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Open questions in atmospheric turbulence: A synthesis from the centenary workshop "100 years of turbulence: Innsbruck 1922 -2022"

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ABSTRACT

In this contribution, we summarize salient findings, discussion points, and community recommendations resulting from the workshop "100 Years of Turbulence: Innsbruck 1922 –2022", held as a centenary celebration of the First meeting on "Hydro- and Aero-dynamics" that took place in Innsbruck in 1922. Participants from numerous countries and continents discussed the significant achievements and major remaining challenges related to atmospheric turbulence over different types of complex surfaces (inhomogeneous terrain, impact of orography, and large roughness elements such as trees or buildings), as well as stratified and non-stationary turbulence. For each of these contexts, directions for future research were proposed, recognizing that current numerical weather and climate models treat turbulence as an unresolved process at the grid-cell scale.

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1. Introduction

Fluid dynamics and especially the turbulent flow of fluids remains “the most important unsolved problem of classical physics" (Feynman et al., 1964). Yet, over the course of the past century, major advances have allowed fluid dynamics to become a core element of accurate weather forecasting, climate projections, and reliable engineering applications. Still, many challenges in understanding and modelling atmospheric turbulence in real-world applications remain. A Workshop on Atmospheric Turbulence with the topic “100 Years of Turbulence: Innsbruck 1922 – 2022“ (Fig. 1) was held from 3 – 5 November 2022 in Innsbruck, Austria, to review remarkable achievements, outline major challenges, and propose directions for future research in atmospheric turbulence. Hosted by the Atmospheric Turbulence group of the Department of Atmospheric and Cryospheric Sciences (ACINN) at the University of Innsbruck, it marked the centenary of the first meeting on hydro- and aero-dynamics, organized by Tullio Levi-Civita and Theodore von Kármán, also in Innsbruck in 1922. This historic meeting brought together scientists from different countries, still recovering from the devastation and distrust of the First World War, to exchange novel insights into the emerging field of fluid dynamics. The results and presentations were published in Kármán and Levi-Civita (1925) as a series of benchmark papers by Theodore von Kármán, Ludwig Prandtl, Vilhelm Bjerknes, Vagn Walfried Ekman, and Werner Heisenberg, among others (cf. Fig. 2)

The field of turbulence research has undergone an unfathomable transformation since this initial meeting, with major advances in theory, and especially observations and numerical modelling, allowing deeper insights into the nature of turbulent flows in a range of settings (e.g. planetary atmospheres, oceans, engineering flows) under what we now call *canonical conditions* (horizontally homogeneous and flat terrain, and without large-scale subsidence). The groundwork led by the pioneering giants in the field still forms the foundation of turbulence modelling to this day. With the progress made through higher resolution numerical modelling of weather and climate, especially in complex settings (such as urban and mountainous areas, polar regions, hurricanes), the need for improvements in the understanding and parametrization of turbulent mixing and transport over realistic surfaces, and under a wide range of stratifications, is becoming more acute (cf. Baklanov and Grisogono, 2007; Baklanov et al., 2011), as the role of atmospheric boundary layer turbulence in all atmospheric processes and many critical engineering applications (energy and food production, resilience, transportation, etc.) is becoming increasingly more recognised (e.g., Edwards et al., 2020).

Fig. 1. AI-generated logo of the centennial turbulence workshop held in Innsbruck (AT) in November 2022 using Stable Diffusion v1.4. Note the missing multiscale character of turbulence.

The 2022 meeting therefore focused on turbulence in the atmospheric boundary layer (ABL) over complex surfaces and conditions, and brought together some 50 turbulence researchers from 14 countries and various continents to discuss major advances in the field over the past century, the current state of atmospheric turbulence research, as well as the major challenges encountered today, with the goal to define and prioritize open research questions for the future.

This review offers a brief, non-exhaustive survey of key milestones in turbulence research achieved over the past century (Section 2), followed by the major discussion points for each of the four topics covered in the workshop that form the core of this manuscript (Section 3): stratified and non-stationary turbulence (Section 3.1), turbulence over surfaces with large roughness elements (Section 3.2), turbulence over inhomogeneous surfaces (Section 3.3), and turbulence over complex orography (Section 3.4). We conclude with community recommendations for fostering future advances in the field (Section 4).

2. Advances in turbulence research since the historical meeting of 1922

The past century has seen unprecedented developments in theory, as well as concepts and approaches that have allowed turbulence to be observed, modelled, and parametrized in atmospheric simulations (as reviewed by Haugen, 1973; Nieuwstadt and van Dop, 1982; Holtslag and Duynkerke, 1998; Rotach and Holtslag, 2025). Lighthouse examples of theoretical concepts include: the turbulence cascade (Richardson and Shaw, 1920; Richardson, 1922) and its underlying statistical theory (Kolmogorov, 1941a,b); Monin-Obukhov Similarity Theory (MOST, Obukhov, 1946; Monin and Obukhov, 1954; Businger et al., 1971; Högström, 1996; Foken and Börngen, 2021) and its derivatives (Nieuwstadt, 1984; Willis and Deardorff, 1974; Grachev et al., 2015); concepts such as fine-scale dissipation intermittency (Kolmogorov, 1962), local intermittency and the collapse of continuous turbulence (Derbyshire, 1999; Fernando and Weil, 2010; van de Wiel et al., 2012), as well as global intermittency (Mahrt, 1989; Sun et al., 2004; van de Wiel et al., 2002); the attached eddy hypothesis (Townsend, 1976); turbulent potential energy (Holliday and Mcintyre, 1981; Zilitinkevich et al., 2013); the inverse cascade (e.g., Sagaut and Cambon, 2008; Zilitinkevich et al., 2021) and many more (see LeMone et al., 2019; Garratt et al., 2020, for overview). *Ancestral galleries* of some of the forerunners in the development of these theories are shown in Fig. 2, inspired by Davidson et al. (2011) and Lumley and Yaglom (2001).

These important advances have been enabled by impressive increases in observational and computational capabilities. On the observational side, these include the development of fast-response sonic anemometers, fine-wire thermocouples and other fast-response sensors (e.g., gas analysers/hygrometers, sodars, Doppler wind lidars, scintillometers etc.) able to capture turbulent eddies and key statistics both in the laboratory and in the field (Bovsheverov and Krasilnikov, 1941; Tatarskii, 1961; Kallistratova, 2002; Foken, 2021). Computationally, the development of Reynolds Average Navier Stokes (RANS) models that fully parametrize turbulence using the theoretical understanding, permitted operations and research in weather, climate, and air quality. Only the increase of computational power over recent decades has allowed for the creation and use (at least in research and non-operational applications) of high-resolution simulations in which the dominant turbulence scales (LES, Large Eddy Simulation, Smagorinsky, 1963; Lilly, 1967; Deardorff, 1970; Moeng and Sullivan, 2015; Stoll et al., 2020) or the full turbulence spectrum including the dissipation range are resolved (DNS, Direct Numerical Simulation, Orszag, 1970; Moin and Mahesh, 1998), with the data-driven turbulence modelling using machine learning approaches proliferating over the last few years (Brunton et al., 2020; Ling et al., 2016).

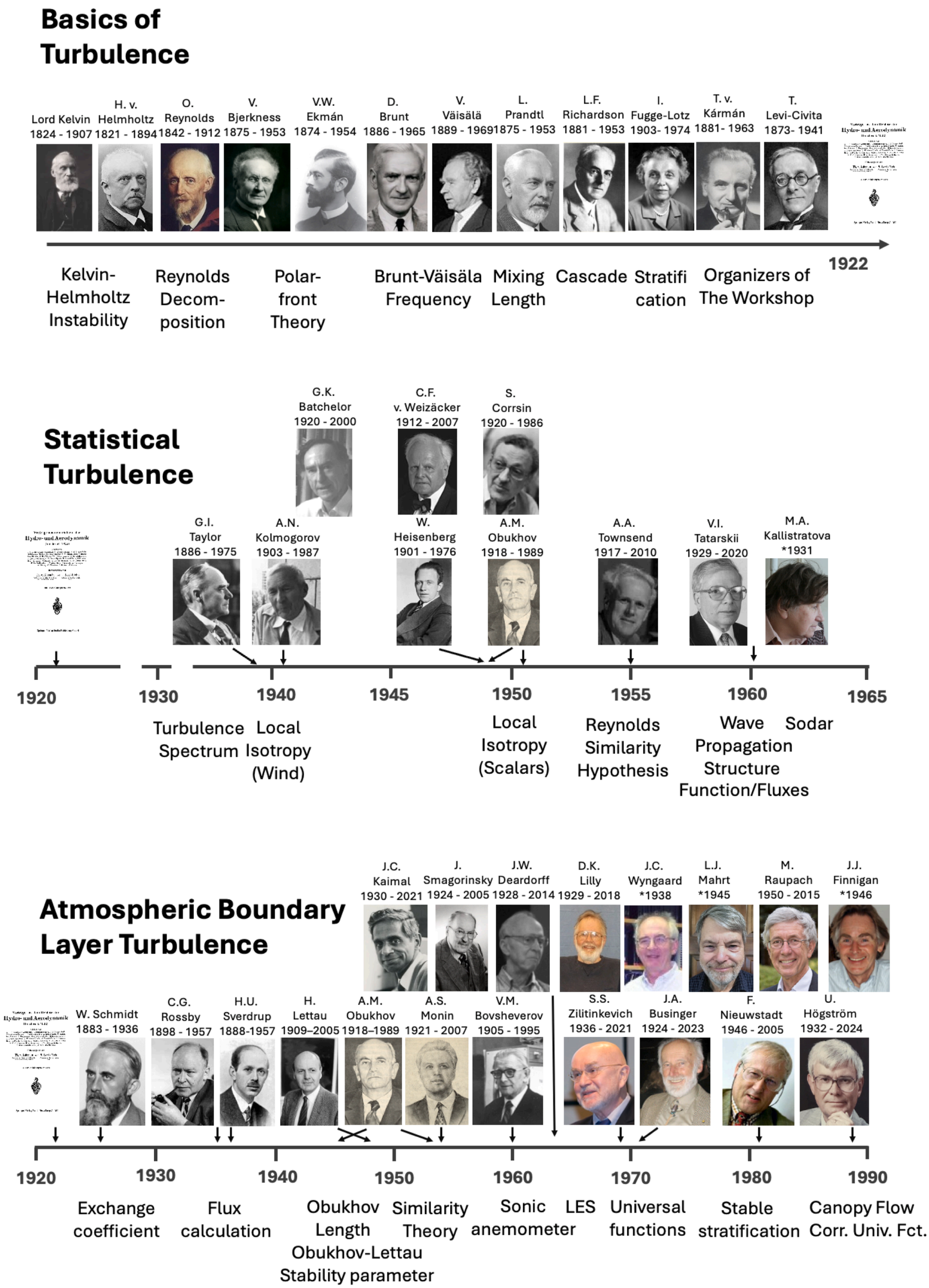

Fig. 2. Historic timeline, names and photographs of a non-exhaustive selection of eminent scientists contributing to different developments in turbulence until the early 90s, from Thomas Foken's presentation.

There is a large consensus that many topics in classical turbulence theory have still not reached a satisfactory level of understanding, description, or predictive skill. In particular, open fundamental questions concern our understanding of how thermally and mechanically driven turbulence interact and what their differences are (e.g., Zilitinkevich et al., 2021), the dynamics and role of coherent structures in turbulent flows (e.g., Deardorff, 1972; LeMone, 1973; Schmidt and Schumann, 1989; McNaughton and Brunet, 2002; Sullivan et al., 2016), the transport of passive and active scalars by turbulence (e.g., Kulmala et al., 2023), the role of turbulent pressure perturbations (e.g., Heinze et al., 2016), the properties of near-wall turbulence (e.g., Marusic et al., 2010), and the theoretical underpinning of similarity theory (e.g., Katul et al., 2011) to name a few. Nonetheless, observational and modelling capabilities over the past 30 years have permitted a major departure from studying only the canonical conditions and embraced more realistic scenarios, especially probing the limits of existing theories in terms of both extreme stable and unstable stratifications, the influence of baroclinity and unsteadiness (e.g., Mahrt and Bou-Zeid, 2020; Ghannam and Bou-Zeid, 2021), as well as realistic surface conditions (e.g., inhomogeneity, orography, plant canopies and urban terrain), and opening up the doors towards universal scaling approaches (e.g., Stiperski and Calaf, 2023).

3. Major challenges in atmospheric turbulence research

3.1. Stratified and non-stationary turbulence

3.1.1. Overview

Stably stratified boundary layers (SBLs) are of considerable scientific and practical importance due to their frequent association with persistent air pollution episodes and degraded performance in numerical weather prediction (NWP) models, particularly in forecasting phenomena such as fog and icing. They are also of emerging importance for renewable energy meteorology. Despite their relevance, SBLs continue to pose significant challenges to theoretical understanding, observational techniques, and numerical modelling. This is especially the case if the stratification is very stable, in which case the flow is often characterized by layering, non-stationary and intermittent turbulence. Thus very stable SBLs manifest themselves through a myriad of different realisations (e.g., upside-down boundary layer, Mahrt, 1999) that escape proper description and magnify our lack of understanding. Compared to the convective boundary layer (CBL), the stratification in SBLs acts as a sink of turbulence kinetic energy (TKE) by reducing its mechanical production (Shah and Bou-Zeid, 2019) and converting it to turbulent potential energy (TPE), so that the resultant forcing of turbulence is weaker but acts on a variety of scales. Turbulent fluxes in SBLs also stem from larger footprints and therefore correspond to larger surface inhomogeneity.

Under very stable stratification, oftentimes, no clear spectral gap separating turbulence from non-turbulent motions is present. Instead, turbulence can become decoupled from the mean flow, and driven by submesoscale motions (e.g., gravity waves and other wave-like motions) that populate the entire range of scales. These external processes cause non-stationarity, intermittency and anisotropy of turbulence (Mahrt, 1999, 2014; Sun et al., 2015; Gucci et al., 2023). At the same time, the observed intermittency can stem from internal variability and instability mechanisms (e.g., bursting, Businger, 1973; Nappo, 1991; van der Linden et al., 2020; Allouche et al., 2022), so that, apart from idealised modelling, it is often unclear which mechanism governs the observed signal. In addition, the non-stationarity pronouncedly impacts the turbulence structure, particularly during the morning and evening transitions (e.g., Nadeau et al., 2013a; Lothon et al., 2014). Due to these challenges, the most important advances in understanding and modelling the SBL and the non-stationarity of turbulence over the past century are only slowly emerging.

3.1.2. Significant achievements

The finding that height is associated with stability through the Obukhov length (Obukhov, 1946) is a major achievement. Building on this result, similarity relations according to MOST (Monin and Obukhov, 1954) are well established for moderate stability in the surface layer (e.g., Kelly and Gryning, 2010). Above the surface layer, however, turbulence shows deviations from MOST and therefore, the local scaling framework (Nieuwstadt, 1984), and the z-less scaling as a limiting behaviour of the local scaling for increasing stability, were introduced. It should be noted that local only refers to height in the local scaling layer, i.e., the *boundary-layer approximation* is still invoked. This concept goes back to Ludwig Prandtl, formalized in Mellor and Yamada (1974), and essentially refers to a horizontally homogeneous boundary layer flow with mean quantities that vary solely with height.

From a practical perspective, large progress in understanding the stable and non-stationary turbulence was enabled by the development of methods and approaches that go beyond the canonical. The recognition of the importance of spatial variability of turbulence, even over homogenous surfaces, has led to the development of methods, such as wavelet analysis, to extract spatio-temporal information from distributed or moving observational platforms, such as research aeroplanes (e.g., Farge, 1992). Due to the steadily improving technological and logistic possibilities, observational campaigns could also be conducted in regions of very stable, long-lived boundary layers (e.g., Zilitinkevich et al., 2002; Poulos et al., 2002; Grachev et al., 2005), as well as in non-stationary conditions (e.g., Higgins et al., 2019; Shupe et al., 2022). With the advance of LES and DNS, a systematic evaluation of SBL parametrizations in NWP and climate models became feasible, for example, in the series of GABLS (GEWEX Atmospheric Boundary Layer Studies, Holtslag, 2006) experiments. In these GABLS studies, LES was used as a reference to reproduce observations of increasing complexity, and then subject to well-coordinated inter-comparison trials, to test the various participating stable ABL parametrizations (see Holtslag et al., 2013, for an overview).

3.1.3. Major remaining challenges

The majority of the previously mentioned achievements rest on the simplifying assumptions of canonical and equilibrium (stationary) conditions, thus addressing only a small simplified subset of real-world conditions, where turbulence is fully developed and is the dominant driver of exchange.

The non-linear interactions between mean flow, sub-mesoscale motions, and turbulence that characterizes the SBL make it imperative to focus not only on turbulence, but also on other small-scale processes associated with radiation, advection, surface inhomogeneity and associated transport, fog, gravity waves, etc. A deeper understanding and improved modelling of these processes, along with their non-linear interactions, are essential. Here, spatio-temporally continuous observational techniques such as distributed temperature sensing (DTS, Thomas et al., 2012) or similar approaches (Haugeneder et al., 2023) at the microscales or (only emerging) lidar retrieval algorithms capable of resolving turbulence (e.g., Wildmann et al., 2019; Coimbra et al., 2025) are of special value, as they capture sub-mesoscale contributions and layering, as well as non-local interactions (Eder et al., 2015; Bodini et al., 2018). The not-commonly-observed pressure terms are crucial when it comes to the maintenance of turbulence in stratified conditions ("the devil is in the pressure terms" as Dmitrii Mironov said during the workshop), as has been recognized in a series of studies after Rotta's seminal work (e.g., Rotta, 1951; Bou-Zeid et al., 2018).

Due to a lack of an observable spectral gap in very stable stratification and non-stationary conditions, a clear separation between processes is lacking. Therefore, the separation of turbulence from non-turbulent components remains a challenge, for which approaches like the multiresolution flux decomposition (Howell and Mahrt, 1997) or break point analysis (e.g., Lord-May and Radić, 2024) appear to offer promising paths.

