Response to the reviewer 1's comments

In general, the paper is rather well written, addressing an interesting subject of intermittent turbulence by means of numerical simulations. The main subject of the study is well described with number of relevant citations, pointing out some of the problems associated with the notion of the term “intermittency” in turbulent flows. My major concerns related to the present manuscript are thus rather focused on the chosen methods, obtained results and conclusions based on them.

We thank the reviewer for the positive comments and constructive suggestions. We have revised the manuscript as suggested. Specifically, two additional simulations were conducted and we added an appendix (Appendix B) to evaluate the impact of simulation configurations, i.e., grid resolution, domain size, on the spatio-temporal characteristics of intermittency. In the following, we respond point-by-point to the reviewers' comments (colored in blue).

Although the general concept of using DNS methods to verify the hypothesis of generation of turbulent intermittency seems to be a good idea, there are several issues that have to be clarified in order to draw any definitive conclusion based on the obtained numerical results.

1) Description of the numerical method/solver in the paper The DNS is performed using an open-source package OpenFOAM. When it comes to the description of the numerical method itself, the authors claim (on page 187) that: ”The governing equations are discretized using the finite-volume method. The spatial and temporal derivatives are discretized with the second-order central scheme and implicit second-order backward scheme, respectively. The pressure equation is solved using pressure implicit with splitting of operators (PISO) algorithm.” Such a description seems to be insufficient and incomplete, as there are infinitely many second order central schemes for discretization of spatial derivatives and also infinitely many second order implicit backward formulas can be constructed for temporal discretization. The detailed description of these methods is not only important for allowing other authors to repeat and verify the simulations, but are also of a key point for interpretation of numerical results that do depend on numerical method being used. This is related with next comments.

We do not agree with the reviewer that the description of our spatial and temporal discretization schemes is incomplete. It is true that there are numerous second order discretization schemes for spatial and temporal differentials; howevever, they all have their specific names, e.g., backward-, forward-, and central-differential schemes for spatial derivatives, second order Runge-Kutta, Crank-Nicolson, implicit Euler backward schemes for temporal derivatives (please refer to Ferziger and Perić, p43-50, p148-151, Chung, p6 and p90, Cebeci et al., p99, and Tu et al., p133). As far as we know, there is only *one* second order central-differential scheme and *one* second order implicit Euler backward scheme. In addition, we had the reference for the PISO algorithm (Issa 1986) for the solution of pressure equation. We believe our description for the numerical method is sufficient and not confusing to readers.

References:

Ferziger, J.H., and Perić, M.: Computational Methods for Fluid Dynamics. Springer, 2002.

Chung, T.J.: Computational Fluid Dynamics. Cambridge University Press, 2002.

Cebeci, T., Shao, J.P., Kafyeke, F., and Laurendeau, E.: Computational Fluid Dynamics for Engineers. Springer, 2005.

Tu, J., Yeoh, G.H., Liu, C.: Computational Fluid Dynamics: A Practical Approach. Butterworth-Heinemann, 2008.

Issa, R.I.: Solution of the Implicitly Discretised Fluid Flow Equations by Operator-splitting, J. Comput. Phys., 62, 40–65, 1986.

2) Choice of the numerical methods It is well known and documented that the numerical methods do affect to certain extent the results of simulations. Especially the convection dominated flows and DNS are prone to numerical artifacts caused by adopted solvers. This includes both the non-physical (numerical) oscillations in solution as well as excessive numerical diffusion introduced by the applied numerical discretization. Thus I will be very careful about justification of the choice of the specific numerical scheme, and will never base any conclusion on a simulations obtained using only a single numerical method. Especially an intriguing case like the one being solved in this paper necessarily needs to clearly distinguish and separate numerical artifacts from physical phenomena. So at least at this point I consider the presented numerical results as insufficient and unconvincing.

We have been careful on choosing a "sufficient" grid resolution in the current paper.

In the original manuscript:

- We collected the grid resolutions of the existing DNS simulations for neutrally and stably stratified channel flows in Table 2. According to Table 2, a relatively fine grid resolution was chosen in the current paper. With the current grid resolution, our simulation results agreed reasonably well with the well-cited spectral DNS benchmark data from Moser et al., 1999 for the neutral case.
- For the stably stratified case (S120), we compared the oblique intermittent turbulence bands reported in the current paper (Fig. 8) with the spectral DNS results shown in Brethouwer et al., 2012 (please refer to Fig. 11c in their paper), and a good agreement was observed.

In the revised manuscript:

- We added an appendix (Appendix B) to further evaluate the influence of grid resolution and domain size on a specific case (S120). Two additional simulations are conducted. For one simulation, the grid resolution is increased by 50% while the domain size is kept unchanged. For the other simulation, the grid resolution is kept unchanged while the domain size is increased by 50% in the horizontal directions. Generally, the new simulation results are qualitatively similar to those shown in Figs. 4 and 8. The control grid resolution and domain size are thus expected to be sufficient to resolve and accommodate the spatio-temporal evolution of intermittent turbulence.

