A New Horizontal Length Scale for a Three-Dimensional Turbulence Parameterization in Mesoscale Atmospheric Modeling over Highly Complex Terrain

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ABSTRACT

The correct simulation of the atmospheric boundary layer (ABL) in highly complex terrain is a challenge for mesoscale numerical weather prediction models. An improvement in model performance is possible if horizontal contributions to turbulence kinetic energy (TKE) production, such as horizontal shear production, are implemented in the model's turbulence parameterization. However, 3D turbulence parameterizations often only have a constant horizontal length scale that depends on the horizontal grid spacing. This is unphysical for mesoscale applications, because such parameterizations were initially developed for much smaller model grid spacings (e.g., for large-eddy simulations). In this study, we develop a new physically based horizontal length scale for the high-resolution mesoscale model COSMO. We analyze days dominated by thermally driven circulations (valley wind days) in the Inn Valley, Austria. Results show that the new horizontal length scale improves TKE simulations in the valley, when horizontal shear processes contribute to the overall TKE budget. Vertical profiles of TKE and transects across the valley indicate that the model simulates the ABL in a more realistic way than standard turbulence schemes, because the new scheme is able to account for terrain inhomogeneities. A model validation with 88 stations in Austria for four case study days indicates no change in the mean surface fields of temperature, relative humidity, and wind speed by the new turbulence parameterization.

1. Introduction

Mountains cover a large part of Earth's surface and have a high impact on exchange processes between the atmospheric boundary layer (ABL) and the free atmosphere (Rotach et al. 2014). The ABL over mountainous areas is characterized by an inhomogeneous structure due to the complexity of the underlying surface (Kalthoff et al. 1998; Rotach and Zardi 2007; De Wekker and Kossmann 2015; Lehner and Rotach 2018). Well-known ABL processes associated with highly complex terrain (HCT) include the thermally induced, diurnal wind circulations occurring on sunny days on different scales, including slope flows, valley

winds, and the plain-to-mountain circulation (Zardi and Whiteman 2013). The strength of these circulations depends on the terrain geometry, radiation, and initial stratification (Wagner et al. 2015a,b; Leukauf et al. 2015; Lang et al. 2015; Leukauf et al. 2017). Furthermore, the thermally induced wind circulations influence the exchange of momentum, heat, mass, pollutants, and moisture between the mountain ABL and the free atmosphere (Rotach et al. 2015; Schmidli 2013; Henne et al. 2004; Leukauf et al. 2016; Weigel et al. 2007a).

The vertical exchange processes over mountainous terrain have been studied extensively [see Rotach et al. (2015) and Serafin et al. (2018) for a detailed overview of the topic], but spatial inhomogeneity also leads to additional horizontal exchange. Observational evidence of horizontal exchange is sparse and usually only available from measurement campaigns. The up-valley wind is associated with sharp horizontal gradients in the wind speed, leading to three-dimensional (3D) shear

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production of turbulence kinetic energy (TKE) as seen, for example, in observations from the Riviera Valley in Switzerland by Weigel et al. (2007b). This shear-generated turbulence is more anisotropic when compared with other sources of turbulence and suggests a minimum of two length scales for parameterizations in numerical weather prediction (NWP) models—one in the vertical direction, and at least one in the horizontal plane (Stiperski and Calaf 2018).

The horizontal grid spacings Δx of operational models have decreased in recent years toward the order of 1 km (Yano et al. 2018). This leads to better representation of terrain, surface characteristics, and soil properties, thus resulting in an improved simulation of the thermally induced wind circulations in Alpine valleys (Schmidli et al. 2018; Jiménez-Esteve et al. 2018). When the up-valley wind is well resolved in major Alpine valleys, the along-valley horizontal gradients in wind speed are also resolved. This raises the question of whether horizontal contributions should be included in mesoscale models' turbulence parameterizations.

Most mesoscale models use common turbulence parameterizations only considering the vertical turbulent exchange assuming that horizontal contributions to turbulence are negligible (Honnert and Masson 2014). However, the assumption of "horizontally homogeneous, flat terrain" is violated in regions with mountainous terrain (Rotach et al. 2017; Rai et al. 2017b)—and mesoscale simulations with 1D turbulence parameterizations show a systematic underestimation of TKE in HCT (Szintai et al. 2010; Couvreur et al. 2016; Goger et al. 2016, 2018).

Horizontal contributions to TKE are rarely included in mesoscale simulations, because their length scale (around 100 m–1 km) lies in a turbulence "gray zone" (Wyngaard 2004) between the pure vertical (1D) treatment of coarse models and the fully 3D isotropic exchange of large-eddy simulations (LES). Honnert (2016) conducted idealized simulations of a convective boundary layer and concluded that 3D effects of turbulence have to be included if Δx is around one-half of the boundary layer height. However, full 3D turbulence parameterizations as employed in LES are designed to only treat the small-scale processes, which are isotropic and therefore use one single length scale, dependent on Δx (e.g., Smagorinsky 1963; Deardorff 1980). Efsthathiou and Beare (2015) tried to overcome this difficulty by blending Smagorinsky's horizontal length scale toward the mesoscale limit with a scale-adaptive weighing function $\Delta x/z_i$, dependent on Δx and the ABL height z_i , leading to a better simulation of potential temperature across the gray zone. A similar approach was followed by Zhang et al. (2018) with introducing an algorithm to blend Deardorff's 3D-TKE toward the mesoscale limit,

improving the representation of the convective boundary layer and turbulent fluxes in the simulations.

Honnert and Masson (2014) pointed out that a 3D turbulence scheme for mesoscale models should account for turbulence anisotropy by adopting different length scales for the vertical and horizontal exchange. Goger et al. (2018) realized this with a "hybrid" turbulence parameterization, where the vertical shear production of TKE is calculated after Mellor and Yamada (1982) and the horizontal shear production (HSP) after Smagorinsky (1963). This approach led to a major improvement of TKE simulation in the Inn Valley, Austria.

