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Interactive Comment

# *Interactive comment on* "Direct numerical simulation of intermittent turbulence under stably stratified conditions" *by* P. He and S. Basu

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## Response to the reviewer 2's comments

The paper adresses a very important point in prediction of environmental flows in general and here aimed towards the understanding of Stratified Atmospheric Wind Behaviour.

The authors simulate intermittent turbulence ( as they loosely identify also as bursting events)They compare field situations in a wide range of conditions as they comment that "This type of non-stationary time-series has been widely observed in geographically and climatologically diverse regions around the world."

We would like to thank the reviewer for his/her comments for our paper. We have revised the manuscript and clarified the definition of intermittency as suggested. In the following, we respond point-by-point to the reviewer's remarks (colored in blue).

In spite of the interest and the new work reflected in the paper. The paper does not define in a clear way the different methods used in the literature to describe and define intermittency.

The long -lasting multiplicity of definitions could be clarified for the benefit of the readers, specially the new-comers from diferent aspects of the study of stratified flows.

We agree with the reviewer that there is a confusion in the turbulence literature in the exact definition of "intermittency". Most of the time, the physics community utilizes this term to signify "small-scale (inertial-range and/or dissipation-range) intermittency". Classic references on this topic include (but not limited to): Kolmogorov (1962), chapter 8 of Frisch (1995), Bohr et al. (1998), chapter 7 of Tsinober (2001). The co-author (Basu) has also contributed in this line of turbulence scaling research: Basu et al. (2007). However, the word "intermittency" can also be used to describe "external or global intermittency". Classic references on this topic include (but not limited to): Townsend (1948), Mahrt (1989), Garcia-Villalba and del Alamo (2011), Brethouwer et al. (2012).

Following the reviewer's recommendation, we have added a paragraph on the definition of intermittency at the beginning of our paper. As such, we decided to cite Tsinober (1998) verbatim since he distinguishes the two types of intermittency in a very succinct manner:

"The term intermittency is used in two distinct (but not independent) aspects of turbulent flows. The first one is the so-called external intermittency. It is associated with what is called here partially turbulent flows, specifically with the strongly irregular and convoluted structure and random movement of the 'boundary' between the turbulent and nonturbulent fluid.. . .The second aspect is the so-called small scale, internal or intrinsic intermittency. It is usually associated with the tendency to spatial and temporal localization of the “fine” or small scale structure(s) of turbulent flows”.

We added appropriate references for both types of intermittency and emphasized that the current paper is on external or global intermittency.

References:

Basu, S., Foufoula-Georgiou, E., Lashermes, B., and Arneodo, A. (2007). “Estimating intermittency exponent in neutrally stratified atmospheric surface layer flows: A robust framework based on magnitude cumulant and surrogate analyses”, Phys. Fluids, 19, 115102.

Bohr, T., Jensen, M. H., Paladin, G., and Vulpiani, A. (1998). Dynamical systems approach to turbulence, Cambridge University Press, 350 pp.

Brethouwer, G., Duguet, Y., and Schlatter, P. (2012). “Turbulent–laminar coexistence in wall flows with Coriolis, buoyancy or Lorentz forces”, J. Fluid Mech., 704, 137–172.

Frisch, U. (1995). Turbulence: The legacy of A. N. Kolmogorov, Cambridge University Press, 296 pp.

García-Villalba, M. and del Álamo, J. C. (2011). “Turbulence modification by stable stratification in channel flow”, Phys. Fluids, 23, p. 045104.

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, 82-85.

Mahrt, L. (1989). “Intermittency of atmospheric turbulence”, J. Atmos. Sci., 46, 79–95.

Townsend, A. A. (1948). “Local isotropy in the turbulent wake of cylinder”, Austr. J. Sci. Res., 1, 161-174.

Tsinober, A. (2001). An informal introduction to turbulence, Kluwer Academic Publish-

ers, 324 pp.

Basic definitions and references from (Kolmogorov 1962),... (noting that scalingl at small scales of turbulence provides a key definition as (2 minus the sixth order velocity structure functions )only if the turbulent flow is local !.

