature measurements, temperature as a function of height will be plotted. This way, a temperature inversion can be observed, which is needed for a nocturnal jet to occur. The measured wind speeds at the different heights will be analysed, as well as the calculated deviations.

At last, an analysis of the root mean square error between the measured and the calculated wind speeds will be done to investigate how well the theoretical wind speeds describe the wind profile.

2 Background

2.1 Historical background

2.1.1 ICOS and Hyltemossa research station

ICOS RI (Integrated Carbon Observation System Research Infrastructure) is a European network, with twelve membership countries, that coordinates national research institutes from seventeen different countries (ICOS RI, n.d.). Their aim is to monitor the greenhouse gases (GHG) in Europe, and provide data from the atmosphere, ecosystems and oceans to scientists and the society. In total they have more than 130 measuring stations.

Lund University is the host of ICOS Sweden, with Stockholm University, Swedish Polar Research Secretariat, Swedish University of Agricultural Sciences, University of Gothenburg and Uppsala University as their partners. ICOS Sweden are monitoring seven stations in Sweden: Abisko-Stordalen (Ecosystem station), Svartberget (Atmospheric and ecosystem station), Degerö (Ecosystem station), Norunda (Atmospheric and ecosystem station), Lanna (Ecosystem station), Östergarnsholm (Ocean station) and Hyltemossa (Atmospheric and ecosystem station). The atmospheric stations are measuring GHG concentrations in the atmosphere, ecosystem stations are measuring GHG concentration and fluxes and also provide meteorological data. Ocean stations measure GHG concentrations in the surface water and in the atmosphere near the surface (ICOS Sweden, n.d.).

Figure 2: Map showing Skåne and the location of Hyltemossa research station (red). Source: Google maps (`https://www.google.com/maps/place/Hyltemossa+Research+Station/@55.6799252,12.2736164,7z/data=!4m5!3m4!1s0x4653e7339e32a287:0xefbbf5e3b81964eb!8m2!3d56.0978042!4d13.420146`). Retrieved 2019-05-01.

Hyltemossa research tower is a 150 m high tower located close to Ljungbyhed in Skåne (56°06'N, 13°25'E), at an elevation of 115 m above sea level. The location is shown in Fig. 2. The tower was installed in 2014 and is located in a ∼19 m high spruce forest, planted in 1983. Close to the tower there are also areas with leaf trees, grassland and open water/lakes (ICOS Sweden, n.d.).

2.2 Teoretical background

2.2.1 Static stability

A measure of how the atmosphere counteracts vertical motion is the static stability. For a de-coupling to occur, there should not be any vertical mixing and therefore the stability of the atmosphere is fundamental to understand. This section follows Holton and Hakim's (Holton & Hakim, 2013) derivation of the static stability.

The atmosphere is assumed to be an ideal gas, and can hence be described by the equation of state:

$$p\alpha = RT \tag{2.1}$$

where p is the pressure, $\alpha = 1/\rho$, ρ is the density, T is the temperature and R is the gas constant. The ideal gas law states that air at the same pressure but with different temperatures have different densities, with warmer air being lighter.

Taking the total derivative (Eq. (A.1) in appendix) of the equation of state gives:

$$p\frac{\mathrm{D}\alpha}{\mathrm{D}t} + \alpha\frac{\mathrm{D}p}{\mathrm{D}t} = R\frac{\mathrm{D}T}{\mathrm{D}t}. \tag{2.2}$$

The thermodynamic energy relation

$$c_v\frac{\mathrm{D}T}{\mathrm{D}t} + p\frac{\mathrm{D}\alpha}{\mathrm{D}t} = J, \tag{2.3}$$

describing the internal energy change (first term on the left) is equal to the difference of the rate of heating per unit mass, J, and work done by the system (second term on the left), can be used with the relation between the gas constant and the specific heat capacity with constant volume, c_v, and at constant pressure, c_p: $c_p = R + c_v$, to rewrite Eq. (2.2).

$$c_p\frac{\mathrm{D}T}{\mathrm{D}t} - \alpha\frac{\mathrm{D}p}{\mathrm{D}t} = c_v\frac{\mathrm{D}T}{\mathrm{D}t} + p\frac{\mathrm{D}\alpha}{\mathrm{D}t} = J. \tag{2.4}$$

Dividing with T and using Eq. (2.1), the following equation is obtained:

$$c_p\frac{\mathrm{D}\ln T}{\mathrm{D}t} - R\frac{\mathrm{D}\ln p}{\mathrm{D}t} = \frac{J}{T} = \frac{\mathrm{D}s}{\mathrm{D}t}, \tag{2.5}$$

with s being the entropy.

An air parcel that do not mixes with its surroundings, but keeps its properties is said to undergo adiabatic processes. Adiabatic processes are processes where no heat is transferred to the surroundings, i.e. $\mathrm{D}s = 0$. However, as Eq. (2.1) states, the temperature will change with pressure. To easier compare the properties of an air parcel and its surroundings, potential temperature is often used in meteorology. Potential temperature is the temperature an air parcel would have if it was brought down to surface pressure adiabatically.

The differential form of Eq. (2.5), for adiabatic processes, can be expressed as

$$c_p \,\mathrm{D} \ln T - R \,\mathrm{D} \ln p = 0. \tag{2.6}$$

Integrating the equation above from surface pressure, p_s, surface temperature, θ, to temperature T at pressure p and using logarithmic rules to rewrite the expression, we get

$$\theta = T \left(\frac{p_s}{p}\right)^{R/c_p}. \tag{2.7}$$

Eq. (2.7) is called Poisson's equation and θ is the potential temperature, mentioned earlier.

To determine the stability of the atmosphere the vertical change of the potential temperature should be investigated. To do this, first, hydrostatic balance is assumed:

$$\frac{\partial p}{\partial z} = -\rho g \tag{2.8}$$

g being the gravitational acceleration. The hydrostatic balance describes a fluid where the gravitational force (acting downwards) is balanced by the pressure gradient force (acting in the direction of lower pressure, i.e upwards).

Taking the derivative of the logarithm of Poisson's equation with respect to z, and using Eqs. (2.1) and (2.8) to simplify, we get

$$\frac{T}{\theta}\frac{\partial \theta}{\partial z} = \frac{\partial T}{\partial z} + \frac{g}{c_p} = \Gamma_d - \Gamma. \tag{2.9}$$

The dry adiabatic lapse rate Γ_d is defined as

$$\Gamma_d \equiv \frac{g}{c_p} \approx -9.8°\mathrm{C/km} \tag{2.10}$$

and the environmental lapse rate Γ is defined as

$$\Gamma \equiv -\frac{\partial T}{\partial z}. \tag{2.11}$$

This means that if the potential temperature is a function of height, the actual environmental lapse rate will differ from the dry adiabatic.

If the potential temperature increases with height, $\partial\theta/\partial z > 0$, a parcel that is displaced adiabatically upward will be colder than its surrounding and thus sink. If it is displaced downward it will be warmer than its surrounding and rise. An atmosphere with such properties is called statically stable since the displaced parcel will return to its original height (or oscillate around the equilibrium). This is an atmosphere where vertical motions are counteracted.

An atmosphere where the potential temperature is constant with height, $\partial\theta/\partial z = 0$, it is called statically neutral. If a parcel is displaced in such an atmosphere it will neither sink nor rise.

If the potential temperature is decreasing with height, $\partial\theta/\partial z < 0$, it is called statically unstable. In such an atmosphere, an air parcel that is displaced upward will be warmer than its surrounding and continue to rise. If it where displaced downward, it will continue to sink. This describes an atmosphere where vertical motions will grow.

2.2.2 Planetary boundary layer

The lowest part of the troposphere is called the Planetary Boundary Layer (PBL). In this layer friction is non-negligible; it experiences both thermal and mechanical turbulence. The depth of the PBL depends on the stability of the troposphere. During very stable conditions it can be as shallow as 30 m, and over 3 km during convective conditions. In the mid-latitudes, it is usually around 1 km (Holton & Hakim, 2013).

The stability of the PBL has a distinct diurnal cycle. During daytime, radiational heating of the surface causes an unstable atmosphere and a thick PBL. During nighttime, the surface cools down and the atmosphere is again stable and the PBL is shallow. This nighttime stability is called a nocturnal inversion and is especially common during cloud free conditions. This is due to the heat absorbed (and radiated back) by the clouds, preventing the surface to cool.

2.2.3 Logarithmic wind profile

The friction that acts on the air near the surface affects how the wind varies with height in the PBL, i.e. the wind profile. This section derives the the logarithmic wind profile, following the derivation in Chapter 8 in Holton and Hakims book *An introduction to dynamic meteorology*, from 2013 (Holton & Hakim, 2013).

To describe the wind, the perturbation method is used. This describes the wind speeds as a mean value (marked with bars) and a perturbation (marked with by primes). It assumes that the mean wind is much larger than the perturbation, $\bar{x} << x'$. u is the velocity in the W-E direction, v in the N-S direction and w is the vertical velocity.

$$
\begin{aligned}
u &= \bar{u} + u' \\
v &= \bar{v} + v' \\
w &= w'
\end{aligned}
$$

In synoptic meteorology, that is large temporal and spatial scale meteorology, the velocity is equal to the average. However when looking at the vertical scale of the PBL, the scale is smaller and the perturbations must be taken into account.

Reynolds averaging can be used to handling the perturbations in a flow. It assumes that small scale perturbations varies quickly and that they can be averaged by looking at the flow for a time scale large enough to describe the trends in the flow. The product of a mean and a perturbation is zero when averaged. The average of a perturbation is zero by definition, i.e.

$$\overline{\bar{X}_1 X_2'} = \overline{X_1'} \bar{X}_2 = 0 \tag{2.12}$$

where X_1 is a field variable and X_2 is another.

