Global climate by Rossby number in the Solar system planets

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Abstract

On the largest scales, planetary climates can be described by their Rossby number ($\textit{Ro}$). $\textit{Ro}$ is in response to $\textit{Gr}/\textit{Re}^2$, where $\textit{Gr}$ is the Grashof number and $\textit{Re}$ is the Reynolds number. We here simplify $\textit{Gr}/\textit{Re}^2$ as $h$, where $h = \textit{H}/\textit{H}_\text{Earth}$ with $\textit{H} = g\textit{P}/(2\pi\textit{V}_e)$ for a planet with surface gravity $g$, rotation period $\textit{P}$ and equatorial velocity $\textit{V}_e$. Unlike $h$, $\textit{Ro}$ is difficult to obtain because of a large diversity in observation. We perform on an in-depth literature search on average (av) and maximum (mx) wind velocity for each planet in the Solar system by various observational methods and by altitude. We explore a correlation between $\textit{Ro}$ and $h$ expressed as a power law with index $\alpha$ based on wind velocities of planets in the Solar system. We obtain a correlation between $\textit{Ro}$ and $h$ with $\alpha = 0.56$ (av) and $\alpha = 0.52$ (mx). Earth’s $H = H_\text{Earth}$ ($h = 1$) is primarily due to lunar tidal interaction, given our relatively distant habitable zone (HZ) to the Sun. Our positive correlation, therefore, suggests exoplanet-moon systems as the ‘go-to-place’ in our searches for potentially advanced life in exosolar system.

Keywords: global climate, Rossby number, exoplanet, habitability

1. Introduction

Currently, there is a vigorous quest for potentially habitable exoplanets, following the pioneering discoveries by Sagittarius Window Eclipsing Extraso-

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lar Planet Search (SWEEPS) in HST \[24]\), Convection, Rotation and planetary Transits (CoRoT) \[3]\, Kepler \[19]\, Kepler’ Second light (K2) \[13]\, Gaia \[16]\, Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) \[18]\ and, today, Transiting Exoplanet Survey Satellite (TESS) \[8]\.

At present, conditions of habitability remain somewhat speculate, though general conditions favoring liquid water and, perhaps, an oxygen-rich atmosphere are essential \[5]\). Of interest also, and perhaps even more speculate, are conditions favoring advanced life. In particular, these conditions may not be the same as those for abiogenies, suggesting the need for co-evolution of life and planetary conditions as a whole. Here, we explore some conditions for a global clement climate relevant to the development of advanced life on Earth.

Planetary climates in our Solar system can be roughly divided into two groups: clement climates on Earth, Mars and Pluto and extreme climates on Jupiter, Saturn, Uranus and Neptune. We shall omit Mercury and Venus. Mercury is omitted for its essentially complete lack of atmosphere; Venus, tidally locked to the Sun, is heated one-sided driving a global climate different from those of the other planets in the Solar system. These kind of different wind patterns are commonly characterized by their Rossby number,

\[
Ro = \frac{U}{2\Omega R},
\]

where \(U\) is the wind velocity of a planetary atmosphere, \(\Omega\) is the angular frequency of planetary rotation. A global clement climate is proposed as a natural condition conducive for advanced life \[31]\.

Quite generally, the global climate of a planet is a buoyancy-driven atmospheric flow on a rotating sphere subject to Coriolis forces. The driving force of buoyancy is governed by the Grashof number

\[
Gr = \frac{\beta \Delta T R^3 g}{\nu^2}
\]

and the induced large scales flows are characterized by the Reynolds number,

\[
Re = \frac{UR}{\nu},
\]
where $g$ is surface gravity, $\beta$ is the coefficient of thermal expansion $\beta = 1/T$, $\Delta T$ is a characteristic scale of the driving temperature difference (e.g., polar-to-equator) induced by exposure to the Sun, $R$ is the radius of a planet, $\nu$ is the kinematic viscosity, and $U = V_e$ is the equatorial velocity, $V_e = \Omega R$.

On the largest scales, the resulting buoyancy-driven flows are effectively described by $Gr/Re^2$. Here, ignoring variants of $\beta \Delta T$ across the different planets, we simplify

$$\frac{Gr}{Re^2} \approx \frac{gP}{2\pi V_e} \equiv H$$

and normalize

$$h = \frac{H}{H_{Earth}}.$$  \hspace{1cm} (5)

$h$ was recently proposed as a habitability index for its general correlation to global climate [31]. Here, we seek to quantify the correlation of $Ro$ to $h$ in the planetary atmospheres of our Solar system ($\S 3$). $Ro$ is not so easy to infer because of a large diversity in observational measurements and associated uncertainties while $h$ is well defined for all Solar system planets. For this reason, we focused on an in-depth literature search on wind velocity data of all planets in the Solar system.