The added complexities of the apparence of internal waves in stratified flows still cast a doubt of whether the spectra at small scales icreases or decreases its slope?

This specific comment of the reviewer is in the context of small-scale intermittency. One of the most widely used statistics characterizing the intermittent nature of small-scale turbulence is the so-called "intermittency exponent" (denoted by $\mu$). From observational and/or simulated data, $\mu$ can be estimated directly or indirectly via several methods. The reviewer mentioned the well-known sixth-order velocity structure function approach (see Anselmet et al. 1984). Other competing estimation approaches have been proposed in the literature. For example, the co-author (Basu) proposed a magnitude cumulant based approach (Basu et al. 2007) a few years ago.

In spite of our background and prior publication in this line of scaling research, we intentionally refrained from including $\mu$-related information in our work. As mentioned before, our present work is on external or global intermittency. For this case, $\mu$ is not a relevant statistic for the quantification of intermittency.

Our paper does document the existence of internal waves in DNS-generated data (see page 14). The influence of internal waves on small-scale intermittency is an intriguing topic and has not been studied (to the best of our knowledge). This topic will be addressed in our future work.

References: Anselmet, F., Gagne, Y., Hopfinger, E. J., and Antonia, R. A. (1984) "High-order velocity structure functions in turbulent shear flows," J. Fluid Mech. 140, 63.

The extraction and comparison of intermittency related effects and descriptors in stably stratified open-channel flows using direct numerical simulation (Open Foam) is important and could clarify the many previous observations and methods previously used and discussed in the literature. Rurther references would be interesting.

We thank the reviewer for commenting on the importance of our DNS work. Traditionally, DNS is only used as a tool for fundamental fluid mechanics studies. In this work, we attempted to make the simulated results more relevant for atmospheric boundary layer studies.

As the Authors claim "Clear signatures of this intriguing phenomenon are observed for a range of stabilities. However, the spatio-temporal characteristics of intermittency are found to be strongly stability-dependent. In general, the bursting events occur often near the bottom wall than in the upper-channel region."

The lax definitions used and the effects at large scales, at integral scales and at cascade or disipative scales are confused often in the literature, but the paper does not attempt to clarify the issues.

At the beginning of the paper, we have clearly distinguished between external intermittency and small-scale (inertial-range and dissipation-range) intermittency. Furthermore, we have now clarified that we are not focusing on small-scale intermittency. We sincerely hope that readers find our modified text to be clear and easy to follow.

It even attempts a Reynolds number dependent intermittency as " A steady coexistence of laminar and turbulent flows is almost always detected at various horizontal planes. This spatially intermittent pattern is found to propagate downstream and strongly correlate with the temporal evolution of intermittency. The forcing of the flow may be a cause or an effect, and it seems that this is not clear !, even in the definitions.

In this study, we addressed a fundamental question: is intermittent turbulence an inherent property of stably stratified boundary layer flows? That is to say, we would like to find out if this phenomenon can be simulated in the absence of any external forcings (e.g., topography, Coriolis force and associated inertial oscillation, mesoscale atmo-



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spheric phenomena). In other words, external forcing is not pertinent for our study. This information appears on page 3.

The hypothesis by Blackadar(1979), strong connection between local stability and intermittent turbulence, is claimed to be corroborated by this modeling study, but this would occur due to internal wave ( or coherent structure ) resonance.

Our DNS results indicate that there is a coexistence of significant wave activity and intermittent turbulence in stably stratified flows. However, the strong spatial-correlation between the low/high $Ri_{gi}$ and the turbulent/laminar regions, observed at the central-channel, strongly corroborates the Blackadar's hypothesis.

The existence of global intermittency (Mahrt, 1989) (also known as turbulent bursting events) in the atmospheric boundary layer (ABL) is well known but very often confused.

Intermittent turbulence is usually characterized as alternately quiescent and bursty portions of an observed time-series, representing laminar and turbulent states of the ABL flow, respectively, but this Reynolds number effect may be just forcing intermittency, or due to a larger scale effect or resonance. Stratification itself introduces internal Non-Linear waves, the spectral regions between integral and Taylor microscales may behave one way, while the dissipation range turbulence has another type of intermittency ( at small scale !)