To be able to apply this on the atmosphere, an incompressible flow (constant density) where mass is conserved is assumed. This yields the continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \tag{2.13}$$

The continuity equation is used to expand the total derivative of the zonal wind:

$$\frac{\mathrm{D}u}{\mathrm{D}t} = \frac{\mathrm{D}u}{\mathrm{D}t} + u\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) = \frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} \tag{2.14}$$

Now the perturbation method is applied to the zonal velocity and the total derivative is averaged. Eq. (2.12) is used to get the simplified expression:

$$\overline{\frac{\mathrm{D}u}{\mathrm{D}t}} = \frac{\bar{\mathrm{D}}\bar{u}}{\mathrm{D}t} + \frac{\partial}{\partial x}(\overline{u'u'}) + \frac{\partial}{\partial y}(\overline{u'v'}) + \frac{\partial}{\partial z}(\overline{u'w'}). \tag{2.15}$$

This equation describes the average change of the zonal velocity following the flow as equal to the sum of the change of the average velocity following the mean flow and the gradient of the average fluxes of momentum. $\overline{u'v'}$ is the meridional turbulent flux of zonal momentum and $\overline{u'w'}$ is the turbulent vertical flux of zonal momentum, which will be further investigated.

One way of approximate a velocity perturbation is to assume that an air parcel will keep its properties a distance ξ' before it mixes with its surrounding. This is called the mixing length hypothesis and it also assumes that the perturbation is proportional to the gradient of the mean flow. When looking at vertical perturbations in the zonal flow, this yields

$$u' = -\xi' \frac{\partial \bar{u}}{\partial z}. \tag{2.16}$$

As friction is slowing down the velocity close to the ground more efficient than higher up, the mean flow is slower close to the ground. $\xi' > 0$ describes an upward displacement and a negative perturbation.

The vertical mean flow is zero, so the same assumptions cannot be made to describe the vertical perturbation. It can however be assumed to be in the same scale as the horizontal perturbation, if the atmosphere is near neutral:

$$w' \approx \xi' \left|\frac{\partial \overline{\mathbf{V}}_h}{\partial z}\right|, \tag{2.17}$$

where $\overline{\mathbf{V}}_h = (\bar{u}, \bar{v})$ is the horizontal mean velocity.

With equation (2.16) and (2.17) an expression for the vertical turbulent flux of momentum is obtained:

$$-\overline{u'w'} = \overline{\xi'^2} \left|\frac{\partial \overline{\mathbf{V}}_h}{\partial z}\right| \frac{\partial \bar{u}}{\partial z}. \tag{2.18}$$

The vertical turbulent flux of zonal momentum then depend on the vertical shear and the mixing length, that is defined as the root mean square parcel displacement:

$$l \equiv \sqrt{(\overline{\xi'^2})}. \tag{2.19}$$

To get an expression for the wind profile in the lower troposphere, it is assumed that in the surface layer (the lowest ∼10 of the PBL, depending on the stability) the flow is parallel to the x-axis, i.e $\overline{\mathbf{V}}_h = (\bar{u}, 0)$, and it is only dependent on the vertical momentum fluxes. The momentum flux can then be expressed as a friction velocity, u_*:

$$u_*^2 \equiv |\overline{(u'w')}| = \overline{l^2} \left| \frac{\partial \bar{u}}{\partial z} \right|^2. \tag{2.20}$$

An assumption that the mixing length is linear with the height near the surface can be made, due to the constrictions the surface set on the scale of the eddies; the eddies cannot go below the surface.

$$l = \kappa x, \tag{2.21}$$

where κ is von Karman's constant, experimentally determined to $k \approx 0.4$. Integrating the square root of Eq. 2.20 from 0 m/s to $\bar{u}$ and from z_0, the roughness length, to z yields the logarithmic wind profile:

$$\bar{u} = \frac{u_*}{\kappa} \ln(z/z_0). \tag{2.22}$$

The roughness length is defined as the height where $\bar{u} = 0$, and depend on the roughness of the surface. For example, an ice surface that is smooth has the roughness length $z_0 \approx 1$ mm, a forest $z_0 \approx 500$ mm, and suburbs $z_0 \approx 1500$ m (Manwell, McGowan, & Rogers, 2010).

2.2.4 Wind profile power law

Another approach to theoretically describe the wind profile in the PBL is the wind profile power law (Manwell et al., 2010; Hsu, Meindl, & Gilhousen, 1994):

$$u = u_r \left(\frac{z}{z_r} \right)^{\alpha} \tag{2.23}$$

where u_r is a reference at height z_r. The exponent α varies with different parameters e.g elevation, roughness of surface, wind speed and temperature.

Manwell et al. states that, even if it is a simple model, research has shown that the wind profile power law and the logarithmic wind profile estimates roughly the same wind shear and that it at 50 m altitude differed from the actual measured value with 1–13% depending on the terrain (Manwell et al., 2010).

3 Method

All measurements were taken by ICOS Sweden at Hyltemossa research tower, only the analysis of the data was made in this project.

3.1 Equipment

Temperature was measured with both a resistance thermometer (a PT100 sensor) and an sonic anemometer. The wind speed was measured with an anemometer (ICOS Sweden, n.d.; rotronic Measurement Solutions, n.d.).

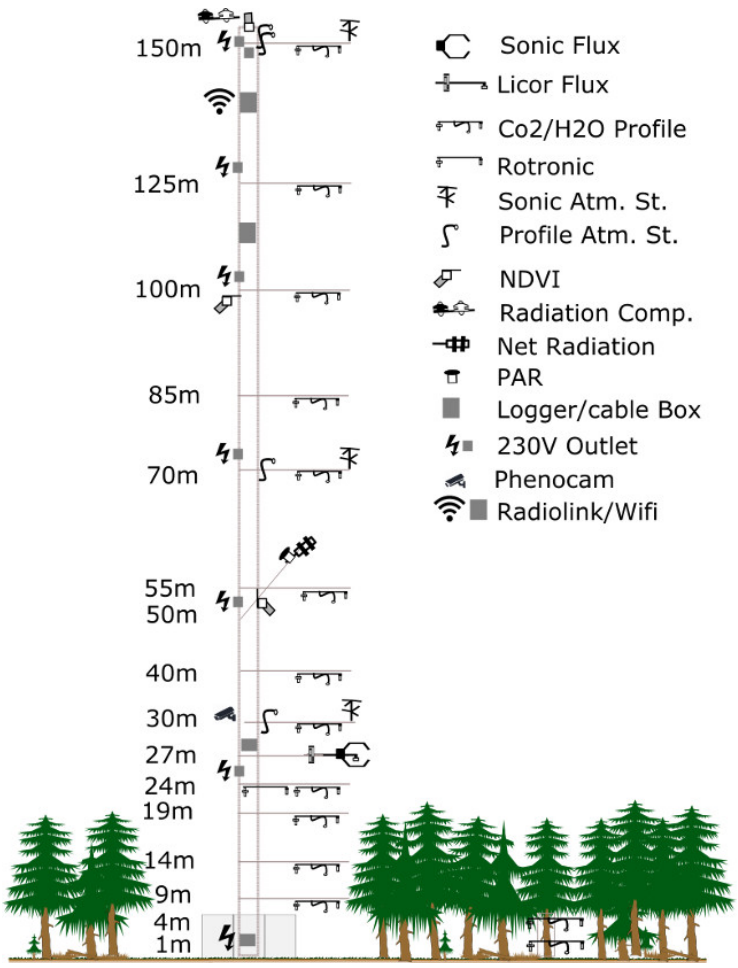


Figure 3: Schematic figure of the Hyltemossa research tower. Wind speed and temperature measured with Sonic Atm. St. (three different heights) and temperature measured with Rotronic (fourteen different heights). Source: `http://www.icos-sweden.se/station_hyltemossa.html`, retrieved 2019-05-01.

The resistance thermometer, Rotronic MP102H, measured at the heights marked 'Rotronic' in Fig. 3, i.e. at 1, 4, 9, 14, 19, 24, 30, 40, 55, 70, 85, 100, 125 and 150 m, every thirty minutes. The sonic anemometer measured temperature and wind speed at the heights marked 'Sonic Atm. St.' in Fig. 3, i.e. at 30, 70 and 150 m, every one hour.

The PT100 sensor measure the resistance in a platinum element. The resistance in a conductor varies with temperature, increasing with increasing temperature. This makes it possible to measure the resistance and calculate the temperature (Preston-Thomas, 1990).

The sonic anemometer is a setup with two transducers. It sends a sonic pulse between the transducers and measures the time for the pulse to reach the other. The time it takes for the pulse depends on the distance between the transducers, the speed of sound and the speed of the air along the axis of the transducers. Sonic anemometers are set up in three direction, which together give the wind speed and the wind direction. The speed of sound depends on the air temperature and thus the temperature be calculated from the measurements (The University of Manchester, Centre for Atmospheric Science, n.d.).

3.1.1 Measurement uncertainties

ICOSs requirement for the temperature measurement is that the uncertainty is not larger than 0.1 K at 0 °C and the precision is 0.1 K. The instruments used should be able to measure in the range -50 to +55 °C. For the wind speed measurement, the accuracy should be at least 0.5 m/s in the interval 0–5 m/s and 10 % in the interval 5–75 m/s. (Sabbatini, Nicolini, Op de Beeck, & Papale, 2017). The instruments should be able to measure wind speeds in the range 0–75 m/s. All the data provided by ICOS have been checked and quality controlled (ICOS CP, n.d.).

3.2 Data

The data used provided by ICOS Sweden and for this report included measurements of temperature and wind speeds. The data covered the time period 2017-09-26 00:00 to 2018-12-31 23:00.

3.3 Analysis

The data was analysed using Python (Code in appendix).

First all measurement errors was taken out of the data. In the data from the anemometer, measurement errors marked '-999.99' were removed. In the data from the rotronic measurement errors marked 'nan' was removed. The data was cut to cover the time period 2017-09-26 00:00 to 2018-12-31 23:00.

3.3.1 Wind speeds

The first assumption that was made was that the nocturnal jet would occur at an altitude higher than 70 m. Therefore, the wind speed deviation from the theoretical values at 150 m was investigated.

The second assumption was that the nocturnal jet would be most pronounced in the late night. It was decided that the wind speed deviation at 03:00, 04:00 and 05:00 would be investigated. It was also assumed that the probability of finding a nocturnal jet during the winter months (December, January, and February) would be higher. The wind speeds at 05:00 for these months were investigated separately.