Multiple MOST-based formulations have been developed for the SBL and are routinely used in NWP and climate models, however, they are known to diverge in very stable stratification, where the question of whether turbulence is decoupled from the surface or not determines the functional similarity form, the shape of which is still not universally accepted (e.g., Foken, 2006; Sandu et al., 2013). An additional theoretical challenge stems from the fact that classic scaling relations are affected by self-correlation in stable stratification (Klipp and Mahrt, 2004; Grachev et al., 2007). Going beyond the simple framework of MOST, the importance of background stratification and flow conditions on SBL (Zilitinkevich et al., 2007) should be further explored. This includes development of scaling formulations using alternative scales such as the buoyancy length scale (Sorbjan, 2006) or the Dougherty-Ozmidov scale (Grachev et al., 2015), or multi-parametric (e.g., Heisel and Chamecki, 2023) and multi-point (e.g., Tong and Nguyen, 2015) approaches, that contain classical MOST as a special case. Here, additional possible influences include the Coriolis parameter, boundary layer depth, net radiation, upwind fetch, aerodynamic and scalar roughness lengths. Another approach involves the stochastic extensions to MOST (Boyko and Vercauteren, 2021), proposed to deal with the unknown physics in very stable stratification.

Although some parametrizations for the very stable boundary layer when turbulence is not the dominant driver (i.e., beyond a critical Richardson number, Basu and Holtslag, 2021) or when it is intermittent (Allouche et al., 2022) exist, generally-valid parametrizations are still lacking resulting in problems such as runaway cooling and lack of a regime-bifurcation in NWP (Grisogono, 2010; van Hooft et al., 2018; Ramsey and Monahan, 2022). Current parametrizations and theoretical models typically do not include interactions with other important drivers such as clouds, aerosols, chemical components, radiative flux divergence. Furthermore these processes are not commonly measured in field campaigns or in permanent observatories (cf. Hoch et al., 2007). Additionally, due to the local nature of the SBL, the parametrizations always require some location-specific adaptations, oftentimes realized through the tuning of parameters for momentum or thermal exchange such as the roughness length, surface conductivity, or similar.

GABLS model intercomparisons (Holtslag, 2006; Holtslag et al., 2013) were fundamental in increasing our understanding of model performance in stable stratification over flat terrain, yet, field and model benchmark studies in complex orography and various atmospheric conditions are still missing. Additionally, although the intrinsic complexity of very stable turbulence can be well understood through LES/DNS studies, LES of the SBL should be viewed with caution since the sub-meter grid spacing of LES required to properly capture energy containing turbulent eddies even in moderately stable boundary layers (Cuxart, 2015), has been achieved only in a handful of very idealized studies (McWilliams et al., 2023). For the rest, the accuracy of model results strongly depends on the ability of the sub-grid-scale (SGS) closure to represent the larger fraction of fluxes and adapt to increasing stability when the Dougherty-Ozmidov scale becomes smaller than the grid scale and thus stability directly affects the SGS eddies (Bou-Zeid et al., 2010). Additionally, the LES models that do not employ pseudo-spectral or higher-order advection schemes cannot reproduce correct spectral characteristics, and particularly dissipation, due to the effects of the associated implicit filter (Mittal and Moin, 1997; Zilitinkevich et al., 2019). The effective resolution can therefore have significant implications for numerical studies of very weak turbulence (Giacomini and Giometto, 2021), potentially limiting the usefulness of findings of LES in understanding realistic small-scale turbulence.

Finally, interaction of other sources such as sub-mesoscale motions/synoptic forcing, surface interaction (radiation/skin temperature, inhomogeneity, moisture) requires further study. While this is true for other regimes of the atmospheric boundary layer too, the delicate balance between a weak forcing and complex redistribution mechanism of turbulence kinetic energy exposes stable, and more so strongly stable, configurations to forcings which otherwise are negligible.

3.1.4. Future directions

Very stable conditions certainly stretch the assumptions behind turbulence parametrizations in NWP, climate, and even LES models, to their limits and beyond. Typically, the 30-min equilibrium conditions assumed to relate local (grid box) turbulence statistics (fluxes) to local flow conditions are not likely to produce physically well-based results.

Although non-stationarity is endemic in stable stratification and its importance and influence extend to wider conditions (e.g., influence of clouds in CBL), its effects remain underappreciated and understudied (Večenaj and and De Wekker, 2015). Non-stationary conditions, therefore, require more attention in theoretical, observational, and modelling contexts, especially if they also result in conditions in which mean flow and turbulence are not in equilibrium (Mahrt and Bou-Zeid, 2020). A formal definition of non-stationarity with a proper limiting behaviour towards stationarity should be established in the community, including its relation to spatial inhomogeneity. Explicit incorporation of temporally evolving boundary layer dynamics can leverage von Kármán's classical integral momentum theory, showing that equilibrium conditions are approached only after a relaxation process involving various time-scales (Fowler et al., 2023). Generalizations of such approaches to ABL dynamics remain a promising future task. For instance, such generalizations would require the development of continuous filtering approaches (beyond Reynolds decomposition) for observational data going beyond the concept of a spectral gap, and might be related to a conceptual shift towards studying spectral characteristics instead of integral (i.e. spatially or temporally averaged) statistics. Resulting model parametrizations in LES, NWP and climate models will have to develop towards non-local treatment, not only in the vertical, but also in the horizontal directions, and possibly even extend beyond the grid cell under consideration.

Machine Learning (ML) may help identify interactions between micro-scale turbulence and (sub-) mesoscale flows as well as formerly unrecognized or neglected forcings. Candidates for the latter are cloud-surface interactions, micro-scale variability of the surface and related dynamic pressure-turbulence interactions, as well as small-scale surface temperature variability. Numerical modelling will continue to be used for simplified (idealized) case studies at horizontal grid spacing of the order of meters or decimetres. If the insights gained from this type of idealized experiments are to find their way into applicable sub-grid scale parametrizations (e.g., in next generation kilometre scale global simulations), accurate surface and especially soil characteristics (soil moisture but also the soil composition necessary for accounting the soil storage terms) would need to be available (possibly from satellite data) at the resolution of the sub-grid scale treatment.

3.2. Turbulence over surfaces with large roughness elements

3.2.1. Overview

Rough surfaces are characterized by large roughness elements that render the air between and immediately above them (up to some two to five times the canopy height, Raupach et al., 1991) distinctly different in its turbulence characteristics from what has long been known as the surface layer (Garratt, 1978). It is therefore necessary to split the surface layer into a roughness sublayer (RS) and an inertial sublayer, as the conditions for applying MOST or equivalent similarity theories are fulfilled only in the latter. If roughness elements have a height of order 10 m or more, as in a forest or an urban area, a substantial part of the lower ABL has the characteristics of the RS, i.e., it is three-dimensional and requires at least an extension of MOST (e.g., Physick and Garratt, 1995; Harman and Finnigan, 2007) or mixing lengths (e.g., Katul et al., 2004) based on the canopy geometry. Given the fact that most NWP and climate models use MOST in one way or another in their surface-exchange parametrization, this poses a significant challenge, especially to environmental modelling, such as predicting heat stress and air pollution in cities or assessing gas exchanges and growth conditions in plant canopies.

3.2.2. Significant achievements

The recognition that turbulence in the RS is different from that in the surface layer (i.e., the inertial sublayer) is certainly a major achievement in itself (Brunet, 2020). RS turbulence can be characterized by typical profiles (so-called "family portraits"). Among them the shear stress profile is probably the most distinctly different from canonical wall-bounded turbulence (including MOST), where the lowest layer is modelled as a constant flux layer (e.g., Rotach, 1999; Kastner-Klein and Rotach, 2004). As a theoretical foundation, the mixing layer analogy (Raupach et al., 1996) relates canopy exchange in RS to inflection point instability using a length scale tied to the vorticity thickness at the height of maximum shear. Interaction with the roughness elements through form and viscous drag then leads to a fully three-dimensional mean flow and associated dispersive fluxes, the experimental determinations of which, however, are a remaining challenge rather than an achievement (Coceal et al., 2006). Dispersive fluxes reflect the fact that canopy exchange is also produced by organized mean flow structures, and the associated non-local processes and scale interactions.

Turbulence in the RS, however, depends on distribution, density, character (solid as buildings, flexible as trees) and height of the roughness elements that introduce additional length scales to the flow (Grimmond and Oke, 1999; Finnigan et al., 2009). In the case of urban geometries, idealized cubed roughness elements have often been studied, which allowed for a certain degree of generalization (e.g., Castro et al., 2006). Explicitly taking into account form and pressure drag on "statistical buildings" in the RS over an urban area allowed to devise a multi-layer urban exchange parameterization (Martilli et al., 2002), which is now incorporated in many community models for weather and climate. The groups of vegetated and urban-type canopies exhibit overall similarities (such as the inflection point mentioned above) but also distinct differences (Rotach and Holtslag, 2025), which renders a unified rough-surface exchange parametrization for numerical models a formidable task. Still, such parametrizations, also known as canopy parametrizations, have been devised either as single-layer or multi-layer variants. With the increase in computing power, LES at very high resolution (grid spacing of order 1 m) has been used to study details of RS turbulence, albeit over limited domains (e.g., Patton et al., 2016; Giometto et al., 2016) or urban footprints (Auvinen et al., 2017) only. In this respect, a major achievement was the implementation of immersed boundary methods to simulate urban surfaces, allowing easier representation of buildings and street canyons on regular (not body-conforming) meshes (Maronga et al., 2020; Gisinger et al., 2015), and even simulating the effect of individual roughness elements such as fractal trees (Chester and Meneveau, 2007; Schröttle and Dörnbrack, 2013). These simulations showcase that the effects of true unresolved roughness on turbulence are not equivalent to those of an effective roughness value that is typically computed a-priori (Bou-Zeid et al., 2009; Kelly and Cavar, 2023) and often assumed to be valid in lower-resolution simulations.

Modelling ABL flow over surfaces that exhibit multi-scale self-similar properties, such as vegetated canopies or power-law Gaussian surfaces, requires careful treatment, as multiple scales of the surface interact with the turbulent flow that is also inherently multi-scale. One method that has been particularly effective at exploiting scale similarity for LES is the dynamic model (Germano et al., 1991), which has been generalized to account for the inherently scale-dependent dynamics in the surface layer (Porté-Agel et al., 2000; Bou-Zeid et al., 2005). Methods that extend these concepts to parametrizations of surface drag forces for flow over multiscale vegetation elements (Chester et al., 2007; Chester and Meneveau, 2007), multiscale orography (Anderson et al., 2012; Kelly and Cavar, 2023), ocean waves and other dynamic surfaces (drifting sand or snow) (Yang et al., 2013) have been developed.

3.2.3. Major remaining challenges

The importance of usually neglected terms (e.g., pressure transport in the TKE budget) or terms arising through the need for spatial averaging (dispersive flux terms) has been pointed out, but their experimental observation (outside of a wind tunnel), as well as numerical modelling even with LES, still remain a challenge both for vegetated (Finnigan, 2000) and urban (Christen et al., 2009) canopies.

Surface exchange parametrizations are still commonly not able to directly take into account spatial variability of canopy characteristics (e.g., lack of under-canopy description of vertical and horizontal inhomogeneity or utilization of the full three-dimensional canopy structure, even when available), and the majority of theoretical developments are still limited to neutrally-stratified flows.

Another set of open questions pertains to the dissimilarity of the scalar versus momentum turbulence, and dispersive transport over rough terrain. Recent studies have shown that this dissimilarity is more pronounced than over flat terrain (Li and Bou-Zeid, 2019), and that turbulent and dispersive fluxes are altered differently as the density of the roughness elements increases. This in turn influences the parametrizations in coarse models, and how the roughness length for heat or other scalars are related to that for momentum (Li et al., 2020).

A major challenge over very rough surfaces is certainly the creation of a unified vegetation + urban parametrization, and associated with it the measurement of the necessary scaling parameters at a global scale. A unified treatment is highly beneficial since most real-world surfaces have a mixture of vegetation and built structures, and increasingly also feature wind or solar farms, such that most surface grid cells would feature multiple types of roughness elements.

An aspect of RS turbulence that is not usually considered when operational NWP and climate modelling is concerned is pollutant dispersion, relevant, among others, to greenhouse gas budgeting in vegetated canopies and air pollution in urban areas (e.g., Rotach, 1999; Martilli et al., 2003; de la Paz et al., 2016). Additionally, the lack of consistent observations of higher order moments means that the non-linear combination of dynamic, thermal and chemistry effects (Schumann, 1989) still requires a better understanding. Note that this is even the case if pollutants are assumed to be passive tracers, since large parts of our understanding of canopy turbulence is confined to near-neutral and modestly (un)stable conditions.

Scale interactions of canopy turbulence with the entire overlying ABL (e.g., urban boundary layer, between the canopy and RS, turbulence and buildings) is still posing a significant challenge and is only beginning to be numerically explored (e.g., Theeuwes et al., 2015). The same is true for the interaction with terrain, such as e.g., a major city in a deep valley (e.g., Medellin, Mexico City, see Fernando, 2010; Ward et al., 2022) or an extensive forest on a steep slope, where the World Meteorological Organization's (WMO) guidelines for stations with a strong focus on large-scale representation cannot be met, therefore reducing the availability of long term systematic observations.

3.2.4. Future directions

The availability of observations of momentum, energy and scalars, and in particular long-term testbed-type observations that build upon the knowledge gained in previous urban (e.g., Rotach et al., 2005) and vegetated (e.g., Raupach et al., 1996) canopy studies, over very rough surfaces of different character are crucial for the development of a unified (urban, vegetation) surface-atmosphere exchange parametrization in relation to canopy morphology. Combination of in-situ/satellite/distributed measurements is seen as a promising pathway to improve three-dimensional canopy representation (e.g., Fenner et al., 2024), possibly with the help of machine learning. A major obstacle for a unified canopy parametrization is the *roughness grey zone* (e.g., Li et al., 2021) where the grid scale of a numerical model approaches the scale of roughness elements. While a hectometric horizontal grid spacing (near future of regional NWP) allows for averaging over sufficiently many trees in a forest (and even more plants in an agricultural field) it may contain one residential building in a suburban area and cover parts of a downtown urban block. Combining very high-resolution (with respect to the shear length scale) LES with appropriate observations will certainly provide suitable information for further progress. Finally, new approaches for data assimilation of urban and canopy data are needed (e.g., Koopmans et al., 2023).

3.3. Turbulence over inhomogeneous surfaces

3.3.1. Overview

The influence of surface inhomogeneity, a prevalent feature of atmospheric boundary layers, on turbulence has long been a challenge to both experimentalists and modellers due to the complexity and many manifestations of associated processes (e.g., internal boundary and equilibrium layers, secondary circulations and the associated advection etc., McNaughton, 1988; Brutsaert, 1998; De Roo and Mauder, 2018). Additionally, the increase in model resolution and the lack of observed energy balance closure (Foken, 2008) in field observations has thrust forward the need to better understand the effect that the variability in the surface (thermal, hydrological, and roughness) characteristics has on boundary layer flows. In this respect, inhomogeneity plays a prominent role in turbulence organization into secondary circulations and in internal boundary layer development (Stoll and Porté-Agel, 2009; Bailey and Stoll, 2013; Mott et al., 2015; Fogarty and Bou-Zeid, 2023; Mironov and Sullivan, 2023), both of which are of critical importance to turbulent exchange processes, mesoscale weather patterns, and other phenomena (Bou-Zeid et al., 2020). With respect to numerical modelling, homogeneity is a decisive assumption made at the model-grid level from the atmospheric point of view (even if the land surface model is designed to account for some heterogeneity, variability is averaged out before the land surface model “communicates" with the atmospheric model). In current model architectures, each atmospheric grid cell is attributed a single value of drag and fluxes of heat and moisture, although these might be computed by approaches such as mosaic and flux blending that aim to capture some implications of heterogeneity (Pielke and Avissar, 1990). By design, the first model level over this grid cell is coupled to the surface through the surface-exchange parametrization, which assumes that i) the grid cell is horizontally homogeneous, ii) the exchange is determined by only the local surface characteristics, and iii) the flow is in equilibrium with the local surface. If the grid spacing is large (order 10 km or more, as in present-day NWP and climate models), the first two assumptions are weakened, but the third is strengthened. The effect of sub-grid scale surface variability can then conceptually be added through either a mosaic approach (where the land model is effectively run at a higher resolution, see discussion on the origin of this approach in Koster and Suarez, 1992) or an equivalent-surface approach (where the inhomogeneous land surface characteristics are averaged in some way to yield the correct grid-averaged fluxes, e.g., an effective surface roughness, Taylor and Teunissen, 1987; Bou-Zeid et al., 2007). However, the principal model design of an atmospheric flow over a homogeneous surface is maintained even when the exchange is determined by the (average) characteristics of the local surface or by its sub-grid scale variability.

3.3.2. Significant achievements

One of the most notable accomplishments in the study of inhomogeneity on turbulence is the understanding of internal boundary layers and internal equilibrium layers (e.g., Brutsaert, 1998; Savelyev and Taylor, 2005). Additionally, a deeper understanding of secondary circulations (Bou-Zeid et al., 2020), their drivers, and the identification of the associated dispersive fluxes (Raupach and Shaw, 1982) that impact the transport of momentum, heat, and pollutants in the ABL has recently been highlighted as a key missing component of the surface energy balance (Margairaz et al., 2020a; Mauder et al., 2020).

The sophistication in representing unresolved inhomogeneity within models has also improved (e.g., Waterman et al., 2024), allowing for more accurate models of turbulent processes that occur above inhomogeneous surfaces. The mosaic approach (Pielke and Avissar, 1990; Seth et al., 1994; Mölders et al., 1996) has been devised to take into account sub-grid scale surface inhomogeneity of a general type in numerical models. Although the structure of the patches is not represented in such methods (that would require running a gridded land model at a higher resolution), they produce more realistic results and allow for a subsequent downscaling of land surface states to higher resolutions (Li et al., 2013).