The afternoon up-valley wind, with the valley width as a dominant horizontal length scale (HLS), has an extent of a few kilometers and is associated with strong gradients in the horizontal wind speed leading to strong HSP. The HSP contributes to the overall TKE budget and leads therefore to an improved simulation of the TKE. However, the HLS as introduced in the hybrid turbulence parameterization of Goger et al. (2018) is constant and proportional to Δx , thus rendering their results—despite their apparent success—to be fortunate at best. Clearly, for mesoscale simulations with a horizontal grid spacing of order 1 km, a constant HLS is unphysical (Wyngaard 2004; Efsthathiou and Beare 2015). A more appropriate approach should account for both spatial and temporal inhomogeneity and depends on the actual state of the ABL (Stull 1988).

In this work, we introduce such a new physically based HLS that is based on ABL variables, such as the mean horizontal wind speed, the horizontal velocity variances, and the ABL height, all dependent on the underlying terrain. Therefore, the new HLS is able to account for (terrain) inhomogeneity, and is furthermore independent of Δx . The new HLS is tested for up-valley wind days with strong HSP and validated with turbulence observations from the Inn Valley.

2. Data and methods

a. Observations

The Innsbruck Box (i-Box) observations (Rotach et al. 2017) are a long-term dataset of turbulence measurements conducted at several locations in the Inn Valley, Austria. The Inn Valley is northeast–southwest-oriented valley with a width of around 2 km at the location of the i-Box stations and a peak-to-peak width of around 10 km. The surrounding mountains range between 2000 and 3000 m above sea level, while the valley depth approximately ranges between 1700 and 2100 m. The flux towers give valuable information of turbulent exchange processes over representative locations in mountainous terrain (valley floor, various slopes).

We will mainly focus on the observations of TKE and its budget terms from the turbulence flux towers at the core sites (see Fig. 1 for the spatial distribution of the stations). Double rotation is used to align the data into a slope-normal coordinate system while fluxes are averaged over a 30-min averaging period. The quality control criteria and the detailed data analysis are described in Stiperski and Rotach (2016). The observed HSP at the valley floor can be estimated from the momentum fluxes at the valley-floor station (CS-VF0), while the horizontal wind speed gradients are estimated from the distance between the valley-floor station and the south-facing-slope station (CS-SF8) as in Göger et al. (2018).

b. Numerical model

Simulations are performed with the NWP model Consortium for Small-Scale Modelling (COSMO), version 5.0, a limited-area model suitable for operational weather forecasting on the mesoscale (Baldauf et al. 2011). The model solves the nonhydrostatic, fully compressible hydrothermodynamical equations on an Arakawa C grid with a third-order Runge–Kutta scheme for time integration (Wicker and Skamarock 2002), a fifth-order advection scheme for temperature, pressure, and velocity, and a second-order advection scheme for moisture (Bott 1989). A fourth-order scheme is used for horizontal diffusion, calculated in terrain-following coordinates after Xue (2000). The model includes a full cloud–radiation feedback with its δ two-stream radiation scheme (Ritter and Geleyn 1992) including topographic shading (Müller and Scherer 2005). Shallow subgrid-scale convection is parameterized with a cumulus scheme after Tiedtke (1989).

The model setup is similar to the operational setup of MeteoSwiss (de Morsier et al. 2012) and was also used in Göger et al. (2018): The inner model domain has a horizontal grid spacing of $\Delta x = 1.1$ km and spans the main Alpine range with 800×600 grid points. The outer domain has a horizontal grid spacing of $\Delta x = 6.6$ km, spans Europe, and is driven by ECMWF IFS-HRES data. The vertical grid consists of 80 vertical levels in terrain-following smooth-level (SLEVE) coordinates

FIG. 1. The locations of the i-Box stations [for more detail see Rotach et al. (2017)] that were taken into account for this study, with topography from the COSMO model ($\Delta x = 1$ km; color contours).

(Leuenberger et al. 2010). The lowest model half-level is located at 10 m above ground, and the first 40 model levels lie within the first 1000 m AGL. The model topography is derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map (NASA et al. 2009), while soil data are available from the Harmonized World Soil Database (FAO et al. 2012). The model uses the multilayer soil model TERRA_ML consisting of eight active soil levels with varying layer depths and eight soil types.

Since one single grid point may not be representative for describing the ABL structure in HCT, we employ a so-called model gridpoint ensemble for the model output: The closest grid point, calculated via Euclidean distance, and the surrounding eight next closest grid points are used for the calculation of an ensemble mean, median, and the 75th and 90th percentiles.

c. Turbulence representation in the model

1) 1D TURBULENCE PARAMETERIZATION (TURB_1D)

The model solves the prognostic equation for the TKE making use of an auxiliary variable q defined by $q = (2\bar{e})^{1/2}$ or vice versa $\bar{e} = q^2/2$ (Mellor and Yamada 1982; Raschendorfer 2001; Buzzi et al. 2011):

$$\underbrace{\frac{D}{Dt} \left(\frac{q^2}{2} \right)}_{\text{tendency}} = \underbrace{-K_H \frac{g}{\theta} \frac{\partial \theta}{\partial z}}_{\substack{\text{buoyancy} \\ \text{production} / \text{consumption}}} + \underbrace{K_M \left[\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right]}_{\text{vertical shear production}} + \underbrace{\frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \left[\alpha_{\text{TKE}} \bar{\rho} \lambda_t q \frac{\partial}{\partial z} \left(\frac{q^2}{2} \right) \right]}_{\text{vertical turbulent transport}} - \underbrace{\frac{q^3}{B_1 \lambda_t}}_{\text{dissipation}}. \quad (1)$$

On the left-hand side there is the tendency of TKE, consisting of a local tendency and an advection part. In

the 1D setup, TKE advection is not added in the TKE budget, however, in the turb_hybrid scheme (see next

section), this term is also included. On the right-hand side the buoyancy production (consumption), vertical shear production, the vertical turbulent transport, and the dissipation rate are present; here, K_H and K_M are the exchange coefficients for heat and momentum. λ_l is a vertical turbulent length scale following Blackadar (1962), and α_{TKE} and B_1 are constants from the Mellor–Yamada framework. As mentioned above, this turbulence scheme only considers vertical turbulent exchange and ignores horizontal contributions to TKE production. At $\Delta x = 1.1$ km, the model falls within the range of the turbulence gray zone leading to a possible overestimation of horizontal velocity variances and the TKE itself (Rai et al. 2017a), artificially increasing simulated TKE. Our simulations show a general underestimation of TKE, therefore it is unlikely that an overestimation due to gray zone effects is important. This scheme is called “turb_1D” hereafter.

