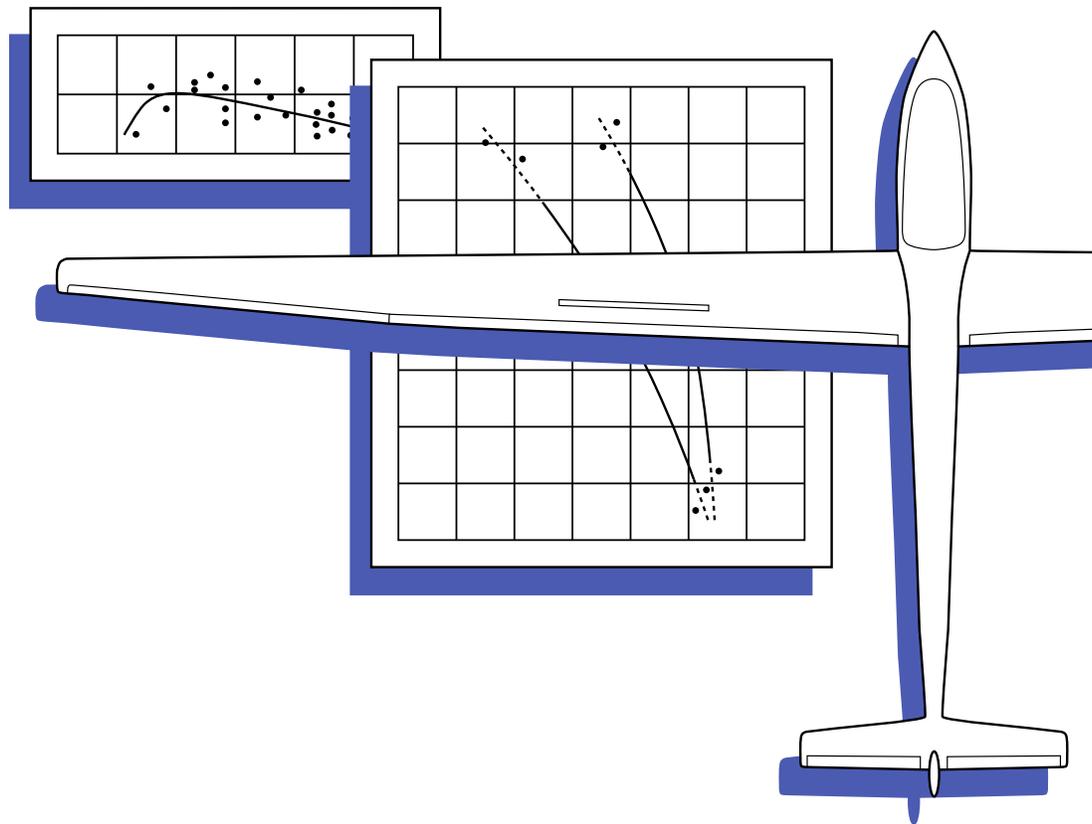


# Technical Soaring

An International Journal



- On the influence of moisture on the strength of thermals



Organisation Scientifique et Technique Internationale du Vol à Voile (OSTIV)  
International Scientific and Technical Organization for Soaring  
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# Technical Soaring



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**From the Editor** ..... 19

**On the influence of moisture on the strength of thermals:**

**A large-eddy simulation case study**

Oliver Maas and Dieter Etling ..... 20

*Technical Soaring (TS)* documents recent advances in the science, technology and operations of motorless aviation.

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## From the Editor

### Publication Date

This issue is the third of Volume 45 of *TS*, corresponding to August-September 2021. For the record, the issue was published in November, 2022.

### Thank you

The previous issue of *Technical Soaring*, Volume 45 No. 2, marked the completion of my term as Editor-in-Chief. It has been my great honor and pleasure to serve the *TS* community. My thanks go to all of you – authors, associate editors, reviewers, and, last but not least, readers. I hope that I have succeeded in positively developing *TS* by introducing new features, such as linking to all cited online literature sources and clickable animations to support the plain text. As it seems, this has been well received by readers.

For the future, I know *Technical Soaring* will be in good hands. Goodbye and stay tuned.

Very Respectfully,  
Arne Seitz

### New Editor-in-Chief

This issue of *Technical Soaring* marks the transition of the Editor-in-Chief position from Dr. Arne Seitz to me. I am honoured and excited to have been entrusted by the OSTIV Board with this important role for the organization and look forward to serving OSTIV and the readers, authors, reviewers, and associate editors of *Technical Soaring* to the best of my abilities. I am very grateful to Arne for the excellent editorial work he has done over the past six years and am pleased to announce that he will continue serving *Technical Soaring* as an Associate Editor, in addition to supporting the journal's publishing with typesetting and layout work. Also previously, as Associate Editor and On-Line Manager, I have had the privilege of working

with Arne since 2016, which offered me a great opportunity to learn the ropes on the editorial duties from him. This has given me the best preparation for, hopefully, a smooth transition. Together with the editorial team, I am looking forward to receiving from authors numerous new manuscripts on the widest range of topics in the science and technology of soaring as well as to receiving comments from our *TS* readers. It will be my pleasure to exchange with you all.