To calculate the logarithmic wind profile, the following equation system was set up from Eq. (2.22):

$$u = a\ln(z+b) + c \tag{3.1}$$

$$u(z_0) = 0 \tag{3.2}$$

This, however, was not possible to solve for b:

$$\left(\frac{z_1+b}{z_0+b}\right)^{u_2} = \left(\frac{z_2+b}{z_0+b}\right)^{u_1}. \tag{3.3}$$

and could therefore not be applied. Instead, z_1 was used a reference height, and an equation system was set up and solved for a and b:

$$u(z) = a\ln\left(\frac{bz}{z_1}\right) \tag{3.4}$$

$$b = \left(\frac{z_2}{z_1}\right)^{\frac{u_1}{u_2-u_1}} \tag{3.5}$$

$$a = u_1/\ln(b). \tag{3.6}$$

The wind speeds, u_1, u_2 at $z_1 = 30$ m and $z_2 = 70$ m respectively, where used to solve the constants a and b. The wind speed at 150 m was then calculated at 03:00, 04:00 and 05:00 for each day in the time period 2017-09-26 00:00–2018-12-31 23:00.

The difference between the measured wind speed at 150 m and the theoretical log. wind speed at 150 m was plotted against the temperature difference between z_1 =70 and z_2 =30 m, $\Delta T = T(z_2) - T(z_1)$. Plots were made for data only measured at 03:00, 04:00 and 05:00 separately, as well as for only during the winter months (December, January and February) at 05:00.

For the wind power profile, Eq. (2.23) was used and the constant α was calculated as

$$\alpha = \frac{\ln(u_1/u_2)}{\ln(z_2/z_1)} \tag{3.7}$$

using the wind speeds, u_1, u_2 at z_1 =30 and z_2 =70 m respectively. The theoretical values of the wind speed at 150 m was then calculated at 03:00, 04:00 and 05:00 for each day in the time period 2017-09-26 00:00–2018-12-31 23:00.

The difference between the measured wind speed at 150 m and the theoretical wind speed at 150 m was plotted against the temperature difference between z_1 =70 and z_2 =30 m, $\Delta T = T(z_2) - T(z_1)$. Plots were made for data only measured at 03:00, 04:00 and 05:00 separatly, as well as for only during the winter months (December, January and February) at 05:00.

For each plot a linear fit was made for the measurements. This was done to be able to see if there were any correlation between the wind speed and the temperature difference. A Pearson product-moment correlation coefficient was calculated, which is a measure of how well the measurements fits with the linear fit and a measure of correlation between the measurements (Lund Research Ltd, n.d.).

The root mean square of the deviations from both theoretical wind profile was calculated. This was done to estimate how well the theoretical wind profiles fitted to the measured winds.

The propagation of uncertainty was calculated for both theoretical wind profiles, with δu_1=δu_2=0.5 m/s, using the following equation:

$$\text{uncertainty} = \sqrt{\left(\frac{\partial u}{\partial u_1}\,\delta u_1\right)^2 + \left(\frac{\partial u}{\partial u_2}\,\delta u_2\right)^2}. \tag{3.8}$$

This was done for all measured values and a mean was calculated.

3.3.2 Temperature profiles

Temperature profiles were plotted for the occasions where the largest winds speed deviations from the theoretical values was observed. This was made for both the deviation from the logarithmic wind profile and the power lay wind profile. The largest deviations were found for 03.00, 04.00 and 05.00, and for 05:00 during the winter months.

The measured wind speed at the three different heights where analysed for the occasions where the largest deviations where observed.

4 Results

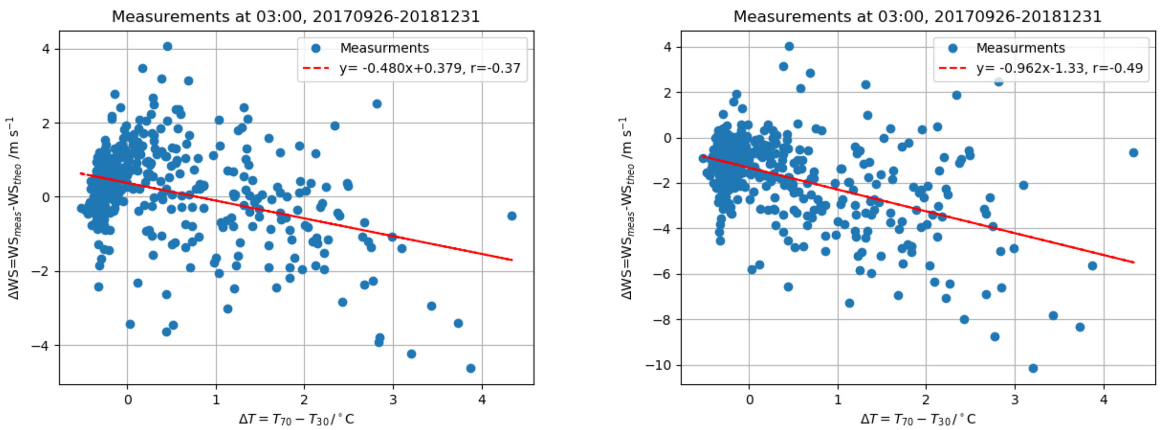
4.1 Wind speed deviation

The table (Table 1) below shows the days when the largest wind speeds deviations where observed, the deviation and the measured wind speed at the different heights.

Table 1: Wind speeds at 30 m (WS30), 70 m (WS70) and 150 m (WS150) for the days when the largest deviation from the theoretical wind profiles where observed. The deviations from the logarithmic wind profile ($\Delta \mathrm{WS}_{log}$) and from the wind profile power law ($\Delta \mathrm{WS}_{pow}$) are also shown.

Date	WS30 /m/s	WS70 /m/s	WS150 /m/s	$\Delta \mathrm{WS}_{log}$ /m/s	$\Delta \mathrm{WS}_{pow}$ /m/s
20171202 03:00	1.56	1.28	5.09	4.1	4.0
20180509 03:00	3.17	6.65	13.3	3.5	–
20181001 03:00	1.85	2.24	5.80	–	3.1
20181107 04:00	2.36	4.38	9.25	3.6	–
20180509 04:00	2.41	4.85	10.61	–	1.6
20180523 05:00	1.84	3.08	8.27	4.1	3.6
20180205 05:00	2.46	5.16	10.03	2.4	–
20171217 05:00	1.62	2.25	4.10	–	1.1

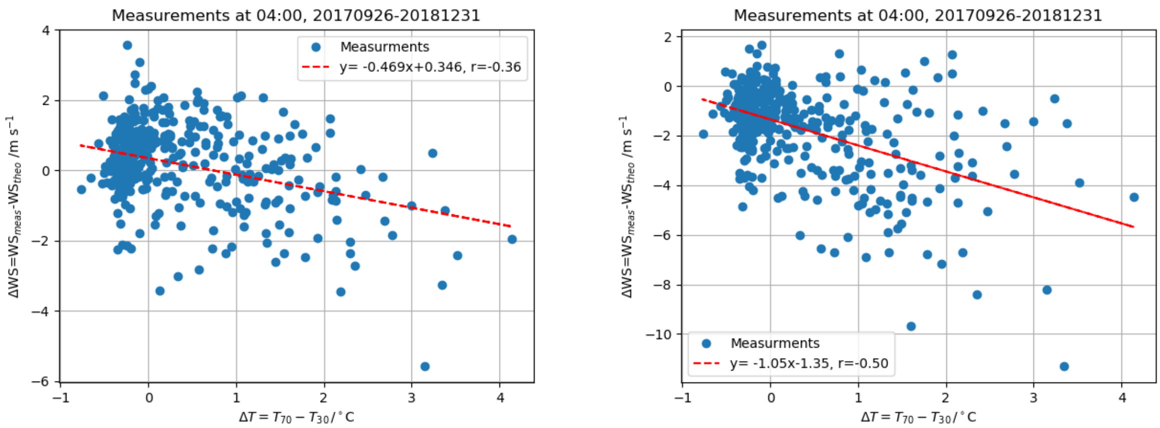
The following plots show the wind speed deviation at 150 m plotted against the temperature difference between 70 and 30 m altitude.



(a) Deviation from the logarithmic wind profile **(b)** Deviation from the power law profile

Figure 4: Deviation from the logarithmic wind profile at z=150 m and temperature difference between z= 70 m and z= 30 m for the time period 2017-09-26 to 2018-12-31. The measurements were taken at 03:00. **a)** Shows the measured wind deviation from the logarithmic wind profile and **b)** the deviation from the power law profile. The red lines shows the linear fit.

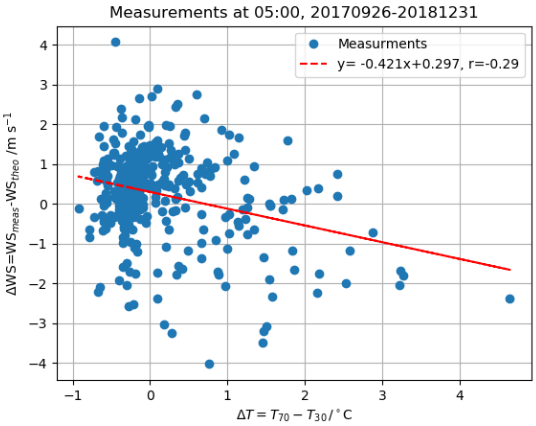
Fig. 4 shows the differences between the measured wind speed at 150 m 03:00 and the theoretical value following **a)** the logarithmic wind profile and **b)** the power law wind profile. The deviation from the power law wind profile is much larger than for the logarithmic wind profile. The power law wind profile seems to overestimate the wind speed at 150 m. For both plots, the linear fit show a trend of lower wind speed when there is a positive temperature difference. However, the correlation coefficient for 4**a)** r=-0.37 and **b)** r=-0.49 are both low and show no actual correlation.