At the beginning of the paper, we have clearly distinguished between external intermittency (aka global intermittency) and small-scale intermittency. In other words, we have now clarified that we are not focusing on inertial-range and dissipation-range intermittency.

Intermittent turbulence was generated in wind-tunnel experiments under idealized settings may be used to compare loose definitions such as: TBE, TF, Ratio of vertical velocity variance,... PDF Kurthosis, Scaling exponents, Modulation of Gradient Ri,... etc.



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Several wind tunnel studies (e.g., Modane wind tunnel) have documented small-scale intermittency in turbulent flows. However, to the best of our knowledge, external or global intermittency in stratified flows has only been reported by Ohya et al., 2008 in his wind tunnel experiments. Since Ohya et al. considered low-level jet type of velocity profiles in his experiments (i.e., external forcings), our results cannot be compared with his data in a quantitative manner. Furthermore, since our paper is on global intermittency, we do not report PDF Kurtosis, scaling exponents, etc.

As the Authors discuss, It is well known "That intermittent turbulence is a truly multi-scale (bursting duration ranging from seconds to hours) and a dynamically complicated (and perhaps complex) phenomenon. It is also known in the literature that this phenomenon portrays intriguing spatial characteristics" ( also temporal !)

With these considerations in mind and considering that the paper performs DNS using OpenFoam, by running an statistical ensamble of cases, the paper could attempt to clarify these controversial issues ( separating effects like due to non-stationarity, to non- homogeneity (different in the vertical/horizontal. even non-locality and 3D and 2D effects. The large potential of this paper is to clarify both the definitions, the ranges, the effects and the causes of intermittency.

In this paper, we characterized global intermittency in a comprehensive manner. We documented various traits of spatial intermittency. As emphasized by the reviewer, we also documented various aspects of “temporal” intermittency throughout the paper. We also provided quantification of intermittency (e.g., intermittency factor) and correlated with relevant fluid properties (e.g., Richardson number).

The stress on the large scale (or forcing intermittency) should be made clearer pointing out the comparison of the simulation conditions with the range of real conditions in the Atmosphere, Many relevant measurements of high frequency in the ABL under stratified conditions (e.g. SABLES, SHEEBA,.. Antartic wind data,... ) have peen parametrized. How do the DNS compare with the scope of existing intermittency data.



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In this study, we try to address a fundamental question: is intermittent turbulence an inherent property of stably stratified boundary layer flows? That is to say, we try to find out if this phenomenon can be simulated in the absence of any external forcings (e.g., topography, Coriolis force and associated inertial oscillation, mesoscale atmospheric phenomena). In the case of real conditions, various atmospheric phenomena (e.g., low-level jets, density current, gravity waves) will further modulate intermittency. At present, only a handful of these processes can be incorporated in a DNS. For example, Werne et al., 2007 studied the wind shear instability and wave-breaking, and analyzed their impacts on optical turbulence. García-Villalba, and del Álamo, 2008 simulated gravity waves in stably stratified flows and discussed their impacts on turbulence structures. Even though these types of idealized simulations cannot capture all the complexities of the atmosphere, they can provide non-trivial information. For example, the vertical variation of bursting events, reported in this study, qualitatively agreed with field observation from the CASES-99 study (Nakamura and Mahrt, 2005).

In conclusion, our paper solely focuses on global intermittency in stratified flows. As such, we refrained from any discussion on small-scale intermittency. We sincerely hope that the revised text in the Introduction makes this aspect of our paper clear.

References:

García-Villalba, M., and del Álamo, J. C.: Turbulence and Internal Waves in a Stably Stratified Channel Flow. High Performance Computing in Science and Engineering. Springer, pp. 217–227, 2008.

Werne, J., Fritts, D., Lund, T.: Simulations and Data Analysis for Air Force Optical Turbulence Forecasting Applications. AFRL-VS-HA-TR-2007-1059, 2007.

Nakamura, R. and Mahrt, L.: A Study of Intermittent Turbulence with CASES-99 Tower Measurements, Bound.-Lay. Meteorol., 114, 367–387, 2005.



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