In $\S 2$, we organize the wind velocities inferred for planets in the Solar system by observing methods and altitudes. In $\S 3$, we report on a correlation of $Ro$ to $h$ using available data on average and maximum wind velocities of planets in the Solar system. In $\S 4$, we summarize our exploration with a future outlook.
2. Data

Wind velocities of planets in the Solar system are observed across different observing atmospheric heights (altitudes) by different methods ranging from ground-based, space-based and in-situ measurements. This poses a challenge in our effort to derive a homogeneous set of data.

Table 1.1: Average wind velocity data for each planet in the Solar system by various observational methods.

| Methods               | Earth | Mars | Jupiter | Saturn | Uranus | Neptune | Pluto |
|-----------------------|-------|------|---------|--------|--------|---------|-------|
| Image Analysis        |       |      |         |        |        |         |       |
| Cloud Movement        |       |      |         |        |        |         |       |
| Atmospheric Marking   | 100$^f$ | 400$^f$ |        |        |        |         |       |
| Surface Topography    | 55    |      |         |        |        |   10$^b$ |       |
|                       | ±21$^*$ |      |         |        |        |         |       |
| Radio Observation     |       |      |         |        |        |         |       |
| Doppler shift         | 90    |      |         |        |        |         |       |
|                       | ±10$^f$ |      |         |        |        |         |       |
| Occultation           | 110   |      |         |        |        |         |       |
|                       | ±40$^n$ |      |         |        |        |         |       |
| Rotation period       |       |      |         |        |        |         |       |
| Descent Probes        | 50    |      |         |        |        |         |       |
|                       | ±10$^i$ |      |         |        |        |         |       |
| Landing               | 23    |      |         |        |        |         |       |
|                       | ±4$^j$ |      |         |        |        |         |       |
| Spectral Emission     |       |      |         |        |        |         |       |
| *unspecified          | 100$^p$ | 500$^p$ |        |        |        |         |       |
| Average values        | 50    | 39   | 97      | 450    | 97     | 325$^*$ | 10    |
|                       | ±10   | ±23  | ±6      | ±71    | ±18    |         |       |

*: Unspecified: cited papers did not mention methods.

$: 55 \text{ m/s is the average of } 70 \text{ m/s, the wind velocity required for activation of Meridiani Planum observed by } Opportunity, \text{ and } 40 \text{ m/s, estimated from image of reversing dust}
streaks (Mars Orbiter).

- The mean wind velocity of Neptune, 325 m/s, is measured also by Voyager 2 with no uncertainty reported.

- $85 \pm 7$ is westward jet velocity in both hemispheres, though a further 40 m/s eastward in the Southern hemisphere exists.

a) Limaye, S. S., 2010 [20]; b) Hammel, H. B., 2001 [10]; c) Sromovsky, L. A. et al, 2005 [27]; d) Hammel, H. B. 1989 [9]; e) Smith, B. A., et al, 1989 [28]; f) Hide, R. 1984 [12]; g) Jerolmack, D. J. et al., 2006 [15]; h) Telfer, M. W. et al., 2018 [28]; i) Keegan, T. J. 1961 [17]; j) Pollack, J. B. et al., 1976 [29]; k) Santee, M. L. et al, 1995 [25]; l) Atkinson, D. H. et al, 1998 [2]; m) Tellmann, S. et al, 2013 [29]; n) Lindal, G. F., 1987 [21]; o) Zalucha, A.M. 2016 [33]; p) Helled, R. et al., 2010 [11]; q) Guide to Space - Universe today [7]; r) Ingersoll, A. P., 1990 [14]; s) Planets, Moons, and Dwarf Planets — NASA [22]

Occasionally, we compromise, e.g., taking wind velocities from the mesosphere of Earth - with negative temperature gradient similar to that at low altitudes - alongside space-based observation of the other planets.

