ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Planets

COMMENTARY

10.1029/2018JE005625

Key Points:
- The year 2018 represents an important anniversary for the Earth's QBO
- Recent results from Cassini convincingly confirm that a similar phenomenon occurs on Saturn
- Similar wave-driven zonal flow phenomena likely occur in the atmospheres of other planets

Correspondence to:
P. L. Read,
peter.read@physics.ox.ac.uk

Citation:
Read, P. L. (2018). A chorus of the winds—On Saturn! *Journal of Geophysical Research: Planets*, *123*, 1007–1011. https://doi.org/10.1029/2018JE005625

Received 29 MAR 2018
Accepted 1 MAY 2018
Accepted article online 10 MAY 2018
Published online 30 MAY 2018

A Chorus of the Winds—On Saturn!

P. L. Read[1]

[1]Department of Physics, University of Oxford, Oxford, UK

Abstract Results from the recently completed Cassini mission (Guerlet et al., 2018, https://doi.org/10.1002/2017JE005419) have demonstrated that Saturn's tropical stratosphere hosts an intriguing oscillation in its zonal (east-west) flow that is a direct analog of the Earth's stratospheric quasi-biennial oscillation or semiannual oscillation. The new results represent a significant advance in characterizing this phenomenon on Saturn, though a number of difficult questions are still outstanding. Is Saturn's equatorial oscillation phase-locked to its seasonal cycle? How many other planets in our Solar System might host such analogs of the quasi-biennial oscillation?

Plain Language Summary It is nearly 60 years since it was discovered that the winds in the Earth's tropical upper atmosphere undergo an almost regular reversal from eastward to westward flow and back with a repeat cycle of around 2 years. The accepted explanation is due to waves in the stratosphere that are generated by convection in the lower atmosphere. Although confined to the tropics, its indirect influence is felt much further afield across the Earth, affecting the predictability of the climate at temperate latitudes. But is this kind of phenomenon found on other planets? In newly published research by Sandrine Guerlet and colleagues, measurements from the Cassini orbiter have been used to show that Saturn also exhibits a similar stratospheric wind reversal but with a period of around 15 Earth years (half of Saturn's year). The new results make a convincing case that Saturn's winds change direction periodically for much the same physical reasons as on Earth. Together with recent observations of wind reversals seen on Jupiter (with a period of around 4 Earth years) and hints of similar phenomena in Venus's atmosphere, this may suggest that such cyclic wind reversals are a common feature of almost all planetary atmospheres.

1. Introduction

The year 2018 marks a number of significant anniversaries concerning a remarkable atmospheric phenomenon, originally discovered on Earth but now being found in other parts of the Solar System, most notably recently in the stratosphere of Saturn (Guerlet et al., 2018). The terrestrial quasi-biennial oscillation (QBO) is a phenomenon in the Earth's tropical stratosphere in which the zonally averaged zonal (east-west) wind over the altitude range ~20–50 km undergoes an almost periodic reversal from eastward to westward and back again, with a cyclic period of around 2 years. Its discovery in observations was announced independently by two researchers, R. J. Reed and R. A. Ebdon, in 1960 (Ebdon, 1960; Reed et al., 1961). But it was not until 50-years ago, in 1968, that a model accounting convincingly for its causal mechanism was published (Lindzen & Holton, 1968; Wallace & Holton, 1968). Although highly simplified and idealized, this laid the foundations for a theoretical understanding of the QBO as a fundamentally nonlinear oscillation, driven by the interactions of upward propagating and eastward propagating or westward propagating internal waves with the mean zonal flow as they dissipated in the stratosphere.