Consideration of inhomogeneous surfaces in experiments and simulations (as opposed to searching for the canonical surface conditions in order to test the canonical theories) has led to a more in-depth assessment of the upwind area of influence for turbulence statistics at a particular receptor location, i.e. footprints (Leclerc and Thurtell, 1990; Schmid, 2002), and potential development of inhomogeneity related scaling parameters (e.g., Margairaz et al., 2020b; Wanner et al., 2022).

3.3.3. Major remaining challenges

Despite these achievements, several challenges remain. A key issue is the balance between synoptic advection and thermal or stress-driven circulations (e.g., Omidvar et al., 2019; Allouche et al., 2023), which determines the mean flow and turbulence structure, critical for accurate NWP. Distinguishing between strongly unstable (free convection limit), neutral-to-stable (forced convection limit), and mixed convection configurations over inhomogeneous terrain, and what flow and fluxes they result in, remains elusive. Moreover, the interaction of buoyant and roughness inhomogeneity poses significant modelling difficulties (Fogarty et al., 2024).

The quest for quasi-universal, scale-adaptive parametrizations continues, as does the need for analytical modelling under arbitrary conditions such as varying stratification, terrain, and wave influences. The complexity of multi-scale surface variability and couplings, both in simulations and between the ABL and man-made structures (e.g., wind turbines, urban areas, solar arrays), presents a formidable challenge (Bou-Zeid et al., 2020). Current modelling frameworks, including the widely used MOST, often fall short when applied to inhomogeneous conditions (Figueroa-Espinoza and Salles, 2014). A parallel challenge is how to predict the unresolved three-dimensional variability of the mean flow and the dispersive fluxes it generates. Hence, there is a pressing need for generalizations or entirely new hypotheses that can account for these complexities. In addition, as inhomogeneity is a challenge for both modellers and experimentalists, the reconciliation of the differences between observations and models is necessary to identify missing processes or imperfect observational strategies and the development of novel observational concepts. The question, however, remains whether it is possible to ever reach a level of universality for inhomogeneous turbulence, at least for classes of similar situations, that was reached for its homogeneous counterpart.

3.3.4. Future directions

Addressing these challenges requires coordinated progress through targeted observations in line with model developments, achieved through close collaboration between experimentalists and modellers (e.g., Wolf et al., 2017; Moderow et al., 2021; Butterworth et al., 2021; Morrison et al., 2023). New measurement technologies, such as uncrewed aerial systems (UAS) or Doppler lidars can help close the knowledge gap, along with the selection of simple enough cases for LES model intercomparisons, and for comparisons and development of analytical solutions and other theoretical approaches. Improved assimilation techniques will help in creating more accurate and reliable models. Furthermore, defining a framework for inhomogeneity that includes classification by scales (e.g., microscale, mesoscale, and their interactions) and impacts (e.g., memory) for all buoyancy, roughness and combined inhomogeneity is essential. Such a classification will have to be formulated in a scale-adaptive framework, thus properly addressing the *Terra Incognita/turbulence grey zone* (Wyngaard, 2004) challenge from both a turbulence and a surface variability perspective. Building a hierarchy from medium- to high-complexity scenarios will enable better physical understanding and improved parametrizations. Ultimately, the goal is to determine whether universality is feasible despite inhomogeneity: if so, how it can be achieved, and if not, what are practical alternatives that may be more heuristic but as effective if they can leverage large datasets and novel machine learning approaches.

3.4. Turbulence over complex orography

3.4.1. Overview

Turbulence over complex orography is characterized by inherent inhomogeneity (arising from the variety of terrain slopes, elevations, expositions, land use, etc.), and complex interactions with multi-scale topographic flows (e.g., Serafin et al., 2018). Effects of orography are therefore closely related to inhomogeneity, however, over orography gravity is a driving force also in the horizontal budget equations (as opposed to acting only in the vertical over flat terrain), and thus makes the thermal and momentum structure even over shallow slopes different from that of flat-terrain flows (Grisogono and Oerlemans, 2001; Farina and Zardi, 2023). Additionally, pressure-flow interactions through the sheer presence of terrain as an obstacle, together with streamline curvature, play an important role in determining the turbulence structure of orographic flows (Kaimal and Finnigan, 1994). In this sense, complexity extends beyond simply the complexity of the orographic features.

Turbulence variability over orography is clearly three-dimensional, despite the fact that numerical models for weather and climate still treat it as one-dimensional, i.e., quite generally invoke the boundary-layer approximation. Operational NWP models furthermore use terrain-following coordinates and are therefore susceptible to numerical errors when simulating flows over steep slopes (Chow et al., 2019), which require special treatment currently only available in research models.

Over complex orography, sources (sinks) of turbulence are the same as over flat surfaces, however, the canonical setting is not that of an ABL flow developing over a horizontal surface of a particular type and topped by an equally horizontal synoptic flow. Turbulent structure is strongly dominated by the location relative to orography (e.g., ridge top or valley floor), as well as height above ground (cf., where the influence of terrain slope, curvature, rapid distortion, and memory effects prevail, Park and Park, 2006; Medeiros and Fitzjarrald, 2015; Brun, 2017; Finnigan et al., 2020), and by the existence of length scales alternative to the Obukhov length, imposed by the flow itself (e.g., Grisogono et al., 2007). Additionally, the non-local turbulence drivers (Weigel and Rotach, 2004) and the strong veering/backing of the flow with height have important implications for complex-terrain turbulence structure and its modelling (Rotach et al., 2008).

Interactions with mesoscale circulations (such as valley or slope flows) or dynamically forced flow responses (such as downslope windstorms) that originate due to the presence of orography, cannot be neglected in the pursuit of a generalized understanding. With respect to the present topic, it is important to note that, as opposed to a canonical flat-terrain ABL, the Mountain Boundary Layer (MoBL, Lehner and Rotach, 2018) is not determined by its turbulence state alone, but also by the exchange processes related to mesoscale terrain-induced flows, even as turbulence continues to play a crucial role in the surface-atmosphere (i.e., terrain-atmosphere) interaction.

3.4.2. Significant achievements

Key achievements include the progress in qualitative understanding of the dynamics of terrain-related mesoscale flows, such as downslope windstorms and thermally driven valley and slope flows, and mechanisms such as von Kármán vortices (e.g., Chow et al., 2013). This progress was facilitated by extensive datasets from major experimental campaigns such as ALPEX (Kuettner and O'Neill, 1981), MAP-Riviera (Rotach et al., 2004), METCRAX (Lehner et al., 2016), T-Rex (Grubišić et al., 2008), and advanced numerical (mostly RANS) simulations. The development of limited-area NWP models and LES has significantly contributed to the qualitative understanding of these processes, filling in the observational gaps or verifying field results (e.g., Rotach and Holtslag, 2025). Additionally, advancements in numerical techniques, including algorithms, discretization, and grids (e.g., sleeve vertical coordinates, immersed boundary conditions), have enabled the nesting of LES within larger NWP models, enhancing our ability to simulate complex orography dynamics (see Chow et al., 2013, for review).

In terms of theoretical approaches in complex orography, large progress has been made for idealized terrain (an infinite slope, a cosine-hill/valley), taking the two-dimensional structure of turbulence into account. The lighthouse examples are the linearized theory of Hunt et al. (1988a,b) - though only applicable to moderate terrain (slopes smaller than ~ 17 degrees) - and the theoretical work on the katabatic flows (e.g., Fedorovich and Shapiro, 2009; Shapiro and Fedorovich, 2014; Xiao and Senocak, 2019). At the same time, the systematic evaluation of turbulence characteristics over complex orography is relatively recent, with the general result that i) scaling seems to be possible (there are cases and conditions where it is successful, i.e., data collapse onto a curve), but ii) the scaling regimes are not the same as those over canonical surfaces (e.g., de Franceschi et al., 2009; Martins et al., 2009; Nadeau et al., 2013b; Sfyri et al., 2018), and they do not agree amongst themselves. However, novel scaling approaches developed in recent years, both for specific conditions such as sloping terrain (e.g., Hang et al., 2021), stable (e.g., Barskov et al., 2018) or neutral (e.g., Kelly and Cavar, 2023) flows, or generalized to all terrain and stratifications (Stiperski et al., 2019; Stiperski and Calaf, 2023), point towards a possibility of a unified scaling over complex orography.

While LES studies of homogeneous boundary layers use periodic boundary conditions, in general, this is not a viable approach for simulations over complex orography. An open boundary condition can be used for such simulations instead, however, in that case turbulence does not develop spontaneously, but needs to be imposed or triggered. Several methods have been developed to achieve realistic turbulent inflow. For example, Le et al. (1997) generate inflow with a prescribed turbulent fluctuations, Lund et al. (1998) recycle and rescale outflow to impose inflow, while Nunalee et al. (2014) use one-way nesting of a domain with complex topography within a flat domain with periodic boundary conditions. These approaches are not directly applicable to the mesoscale (RANS) to microscale (LES) coupling, where turbulence characteristics on the inflow to the microscale domain are not known a priori. Muñoz-Esparza et al. (2014) developed a cell perturbation method, perturbing potential temperature at the domain boundaries to trigger turbulence development consistent with a range of atmospheric stability conditions (see also Muñoz-Esparza and Kosović, 2018). In addition, the development and implementation of immersed boundary conditions (e.g., Lundquist et al., 2010, 2012; Bao et al., 2018) or additional treatments in terrain-following coordinates (Epifanio, 2007; Krieger et al., 2025) have allowed successful simulations of flows over steep slopes.

3.4.3. Major remaining challenges

Despite the previously mentioned advances, several challenges persist, especially related to the turbulence structure of realistic orographic flows, their multiscale nature, and scale interactions. One major obstacle is the lack of comprehensive observations of small-scale terrain-related phenomena such as upslope and downslope winds. These remain elusive due to the difficulty in isolating terrain-related winds from synoptic influences. Additionally, capturing the full vertical extent of terrain-related flows is still a challenge, both very close to the surface (e.g. katabatic flows, Charrondière et al., 2022) and above the first several meters (e.g., anabatic flows). In fact, the correct measurement strategies for turbulence in complex orography (e.g., terrain-following or vertical set-up of instrumentation) are still an open question (Stiperski and Rotach, 2016). Additionally, the current WMO's guidelines for temperature and wind speed measurements (2 m and 10 m respectively) are inappropriate over sloping terrain, where the existence of low level jets (e.g., katabatic) below that height means that the standard observations are not representative of the relevant flow conditions (e.g., Nicholson et al., 2025). Finally, the inherent inhomogeneity of processes over complex orography calls for a distributed network approach to address the question of representativeness of observations, as well as to systematically observe horizontal variations in turbulent flows.

The challenge of theoretical treatment of orographic flows remains in their three-dimensional nature and realistic multi-scale nature of the orography. Classical treatments only use idealized terrain, and turbulence closures adopted from flat terrain, and hence are reliant on the boundary layer approximation. In addition, there is still a lack of theoretical underpinning of turbulence structure of topographic flows in stratified conditions. Finally, the understanding of upscale transfer of energy from turbulence into its organization as coherent structures and mesoscale flows remains a challenge that is of special importance for non-closure of the surface energy balance, especially acute over orography (e.g., Babić et al., 2021; Lehner et al., 2021). Achieving a unified theory of complex terrain turbulence and appropriate turbulence parametrizations reflecting complex-terrain effects in NWP models is crucial, as the complex orography setting means that the assumptions of MOST are systematically violated.

The creation of such unified parametrizations relies on data gathered from multiple complex settings, but also on accurate very high resolution numerical modelling. The validation of turbulence-resolving simulations, however, requires the development of new methods to assess the spatio-temporal variability of flow features accurately, as the interaction and transport between different scales necessitate a focus on both spatial coupling and temporal evolution. The numerical modelling over complex orography is also challenged by the existence of multiple gray zones related to flow as well as surface conditions (Chow et al., 2019). The computational cost of simulations with the high spatial resolution required in complex orography also limits our confidence in the stratified turbulence structure over orography and our ability to quantify uncertainty, posing a significant challenge in modelling. This is especially the case for scalar transport, which is often predicted less accurately compared to momentum transport.

3.4.4. Future directions

To address the many remaining challenges, several potential steps forward have been identified. Three-dimensional ABL closures, simulations with increased model resolutions (e.g., Mellor and Yamada, 1982; Juliano et al., 2022), and higher-order numerical schemes can enhance model accuracy, while the use of immersed boundary condition methods and simpler parametrizations may facilitate model implementation. In this respect advancing robust mesoscale-to-microscale coupling methods in multiscale modelling approaches is a critical future direction for improving realistic atmospheric simulations of complex topographic flows (Haupt et al., 2019).

Field campaigns such as Askervein (Taylor and Teunissen, 1987), Cinder Cone (Apsley and Castro, 1997), MAP-Riviera (Rotach and Zardi, 2007), MATERHORN (Fernando et al., 2015), ALEX17 (Santos et al., 2019), Perdigão (Fernando et al., 2019), and most recently TEAMx (Rotach et al., 2022) are essential for gathering detailed observations both close to the surface and in the upper parts of the MoBL, while cooperation between modellers and experimentalists is vital for advancing our understanding of multi-scale interactions in MoBL. Three-dimensional observational techniques that fill in the observational gray zone, e.g., UAS and their swarms (Wildmann et al., 2019), DTS or similar techniques, coupled with Lidar and other remote-sensing observations (e.g., Mack et al., 2025), together with turbulence tower networks such as i-Box (e.g., Rotach et al., 2017), are needed to map the full multiscale and three-dimensional structure of the MoBL.

An improved understanding of the coupling between thermal and dynamic effects is essential, as is the extension of MOST to complex orography, or its supplementation by a more generalized theory. The further development of anisotropy scaling (Stiperski et al., 2019; Stiperski and Calaf, 2023; Charrondière and Stiperski, 2024; Mosso et al., 2024, 2025) appears to be a promising new approach in this direction.

Furthermore, a deeper understanding of the effects of different terrain (e.g., terrain curvature, Finnigan, 2024) and flow features (e.g., existence of the law-of-the-wall very close to the surface, Charrondière et al., 2022) are crucial for developing more generalized theories and more appropriate surface exchange parametrizations. Here in particular progress can be made by identifying quasi-ideal cases of stratified flow over mountains for systematic studies with a range of high-resolution modelling approaches (similar to GABLS).

In conclusion, while individual mesoscale processes in complex orography are well understood, their interactions, which often lead to nonlinear and complex dynamics, remain a significant research frontier. Idealized studies, LES and RANS model intercomparisons, and advanced experimental concepts involving area-wide, three-dimensional scanning and cascades of measurements are necessary to overcome these challenges. The integration of these approaches will advance our understanding and modelling capabilities, ultimately leading to more accurate predictions of atmospheric behaviour over complex orography.

4. Message for stakeholders

As a community, the workshop participants highlighted several important take-home messages for stakeholders to stimulate advances in understanding and modelling realistic turbulent flows over the next century.

4.1. Observations

There is a need for comprehensive, openly available, and well-documented databases of turbulence observations (such as Earth Observing Laboratory EOL Field Data Archive https://data.eol.ucar.edu/) from a variety of locations, and of long enough duration to cover the broad range of synoptic conditions that are also shifting with climate change. This will allow the advancement of understanding of not only the most common turbulence regimes, but especially the more rarely encountered or less well understood ones. This is especially the case for very stable stratification, where processes other than turbulence drive the exchange. In addition, multi-decadal observational networks are needed to close the knowledge gap on climatic scales. These datasets would be used for process studies, as well as model validation, and will ideally become part of operational (mesonet-type of) networks at selected sites.

There is additionally an acute need to store the unprocessed high-resolution turbulence measurements (instead of just averaged fluxes) to allow for reprocessing of turbulence statistics as new methods are developed (e.g., Schaller et al., 2017) or new findings (Stiperski and Calaf, 2018) warrant revisiting and recalculating statistics of older observational datasets, or for applications that were not initially intended. It is well established that the processing of turbulence integral statistics depends on the applications: for turbulence studies under stable stratification, usually very short averaging times are chosen to avoid contamination of computed fluxes with non-turbulent contributions (e.g., Vickers and Mahrt, 2003; Mahrt and Thomas, 2016); when evaluating energy balance closure or budgets of other scalars at a particular site, it might be necessary to compute longer averages (e.g., Finnigan et al., 2003).

Given the prevalent spatial inhomogeneity of turbulent flows over realistic surfaces, it is paramount that future campaigns not only observe turbulence at multiple observational heights, but also contain spatially explicit observations (e.g., multi-tower networks, DTS, Zeller et al., 2021), allowing for the computation of, for example, dispersive fluxes (e.g., Morrison et al., 2023) or spatial turbulence statistics (Hilland et al., 2022). Additionally, fully understanding non-canonical boundary layer turbulence requires knowledge of processes other than turbulence. It is therefore of great importance that future observational campaigns and networks also include observations of radiation, soil properties (e.g., Katul et al., 2012), rainfall, dust transport, as well as general boundary layer profiles.

4.2. Modelling

LES/DNS have originally been developed and applied for homogeneous and flat (or infinite constant slope) terrain. With increasing computing power, some codes originally designed for RANS are being used in LES mode over realistic surfaces (e.g., WRF, ICON, MesoNH). However, many of the common and practical numerical approaches (e.g., periodic boundary conditions, triggering of turbulence when downscaling from RANS to LES) cannot simply be transferred to inhomogeneous, terrain-influenced, very rough surface conditions. The work on further developing methods that properly couple realistic mesoscale simulations to realistic, very high resolution LES is therefore needed.

Additionally, current numerical models for weather and climate, as well as many LES codes, still use wall models and SGS parametrizations developed for flat and horizontally homogeneous terrain (including MOST) even over realistic orography and very rough surfaces. The reason is that realistic wall models are missing, and more effort should be placed at developing them (see Freire and Chamecki, 2021, for recent progress on this front). This mismatch is particularly relevant when using observations (e.g., from a site in complex orography or an urban park) for model verification, and similarly, if output of an NWP or climate model is used to force an applied simulation for pollutant dispersion, a specific hydrometeorological event, or the like. Similarly, the existence of submesoscale motions and secondary circulations requires a revisit and rethink of turbulence modelling for NWP models (Calaf et al., 2023).

