How Can We Improve the Driving of the Quasi-Biennial Oscillation in Climate Models?

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Key Points:
- A new observational study neatly assesses the forcing of the Quasi-Biennial Oscillation by tropical gravity waves
- The study combines atmospheric profile information with long-duration balloon measurements of wave activity near their source region
- The study shows a way to improve constraints on gravity-wave parameterization in climate models

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How Can We Improve the Driving of the Quasi-Biennial Oscillation in Climate Models?

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Abstract The Quasi-Biennial Oscillation (QBO) of zonal-mean zonal winds in the tropical stratosphere is a conspicuous feature of the Earth climate. Its influence virtually extends to the whole atmosphere. The QBO is driven by the dissipation of waves generated by deep convection in the tropics. Yet a significant fraction of these waves have spatial scales that are not explicitly resolved in current climate models, so that the evolution of the QBO in a changing climate still remains unclear. A study by Vincent and Alexander (2020, https://doi.org/10.1029/2020JD032779) shows that recent long-duration balloon observations, combined with information on the vertical structure of the tropical atmosphere, could contribute to provide significantly improved constraints on wave parameterization in models.

Plain Language Summary In the tropics, the regular alternation with a period of ∼27 months of westward and eastward winds between 16- and 30-km altitude is known as the Quasi-Biennial Oscillation (QBO), and it influences the global atmospheric circulation in a variety of ways. The QBO results from the dissipation of atmospheric waves that propagate vertically in the atmosphere from their source region below 10-km altitude. These waves have horizontal scales ranging from some tens to some thousands of kilometers. The smaller-scale waves are not properly represented in current climate models, despite their importance in determining the characteristics of the QBO. A study by Vincent and Alexander (2020, https://doi.org/10.1029/2020JD032779), which has used observations collected on balloons that fly for months at 20-km altitude in the atmosphere, provides a new way to better characterize those waves, and hence improves the simulation of the QBO in climate models.

1. Introduction

The Quasi-Biennial Oscillation (QBO), a prominent feature of the Earth climate, primarily relates to the oscillation of the zonal-mean zonal wind in the equatorial stratosphere with an averaged period of 27 months. Figure 1 displays the typical QBO signal over the past 15 years: westward and eastward phases of 20–30 m s^{-1} amplitude that descend from the middle to the lower stratosphere.

Despite sporadic observations of both eastward and westward winds in the tropical stratosphere since the Krakatau eruption in 1883 (e.g., Hamilton, 1998), the QBO discovery dates back to the early 1960s (Ebdon, 1960; Ebdon & Veryard, 1961; Reed et al., 1961) and relied on the analysis of regular observations of radar-tracked balloon winds at Canton Island (2.8° S, 171.7° W). Subsequent developments in both the theory (e.g., Booker & Bretherton, 1967; Matsuno, 1966) and the observations (e.g., Maruyama, 1967; Wallace & Kousky, 1968; Yanai & Maruyama, 1966) of atmospheric waves led Lindzen and Holton (1968) and Holton and Lindzen (1972) to propose a physical explanation of the QBO that still essentially holds today: The alternating zonal-mean eastward and westward winds result from the deposition in the mean flow of momentum fluxes transported by equatorial waves from their source region in the troposphere to the height in the stratosphere where they dissipate.

Numerous processes of the global atmosphere are affected by the QBO. Holton and Tan (1980) have for instance shown that the QBO modulates the amplitude of planetary waves in the winter stratosphere, which in turn affects the occurrence of sudden stratospheric warmings, that is, the stability of the wintertime polar vortices (Baldwin & Dunkerton, 1998). Stratospheric ozone and water vapor present significant QBO-related variations both in the tropics and extratropics (Baldwin et al., 2001; Randel & Wu, 1996, and references therein). The selective filtering of vertically propagating waves by QBO phases at stratospheric levels induces a QBO signature in the tropical mesosphere and lower thermosphere (e.g., Garcia & Sassi, 1999; Huang

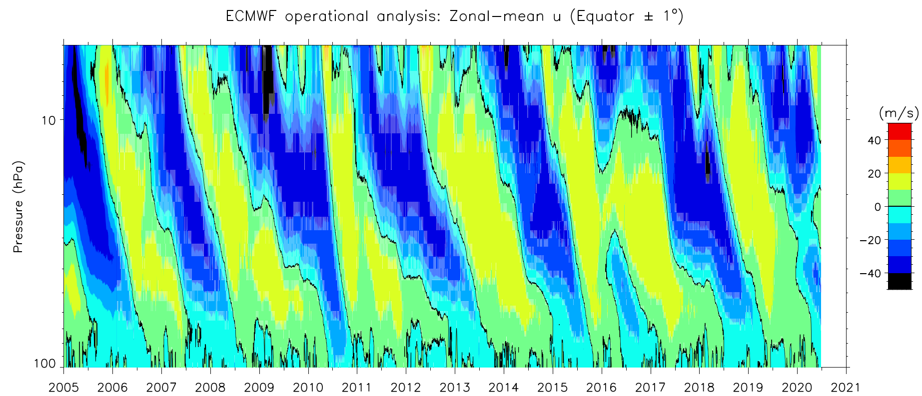

Figure 1. Zonal-mean zonal wind within ±1° of the equator in operational analyses of the European Centre for Medium-range Weather Forecasts since 1 January 2005. The *y* axis spans from 100 hPa (∼16 km) to 5 hPa (∼36 km), which typically corresponds to the QBO vertical extent. Year labels are positioned on 1 January each year. The zero wind line is indicated by the black contour. Note the westward disruptions at lower altitudes (∼40 hPa) in 2016 and 2020.

et al., 2008). The influence of the QBO also reaches the troposphere: Recently, for instance, Son et al. (2017) have shown that the Madden-Julian Oscillation (Madden & Julian, 1972), a prominent mode of variation of tropical deep convection during boreal winter, is favored during QBO easterly phases.

