Delft University of Technology

Additional Thesis

A realistic simulation of Leipzig Wind Profile

Yi Dai
4817362

September 15, 2019

abstract

Over the years, the Leipzig Wind Profile observed under near neutral condition has been considered as an essential benchmark for idealized friction layer models. However, the general weather condition for the Leipzig Wind Profile still remains a mystery after nearly 90 years. In order to simulate this event and try to recreate the weather conditions at that time, the WRF model driven by two types of reanalysis data setting up with two domains is launched. The model captures the wind physics well, except for a small deviation around 800 meters. Additionally, the simulated surface friction velocity and surface heat flux at Leipzig are close to the validation value. The simulated temperature slope at Lindenberg has some deviation compared to the documented value, which may be caused by the vertical coarse resolution and sensitive temperature fluctuations over the height. Moreover, there may have been rain or drizzle when the observation took place and this may have contributed to the near neutral condition feature. A finer resolution simulation could be run to investigate this further.

1 Introduction

On October 20th 1931, Mildner took wind observations using 28 pilot balloons with 2 theodolites from 09 UTC to 16 UTC near the airport of Leipzig in Germany. The only existing weather measurement at the time is a temperature slope at Lindenberg, which is about 100 miles from Leipzig, showing 0.65K per 100 meters lapse rate(200m-600m) at 14 UTC. Mildner also documented that there was no indication of convection processes occurring but only an uniform air mass during the seven hour observation[9].

Over the years, many researchers investigated the friction layer under steady neutral condition by simulating Leipzig Wind Profile. In order to capture this wind profile, the idealized solution is to solve the equations of motion based on Newton's second law for atmospheric flow. The most problematic terms in these equations such as turbulence stress and flux are parameterized by manipulation of the exchange coefficient based on different assumptions, using various terms to interpret the physics behind it. The analytical solutions based on the parallelism of turbulence stress and wind shear is given by Lettau(1950)[8] and the Leipzig dataset including the calculated exchange coefficient from Mildner(1932)[9] are re-examined based on this formula. With the wind profile data table provided by Lettau(1950)[8], a spectrum of models for the exchange coefficient are popping up over the years which are summarized in table [1].

Table 1: List of parameterization models

Author	Model
Lettau(1950)	$\overline{u_i u_j} \parallel \nabla u$
Alfred(1962)	$K_m = \epsilon^{1/3} l^{4/3}$
Yamamoto(1968)	$K_m = kzu_* \frac{1}{\varphi}$
Swinbank(1970)	$\overline{u_i u_j} \parallel u$
DJ. Carson (1973)	Lettau & Swinbank
Lupini(1975)	WKB approximation
Detering(1985)	$K_m = c_k \frac{E^2}{\varepsilon}$
Duynkerke(1988)	$K_m = c_\mu E^2/\epsilon$
RIOPELLE (1989)	$\boldsymbol{K}_z^m = \boldsymbol{C}_\mu \frac{\boldsymbol{k}^2}{\varepsilon^k}$
Apsley(1997)	two $v_t \sim u_0 l_m$ & two $k-\varepsilon$

The misinterpretation between Lettau(1950) and Swinbank(1970)[14] has raised the attention on the importance of making right assumptions. Lettau assumed the parallelism between turbulence stress and wind shear based on a flux gradient relationship. However, the semi-parallelism from Swinbank between turbulence stress and wind vector was derived from the similar distribution feature of these plots. Although later Carson(1973)[2] proved the correction of Lettau's parallelism and argued the contradictory assumption of Swinbank which rejected the assumption from Lettau and derived the feature from Lettau's re-exammed data.

The evidence of slightly stable condition for the Leipzig Wind Profile grew since Duynkerke(1988) tested it by applying an $E-\epsilon$ model. He also argued the difficulty of capturing neutral condition data because small stability effects could influence the neutral condition drastically[4]. This model followed by Riopelle(1989)[12] model. The Obukhov length and Richardson number are included in the equations of motion and turbulence closure equations in order to account for the stability effect. The results from the mathematical model, including the wind profile and exchange coefficient, came very close to the observational data with a surface heat flux of -0.017Km^{-1}, which supports the slightly stable condition argument.