### About this issue

The Maas and Etling article in this issue deals with the numerical study of thermals, and in particular the influence of moisture on thermal strength. The authors use a Large Eddy Simulation (LES) model and focus on the case of thermals with no cloud formation. Their findings shed light on the different effects of humidity between the surface and the upper portions of a thermal, where due to entrainment of dry air from the free atmosphere thermal strength is increased due to the humidity effect on buoyancy. This will hopefully help in offering valuable theoretical insights for the interpretation of flight experiments and the general understanding of this key subject of thermals for the soaring pilot community.

### Acknowledgements

We gratefully acknowledge Associate Editor Arne Seitz who oversaw the review of the Maas and Etling paper in this issue.

Very Respectfully,  
Kurt Sermeus  
Editor-in-Chief, *Technical Soaring*  
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# On the influence of moisture on the strength of thermals: A large-eddy simulation case study

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## Abstract

**Thermals in the atmosphere are driven by buoyancy forces due to density differences between air parcels and their environment (Archimedes principle). Here we present some estimates on the contribution of moisture on the strength of thermals based on numerical simulations with a large-eddy-simulation model (LES).**

## Nomenclature

$A$	vertical acceleration of an air parcel [ $m/s^2$ ]
$B$	buoyancy force per unit volume [ $N/m^3$ ]
$B_s$	surface buoyancy flux [ $Km/s$ ]
$Bo$	Bowen ratio [-]
$c_p$	specific heat of air [ $1004J/(kgK)$ ]
$g$	acceleration due to gravity [ $9.81 m/s^2$ ]
$p$	air pressure [ $Pa$ ]
$q$	specific humidity [-]
$Q$	total heat flux [ $W/m^2$ ]
$Q_l$	latent heat flux [ $W/m^2$ ]
$Q_s$	sensible heat flux [ $W/m^2$ ]
$R$	universal gas constant [ $287.04 J/(kgK)$ ]
$T$	temperature [ $K$ ]
$T_v$	virtual temperature [ $K$ ]
$w_*$	convective velocity scale [ $m/s$ ]
$z_i$	inversion layer height [ $m$ ]
$\theta$	potential temperature [ $K$ ]
$\theta_v$	virtual potential temperature [ $K$ ]
$\rho$	air density [ $kg/m^3$ ]
$()'$	deviation from the horizontal mean
$()_p$	index for an air parcel
$()_e$	index for the environment

## Introduction

There has been some debate in recent years within the soaring community on the contribution of atmospheric moisture content on thermals, especially if moisture might be even the dominating factor on thermal strength. The arguments are based mainly on measurements of temperature and moisture (in terms of specific humidity) inside and outside thermals obtained by gliders and

aircrafts equipped with instruments [1], [2], [3]. But as the temperature and moisture differences between thermals and their environment are quite small, this question has not been answered by measurements without doubt. Here we present a complementary approach based on numerical simulations for a field of thermals in the atmospheric boundary layer as heated from below. The method is to apply a so-called Large-Eddy-Simulation model (LES) which resolves the largest eddies in the convective atmospheric boundary layer [4], [5]. In order to quantify the effect of the moisture content of rising thermals on the vertical velocity (updrafts), vertical profiles of temperature and specific humidity have been varied systematically by applying different values for latent heat flux (moisture flux) and sensible heat flux (temperature flux) as forcing at the earth surface. In order to quantify the contribution of moisture on the strength of thermals, various data on temperature, specific humidity and vertical velocity have been extracted from the 3-D simulations. The influence of moisture on the structure of the convective boundary layer has been also investigated by Patton et al. [6]

## The influence of moisture in Archimedes principle

The vertical acceleration ( $A$ ) of air parcels in the atmosphere is based on Archimedes principle which can be formally expressed by the buoyancy force ( $B$ ) as:

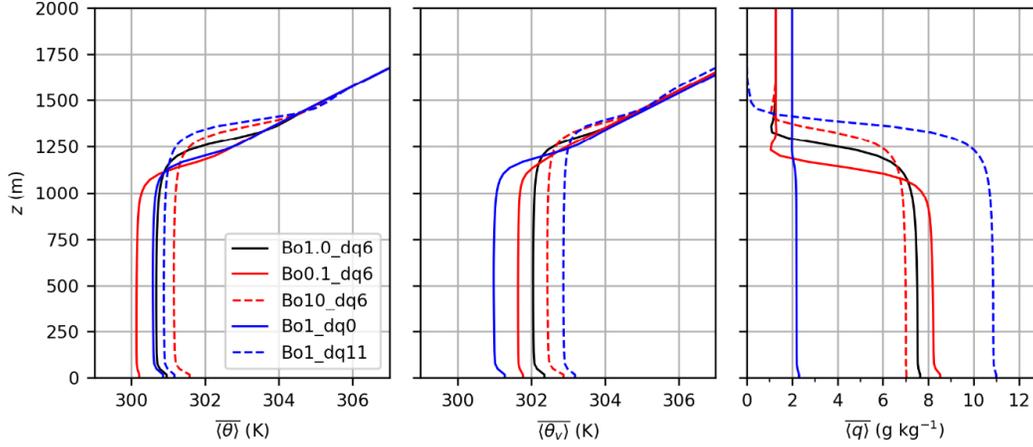
$$B = \rho_p A = -g(\rho_p - \rho_e), \quad (1)$$

