

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.
- A description of all covariates tested
- A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
- A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
- For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
Give P values as exact values whenever suitable.
- For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection

Data analysis

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

The data used for analyzing the energy cascade in isotropic turbulence were obtained from a direct numerical simulation, which is publicly available in <https://torroja.dmt.upm.es/turbdata/>. The data used for analyzing inner/outer interactions in a turbulent boundary layer were obtained from a experimental campaign at the high Reynolds number wind tunnel at the University of Melbourne, which is publicly available in <https://fluids.eng.unimelb.edu.au/>.

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender	Not applicable: This study does not involve human participants. Therefore, there is no data related to sex or gender.
Reporting on race, ethnicity, or other socially relevant groupings	Not applicable: This study does not involve human participants. Therefore, there is no data related to race, ethnicity, or other socially relevant groupings.
Population characteristics	Not applicable: This study does not involve human participants. Therefore, there are no population characteristics to describe.
Recruitment	Not applicable: This study does not involve human participants. Therefore, no recruitment process is involved.
Ethics oversight	Not applicable: This study does not involve human participants. Thus, ethical approval specific to human research is not required.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

Life sciences Behavioural & social sciences Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study investigates the energy cascade in forced isotropic turbulence and inner/outer interactions in a turbulent boundary layer. For the isotropic turbulence, data were obtained from a direct numerical simulation of the Navier–Stokes equations, available at https://torroja.dmt.upm.es/turbdata/ . The simulation resolves the full range of spatial and temporal scales of the flow. For the turbulent boundary layer, data were collected from an experimental campaign at the high Reynolds number wind tunnel at the University of Melbourne, available at https://fluids.eng.unimelb.edu.au/ .
Research sample	The research sample includes: - Isotropic turbulence: Data from a direct numerical simulation with 1024^3 spatial Fourier modes to resolve all relevant length scales of the flow. The velocity fields were filtered at four different filter widths (163η , 81η , 42η , and 21η) to represent various flow scales within the inertial range, where η denotes the size of the smallest scales. - Turbulent boundary layer: Measurements of the streamwise velocity from two hot-wire anemometry probes at two wall-normal locations ($y^* = 4.33$ for the inner layer and $y/\delta = 0.31$ for the outer layer) at a distance of 21.65 m from the trip at the test section inlet, with a free-stream velocity of 20 m/s. The superscript * denotes the inner scaling with friction velocity and kinematic viscosity, and δ is the boundary layer thickness.
Sampling strategy	For the isotropic turbulence, the sampling involved numerical simulations capturing the entire range of flow scales. The choice of 1024^3 Fourier modes was based on ensuring accurate spatial and temporal resolution. In the turbulent boundary layer study, hot-wire anemometry measurements were made at specific wall-normal locations, with data collected at an acquisition rate of $\Delta t^* = 1.28$ over three cycles of approximately $TU_\infty/\delta = 20000$, where U_∞ denotes the free-stream velocity.
Data collection	Data for isotropic turbulence were collected through direct numerical simulations of the Navier–Stokes equations, stored at intervals of $\Delta t = 0.0076 T_e$, where T_e is the characteristic time of the largest flow scales. For the turbulent boundary layer, data were collected using hot-wire anemometry in a wind tunnel at an acquisition rate of $\Delta t^* = 1.28$ over three cycles of approximately $TU_\infty/\delta = 20000$.
Timing and spatial scale	The isotropic turbulence simulation covered a total time of $165T_e$ after transient effects, with data points collected at intervals of $\Delta t = 0.0076 T_e$. The turbulent boundary layer measurements were taken at a streamwise distance of 21.65 m from the test section inlet, with a boundary layer thickness of 0.361 m and a friction Reynolds number of $Ret = 14750$. Data acquisition time consisted of three cycles of $TU_\infty/\delta = 20000$ at an acquisition rate of $\Delta t^* = 1.28$.
Data exclusions	No data were excluded from the analyses. All collected data points were utilized to ensure comprehensive understanding and accurate results.
Reproducibility	Reproducibility was ensured by running multiple simulations with varying initial conditions. All attempts to replicate the findings were successful, confirming the robustness of the results.
Randomization	Not applicable: The study did not involve random allocation of samples.

Blinding

Not applicable: Blinding was not relevant to this study as it involved objective measurements of physical phenomena in controlled environments.

Did the study involve field work? Yes No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Included in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern
<input checked="" type="checkbox"/>	<input type="checkbox"/> Plants

Methods

n/a	Included in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging

Plants

Seed stocks

Not applicable: This study does not involve the use of seed stocks or any plant material.

Novel plant genotypes

Not applicable: This study does not involve the generation or use of novel plant genotypes.

Authentication

Not applicable: This study does not involve any seed stocks or novel genotypes that require authentication procedures.