Around the same time, observational studies also began to elucidate what kinds of wave might be responsible for driving the QBO with the identification of equatorial Kelvin waves as one form of large-scale eastward propagating wave (Wallace & Kousky, 1968a, 1968b). Thus, began the process of investigating precisely *how* such a remarkably strong, coherent and nearly periodic interannual oscillation could be sustained within an otherwise chaotic atmosphere. Some 10 years later, just 40-years ago, the validity of these early theoretical studies was confirmed in the ingenious laboratory experiments of Plumb and McEwan (1978), which demonstrated the basic mechanism modeled by Lindzen and Holton (1968) and Holton and Lindzen (1972) in action, using a pattern of standing internal gravity waves in a stratified fluid forced at the lower boundary. The QBO is now widely understood to be driven by a whole spectrum of atmospheric waves, ranging from the large-scale equatorially trapped planetary modes (Kelvin and mixed Rossby-gravity waves) to a host of much smaller-scale internal gravity waves (see Baldwin et al., 2001, for a comprehensive review), and affects the whole atmosphere on interannual and intraseasonal timescales.

2. How Does it Work?

The details of precisely how the QBO and similar phenomena are driven are mathematically complex and still being worked out in detail. But the essence of the mechanism can be understood with reference to some simple principles, based on the results of wave-mean flow interaction theory (e.g., Andrews & McIntyre, 1978; Bühler, 2014), which can be expressed as follows.

1. Waves in fluids can transport a form of momentum in the direction of their phase velocity (the so-called *pseudomomentum*, $u' \cdot \xi' x$, where u' and ξx are, respectively, perturbation velocity and particle displacements in the x direction, representing the force exerted when a wave interacts with matter). This is more complicated than simple momentum in the fluid within a shear flow, especially when the waves are dispersive; for example, see Bühler (2014) for more details.
2. Such waves will extract momentum from the background flow where they are generated and subsequently deposit their (pseudo)momentum where they are strongly dissipated, either by internal damping processes (viscous or radiative) or by breaking and overturning.
3. Dissipating waves will tend to accelerate a mean flow in the same direction as their phase speed, with the greatest acceleration taking place where the background flow velocity is comparable to the phase speed (known as a *critical line or layer*).

The basic sequence of events driving a cyclic wave-driven zonal flow oscillation can be understood with reference to Figure 1, which shows profiles of the zonal flow at different times during the cycle. The scenario assumes that a spectrum of waves is driven upwards from below and includes at least waves with both eastward (positive) and westward (negative) phase velocities $\pm c$. Figure 1a shows the oscillation with a westward phase of the oscillation already well advanced. The waves with westward phase velocity $-c$ are predominantly dissipated just below the peak of the westward flow around an altitude of 150 km, where the mean zonal flow almost matches $-c$. This accelerates the flow just below the peak toward $-c$, moving the peak downward at later times. The waves with $+c$ are dissipated at even lower altitude at this phase, creating a strong vertical shear in the zonal flow that also helps to dissipate the zonal flow itself at the bottom of the domain.

Figure 1b shows the position some time later, when the low-level eastward zonal flow has disappeared, allowing waves with $+c$ to propagate to high altitudes. These waves will grow in amplitude as density decreases with height, eventually breaking and dissipating at high altitude, accelerating an eastward zonal flow (at around 450-km altitude on Saturn). Meanwhile, the westward wave has almost brought the westward peak of zonal flow to the bottom of the domain.

Some time later still (Figure 1c), the eastward wave has accelerated much of the upper atmosphere above 200 km in an eastward direction, while the westward wave now dominates below, generating strong westward flow near the bottom of the model. Finally, in Figure 1d the eastward waves have brought the eastward peak of the zonal flow almost to the bottom of the domain, leaving just a shallow region of strongly sheared westward flow below 150 km, representing the inverse of the case shown in Figure 1a. The cycle then repeats to return the flow to the initial state, and so on.

The amplitude of the zonal flow oscillation depends on the phase speeds of the forced waves. The return period of the oscillation, however, depends primarily on the strength of the wave forcing and the size of the domain, though may be modified by other processes such as a large-scale upwelling circulation. The key ingredients needed to create such a cycle are thus seen to include stable stratification, some forcing near the lower boundary of a spectrum of upward propagating waves with both eastward and westward phase speeds and some form of damping of these waves at high and intermediate altitudes. All of these ingredients are commonly found in the stratospheres of most planetary atmospheres, not just on Earth. So it should not be surprising (with the benefit of hindsight!), therefore, that such cycles might be found in the stratospheres of other dynamically active planets.