where  $g$  is gravity,  $\rho_p$  the density of an air parcel and  $\rho_e$  the density of its environment.  $A = dw/dt$ , where  $w$  is the vertical velocity and  $t$  is time. The air density  $\rho$  is defined by air pressure  $p$ , air temperature  $T$  and moisture content (specific humidity  $q$ ) through the ideal gas law:

$$p = R\rho(1 + 0.6q)T. \quad (2)$$

where  $R$  is the universal gas constant. Inserting (2) in (1), the vertical acceleration can be expressed by air temperature  $T$  and

This article has been reviewed according to the *TS* Fast Track Scheme. Presented at the XXXV OSTIV Congress, 19 – 23 July 2021 (Online)



**Fig. 1: Horizontal and temporal averaged profiles of potential temperature  $\theta$ , virtual potential temperature  $\theta_v$  and specific humidity  $q$  for the five cases Bo1.0.dq6 (reference), Bo0.1.dq6 (wet surface), Bo10.dq6 (dry surface), Bo1.dq0 (no humidity difference between the Boundary Layer (BL) and the Free Atmosphere (FA)) and Bo1.dq11 (high humidity difference between BL and FA).**

specific humidity  $q$  approximately by:

$$A = g \frac{(T_p - T_e)}{T_e} + g0.6 (q_p - q_e) = A_r + A_q. \quad (3)$$

It is common to combine the last two terms in (2) to form the so-called virtual temperature  $T_v$ :

$$T_v = (1 + 0.6q)T. \quad (4)$$

By using (4), the vertical acceleration  $A$  provided by buoyancy forces (3) can also be written as:

$$A = g \frac{(T_{vp} - T_{ve})}{T_{ve}}. \quad (5)$$

In a dry atmosphere ( $q = 0$ ), thermals are driven by the temperature differences between the thermal and its environment, where updrafts are generated for  $T_p > T_e$ . In a moist atmosphere ( $q > 0$ ), moisture differences between thermals and their environment provide an additional acceleration, where updrafts are supported for ( $q_p > q_e$ ), i.e. air parcels are moister than their environment. To provide an example of the magnitudes of the vertical acceleration due to temperature differences ( $A_r$ ) and due to moisture differences ( $A_q$ ) let us assume typical values as found in moist thermals (see Fig. 4):  $T_p - T_e = 0.2K$ ,  $q_p - q_e = 0.2 g/kg = 0.0002$ . Then we have:  $A_r = 0.007 m/s^2$ ,  $A_q = 0.0012 m/s^2$  and  $A_q/A = 0.15 = 15\%$ . Hence moisture (specific humidity) contributes to the strength of thermals but is not the dominating factor. In meteorology it is also common to introduce a new temperature measure called ‘‘potential temperature’’, designated by the Greek symbol  $\theta$  which is related to air temperature  $T$  by:

$$\theta = T \left( \frac{p_0}{p} \right)^\kappa, \quad (6)$$

where  $p_0 = 1000 hPa$  and  $\kappa = 0.262$ .

The potential temperature is a conserved quantity for adiabatic processes e.g. for an ascending air parcel  $\theta$  is constant whereas temperature  $T$  is decreasing with height. Hence the vertical stratification in the atmosphere can be easily identified by profiles of  $\theta$ , as  $\theta(z)$  is constant for adiabatic (neutral) stratification, decreases with height in unstable conditions and is increasing for stable stratification. Examples for profiles of potential temperature  $\theta$  and virtual potential temperature  $\theta_v$  are displayed in Fig 1.

## Numerical Setup

The numerical simulations were conducted with the **PAR**allelized **L**arge-eddy simulation **M**odel **PALM**, developed at the Leibniz University Hannover, Germany [7]. Classical simulation methods, that are e.g. used for the numerical weather forecast, only simulate the mean flow, such as the mean wind speed and mean temperature profile. Large-eddy simulation (LES), however, is a simulation method that explicitly resolves the largest eddies (turbulent motions) of the turbulent lower atmosphere, i.e. the boundary layer (BL). Hence, the properties of updrafts and downdrafts can be investigated.