In research applications of LES, the use of high-order accuracy schemes (Giacomini and Giometto, 2021) or spectral methods is necessary to capture a correct turbulence cascade, as is using a sufficient resolution to correctly capture the energy-containing eddies (Cuxart, 2015, LES generally assumes that >80 % of the turbulence kinetic energy is resolved). Over complex surfaces, in studying non-steady and multi-scale flows, such as discussed here, grid-adaptive simulations that seek a local (space or time) resolution optimum dependent on the physical flow characteristics, offer a promising path (van Hooft et al., 2018).

Finally, as with the observations, there is an acute need for openly available databases of LES/DNS simulation outputs over non-canonical surfaces. Furthermore, openly sharing the LES/DNS data, including tools for efficient access, is pivotal for future progress. Databases such as Johns Hopkins Turbulence Database https://turbulence.idies.jhu.edu(JHTDB, 2025) system (Li et al., 2008; Graham et al., 2016) or Refubium https://refubium.fu-berlin.de/handle/fub188/42710 (Ansorge, 2025) already include data from multiple atmospheric very high resolution LES (e.g., McWilliams et al., 2023; Zhu et al., 2025; Xiao et al., 2025; Nazarian et al., 2025) and DNS studies (e.g., Ansorge and Mellado, 2014; Ansorge, 2019).

4.3. Synergies

To properly close the knowledge gaps, it is essential to use approaches that integrate both modelling and observations, and it is thus imperative to strengthen interactions between experimentalists and modellers through regular exchanges, workshops, projects, and targeted benchmark studies such as GABLS. A coordinated modelling efforts should also precede and not only follow measurement campaigns, in order to guide their design and anticipate problems as well as outcomes, thus allowing for more targeted observations.

To address some of the most urgent questions, the way forward is to build a community set of simulations and observations. That requires access to large and efficient data storage solutions – repositories that are large enough to store long-term raw datasets of both simulation outputs and observations. Additionally, developing methods of model evaluation over non-canonical surfaces is needed, as are tools that allow us to leverage the insight of data assimilation/fusion for turbulence simulations to improve the forcing of case studies. There is also a need to better quantify the uncertainties in models and modelling approaches, as well as in observations.

Finally, it is vital for funding agencies to recognize both the wealth of information contained in existing datasets, as well as the value of observations that can be generated with novel observational technologies. The majority of existing observational datasets are underutilized due to challenges in obtaining funding for analysis of existing data. However, only leveraging multi-dataset approaches and therefore relying on reanalysis of existing datasets can lead to a needed breakthrough in creating universal scaling approaches or parametrizations (e.g., Ghannam et al., 2018; Stiperski et al., 2021; Stiperski and Calaf, 2023; Waterman et al., 2025).

5. Conclusions

The study of turbulence over complex surface (inhomogeneous, orographic, rough) is at a pivotal juncture: significant advancements were made in the last decades, but numerous challenges still need to be overcome. By fostering collaboration, leveraging new technologies, and refining theoretical frameworks, the scientific community can continue to unravel the complexities of atmospheric turbulence, leading to enhanced understanding of environmental processes and more accurate atmospheric models.

CRediT authorship contribution statement

Ivana Stiperski: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Funding acquisition, Conceptualization; **Mathias W. Rotach:** Writing – review & editing, Writing – original draft, Conceptualization; **Cedrick Ansorge:** Writing – review & editing; **Alexander Baklanov:** Writing – review & editing, Writing – original draft; **Danijel Belušić:** Writing – review & editing; **Elie Bou-Zeid:** Writing – review & editing, Writing – original draft; **Christophe Brun:** Writing – review & editing; **Andreas Christen:** Writing – review & editing, Writing – original draft; **Nelson Luís Dias:** Writing – review & editing; **Andreas Dörnbrack:** Writing – review & editing; **Thomas Foken:** Writing – review & editing, Writing – original draft, Visualization; **Andrey Grachev:** Writing – review & editing, Writing – original draft; **Albert A. M. Holtslag:** Writing – review & editing, Writing – original draft; **Mark Kelly:** Writing – review & editing; **Petra Klein:** Writing – review & editing; **Branko Kosović:** Writing – review & editing, Writing – original draft; **Charles Meneveau:** Writing – review & editing, Writing – original draft; **Luca Mortarini:** Writing – review & editing; **Edward G. Patton:** Writing – review & editing, Writing – original draft; **Gert-Jan Steeneveld:** Writing – review & editing; **Christoph Thomas:** Writing – review & editing; **Silvia Trini Castelli:** Writing – review & editing; **Dino Zardi:** Writing – review & editing, Writing – original draft.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare the following personal relationships which may be considered as potential competing interests: Gert-Jan Steneveld is the co-Editor-in-Chief of JEMS, Albert A.M. Holtslag is the Associate Editor, and Mathias W. Rotach is a members of the journal's International Advisory Board.

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Appendix A. Centenary workshop “100 years of turbulence: innsbruck 1922 – 2022“

The Centenary workshop “100 Years of Turbulence: Innsbruck 1922 – 2022” was based on a small number of targeted keynote presentations (available on YouTube under https://youtube.com/playlist?list=PLSG9jZZViQwYZu5MV14CR0Tpa7VfWw5eR&si=E2t6w0IzyTLw-wfJ, Workshop on atmospheric turbulence “100 years of turbulence: Innsbruck 1922-2022") meant to stimulate in-depth discussions in smaller groups, aimed at increasing the dialogue between diverse methodological approaches and applications. The workshop started with three presentations exploring the history of atmospheric turbulence (see Section 2), and an inspiring lecture by Prof. Giovanni Battimelli, who provided an overview of the historical background of the 1922 meeting. This was followed by a brief overview of 100 years of atmospheric turbulence research and a tribute to the legacy of Sergej Zilitinkevich, who sadly passed away in the year preceding the workshop. His remarkable contributions to a multitude of topics in geophysical turbulence are seminal (Zilitinkevich et al., 2021; Mironov and Sullivan, 2023).

The main part of the workshop dealt with recent advances in turbulence theory, observations and modelling, especially the extensions of classical similarity theory to non-canonical surfaces, i.e. for the four major topics:

1. Stratified and non-stationary turbulence (Section 3.1)
2. Turbulence over surfaces with large roughness elements (Section 3.2)
3. Turbulence over inhomogeneous surfaces (Section 3.3)
4. Turbulence over complex orography (Section 3.4)

Each session consisted of two keynote presentations followed by short statements by the keynote speakers highlighting the biggest achievements over the past century and the greatest challenges ahead. These greatest challenges were then taken into smaller groups for focused discussion. Group discussions explored present challenges and the future of turbulence research from the perspective of theory, measurements, numerical modelling, and applications. The outcomes of the discussions from each group were presented and further discussed in a plenary session. Additional short talks on novel findings in different fields were held on the afternoon of the second and last day of the event.

The group discussions formed the core of the workshop, and each group was chosen to balance the mix of participants with a variety of backgrounds (observational, modelling, theoretical) and career stages (senior and mid-career) to allow cross-pollination of ideas, especially across disciplines. Groups differed for each session to ensure that participants interacted with all the other participants.

List of workshop participants in alphabetical order by last name (see Fig. A.1): Cedrick Ansorge (1, rapporteur, session chair), Georgios Bagiatis (2), Alexander Baklanov (3, keynote speaker), Giovanni Battimelli (4, keynote speaker), Danijel Belušić (5, rapporteur), Elie Bou-Zeid (6, keynote speaker), Christophe Brun (7, rapporteur), Claudine Charrondièr (8), Andreas Christen (9, keynote speaker), Martina Destro (10), Nelson Luis Dias (11, rapporteur), Andreas Dörnbrack (12, rapporteur), Igor Esau (13), Thomas Foken (14, keynote speaker), Lorenzo Giovannini (15, session chair), Brigitta Goger (16, session chair), Andrey Grachev (17, keynote speaker), Branko Grisogono (18), Albert A.M.

Fig. A.1. Group photo from the Workshop “100 years of turbulence: Innsbruck 1922-2022". The numbers correspond to the list of participants in the text.

(Bert) Holtslag (19, keynote speaker), Thomas Karl (20), Mark Kelly (21, rapporteur), Alexander Kendl (22), Petra Klein (23, rapporteur), Branko Kosović (24, keynote speaker), Manuela Lehner (25, session chair), Dan Li (26, session chair), Charles Meneveau (27, keynote speaker), Dmitrii Mironov (28), Luca Mortarini (29, rapporteur), Samuele Mosso (30), Edward (Ned) Patton (31, keynote speaker), Igor Petenko (32), Lena Pfister (33), Yue Qin (34), Joachim Reuder (35), Mathias Rotach (36, rapporteur, session chair), Gaspard Simonet (37), Gert-Jan Steeneveld (38, rapporteur), Ivana Stiperski (39, organizer), Christoph Thomas (40, rapporteur), Silvia Trini Castelli (41, rapporteur), Željko Večenaj (42, session chair), Nadia Vendrame (43), Helen Ward (44), Georg Wohlfahrt (45, session chair), Chuixiang Yi (46) , Dino Zardi (47, keynote speaker), Andrea Zonato (48).

References

Allouche, M., Bou-Zeid, E., Ansorge, C., Katul, G.G., Chamecki, M., Acevedo, O., Thanekar, S., Fuentes, J.D., 2022. The detection, genesis, and modeling of turbulence intermittency in the stable atmospheric surface layer. J. Atmos. Sci. 79 (4), 1171–1190. https://doi.org/10.1175/jas-d-21-0053.1

Allouche, M., Bou-Zeid, E., Iipponen, J., 2023. The influence of synoptic wind on land–sea breezes. Q. J. R. Meteorolog. Soc. 149 (757), 3198–3219. https://doi.org/10.1002/qj.4552

Anderson, W., Passalacqua, P., Porté-Agel, F., Meneveau, C., 2012. Large-eddy simulation of atmospheric boundary-layer flow over fluvial-like landscapes using a dynamic roughness model. Boundary Layer Meteorol. 144, 263–286. https://doi.org/10.1007/s10546-012-9722-9

Ansorge, C., 2019. Scale dependence of atmosphere–surface coupling through similarity theory. Boundary Layer Meteorol. 170 (1), 1–27. https://doi.org/10.1007/s10546-018-0386-y

Ansorge, C., 2025. Refubium database. https://refubium.fu-berlin.de/handle/fub188/42710.

Ansorge, C., Mellado, J.P., 2014. Global intermittency and collapsing turbulence in the stratified planetary boundary layer. Boundary Layer Meteorol. 153 (1), 89–116. https://doi.org/10.1007/s10546-014-9941-3

Apsley, D.D., Castro, I.P., 1997. Numerical modelling of flow and dispersion around Cinder Cone Butte. Atmos. Environ. 31 (7), 1059–1071. https://doi.org/10.1016/S1352-2310(96)00213-0

Auvinen, M., Järvi, L., Hellsten, A., Rannik, U., Vesala, T., 2017. Numerical framework for the computation of urban flux footprints employing large-eddy simulation and Lagrangian stochastic modeling. Geosci. Model Dev. 10 (11), 4187–4205. https://doi.org/10.5194/gmd-10-4187-2017

Babić, N., Stiperski, I., Marinović, I., Večenaj, Ž., De Wekker, S. F.J., 2021. Examining relationships between entrainment-driven scalar dissimilarity and surface energy balance underclosure in a semiarid valley. Agric. For. Meteorol. 298-299, 108272. https://doi.org/10.1016/j.agrformet.2020.108272

Bailey, B.N., Stoll, R., 2013. Turbulence in sparse, organized vegetative canopies: a large-eddy simulation study. Boundary Layer Meteorol. 147 (3), 369–400. https://doi.org/10.1007/s10546-012-9796-4

Baklanov, A., Grisogono, B. (Eds.), 2007. Atmospheric Boundary Layers: Nature, Theory and Applications to Environmental Modelling and Security. Springer.

Baklanov, A.A., Grisogono, B., Bornstein, R., Mahrt, L., Zilitinkevich, S.S., Taylor, P., Larsen, S.E., Rotach, M.W., Fernando, H.J.S., 2011. The nature, theory, and modeling of atmospheric planetary boundary layers. Bull. Am. Meteorol. Soc. 92 (2), 123–128. https://doi.org/10.1175/2010BAMS2797.1

Bao, J., Chow, F.K., Lundquist, K.A., 2018. Large-eddy simulation over complex terrain using an improved immersed boundary method in the weather research and forecasting model. Mon. Weather Rev. 146 (9), 2781–2797. https://doi.org/10.1175/MWR-D-18-0067.1

Barskov, K.V., Glazunov, A.V., Repina, I.A., Stepanenko, V.M., Lykossov, V.N., Mammarella, I., 2018. On the applicability of similarity theory for the stable atmospheric boundary layer over complex terrain. zv. Atmos. Oceanic Phys. 54 (5), 462–471. https://doi.org/10.1134/S0001433818050031

Basu, S., Holtslag, A. A.M., 2021. Turbulent Prandtl number and characteristic length scales in stably stratified flows: steady-state analytical solutions. Environ. Fluid Mech. 21 (6), 1273–1302. https://doi.org/10.1007/s10652-021-09820-7

Bodini, N., Lundquist, J.K., Newsom, R.K., 2018. Estimation of turbulence dissipation rate and its variability from sonic anemometer and wind doppler lidar during the XPIA field campaign. Atmos. Meas. Tech. 11 (7), 4291–4308. https://doi.org/10.5194/amt-11-4291-2018

Bou-Zeid, E., Anderson, W., Katul, G.G., Mahrt, L., 2020. The persistent challenge of surface heterogeneity in boundary-layer meteorology: a review. Boundary Layer Meteorol. 177 (2), 227–245. https://doi.org/10.1007/s10546-020-00551-8

Bou-Zeid, E., Gao, X., Ansorge, C., Katul, G.G., 2018. On the role of return to isotropy in wall-bounded turbulent flows with buoyancy. J. Fluid Mech. 856, 61–78. https://doi.org/10.1017/jfm.2018.693

Bou-Zeid, E., Higgins, C., Huwald, H., Meneveau, C., Parlange, M.B., 2010. Field study of the dynamics and modelling of subgrid-scale turbulence in a stable atmospheric surface layer over a glacier. J. Fluid Mech. 665, 480–515. https://doi.org/10.1017/s0022112010004015

Bou-Zeid, E., Meneveau, C., Parlange, M., 2005. A scale-dependent Lagrangian dynamic model for large eddy simulation of complex turbulent flows. Phys. Fluids 17 (2), 025105. https://doi.org/10.1063/1.1839152

Bou-Zeid, E., Overney, J., Rogers, B.D., Parlange, M.B., 2009. The effects of building representation and clustering in large-eddy simulations of flows in urban canopies. Boundary Layer Meteorol. 132 (3), 415–436. https://doi.org/10.1007/s10546-009-9410-6

Bou-Zeid, E., Parlange, M.B., Meneveau, C., 2007. On the parameterization of surface roughness at regional scales. J. Atmos. Sci. 64 (1), 216–227. https://doi.org/10.1175/jas3826.1

Bovsheverov, V.M., Krasilnikov, V.A., 1941. Preliminary results of acoustic sounding of the atmosphere by an monochromatic beam (in Russian). Dokl. Akad. Nauk SSSR 32, 44–46.

Boyko, V., Vercauteren, N., 2021. Multiscale shear forcing of turbulence in the nocturnal boundary layer: a statistical analysis. Boundary Layer Meteorol. 179 (1), 43–72. https://doi.org/10.1007/s10546-020-00583-0

Brun, C., 2017. Large-eddy simulation of a katabatic jet along a convexly curved slope: 2. Evidence of Görtler vortices. J. Geophys. Res. Atmos. 122 (10), 5190–5210. https://doi.org/10.1002/2016JD025416

Brunet, Y., 2020. Turbulent flow in plant canopies: historical perspective and overview. Boundary Layer Meteorol. 177 (2), 315–364. https://doi.org/10.1007/s10546-020-00560-7

Brunton, S.L., Noack, B.R., Koumoutsakos, P., 2020. Machine learning for fluid mechanics. Annu. Rev. Fluid Mech. 52, 477–508. https://doi.org/10.1146/annurev-fluid-010719-060214

Brutsaert, W., 1998. Land-surface water vapor and sensible heat flux: spatial variability, homogeneity, and measurement scales. Water Resour. Res. 34 (10), 2433–2442. https://doi.org/10.1029/98wr01340

Businger, J.A., Wyngaard, J.C., Izumi, Y., Bradley, E.F., 1971. Flux-profile relationships in the atmospheric surface layer. J. Atmos. Sci. 28 (2), 181–189. https://doi.org/10.1175/1520-0469(1971)028<0181:FPRITA>2.0.CO;2

Businger, J.C., 1973. Workshop on Micrometeorology. Americal Meteorological Society. chapter Turbulent transfer in the atmospheric surface layer. pp. 67–100.