One of important terms intensively used to interpret the exchange coefficient is mixing length scale. A comparison of mixing length models could be found in Pena(2010)[11]. Logarithmic, Blackadar with limited value, Lettau and Gryning mixing length model are compared. But None of the models are able to capture internal boundary layer turbulent mixing length features[3].

The Leipzig Wind Profile observed by Mildner has been taken as the reference dataset under the idealized neutral, horizontal homogeneous and uniform condition since it published. Although it is argued that it may have been taken under slight stable, close to neutral condition, the Leipzig Wind Profile dataset is still considered as one of the most important benchmarks in atmospheric modelling because of its unparalleled features. One of the difficulties in atmospheric modelling is the verification process. Weather models require abundant reliable datasets as input so that the model captures the physics behind the data. The Leipzig Wind Profile taken under nearly neutral condition could be used for verification of standard models.

However, the general weather conditions of this Leipzig event is unknown and the atmospheric condition argument need more validations. The aforementioned idealized models trying to capture the physics of Leipzig Wind Profile by only using motion equations or by accounting the effect of stability. This may only capture part of the physics with part of data fitting. Furthermore, the internal boundary turbulence feature has not been captured by any these models. To deduce the weather conditions of Leipzig Wind Profile and perfect the idealized mathematical model, this study uses WRF, a state of the art weather forecast model, to run realistic simulation of Leipzig Wind Profile. The model configuration is described in section 2. The simulation results are interpreted in section 3. This is followed by the conclusion and future prospects in section 4.

2 WRF setup and Datasets

The present study uses Weather Research and Forecast(WRF) model to simulate the historical event Leipzig Wind Profile in 1931. The WRF model is an atmospheric numerical weather system used for weather forecasts and scientific research. This system is equipped with advanced dynamic solvers for model physics[13]. The model physics include microphysics, cumulus parameterization, surface physics, planetary boundary layer physics and atmospheric radiation physics. The microphysics which resolve the processes of water vapor, cloud and precipitation used in this study is the WSM5 class scheme, which has better representation of the ice cloud radiation feedback[6]. The radiation process is computed by the RRTMG scheme and the surface layer option is chosen with revised MM5 Monin Obukhov similarity scheme. In order to resolve the effect of entrainment during near neutral condition, the YSU scheme is used to drive the planetary boundary layer physics[7]. In addition, the unified Noah land surface model in land surface scheme provides 4 layer soil temperature for planetary boundary layer scheme as lower boundary condition.

The model is setup with two domains over Europe with Leipzig station at the center[Fig.1]. Domain 1 and 2 has a horizontal resolution of 30km and 10km respectively. The total simulation time is 24 hours starting from 0UTC at 20th October 1931 and it has an hourly output. The model is driven by the two types reanalysis data: NOAA Twentieth Century Global Reanalysis Version 2c (20CR)[10] and ECMWF Atmospheric Reanalysis of the 20th Century (ERA-20C)[5]. These climate reanaysis data are the archived datasets which absorb various sources of observation data with assimilation model. The reconstructed data then could be used in both global and local climate model. In our model, the data was interpolated into 51 vertical levels up to the free atmosphere.

