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Applicability of the Reynolds Number as a Metric for Planetary Boundary Layer Turbulence: A Comparative Study of Venus, Earth, Mars, and Jupiter

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Abstract. The planetary boundary layer (PBL) mediates the exchange of heat, momentum, and mass between a planetary surface and its overlying atmosphere, where turbulent processes govern vertical energy transport. Given the stark disparities in atmospheric properties across Venus, Earth, Mars, and Jupiter, it remains an open question whether the conventional Reynolds number (Re) remains a valid metric for cross-planetary comparisons of boundary layer turbulence. Using published mission datasets, atmospheric profiles, and peer-reviewed literature, we compile key dynamical parameters—atmospheric density, dynamic viscosity, characteristic wind speed, and characteristic length scale—to derive representative Re values for these four planetary bodies. These estimates are then benchmarked against observed and numerically simulated turbulence regimes. The calculated Re values follow the descending order: Jupiter (10^{10}) > Venus (10^{9}) > Earth (10^{8}) > Mars (10^{7}). While values for Jupiter and Earth align well with documented turbulent behaviors, Venus exhibits a high Re alongside weak surface winds and subdued turbulence. Conversely, Mars yields the lowest Re despite hosting vigorous convective boundary layer turbulence. These divergences indicate that Re does not scale linearly with actual turbulence intensity across distinct planetary regimes. Consequently, while Re provides a useful quantitative baseline for cross-planetary scaling, it cannot serve as a standalone criterion for assessing boundary-layer turbulence strength. This work does not attempt to derive a universal scaling law. Instead, using publicly available data, it systematically delineates the conditions under which a single Reynolds-number criterion holds and where it breaks down across planetary scales.

Keywords: Reynolds number, planetary boundary layer, turbulence, planets, comparative planetology

1. Introduction

The planetary boundary layer (PBL) constitutes the critical interface that mediates the direct exchange of momentum, heat, and mass between a planetary surface and its overlying atmosphere. Turbulent motions within this layer dictate the rates of these transport processes, making their characterization essential for understanding overall atmospheric dynamics [1]. Among solar system

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bodies, Venus, Earth, Mars, and Jupiter exhibit substantial differences in atmospheric density, near-surface wind speed, dynamic viscosity, and characteristic length scales. In fluid dynamics, the Reynolds number (Re) quantifies the ratio of inertial forces to viscous forces within a flow [2]. While prior investigations have examined the boundary layers and associated turbulent regimes of these planets individually, few studies have systematically evaluated them within a unified Re framework. This raises a fundamental question: can Re serve as a consistent metric for comparing boundary-layer turbulence across disparate planetary environments?

To address this question, we conduct a comparative analysis of Venus, Earth, Mars, and Jupiter. Using public mission data and atmospheric profiles, we compile key parameters—atmospheric density, dynamic viscosity, wind speed, and length scale—to calculate representative Re values for each planet. We then compare these values with turbulence characteristics reported in previous observational and numerical simulation studies to identify points of agreement and discrepancy. Through this comparison, we test the utility of Re as a cross-planetary turbulence metric, highlight the limitations of relying on a single dimensionless parameter, and lay the groundwork for future multi-parameter investigations.

2. Data calculation and observed turbulence regimes

2.1. Input data and reynolds number estimation

This study focuses on Earth, Mars, Jupiter, and Venus. Using public planetary atmospheric records, exploration mission datasets, and relevant literature, we compiled the baseline parameters required to calculate Re: atmospheric density (ρ), near-surface wind speed (v), characteristic length scale (L), and dynamic viscosity (μ). For parameters exhibiting a range of reported values in the literature, median values were adopted to perform order-of-magnitude estimations, ensuring consistency and comparability across the target bodies. The Reynolds number was calculated using Eq. (1):

$$Re = \frac{\rho v L}{\mu} \tag{1}$$

Table 1. Boundary layer parameters and calculated reynolds numbers for the four target planets

Planet	ρ (kg/m³)	μ (Pa·s)	v Range(m/s)	v Adopted (m/s)	L (km)	Re
Venus	64.8 [3]	3.12×10^{-5} [4]	0.1-10 [3]	0.5	2 [5]	2.08×10^{9}
Earth	1.225 [3]	1.789×10^{-5} [6]	1-10 [3]	5.5	1 [7]	3.77×10^{8}
Mars	1.55×10^{-2} [3]	1.289×10^{-5} [6]	5-20 [3]	12.5	5 [8]	7.52×10^{7}
Jupiter	0.171 [9]	1.12×10^{-5} [10]	80-100 [11]	90	28 [9]	3.85×10^{10}

Note. (1) The daytime characteristic length scale for Mars is based on Viking lander data, which reported maximum afternoon mixed-layer heights between 3.6 and 9.2 km; a representative value of 5 km was adopted for this estimate. (2) Because planetary atmospheric properties vary with altitude, latitude, and local time, the calculated Re values are intended for order-of-magnitude comparisons rather than instantaneous, localized measurements.

2.2. Observed turbulence characteristics and diagnostic criteria

To benchmark the calculated Reynolds numbers against actual atmospheric boundary layer behaviors, turbulent activity on Venus, Earth, Mars, and Jupiter was qualitatively categorized based on evidence from existing studies. Given that observational techniques and numerical models differ

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substantially across the literature, boundary-layer turbulence cannot be treated as a directly comparable, unified scalar quantity. Instead, turbulent activity is classified into four qualitative regimes—weak, moderate, relatively strong, and strong—by synthesizing multiple lines of published evidence, including near-surface wind regimes, vertical mixing and stable stratification, boundary-layer depth, eddy scales, and kinetic energy spectra (Table 2).