Butterworth, B.J., Desai, A.R., Townsend, P.A., Petty, G.W., Andresen, C.G., Bertram, T.H., Kruger, E.L., Mineau, J.K., Olson, E.R., Paleri, S., Pertzborn, R.A., Pettersen, C., Stoy, P.C., Thom, J.E., Vermeuel, M.P., Wagner, T.J., Wright, D.B., Zheng, T., Metzger, S., Schwartz, M.D., Iglinski, T.J., Mauder, M., Speidel, J., Vogelmann, H., Wanner, L., Augustine, T.J., Brown, W. O.J., Oncley, S.P., Buban, M., Lee, T.R., Cleary, P., Durden, D.J., Florian, C.R., Lantz, K., Riihimaki, L.D., Sedlar, J., Meyers, T.P., Plummer, D.M., Guzman, E.R., Smith, E.N., Sühring, M., Turner, D.D., Wang, Z., White, L.D., Wilczak, J.M., 2021. Connecting land–atmosphere interactions to surface heterogeneity in CHEESEHEAD19. Bull. Am. Meteorol. Soc. 102 (2), E421 – E445. https://doi.org/10.1175/BAMS-D-19-0346.1

Calaf, M., Vercauteren, N., Katul, G.G., Giometto, M.G., Morrison, T.J., Margairaz, F., Boyko, V., Pardyjak, E.R., 2023. Boundary-layer processes hindering contemporary numerical weather prediction models. Boundary Layer Meteorol. 186 (1), 43–68. https://doi.org/10.1007/s10546-022-00742-5

Castro, I.P., Cheng, H., Reynolds, R., 2006. Turbulence over urban-type roughness: deductions from wind-tunnel measurements. Boundary Layer Meteorol. 118 (1), 109–131. https://doi.org/10.1007/s10546-005-5747-7

Charrondière, C., Brun, C., Cohard, J.-M., Sicart, J.-E., Obligado, M., Biron, R., Coulaud, C., Guyard, H., 2022. Katabatic winds over steep slopes: overview of a field experiment designed to investigate slope-normal velocity and near-surface turbulence. Boundary Layer Meteorol. 182 (1), 29–54. https://doi.org/10.1007/s10546-021-00644-y

Charrondière, C., Stiperski, I., 2024. Spectral scaling of unstably stratified atmospheric flows: turbulence anisotropy and the low-frequency spread. Q. J. R. Meteorolog. Soc. 150 (764), 4196–4216. https://doi.org/10.1002/qj.4811

Chester, S., Meneveau, C., 2007. Renormalized numerical simulation of flow over planar and non-planar fractal trees. Environ. Fluid Mech. 7, 289–301. https://doi.org/10.1007/s10652-007-9026-7

Chester, S., Meneveau, C., Parlange, M.B., 2007. Modeling turbulent flow over fractal trees with renormalized numerical simulation. J. Comput. Phys. 225 (1), 427–448. https://doi.org/10.1016/j.jcp.2006.12.009

Chow, F.K., De Wekker, S. F.J., Snyder, B.J. (Eds.), 2013. Mountain Weather Research and Forecasting: Recent Progress and Current Challenges. Springer.

Chow, F.K., Schär, C., Ban, N., Lundquist, K.A., Schlemmer, L., Shi, X., 2019. Crossing multiple gray zones in the transition from mesoscale to microscale simulation over complex terrain. Atmosphere 10 (5). https://doi.org/10.3390/atmos10050274

Christen, A., Rotach, M.W., Vogt, R., 2009. The budget of turbulent kinetic energy in the urban roughness sublayer. Boundary Layer Meteorol. 131 (2), 193–222. https://doi.org/10.1007/s10546-009-9359-5

Coceal, O., Thomas, T.G., Castro, I.P., Belcher, S.E., 2006. Mean flow and turbulence statistics over groups of urban-like cubical obstacles. Boundary Layer Meteorol. 121 (3), 491–519. https://doi.org/10.1007/s10546-006-9076-2

Coimbra, I.L., Mann, J., Palma, J.M.L.M., Batista, V.T.P., 2025. Exploring dual-lidar mean and turbulence measurements over Perdigão's complex terrain. Atmos. Meas. Tech. 18 (1), 287–303. https://doi.org/10.5194/amt-18-287-2025

Cuxart, J., 2015. When can a high-resolution simulation over complex terrain be called LES? Front. Earth Sci. 3. https://doi.org/10.3389/feart.2015.00087

Davidson, P.A., Kaneda, Y., Moffatt, K., Sreenivasan, K.R. (Eds.), 2011. A Voyage Through Turbulence. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139018241

de Franceschi, M., Zardi, D., Tagliazucca, M., Tampieri, F., 2009. Analysis of second – order moments in surface layer turbulence in an Alpine valley. Q. J. R. Meteorolog. Soc. 135 (644), 1750–1765. https://doi.org/10.1002/qj.506

de la Paz, D., Borge, R., Martilli, A., 2016. Assessment of a high resolution annual WRF-BEP/CMAQ simulation for the urban area of Madrid (Spain). Atmos. Environ. 144, 282–296. https://doi.org/10.1016/j.atmosenv.2016.08.082

De Roo, F., Mauder, M., 2018. The influence of idealized surface heterogeneity on virtual turbulent flux measurements. Atmos. Chem. Phys. 18 (7), 5059–5074. https://doi.org/10.5194/acp-18-5059-2018

Deardorff, J.W., 1970. A numerical study of three-dimensional turbulent channel flow at large Reynolds numbers. J. Fluid Mech. 41 (2), 453–480. https://doi.org/10.1017/S0022112070000691

Deardorff, J.W., 1972. Numerical investigation of neutral and unstable planetary boundary layers. J. Atmos. Sci. 29 (1), 91–115. https://doi.org/10.1175/1520-0469(1972)029<0091:NIONAU>2.0.CO;2

Derbyshire, S.H., 1999. Boundary-layer decoupling over cold surfaces as a physical boundary-instability. Boundary Layer Meteorol. 90 (2), 297–325. https://doi.org/10.1023/A:1001710014316

Eder, F., Schmidt, M., Damian, T., Träumner, K., Mauder, M., 2015. Mesoscale eddies affect near-surface turbulent exchange: evidence from lidar and tower measurements. J. Appl. Meteorol. Climatol. 54 (1), 189–206. https://doi.org/10.1175/JAMC-D-14-0140.1

Edwards, J.M., Beljaars, A. C.M., Holtslag, A. A.M., Lock, A.P., 2020. Representation of boundary-layer processes in numerical weather prediction and climate models. Boundary Layer Meteorol. 177 (2), 511–539. https://doi.org/10.1007/s10546-020-00530-z

Epifanio, C.C., 2007. A method for imposing surface stress and heat flux conditions in finite-difference models with steep terrain. Mon. Weather Rev. 135 (3), 906–917. https://doi.org/10.1175/MWR3297.1

Farge, M., 1992. Wavelet transforms and their applications to turbulence. Annu. Rev. Fluid Mech. 24 (Volume 24, 1992), 395–458. https://doi.org/10.1146/annurev.fl.24.010192.002143

Farina, S., Zardi, D., 2023. Understanding thermally driven slope winds: recent advances and open questions. Boundary Layer Meteorol. 189 (1), 5–52. https://doi.org/10.1007/s10546-023-00821-1

Fedorovich, E., Shapiro, A., 2009. Structure of numerically simulated katabatic and anabatic flows along steep slopes. Acta Geophys. 57 (4), 981–1010. https://doi.org/10.2478/s11600-009-0027-4

Fenner, D., Christen, A., Grimmond, S., Meier, F., Morrison, W., Zeeman, M., Barlow, J., Birkmann, J., Blunn, L., Chrysoulakis, N., Clements, M., Glazer, R., Hertwig, D., Kotthaus, S., König, K., Looschelders, D., Mitraka, Z., Poursanidis, D., Tsirantonakis, D., Bechtel, B., Benjamin, K., Beyrich, F., Briegel, F., Feigel, G., Gertsen, C., Iqbal, N., Kittner, J., Lean, H., Liu, Y., Luo, Z., McGrory, M., Metzger, S., Paskin, M., Ravan, M., Ruhtz, T., Saunders, B., Scherer, D., Smith, S.T., Stretton, M., Trachte, K., Hove, M.V., 2024. Urbisphere-Berlin campaign: investigating multiscale urban impacts on the atmospheric boundary layer. Bull. Am. Meteorol. Soc. 105 (10), E1929 – E1961. https://doi.org/10.1175/BAMS-D-23-0030.1

Fernando, H., Mann, J., Palma, J., Lundquist, J.K., Barthelmie, R.J., Belo-Pereira, M., Brown, W., Chow, F.K., Gerz, T., Hocut, C.M., et al., 2019. The Perdigão: peering into microscale details of mountain winds. Bull. Am. Meteorol. Soc. 100 (5), 799–819. https://doi.org/10.1175/BAMS-D-17-0227.1

Fernando, H.J.S., 2010. Fluid dynamics of urban atmospheres in complex terrain. Annu. Rev. Fluid Mech. 42 (1), 365–389. https://doi.org/10.1146/annurev-fluid-121108-145459

Fernando, H.J.S., Pardyjak, E.R., Sabatino, S.D., Chow, F.K., De Wekker, S. F.J., Hoch, S.W., Hacker, J., Pace, J.C., Pratt, T., Pu, Z., Steenburgh, W.J., Whiteman, C.D., Wang, Y., Zajic, D., Balsley, B., Dimitrova, R., Emmitt, G.D., Higgins, C.W., Hunt, J.C.R., Knievel, J.C., Lawrence, D., Liu, Y., Nadeau, D.F., Kit, E., Blomquist, B.W., Conry, P., Coppersmith, R.S., Creegan, E., Felton, M., Grachev, A., Gunawardena, N., Hang, C., Hocut, C.M., Huynh, G., Jeglum, M.E., Jensen, D., Kulandaivelu, V., Lehner, M., Leo, L.S., Liberzon, D., Massey, J.D., McEnerney, K., Pal, S., Price, T., Sghiatti, M., Silver, Z., Thompson, M., Zhang, H., Zsedrovits, T., 2015. The MATERHORN: unraveling the intricacies of mountain weather. Bull. Am. Meteorol. Soc. 96 (11), 1945–1967. https://doi.org/10.1175/BAMS-D-13-00131.1

Fernando, H.J.S., Weil, J.C., 2010. Whither the stable boundary layer? A shift in the research agenda. Bull. Am. Meteorol. Soc. 91 (11), 1475–1484. https://doi.org/10.1175/2010BAMS2770.1

Feynman, R.P., Leighton, R.B., Sands, M., 1964. The Feynman Lectures on Physics. Vol. 2: Mainly Electromagnetism and Matter.

Figueroa-Espinoza, B., Salles, P., 2014. Local Monin–Obukhov similarity in heterogeneous terrain. Atmos. Sci. Lett. 15 (4), 299–306. https://doi.org/10.1002/asl2.503
Finnigan, J., 2000. Turbulence in plant canopies. Annu. Rev. Fluid Mech. 32 (Volume 32, 2000), 519–571. https://doi.org/10.1146/annurev.fluid.32.1.519
Finnigan, J., Ayotte, K., Harman, I., Katul, G., Oldroyd, H., Patton, E., Poggi, D., Ross, A., Taylor, P., 2020. Boundary-layer flow over complex topography. Boundary Layer Meteorol. 177 (2), 247–313. https://doi.org/10.1007/s10546-020-00564-3
Finnigan, J.J., 2024. Streamline coordinates in three-dimensional turbulent flows. J. Fluid Mech. 999, A101. https://doi.org/10.1017/jfm.2024.723
Finnigan, J.J., Clement, R., Malhi, Y., Leuning, R., Cleugh, H.A., 2003. A re-evaluation of long-term flux measurement techniques part I: averaging and coordinate rotation. Boundary Layer Meteorol. 107 (1), 1–48. https://doi.org/10.1023/A:1021554900225
Finnigan, J.J., Shaw, R.H., Patton, E.G., 2009. Turbulence structure above a vegetation canopy. J. Fluid Mech. 637, 387–424. https://doi.org/10.1017/S0022112009990589
Fogarty, J., Bou-Zeid, E., 2023. The atmospheric boundary layer above the marginal ice zone: scaling, surface fluxes, and secondary circulations. Boundary Layer Meteorol. 189 (1–3), 53–76. https://doi.org/10.1007/s10546-023-00825-x
Fogarty, J., Bou-Zeid, E., Bushuk, M., Calaf, M., Allouche, M., Ghannam, K., 2024. Numerical simulations of satellite-sensed surface maps in the marginal ice zone . https://doi.org/10.22541/essoar.172251979.90440727/v1
Foken, T., 2006. 50 years of the Monin–Obukhov similarity theory. Boundary Layer Meteorol. 119 (3), 431–447. https://doi.org/10.1007/s10546-006-9048-6
Foken, T., 2008. The energy balance closure problem: an overview. Ecol. Appl. 18 (6), 1351–1367. https://doi.org/10.1890/06-0922.1
Foken, T., 2021. Springer Handbook of Atmospheric Measurements. Springer Cham. https://doi.org/10.1007/978-3-030-52171-4
Foken, T., Börngen, M., 2021. Lettau's contribution to the Obukhov length scale: a scientific historical study. Boundary Layer Meteorol. 179 (3), 369–383. https://doi.org/10.1007/s10546-021-00606-4
Fowler, M., Zaki, T.A., Meneveau, C., 2023. A multi-time-scale wall model for large-eddy simulations and applications to non-equilibrium channel flows. J. Fluid Mech. 974, A51. https://doi.org/10.1017/jfm.2023.585
Freire, L.S., Chamecki, M., 2021. Large-eddy simulation of smooth and rough channel flows using a one-dimensional stochastic wall model. Comput. Fluids 230, 105135. https://doi.org/10.1016/j.compfluid.2021.105135
Garratt, J., Wilczak, J., Holtslag, A., Schmid, H.P., Grachev, A., Beljaars, A., Foken, T., Chen, F., Fairall, C., Hicks, B., Kusaka, H., Martilli, A., Masson, V., Mauder, M., Oncley, S., Rotach, M., Tjernström, M., 2020. Commentaries on top-cited Boundary-Layer Meteorology articles. Boundary Layer Meteorol. 177 (2), 169–188. https://doi.org/10.1007/s10546-020-00563-4
Garratt, J.R., 1978. Flux profile relations above tall vegetation. Q. J. R. Meteorolog. Soc. 104 (439), 199–211. https://doi.org/10.1002/qj.49710443915
Germano, M., Piomelli, U., Moin, P., Cabot, W.H., 1991. A dynamic subgrid-scale eddy viscosity model. Phys. Fluids A Fluid Dyn. 3 (7), 1760–1765. https://doi.org/10.1063/1.857955
Ghannam, K., Bou-Zeid, E., 2021. Baroclinicity and directional shear explain departures from the logarithmic wind profile. Q. J. R. Meteorolog. Soc. 147 (734), 443–464. https://doi.org/10.1002/qj.3927
Ghannam, K., Katul, G.G., Bou-Zeid, E., Gerken, T., Chamecki, M., 2018. Scaling and similarity of the anisotropic coherent eddies in near-surface atmospheric turbulence. J. Atmos. Sci. 75 (3), 943–964. https://doi.org/10.1175/JAS-D-17-0246.1
Giacomini, B., Giometto, M.G., 2021. On the suitability of second-order accurate finite-volume solvers for the simulation of atmospheric boundary layer flow. Geosci. Model Dev. 14 (3), 1409–1426. https://doi.org/10.5194/gmd-14-1409-2021
Giometto, M.G., Christen, A., Meneveau, C., Fang, J., Krafczyk, M., Parlange, M.B., 2016. Spatial characteristics of roughness sublayer mean flow and turbulence over a realistic urban surface. Boundary Layer Meteorol. 160 (3), 425–452. https://doi.org/10.1007/s10546-016-0157-6
Gisinger, S., Dörnbrack, A., Schröttle, J., 2015. A modified Darcy's law. Theor. Comput. Fluid Dyn. 29 (4), 343–347. https://doi.org/10.1007/s00162-015-0357-6
Grachev, A.A., Andreas, E.L., Fairall, C.W., Guest, P.S., Persson, P. O.G., 2007. SHEBA flux–profile relationships in the stable atmospheric boundary layer. Boundary Layer Meteorol. 124 (3), 315–333. https://doi.org/10.1007/s10546-007-9177-6
Grachev, A.A., Andreas, E.L., Fairall, C.W., Guest, P.S., Persson, P. O.G., 2015. Similarity theory based on the Dougherty–Ozmidov length scale. Q. J. R. Meteorolog. Soc. 141 (690), 1845–1856. https://doi.org/10.1002/qj.2488
Grachev, A.A., Fairall, C.W., Persson, P. O.G., Andreas, E.L., Guest, P.S., 2005. Stable boundary-layer scaling regimes: the SHEBA data. Boundary Layer Meteorol. 116 (2), 201–235. https://doi.org/10.1007/s10546-004-2729-0
Graham, J., Kanov, K., Yang, X., Lee, M., Malaya, N., Lalescu, C.C., Burns, R., Eyink, G., Szalay, A., Moser, R.D., et al., 2016. A web services accessible database of turbulent channel flow and its use for testing a new integral wall model for LES. J. Turbul. 17 (2), 181–215. https://doi.org/10.1080/14685248.2015.1088656
Grimmond, C.S.B., Oke, T.R., 1999. Aerodynamic properties of urban areas derived from analysis of surface form. J. Appl. Meteorol. 38 (9), 1262–1292. https://doi.org/10.1175/1520-0450(1999)038<1262:APOUAD>2.0.CO;2
Grisogono, B., 2010. Generalizing 'z-less' mixing length for stable boundary layers. Q. J. R. Meteorolog. Soc. 136 (646), 213–221. https://doi.org/10.1002/qj.529
Grisogono, B., Kraljević, L., Jeričević, A., 2007. The low-level katabatic jet height versus Monin–Obukhov height. Q. J. R. Meteorolog. Soc. 133 (629), 2133–2136. https://doi.org/10.1002/qj.190
Grisogono, B., Oerlemans, J., 2001. A theory for the estimation of surface fluxes in simple katabatic flows. Q. J. R. Meteorolog. Soc. 127 (578), 2725–2739. https://doi.org/10.1002/qj.49712757811
Grubišić, V., Doyle, J.D., Kuettner, J., Dirks, R., Cohn, S.A., Pan, L.L., Mobbs, S., Smith, R.B., Whiteman, C.D., Czyzyk, S., Vosper, S., Weissmann, M., Haimov, S., De Wekker, S. F.J., Chow, F.K., 2008. The Terrain-induced Rotor Experiment. Bull. Am. Meteorol. Soc. 89 (10), 1513–1533. https://doi.org/10.1175/2008BAMS2487.1
Gucci, F., Giovannini, L., Stiperski, I., Zardi, D., Vercauteren, N., 2023. Sources of anisotropy in the Reynolds stress tensor in the stable boundary layer. Q. J. R. Meteorolog. Soc. 149 (750), 277–299. https://doi.org/https://doi.org/10.1002/qj.4407
Hang, C., Oldroyd, H.J., Giometto, M.G., Pardyjak, E.R., Parlange, M.B., 2021. A local similarity function for katabatic flows derived from field observations over steep- and shallow-angled slopes. Geophys. Res. Lett. 48 (23), 1–11. https://doi.org/10.1029/2021GL095479
Harman, I.N., Finnigan, J.J., 2007. A simple unified theory for flow in the canopy and roughness sublayer. Boundary Layer Meteorol. 123, 339–363. https://doi.org/10.1007/s10546-006-9145-6
Haugen, D.A. (Ed.), 1973. Workshop on Micrometeorology. American Meteorological Society.
Haugeneder, M., Lehning, M., Reynolds, D., Jonas, T., Mott, R., 2023. A novel method to quantify near-surface boundary-layer dynamics at ultra-high spatio-temporal resolution. Boundary Layer Meteorol. 186 (2), 177–197. https://doi.org/10.1007/s10546-022-00752-3
Haupt, S.E., Kosovic, B., Shaw, W., Berg, L.K., Churchfield, M., Cline, J., Draxl, C., Ennis, B., Koo, E., Kotamarthi, R., Mazzaro, L., Mirocha, J., Moriarty, P., Muñoz-Esparza, D., Quon, E., Rai, R.K., Robinson, M., Sever, G., 2019. On bridging a modeling scale gap: mesoscale to microscale coupling for wind energy. Bull. Am. Meteorol. Soc. 100 (12), 2533–2550. https://doi.org/10.1175/BAMS-D-18-0033.1
Heinze, R., Mironov, D., Raasch, S., 2016. Analysis of pressure-strain and pressure gradient-scalar covariances in cloud-topped boundary layers: a large-eddy simulation study. J. Adv. Model. Earth Syst. 8 (1), 3–30. https://doi.org/10.1002/2015MS000508
Heisel, M., Chamecki, M., 2023. Evidence of mixed scaling for mean profile similarity in the stable atmospheric surface layer. J. Atmos. Sci. 80 (8), 2057–2073. https://doi.org/10.1175/JAS-D-22-0260.1
Higgins, C.W., Drake, S.A., Kelley, J., Oldroyd, H.J., Jensen, D.D., Wharton, S., 2019. Ensemble-averaging resolves rapid atmospheric response to the 2017 total solar eclipse. Front. Earth Sci. 7. https://doi.org/10.3389/feart.2019.00198
Hilland, R. V.J., Bernhofer, C., Bohmann, M., Christen, A., Katurji, M., Maggs-Kölling, G., Krauß, M., Larsen, J.A., Marais, E., Pitacco, A., Schumacher, B., Spirig, R., Vendrame, N., Vogt, R., 2022. The Namib turbulence experiment: investigating surface–atmosphere heat transfer in three dimensions. Bull. Am. Meteorol. Soc. 103 (3), E741–E760. https://doi.org/10.1175/bams-d-20-0269.1
Hoch, S.W., Calanca, P., Philipona, R., Ohmura, A., 2007. Year-round observation of longwave radiative flux divergence in greenland. J. Appl. Meteorol. Climatol. 46 (9), 1469–1479. https://doi.org/10.1175/JAM2542.1
Högström, U., 1996. Review of some basic characteristics of the atmospheric surface layer. Boundary Layer Meteorol. 78 (3), 215–246. https://doi.org/10.1007/BF00120937
Holliday, D., Mcintyre, M.E., 1981. On potential energy density in an incompressible, stratified fluid. J. Fluid Mech. 107, 221–225. https://doi.org/10.1017/S0022112081001742
Holtslag, A.A.M., Duynkerke, P.G., 1998. Clear and Cloudy Boundary Layers. Royal Netherlands Academy of Sciences, Amsterdam, The Netherlands.
Holtslag, A.A.M., Svensson, G., Baas, P., Basu, S., Beare, B., Beljaars, A.C.M., Bosveld, F.C., Cuxart, J., Lindvall, J., Steeneveld, G.J., Tjernström, M., De Wiel, B. J. H.V., 2013. Stable atmospheric boundary layers and diurnal cycles: challenges for weather and climate models. Bull. Am. Meteorol. Soc. 94 (11), 1691–1706. https://doi.org/10.1175/BAMS-D-11-00187.1
Holtslag, B., 2006. Preface: GEWEX atmospheric boundary-layer study (GABLS) on stable boundary layers. Boundary Layer Meteorol. 118 (2), 243–246. https://doi.org/10.1007/s10546-005-9008-6
Howell, J.F., Mahrt, L., 1997. Multiresolution flux decomposition. Boundary Layer Meteorol. 83 (1), 117–137. https://doi.org/10.1023/A:1000210427798
Hunt, J.C.R., Leibovich, S., Richards, K.J., 1988a. Turbulent shear flows over low hills. Q. J. R. Meteorolog. Soc. 114 (482), 1435–1470. https://doi.org/10.1002/qj.49711448405
Hunt, J.C.R., Richards, K.J., Brighton, P.W.M., 1988b. Stably stratified shear flow over low hills. Q. J. R. Meteorolog. Soc. 114 (482), 859–886. https://doi.org/10.1002/qj.49711448203
JHTDB, 2025. Johns Hopkins Turbulence Database. https://turbulence.idies.jhu.edu.
Juliano, T.W., Kosović, B., Jiménez, P.A., Eghdami, M., Haupt, S.E., Martilli, A., 2022. "Gray Zone" simulations using a three-dimensional planetary boundary layer parameterization in the weather research and forecasting model. Mon. Weather Rev. 150 (7), 1585–1619. https://doi.org/10.1175/MWR-D-21-0164.1
Kaimal, J.C., Finnigan, J.J., 1994. Atmospheric boundary layer flows: their structure and measurement. Oxford University Press, Oxford, UK. https://doi.org/10.1093/oso/9780195062397.001.0001
Kallistratova, M.A., 2002. Acoustic waves in the turbulent atmosphere: a review. J. Atmos. Oceanic Technol. 19 (8), 1139–1150. https://doi.org/10.1175/1520-0426(2002)019<1139:AWITTA>2.0.CO;2
Kastner-Klein, P., Rotach, M.W., 2004. Mean flow and turbulence characteristics in an urban roughness sublayer. Boundary Layer Meteorol. 111 (1), 55–84. https://doi.org/10.1023/B:BOUN.0000010994.32240.b1
Katul, G.G., Konings, A.G., Porporato, A., 2011. Mean velocity profile in a sheared and thermally stratified atmospheric boundary layer. Phys. Rev. Lett. 107, 268502. https://doi.org/10.1103/PhysRevLett.107.268502
Katul, G.G., Mahrt, L., Poggi, D., Sanz, C., 2004. One- and two-equation models for canopy turbulence. Boundary Layer Meteorol. 113 (1), 81–109. https://doi.org/10.1023/B:BOUN.0000037333.48760.e5
Katul, G.G., Oren, R., Manzoni, S., Higgins, C., Parlange, M.B., 2012. Evapotranspiration: a process driving mass transport and energy exchange in the soil-plant-atmosphere-climate system. Rev. Geophys. 50 (3). https://doi.org/10.1029/2011RG000366