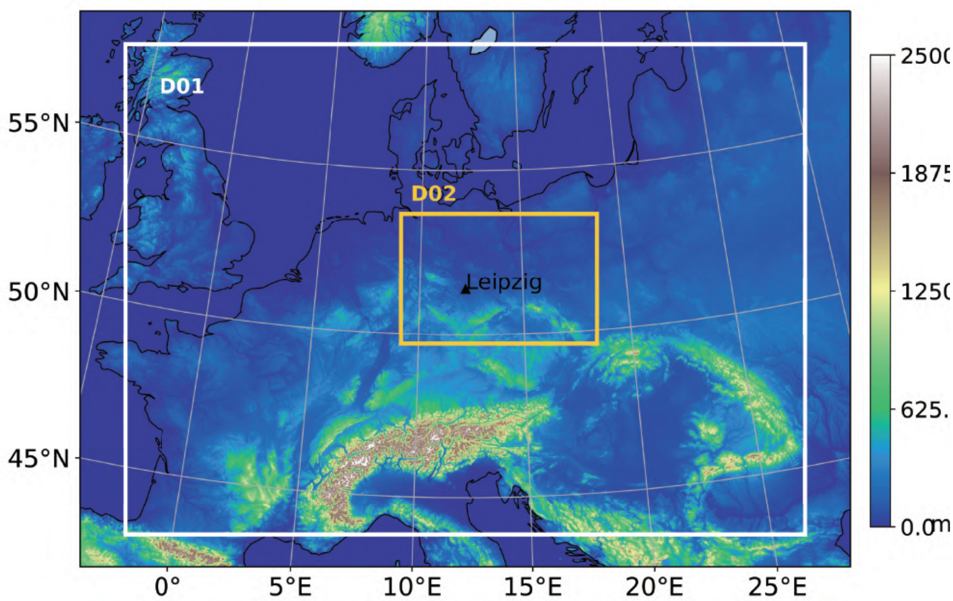

Figure 1: The domain setup over Europe with Leipzig as center

3 Results

The results of this simulation are presented by analysis of various representative variables such as wind profile and temperature profile for both two reanalysis data. In this section, the wind profile at Leipzig is compared with measurement data from Lettau(1950). Then there are some validation in terms of surface heat flux and surface friction velocity. This is followed by the reflectivity, pressure and temperature 2-D plot in the WRF inner domain. Finally, it concludes with validation of the Lindenberg data.

3.1 Wind profile

Figure 2 shows the comparison of simulated hourly averaged wind profile and measurement data from Lettua(1950) at Leipzig. The left part of this plot shows the V component of velocity and right part the U component. The simulation results agree well with the observed wind profile except there is a small deviation around 800meters. It also could be seen from the hodograph for two simulation and observation data in Fig[3]. The simulation driven by the 20RC dataset gives better results than the ERA-20C in terms of simulating this wind profile. The 20RC dataset is nearly the same as the observed data below 450 meters. Above that height, the deviation may be caused by the historical urban flow around 700 meters which is shown by the maximum mixing length plot from Detering(1985)[3]. The reason to average the data is that the data is taken during that day without specified time. To unsample and compare with the measurement data, we choose an averaging time between 14 UTC to 16 UTC.

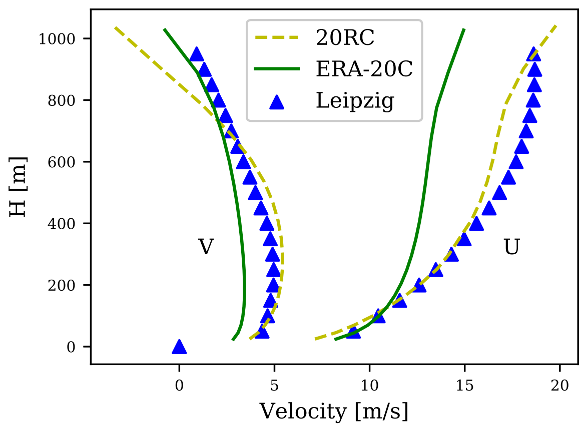

Figure 2: The vertical wind profile of U, V component for two datasets WRF simulation and Leipzig observation from 14 UTC to 16 UTC