2. How Well Do We Understand the QBO?

While the seminal papers have set up the general framework with which we continue to understand how the QBO is generated, the following studies have underlined the complexity associated with wave-mean flow interactions in the tropical stratosphere. Dunkerton (1997), Sato and Dunkerton (1997), and Kawatani et al. (2010) for instance showed that the driving of QBO winds not only results from planetary-scale waves but also from a wide range of pure and initia gravity waves with timescales and horizontal wavelengths typically less than a few days and a few thousands km. These shorter-scale waves are less prone to be explicitly resolved by climate models, and simulating a realistic QBO in those models has been a long-lasting challenge (e.g., Scaife et al., 2000). Even today, modeled QBOs rely on a subtle balance between resolved and parameterized waves that varies from one model to the other and typically depends on model horizontal and vertical resolutions, numerical dissipation, vertical domain, and parameterizations of atmospheric physics (Butchart et al., 2018). State-of-the-art climate models hence still significantly disagree on how the QBO will respond to a warming climate, even if a decrease in QBO-wind amplitude is a robust feature in those models (Richter et al., 2020). On the other hand, observations of the QBO signal in the atmosphere have shown recent anomalies or disruptions (Coy et al., 2017; Newman et al., 2016; Osprey et al., 2016), which have never been observed before and thus raise the question of whether they result from climate changes (see 2016 and 2020 in Figure 1).

The current climate model shortcomings call for improved parameterizations of convectively generated gravity waves (Richter et al., 2020). An ideal parameterization would bind source-level momentum fluxes to model convection and distribute it realistically across wave phase speeds (e.g., Bushell et al., 2015; de la Cámara & Lott, 2015; Richter et al., 2010), notably to simulate the gravity-wave intermittency (Hertzog et al., 2012) and thus accurately reproduce the vertical distribution of wave drag in the atmosphere. It would also allow the wave packets to propagate in all directions in the atmosphere (Amemiya & Sato, 2016; Ribstein & Achatz, 2016). All this should allow parameterizations to more accurately represent wave momentum flux deposition and QBO forcing.

3. Improving Gravity-Wave Parameterizations

The recent study by Vincent and Alexander (2020) illustrates a way forward. The authors have combined standard radiosounding observations that provide atmospheric profiles up to the top of the QBO extent to novel meteorological measurements obtained along flights of superpressure balloons (SPB) at ∼19 km altitude. These balloons, developed by Centre National d'Études Spatiales (CNES, the French space agency), can fly for several months on constant-density surfaces in the lower stratosphere. They are advected by the wind and are thus able to circumnavigate the Earth while collecting observations with a temporal resolution sufficient to resolve the whole atmospheric wave spectrum (Podglajen et al., 2016).

Vincent and Alexander (2020) have focused on two gravity-wave packets with periods near 1 and 3 days and horizontal wavelengths near 970 and 5,500 km, which were observed while an SPB flight was flying close to Manus Island in the western Pacific. SPB observations are particularly well suited to described wave-packet characteristics (Boccara et al., 2008; Geller et al., 2013; Vincent & Hertzog, 2014), and Vincent and Alexander (2020) used SPB observations to derive the wave momentum fluxes and phase speeds. They were then able to identify the same wave packets in the radiosoundings performed on Manus Island and to provide an estimate of their height of dissipation, which occurs when the wave phase speed matches the background wind (the so-called critical level). They notably show that such packets may account for a significant fraction of the forcing required to drive the QBO.

Vincent and Alexander (2020)'s work noticeably relies on the high resolution of the balloon-borne data sets, either in the time domain for SPB observations or in the vertical for radiosoundings. The study appropriately discusses how insufficient resolution (either in observations or in models) may lead to erroneous estimates of wave forcing.

The wave packets studied in Vincent and Alexander (2020) correspond to inertia-gravity with relatively large horizontal scales that would likely favor their explicit representation in modern climate models. Yet their method can certainly extend to pure gravity waves with shorter wavelengths (with perhaps special care at the very high frequency end Vincent & Hertzog, 2014), which are essentially handled by parameterizations in those models.

4. Conclusion

Vincent and Alexander (2020) neatly illustrates how observations covering virtually the whole vertical domain between wave sources and dissipation heights can be used to advance our understanding of wave forcing in the tropical stratosphere. The forthcoming ∼50 SPB flights that will be performed in 2019–2025 within Strateole-2 (Haase et al., 2018) should provide many new opportunities to extend this work and explore the role of all equatorial waves in driving the QBO. They will in particular include new instrumentation with profiling capabilities that will enhance tropical wave characterization.

The study by Vincent and Alexander (2020) most importantly highlights that efforts to improve our confidence in future climate projections in part rely on a better understanding of fundamental processes in the atmosphere. It is thus critical that funding agencies worldwide continue to support the networks and campaigns that provide the detailed observations required to address these processes.

Data Availability Statement

ECMWF operational analyses are available in the ECMWF operational archive. They are freely accessible for researchers in ECMWF member and cooperating states but are subject to licensing for researchers from other states. Access to the data for those researchers is therefore associated with the purchase of a "archive-data" license at ECMWF. ECMWF may elect to waive the associated fee on a case-by-case basis. On the other hand, the ECMWF Era-Interim reanalysis that covers the January 1979 to August 2019 time period is publicly available.

Acknowledgments
Figure 1 uses operational analyses of the European Center for Medium-range Weather Forecasts (ECMWF) forecast system since it is produced daily by the author.

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