Kelly, M., Cavar, D., 2023. Effective roughness and displaced mean flow over complex terrain. Boundary Layer Meteorol. 186 (1), 93–123. https://doi.org/10.1007/s10546-022-00748-z

Kelly, M., Gryning, S.-E., 2010. Long-term mean wind profiles based on similarity theory. Boundary Layer Meteorol. 136 (3), 377–390. https://doi.org/10.1007/s10546-010-9509-9

Klipp, C.L., Mahrt, L., 2004. Flux–gradient relationship, self-correlation and intermittency in the stable boundary layer. Q. J. R. Meteorolog. Soc. 130 (601), 2087–2103. https://doi.org/10.1256/qj.03.161

Kolmogorov, A.N., 1941a. Dissipation of energy in locally isotropic turbulence. Dokl. Akad. Nauk SSSR 32, 19–21.

Kolmogorov, A.N., 1941b. The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers. Dokl. Akad. Nauk SSSR 30, 299–303.

Kolmogorov, A.N., 1962. A refinement of previous hypotheses concerning the local structure of turbulence in a viscous incompressible fluid at high reynolds number. J. Fluid Mech. 13 (1), 82–85. https://doi.org/10.1017/S0022112062000518

Koopmans, S., van Haren, R., Theeuwes, N., Ronda, R., Uijlenhoet, R., Holtslag, A. A.M., Steeneveld, G.-J., 2023. The set-up and evaluation of fine-scale data assimilation for the urban climate of Amsterdam. Q. J. R. Meteorolog. Soc. 149 (750), 171–191. https://doi.org/https://doi.org/10.1002/qj.4401

Koster, R.D., Suarez, M.J., 1992. A comparative analysis of two land surface heterogeneity representations. J. Clim. 5 (12), 1379–1390. https://doi.org/10.1175/1520-0442(1992)005<1379:acaotl>2.0.co;2

Krieger, N., Wernli, H., Sprenger, M., Kühnlein, C., 2025. Revealing the dynamics of a local Alpine windstorm using large-eddy simulations. Weather Clim. Dyn. 6 (2), 447–469. https://doi.org/10.5194/wcd-6-447-2025

Kuettner, J.P., O'Neill, T. H.R., 1981. ALPEX the GARP mountain subprogram. Bull. Am. Meteorol. Soc. 62 (6), 793–805. https://doi.org/10.1175/1520-0477-62.6.793

Kulmala, M., Kokkonen, T., Ezhova, E., Baklanov, A., Mahura, A., Mammarella, I., Bäck, J., Lappalainen, H.K., Tyuryakov, S., Kerminen, V.-M., Zilitinkevich, S., Petäjä, T., 2023. Aerosols, clusters, greenhouse gases, trace gases and boundary-layer dynamics: on feedbacks and interactions. Boundary Layer Meteorol. 186 (3), 475–503. https://doi.org/10.1007/s10546-022-00769-8

Kármán, T., Levi-Civita, T. (Eds.), 1925. Vorträge aus dem Gebiete der Hydro- und Aerodynamik (Innsbruck 1922). Springer, Berlin. https://doi.org/10.1007/978-3-662-00280-3

Le, H., Moin, P., Kim, J., 1997. Direct numerical simulation of turbulent flow over a backward-facing step. J. Fluid Mech. 330, 349–374. https://doi.org/10.1017/S0022112096003941

Leclerc, M.Y., Thurtell, G.W., 1990. Footprint prediction of scalar fluxes using a Markovian analysis. Boundary Layer Meteorol. 52 (3), 247–258. https://doi.org/10.1007/BF00122089

Lehner, M., Rotach, M.W., 2018. Current challenges in understanding and predicting transport and exchange in the atmosphere over mountainous terrain. Atmosphere 9 (7). https://doi.org/10.3390/atmos9070276

Lehner, M., Rotach, M.W., Sfyri, E., Obleitner, F., 2021. Spatial and temporal variations in near-surface energy fluxes in an alpine valley under synoptically undisturbed and clear-sky conditions. Q. J. R. Meteorolog. Soc. 147 (737), 2173–2196. https://doi.org/10.1002/qj.4016

Lehner, M., Whiteman, C.D., Hoch, S.W., Crosman, E.T., Jeglum, M.E., Cherukuru, N.W., Calhoun, R., Adler, B., Kalthoff, N., Rotunno, R., et al., 2016. The METCRAX II field experiment: a study of downslope windstorm-type flows in Arizona's Meteor Crater. Bull. Am. Meteorol. Soc. 97 (2), 217–235. https://doi.org/10.1175/BAMS-D-14-00238.1

LeMone, M.A., 1973. The structure and dynamics of horizontal roll vortices in the planetary boundary layer. J. Atmosp. Sci. 30 (6), 1077–1091. https://doi.org/10.1175/1520-0469(1973)030<1077:TSADOH>2.0.CO;2

LeMone, M.A., Angevine, W.M., Bretherton, C.S., Chen, F., Dudhia, J., Fedorovich, E., Katsaros, K.B., Lenschow, D.H., Mahrt, L., Patton, E.G., Sun, J., Tjernström, M., Weil, J., 2019. 100 years of progress in boundary layer meteorology. Meteorol. Monogr. 59, 9.1–9.85. https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0013.1

Li, D., Bou-Zeid, E., Barlage, M., Chen, F., Smith, J.A., 2013. Development and evaluation of a mosaic approach in the WRF-Noah framework. J. Geophys. Res. Atmos. 118 (21). https://doi.org/10.1002/2013jd020657

Li, Q., Bou-Zeid, E., 2019. Contrasts between momentum and scalar transport over very rough surfaces. J. Fluid Mech. 880, 32–58. https://doi.org/10.1017/jfm.2019.687

Li, Q., Bou-Zeid, E., Grimmond, S., Zilitinkevich, S., Katul, G., 2020. Revisiting the relation between momentum and scalar roughness lengths of urban surfaces. Q. J. R. Meteorolog. Soc. 146 (732), 3144–3164. https://doi.org/10.1002/qj.3839

Li, Q., Yang, J., Yang, L., 2021. Impact of urban roughness representation on regional hydrometeorology: an idealized study. J. Geophys. Res.: Atmos. 126 (4), e2020JD033812. e2020JD033812 2020JD033812. https://doi.org/10.1029/2020JD033812

Li, Y., Perlman, E., Wan, M., Yang, Y., Meneveau, C., Burns, R., Chen, S., Szalay, A., Eyink, G., 2008. A public turbulence database cluster and applications to study Lagrangian evolution of velocity increments in turbulence. J. Turbul. (9), N31. https://doi.org/10.1080/14685240802376389

Lilly, D.K., 1967. The representation of small-scale turbulence in numerical simulation experiments. In: Proceedings of IBM Scientific Computing Symposium on Environmental Sciences, IBM Form No. 320–1951, p. 195–210.

Ling, J., Kurzawski, A., Templeton, J., 2016. Reynolds averaged turbulence modelling using deep neural networks with embedded invariance. J. Fluid Mech. 807, 155–166. https://doi.org/10.1017/jfm.2016.615

Lord-May, C., Radić, V., 2024. Improved processing methods for eddy covariance measurements in calculating sensible heat fluxes at glacier surfaces. J. Glaciol. . https://doi.org/10.1017/jog.2024.39

Lothon, M., Lohou, F., Pino, D., Couvreux, F., Pardyjak, E.R., Reuder, J., Vilà-Guerau de Arellano, J., Durand, P., Hartogensis, O., Legain, D., Augustin, P., Gioli, B., Lenschow, D.H., Faloona, I., Yagüe, C., Alexander, D.C., Angevine, W.M., Bargain, E., Barrié, J., Bazile, E., Bezombes, Y., Blay-Carreras, E., van de Boer, A., Boichard, J.L., Bourdon, A., Butet, A., Campistron, B., de Coster, O., Cuxart, J., Dabas, A., Darbieu, C., Deboudt, K., Delbarre, H., Derrien, S., Flament, P., Fourmentin, M., Garai, A., Gibert, F., Graf, A., Groebner, J., Guichard, F., Jiménez, M.A., Jonassen, M., van den Kroonenberg, A., Magliulo, V., Martin, S., Martinez, D., Mastrorillo, L., Moene, A.F., Molinos, F., Moulin, E., Pietersen, H.P., Piguet, B., Pique, E., Román-Cascón, C., Rufin-Soler, C., Saïd, F., Sastre-Marugán, M., Seity, Y., Steeneveld, G.J., Toscano, P., Traullé, O., Tzanos, D., Wacker, S., Wildmann, N., Zaldei, A., 2014. The BLLAST field experiment: boundary-layer late afternoon and sunset turbulence. Atmos. Chem. Phys. 14 (20), 10931–10960. https://doi.org/10.5194/acp-14-10931-2014

Lumley, J.L., Yaglom, A.M., 2001. A century of turbulence. Flow Turbul. Combust. 66 (3), 241–286. https://doi.org/10.1023/A:1012437421667

Lund, T.S., Wu, X., Squires, K.D., 1998. Generation of turbulent inflow data for spatially-developing boundary layer simulations. J. Comput. Phys. 140 (2), 233–258. https://doi.org/10.1006/jcph.1998.5882

Lundquist, K.A., Chow, F.K., Lundquist, J.K., 2010. An immersed boundary method for the Weather Research and Forecasting model. Mon. Weather Rev. 138 (3), 796–817. https://doi.org/10.1175/2009MWR2990.1

Lundquist, K.A., Chow, F.K., Lundquist, J.K., 2012. An immersed boundary method enabling large-eddy simulations of flow over complex terrain in the WRF model. Mon. Weather Rev. 140 (12), 3936–3955. https://doi.org/10.1175/MWR-D-11-00311.1

Mack, L., Kähnert, M., Rauschenbach, Q., Frank, L., Hasenburg, F.H., Huss, J.-M., Jonassen, M.O., Malpas, M., Batrak, Y., Remes, T., Pirk, N., Thomas, C.K., 2025. Stable boundary layers in an arctic fjord-valley system: evaluation of temperature profiles observed from fiber-optic distributed sensing and comparison to numerical weather prediction systems at different resolutions. J. Geophys. Res. Atmos. 130 (2), e2024JD042825. https://doi.org/10.1029/2024JD042825

Mahrt, L., 1989. Intermittency of atmospheric turbulence. J. Atmos. Sci. 46 (1), 79–95. https://doi.org/10.1175/1520-0469(1989)046<0079:IOAT>2.0.CO;2

Mahrt, L., 1999. Stratified atmospheric boundary layers. Boundary Layer Meteorol. 90 (3), 375–396. https://doi.org/10.1023/A:1001765727956

Mahrt, L., 2014. Stably stratified atmospheric boundary layers. Annu. Rev. Fluid Mech. 46 (1), 23–45. https://doi.org/10.1146/annurev-fluid-010313-141354

Mahrt, L., Bou-Zeid, E., 2020. Non-stationary boundary layers. Boundary Layer Meteorol. 177 (2–3), 189–204. https://doi.org/10.1007/s10546-020-00533-w

Mahrt, L., Thomas, C.K., 2016. Surface stress with non-stationary weak winds and stable stratification. Boundary Layer Meteorol. 159 (1), 3–21. https://doi.org/10.1007/s10546-015-0111-z