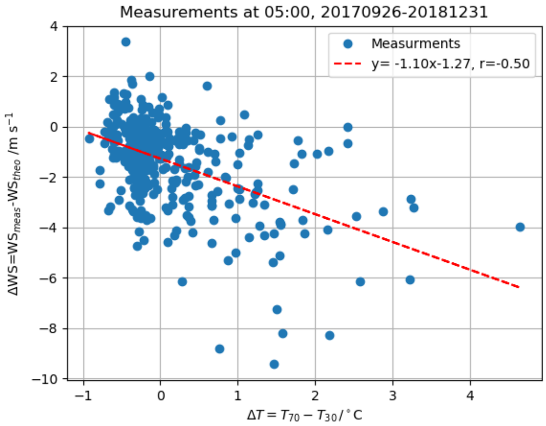
(a) Deviation from the logarithmic wind profile **(b)** Deviation from the power law profile

Figure 5: Deviation from the logarithmic wind profile at z=150 m and temperature difference between z= 70 m and z= 30 m for the time period 2017-09-26 to 2018-12-31. The measurements were taken at 04:00. **a)** Shows the measured wind deviation from the logarithmic wind profile and **b)** the deviation from the power law profile. The red lines shows the linear fit.

The plots in Fig. 5 shows the wind speed difference between the measured wind speed at 150 m 04:00 and **a)** the logarithmic wind profile and **b)** the power law wind profile. The deviation from the logarithmic wind profile is generally smaller and more positive than the deviation from the power law profile, which again seems to overestimate the wind speed at 150 m. The correlation coefficients for the linear fits are both low for these plots as well. For the logarithmic wind profile r=-0.36 and for the wind profile power law r=-0.50.



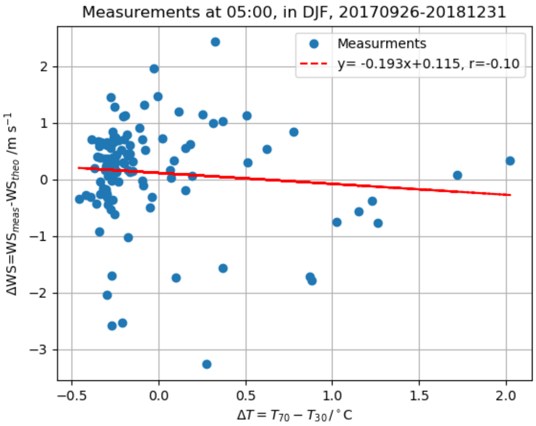
(a) Deviation from the logarithmic wind profile



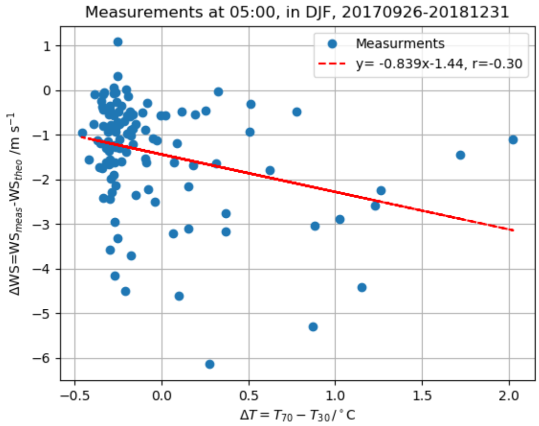
(b) Deviation from the power law profile

Figure 6: Deviation from the logarithmic wind profile at z=150 m and temperature difference between z= 70 m and z= 30 m for the time period 2017-09-26 to 2018-12-31. The measurements were taken at 03:00. **a)** Shows the measured wind deviation from the logarithmic wind profile and **b)** the deviation from the power law profile. The red lines shows the linear fit.

Fig. 6 shows the wind speed difference between the measured wind speed at 150 m 05:00 and **a)** the logarithmic wind profile and **b)** the power law wind profile. As in the plots showing the deviations at 03:00 and 04:00, the power law profile seems to overestimate the wind at 150 m. Again the correlation coefficient show no relation between the wind speed at 150 m and the temperature difference in either plot.



(a) Deviation from the logarithmic wind profile



(b) Deviation from the power law profile

Figure 7: Deviation from the logarithmic wind profile at z=150 m and temperature difference between z= 70 m and z= 30 m for the time period 2017-09-26 to 2018-12-31. The measurements were taken at 05:00 during the winter months: December, January and February. **a)** Shows the measured wind deviation from the logarithmic wind profile and **b)** the deviation from the power law profile. The red lines shows the linear fit.

The plots in Fig. 7 shows the wind speed difference between the measured wind speed at 150 m 05:00 during the winter months and **a)** the logarithmic wind profile and **b)** the power law wind profile. The deviations from both theoretical wind profiles are generally smaller when only including data from the winter months. The correlation coefficients are low for both linear fits, and show no correlation between the wind speed and temperature difference.

4.1.1 Root mean square errors and propagation of uncertainty

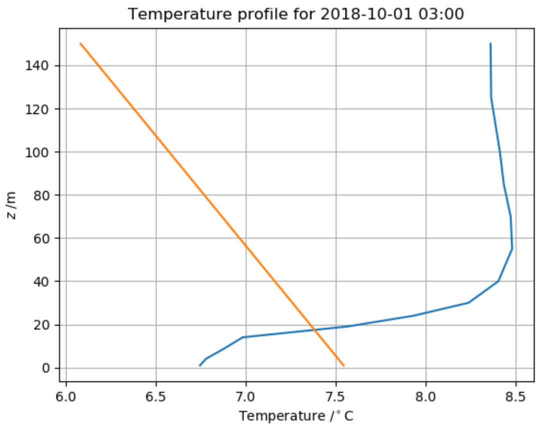
Table 2: This table shows the root mean square errors (RMSE) for the logarithmic and the power law wind profiles' estimation of the wind speed at 150 m for the different times that the measurements where taken.

Time	RMSE log. profile /m/s	RMSE pow. profile /m/s
03:00	1.18	2.45
04:00	1.10	2.36
05:00	1.07	2.05
05:00, DJF	0.88	1.85

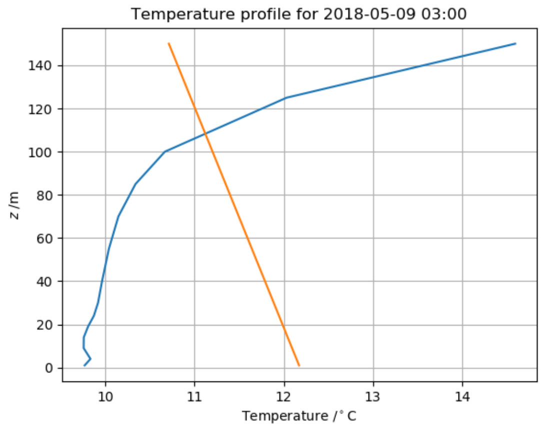
The propagation of uncertainty for the logarithmic wind profile was calculated to be 0.9 m/s. For the power law wind profile the uncertainty was calculated to be 0.3 m/s. Comparing the uncertainty with the mean wind speed at 150 m/s yields a 12% and 4 % uncertainty for the log. and pow. law wind profile respectively.

4.2 Temperature profiles

The following figures show the temperature profiles for the days when the largest wind speed deviations from the theoretical values have been observed.



(a) Temperature profile 2018-10-01 03:00.

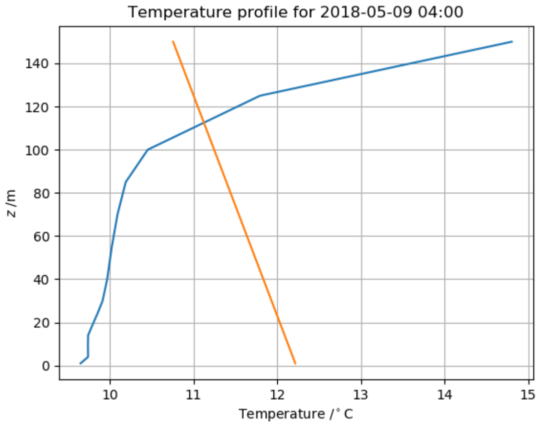


(b) Temperature profile for 2018-05-09 03:00

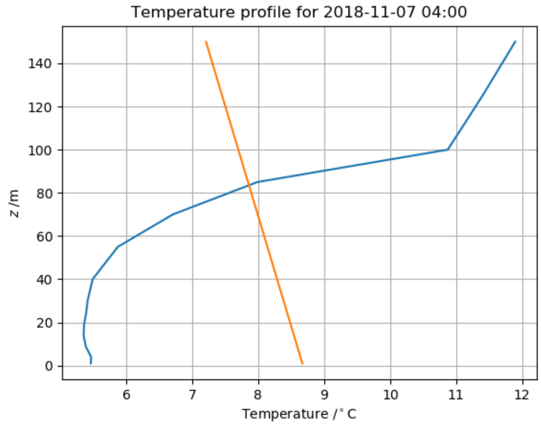
Figure 8: Temperature profiles (blue) for the dates where the largest wind speed deviations at 03:00, in the time period 2017-09-29 to 2018-12-31, from the **a)** logarithmic wind profile and **b)** the power law wind profile, was observed. The dry adiabatic lapse rate is shown in orange.

The largest deviation from both theoretical wind speed values at 03:00 was observed at 2017-12-02. The deviation from the logarithmic wind profile was ΔWS=4.1 m/s and from the power law profile ΔWS=4.0 m/s. However, the actual measured wind speed is higher at 30 m than on 70 m. This makes it not possible to apply neither the logarithmic wind profile nor the power law wind profile. Instead the second largest wind speeds deviations were further investigated.

The second largest deviation from the logarithmic wind profile, ΔWS=3.5 m/s, was observed 2018-10-01, and is shown in Fig. 8**a)**. It shows a temperature inversion up to $\sim$40 m and above a small decrease in temperature with height. Fig. 8**b)** shows the temperature profile for 2018-05-09. The deviation from the power law wind profile was ΔWS=3.1 m/s. There is a weak inversion up to $\sim$100 m and a stronger inversion above.



(a) Temperature profile for 2018-05-09 04:00.



(b) Temperature profile for 2018-11-07 04:00

Figure 9: Temperature profiles (blue) for the dates where the largest wind speed deviations at 04:00, during the time period 2017-09-29 to 2018-12-31, from **a)** the logarithmic wind profile and **b)** the wind power law profile, was observed. The dry adiabatic lapse rate is shown in orange.

Fig. 9 **a)** show the temperature profile for 2018-11-07 at 04:00. At this time, the largest wind speed deviation from the logarithmic wind profile at 04:00 was observed, ΔWS=3.6 m/s. The temperature profile shows a weak inversion up to $\sim$100 m and above that, a stronger inversion.