The simulations are initialized with potential temperature  $\theta$  and specific moisture  $q$  being constant up to the inversion height  $z_i$  (about  $1000m$ ), hence the BL is neutrally stratified with respect to temperature as well with respect to moisture. Above  $z_i$  a stably stratified free atmosphere (FA) is prescribed with  $\theta(z)$  increasing with height by  $1K/(100m)$  and a moisture jump  $\Delta q$  with dryer FA above (see Fig. 1). The development of vertical profiles of temperature and moisture with time is forced by applying a sensible heat flux ( $Q_s$ ) and a latent heat flux ( $Q_l$ ) at the earth surface. These fluxes have to compensate energy fluxes due to incoming solar radiation, the ground heat flux and net-longwave radiation in order to fulfil the energy balance at the earth surface. As sensible heat flux is related to air temperature and latent heat flux to evaporation,  $Q_s$  might also be called tem-

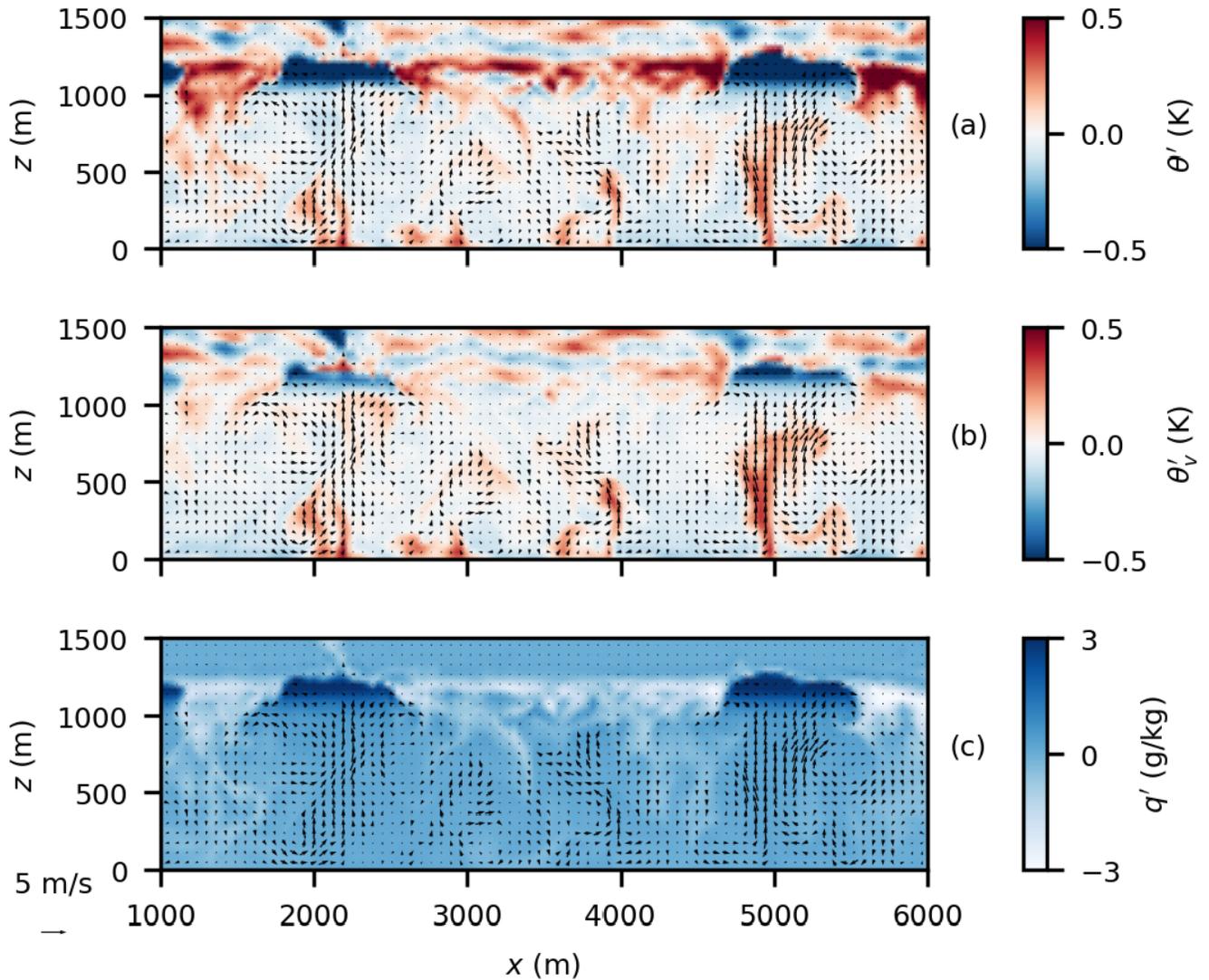


Fig. 2: Vertical cross sections of potential temperature excess  $\theta'$  (a) (click here for animation) , virtual potential temperature excess  $\theta'_v$  (b) and specific humidity excess  $q'$  (c) (click here for animation) for the case Bo1\_dq6 (arrows indicate flow velocity)

perature flux and  $Q_l$  named moisture flux. The input of heat and moisture fluxes at the surface of a neutrally stratified BL is leading the formation of unstably stratified temperature and moisture profiles (see Fig. 1), hence initiating thermal convection in the form of rising thermals (see Fig. 2).