Margairaz, F., Pardyjak, E.R., Calaf, M., 2020a. Surface thermal heterogeneities and the atmospheric boundary layer: the relevance of dispersive fluxes. Boundary Layer Meteorol. 175 (3), 369–395. https://doi.org/10.1007/s10546-020-00509-w

Margairaz, F., Pardyjak, E.R., Calaf, M., 2020b. Surface thermal heterogeneities and the atmospheric boundary layer: the thermal heterogeneity parameter. Boundary Layer Meteorol. 177 (1), 49–68. https://doi.org/10.1007/s10546-020-00544-7

Maronga, B., Banzhaf, S., Burmeister, C., Esch, T., Forkel, R., Fröhlich, D., Fuka, V., Gehrke, K.F., Geletič, J., Giersch, S., Gronemeier, T., Groß, G., Heldens, W., Hellsten, A., Hoffmann, F., Inagaki, A., Kadasch, E., Kanani-Sühring, F., Ketelsen, K., Khan, B.A., Knigge, C., Knoop, H., Krč, P., Kurppa, M., Maamari, H., Matzarakis, A., Mauder, M., Pallasch, M., Pavlik, D., Pfafferott, J., Resler, J., Rissmann, S., Russo, E., Salim, M., Schrempf, M., Schwenkel, J., Seckmeyer, G., Schubert, S., Sühring, M., von Tils, R., Vollmer, L., Ward, S., Witha, B., Wurps, H., Zeidler, J., Raasch, S., 2020. Overview of the PALM model system 6.0. Geosci. Model Dev. 13 (3), 1335–1372. https://doi.org/10.5194/gmd-13-1335-2020

Martilli, A., Clappier, A., Rotach, M.W., 2002. An urban surface exchange parameterisation for mesoscale models. Boundary Layer Meteorol. 104 (2), 261–304. https://doi.org/10.1023/A:1016099921195

Martilli, A., Roulet, Y.-A., Junier, M., Kirchner, F., Rotach, M.W., Clappier, A., 2003. On the impact of urban surface exchange parameterisations on air quality simulations: the Athens case. Atmos. Environ. 37 (30), 4217–4231. https://doi.org/10.1016/S1352-2310(03)00564-8

Martins, C.A., Moraes, O. L.L., Acevedo, O.C., Degrazia, G.A., 2009. Turbulence intensity parameters over a very complex terrain. Boundary Layer Meteorol. 133 (1), 35–45. https://doi.org/10.1007/s10546-009-9413-3

Marusic, I., McKeon, B.J., Monkewitz, P.A., Nagib, H.M., Smits, A.J., Sreenivasan, K.R., 2010. Wall-bounded turbulent flows at high Reynolds numbers: recent advances and key issues. Phys. Fluids 22 (6), 065103. https://doi.org/10.1063/1.3453711

Mauder, M., Foken, T., Cuxart, J., 2020. Surface-energy-balance closure over land: a review. Boundary Layer Meteorol. 177 (2), 395–426. https://doi.org/10.1007/s10546-020-00529-6

McNaughton, K.G., 1988. Effects of windbreaks on turbulent transport and microclimate. Agric. Ecosyst. Environ. 22-23, 17–39. https://doi.org/10.1016/0167-8809(88)90006-0

McNaughton, K.G., Brunet, Y., 2002. Townsend's hypothesis, coherent structures and Monin–Obukhov similarity. Boundary Layer Meteorol. 102 (2), 161–175. https://doi.org/10.1023/A:1013171312407

McWilliams, J.C., Meneveau, C., Patton, E.G., Sullivan, P.P., 2023. Stable boundary layers and subfilter-scale motions. Atmosphere 14 (7), 1107. https://doi.org/10.3390/atmos14071107

Medeiros, L.E., Fitzjarrald, D.R., 2015. Stable boundary layer in complex terrain. part II: geometrical and sheltering effects on mixing. J. Appl. Meteorol. Climatol. 54 (1), 170–188. https://doi.org/10.1175/JAMC-D-13-0346.1

Mellor, G.L., Yamada, T., 1974. A hierarchy of turbulence closure models for planetary boundary layers. J. Atmos. Sci. 31 (7), 1791–1806. https://doi.org/10.1175/1520-0469(1974)031 < 1791:AHOTCM > 2.0.CO;2

Mellor, G.L., Yamada, T., 1982. Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys. 20 (4), 851–875. https://doi.org/10.1029/RG020i004p00851

Mironov, D.V., Sullivan, P.P., 2023. Turbulence structure and mixing in strongly stable boundary-layer flows over thermally heterogeneous surfaces. Boundary Layer Meteorol. 187 (1), 371–393. https://doi.org/10.1007/s10546-022-00766-x

Mittal, R., Moin, P., 1997. Suitability of upwind-biased finite difference schemes for large-eddy simulation of turbulent flows. AIAA J. 35 (8), 1415–1417. https://doi.org/10.2514/2.253

Moderow, U., Grünwald, T., Queck, R., Spank, U., Bernhofer, C., 2021. Energy balance closure and advective fluxes at ADVEX sites. Theor. Appl. Climatol. 143 (1), 761–779. https://doi.org/10.1007/s00704-020-03412-z

Moeng, C.-H., Sullivan, P.P., 2015. Numerical models – Large-eddy Simulation. In: North, G.R., Pyle, J., Zhang, F. (Eds.), Encyclopedia of Atmospheric Sciences (Second Edition). Academic Press, Oxford, pp. 232–240. https://doi.org/10.1016/B978-0-12-382225-3.00201-2

Moin, P., Mahesh, K., 1998. Direct numerical simulation: a tool in turbulence research. Annu. Rev. Fluid Mech. 30 (Volume 30, 1998), 539–578. https://doi.org/10.1146/annurev.fluid.30.1.539

Monin, A.S., Obukhov, A.M., 1954. Basic laws of turbulent mixing in the surface layer of the atmosphere. Dokl. Akad. Nauk SSSR 24 (151), 163–187.

Morrison, T.J., Calaf, M., Pardyjak, E.R., 2023. A full three-dimensional surface energy balance over a desert playa. Q. J. R. Meteorolog. Soc. 149 (750), 102–114. https://doi.org/10.1002/qj.4397

Mosso, S., Calaf, M., Stiperski, I., 2024. Flux-gradient relations and their dependence on turbulence anisotropy. Q. J. R. Meteorolog. Soc. 150 (763), 3346–3367. https://doi.org/10.1002/qj.4762

Mosso, S., Lapo, K., Stiperski, I., 2025. Revealing the drivers of turbulence anisotropy over complex terrain: an interpretable machine learning approach. Boundary Layer Meteorol. . https://doi.org/10.48550/arXiv.2503.15276

Mott, R., Daniels, M., Lehning, M., 2015. Atmospheric flow development and associated changes in turbulent sensible heat flux over a patchy mountain snow cover. J. Hydrometeorol. 16 (3), 1315–1340. https://doi.org/10.1175/JHM-D-14-0036.1

Muñoz-Esparza, D., Kosović, B., 2018. Generation of inflow turbulence in large-eddy simulations of nonneutral atmospheric boundary layers with the cell perturbation method. Mon. Weather Rev. 146 (6), 1889–1909. https://doi.org/10.1175/MWR-D-18-0077.1

Muñoz-Esparza, D., Kosović, B., Mirocha, J., van Beeck, J., 2014. Bridging the transition from mesoscale to microscale turbulence in numerical weather prediction models. Boundary Layer Meteorol. 153, 409–440. https://doi.org/10.1007/s10546-014-9956-9

Mölders, N., Raabe, A., Tetzlaff, G., 1996. A comparison of two strategies on land surface heterogeneity used in a mesoscale β meteorological model. Tellus A: Dyn. Meteorol. Oceanogr. . https://doi.org/10.3402/tellusa.v48i5.12203

Nadeau, D.F., Pardyjak, E.R., Higgins, C.W., Huwald, H., Parlange, M.B., 2013a. Flow during the evening transition over steep alpine slopes. Q. J. R. Meteorolog. Soc. 139 (672), 607–624. https://doi.org/10.1002/qj.1985

Nadeau, D.F., Pardyjak, E.R., Higgins, C.W., Parlange, M.B., 2013b. Similarity scaling over a steep alpine slope. Boundary Layer Meteorol. 147 (3), 401–419. https://doi.org/10.1007/s10546-012-9787-5

Nappo, C.J., 1991. Sporadic breakdowns of stability in the PBL over simple and complex terrain. Boundary Layer Meteorol. 54, 69–87. https://doi.org/10.1007/BF00119413

Nazarian, N., Lu, J., Lipson, M., Liu, S., Hart, M.A., Krayenhoff, S., Blunn, L., Martilli, A., 2025. UrbanTALES: a comprehensive LES dataset for urban canopy layer turbulence analyses and parameterization development . https://doi.org/10.31223/X58X3B

Nicholson, L., Stiperski, I., Nitti, G., Prinz, R., Georgi, A., Groos, A.R., Shaw, T.E., Sauter, T., Haugeneder, M., Mott, R., Sicart, J.-E., Brock, B.W., Albers, R., Allegri, B., Barral, H., Biron, R., Charrondiere, C., Coulaud, C., Fischer, A., Reynolds, D., Richter, N., Schroeder, M., Vettori, P., Voordendag, A., Wydra, C., 2025. The second HinterEisFerner EXperiment (HEFEX II): initial insights into boundary layer structure and surface-atmosphere exchange processes from intensive observations at a valley glacier. Bull. Am. Meteorol. Soc. 106, E2143–E2169. https://doi.org/10.1175/BAMS-D-24-0010.1

Nieuwstadt, F.T.M., 1984. Some aspects of the turbulent stable boundary layer. Boundary Layer Meteorol. 30 (1), 31–55. https://doi.org/10.1007/BF00121948

Nieuwstadt, F.T.M., van Dop, H. (Eds.), 1982. Atmospheric Turbulence and Air Pollution Modelling. Springer.

Nunalee, C.G., Kosović, B., Bieringer, P.E., 2014. Eulerian dispersion modeling with WRF-LES of plume impingement in neutrally and stably stratified turbulent boundary layers. Atmos. Environ. 99, 571–581. https://doi.org/10.1016/j.atmosenv.2014.09.070

Obukhov, A.M., 1946. Turbulence in an atmosphere with a non-uniform temperature. Trudy Inst. Teoret. Geophys. Akad. Nauk SSSR. 1, 95–115.

Omidvar, H., Bou-Zeid, E., Chiaramonte, M., 2019. Physical determinants and reduced models of the rapid cooling of urban surfaces during rainfall. J. Adv. Model. Earth Syst. 11 (5), 1364–1380. https://doi.org/10.1029/2018ms001528

Orszag, S.A., 1970. Analytical theories of turbulence. J. Fluid Mech. 41 (2), 363–386. https://doi.org/10.1017/S0022112070000642

Park, M.-S., Park, S.-U., 2006. Effects of topographical slope angle and atmospheric stratification on surface-layer turbulence. Boundary Layer Meteorol. 118 (3), 613–633. https://doi.org/10.1007/s10546-005-7206-x

Patton, E.G., Sullivan, P.P., Shaw, R.H., Finnigan, J.J., Weil, J.C., 2016. Atmospheric stability influences on coupled boundary layer and canopy turbulence. J. Atmos. Sci. 73, 1621–1647. https://doi.org/10.1175/JAS-D-15-0068.1

Physick, W.L., Garratt, J.R., 1995. Incorporation of a high-roughness lower boundary into a mesoscale model for studies of dry deposition over complex terrain. Boundary Layer Meteorol. 74 (1–2), 55–71. https://doi.org/10.1007/bf00715710

Pielke, R.A., Avissar, R., 1990. Influence of landscape structure on local and regional climate. Landsc. Ecol. 4 (2), 133–155. https://doi.org/10.1007/BF00132857

Porté-Agel, F., Meneveau, C., Parlange, M.B., 2000. A scale-dependent dynamic model for large-eddy simulation: application to a neutral atmospheric boundary layer. J. Fluid Mech. 415, 261–284. https://doi.org/10.1017/S0022112000008776

Poulos, G.S., Blumen, W., Fritts, D.C., Lundquist, J.K., Sun, J., Burns, S.P., Nappo, C., Banta, R., Newsom, R., Cuxart, J., Terradellas, E., Balsley, B., Jensen, M., 2002. Cases-99: a comprehensive investigation of the stable nocturnal boundary layer. Bull. Am. Meteorol. Soc. 83 (4), 555–581. https://doi.org/10.1175/1520-0477(2002)083 < 0555:CACIOT > 2.3.CO;2

Ramsey, E., Monahan, A.H., 2022. Empirical low-dimensional dynamics of atmospheric stable boundary layer temperature inversions. J. Atmos. Sci. 79 (7), 1965–1984. https://doi.org/10.1175/JAS-D-21-0205.1

Raupach, M.R., Antonia, R.A., Rajagopalan, S., 1991. Rough-wall turbulent boundary layers. Appl. Mech. Rev. 44 (1), 1–25. https://doi.org/10.1115/1.3119492

Raupach, M.R., Finnigan, J.J., Brunei, Y., 1996. Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy. Boundary Layer Meteorol. 78 (3), 351–382. https://doi.org/10.1007/BF00120941

Raupach, M.R., Shaw, R.H., 1982. Averaging procedures for flow within vegetation canopies. Boundary Layer Meteorol. 22 (1), 79–90. https://doi.org/10.1007/BF00128057

Richardson, L.F. (Ed.), 1922. Weather Prediction by Numerical Process. Cambridge University Press, Cambridge, UK.

Richardson, L.F., Shaw, W.N., 1920. The supply of energy from and to atmospheric eddies. Proc. R. Soci. London. Series A Containing Papers Math. Phys. Character 97 (686), 354–373. https://doi.org/10.1098/rspa.1920.0039

Rotach, M.W., 1999. On the influence of the urban roughness sublayer on turbulence and dispersion. Atmos. Environ. 33 (24), 4001–4008. https://doi.org/10.1016/S1352-2310(99)00141-7

Rotach, M.W., Andretta, M., Calanca, P., Weigel, A.P., Weiss, A., 2008. Boundary layer characteristics and turbulent exchange mechanisms in highly complex terrain. Acta Geophys. 56 (1), 194–219. https://doi.org/10.2478/s11600-007-0043-1

Rotach, M.W., Calanca, P., Graziani, G., Gurtz, J., Steyn, D.G., Vogt, R., Andretta, M., Christen, A., Cieslik, S., Connolly, R., De Wekker, S. F.J., Galmarini, S., Kadygrov, E.N., Kadygrov, V., Miller, E., Neininger, B., Rucker, M., Gorsel, E.V., Weber, H., Weiss, A., Zappa, M., 2004. Turbulence structure and exchange processes in an Alpine valley: the Riviera project. Bull. Am. Meteorol. Soc. 85 (9), 1367–1386. https://doi.org/10.1175/BAMS-85-9-1367

Rotach, M.W., Holtslag, A.A.M., 2025. Ideal and Real Atmospheric Boundary Layers. Academic Press, London, UK.

Rotach, M.W., Serafin, S., Ward, H.C., Arpagaus, M., Colfescu, I., Cuxart, J., De Wekker, S. F.J., Grubišic, V., Kalthoff, N., Karl, T., Kirshbaum, D.J., Lehner, M., Mobbs, S., Paci, A., Palazzi, E., Bailey, A., Schmidli, J., Wittmann, C., Wohlfahrt, G., Zardi, D., 2022. A collaborative effort to better understand, measure, and model atmospheric exchange processes over mountains. Bull. Am. Meteorol. Soc. 103 (5), E1282 – E1295. https://doi.org/10.1175/BAMS-D-21-0232.1

Rotach, M.W., Stiperski, I., Fuhrer, O., Goger, B., Gohm, A., Obleitner, F., Rau, G., Sfyri, E., Vergeiner, J., 2017. Investigating exchange processes over complex topography: the Innsbruck box (i-Box). Bull. Am. Meteorol. Soc. 98 (4), 787–805. https://doi.org/10.1175/BAMS-D-15-00246.1

Rotach, M.W., Vogt, R., Bernhofer, C., Batchvarova, E., Christen, A., Clappier, A., Feddersen, B., Gryning, S.-E., Martucci, G., Mayer, H., Mitev, V., Oke, T.R., Parlow, E., Richner, H., Roth, M., Roulet, Y.-A., Ruffieux, D., Salmond, J.A., Schatzmann, M., Voogt, J.A., 2005. BUBBLE – an urban boundary layer meteorology project. Theor. Appl. Climatol. 81 (3), 231–261. https://doi.org/10.1007/s00704-004-0117-9

Rotach, M.W., Zardi, D., 2007. On the boundary-layer structure over highly complex terrain: key findings from MAP. Q. J. R. Meteorolog. Soc. 133 (625), 937–948. https://doi.org/10.1002/qj.71

Rotta, J., 1951. Statistische theorie nichthomogener turbulenz. Zeitschrift für Physik 129 (6), 547–572. https://doi.org/10.1007/BF01330059

Sagaut, P., Cambon, C., 2008. Homogeneous Turbulence Dynamics. Cambridge University Press.