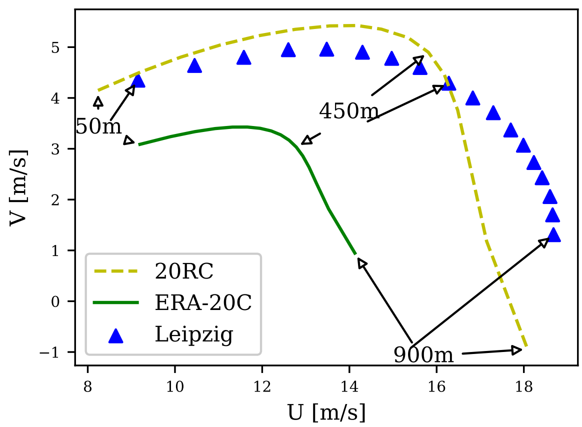

Figure 3: The hodograph for two datasets WRF simulation and Leipzig observation with the annotation of vertical height from 14 UTC to 16 UTC

3.2 Temperature profile

Figure 4 shows the temperature profile at Leipzig in the morning(9-10 UTC). The growing boundary layer height between 400 meters to 500 meters could be seen for both datasets. This feature is also mentioned in Lettau(1950)[8] & Riopelle(1988)[12]. Overall, the ERA-20C dataset gives lower temperatures than the 20CR on the ground also over the whole profile. But the 20CR better presents the decreasing trend above inversion layer compared with the ERA-20C data.

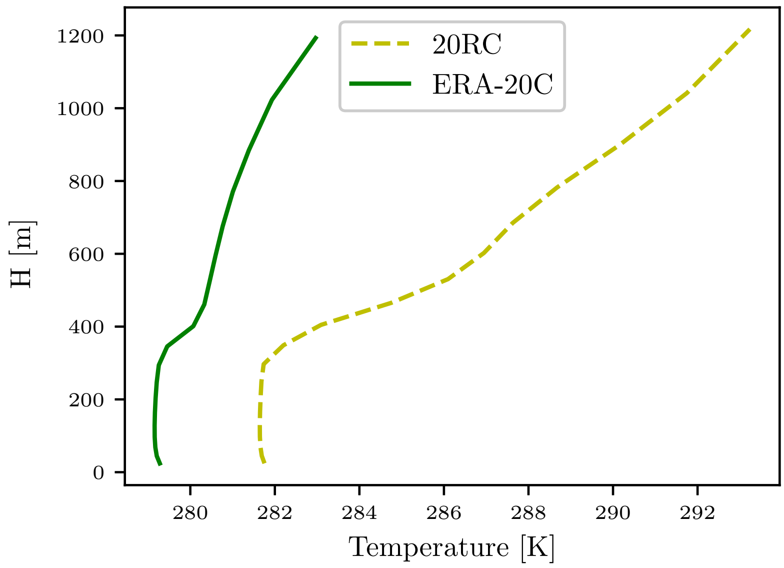

Figure 4: The temperature profile for two datasets simulation at Leipzig in 9 UTC

3.3 Validation point at Leipzig

Figure 5 and 6 show hourly surface friction velocity and surface heat flux development respectively at Leipzig on 20th Oct 1931. The hourly simulation results are compared with the calculation value of surface friction velocity from Apsley(1996)[1] and the modelled value of surface heat flux from Riopelle(1988)[12] respectively. Two dataset simulation give similar results. The surface friction velocity fluctuates around $0.6ms^{-1}$ except the early morning time during initialization of the model. The simulated value is close to the calculation value from Apsley(1996) which is $0.65ms^{-1}$. In terms of surface heat flux, there is a huge jump during noon time because of the increasing solar irradiance. After 15 UTC, the surface heat flux is close to the modelled value -$0.017kms^{-1}$ from Riopelle(1988)[12] for both two dataset.

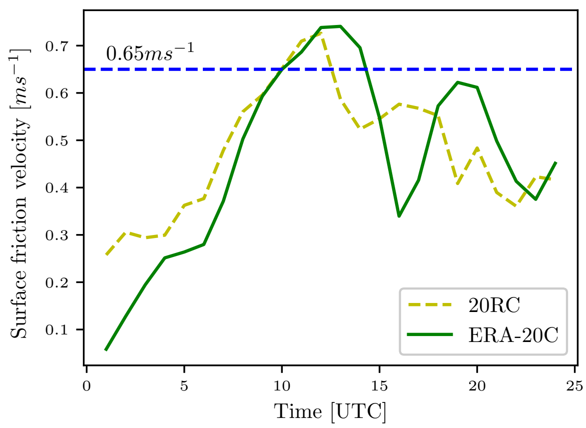

Figure 5: Hourly surface friction velocity for two datasets simulation on 20th Oct 1931 comparing to calculation value $0.65ms^{-1}$ [1]