In micrometeorology, the relation between sensible heat flux and latent heat flux is called Bowen ratio, defined as

$$Bo = Q_s / Q_l. \quad (7)$$

A large Bowen ratio occurs if the surface is dry and most of the heat flux is used to heat up the near-surface air. A small Bowen ratio represents a wet surface and most of the heat flux is used for evaporation of water, so that the humidity of the near-surface air increases. In nature, a large variety of combinations for sensible and latent heat flux can be observed, even for the

same Bowen ratio. In order to restrict our simulations to a few simple cases, we performed all runs with the same total heat flux  $Q = Q_s + Q_l = 200 \text{ W/m}^2$  and varied within this limit the Bowen ratio between 0.1 and 10 (see Table 1).

The humidity difference between the BL and the FA is varied from  $0 \text{ g/kg}$  to  $11 \text{ g/kg}$ , as can be seen in the profiles of specific humidity in Fig. 1. The domain size in all cases is  $L_x = 8192 \text{ m}$ ,  $L_y = 5120 \text{ m}$  and  $L_z = 3300 \text{ m}$ , so that several convection cells fit into the domain. The grid spacing is  $32 \text{ m}$  in all directions, which is enough to resolve thermals that have a typical diameter of several  $100 \text{ m}$ . Cyclic boundary conditions are applied at the lateral boundaries. A Rayleigh damping layer at the top of the domain prevents the reflection of gravity waves that are triggered by thermals penetrating the inversion layer. Monin-Obukhov similarity is assumed between the surface and the lowest grid level.

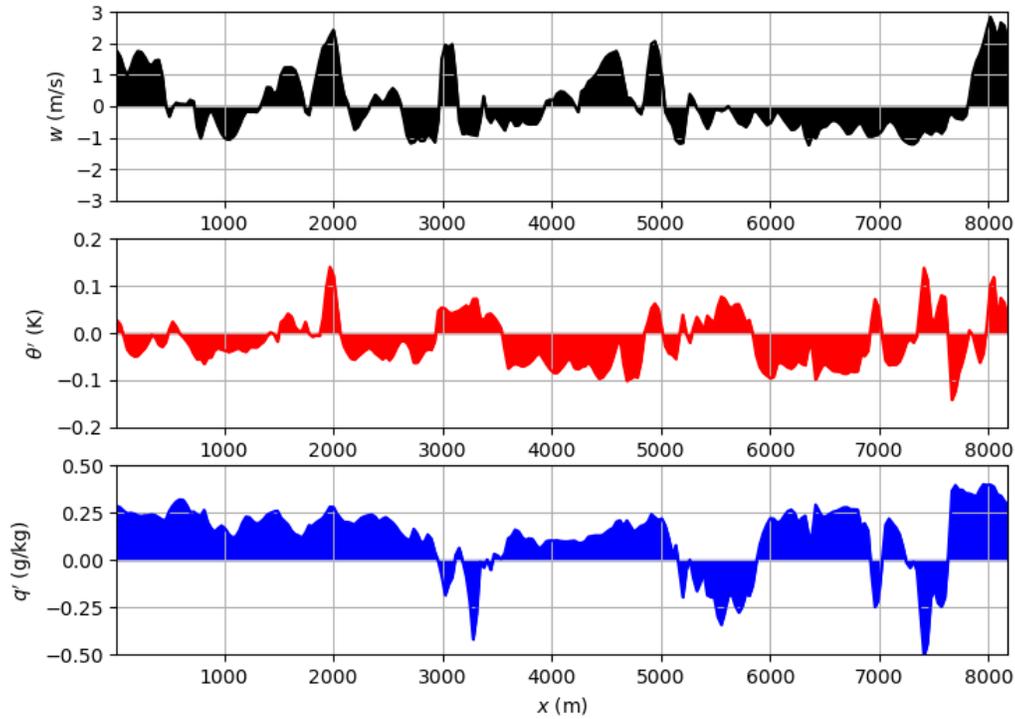
Case	$Bo$	$\Delta q$ g/kg	$w_*$ m/s	$z_i$ m	$z_T$ m	$z_B$ m	$\frac{z_T}{z_i}$	$\frac{z_B}{z_i}$	$\frac{z_B - z_T}{z_i}$
Bo1_dq6	1	6	1.54	1296	941	1106	0.73	0.85	0.12
Bo0.1_dq6	0.1	6	0.99	1168	664	958	0.57	0.82	0.25
Bo10_dq6	10	6	1.87	1360	1091	1203	0.80	0.88	0.08
Bo1_dq0	1	0	1.51	1200	984	997	0.82	0.83	0.01
Bo1_dq11	1	11	1.58	1392	1014	1201	0.73	0.86	0.13

**Table 1: Overview of the five simulated cases with Bowen ratio  $Bo$ , specific humidity difference between BL and FA  $\Delta q$ , typical updraft velocity  $w_*$  (convective velocity scale), inversion height  $z_i$ , height at which updrafts ( $w > w_*$ ) have zero temperature excess  $z_T$  or have zero buoyancy  $z_B$ .**

The simulations ran for 2 hours physical time, the profiles are averaged over the last 15 minutes and the vertical cross sections are obtained from the last time step. In order to keep this investigation simple, we choose the basic temperature and humidity profiles in such a way that no condensation of water vapor will occur within the BL, hence no cumulus clouds will form. In such a way we can investigate the pure effect of moisture content in the BL on buoyancy forces and hence on thermals. Of

course, if condensation would be permitted, the release of latent heat would lead to additional buoyancy in the thermals at condensation level and the updrafts will become stronger than in the case without cloud formation. We also assume that there is no background wind.