The largest deviation from the power law wind profile, ΔWS=1.6 m/s, at 04:00 was observed at 2018-05-09. Fig. 9 **b)** shows the temperature profile at that time. It shows a near neutral atmosphere up to $\sim$40 m a strong inversion up to $\sim$100 m and above that, a weaker inversion.

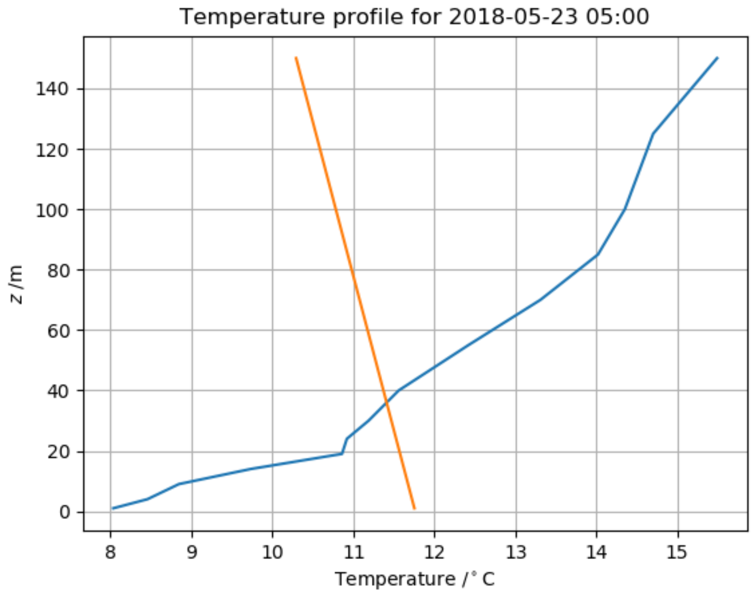
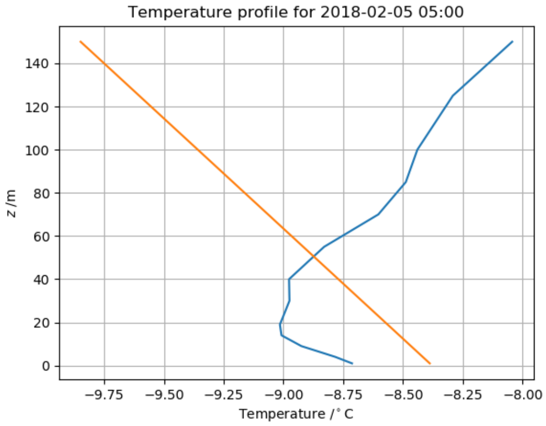
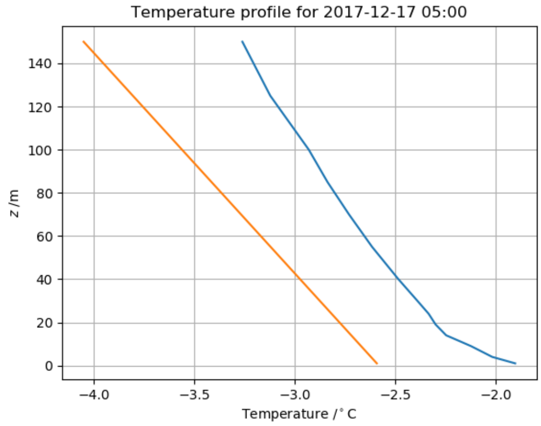


Figure 10: Temperature profile (blue) for 2018-05-23 05:00. The largest deviations from both the logarithmic and the power law wind profile at 05:00 during the time period 2017-09-29 to 2018-12-31 was found at this day. The dry adiabatic lapse rate is shown in orange.

Fig. 10 shows the temperature profile from when the largest deviations from both theoretical wind profiles at 05:00 were found. It shows an inversion that extends to 150 m altitude. The inversion is stronger in the lowest 20 m. The deviation from the logarithmic wind profile was ΔWS= 4.1 m/s, the deviation from the power law wind profile was ΔWS=3.6 m/s.



(a) Temperature profile 2018-02-05 05:00.



(b) Temperature profile for 2017-12-17 05:00

Figure 11: Temperature profiles (blue) for the dates where the largest wind speed deviations, during December- February in the time period 2017-09-29 to 2018-12-31, from the **a)** logarithmic wind profile and **b)** the power law wind profile, was observed. The dry adiabatic lapse rate is shown in orange.

When looking at the data for only the winter months, the largest deviation from the logarithmic wind profile was ΔWS=2.4 m/s at 2018-02-05. The temperature profile shown in Fig. 11 **a)** for that day, shows a decreasing temperature with height up to $\sim$18 m. Above that the temperature increases with height. The scale is small however, the temperature difference between 20 and 150 m is only $\sim$ 1°C. The deviation from the power law wind profile was ΔWS=1.1 m/s at 2017-12-17. The temperature profile shown in Fig. 11 **b)** show a decrease of temperature with height.

5 Discussion

5.1 Data analysis

The large distance between the wind speed measurements give some problems. Since the nocturnal jet have a strong vertical shear and thus a small spatial distribution, the nocturnal jet could theoretically have appeared between the 70 and 150 m measurements and would then not have been detected. Also, if a nocturnal jet appeared above 150 m, it would not have been detected. Thus, this method only detects nocturnal jet in the vicinity of the 150 m altitude.

When making a theoretical wind profile with only two values, the uncertainty in the measurements makes a larger impact. If measurements were taken at more numerous heights, a fit to the measurements could have been done instead of taking the exact values. The uncertainty in the wind measurements are large ($\pm$0.5 m/s) and would affect the theoretical wind profiles significantly. The propagation of uncertainty is large, especially for the logarithmic wind profile (0.9 m/s compared to 0.3 m/s for the pow. law wind profile). Comparing the uncertainty with the mean wind speed at 150 m/s yields a 12% and 4 % uncertainty for the log. and pow. law wind profile respectively.

The linear fit of the wind deviation and the temperature difference between 70 m and 30 m was done to see if there were any correlation between an inversion in this layer and the wind speed. A correlation coefficient was calculated to see if it was justified to do a linear approximation to the scattered data.

The time period investigated is short, it covers about 450 days. The tower has been measuring data from 2014, and data was available from 2015 for the temperature plots. However the data of the wind speeds limited the time period and no reason was found to investigate temperature profile when no wind speed data was available. A longer time period would have given a more reliable result for the root mean square error estimation.

5.2 Wind speed deviation

None of the deviations shown in Table 1 are large enough to indicate a nocturnal jet. This could be either because no nocturnal jet has occurred close to 150 m during this time period or because the theoretical wind profiles does not describe the winds in the PBL correctly.

The linear fits where made to see if there were clear correlation between the wind speed deviation and the temperature difference. The correlation coefficients for all the plots (Fig. 4-7) have a value in the range -0.50–0.10. This is in the range of moderate correlation to uncorrelated (Zhi, Yuexin, Jin, Lujie, & Zijian, 2017). No conclusions can me made of this, other than that an inversion in the 30–70 m layer is no sign of anomalously high wind speed at 150 m.

5.2.1 Root mean square errors

Table 2 shows the root mean square error (RMSE) for the two profiles. It shows that the logarithmic wind profile has smaller deviations from the measured values than the power law profile. The RMSEs are smaller for measurements taken at 05:00 and the RMSE is smaller for both the wind profiles when only the winter months are analysed.

The RMSE is smaller later in night and during the winter months. This cannot be explained. The atmosphere should be more stable during late night and during winter, but as both theoretical profiles assume neutral stability, this is not the explanation.

Both the wind profiles are assuming a flat surface, which is not true: the surface near the tower is not absolutely flat. Also the forest is not taken into account in either theoretical approximations. A better theoretical wind profile would be to apply a no-slip boundary condition to the logarithmic wind profile: at the surface of the ground, $z = 0$, the velocity of the flow must be zero, $WS = 0$ (Lautrup, 2011). Or, an even better approach would be to apply the roughness length, z_0 defined as the height where $\bar{u} = 0$, which would take the surrounding forest into account. However, the calculated values for the wind speed at $z = 0$ and $z = 500$ mm have not been investigated.

5.3 Temperature profiles

The maximum wind speed of a nocturnal jet is usually observed at the top of the nocturnal inversion (Frisch et al., 1992), which must be above 150 m in Fig. 8**b)**, since the temperature does not start to decrease with height below that. When looking at the observed wind speed for this day, the wind speeds are low at 30 and 70 m. At 150 m the wind speed has increased, but it is too low to indicate a nocturnal jet.

In Fig. 8**a)** the top of the inversion is at ∼40 m, which would indicate that, if there was a nocturnal jet at this moment, the strongest wind speed would be at this height. When looking at the measured wind speeds, the highest value is found at 150 m, contradicting that there would be a wind maximum at ∼40 m. The wind speed at 30 m is not large enough to indicate a nocturnal jet. The problem with only having three measurement height is clear here, since the measurements at 30 and 70 m are assumed to follow the theoretical wind profiles.

In Fig. 9**a)**, the lowest ∼100 m has a weak inversion. Above, the temperature starts to increase rapidly. As the top of the inversion is higher up than what the tower can measure, a nocturnal jet should not be (and is not) visible in this data.

A cold layer of air up to ∼60 m and a warmer layer above is shown in Fig. 9 b). The temperature difference is rather large between the two layers, ∼5 °C between 0-40 m and ∼11 °C above 100 m. Again, if a nocturnal jet would have appeared at this day, it would have been higher up than the tower take measurements.

Fig. 10 show a temperature that increases throughout the 150 m layer. A nocturnal jet should not be visible in this data as the top of the inversion is above the measurements. The measured wind speed at 150 m is relatively high (8.3 m/s) compared to the wind speeds at 30 (1.8 m/s) and 70 m (3.1 m/s), which could indicate a nocturnal jet higher up.

The temperature profile in Fig. 11**a)** shows that the forest is warmer than the air right above. Above the forest there is a cold layer up to ∼40 m after which the temperature starts to increase. The temperature difference in the layer is ∼1 °C in the top layer, which is relatively small.