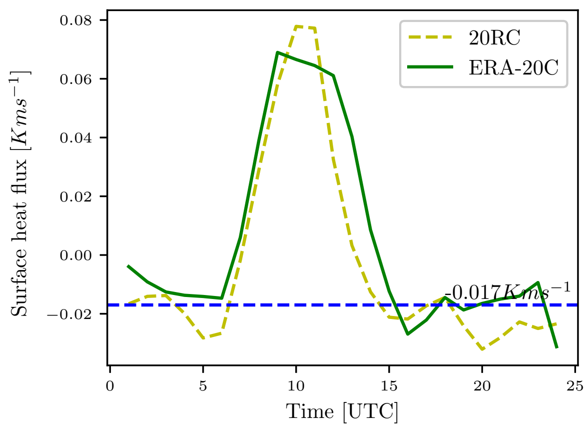

Figure 6: Hourly surface heat flux for two datasets simulation on 20th Oct 1931 comparing to modelled value -$0.017Kms^{-1}$ [12]

3.4 2D plots of inner domain

Figure 7 and Figure 8 present 2D plots of the WRF inner domain. Figure 7 shows the reflectivity development over the inner domain every 3 hours from 12 UTC to 18 UTC. It can be seen that the signal was developing northwestly overtime. If the value of reflectivity is over 15 dBz, it indicates drizzle occurring at that time. Higher intensity signal only covers a relatively small area around the Leipzig station. Figure 8 gives the distribution of the temperature, pressure and wind directions. First of all, the temperature rises during the morning as the solar irradiance increases and falls during the sunset over the inner domain. High pressure is located north which pushes the mesoscale wind from north to south and the surface wind direction is mainly southwestly before 18 UTC. After that, the surface wind direction flows from west to east. With these two 2D plots, we could basically deduce the weather story on the 20th Oct 1931. For example, we can answer the question of whether there is rainfall or drizzle falling at that time. If there is, does the rainfall contribute to the atmospheric condition present at the time? However, we could not draw further conclusions right now because of the coarse resolution of the model. With finer resolution model, the development pattern between the reflectivity and temperature distribution around Leipzig stations may be correlated to determine this contribution. Futhermore, another reason why the rainfall event cannot be determined, is because of the lack of validation data (historical synoptic map)to support these 2D plot simulation results.