2) HYBRID TURBULENCE PARAMETERIZATION (TURB_HYBRID)

Two additional contributions can be added to the model’s TKE equation [Eq. (1)]: First, the advection of TKE is computed the same way as advective tendencies of other quantities and is added in the follow-up time step to the TKE budget. Second, the HSP is added as an additional tendency:

$$\frac{\partial}{\partial t} \left(\frac{q^2}{2} \right)_{\text{HSP}} = (c\Delta x)^2 \left[\underbrace{\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2}_{\text{confluence}} + \underbrace{\frac{1}{2} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2}_{\text{shear}} \right]^{3/2}. \quad (2)$$

where $c = 0.2$ is the dimensionless Smagorinsky constant multiplied with a length scale, usually Δx , for both the x and y directions. This approach was initially developed to keep the overall circulation stable in flows with large gradients (Smagorinsky 1963, 1990). The scheme’s HLS depends on Δx and is suitable for LES assuming 3D turbulence isotropy. However, this approach is unphysical for mesoscale simulations, because turbulence length scales usually vary in time and space and depend on real physical processes (Stull 1988). Furthermore, it is not clear whether Δx as a length scale is the right choice for mesoscale simulations in complex terrain, because HSP-generating processes are sensitive to terrain representation (Schmidli et al. 2018). Despite its deficiencies, this scheme was applied in Goger et al. (2018) and led to a more successful simulation of TKE compared to the turb_1D

scheme. We will use this turbulence scheme for further reference and call it “turb_hybrid” hereafter.

3) NEW HORIZONTAL LENGTH SCALE FOR THE TURB_HYBRID SCHEME (TURB_PSEUDO3D)

Since both the turb_1D and turb_hybrid schemes have some disadvantages, we develop a new length scale for HSP in HCT. The simplest approach for a turbulence length scale is

$$\lambda = U\tau, \quad (3)$$

where U is the velocity scale and τ is the corresponding time scale. Since our study area is dominated by HCT, we aim for an HLS that takes spatial inhomogeneities and the ABL structure into account.

Therefore we use the mean horizontal wind speed U as a velocity scale. As a time scale we choose the Lagrangian integral time scale (LIT) T_L , which can be interpreted as the “memory of turbulence” (Wyngaard 2010): Large values of T_L correspond to low turbulence exchange, whereas small values of T_L suggest a highly turbulent boundary layer. Hanna (1982) formulated a basic parameterization for the LIT:

$$T_{L,u,v} = 0.15 \frac{z_i}{\sigma_{u,v}}, \quad (4)$$

where $T_{L,u}$ and $T_{L,v}$ are the streamwise and spanwise LITs, z_i is the ABL height, and σ_u and σ_v are the streamwise and spanwise horizontal velocity variances. The LIT is an important quantity for turbulent dispersion modeling and is dependent on the state of the ABL. Equation (4) is a largely simplified parameterization approach, based on empirical relations derived from observations from the Minnesota ABL experiments (Kaimal et al. 1976; Kaimal and Wyngaard 1990).

In HCT, many methods exist to determine the ABL height z_i . Since the new turbulence length scale should be useful for various applications, we decide to determine the ABL height through a bulk Richardson number approach as described in Seibert et al. (2000):

$$\text{Ri}_b(z) = \frac{g z [\theta(z) - \theta(z_1)]}{\bar{\theta} u^2(z) + v^2(z)}, \quad (5)$$

where g is the acceleration due to gravity, $\bar{\theta}$ is the mean potential temperature over the column, z is the current height, z_1 is the height of the lowest model level, and u and v are wind components. The ABL height is defined as the height at which the bulk Richardson number reaches a critical value Ri_c . In the COSMO model, a

value of $Ri_c = 0.22$ (Vogelezang and Holtslag 1996) for unstable conditions ($\partial\theta/\partial z < 0$) and a value of $Ri_c = 0.33$ (Wetzel 1982) for stable conditions ($\partial\theta/\partial z > 0$) is used. The atmospheric stability is determined from the potential temperature profile extracted from the four lowest model levels. This method has been applied in previous studies to determine the ABL height from model output (e.g., Szintai et al. 2010; Collaud Coen et al. 2014; Duine and De Wekker 2017).

The values of σ_u and σ_v are determined with an indirect approach. Ideally (i.e., over flat terrain) one would use parameterized profiles of the velocity variances (σ_u , σ_v , and σ_w) to assess the relative contribution of each velocity variance to the TKE and distribute the TKE obtained from the model parameterization accordingly. Since we are not aware of such published variance profiles for complex terrain, we use as a first guess ideal-terrain profiles. In their air pollution modeling work, Rotach et al. (1996) and De Haan and Rotach (1998) suggest functions for the determination of the velocity variances for unstable [Eqs. (6)–(8)] and stable [Eqs. (9)–(11)] conditions, respectively:

$$\frac{\sigma_u^2}{u_*^2} = 0.35 \left(\frac{z_i}{\kappa L} \right)^{2/3} + \left(5 - 4 \frac{z}{z_i} \right), \quad (6)$$

$$\frac{\sigma_v^2}{u_*^2} = 2 \left(1 - \frac{z}{z_i} \right), \quad (7)$$

$$\frac{\sigma_w^2}{w_*^2} = 1.5 \left(\frac{z}{z_i} \right)^{2/3} \exp \frac{-2z}{z_i} + \left(1.7 - \frac{z}{z_i} \right) \left(\frac{u_*}{w_*} \right)^2, \quad (8)$$

$$\frac{\sigma_u^2}{u_*^2} = \left(5 - 4 \frac{z}{z_i} \right), \quad (9)$$

$$\frac{\sigma_v^2}{u_*^2} = 2 \left(1 - \frac{z}{z_i} \right), \quad \text{and} \quad (10)$$

$$\frac{\sigma_w^2}{w_*^2} = 1.4 \left(1 - \frac{z}{z_i} \right). \quad (11)$$

Here, u_* is the friction velocity, κ is the von Kármán constant, L is the Obukhov length, and w_* is the convective velocity scale. Summarizing this indirect approach, we introduce the stability and location dependence of the velocity variances, based on ideal-terrain similarity profiles, to estimate their relative importance under the constraint that they sum up to the modeled TKE. The resulting two horizontal variances are then used for the calculation of the LIT [Eq. (4)]. This approach is preferred over a simpler one (e.g., assuming isotropy), because the ratio of the

velocity variances has a diurnal variation, dependent on the ABL state.