3. Saturn's SEO and Cassini

The recent paper by Guerlet et al. (2018) presents a host of new observations that systematically document a zonal flow oscillation, similar to the Earth's QBO, that occurs in Saturn's tropical stratosphere. This oscillation

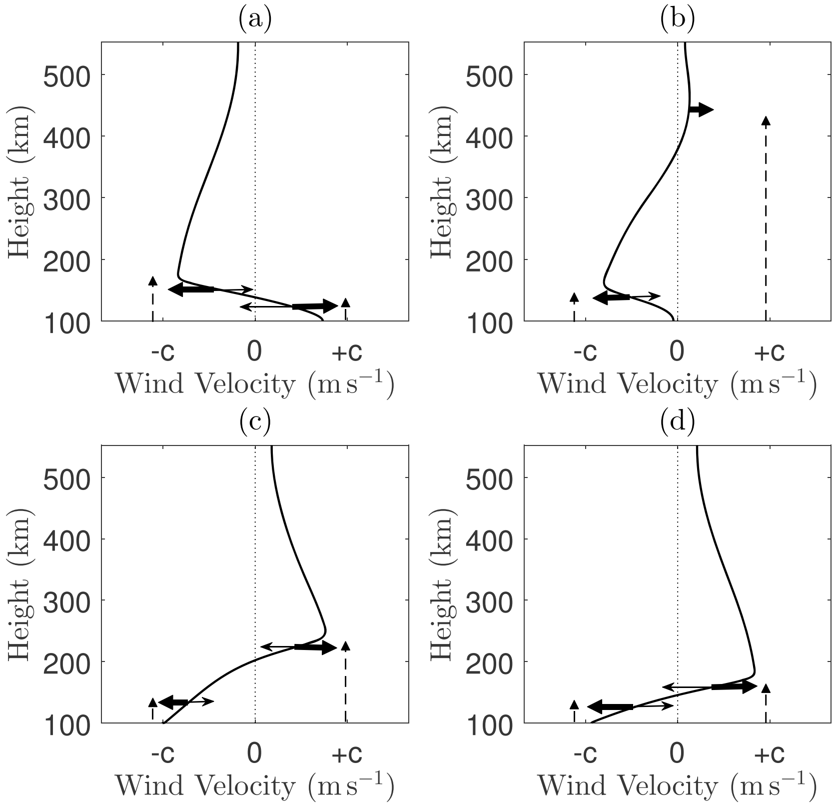

Figure 1. A series of vertical profiles of zonal flow in an atmosphere such as that of Saturn during the first half of a quasi-biennial oscillation or Saturn's equatorial oscillation cycle, driven schematically by a pair of waves with equal and opposite phase speeds $\pm c$. The zonal flow is shown as a continuous solid line in each case. Upward propagating waves are indicated by vertical dashed arrows, and the sense of acceleration of the zonal flow where the waves dissipate is indicated by horizontal arrows, with the dominant acceleration shown in bold. Profiles were computed from a version of the 1-D model due to Holton and Lindzen (1972) by Dr. Kylash Rajendran (personal communication, 2018), adapted for Saturn's stratospheric domain and reproduced with permission.

(known as Saturn's equatorial oscillation or SEO) was first reported in 2008 (another significant anniversary in 2018: Fouchet et al., 2008; Orton et al., 2008), based on a combination of infrared ground-based astronomical observations and measurements taken from the Composite Infrared Spectrometer (CIRS) instrument on the Cassini Orbiter spacecraft. These early observations used the mapping capability of Cassini during the early years of its mission to obtain a clear snapshot of the structure of the zonal winds and temperature in Saturn's stratosphere to show how these patterns resembled those found in the Earth's stratosphere at a particular point in the QBO cycle. But they had to rely on relatively crude observations from ground-based telescopes, which could not resolve the detailed structure of the flow, to indicate the cyclic behavior of tropical temperatures in Saturn's stratosphere and hence to estimate the period of the oscillation. This turned out to be ~14.7 Earth years, which happens to coincide with around half of a Saturnian year.