The simulations can be performed on a modern notebook, given this grid spacing and domain size. Note that [4] used a similar domain size and grid spacing for their large-eddy simula-



**Fig. 3: Vertical velocity  $w$ , potential temperature difference  $\theta'$  and specific humidity difference  $q'$  along a horizontal transect located at  $y = 16m, z = 816m$ .**

tion study and that a supercomputer was required for performing the simulations in the year 1989.

## Results

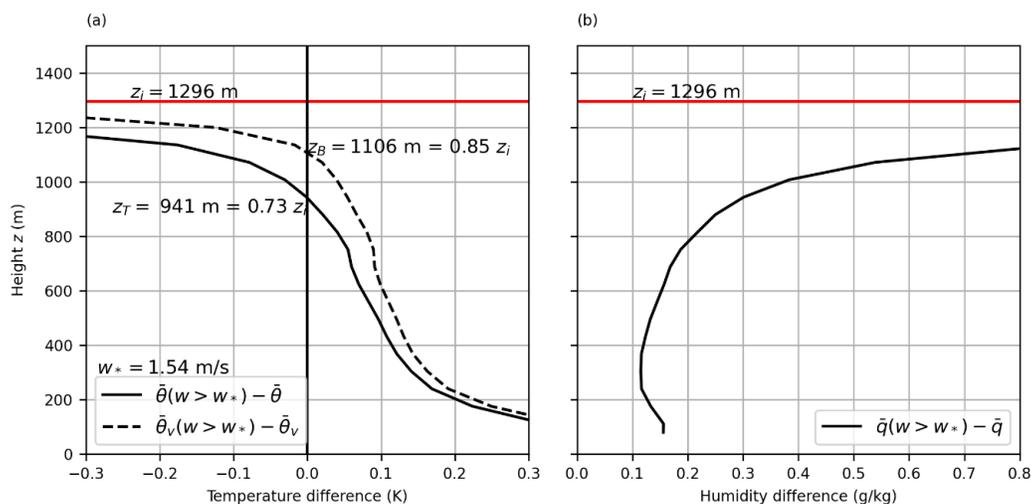
Figure 2 shows vertical cross sections of potential temperature, virtual potential temperature and specific humidity as deviations ( $\theta'$ ,  $\theta'_v$ ,  $q'$ ) from the respective horizontal mean value for the case Bo1\_dq6 (dry surface). Two large updrafts with a distance of about  $2.3 z_i$  can be identified. As can be seen in Fig. 2a, these updrafts are relatively warm near the surface, but are relatively cold near the top of the BL. Figure 2c shows that the humidity excess of updrafts is highest at the top of the BL but it is nearly zero near the surface. The high humidity differences  $q'$  at the top of the updrafts adds buoyancy so that relatively cold updrafts (negative  $\theta'$ ) can still be positively buoyant (positive  $\theta'_v$ ). Beside the updrafts, warm and dry air is entrained from the FA into the BL (top left and right), which enhances the humidity excess but diminishes the temperature excess of updrafts.

In Fig. 3 horizontal cross sections through the thermal field displayed in Fig. 2 along a transect at 816 m height are shown. The variations of temperature and moisture show similar structures as found by aircraft observations in the convective boundary layer [1], [2]. A variety of thermals can be seen like warm and moist updrafts or cool and dry updrafts which show, that the simple picture that updrafts are always related to positive temperature excess (being warmer than their environment) is not always true within a field of thermals.

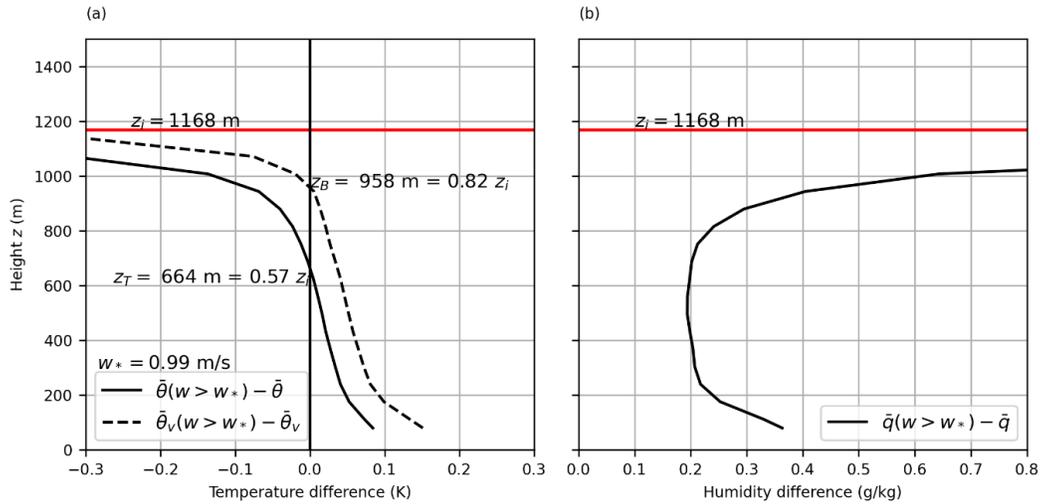
Figure 4(a) shows vertical profiles of the mean temperature excess and the mean virtual temperature excess of all updrafts for the case Bo1\_dq6. In order to investigate only updrafts that are usable for soaring, we included only updrafts with a vertical velocity  $w < w_*$ , where  $w_* = (g/\bar{T}_0 z_i B_s)^{1/3}$  is the so called convective velocity scale [3], [4], which indicates a typical updraft velocity for a given surface temperature  $\bar{T}_0$ , inversion