The new HSP term results:

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{q^2}{2} \right)_{\text{HSP}} &= U^2 T_{L,u} T_{L,v} \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 \right. \\ &\quad \left. + \frac{1}{2} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right]^{3/2}, \end{aligned} \quad (12)$$

and is added to the model's TKE equation [Eq. (1)] instead of Eq. (2). This scheme is similar to the `turb_hybrid` scheme, but with a different HLS, and is labeled “`turb_pseudo3D`” in the following.

3. Case study

We choose 1 July 2015 for a case study on the turbulent structure of the ABL. This day was dominated by weak synoptic forcing, leading to a well-developed thermally induced wind circulation in the Inn Valley including a strong up-valley wind in the afternoon. This day was also used in the detailed TKE budget analysis of Göger et al. (2018) with the `turb_1D` and `turb_hybrid` schemes.

a. Time series

1) HLS

Figure 2 shows time series of the calculated HLS from the simulation with the `turb_pseudo3D` scheme [where $T_L = (T_{L,u} T_{L,v})^{1/2}$] together with $\lambda = c\Delta x$ of the `turb_hybrid` scheme from the lowest model level (Figs. 2a,c) and the horizontal wind speeds and directions from the `turb_pseudo3D` scheme with observations (Figs. 2b,d) from two i-Box stations (CS-VF0, at the valley floor, and CS-NF27, at the north-facing slope).

The HLS of the `turb_pseudo3D` scheme is generally small when almost no turbulence is present (during the nighttime), but this changes when the sun rises (around 0530 UTC): λ starts to increase at both stations. At the valley-floor site (Fig. 2a), the first peak is related to the onset of turbulence in the morning and the developing convective ABL; at the north-facing-slope station (Fig. 2b), weak upslope flows (Fig. 2d) directly emerge after sunrise (0530 UTC) and last until they weaken because the lower part of the north-facing slope is then shaded in the east–west-oriented valley (around 0900 UTC). The onset of the up-valley wind is around noon (1200 UTC) with a change in wind direction toward easterlies at the valley-floor station (Fig. 2b), and this is also visible in the HLS. At the valley floor, the

FIG. 2. Time series from the lowest model level of the HLS of the turb_pseudo3D scheme (purple colors) together with the HLS from the turb_hybrid scheme (blue) at two different sites: (a) CS-VF0 and (c) CS-NF27 (see Fig. 1). Also shown are time series of wind speed (orange) and wind direction (blue) of model output [solid line: median of ensemble; dashed lines: mean of ensemble; shaded areas: 75th percentile (dark) and 90th percentile (light) of the ensemble] from the turb_pseudo3D scheme and observations (dots in corresponding colors) from two i-Box stations: (b) CS-VF0 and (d) CS-NF27.

HLS reaches its second maximum in the afternoon at 1500 UTC (Fig. 2a), synchronous with the maximum in horizontal wind speed. The HLS from the turb_pseudo3D scheme is larger than the constant length scale from the turb_hybrid scheme during the up-valley wind phase, related to strong wind speeds reaching up to 7 m s^{-1} .

The situation is different at the north-facing-slope station with a weaker influence from the up-valley wind, visible in wind speeds not exceeding 3 m s^{-1} . This results in a smaller HLS of the turb_pseudo3D scheme, and only its maximum reaches the values of $\lambda = c\Delta x$ of the turb_hybrid scheme. In the late afternoon, with decreasing wind speeds, the HLS of the turb_pseudo3D scheme also decreases until it again reaches almost zero in the nighttime.

2) HSP

Figure 3a shows the modeled HSP of TKE from the turb_1D scheme, the turb_hybrid scheme, and the turb_pseudo3D scheme together with the resulting TKE (Fig. 3b) and observations from the valley-floor station (CS-VF0). The turb_1D scheme clearly underestimates the TKE values in the afternoon hours when the up-valley wind is dominant. The schemes with HSP (turb_hybrid and turb_pseudo3D) simulate the TKE between 1200 and 1800 UTC more realistically.

The turb_pseudo3D scheme is able to capture HSP starting at 1200 UTC with a steeper increase than the

turb_hybrid scheme. The maxima in HSP of the turb_pseudo3D and turb_hybrid schemes are synchronous—however, the new scheme produces higher values of HSP in better agreement with the HSP maximum of the observations. When the valley wind weakens, the HSP decreases faster until it reaches almost zero at 1800 UTC in the turb_pseudo3D scheme. This can be explained with the strong decrease in wind speed until 1800 UTC (Fig. 2) and the turb_pseudo3D scheme's dependence on the wind speed. The model is now able to simulate a sharp decrease during the evening transition while the turb_hybrid scheme suggests a more gradual decrease.

At the north-facing-slope station (CS-NF27), the turb_1D scheme produces too-low TKE values (Fig. 4), mainly because the vertical shear production is underestimated by the model, visible in the too-small TKE values simulated by the turb_1D scheme [for the full TKE budget see Goger et al. (2018), their Fig. 5]. On the other hand, the turb_hybrid scheme produces large amounts of HSP leading to TKE values close to the observations. Combined with the underestimated vertical shear production, this leads to “correct” TKE values rather by chance than based on capturing the right physical processes. When the turb_pseudo3D scheme is employed, the TKE simulation is better than in the turb_1D scheme, but still underestimating the TKE in the afternoon. This is due to two reasons: the turb_pseudo3D scheme produces less HSP, because a smaller HLS is calculated than in the

FIG. 3. Time series of observations (connected black dots) and the gridpoint ensemble of model output [line: median of ensemble; dashed lines: mean of ensemble; shaded areas: 75th percentile (dark) and 90th percentiles (light) of the ensemble] of the (a) HSP and (b) TKE from the lowest model level at the valley-floor station (CS-VF0) from the three schemes *turb_1D* (orange), *turb_hybrid* (blue), and *turb_pseudo3D* (pink). Note that the observations of HSP are crude estimates that are based on differences at different i-Box sites to approximate the differentials (see section 2a).

turb_hybrid scheme (Fig. 3c). The second reason is that the vertical shear production is underestimated by the model. Since the lowest model level is located at 10 m above ground, it is likely that with this vertical grid spacing the slope flows are not resolved accurately, resulting in a too-weak vertical wind speed gradient for a realistic simulation of vertical shear production.