The relatively long period of such a cycle makes it very difficult to pin down many details of its behavior, especially given the remoteness of Saturn from Earth. The ground-based observations extended as far back as the mid-1980s (Orton et al., 2008), but neither these nor the early Cassini observations provided many details of which kinds of wave were driving the oscillation or how they transported momentum within the atmosphere.

Cassini completed its 20-year mission in September 2017, having spent more than 13 years in orbit around Saturn. During that time it was possible to compile a long sequence of observations from the orbiter that could examine in detail how the SEO would evolve over almost a complete cycle. In their latest paper, Guerlet et al. (2018) use data obtained over a 10-year baseline from the CIRS instrument, mostly pointing at the limb of the planet to optimize vertical resolution, that enabled the retrieval of atmospheric temperature structure over an altitude range from the cloud tops up to a pressure level of around 0.01 hPa, around 600 km above the clouds. This clearly shows a pattern in the tropical zonal mean temperature structure with successive maxima and minima descending over time, consistent with a ∼15-year period. The corresponding pattern of horizontal wind could be deduced by integrating the geostrophically balanced thermal wind shear equation in height (e.g., Vallis, 2006), using the measured temperature patterns.

The patterns of temperature and zonal wind in latitude and height have a number of features in common with what is observed in the Earth's stratosphere, confirming the analogy between Saturn's SEO and Earth's QBO more strongly than ever before. Guerlet et al. (2018) were even able to measure the rate of descent of the pattern at different heights, deducing a faster rate of descent at high altitudes compared with lower down. This is precisely what one would expect if the mechanism maintaining Saturn's SEO was similar to the wave-induced acceleration process responsible for the QBO and even allowed the authors to estimate the magnitude of the wave-induced stresses necessary to generate such a descent rate.

The nature of the waves producing this phenomenon is also an essential element to be understood in characterizing the SEO, but the information required to confirm this was beyond the capabilities of CIRS or any other instrument yet pointed toward Saturn. But Guerlet et al. (2018) did manage to detect a variety of zonally periodic structures in nadir soundings of temperature that are suggestive of a number of different wave modes at various latitudes close to the equator. A few of these had the signature of an equatorially trapped Rossby wave (not to be confused with the classical Rossby-Haurwitz waves typical of higher latitudes), though other waves were not so easy to classify. But it was clear that Saturn's stratosphere is not short of candidate waves that could contribute to a wave-driven oscillation of the zonal wind in the tropics.

The implied period for the oscillation, close to half of a Saturnian year, is intriguing and raises a clear question as to whether this is a coincidence or physically connected with Saturn's seasonal cycle. A wave-driven phenomenon similar to the QBO is also found in the Earth's stratosphere and mesosphere, but with a period of precisely 6 months, for which the seasonal cycle is known to play a crucial role (Baldwin et al., 2001). The seasonal migration of the thermal equator and center of upwelling in the Earth's stratosphere and mesosphere also leads to a meridional overturning circulation, in which the action of the Coriolis effect leads to an additional forcing of the westward zonal wind with a period of precisely half a year. This leads to a robust synchronization of this so-called Semi-Annual Oscillation (or SAO), even though the eastward phase is driven only by upward propagating waves.