Observational techniques to measure wind velocities of a planet are mostly by image analysis, radio observations, in-situ probes and spectral methods (Tables 1.1-2). For instance, wind velocities can be obtained from images of cloud movement, atmospheric markings, e.g., Jupiter’s Giant Red Spot, and surface topography, e.g., Pluto’s dunes. Also, wind velocities can be obtained via radio observation: radio Doppler shift, radio occultation, and radio rotation period. Additionally, wind velocities have been measured by in-situ probes: descent probes and Landers. Furthermore, wind velocities can be obtained through spectral methods such as thermal emission. Tables 1.1-2 summarize our literature search on wind velocities for each planet in the Solar system by various methods. In this table, uncertainties refer to scatter in data from multiple measurements reported in the literature. For this broad range of measurement approaches, our references are listed in the notes of Table 1.1-2.

Pluto is an interesting special case with wind velocities estimated for the first time by the New Horizons mission [3]. In its extremely tenuous atmosphere, wind velocities are now inferred from atmospheric temperature structure and also from dunes on its surface. The first shows that winds concentrate about polar regions, from greater than 10 m/s down to a few m/s at intermediate latitudes [33]. This is corroborated by wind velocities of about 10 m/s inferred from dunes at similar intermediate latitudes [28]. Thus, we use Pluto’s wind velocity of 10 m/s in Table 1.1-2. With no known uncertainties, uncertainty is left unspecified in Table 1.1-2.

Quite generally, wind velocities vary with altitude. As a compromise in deriving a reasonably homogeneous data set, we would focus on velocities in layers with negative temperature
Table 1.2: Maximum wind velocity data for each planet in the Solar system by various observational methods.

| Methods            | Earth  | Mars   | Jupiter | Saturn | Uranus | Neptune | Pluto |
|--------------------|--------|--------|---------|--------|--------|---------|-------|
| Cloud Movement     | 50°    | 40°    | 170°    | 450°   | 240±50°| 560°    | 10°   |
| Atmospheric Marking|        |        |         |        |        |         |       |
| Surface Topography |        |        |         |        |        |         |       |
| Doppler shift      |        |        | 175     | ±25°   |        |         |       |
| Occultation        | 170°   |        |         |        | 10°    |         |       |
| Rotation period    |        |        |         |        |        |         |       |
| Descent Probes     | 70°    |        |         |        |        |         |       |
| Landing            |        |        |         |        |        |         |       |
| Thermal Emission   | 85     | ±7°    |         |        |        |         |       |
| unspecific         | 172°   | 500°   | 250°    | 556°   |        |         |       |
| Maximum value      | 60     | 98     | 172     | 475    | 235    | 505     | 10    |
|                    | ±14    | ±66    | ±3      | ±35    | ±24    | ±91     |       |

gradients. On Earth, there are two such layers, at low altitudes 0-10 km and at high altitudes 50-80 km. Most other planets in the Solar system have a similar structure, excluding perhaps Uranus and Mars [1]. In Table 2, we list results for Earth, Mars and Pluto by altitude. These data are indeed consistent with the mean of the average (av) and maximum (ma) values of Table 1.1-2. On this admittedly limited basis, we shall proceed with the data for all planets in Table 1.1-2 despite the absence of such explicit data by altitude for the other four planets.
Table 2: Wind velocities of the planets in the Solar system in the two temperature-negative gradient regions by altitude. See the notes of Table 1.1 for references.

| Altitude(km) | Earth | Mars | Pluto |
|--------------|-------|------|-------|
| 50 ~ 80      | $50 \pm 10^{ac}$ | $85 \pm 5^r$ |       |
| 0 ~ 10       |       | $40^a$ | $10^g$ |

3. A $Ro$-$h$ correlation

We calculate $Ro$ from the wind velocities of Table 1.1-2 and $h$ from the physical parameters of planets in the Solar system. Table 3.1-2 summarizes our estimates of $Ro$ and $h$ for all planets in the Solar system excluding Mercury and Venus.

Table 3.1: Average values of $Ro$ and $h$ for all planets in the Solar system, where $\hat{Ro} = Ro/Ro_{Earth}$.

|       | Earth | Mars | Jupiter | Saturn | Uranus | Neptune | Pluto |
|-------|-------|------|---------|--------|--------|---------|-------|
| $Ro$  | 95.2  | 144  | 6.8     | 38.9   | 33.2   | 106     | 651   |
| $\hat{Ro}$ | 1    | 1.51 | 0.07    | 0.41   | 0.35   | 1.11    | 6.84  |
| $h$   | 1.00  | 0.76 | 0.04    | 0.02   | 0.12   | 0.14    | 13    |

Table 3.2: Maximum values of $Ro$ and $h$ for all planets in the Solar system, where $\hat{Ro} = Ro/Ro_{Earth}$.