3) SIMULATIONS WITH $\Delta x = 2.2$ KM AND VARIOUS HORIZONTAL LENGTH SCALES

As outlined in the introduction, the major motivation of this work is to replace the unphysical HLS of the *turb_hybrid* scheme with a physically more founded length scale. One of the requirements for this new length scale would be that it does not depend on Δx or the choice of the parameter c . To evaluate the sensitivity of the *turb_hybrid* scheme we conducted a number of simulations on two horizontal grid spacings ($\Delta x = 1.1$ and $\Delta x = 2.2$ km) and changed the default HLS, which is $c\Delta x$. An overview of the simulations is shown in Table 1. The changed HLSs are $\lambda = c500$ and $\lambda = c2000$ m for the $\Delta x = 1.1$ km, and $\lambda = c1000$ m for $\Delta x = 2.2$ km, respectively, to test the impact of an either halved (or doubled) HLS.

FIG. 4. As in Fig. 3, but for the station on the north-facing slope (CS-NF27).

Figure 5 shows the time series of TKE from 1 July 2015 with two different grid spacings ($\Delta x = 1.1$ and $\Delta x = 2.2$ km) for the three turbulence schemes and the additional simulations with various length scales of the *turb_hybrid* scheme. At $\Delta x = 2.2$ km, all simulations fail to represent the timing and the magnitude of the TKE maximum. Apparently, at this Δx the model is not suitable for simulating all relevant processes, such as the up-valley wind, appropriately. Wagner et al. (2014) showed that at least $\Delta x = 1.1$ km is required for the correct representation of the dimensions of the Inn Valley in a NWP model. Even the “best” turbulence scheme cannot compensate for that, as long as the topography is not represented correctly. The *turb_hybrid_dx2_L2200* scheme, which would be the default setting if the *turb_hybrid* scheme is chosen, shows unrealistically high values of TKE. The magnitude of TKE in the *turb_1D* and *turb_pseudo3D* schemes is smaller, mainly because HSP is not unrealistically high; however, the TKE is still overestimated, mainly due to too-high vertical shear production.

The *turb_hybrid_dx1_L1100* and *turb_pseudo3D_dx1* schemes with $\Delta x = 1.1$ km are the best choice to simulate the TKE structure at the valley floor. The *turb_hybrid_dx1_L500* scheme underestimates TKE values like the *turb_1D_dx1* scheme, suggesting that half the default HLS is already too low for an HLS at $\Delta x = 1.1$ km. The *turb_hybrid_dx1_L2000* scheme, with doubled HLS, leads to an overestimation of TKE. To conclude, an HLS on the order of 1 km is

TABLE 1. Overview of the simulations with the three turbulence schemes and two horizontal grid spacings (indicated by “dx” in the abbreviated scheme name). The turb_hybrid scheme has three additional test simulations with different HLSs in meters (indicated by “L” in the abbreviation).

Grid spacing	turb_1D	turb_pseudo3D	turb_hybrid
$\Delta x = 1.1$ km	turb_1D_dx1	turb_pseudo3D_dx1	turb_hybrid_dx1_L1100 (default) turb_hybrid_dx1_L500 turb_hybrid_dx1_L2000
$\Delta x = 2.2$ km	turb_1D_dx2	turb_pseudo3D_dx2	turb_hybrid_dx2_L2200 (default) turb_hybrid_dx2_L1000

appropriate for TKE simulation in the Inn Valley. However, the turb_hybrid scheme has to be tuned and tested to find the right HLS for each area of interest, suggesting that it is not automatically suitable for any other location in HCT. The turb_pseudo3D scheme is able to capture the right physical processes without a grid spacing dependency and is therefore universally applicable.

b. Vertical profiles

Figure 6 shows the vertical profiles from the model output at the valley-floor station (CS-VF0) at 1300 UTC. The vertical profile of HSP at CS-VF0 (Fig. 6a) shows a clear maximum near the surface with both the turb_hybrid and the turb_pseudo3D schemes. The HSP has a secondary maximum at around 250 m AGL in the turb_pseudo3D scheme, because the strong up-valley wind has a jetlike structure with high wind speeds through the vertical column of the valley atmosphere (Goger et al. 2018). This is also evident from the vertical TKE profile (Fig. 6b): The turb_pseudo3D scheme produces higher TKE values at around 500 m above ground level (AGL) while this secondary maximum is not present in the turb_hybrid simulation.

Unfortunately, we do not have observations of vertical profiles of TKE from the current case study day (1 July 2015) to validate this secondary TKE maximum and therefore use scaling arguments. Baur (2015) analyzed aircraft observations of TKE in the Inn Valley from three valley wind days in late summer 2013 and applied mixed-layer scaling after Deardorff (1970) to the observed TKE profiles. This method was already successfully used for TKE scaling in a study in the Rivera Valley, Switzerland (Weigel and Rotach 2004). Weigel et al. (2007b) have demonstrated that daytime TKE profiles in a steep valley scale well using surface data (i.e., surface sensible heat flux) from a site within the valley where the heat flux is closely correlated to the strength of the (bulk) valley wind. The convective velocity scale

$$w_* = [(g/\theta_0)z_i \overline{w'\theta'_0}]^{1/3}$$

is therefore taken from the north-facing-slope station CS-NF10, because Baur (2015) determined in the aforementioned study this station as an “optimal site” for the scaling of TKE profiles in the Inn Valley.

FIG. 5. Time series of observed TKE (black dotted line) and simulated TKE from various horizontal shear parameterization options (colors; listed in Table 1) from the valley-floor station (CS-VF0).