height  $z_i$  and surface buoyancy flux  $B_s = (\overline{w'\theta'_v})_0$  which can be related to the sensible heat flux  $Q_s$  and latent heat flux  $Q_l$  by  $B_s = a(Q_s + 0.07Q_l)$ , where  $a = 1/(\rho c_p)$ . It can be seen that the temperature differences between updrafts and their environment are in general very small (only about 0.1 K). The temperature excess decreases from more than 0.2 K below 200 m to less than 0.1 K in the middle of the BL. At  $z = z_T = 941$  m (or  $0.73 z_i$ ) the temperature excess is zero. However, at that height the updrafts are still positively buoyant (have a positive virtual temperature difference  $\theta'_v$ ) due to the humidity difference between the updrafts and their environment (shown in Fig. 4(b)). This humidity excess in the upper third of thermals has been also observed during inflight measurements of temperature and moisture by [3]. The buoyancy of updrafts becomes zero somewhat higher at  $z = z_B = 1106$  m (or  $0.85 z_i$ ). The humidity excess of thermals is highest at the top of the updrafts, not because they gain humidity during their ascend but rather because the surrounding air is dryer at that height due to the entrainment of dry air from the FA. Temperature and virtual temperature differences become negative at the top of updrafts, reaching values of  $-0.3$  K.

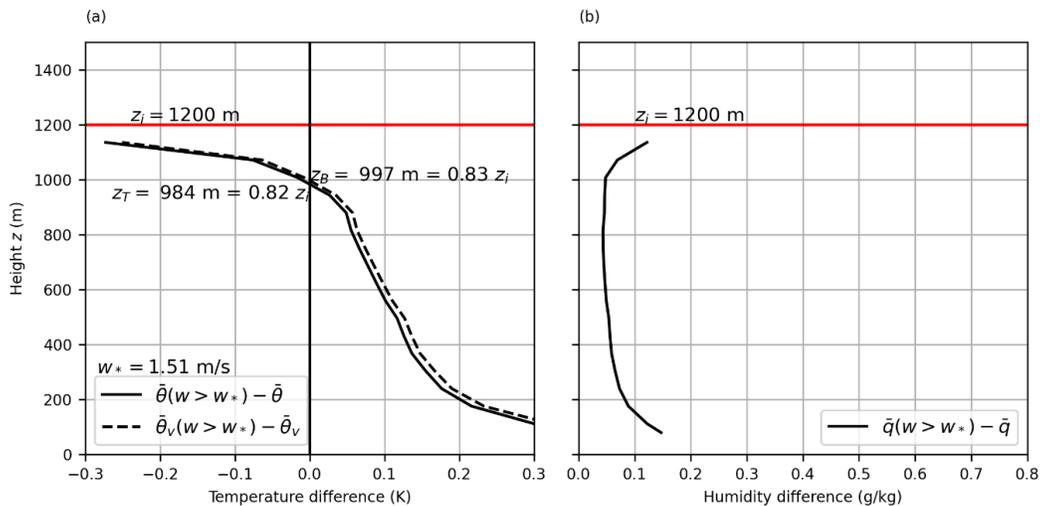
In Fig. 5 the same profiles are shown as in Fig. 4 but for the case Bo0.1\_dq6 (moist surface). Here, the temperature differences are smaller, but the influence of moisture on the virtual temperature excess (and hence on buoyancy) is more dominant as in the case with Bowen ratio  $Bo = 1$ . At 200 m height, e.g., one half of the buoyancy is generated by temperature excess (0.05 K) and one half is generated by humidity excess, so that a virtual temperature excess of 0.1 K is obtained. In Fig. 6 these profiles are shown for the same Bowen ratio ( $Bo = 1$ ) as in Fig. 4, but there is no jump of specific humidity ( $\Delta q = 0$ ) at the inversion height. Here the influence of moisture on the temperature excess is quite small as compared to the result shown in Fig. 4, especially in the upper part of the BL. This shows, that the en-



**Fig. 4: Vertical profiles of temperature excess and virtual temperature excess (a) and humidity excess (b) of all updrafts that are stronger than  $w_*$  for the case Bo1\_dq6**



**Fig. 5: Vertical profiles of temperature excess and virtual temperature excess (a) and humidity excess (b) of all updrafts that are stronger than  $w_*$  for the case Bo0.1\_dq6.**



**Fig. 6: Vertical profiles of temperature excess and virtual temperature excess (a) and humidity excess (b) of all updrafts that are stronger than  $w_*$  for the case Bo1\_dq0.**

trainment of dry air from the FA above the inversion layer plays an important role on the influence of moisture on buoyancy, as can be seen by comparing the results with Fig. 4 and 5 and the summary of results in Table 1.