Please see the following text for the new appendix:

"Appendix B: Influence of Simulation Configurations

In this appendix, we evaluate the influence of simulation configurations, e.g., grid resolution, domain size, on the spatio-temporal characteristics of intermittency. Two additional simulations are conducted for the $Re_\tau = 180$, $Ri_\tau = 120$ case. For one simulation, the horizontal grid resolution is increased to $\Delta x^+ = 5.9$ and $\Delta z^+ = 2.9$ while the domain size is kept to $L_x/h = 8\pi$ and $L_z/h = 4\pi$. For the other simulation, the horizontal grid resolution is fixed to $\Delta x^+ = 8.8$ and $\Delta z^+ = 4.4$, but the domain size is enlarged to $L_x/h = 12\pi$ and $L_z/h = 6\pi$. Other simulation configurations are same to the S120 case in Table 1. The simulations are run for 10 non-dimensional time. Fig. A3 shows the time-series of vertical velocity and contours of v'^2 at a x–z plane for these two simulations. Generally, the spatio-temporal characteristics of intermittency are qualitatively similar to what was observed in Figs. 4 and 8, e.g., the oblique turbulence band and the height-dependency of temporal intermittency. The control grid resolution and domain size in Table 1 are thus expected to be sufficient to resolve and accommodate the spatio-temporal evolution of intermittent turbulence. "

In summary, based on the above results, it is safe to conclude that the simulated intermittency in the current paper is of physical instead of numerical artifacts. There is no indication of non-physical oscillations or numerical diffusion in the simulated results. We are confident that the current grid resolution is sufficient to capture the characteristics of intermittent turbulence.

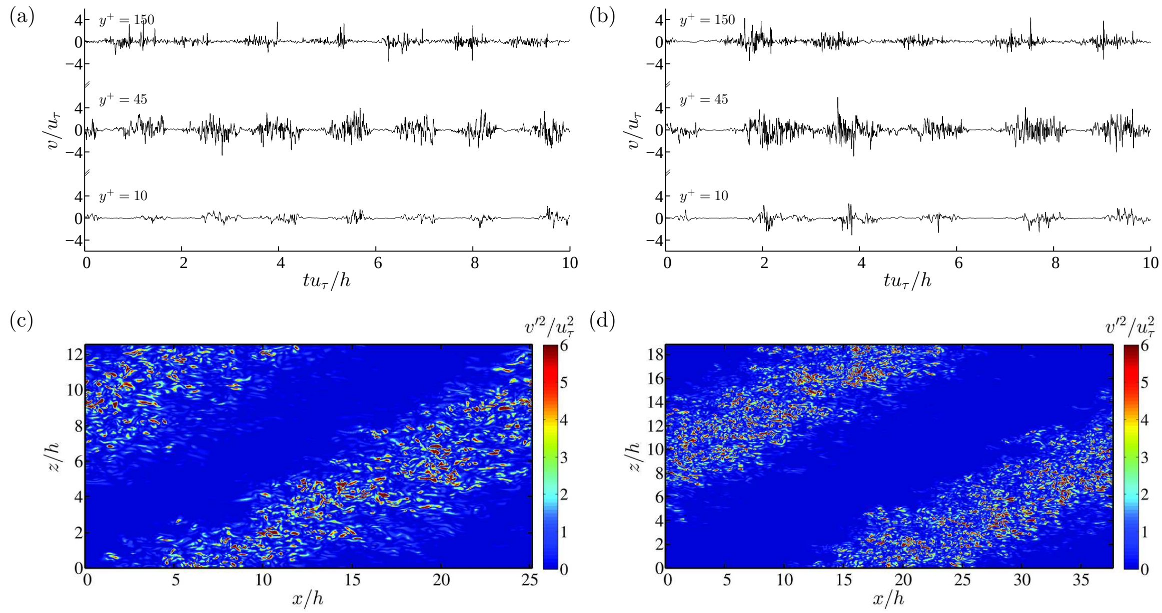

Figure A3: Influence of simulation configurations on the spatio-temporal characteristics of intermittency ($Re_\tau = 180$, $Ri_\tau = 120$). (a) and (b) are time-series of vertical velocity in the channel; (c) and (d) are instantaneous contours of v'^2 at the x–z plane located at $y^+ = 45$. For (a) and (c), the horizontal grid resolutions are $\Delta x^+ = 5.9$ and $\Delta z^+ = 2.9$, and the domain sizes are $L_x/h = 8\pi$ and $L_z/h = 4\pi$; for (b) and (d), the horizontal grid resolutions are $\Delta x^+ = 8.8$ and $\Delta z^+ = 4.4$, and the domain sizes are $L_x/h = 12\pi$ and $L_z/h = 6\pi$.