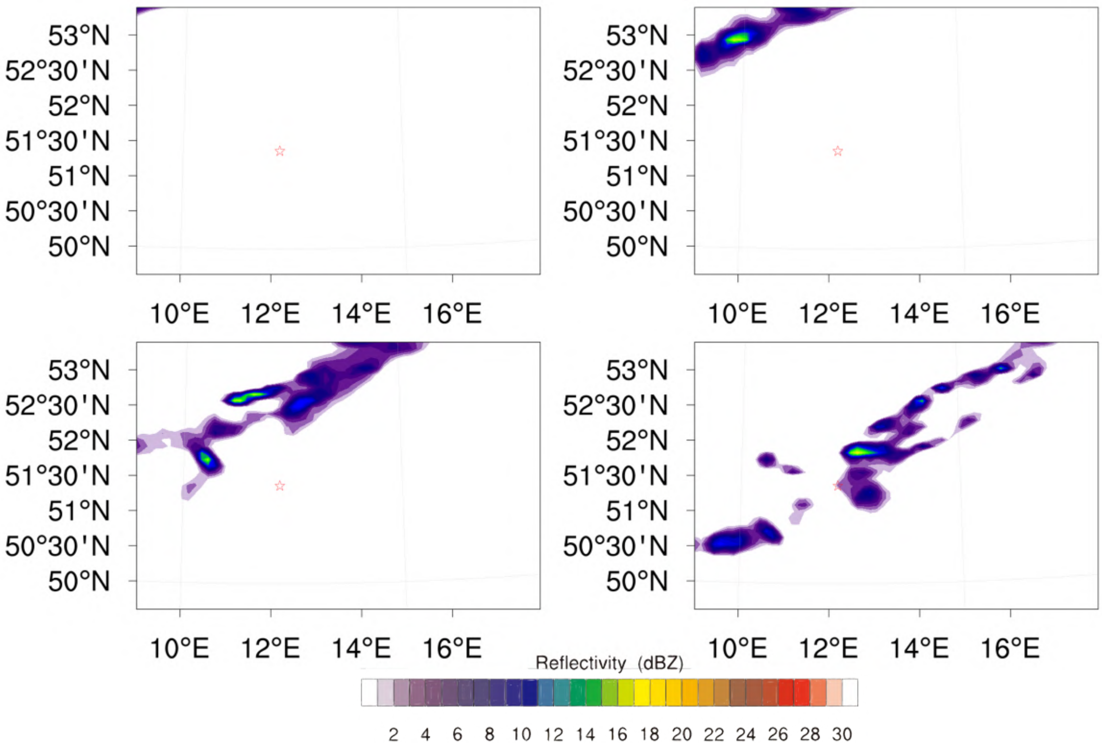

Figure 7: The reflectivity development over the inner WRF domain starting from 12 UTC with 2 hours interval(12 UTC, 14 UTC, 16 UTC, 18 UTC from left to right from up to down).The star showing the Leipzig station location. The colormap has 1dBz interval

3.5 Lindenberg validation

To further validate the simulation results, the temperature profile and potential temperature profile at Lindenberg is also plotted in figure 9 and figure 10 to compare with the measurement data at 14UTC in Lindenberg[8]. The simulated temperature slope and potential temperature slope between 200 meters and 600 meter are -0.94$K/100m$ and 0.026$K/100m$ for 20CR dataset compared to the measurement data from Lettau(1952) -0.65$K/100m$ and 0.35$K/100m$ respectively. There is some deviation of the slope value for both two datasets expecially the ERA-20C dataset. The reason for this is the coarse resolution we are running and the sensitivity of the slope to the vertical temperature fluctuations. If the vertical resolution did not resolve the temperature fluctuation, then the slope will be largely influenced. The plan is to run the simulation with a finer vertical resolution.