The heights for zero temperature excess  $z_T$  and zero buoyancy  $z_B$  of updrafts for all five cases are listed in Table 1. The updrafts reach zero buoyancy at about  $0.85 z_i$ , relatively independent of the Bowen ratio  $Bo$  and the humidity difference  $\Delta q$  between BL and FA. However, the height of zero temperature excess of updrafts  $z_T$  varies significantly and can be as low as  $0.57 z_i$  for the case with  $Bo = 0.1$  (wet surface). Note that in this case the updrafts are generally weaker (indicated by a small  $w_*$ ), because most of the available surface heat flux is used for evaporation (latent heat flux), which is ineffective in generating

buoyancy. A large difference between  $z_B$  and  $z_T$  is achieved for wet surfaces ( $Bo = 0.1$ ) and large humidity differences between BL and FA ( $\Delta q = 11$ ) and nearly no difference between  $z_B$  and  $z_T$  is achieved for  $\Delta q = 0$ . Hence, the contribution of humidity on the buoyancy of updrafts is only dominant, if dry air is entrained from the FA into the BL. For very dry surfaces  $Bo = 10$  or small humidity difference between BL and FA ( $\Delta q = 0$ ), humidity effects play a minor role. In this case, the temperature excess of updrafts vanishes relatively late at  $z_T = 0.80 z_i$  ( $Bo = 10$ ) or  $z_T = 0.82 z_i$  ( $\Delta q = 0$ ).

## Conclusions

With this study we showed that large-eddy simulation is a suitable method for the investigation of thermals, as the

spatiotemporal properties of thermals can be extracted while the boundary conditions can be controlled and systematically changed. The results show that updrafts become neutrally buoyant at about  $0.85 z_i$ , more or less independent of Bowen ratio and humidity difference between the boundary layer and the free atmosphere. However, the temperature excess of updrafts becomes zero at heights between  $0.57 z_i$  and  $0.82 z_i$ , with lower values for small Bowen ratios and high humidity differences. As humidity-driven buoyancy partly replaces temperature-driven buoyancy, humidity effects do not lead to stronger thermals but rather lead to colder thermals, for a given surface buoyancy flux. For a given surface heat flux, the strongest updrafts are achieved at high Bowen ratios (dry surfaces). The entrainment of dry air from a dry free atmosphere into a humid boundary layer significantly strengthens the upper part of updrafts.

It should be remembered however, that there is no water vapor condensation and hence cloud formation in our study. We wanted to focus on the direct effect of air moisture on buoyancy forces and hence on the formation of thermals. Once cloud formation is permitted, the indirect effect of moisture on the strength of thermals due to release of latent heat above the condensation level comes into play and can lead to stronger thermals than in the case without clouds. Important research topics for the future could be to study the effects of clouds, vegetation or wind on the structure of thermals.

### References

- [1] Kiessling, A., “Measurement results from warm air thermals over the Namibian steppe.” *Proceedings XXXIV OSTIV Congress, Hosín, Czech Republic, 28 July – 3 August 2018*, 2018, pp. 126–129.
- [2] Lenschow, D. H., “Aircraft Measurements in the Boundary Layer.” *Probing the Atmospheric Boundary Layer*, edited by D. H. Lenschow, American Meteorological Society, Boston, MA, USA, 1986, pp. 39–55, [https://doi.org/10.1007/978-1-944970-14-7\\_5](https://doi.org/10.1007/978-1-944970-14-7_5).
- [3] Predelli, O. and Niedernhagen, R., “Humidity, the dominating force of thermal updrafts.” *Technical Soaring*, Vol. 45, No. 1, 2021, pp. 2–11.
- [4] Schmidt, H. and Schumann, U., “Structure of the convective boundary layer derived from large-eddy simulations,” *Technical Soaring*, Vol. 14, No. 4, 1990, pp. 118–123.
- [5] Stoll, R., Gibbs, J. A., Salesky, S. T., Anderson, W., and Calaf, M., “Large-Eddy Simulation of the Atmospheric Boundary Layer.” *Boundary-Layer Meteorology*, Vol. 177, 2020, pp. 541–581, <https://doi.org/10.1007/s10546-020-00556-3>.
- [6] Patton, E. G., Sullivan, P. P., and Moeng, C.-H., “The Influence of Idealized Heterogeneity on Wet and Dry Planetary Boundary Layers Coupled to the Land Surface.” *Journal of Atmospheric Sciences*, Vol. 62, 2005, pp. 2078–2097.
- [7] Maronga, B. et al., “Overview of the PALM model system 6.0.” *Geoscientific Model Development*, Vol. 13, No. 3, 2020, pp. 1335–1372, <https://doi.org/10.5194/gmd-13-1335-2020>.