Reference:

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

3) Choice of computational domain and grid As noted above, the DNS itself is very sensitive to numerical setup and prone to numerical artifacts. Thus one of the things I am missing in this specific case is a kind of sensitivity test to these factors. In the presented case all the simulations were performed on a computational domain of the same length using a periodic boundary conditions. Using this setup the simulation leads to occurrence of periodic (or better to say) recurring phenomena in the computational field, however there is no clear evidence on if (how much) these events depend on specific computational setup. Will the spatio-temporal evolution be affected by a change of size or aspect ratio of the computational domain or by the grid resolution? Without such a verification I will hesitate to accept all the observed phenomena as being really physical.

Please see our resposne to point 2. The control domain size is shown to be sufficient to accommodate the spatio-temporal evolution of intermittent turbulence.

4) Grid resolution versus accuracy The authors opted for a numerical solver using a second order accurate discretization for both spatial and temporal derivatives. It's a question if this level of numerical accuracy is sufficient for reliable DNS simulations. It would be nice to have at least some references based evidence for similar cases that second order method (for given grid resolution) is enough to properly capture and resolve such fine scale an low amplitude events as those intermittent bursts studied here. The details on available DNS simulations given in Table 2, page 215, shows for example information about grid cell sizes, but fails to show what was the order of accuracy for the applied numerical method. The combination of grid resolution together with the order of accuracy is what defines the size of the error. So the grid resolution that is sufficient for one numerical method (for a given case being solved) doesn't necessarily has to be sufficient

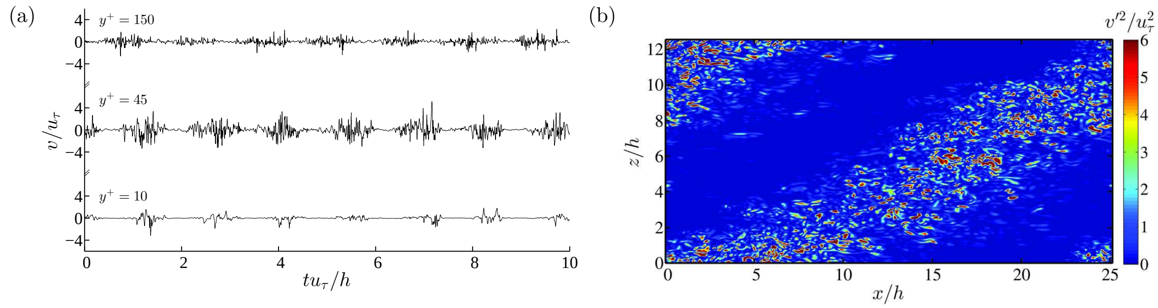

Figure B1: Influence of time step on the spatio-temporal characteristics of intermittency ($Re_\tau = 180$, $Ri_\tau = 120$). (a) time-series of vertical velocity in the channel; (b) instantaneous contours of v'^2 at the x–z plane located at $y^+ = 45$. The time step is reduced to 20% of the value used in the S120 case.

for another numerical method. So again, the independence of the presented numerical results on the chosen spatial (and temporal) cell sizes is not clearly demonstrated.

We have added the information for grid resolution and order of accuracy for the finite-volume and finite-difference methods in Table 2 as suggested.

It is true that the second-order spatial discretization may introduce uncertainty if the grid resolution is insufficient. However, as mentioned above, we have compared the current DNS results with the benchmark DNS results using spectral method. In addition, we added an appendix to further evaluate the impact of grid resolution on the simulated spatio-temporal characteristics of intermittency. There is no indication that the current control grid resolution is insufficient. Furthermore, it is important to note that this study focuses on the characteristic of global (large-scale) intermittency instead of small-scale (inertial-scale) intermittency, the second order spatial discretization is expected to be sufficient to capture large-scale evolution of spatio-temporal intermittency with the current grid resolution (Nieuwstadt, 2005). Please note that with a similar grid resolution, the second-order spatial discretization has been used in DNS studies for both neutrally stratified (Bernardini et al., 2014) and stably stratified (Nieuwstadt, 2005) channel flows.

Regarding the impact of time step on our simulation results, we conducted another simulation with the time step reduced to 20% of value used in the S120 case, as can be seen in Fig. B1. Again, no significant difference is observed between Fig. B1 and those shown in Figs. 4 and 8 in the revised manuscript. To avoid redundancy, we did not include this figure in the revised manuscript.

Reference:

Nieuwstadt, F. T. M.: Direct numerical simulation of stable channel flow at large stability, Bound.-Lay. Meteorol., 116, 277–299, 2005.

Bernardini, M. and Pirozzoli, S. and Orlandi, P.: Velocity statistics in turbulent channel flow up to $Re_\tau = 4000$, J. Fluid Mech., 742, 171–191, 2014.

To sum up the comments, the problem is interesting, chosen approach seems to be appropriate, but the numerical results are not convincing and insufficient to support (without any doubts) the conclusions given by authors. I recommend the paper to be revised before being reconsidered for publication. I hope these comments will help the authors to improve their manuscript.

Based on the reviewer's suggestions, we have conducted additional simulations to further confirm that the simulation configurations, i.e., grid resolution, domain size, are sufficient for capturing the spatio-temporal characteristics of intermittency. We believe that the new results improve the robustness of our numerical methods and further support the conclusions drawn in the paper.