|       | Earth | Mars | Jupiter | Saturn | Uranus | Neptune | Pluto |
|-------|-------|------|---------|--------|--------|---------|-------|
| $Ro$  | 114   | 362  | 12      | 41.1   | 80.4   | 164     | 651   |
| $\hat{Ro}$ | 1    | 3.17 | 0.1     | 0.36   | 0.70   | 1.44    | 5.70  |
| $h$   | 1.00  | 0.76 | 0.04    | 0.02   | 0.12   | 0.14    | 13    |

We consider the correlation of $Ro$ to $h$ be of the form of a power law:

$$Ro = c_0 \left( \frac{Gr}{Ro^2} \right)^\alpha \propto h^\alpha,$$

(6)

To estimate the power law index $\alpha$, we draw a loglog plot of our $Ro$ to $h$ and calculate $\alpha$ by using the MatLab `fitnlm` ($h$, $Ro$, $y$, $B_0$). Here, $y$ is the linear function $y = ax + b$ with $y = \log_{10} Ro$ and $x = \log_{10} h$ , and $B_0$ are initial data of the unknown coefficients $a$ and $b$. 

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Figure 1 shows our result for Ro using average wind velocities and our estimate $\alpha = 0.56$ with standard error of 0.15, giving equal weights to all planets in the Solar system. The same figure shows our result for Ro using maximum wind velocities and our estimate $\alpha = 0.52$ with standard error of 0.14 obtained similarly.

![Figure 1: The power law correlation of Ro and h using average wind velocities (left panel) and maximum wind velocities (right panel) based on equal weights to all planets in the Matlab routine fitnlm with $\pm 1\sigma$ (pink line)](image)

4. Conclusion and Outlook

Here, we have reviewed wind velocity data of the planets in the solar system by observational methods (Table 1.1) and altitudes (Table 1.2). We used this review to explore a novel correlation of Ro and h. Ro characterizes the response to $Gr/Re^2$ measured by wind velocity. Jupiter, Saturn, Uranus and Neptune have low Ro and indeed show global extreme climate. On the other hand, Mars, Earth and Pluto have high Ro and indeed show global clement climate.

$h$ is our reduced expression for $Gr/Re^2$ and, relatively easy to observe for planets of our Solar system, may indeed indicate potentially favorable conditions to advanced life. Jupiter, Saturn, Uranus and Neptune have small h-values because they are fast spinning whereas Mars, Earth and Pluto are slow spinning, indicated by the respective h-values.

Quantitatively, Ro and h satisfy a power law with index of $\alpha = 0.56$ and $\alpha = 0.52$ based on average (av) and, respectively, maximum (mx) wind velocities in Table 1.1-2, upon attributing equal weights to all planets.

While the observed positive correlation of Ro and h appears to be robust, there is clearly a need for data with a much more uniform uncertainty than which is available today, especially by what would be an anomalous tilt by Jupiter in estimates of $\alpha$ weighted by present uncertainties.
However, $h$ will be difficult to observe for relatively small potentially Earth-like exoplanets. Quite generally, $h$ of order unity corresponds to slow spin. Slow spin, in turn, can be attributed to lunar tidal interactions in relatively distant habitable zones such as ours around the Sun. It appears, therefore, that exoplanet-moon systems are possibly the go-to-places for advanced life in exosolar systems [30].

The upcoming James Webb Space Telescope (JWST) [6] and the Extremely Large Telescope (ELT) [32] may guide us to such systems in the near future.

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References

[1] Nagy A.N. et al. Ingo Mueller-Wodarg. Comparative Aeronomy. Space Science Reviews 139 (1-4) (2008). ISBN-978-0-387-87824-9.

[2] Atkinson D.H. et al. The Galileo Probe Doppler Wind Experiment: Measurement of the deep zonal winds on Jupiter. Geophysics Research 103 (E10) (1998) 22,911-22,928.

[3] Auvergne M. et al. The CoRoT satellite in flight: description and performance. Astronomy & Astrophysics 506 (1) (2009) 411-424.

[4] Fountain G.H. et al. The New Horzions Spacecraft. Space Science Reviews 140 (1-4) (2008) 23-47.

[5] Franck S. et al. Habitable zone for Earth-like planets in the solar system. Planetary and Space Science 48 (2000) 1099-1105.

[6] Gardner J.P. et al. The James Webb Space Telescope. Space Science Reviews 123 (2006) 485.