FIG. 6. Vertical profiles from the valley-floor station (CS-VF0) at 1300 UTC of (a) the HSP, (b) the TKE, and (c) the scaled TKE profile after Baur (2015). The different colors represent the three different schemes (orange: turb_1D; blue: turb_hybrid; pink: turb_pseudo3D), and the lines in (c) denote the linear regression line obtained from observations in the Rivera Valley (dashed line) after Weigel and Rotach (2004) and the Inn Valley (black line) after Baur (2015).

Figure 6c shows the result when the scaling is applied to the vertical TKE profile from the model output of all three turbulence parameterizations. The dashed black line denotes the linear regression line from the Rivera Valley, while the full black line denotes the linear regression line determined for the Inn Valley by Baur (2015). The scaled vertical profiles of the turb_1D and turb_hybrid schemes show little agreement with the regression lines, especially at upper levels (between $z/z_i = 0.2$ – 1). On the other hand, the TKE values of the turb_pseudo3D scheme show a better match with the regression lines; and the agreement with the “Inn Valley scaling” by Baur (2015) is especially good. This allows us to conclude cautiously, although we are comparing different days, that large values of TKE at upper levels (as modeled with the turb_pseudo3D scheme) in the Inn Valley are realistic.

c. General ABL structure

Figure 7 shows the vertical south-to-north transect across the Inn Valley in the south, the Karwendel mountains with many smaller valleys, and the Alpine foreland in the north. The chosen simulation is from the turb_pseudo3D scheme, and the time is 1500 UTC when the up-valley wind in the Inn Valley reaches its maximum and the HSP at the valley floor is strongest. In the upper part of the north-facing slope of the Inn Valley, weak upslope flows

still prevail, while in the lower part of the valley the strong up-valley wind dominates, with a wind speed maximum up to 10 m s^{-1} in the valley center. The smaller side valleys in the Karwendel mountains have no such strong up-valley wind; in general, the flow structure is southerly, suggesting that the general plain-to-mountain circulation is overlapping local slope flows and/or up-valley winds.

Figure 7b shows the TKE distribution, where the black contour lines show the difference in TKE values from the simulation with the turb_1D scheme. At the height of the mountaintops, TKE reaches values up to $3 \text{ m}^2 \text{ s}^{-2}$ due to strong mountaintop shear (also observed in Weigel et al. 2007b). The ABL in the Inn Valley and the side valleys is well developed; TKE reaches values of up to $2 \text{ m}^2 \text{ s}^{-2}$ in the Inn Valley at the same location where a strong horizontal wind speed gradient is present. The strong TKE maximum related to the horizontal wind speed gradient and the high TKE values throughout the valley are the major differences to the turb_1D scheme, where no such inhomogeneous TKE structure is present. Furthermore, the turb_pseudo3D scheme simulates larger TKE values than the turb_1D scheme throughout the valley. If we see TKE as an indicator of a turbulent ABL, this transect shows that the turb_pseudo3D scheme is able to simulate a much deeper, but also a more heterogeneous ABL, which is likely more realistic.

FIG. 7. Interpolated cross sections along the orange line in the inset in the upper-right corner of (b) at 1500 UTC from the turb_pseudo3D simulation of 1 Jul 2015 showing (a) along-valley wind speed (colors), the projection of the horizontal wind component to the cross section with the vertical component (wind vectors), and potential temperature (contours; intervals every 1 K) and (b) TKE (color contours) and TKE difference between the turb_pseudo3D and turb_1D schemes (black contour lines; intervals every $0.2\text{-m}^2\text{s}^{-2}$ and positive values denote more TKE in the turb_pseudo3D scheme).

4. Model validation

a. TKE in the Inn Valley

One single case study might not be representative of the full impact of the turb_pseudo3D scheme. Therefore, we simulated three additional valley wind days besides 1 July 2015 in the Inn Valley: 16 September 2014, 29 August 2015, and 8 September 2015. These days were also used for the model validation in Goger et al. (2018). Over these four days, we calculate the bias and the rmse as follows:

$$\text{bias} = \frac{1}{N_s} \sum_{s=1}^{N_s} \left(\frac{1}{N_t} \sum_{t=1}^{N_t} M_i - O_i \right) \quad \text{and} \quad (13)$$

$$\text{rmse} = \left\{ \frac{1}{N_s} \sum_{s=1}^{N_s} \left[\frac{1}{N_t} \sum_{t=1}^{N_t} (M_i - O_i)^2 \right] \right\}^{1/2}, \quad (14)$$

where M_i is the median of the gridpoint ensemble, O_i are the i-Box observations, N_t is the number of time steps, and N_s is the number of i-Box stations taken into account.

Table 2 shows the averaged bias and rmse values of TKE averaged over stations at or close to the valley floor under the influence of a strong up-valley wind (CS-VF0, CS-SF1, and CS-SF9), and of slope stations with lower wind speeds (CS-NF11 and CS-NF27). As a time period,

we choose the up-valley wind phase, roughly between 1200 and 1800 UTC. The three different schemes exhibit the largest differences in TKE simulation during the up-valley wind phase because HSP is strongest at this time period (see Figs. 3 and 4). For the other time periods, the differences due to the parameterization scheme are small as pointed out in Goger et al. (2018), because the dominant source of TKE is not shear production.

The turb_1D scheme underestimates simulated TKE at both the valley floor and the slopes visible in the bias. This changes with the turb_hybrid scheme: The bias is reduced, but is positive at the valley floor stations under a strong up-valley wind influence, suggesting too-high values of HSP in the scheme. The turb_pseudo3D scheme shows a similar behavior as the turb_hybrid scheme: The TKE is overestimated at the valley floor with a larger variability in TKE suggesting higher inhomogeneity of the TKE structure, mainly visible in the rmse values.

A different pattern is visible at the slope stations (CS-NF10 and CS-NF27): The turb_1D scheme strongly underestimates TKE, while the turb_hybrid scheme produces too much TKE. The high values of TKE by the turb_hybrid scheme are mainly a result of the scheme producing unrealistically high values of HSP. The turb_pseudo3D scheme shows a reduction in both bias and rmse relative to the other two schemes, although the

TABLE 2. Bias and rmse of TKE of four simulated valley wind days with the three schemes turb_1D, turb_hybrid, and turb_pseudo3D for the time period of the up-valley wind phase (between 1200 and 1800 UTC). “Valley floor” includes the averaged values of sites CS-VF0, CS-SF8, and CS-SF1; “slopes” includes the values of CS-NF10 and CS-NF27. The averaged values over all five stations are summarized in “Overall.”