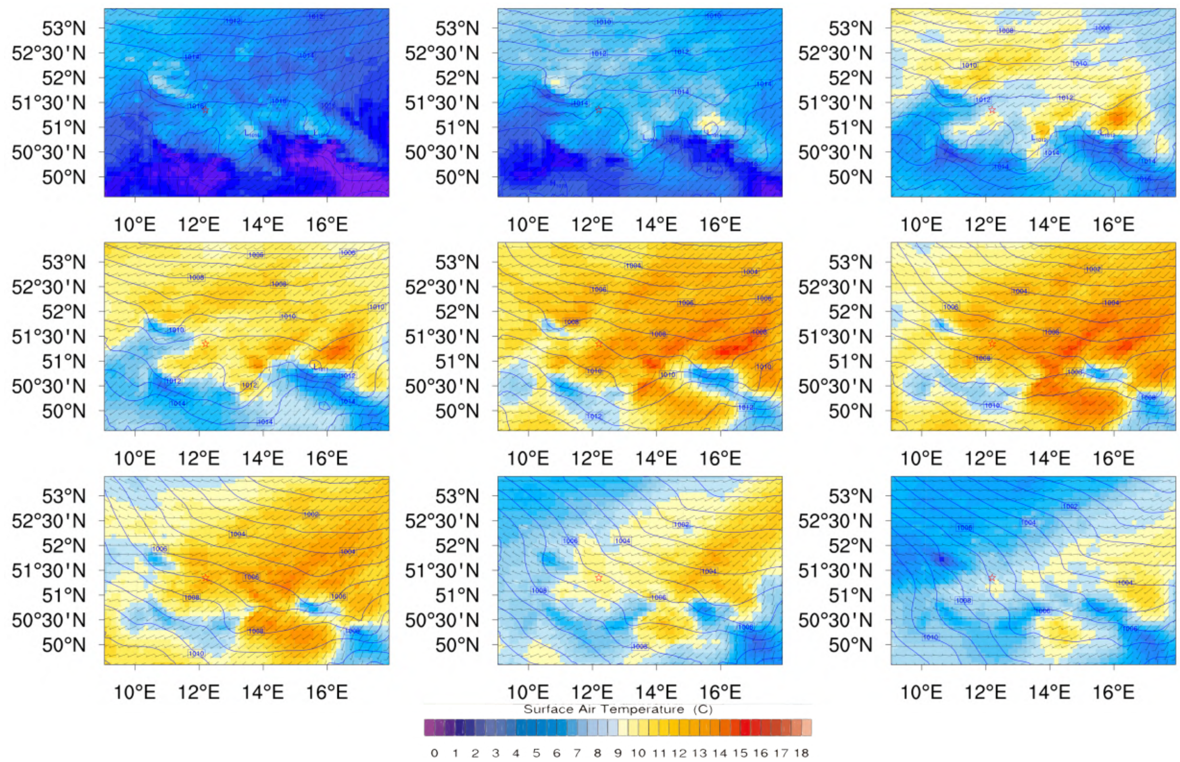

Figure 8: The surface air temperature, sea level pressure, wind distribution over inner WRF domain starting from 6 UTC with 2 hours interval(6 UTC, 8 UTC, 10 UTC, ..., 18 UTC, 20 UTC, 22 UTC from left to right from up to down) with the star showing the station location. The surface air temperature colorbar and the sea level pressure contour has an interval of 0.5K and 1hPa respectively.

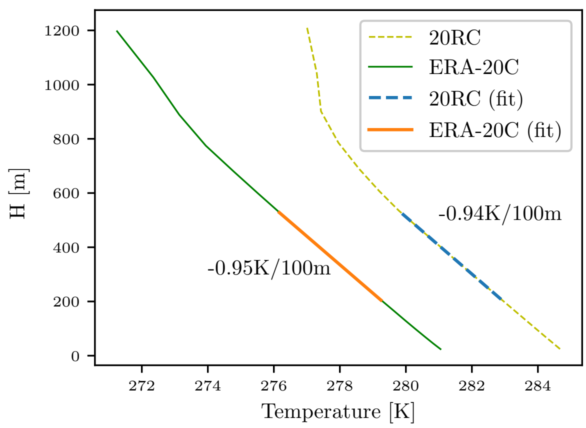

Figure 9: The temperature profile for two datasets simulation at Lindenberg at 14 UTC with the fitting line from 200m to 600m

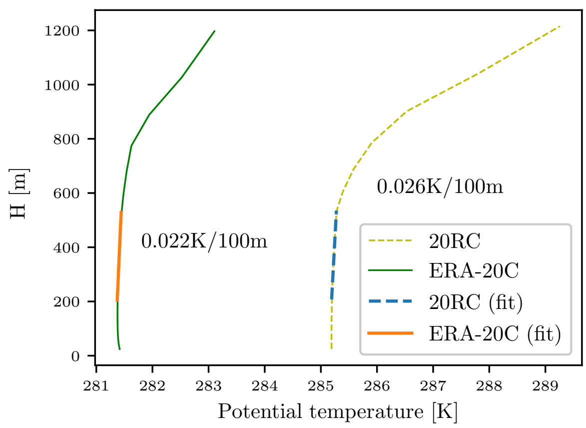

Figure 10: The potential temperature profile for two datasets simulation at Lindenberg at 14 UTC with the fitting line from 200m to 600m

4 Conclusions

The current simulation of the Leipzig event seems to be generally reliable. Various weather variables were investigated during the time of the observation to deduce the atmospheric and weather conditions at Leipzig.