In an atmosphere like the one shown in Fig. 11**b)**, a nocturnal jet could not appear. The temperature profile describes a unstable atmosphere where mixing would take place. This mixing would prevent the development of a nocturnal jet. The measured wind speeds at the different height does not differ as largely as for the other days, which could be interpreted as a sign of mixing.

6 Outlook

No nocturnal jet could be found at 150 m at Hyltemossa research station in the time period 2017-09-26–2018-12-31 with this method.

No correlation between a temperature inversion in the 30–70 m layer and wind speed deviations at 150 m can be made.

The logarithmic wind profile gives a better description of the wind profile in the lower Planetary boundary layer. A more reliable value of root mean square error could be obtained by analysing a longer time period.

A better result could be obtain if data was measured at more numerous heights. This would make the theoretical wind profiles more reliable and wind profiles could have been analysed.

References

Ahrens, C. D. (2009). *Meteorology today: An introduction to weather, climate, and environment.* Belmont, Ca.: Brooks / Cole, Cengage Learning.

Davis, P. A. (2000). Development and mechanisms of the nocturnal jet. *Meteorlogical Applications*, *7*(3), pp. 239-246.

Frisch, A. S., Orr, B. W., & Martner, B. E. (1992). Doppler radar observations of the development of a boundary-layer nocturnal jet. *Monthly Weather Review*, *120*(1), 3-16.

Holton, J. R. (1967). The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, *19*(2), pp. 200-205. doi: 10.3402/tellusa.v19i2.9766

Holton, J. R., & Hakim, G. J. (2013). *An introduction to dynamic meteorology.* Amsterdam: Elsevier.

Hsu, S. A., Meindl, E. A., & Gilhousen, D. B. (1994). Determining the power-law wind-profile exponent under near-neutral stability conditions at sea. *Journal of Applied Meteorology*, *33*(6), 757-765.

ICOS CP. (n.d.). *ICOS Carbon Portal.* https://www.icos-cp.eu/. (Accessed on 2019-05-01)

ICOS RI. (n.d.). *ICOS Research Infrastructure.* https://www.icos-ri.eu/. (Accessed on 2019-05-01)

ICOS Sweden. (n.d.). *ICOS Sweden.* http://www.icos-sweden.se/. (Accessed on 2019-05-01)

Lautrup, B. (2011). *Physics of continuous matter: Exotic and everyday phenomena in the macroscopic world.* Boca Raton, Fla: CRC.

Lund Research Ltd. (n.d.). *Pearson product-moment correlation.* https://statistics.laerd.com/statistical-guides/pearson-correlation-coefficient-statistical-guide.php. (Accessed on 2019-05-01)

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained : Theory, design and application.* New York: John Wiley & Sons.

Preston-Thomas, H. (1990). The international temperature scale of 1990 (its-90). *Metrologia*, *27*(2).

rotronic Measurement Solutions. (n.d.). *Hygroclip2 advanced.* `https://www.swema.se/Prod_docs/Rotronic_prodblad/HC2A_datablad.pdf`. (Accessed: 2019-05-01)

Sabbatini, S., Nicolini, G., Op de Beeck, M., & Papale, D. (2017). Icos ecosystem instructions for air meteorological measurements (ta, rh, pa, ws, wd)(version 20170130). Retrieved from `https://doi.org/10.18160/nheg-4kww`

Singh, M. P., McNider, R. T., & Lin, J. T. (1993). An analytical study of diurnal wind-structure variations in the boundary layer and the low-level nocturnal jet. *Boundary-Layer Meteorology*, *63*(4), 397–423.

Stull, R. B. (2017). *Practical meteorology: An algebra-based survey of atmospheric science.* Vancouver, BC, Canada: University of British Columbia.

The University of Manchester, Centre for Atmospheric Science. (n.d.). *Sonic anemometers.* http://www.cas.manchester.ac.uk/restools/instruments/meteorology/sonic/. (Accessed on 2019-05-01)

Zhi, X., Yuexin, S., Jin, M., Lujie, Z., & Zijian, D. (2017, Oct). Research on the pearson correlation coefficient evaluation method of analog signal in the process of unit peak load regulation. In *2017 13th ieee international conference on electronic measurement instruments (icemi)* (p. 522-527). doi: 10.1109/ICEMI.2017.8265997

A Total derivative

The total derivative, Eq. (A.1), is the co-moving derivative.

$$\frac{\mathrm{D}}{\mathrm{D}t} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} \tag{A.1}$$

where u, v and w is an air parcels velocity in the x, y and z direction respectively.

The averaged total derivative:

$$\frac{\bar{\mathrm{D}}}{\mathrm{D}t} \equiv \frac{\partial}{\partial t} + \bar{u}\frac{\partial}{\partial x} + \bar{v}\frac{\partial}{\partial y} + \bar{w}\frac{\partial}{\partial z} \tag{A.2}$$

B Code

B.1 Measurement errors

```
from scipy import *
from pylab import *
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import datetime
```

To open the data files:

```
m3="m3.MTO"
file3m=open

m30="m30.MTO
file30m=open(m30,"r")

m70="m70.MTO"
file70m=open(m70,"r")

m150="m150.MTO"
file150m=open(m150,"r")

r30="r30.MTO"
file30r=open(r30,"r")

r70="r70.MTO"
file70r=open(r70,"r")
```

```
r150="r150.MTO"
file150r=open(r150, "r")
```

The data in the file:
```
'''Site;SamplingHeight;Year;Month;Day;Hour;Minute;DecimalDate;AP;Stdev;
NbPoints;Flag;QualityId;RH;Stdev;NbPoints;Flag;QualityId;AT;Stdev;NbPoints;
Flag;QualityId;WD;Stdev;NbPoints;Flag;QualityId;WS;Stdev;NbPoints;Flag;
QualityId;InstrumentId\n
What 'Flag' means:
- Flag 'N' = data incorrect before manual quality control\n",
- Flag 'O' = data correct after manual quality control\n",
- Flag 'K' = data incorrect after manual quality control\n"'''
```

To separate:
```
m3_list=[ ]
m30_list=[ ]
m70_list=[ ]
m150_list=[ ]
r30_list=[ ]
r70_list=[ ]
r150_list=[ ]

for line in file30r:
    r30_list.append(line.split(sep=';'))
for line in file70r:
    r70_list.append(line.split(sep=';'))
for line in file150r:
    r150_list.append(line.split(sep=';'))
for line in file70m:
    m70_list.append(line.split(sep=';'))
for line in file30m:
    m30_list.append(line.split(sep=';'))
for line in file150m:
    m150_list.append(line.split(sep=';'))
```

To take away data in r30 and r150 that weren't in r70:
```
del r30_list[2747]
del r30_list[2746]
```

```
del r30_list[2745]
del r30_list[2744]
del r30_list[2743]
del r30_list[2742]

del r150_list[2747]
del r150_list[2746]
del r150_list[2745]
del r150_list[2744]
del r150_list[2743]
del r150_list[2742]
```

To take away the information in the beginning of each file:

```
m3_cut=m3_list[39:]
m30_cut=m30_list[39:]
m70_cut=m70_list[39:]
m150_cut=m150_list[39:]

r30_cut=r30_list[35:]
r70_cut=r70_list[35:]
r150_cut=r150_list[35:]
```

Air temperature (Degrees Celcius)

```
T30_list=[]
T70_list=[]
T150_list=[]
```

```
for i in range(len(r30_cut)):
    if i==0:
        T30_list.append(r30_cut[i][18])
        T70_list.append(r70_cut[i][18])
        T150_list.append(r150_cut[i][18])
    else:
        T30_list.append(float(r30_cut[i][18]))
        T70_list.append(float(r70_cut[i][18]))
        T150_list.append(float(r150_cut[i][18]))
for i in range(len(m30_cut)):
    T30_list.append(float(m30_cut[i][8]))
    T70_list.append(float(m70_cut[i][8]))
    T150_list.append(float(m150_cut[i][8]))
```

Wind speed (m/s)

```
WS30_list=[]
WS70_list=[]
WS150_list=[]

for i in range(len(r30_cut)):
    if i==0:
        WS30_list.append(r30_cut[i][28])
        WS70_list.append(r70_cut[i][28])
        WS150_list.append(r150_cut[i][28])
    else:
        WS30_list.append(float(r30_cut[i][28]))
        WS70_list.append(float(r70_cut[i][28]))
        WS150_list.append(float(r150_cut[i][28]))
for i in range(len(m30_cut)):
    WS30_list.append(float(m30_cut[i][22]))
    WS70_list.append(float(m70_cut[i][22]))
    WS150_list.append(float(m150_cut[i][22]))
```

Date decimal form, year, date, month and hour lists
Date_list: decimal form
Time_list: YYYYMMDD-HHMM
Year_list:YYYY
Month_list: MM
Hour_list:HH

```
Date_list=[]
Time_list=[]
Hour_list=[]
Month_list=[]
Year_list=[]

for i in range(len(r30_cut)):
    if i==0:
        Date_list.append(r30_cut[i][7])
        Time_list.append(r30_cut[i][2]+r30_cut[i][3]+r30_cut[i][4]+'-'+r30_cut[i][5]+r30_cut[i][6])
        Hour_list.append(r30_cut[i][5])
        Month_list.append(r30_cut[i][3])
        Year_list.append(r30_cut[i][2])
    else:
        Date_list.append(float(r30_cut[i][7]))
        Time_list.append(r30_cut[i][2]+r30_cut[i][3]+r30_cut[i][4]+'-'+r30_cut[i][5]+r30_cut[i][6])
        Hour_list.append(float(r30_cut[i][5]))
        Month_list.append(float(r30_cut[i][3]))
        Year_list.append(float(r30_cut[i][2]))

for i in range(len(m30_cut)):
    Date_list.append(float(m30_cut[i][7]))
    Time_list.append(m30_cut[i][2]+m30_cut[i][3]+m30_cut[i][4]+'-'+m30_cut[i][5]+m30_cut[i][6])
    Hour_list.append(float(m30_cut[i][5]))
    Month_list.append(float(m30_cut[i][3]))
    Year_list.append(float(m30_cut[i][2]))
```