	Bias ($\text{m}^2 \text{s}^{-2}$)			Rmse ($\text{m}^2 \text{s}^{-2}$)		
	turb_1D	turb_hybrid	turb_pseudo3D	turb_1D	turb_hybrid	turb_pseudo3D
Valley floor	−0.42	0.09	0.25	0.47	0.38	0.47
Slopes	−0.51	0.27	−0.15	0.53	0.47	0.42
Overall	−0.46	0.10	0.08	0.51	0.37	0.43

TKE is still underestimated (visible in the bias value). This is due to two factors: at the north-facing slopes of the Inn Valley wind speed is lower, and vertical shear production is underestimated by the model (also visible in the turb_1D scheme’s bias). Still, the turb_pseudo3D scheme has the lowest rmse value, suggesting the closest match to the observations.

The averaged values for all i-Box stations (“Overall” in Table 2) show that the turb_pseudo3D scheme is able to simulate the 3D processes as well as the turb_hybrid scheme does and also leads to a reduction in bias and rmse relative to the turb_1D scheme.

b. Meteorological variables across Austria

Göger et al. (2018) have shown that the impact of a 3D turbulence scheme such as the turb_hybrid scheme on mean meteorological fields is minor, but positive. For example, the turning of the wind associated with the upslope flows in the morning is simulated more accurately. All this was based on the same experimental data (i-Box sites), which were used to develop and test the turbulence scheme. However, we cannot rule out that the introduction of a new turbulence scheme might have a negative impact at other locations, where we cannot check the validity of the TKE simulation due to missing turbulence measurements.

Therefore, although the turbulence schemes including 3D shear production positively influence the ABL representation in the model, we have to assess their influence on general meteorological fields. For operational approaches, it is important that a new parameterization scheme does not lead to a worse model performance than with the previous parameterization scheme. Therefore, we selected data from 88 automatic weather stations across Austria for the four case study days mentioned in section 4a with the same numerical setup as described in section 2b. The diagnostic model variables 2-m temperature, 2-m relative humidity, and 10-m wind speed are compared against observations and the rmse is calculated over the entire four days (24 h) with Eq. (14). The 24-h bias values contain compensating errors due the strong diurnal cycle of the quantities, therefore, we do not show them.

Table 3 shows the results for the three different turbulence schemes. The turb_pseudo3D scheme was initially designed to account for the inhomogeneity of HCT, therefore we divide the station locations in “HCT” and “flat terrain” to evaluate its impact. The criterion for HCT is met when the subgrid-scale orography (SSO) standard deviation, calculated after Baines and Palmer (1990), exceeds 50 m. All the other stations with SSO standard deviation below 50 m are classified as flat terrain, resulting in 54 stations meeting that criterion.

TABLE 3. Rmse of three standard meteorological variables (2-m temperature, 2-m relative humidity, and 10-m wind speed from diagnostic model output) of four simulated valley wind days with the three schemes (turb_1D, turb_hybrid, and turb_pseudo3D) for the whole simulation time of 24 h. Stations with an SSO standard deviation below 50 m are classified as “flat terrain,”; stations with and SSO standard deviation larger than 50 m are classified as “HCT.” The averaged values over all 88 stations across Austria are summarized in “Overall.”

	Terrain	Rmse turb_1D	Rmse turb_hybrid	Rmse turb_pseudo3D
2-m temperature (K)	HCT	2.09	2.07	2.09
	Flat terrain	1.49	1.48	1.48
	Overall	1.72	1.71	1.71
2-m relative humidity (%)	HCT	10.95	10.58	10.40
	Flat terrain	8.92	8.91	9.17
	Overall	9.70	9.55	9.65
10-m wind speed (m s^{-1})	HCT	1.12	1.12	1.14
	Flat terrain	1.05	1.06	1.06
	Overall	1.08	1.08	1.09

A comparison of the three turbulence schemes shows almost no difference in the rmse of the 2-m temperature, suggesting that the `turb_hybrid` and `turb_pseudo3D` schemes do not alter the model performance. The only difference in rmse is visible between the HCT stations and the flat-terrain stations, suggesting that complex topography is still a factor leading to worse model performance. The changes in 2-m relative humidity remain very small with the introduction of 3D effects. For 10-m wind speed, no differences between the turbulence schemes or the different locations are found.

To summarize, the `turb_pseudo3D` scheme does not affect the model performance in a negative way for our four case study days. The rmse remains the same for most of the variables suggesting that the 3D effects do not worsen (and do not improve) the overall model performance for both complex and flat terrain, while the ABL representation is improved.

5. Discussion

The present study highlights the important contribution of HSP to the TKE budget in HCT. The two parameterization schemes with HSP (`turb_hybrid` and `turb_pseudo3D`) simulate TKE in a more realistic way than the 1D Mellor–Yamada scheme (`turb_1D`) when a strong up-valley wind is present, although all three schemes show similar performance before noon (with a convective ABL) and during the nighttime (with a stable ABL). The `turb_pseudo3D` scheme is able to produce HSP at the correct time and location when it is required and performs as well as the `turb_hybrid` scheme for the general meteorological fields (see Table 3). Its major advantage is that the HLS is variable in space and time, reflects the local turbulence state and is not dependent on the grid spacing (which is not appropriate in a mesoscale model).