Saturn's obliquity of around 27° leads to a substantial seasonal cycle in its stratosphere that would presumably provide a strong forcing of the zonal mean circulation with a period of half a Saturnian year, perhaps enough to produce qualitatively the same synchronization as seen in the Earth's SAO. But sporadic disturbances, such as major El Niño events, can occasionally disrupt the smooth passage of the Earth's QBO, such as was seen in 2015–2016 (e.g., Dunkerton, 2016; Newman et al., 2016). Such a disruption was also reported for Saturn's SEO by Fletcher et al. (2017), due to a major convective outbreak in Saturn's atmosphere in late 2010. But the most recent data suggest that this disruption was only temporary and the SEO had more or less returned to its normal state by 2015.

4. Open Issues

The Cassini measurements presented by Guerlet et al. (2018) and other reports since 2008 make a convincing case for Saturn's SEO to be a close analog of the Earth's stratospheric QBO or SAO. This brings the number of planets with confirmed identifications of such wave-driven zonal flow oscillations to three, together with Jupiter's Quasi-Quadrennial Oscillation or QQO (Leovy et al., 1991). Jupiter's QQO has a nominal period of around 4 Earth years, which does not bear an obvious relationship to its orbital period of 11.86 years. But this is not unduly surprising given Jupiter's very small obliquity (3.1°) and consequently very weak seasonality. However, it is still unclear whether Saturn's SEO is actually synchronized to its seasonal cycle in the same way as the Earth's SAO. Only time will tell as the observational record grows to cover more than one cycle. But given the duration of this cycle, we are going to have to be patient!

A related question concerns the precise mechanism driving Saturn's SEO. Guerlet et al. (2018) have identified a few candidate wave modes that might be playing a role, but the observations are simply not capable of settling this question conclusively. Spatial resolution was one key factor, but Cassini's observing schedule could also only allow a few sporadic campaigns of measurements with the required coverage, and even then only for snapshots and not for longer sequences capable of determining phase speeds of the waves. For this question, therefore, there is probably no alternative but to resort to testing hypotheses using models of varying sophistication. Full-scale global circulation models tend to struggle to capture QBO-like oscillations because of the need for high spatial resolution, especially in the vertical, and their inability to represent the full spectrum of waves that might be relevant. So researchers may need to use more idealized models to establish plausible scenarios, but this is a question that is unlikely to be fully resolved for some time to come.

Finally, what of other planets in our Solar System and beyond? The mechanism underlying the QBO, QQO, and SEO would seem to be fairly universal and so may well be active in any planet with a substantial atmosphere. A possible cyclic oscillation has been reported for some time in Venus's atmosphere (e.g., Del Genio & Rossow, 1990), for example, while an oscillation somewhat resembling a semiannual oscillation has been found in simulations from a Mars global circulation model (Kuroda et al., 2008, another significant anniversary?), though this has yet to be confirmed in observations. The situation concerning the outer planets, Uranus and Neptune, is virtually unknown, but who knows what the next significant QBO anniversaries in 2020 and 2028 might bring?

Acknowledgments
P. L. R. acknowledges support from the UK Science and Technology Facilities Council and the UK Space Agency under grants ST/N00082X/1 and ST/R001499/1. I am grateful to Kylash Rajendran for producing Figure 1. This paper reviews the work of others and the relevant data can be obtained from the references cited in the text.

References

Andrews, D. G., & McIntyre, M. (1978). Generalized Eliassen-Palm and Charney-Drazin theorems for waves on axisymmetric mean flows in compressible atmospheres. *Journal of the Atmospheric Sciences*, *33*, 2031–2048.

Baldwin, M. P., Gray, L., Dunkerton, T. J., Hamilton, K., Haynes, P., Randel, W. J., et al. (2001). The quasi-biennial oscillation. *Reviews of Geophysics*, *39*, 179–230.

Bühler, O. (2014). *Waves and Mean Flows*. Cambridge, UK: Cambridge University Press.

Del Genio, A. D., & Rossow, W. B. (1990). Planetary scale waves and the cyclic nature of cloud top dynamics on Venus. *Journal of the Atmospheric Sciences*, *47*, 293–318.