[7] Guide to Space - Universe today.
http://www.universetoday.com/13860/guide-to-space.

[8] Ricker G.R. et al. Transiting Exoplanet Survey Satellite. Astronomical Telescopes, Instruments, and Systems 1 (1) (2015) 14012P. doi:10.1117/1.JATIS.1.1.014003
[9] Hammel H.B. et al. Neptune’s wind speeds obtained by tracking clouds in the Voyager images. Science 245 (4824) (E10) (1989) 1367-1369.

[10] Hammel H.B. et al. New measurements of the Winds of Uranus. Icarus 153 (2) (2001) 229-235. doi:10.1006/icar.2001.6689

[11] Helled R. et al. Uranus and Neptune: Shape and Rotation. Icarus 210 (1) (2010) 446-454.

[12] Hide R. Rotation of the Atmospheres of the Earth and Planets. Philosophical Transactions of the Royal Society of London A313 (1524) (1984) 107-121.

[13] Howell S.B. et al. The K2 Mission: Characterization and Early Results. the Astronomical Society of the Pacific 126 (938) (2014) 398.

[14] Ingersoll A.P. Atmospheric Dynamics of the Outer Planets. Science 248 (4953) (1990) 308-315.

[15] Jerolmack D.J. et al. Spatial grain size sorting in eolian ripples and estimation of wind conditions on planetary surface: Application to Meridiani Planum, Mars. Geophysical Research 111 (E12S02) (2006). doi:10.1029/2005JE002544

[16] Jordan S. The Gaia project: Technique, performance and status Astronomische Nachrichten 329 (9-10) (2008). doi:10.1002/asna.200811065

[17] Keegan T.J. Winds and circulations in the mesosphere. ARS 31 (8) (1961) 1060-1066.

[18] Knapp M. et al. ASTERIA: Arcsecond Space Telescope Enabling Research in Astrophysics American Geophysical Union, Fall Meeting (2017).

[19] Koch D. et al. Overview and status of the Kepler Mission. SPIE Conference 5487, Glasgow 2004, Retrieved 2010

[20] Limaye S.S. Measuring winds on Venus and other planets. 10th International Wind Workshop, Tokyo 31 (2010).

[21] Lindal G.F. et al. The atmosphere of Uranus: Results of Radio Occultation Measurement with Voyager2. Geophysical Research 92 (A13) (1987) 14,987-15,001.

[22] Planets, Moons, and Dwarf Planets— NASA. https://www.nasa.gov/content/planets-moons-and-dwarf-planets.

[23] Pollack J.B. et al. Winds on Mars during the Viking season: Predictions based on a general circulation model with topography. Geophysical Research 3 (8) (1976) 3907-3915.
[24] Sahu K.C. et al. Transiting Planets in the Galactic Bulge from SWEEPS Survey and Implications. Transiting Planets, Proceedings of the International Astronomical Union, IAU Symposium 253 (2009) 45-53.

[25] Santee M.L. et al. Diagnostic calculations of the circulation in the Martian atmosphere. Geophysical Research 100 (E3) (1995) 5465-5484.

[26] Smith B.A. et al. Voyager2 at Neptune: Imaging Science Results. Science 246 (4936) (1989) 1422-1449. doi:10.1126/science.246.4936.1422

[27] Sromovsky L.A. et al. Dynamics of cloud features on Uranus. Icarus 179 (2005) 459-484. doi:10.1016/j.icarus.2005.07.022

[28] Telfer M.W. et al. Dunes on Pluto. Science 360 (2018) 992-997.

[29] Tellmann S. et al. The structure of Mars lower atmosphere from Mars Express Radio Science (MaRS) occultation measurements. Geophysical Research 118 (2013) 306-320. doi:10.1002/jgre.20058

[30] van Putten, M.H.P.M. Scaling in global tidal dissipation of Earth-Moon system. New Astronomy 54 (2017) 115-121. doi:10.1016/j.newast.2017.01.012

[31] van Putten, M.H.P.M. Moon as a proxy for global clement on exoplanets. SEEC Symposium 2018 - Biogenic Conditions on Early Terrestrial planets and Exoplanets (2018).

[32] Vernin J. et al. European Extremely Large Telescope Site Characterization I: Overview. the Astronomical Society of the Pacific 123 (909) (2011) 13341346.

[33] Zalucha A.M. An atmospheric general circulation model for Pluto with predictions for New Horizons temperature profiles. Monthly Notices of the Royal Astronomical Society MNRAS 459 (2016) 902-923.