The `turb_pseudo3D` scheme's HLS depends on a quite simple parameterization of the LIT after Hanna (1982). This parameterization is also used in other models, for example, in the FLEXPART model (Stohl et al. 2005), but the major difference is that it is applied for another purpose, namely, particle dispersion. To our knowledge, the LIT after Hanna (1982) has not yet been used for the parameterization of HSP in models. Other parameterizations of horizontal exchange (e.g., Zhang et al. 2018), which also account for gray-zone grid spacings, often depend on Δx by altering the “known” parameterizations from LES (Smagorinsky 1963; Deardorff 1980). These new schemes might deliver promising results over flat terrain; however, they encounter the same problems as the `turb_hybrid` scheme, since Δx is a major factor for the correct simulation of

physical processes in HCT (Wagner et al. 2014). As shown in Fig. 5, a sufficiently small Δx does not necessarily correspond to an optimal HLS in the TKE parameterization. The `turb_pseudo3D` scheme is ideal for applications in HCT, because it is able to capture HCT-related 3D processes without a grid spacing dependency. We tested the `turb_pseudo3D` scheme for situations, where strong HSP was expected to occur—namely, a valley wind day in HCT. However, the `turb_pseudo3D` scheme still should be evaluated for other locations and especially also for other weather situations.

We chose the Richardson number method to determine the ABL height in HCT, but numerous other methods exist to determine the ABL height (Seibert et al. 2000; Wagner et al. 2014; Lehner and Rotach 2018). Another possible method is to detect a certain threshold in the vertical profile of TKE (Weigel et al. 2007b). This approach could be alternatively used for the `turb_pseudo3D` scheme because of the high TKE values throughout the valley atmosphere (Figs. 6 and 7). The large ABL height would therefore lead to higher HSP throughout the valley atmosphere—however, the determination of the ABL height with a certain TKE threshold in the model still needs further development. When TKE is taken as an indicator of a turbulent ABL, the model abandons the often criticized terrain-following ABL of coarse NWP models and moves toward the so-called mountain boundary layer concept as described in Lehner and Rotach (2018): The `turb_pseudo3D` scheme can account for terrain heterogeneity, and therefore the simulated ABL over the Alps becomes more inhomogeneous.

The observations that we have—TKE time series, the model validation, and the scaled vertical profiles of TKE—give a first overview and suggest that the `turb_pseudo3D` scheme is able to generate horizontal contributions to the TKE budget in a realistic way. However, the `turb_pseudo3D` scheme definitely needs further testing and a more detailed evaluation and validation. The LIT can be estimated from the autocorrelation of turbulence spectra from flux tower observations. However, the direct comparison between the observed T_L from spectra and the parameterized T_L from the model might be difficult, because the model does not resolve all observed scales. Another approach is to compare the HSP with observations. However, observing HSP is in general a challenge, because this requires an array of turbulence flux towers or remote sensing systems, which are expensive appliances often only used in measurement campaigns. Observed vertical TKE profiles in HCT would also give important information to validate the `turb_pseudo3D` scheme's performance in TKE simulation.

6. Summary and conclusions

Mesoscale atmospheric modeling faces numerous challenges in highly complex terrain. One of those challenges is the right choice of a turbulence representation. We performed numerical simulations with different horizontal length scales for horizontal shear production in very complex terrain. Besides a 1D turbulence scheme considering only vertical exchange (turb_1D), and a 3D turbulence scheme adding HSP to the TKE budget with an HLS that is dependent on Δx (turb_hybrid), we introduced a new HLS based on physical processes and varying in time and space (turb_pseudo3D). We evaluated the model performance in an Alpine valley with case studies when a strong up-valley wind associated with HSP is present. During the up-valley wind phases, 3D effects are essential for the correct simulation of TKE as shown by our results. The time series of TKE simulated with the turb_pseudo3D scheme yield best results at stations with a strong up-valley wind. Vertical profiles of simulated TKE and cross sections of the ABL suggest that the turb_pseudo3D scheme is able to simulate a realistic ABL over mountainous terrain. This leads to the following conclusions:

- 1) The HLS of the new turb_pseudo3D scheme has a physical meaning based on the ABL height, the horizontal velocity variances, and the mean horizontal wind speed. This leads to a diurnal and spatial variation of the length scale.
- 2) During the up-valley wind phase, when strong HSP is present, the turb_pseudo3D scheme leads to a realistic simulation of TKE on the valley floor, performing better than the turb_hybrid scheme (with a constant HLS).
- 3) At slope stations, the improvement in TKE simulation with the turb_pseudo3D scheme is not as large, mostly because of low wind speeds and the underestimated vertical shear production. The turb_hybrid scheme, on the other hand, exhibits too-large HSP of TKE, thus rendering the resulting TKE to be very “accurate”—albeit for the wrong reason.
- 4) The model validation with TKE observations shows that the turb_pseudo3D scheme is not much better than the turb_hybrid scheme for the four simulated days. This is likely due to the fact that—for exactly this region, such days and the horizontal grid spacing ($\Delta x = 1.1$ km)—the turb_hybrid scheme turns out to be “perfect” by chance. However, its physical background makes the turb_pseudo3D scheme more likely transferable to other sites.
- 5) The vertical profiles of TKE as simulated by the turb_pseudo3D scheme suggest higher TKE values throughout the valley atmosphere than with the other

two schemes (turb_1D and turb_hybrid). An application of ABL scaling to the vertical profiles shows favorable agreement with the regression lines from observations, pointing toward the realistic character of higher TKE values at upper levels.

- 6) The overall TKE structure over mountainous terrain is altered by the turb_pseudo3D scheme compared to the 1D scheme. Because of the high values of TKE throughout the valley atmosphere, the ABL becomes more spatially inhomogeneous corresponding to the underlying mountains and is not terrain following anymore.
- 7) The turb_pseudo3D scheme yields improvements to the TKE representation in the model. However, a model validation over 88 stations in Austria shows that the choice of the turbulence scheme has a minor impact on simulated near-surface values. This suggests that the model simulates a better turbulence structure and a better transferability of the new turb_pseudo3D scheme (relative to the turb_hybrid scheme) without altering the traditionally verified quantities.

Horizontal contributions are essential for the TKE budget in an Alpine valley. Furthermore, their correct representation in mesoscale NWP models is not trivial and should include a correct physical background. An improved simulation of the ABL in a mesoscale model brings benefits to multiple meteorological applications in complex terrain, for example, ecology, agriculture, urban planning, wind energy, transportation, air pollution, and climate change (De Wekker et al. 2018). Therefore, more research at locations dominated by mountainous topography, especially on the experimental side (e.g., extensive measurement campaigns), might shed more light on 3D turbulent processes and their mechanisms.

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