Take away error values

```
wrong_list=[]
wrong_list2=[]
```

To find the errors:

```
for i in range(len(T30_list)):
    if T30_list[i]==-999.99:
        wrong_list.append(i)

for i in range(len(T70_list)):
    if T70_list[i]==-999.99:
        wrong_list2.append(i)
```

wrong_list==wrong_list2 was True, so only wrong_list is used

To take them away:

```
T30_cut=[]
RH30_cut=[]
WS30_cut=[]

T70_cut=[]
RH70_cut=[]
WS70_cut=[]

T150_cut=[]
RH150_cut=[]
WS150_cut=[]

Date_cut=[]
Time_cut=[]
Hour_cut=[]
Month_cut=[]
Year_cut=[]


for i in range(len(T30_list)):
    if i==0:
        pass
    else:
        if i in wrong_list:
            pass
        else:
            T30_cut.append(T30_list[i])
            T70_cut.append(T70_list[i])
            T150_cut.append(T150_list[i])
            RH30_cut.append(RH30_list[i])
            RH70_cut.append(RH70_list[i])
            RH150_cut.append(RH150_list[i])
            WS30_cut.append(WS30_list[i])
            WS70_cut.append(WS70_list[i])
            WS150_cut.append(WS150_list[i])
            Date_cut.append(Date_list[i])
            Time_cut.append(Time_list[i])
            Hour_cut.append(Hour_list[i])
            Month_cut.append(Month_list[i])
            Year_cut.append(Year_list[i])
```

To create a data frame, first zipping them together, then creating data frame and giving the columns names. Also saving the data fram as Hyltemossa_cut.csv:

```
List_cut=list(zip(Time_cut, Year_cut, Month_cut, Hour_cut, T30_cut, RH30_cut,
        WS30_cut, T70_cut, RH70_cut, WS70_cut,T150_cut, RH150_cut, WS150_cut))

df_cut1=pd.DataFrame(data=List_cut, columns=['Date', 'Year', 'Month', 'Hour','T30',
        'RH30','WS30','T70','RH70','WS70','T150','RH150','WS150'])

df_cut1.to_csv('Hyltemossa_cut.csv',index=False,header=False)
```

To take away the measurement errors in the wind speed measurements: only saving the measurement values that are larger than zero (taking away all '-999.99' values, also the magnitude of the wind must be larger than zero anyway) df_cut2=df_cut1[df_cut1['WS30']>0]

```
df_cut3=df_cut2[df_cut2['WS70']>0]

df_cut4=df_cut3[df_cut3['WS150']>0]
```

To only get the data 20170926-20181231:

```
df_2017=df_cut4[df_cut4['Year']==2017]
df_2018=df_cut4[df_cut4['Year']==2018]
yearframes=(df_2017,df_2018)

df_cut=pd.concat(yearframes)
```

B.2 Calculation of theoretical wind speeds

wind profile power law: u=u_r (z/z_r)ˆ a"'

defining a function that calculates 'a' with input u1, u2 and returning the calculated wind speed at 150 m. z_1, z_2 same for all measurements, so those values were put into the equation directly.

```
def plu(u1,u2):
    a=np.log(u2/u1)/np.log(70/30)
    return u1*(150/30)**a
```

logarithmic wind profile: u=a*np.log(b*z/z_1)

Defining a function that calculates 'a' and 'b' with input u1, u2 and returning the calculated wind speed at 150 m. z_1, z_2 same for all measurements, so those values were put into the equation directly.

```
def llu(u1,u2):
    b=(7/3)**(u1/(u2-u1))
    a=u1/np.log(b)
    return a*np.log((b*150)/30)
```

Adding new columns to the data frame with the calculated wind speeds:

```
df_cut['plu']=plu(df_cut['WS30'], df_cut['WS70'])
df_cut['llu']=llu(df_cut['WS30'], df_cut['WS70'])
```

Defining a function that calculate and return the difference between two values.

```
def dif(ru,thu):
    return ru-thu
```

Adding the differences of theoretical values and measured values to dataframe:

```
df_cut['diffplu']=dif(df_cut['WS150'], df_cut['plu'])
df_cut['diffllu']=dif(df_cut['WS150'], df_cut['llu'])
df_cut['diftemp']=dif(df_cut['T70'], df_cut['T30'])
```

to get only the measurements for the following hours, by creating new data frames

```
df_03=df_cut[df_cut['Hour']==3.0]
df_04=df_cut[df_cut['Hour']==4.0]
df_05=df_cut[df_cut['Hour']==5.0]
```

to only look at the winter months (dec, jan, feb) at 05:00, by creating new data frames for each month and then join them together

```
df_05_J=df_05[df_05['Month']==1.0]
df_05_F=df_05[df_05['Month']==2.0]
df_05_D=df_05[df_05['Month']==12]
frames05=[df_05_D,df_05_J,df_05_F]
df_DJF_05=pd.concat(frames05)
```

B.2.1 Plotting wind deviation

To get the constant for the linear fit (1 indicates that it's a first order polynomial) and to get the correlation coefficient r:

np.polyfit(x, y, 1) reurns k, m
y=k*x+m

np.corrcoef(x,y)

power law plots, measurements from all days

plt.figure(1)
plt.plot(df_03['diftemp'],df_03['diffplu'], 'o', label=('Measurments'))
plt.plot(df_03['diftemp'],-0.96169385*df_03['diftemp']-1.32704846,'r–',label=('y= -0.962x-1.33, r=-0.49'))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1})')
plt.title('Measurements at 03:00, 20170926-20181231')
plt.grid()
plt.legend()
plt.plot()
plt.show()

plt.figure(2)
plt.plot(df_04['diftemp'],df_04['diffplu'], 'o', label=('Measurments'))
plt.plot(df_04['diftemp'],-1.04848595*df_04['diftemp']-1.34818763,'r–',label=('y= -1.05x-1.35, r=-0.50'))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1}')
plt.title('Measurements at 04:00, 20170926-20181231')
plt.grid()
plt.legend()
plt.plot()
plt.show()

plt.figure(3)
plt.plot(df_05['diftemp'],df_05['diffplu'], 'o', label=('Measurments'))
plt.plot(df_05['diftemp'],-1.10087877*df_05['diftemp']-1.27301975,'r–',label=('y= -1.10x-1.27, r=-0.50'))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1}')
plt.title('Measurements at 05:00, 20170926-20181231')

plt.grid()
plt.legend()
plt.plot()
plt.show()

log law plots, measurements from all days

plt.figure(4)
plt.plot(df_03['diftemp'],df_03['diffllu'], 'o', label=('Measurments'))
plt.plot(df_03['diftemp'],-0.47971255*df_03['diftemp']+0.37888712,'r–',label=('y= -0.480x+0.379, r=-0.37'))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1}')
plt.title('Measurements at 03:00, 20170926-20181231')
plt.grid()
plt.legend()
plt.plot()
plt.show()

plt.figure(5)
plt.plot(df_04['diftemp'],df_04['diffllu'], 'o', label=('Measurments'))
plt.plot(df_04['diftemp'],-0.46934194*df_04['diftemp']+0.34551945,'r–',label=('y= -0.469x+0.346, r=-0.36'))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1}')
plt.title('Measurements at 04:00, 20170926-20181231')
plt.grid()
plt.legend()
plt.plot()
plt.show()

plt.figure(6)
plt.plot(df_05['diftemp'],df_05['diffllu'], 'o', label=('Measurments'))
plt.plot(df_05['diftemp'],-0.42106747*df_05['diftemp']+0.29741789,'r–',label=('y= -0.421x+0.297, r=-0.29'))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1}')
plt.title('Measurements at 05:00, 20170926-20181231')
plt.grid()
plt.legend()
plt.plot()
plt.show()

log law plot, measurements from the winter days

plt.figure(7)
plt.plot(df_DJF_05['diftemp'],df_DJF_05['diffllu'], 'o', label=('Measurments'))
plt.plot(df_DJF_05['diftemp'],-0.19277219*df_DJF_05['diftemp']+0.11539916,'r–',label=('y= -0.193x+0.115, r=-0.10')))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1}')
plt.title('Measurements at 05:00, in DJF, 20170926-20181231')
plt.grid()
plt.legend()
plt.plot()
plt.show()

power law plot, measuements from the winter days

plt.figure(8)
plt.plot(df_DJF_05['diftemp'],df_DJF_05['diffplu'], 'o', label=('Measurments'))
plt.plot(df_DJF_05['diftemp'],-0.8395826*df_DJF_05['diftemp']-1.4376983,'r–',label=('y= -0.839x-1.44, r=-0.30'))
plt.xlabel(r'$\Delta T = T_{70} - T_{30}$ /°C')
plt.ylabel(r'ΔWS=WS$_{meas}$-WS$_{theo}$ /m s^{-1}')
plt.title('Measurements at 05:00, in DJF, 20170926-20181231')
plt.grid()
plt.legend()
plt.plot()
plt.show()

B.2.2 Error estimations and propagation of uncertainty

mean squared error: first squaring the differences from the measured values, then taking the mean of the square:

```
df_03['MSEllu']=df_03['diffllu']**2
df_03['MSEplu']=df_03['diffplu']**2

df_04['MSEllu']=df_04['diffllu']**2
df_04['MSEplu']=df_04['diffplu']**2

df_05['MSEllu']=df_05['diffllu']**2
df_05['MSEplu']=df_05['diffplu']**2

df_DJF_05['MSEllu']=df_DJF_05['diffllu']**2
df_DJF_05['MSEplu']=df_DJF_05['diffplu']**2


MSEl_03=df_03['MSEllu'].mean()
MSEp_03=df_03['MSEplu'].mean()

MSEl_04=df_04['MSEllu'].mean()
MSEp_04=df_04['MSEplu'].mean()

MSEl_05=df_05['MSEllu'].mean()
MSEp_05=df_05['MSEplu'].mean()

MSEl_DJF=df_DJF_05['MSEllu'].mean()
MSEp_DJF=df_DJF_05['MSEplu'].mean()
```

root mean square: taking the root of the MSE"'

```
RMSEl_03=np.sqrt(MSEl_03)
RMSEp_03=np.sqrt(MSEp_03)

RMSEl_04=np.sqrt(MSEl_04)
RMSEp_04=np.sqrt(MSEp_04)

RMSEl_05=np.sqrt(MSEl_05)
RMSEp_05=np.sqrt(MSEp_05)

RMSEl_DJF=np.sqrt(MSEl_DJF)
RMSEp_DJF=np.sqrt(MSEp_DJF)
```