On October 20th, 1931, the surface temperature starts to increase first at the northern side of Leipzig station. The boundary layer started to grow as more solar radiation heated up the surface and it went up to 500 meter around 10 UTC. At 9 UTC, Mildner started setup the observation equipment and launched the balloons. At the same time, the surface heat flux was also increasing to a highest level of $0.07Kms^{-1}$ from 11 UTC to

12 UTC. It then decreased to a level around -0.017Kms^{-1} at 15 UTC. The surface friction velocity rose to a level around 0.65ms^{-1} around noon. Around 14 UTC, the wind profile observation may being noted down for next 2-3 hours. During the same time, the temperature nearly reached a maximum of around 12°C near the Leipzig station. After 14 UTC, there is weak cloud development flowing from northwest to southeast which may indicate drizzle falling. After that, the temperature firstly started to cool down in the southwest direction and slowly also around Leipzig station to 8°C at 18 UTC. The pressure distribution around the Leipzig station is also changing during this day. It has a high pressure north low pressure south system in the morning and it changed to high pressure northwest low pressure southeast system in the afternoon.

This description is based on the simulation results with the validation of measurement data and modelled data. The atmospheric condition agrees with many argument showing slightly stable and near neutral condition. The general weather conditions may support the future researches in Leipzig but also need further validation. A fine resolution simulation is needed to resolve the vertical radiation physics as well as the rainfall signal.

References

Apsley, D. D., & Castro, I. P. (1997). A limited-length-scale k-ε model for the neutral and stably-stratified atmospheric boundary layer. *Boundary-layer meteorology*, *83*(1), 75–98.

Carson, D., & Smith, F. (1973). The leipzig wind profile and the boundary layer wind-stress relationship. *Quarterly Journal of the Royal Meteorological Society*, *99*(419), 171–177.

Detering, H., & Etling, D. (1985). Application of the e-ε turbulence model to the atmospheric boundary layer. *Boundary-Layer Meteorology*, *33*(2), 113–133.

Duynkerke, P. (1988). Application of the e–ε turbulence closure model to the neutral and stable atmospheric boundary layer. *Journal of the atmospheric sciences*, *45*(5), 865–880.

Era-20c project (ecmwf atmospheric reanalysis of the 20th century). (2014). Boulder CO: Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. Retrieved from https://doi.org/10.5065/D6VQ30QG

Hong, S.-Y., Dudhia, J., & Chen, S.-H. (2004). A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Monthly Weather Review*, *132*(1), 103–120.

Hong, S.-Y., Noh, Y., & Dudhia, J. (2006). A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly weather review*, *134*(9), 2318–2341.

Lettau, H. (1950). A re-examination of the “leipzig wind profile” considering some relations between wind and turbulence in the frictional layer. *Tellus*, *2*(2), 125–129.

Mildner, P. (1932). Über die reibung in einer speziellen luftmasse in den untersten schichten der atmosphäre. *Beitr Phys freien Atmosphäre*, *19*, 151–158.

Noaa/cires twentieth century global reanalysis version 2c. (2015). Boulder CO: Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. Retrieved from https://doi.org/10.5065/D6N877TW

Peña, A., Gryning, S.-E., Mann, J., & Hasager, C. B. (2010). Length scales of the neutral wind profile over homogeneous terrain. *Journal of Applied Meteorology and Climatology*, *49*(4), 792–806.

Riopelle, G., & Stubley, G. (1989). The influence of atmospheric stability on the ‘leipzig’boundary-layer structure. *Boundary-Layer Meteorology*, *46*(3), 207–227.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D., Duda, M., et al. (2008). A description of the advanced research (wrf) model, version 3. *Natl. Ctr. Atmos. Res., Boulder, CO*.

Swinbank, W. (1970). Structure of wind and the shearing stress in the planetary boundary layer. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Ser. A, Meteorologie und Geophysik*, *19*(1), 1–12.