Dunkerton, T. J. (2016). The quasi-biennial oscillation of 2015-2016: Hiccup or death spiral? *Geophysical Research Letters*, *43*, 10,547–10,552. https://doi.org/10.1002/2016GL070921

Ebdon, R. A. (1960). Notes on the wind flow at 50 mb in tropical and subtropical regions in january 1957 and in 1958. *Quarterly Journal of the Royal Meteorological Society*, *86*, 540–542.

Fletcher, L. N., Guerlet, S., Orton, G. S., Cosentino, R. G., Fouchet, T., Irwin, P. G. J., et al. (2017). Disruption of Saturn's quasi-periodic equatorial oscillation by the great northern storm. *Nature Astronomy*, *1*, 765–770. https://doi.org/10.1038/s41550-017-0271-5

Fouchet, T., Guerlet, S., Strobel, D. F., Simon-Miller, A. A., Bézard, B., & Flasar, F. M. (2008). An equatorial oscillation in Saturn's middle atmosphere. *Nature*, *453*, 200–202. https://doi.org/10.1038/nature06912.

Guerlet, S., Fouchet, T., Spiga, A., Flasar, F. M., Fletcher, L. N., Hesman, B. E., & Gorius, N. (2018). Equatorial oscillation and planetary wave activity in Saturn's stratosphere through the Cassini epoch. *Journal of Geophysical Research: Planets*, *123*, 246–261. https://doi.org/10.1002/2017JE005419

Holton, J. R., & Lindzen, R. S. (1972). An updated theory for the quasi-biennial cycle of the tropical stratosphere. *Journal of the Atmospheric Sciences*, *29*, 1076–1080.

Kuroda, T., Medvedev, A. S., Hartogh, P., & Takahashi, M. (2008). Semiannual oscillations in the atmosphere of Mars. *Geophysical Research Letters*, *35*, L23202. https://doi.org/10.1029/2008GL036061

Leovy, C. B., Friedson, A. J., & Orton, G. S. (1991). The quasi-quadrennial oscillation of Jupiter's equatorial stratosphere. *Nature*, *354*, 380–382. https://doi.org/10.1038/354380a0.

Lindzen, R. S., & Holton, J. R. (1968). A theory of the quasi-biennial oscillation. *Journal of the Atmospheric Sciences*, *25*, 1095–1107.

Newman, P. A., Coy, L., Pawson, S., & Lait, L. R. (2016). The anomalous change in the QBO in 2015–2016. *Geophysical Research Letters*, *43*, 8791–8797. https://doi.org/10.1002/2016GL070373

Orton, G. S., Yanamandra-Fisher, P. A., Fisher, B. M., Friedson, A. J., Parrish, P. D., Nelson, J. F., et al. (2008). Semi-annual oscillations in Saturn's low-latitude stratospheric temperatures. *Nature*, *453*, 196–199. https://doi.org/10.1038/nature06897

Plumb, R. A., & McEwan, A. D. (1978). The instability of a forced standing wave in a viscous stratified fluid: A laboratory analogue of the quasi-biennial oscillation. *Journal of the Atmospheric Sciences*, *35*, 1827–1839.

Reed, R. G., Campbell, W. J., Rasmussen, L. A., & Rogers, D. G. (1961). Evidence of downward-propagating annual wind reversal in the equatorial stratosphere. *Journal of Geophysical Research*, *66*, 813–818.

Vallis, G. K. (2006). *Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation*. Cambridge, UK: Cambridge University Press.

Wallace, J. M., & Holton, J. R. (1968). A diagnostic numerical model of the quasi-biennial oscillation. *Journal of the Atmospheric Sciences*, *25*, 280–292.

Wallace, J. M., & Kousky, V. E. (1968a). Observational evidence of Kelvin waves in the tropical stratosphere. *Journal of the Atmospheric Sciences*, *25*, 900–907.

Wallace, J. M., & Kousky, V. E. (1968b). On the relation between Kelvin waves and the quasi-biennial oscillation. *Journal of the Meteorological Society of Japan*, *46*, 496–502.