Atmospheric soundings by Seiff et al. revealed stable stratification above 15–20 km, while Florensky et al. reported low near-surface wind velocities and limited aeolian erosion, both pointing to subdued mixing and weak wind activity near the Venusian surface [12, 13]. Large-eddy simulations by Gheynani and Taylor comparing the convective boundary layers of Earth and Mars demonstrated that Mars sustains substantially deeper boundary layers and larger eddy structures, driving markedly more vigorous convective turbulence [14]. For Jupiter, Read et al. synthesized multiscale structures in the cloud decks and kinetic energy spectra derived from cloud-tracking winds, confirming pronounced, highly energetic turbulent activity across the atmosphere [15].

Table 2. Boundary layer turbulence characteristics and qualitative classification criteria across four planets

Planet	References	Key Evidence	Qualitative Assessment
Venus	[12, 13]	Stable stratification above 15–20 km; near-surface winds of ~0.5–1.0 m/s; weak aeolian surface erosion.	Weak (extremely subdued turbulence)
Earth	[14]	Convective boundary layer (CBL) simulations show prototypical terrestrial convective and vortical structures, serving as the baseline for comparison with Mars.	Moderate (intermediate turbulence intensity)
Mars	[14]	Boundary layer depth is ~4 times that of Earth; vortex column height and diameter reach ~6 and ~10 times terrestrial scales, respectively; simulations demonstrate markedly more vigorous convective activity.	Relatively strong (exceeding terrestrial turbulence)
Jupiter	[15]	Multiscale cloud features spanning bands to vortices; wind speeds reaching tens to hundreds of m/s; kinetic energy spectra from cloud-tracking winds reveal energy injection at ~2,000 kmscales cascading to both large and small scales.	Strong (pronounced, highly active turbulence)

3. Synthesis and comparative analysis

3.1. Rankings of calculated reynolds numbers and observed turbulence regimes

Based on the calculations in Table 1, the Reynolds numbers for Jupiter, Venus, Earth, and Mars are 3.85×10^{10}, 2.08×10^{9}, 3.77×10^{8}, and 7.52×10^{7}, respectively, yielding a decreasing order of Jupiter > Venus > Earth > Mars. In terms of order of magnitude, Jupiter yields the highest Re ($\sim 10^{10}$) while Mars records the lowest ($\sim 10^{7}$), spanning roughly three orders of magnitude across the four planetary bodies. Specifically, the Re of Jupiter is approximately 18.5 times that of Venus, Venus is 5.5 times that of Earth, and Earth is 5 times that of Mars, highlighting substantial disparities in flow regimes across planetary settings.

In contrast, the literature-derived evidence compiled in Table 2 characterizes atmospheric boundary layer turbulence in a distinctly different hierarchy: Jupiter exhibits the most vigorous turbulent activity, followed by Mars and Earth, while Venus remains the weakest. This observed sequence diverges markedly from the calculated Re ranking, demonstrating that boundary layer turbulence intensity does not correlate positively or scale monotonically with the Reynolds number across disparate planetary environments.

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3.2. Discrepancies and agreements between theoretical and observed hierarchies

The two sequences show clear differences. For Jupiter, a high calculated Re matches observed reality; its extreme wind speeds and kinetic energy spectra reflect intense turbulence. Earth sits in the middle in both cases, ranking third with moderate values.

In sharp contrast, Mars and Venus display severe mismatches between predicted and observed regimes. Despite possessing the lowest calculated Re ($\sim 10^7$), Mars exhibits turbulence intensity second only to Jupiter, driven by towering vortex columns and expansive convective structures. This mismatch indicates that factors beyond Re, notably intense thermal convection, strongly govern boundary-layer turbulence in thin atmospheres [14]. Conversely, Venus yields the second-highest calculated Re, yet its muted surface wind speeds and negligible aeolian erosion place its actual turbulence intensity last among the four bodies. The quiescent Venusian environment reveals that evaluating the balance between inertial and viscous forces alone is insufficient to characterize boundary-layer dynamics under conditions of minimal mean flow.

4. Conclusion and outlook

This study evaluates planetary boundary layer Reynolds numbers across Venus, Earth, Mars, and Jupiter using publicly available datasets, and benchmarks these calculations against documented turbulent behaviors from observational and numerical studies. The calculated Re values decrease in the order Jupiter > Venus > Earth > Mars. While estimates for Jupiter and Earth correspond well with established turbulent regimes, Venus and Mars deviate substantially from this scaling pattern: Venus maintains a high Re alongside suppressed near-surface turbulence, whereas Mars displays the lowest Re despite hosting vigorous convective boundary layer dynamics. Although Re establishes a unified quantitative baseline, it cannot independently characterize boundary-layer turbulence across diverse atmospheric settings, nor can it serve as a universal criterion for assessing turbulent intensity. The value of this work lies in translating qualitative descriptions of planetary turbulence into order-of-magnitude comparisons. Anomalies such as those observed for Venus and Mars clearly illustrate the limits of using Re as a standalone metric.

This analysis has several limitations. First, planetary atmospheric properties vary with time, altitude, and geographic location. Since we adopt median values for order-of-magnitude estimation, these values do not capture real-time atmospheric variations. Second, our four-level turbulence classification remains qualitative, as the literature draws on highly disparate observational techniques and simulation frameworks. In addition, inconsistencies in the definition and selection of characteristic length scales across different planetary bodies introduce uncertainties into the precise Re values. Future investigations can build upon this comparative framework by incorporating standardized observational metrics and coupling Re with complementary dimensionless numbers—such as the Richardson number (Ri) and Rossby number (Ro)—to develop a multi-parameter diagnostic framework that systematically maps the validity boundaries of hydrodynamic scaling across planetary boundary layers.

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