Propagation of uncertainty
uncertainty of wind speed=0.5m/s

```
def proplog(u1,u2):
    return np.sqrt((np.log(np.exp(u1/u2)*3)*0.5)**2+((u1**2/u2**2)*0.5)**2)
```

df_cut['proplog']=proplog(df_cut['WS30'], df_cut['WS70'])

mean value of 'proplog': 0.8695328090402341

```
def proppow(u1,u2):
    return np.sqrt(((((np.log(5)-np.log(7/3))/np.log(7/3))*5**(np.log(u1/u2)/np.log(7/3)))*0.5)**2
            +((((u1*np.log(5))/(u2*np.log(7/3)))*5**(np.log(u1/u2)/np.log(7/3)))*0.5)**2)
```

df_cut['proppow']=proppow(df_cut['WS30'], df_cut['WS70'])

mean value of 'proppow': 0.29694578879187705

B.3 Temperature profiles

Create data frames, cutting away the headers and the data from 2017 that weren't in the other data set.

```
data17=pd.read_csv("SE-Htm_T-profile_2017_CP_flag.txt", header=None)
data18=pd.read_csv("SE-Htm_T-profile_2018_CP_flag.txt", header=None)

d17_cut=data17.iloc[12865:,]
d18_cut=data18.iloc[2:,]
frames=(d17_cut,d18_cut)
datatot = pd.concat(frames)
```

To name the columns. 'Ta1' stands for Temperature air at 1 m, 'Ta4' for the temperature at 4 m and so on. 'qc' stands for quality check.

```
datatot.columns=['Date', 'Time', 'Ta1','Ta4', 'Ta9', 'Ta14', 'Ta19', 'Ta24', 'Ta30', 'Ta40',
                 'Ta55', 'Ta70', 'Ta85', 'Ta100', 'Ta125', 'Ta148','qc14','qc13', 'qc12',
                 'qc11', 'qc10', 'qc9', 'qc8', 'qc7','qc6', 'qc5', 'qc4', 'qc3', 'qc2', 'qc1']
```

To only get the temperature measurements:

```
datatot=datatot.drop(['qc14','qc13', 'qc12', 'qc11', 'qc10', 'qc9', 'qc8', 'qc7','qc6', 'qc5',
                      'qc4', 'qc3', 'qc2', 'qc1'], axis=1)
```

Creating data frames with only specific times:

```
Ta_03=datatot[datatot['Time']=='03:00:00']
Ta_04=datatot[datatot['Time']=='04:00:00']
Ta_05=datatot[datatot['Time']=='05:00:00']
```

To be able to plot for a specific day, the transpose of the data frame was needed. First the date and time columns were removed, then the temp. data was transposed. Then a data frame was created from the transposed date column and was set as the column name for the new temperature matrices.

```
Ta_03cut=Ta_03.drop(['Date', 'Time'], axis=1)
Ta_04cut=Ta_04.drop(['Date', 'Time'], axis=1)
Ta_05cut=Ta_05.drop(['Date', 'Time'], axis=1)

df_date=Ta_03['Date']
df_date=df_date.T

Ta_03cut=Ta_03cut.T
Ta_03cut.columns=df_date

Ta_04cut=Ta_04cut.T
Ta_04cut.columns=df_date

Ta_05cut=Ta_05cut.T
Ta_05cut.columns=df_date
```

To get the max wind deviation in the different dataframes dataframe.max() where used, then dataframe.loc where used to get the dates for when that value was measured.

```
03:00:
df_03.loc[df_03['diffplu']==df_03['diffplu'].max()]
df_03.loc[df_03['difflu']==df_03['difflu'].max()]
```

max dev in diffplu, date: 20171202
max dev in difflu, date: 20171202

However, the wind speed at 70 m was lower than the wind speed at 30 m. To be able to apply the theoretical wind profiles, this date was removed from the data frame and the second highest deviation was found.

```
df_03_new=[df_03[df_03['diffplu']<4.0165525823924133]]
```

second max dev in diffplu, date: 20181001
second max dev in difflu, date: 20180509

04:00
df_04.loc[df_04['diffplu']==df_04['diffplu'].max()]
df_04.loc[df_04['difflu']==df_04['difflu'].max()]

max dev in diffplu, date: 20181107
max dev in difflu, date: 20180509

05:00
df_05.loc[df_05['diffplu']==df_05['diffplu'].max()]
df_05.loc[df_05['difflu']==df_05['difflu'].max()]

max dev in diffplu, date: 20180523
max dev in difflu, date: 20180523

DJF 05:00
df_DJF_05.loc[df_DJF_05['diffplu']==df_DJF_05['diffplu'].max()]
df_DJF_05.loc[df_DJF_05['difflu']==df_DJF_05['difflu'].max()]

max dev in diffplu, date: 20171217
max dev in difflu, date: 20180205

Creating a function that calculates the dry adiabatic lapse rate:

```
def DALR(z,m):
        y=-(9.8/1000)*z+m
        return y
```

Creating a list of the heights and then plotting the days with the max dev from the theoretical wind profiles. It was for some reason not possible to plot the column in the dataframe so lists with the temerature measurements were made and plotted instead.

z_list=[1,4,9,14,19,24,30,40,55,70,85,100,125,150]

```
T03_llu=[9.768333, 9.833333, 9.756667, 9.758333, 9.806667, 9.871667, 9.918333, 9.963333,
        10.040000, 10.146667, 10.338333, 10.668333, 12.033333, 14.596667]
T03_plu=[6.746500, 6.778833, 6.884500, 6.983667, 7.564500, 7.932333, 8.238333, 8.403333,
        8.480000, 8.471667, 8.433333, 8.411667, 8.363333, 8.360000]
T04_list=[5.464333,5.468500, 5.386167, 5.355500, 5.361667, 5.392667, 5.415500, 5.492167,
        5.874000, 6.707667, 7.988333, 10.873333, 11.400000, 11.895000]
```

```
T04_list2=[9.651667, 9.741667, 9.740000, 9.741667, 9.796667, 9.853333, 9.915000, 9.970000,
           10.025000, 10.093333, 10.191667,10.455000,11.796667,14.805000]
T05_list=[8.036833,8.458333,8.846667,9.733333,10.860000,10.920000,11.188333,11.560000,12.420000,
          13.310000,14.020000, 14.351667, 14.701667,15.490000]
TDJF_list=[-1.902500,-2.016833,-2.122500,-2.246167,-2.298667,-2.333667,-2.389667,-2.484167,
           -2.615333,-2.730167,-2.837167,-2.930500,-3.122333,-3.261167]
TDJF_list2=[-8.713333,-8.783333,-8.925000,-9.008333,-9.015000,-8.996667,-8.975000,-8.976667,
            -8.830000,-8.603333,-8.488333,-8.440000,-8.291667,-8.043500]
```

Calculating the 'm' value, to get the dry adiabatic lapse rate in the middle of the plot

```
m_03=(T03_llu[0]+T03_llu[-1])/2
DALR03=[]
for z in z_list:
    DALR03.append(DALR(z,m_03))
```

```
m2_03=(T03_plu[0]+T03_plu[-1])/2
DALR032=[]
for z in z_list:
    DALR032.append(DALR(z,m2_03))
m_04=(T04_list[0]+T04_list[-1])/2
DALR04=[]
for z in z_list:
    DALR04.append(DALR(z,m_04))
m2_04=(T04_list2[0]+T04_list2[-1])/2
DALR042=[]
for z in z_list:
    DALR042.append(DALR(z,m2_04))
m_05=(T05_list[0]+T05_list[-1])/2
DALR05=[]
for z in z_list:
    DALR05.append(DALR(z,m_05))
m_DJF=(TDJF_list[0]+TDJF_list[-1])/2
DALRDJF=[]
for z in z_list:
    DALRDJF.append(DALR(z,m_DJF))
m2_DJF=(TDJF_list2[0]+TDJF_list2[-1])/2
DALRDJF2=[]
for z in z_list:
    DALRDJF2.append(DALR(z,m2_DJF))
```

Plotting:

```
plt.figure(9)
plt.plot(T03_list, z_list)
plt.plot(DALR03, z_list)
plt.grid()
plt.xlabel('Temperature /°C')
plt.ylabel('z /m')
plt.title('Temperature profile for 2017-12-02 03:00')
plt.show()
```

```
plt.figure(10)
plt.plot(T03_plu, z_list)
plt.plot(DALR032, z_list)
plt.grid()
plt.xlabel('Temperature /°C')
plt.ylabel('z /m')
plt.title('Temperature profile for 2018-10-01 03:00')
plt.show()

plt.figure(11)
plt.plot(T04_list, z_list)
plt.plot(DALR04,z_list)
plt.grid()
plt.xlabel('Temperature /°C')
plt.ylabel('z /m')
plt.title('Temperature profile for 2018-11-07 04:00')
plt.show()

plt.figure(12)
plt.plot(T04_list2, z_list)
plt.plot(T04_list2, z_list)
plt.grid()
plt.xlabel('Temperature /°C')
plt.ylabel('z /m')
plt.title('Temperature profile for 2018-11-07 04:00')
plt.show()

plt.figure(13)
plt.plot(T05_list, z_list)
plt.plot(DALR05, z_list) plt.grid()
plt.xlabel('Temperature /°C')
plt.ylabel('z /m')
plt.title('Temperature profile for 2018-11-07 05:00')
plt.show()
```

```
plt.figure(14)
plt.plot(TDJF_list, z_list)
plt.plot(DALRDJF,z_list)
plt.grid()
plt.xlabel('Temperature /°C')
plt.ylabel('z /m')
plt.title('Temperature profile for 2017-12-17 05:00')
plt.show()

plt.figure(15)
plt.plot(TDJF_list2, z_list)
plt.plot(DALRDJF2, z_list)
plt.grid()
plt.xlabel('Temperature /°C')
plt.ylabel('z /m')
plt.title('Temperature profile for 2018-02-05 05:00')
plt.show()
```