Sandu, I., Beljaars, A., Bechtold, P., Mauritsen, T., Balsamo, G., 2013. Why is it so difficult to represent stably stratified conditions in numerical weather prediction (NWP) models? J. Adv. Model. Earth Syst. 5 (2), 117–133. https://doi.org/10.1002/jame.20013

Santos, P., Mann, J., Vasiljevic, N., Courtney, M., Rodrigo, J.S., Cantero, E., 2019. The Alaiz experiment (ALEX17): wind field and turbulent fluxes in a large-scale and complex topography with synoptic forcing. Technical University of Denmark. https://doi.org/10.11583/DTU.c.4508597.v1

Savelyev, S.A., Taylor, P.A., 2005. Internal boundary layers: I. height formulae for neutral and diabatic flows. Boundary Layer Meteorol. 115 (1), 1–25. https://doi.org/10.1007/s10546-004-2122-z

Schaller, C., Göckede, M., Foken, T., 2017. Flux calculation of short turbulent events – comparison of three methods. Atmos. Meas. Tech. 10 (3), 869–880. https://doi.org/10.5194/amt-10-869-2017

Schmid, H.P., 2002. Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric. For. Meteorol. 113 (1), 159–183. https://doi.org/10.1016/S0168-1923(02)00107-7

Schmidt, H., Schumann, U., 1989. Coherent structure of the convective boundary layer derived from large-eddy simulations. J. Fluid Mech. 200, 511–562. https://doi.org/10.1017/S0022112089000753

Schröttle, J., Dörnbrack, A., 2013. Turbulence structure in a diabatically heated forest canopy composed of fractal pythagoras trees. Theor. Comput. Fluid Dyn. 27 (3), 337–359. https://doi.org/10.1007/s00162-012-0284-8

Schumann, U., 1989. Large-eddy simulation of turbulent diffusion with chemical reactions in the convective boundary layer. Atmos. Environ. (1967) 23 (8), 1713–1727. https://doi.org/10.1016/0004-6981(89)90056-5

Serafin, S., Adler, B., Cuxart, J., De Wekker, S. F.J., Gohm, A., Grisogono, B., Kalthoff, N., Kirshbaum, D.J., Rotach, M.W., Schmidli, J., Stiperski, I., Večenaj, Ž., Zardi, D., 2018. Exchange processes in the atmospheric boundary layer over mountainous terrain. Atmosphere 9(3) (102). https://doi.org/10.3390/atmos9030102

Seth, A., Giorgi, F., Dickinson, R.E., 1994. Simulating fluxes from heterogeneous land surfaces: explicit subgrid method employing the biosphere-atmosphere transfer scheme (BATS). J. Geophys. Res. Atmos. 99 (D9), 18651–18667. https://doi.org/10.1029/94JD01330

Sfyri, E., Rotach, M.W., Stiperski, I., Bosveld, F.C., Manuela, L., Obleitner, F., 2018. Scalar-flux similarity in the layer near the surface layer over mountainous terrain. Boundary Layer Meteorol. , 1–36. https://doi.org/10.1007/s10546-018-0365-3

Shah, S., Bou-Zeid, E., 2019. Rate of decay of turbulent kinetic energy in abruptly stabilized Ekman boundary layers. Phys. Rev. Fluids 4 (7). https://doi.org/10.1103/physrevfluids.4.074602

Shapiro, A., Fedorovich, E., 2014. A boundary-layer scaling for turbulent katabatic flow. Boundary Layer Meteorol. 153 (1), 1–17. https://doi.org/10.1007/s10546-014-9933-3

Shupe, M.D., Rex, M., Blomquist, B., Persson, P. O.G., Schmale, J., Uttal, T., Althausen, D., Angot, H., Archer, S., Bariteau, L., Beck, I., Bilberry, J., Bucci, S., Buck, C., Boyer, M., Brasseur, Z., Brooks, I.M., Calmer, R., Cassano, J., Castro, V., Chu, D., Costa, D., Cox, C.J., Creamean, J., Crewell, S., Dahlke, S., Damm, E., de Boer, G., Deckelmann, H., Dethloff, K., Dütsch, M., Ebell, K., Ehrlich, A., Ellis, J., Engelmann, R., Fong, A.A., Frey, M.M., Gallagher, M.R., Ganzeveld, L., Gradinger, R., Graeser, J., Greenamyer, V., Griesche, H., Griffiths, S., Hamilton, J., Heinemann, G., Helmig, D., Herber, A., Heuzé, C., Hofer, J., Houchens, T., Howard, D., Inoue, J., Jacobi, H.-W., Jaiser, R., Jokinen, T., Jourdan, O., Jozef, G., King, W., Kirchgaessner, A., Klingebiel, M., Krassovski, M., Krumpen, T., Lampert, A., Landing, W., Laurila, T., Lawrence, D., Lonardi, M., Loose, B., Lüpkes, C., Maahn, M., Macke, A., Maslowski, W., Marsay, C., Maturilli, M., Mech, M., Morris, S., Moser, M., Nicolaus, M., Ortega, P., Osborn, J., Pätzold, F., Perovich, D.K., Petäjä, T., Pilz, C., Pirazzini, R., Posman, K., Powers, H., Pratt, K.A., Preußer, A., Quéléver, L., Radenz, M., Rabe, B., Rinke, A., Sachs, T., Schulz, A., Siebert, H., Silva, T., Solomon, A., Sommerfeld, A., Spreen, G., Stephens, M., Stohl, A., Svensson, G., Uin, J., Viegas, J., Voigt, C., von der Gathen, P., Wehner, B., Welker, J.M., Wendisch, M., Werner, M., Xie, Z., Yue, F., 2022. Overview of the MOSAiC expedition: atmosphere. Elem. Sci. Anth. 10 (1), 00060. https://doi.org/10.1525/elementa.2021.00060

Smagorinsky, J., 1963. General circulation experiments with the primitive equations: I. The basic experiment. Mon. Weather Rev. 91 (3), 99–164. https://doi.org/10.1175/1520-0493(1963)091 < 0099:GCEWTP > 2.3.CO;2

Sorbjan, Z., 2006. Local structure of turbulence in stably stratified boundary layers. J. Atmos. Sci. 63 (5), 1526–1537. https://doi.org/10.1175/JAS3704.1

Stiperski, I., Calaf, M., 2018. Dependence of near-surface similarity scaling on the anisotropy of atmospheric turbulence. Q. J. R. Meteorolog. Soc. 144, 641–657. https://doi.org/10.1007/BF00712392

Stiperski, I., Calaf, M., 2023. Generalizing Monin-Obukhov similarity theory (1954) for complex atmospheric turbulence. Phys. Rev. Lett. 130, 124001. https://doi.org/10.1103/PhysRevLett.130.124001

Stiperski, I., Calaf, M., Rotach, M.W., 2019. Scaling, anisotropy, and complexity in near-surface atmospheric turbulence. J. Geophys. Res. Atmos. 124, 1428–1448. https://doi.org/10.1029/2018JD029383

Stiperski, I., Katul, G.G., Calaf, M., 2021. Universal return to isotropy of inhomogeneous atmospheric boundary layer turbulence. Phys. Rev. Lett. 126, 194501. https://doi.org/10.1103/PhysRevLett.126.194501

Stiperski, I., Rotach, M.W., 2016. On the measurement of turbulence over complex mountainous terrain. Boundary Layer Meteorol. 159 (1), 97–121. https://doi.org/10.1007/s10546-015-0103-z

Stoll, R., Gibbs, J.A., Salesky, S.T., Anderson, W., Calaf, M., 2020. Large-eddy simulation of the atmospheric boundary layer. Boundary Layer Meteorol. 177 (2), 541–581. https://doi.org/10.1007/s10546-020-00556-3

Stoll, R., Porté-Agel, F., 2009. Surface heterogeneity effects on regional-scale fluxes in stable boundary layers: surface temperature transitions. J. Atmos. Sci. 66 (2), 412–431. https://doi.org/10.1175/2008JAS2668.1

Sullivan, P.P., Weil, J.C., Patton, E.G., Jonker, H. J.J., Mironov, D.V., 2016. Turbulent winds and temperature fronts in large-eddy simulations of the stable atmospheric boundary layer. J. Atmos. Sci. 73 (4), 1815–1840. https://doi.org/10.1175/JAS-D-15-0339.1

Sun, J., Lenschow, D.H., Burns, S.P., Banta, R.M., Newsom, R.K., Coulter, R., Frasier, S., Ince, T., Nappo, C., Balsley, B.B., Jensen, M., Mahrt, L., Miller, D., Skelly, B., 2004. Atmospheric disturbances that generate intermittent turbulence in nocturnal boundary layers. Boundary Layer Meteorol. 110 (2), 255–279. https://doi.org/10.1023/A:1026097926169

Sun, J., Nappo, C.J., Mahrt, L., Belušić, D., Grisogono, B., Stauffer, D.R., Pulido, M., Staquet, C., Jiang, Q., Pouquet, A., Yagüe, C., Galperin, B., Smith, R.B., Finnigan, J.J., Mayor, S.D., Svensson, G., Grachev, A.A., Neff, W.D., 2015. Review of wave-turbulence interactions in the stable atmospheric boundary layer. Rev. Geophys. 53 (3), 956–993. https://doi.org/10.1002/2015RG000487

Tatarskii, V.I., 1961. Wave Propagation in a Turbulent Medium. Dover.

Taylor, P.A., Teunissen, H.W., 1987. The Askervein Hill project: overview and background data. Boundary Layer Meteorol. 39 (1), 15–39. https://doi.org/10.1007/BF00121863

Theeuwes, N.E., Steeneveld, G.-J., Ronda, R.J., Rotach, M.W., Holtslag, A. A.M., 2015. Cool city mornings by urban heat. Environ. Res. Lett. 10 (11), 114022. https://doi.org/10.1088/1748-9326/10/11/114022

Thomas, C.K., Kennedy, A.M., Selker, J.S., Moretti, A., Schroth, M.H., Smoot, A.R., Tufillaro, N.B., Zeeman, M.J., 2012. High-resolution fibre-optic temperature sensing: a new tool to study the two-dimensional structure of atmospheric surface-layer flow. Boundary Layer Meteorol. 142 (2), 177–192. https://doi.org/10.1007/s10546-011-9672-7

Tong, C., Nguyen, K.X., 2015. Multipoint Monin–Obukhov similarity and its application to turbulence spectra in the convective atmospheric surface layer. J. Atmos. Sci. 72 (11), 4337–4348. https://doi.org/10.1175/JAS-D-15-0134.1

Townsend, A.A. (Ed.), 1976. The Structure of Turbulent Shear Flow. Cambridge University Press, Cambridge, UK.

van de Wiel, B.J.H., Moene, A.F., Jonker, H.J.J., 2012. The cessation of continuous turbulence as precursor of the very stable nocturnal boundary layer. J. Atmos. Sci. 69 (11), 3097–3115. https://doi.org/10.1175/JAS-D-12-064.1

van de Wiel, B.J.H., Moene, A.F., Ronda, R.J., de Bruin, H.A.R., Holtslag, A.A.M., 2002. Intermittent turbulence and oscillations in the stable boundary layer over land. part II: a system dynamics approach. J. Atmos. Sci. 59 (17), 2567–2581. https://doi.org/10.1175/1520-0469(2002)059 < 2567:ITAOIT > 2.0.CO;2

van der Linden, S. J.A., van de Wiel, B. J.H., Petenko, I., van Heerwaarden, C.C., Baas, P., Jonker, H. J.J., 2020. A Businger mechanism for intermittent bursting in the stable boundary layer. J. Atmos. Sci. 77 (10), 3343–3360. https://doi.org/10.1175/JAS-D-19-0309.1

van Hooft, J.A., Popinet, S., van Heerwaarden, C.C., van der Linden, S. J.A., de Roode, S.R., van de Wiel, B. J.H., 2018. Towards adaptive grids for atmospheric boundary-layer simulations. Boundary Layer Meteorol. 167 (3), 421–443. https://doi.org/10.1007/s10546-018-0335-9

Večenaj, Ž, De Wekker, S. F. J., 2015. Determination of non-stationarity in the surface layer during the T-REX experiment. Q. J. Roy. Meteorol. Soc. 141 (690), 1560-1571. https://doi.org/10.1002/qj.2458

Vickers, D., Mahrt, L., 2003. The cospectral gap and turbulent flux calculations. J. Atmos. Oceanic Technol. 20 (5), 660–672. https://doi.org/10.1175/1520-0426(2003)20 < 660:TCGATF > 2.0.CO;2

Wanner, L., Calaf, M., Mauder, M., 2022. Incorporating the effect of heterogeneous surface heating into a semi-empirical model of the surface energy balance closure. PLoS One 17 (6), 1–21. https://doi.org/10.1371/journal.pone.0268097

Ward, H.C., Rotach, M.W., Gohm, A., Graus, M., Karl, T., Haid, M., Umek, L., Muschinski, T., 2022. Energy and mass exchange at an urban site in mountainous terrain – the Alpine city of Innsbruck. Atmos. Chem. Phys. 22 (10), 6559–6593. https://doi.org/10.5194/acp-22-6559-2022

Waterman, T., Bragg, A.D., Hay-Chapman, F., Dirmeyer, P.A., Fowler, M.D., Simon, J., Chaney, N., 2024. A two-column model parameterization for subgrid surface heterogeneity driven circulations. J. Adv. Model. Earth Syst. 16 (5). https://doi.org/10.1029/2023ms003936

Waterman, T.S., Stiperski, I., Chaney, N., Calaf, M., 2025. Evaluating anisotropy-based Monin-Obukhov similarity theory over canopies and complex terrain [manuscript under review]. Q. J. R. Meteorolog. Soc. . https://doi.org/https://doi.org/10.48550/arXiv.2502.13970

Weigel, A.P., Rotach, M.W., 2004. Flow structure and turbulence characteristics of the daytime atmosphere in a steep and narrow Alpine valley. Q. J. R. Meteorolog. Soc. 130 (602), 2605–2627. https://doi.org/10.1256/qj.03.214

Wildmann, N., Bodini, N., Lundquist, J.K., Bariteau, L., Wagner, J., 2019. Estimation of turbulence dissipation rate from Doppler wind lidars and in situ instrumentation for the Perdigão 2017 campaign. Atmos. Meas. Tech. 12 (12), 6401–6423. https://doi.org/10.5194/amt-12-6401-2019

Willis, G.E., Deardorff, J.W., 1974. A laboratory model of the unstable planetary boundary layer. J. Atmos. Sci. 31 (5), 1297–1307. https://doi.org/10.1175/1520-0469(1974)031 < 1297:ALMOTU > 2.0.CO;2

Wolf, B., Chwala, C., Fersch, B., Garvelmann, J., Junkermann, W., Zeeman, M.J., Angerer, A., Adler, B., Beck, C., Brosy, C., Brugger, P., Emeis, S., Dannenmann, M., De Roo, F., Diaz-Pines, E., Haas, E., Hagen, M., Hajnsek, I., Jacobeit, J., Jagdhuber, T., Kalthoff, N., Kiese, R., Kunstmann, H., Kosak, O., Krieg, R., Malchow, C., Mauder, M., Merz, R., Notarnicola, C., Philipp, A., Reif, W., Reineke, S., Rödiger, T., Ruehr, N., Schäfer, K., Schrön, M., Senatore, A., Shupe, H., Völksch, I., Wanninger, C., Zacharias, S., Schmid, H.P., 2017. The SCALEX campaign: scale-crossing land surface and boundary layer processes in the TERENO-preAlpine observatory. Bull. Am. Meteorol. Soc. 98 (6), 1217–1234. https://doi.org/10.1175/BAMS-D-15-00277.1

Wyngaard, J.C., 2004. Toward numerical modeling in the "Terra Incognita". J. Atmos. Sci. 61 (14), 1816–1826. https://doi.org/10.1175/1520-0469(2004)061 < 1816:TNMITT > 2.0.CO;2

Xiao, C.-N., Senocak, I., 2019. Stability of the Prandtl model for katabatic slope flows. J. Fluid Mech. 865, R2. https://doi.org/10.1017/jfm.2019.132

Xiao, S., Zhu, X., Narasimhan, G., Gayme, D.F., Meneveau, C., 2025. Wind farm dynamics over a diurnal cycle: analysis of a comprehensive large eddy simulation, web-services accessible dataset. preprint . https://doi.org/10.48550/arXiv.2510.05005

Yang, D., Meneveau, C., Shen, L., 2013. Dynamic modelling of sea-surface roughness for large-eddy simulation of wind over ocean wavefield. J. Fluid Mech. 726, 62–99. https://doi.org/10.1017/jfm.2013.215

Youtube, 2022. Workshop on atmospheric turbulence "100 years of turbulence: Innsbruck 1922–2022". https://youtube.com/playlist?list = PLSG9jZ-ZViQwYZu5MV14CR0Tpa7VfWw5eR&si = E2t6w0IzyTLw-wfJ.

Zeller, M.-L., Huss, J.-M., Pfister, L., Lapo, K.E., Littmann, D., Schneider, J., Schulz, A., Thomas, C.K., 2021. The NY-Ålesund turbulence fiber optic experiment (NYTEFOX): investigating the arctic boundary layer, Svalbard. Earth Syst. Sci. Data 13 (7), 3439–3452. https://doi.org/10.5194/essd-13-3439-2021

Zhu, X., Xiao, S., Narasimhan, G., Martinez-Tossas, L.A., Schnaubelt, M., Lemson, G., Szalay, A., Gayme, D.F., Meneveau, C., 2025. JHTDB-wind: web-accessible large-eddy simulation database of a wind farm with virtual sensor querying. Wind Energy Sci. . https://doi.org/10.5194/wes-2025-124

Zilitinkevich, S., Druzhinin, O., Glazunov, A., Kadantsev, E., Mortikov, E., Repina, I., Troitskaya, Y., 2019. Dissipation rate of turbulent kinetic energy in stably stratified sheared flows. Atmos. Chem. Phys. 19 (4), 2489–2496. https://doi.org/10.5194/acp-19-2489-2019

Zilitinkevich, S., Esau, I., Baklanov, A., 2007. Further comments on the equilibrium height of neutral and stable planetary boundary layers. Q. J. R. Meteorolog. Soc. 133 (622), 265–271. https://doi.org/10.1002/qj.27

Zilitinkevich, S., Kadantsev, E., Repina, I., Mortikov, E., Glazunov, A., 2021. Order out of chaos: shifting paradigm of convective turbulence. J. Atmos. Sci. 78 (12), 3925–3932. https://doi.org/10.1175/JAS-D-21-0013.1

Zilitinkevich, S.S., Elperin, T., Kleeorin, N., Rogachevskii, I., Esau, I., 2013. A hierarchy of energy- and flux-budget (EFB) turbulence closure models for stably-stratified geophysical flows. Boundary Layer Meteorol. 146 (3), 341–373. https://doi.org/10.1007/s10546-012-9768-8

Zilitinkevich, S.S., Perov, V.L., King, J.C., 2002. Near-surface turbulent fluxes in stable stratification: calculation techniques for use in general-circulation models. Q. J. R. Meteorolog. Soc. 128 (583), 1571–1587. https://doi.org/10.1002/qj.200212858309