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SUPPLEMENTARY MATERIALS

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ATMOSPHERIC SCIENCE

An unexpected disruption of the atmospheric quasi-biennial oscillation

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One of the most repeatable phenomena seen in the atmosphere, the quasi-biennial oscillation (QBO) between prevailing eastward and westward wind jets in the equatorial stratosphere (approximately 16 to 50 kilometers altitude), was unexpectedly disrupted in February 2016. An unprecedented westward jet formed within the eastward phase in the lower stratosphere and cannot be accounted for by the standard QBO paradigm based on vertical momentum transport. Instead, the primary cause was waves transporting momentum from the Northern Hemisphere. Seasonal forecasts did not predict the disruption, but analogous QBO disruptions are seen very occasionally in some climate simulations. A return to more typical QBO behavior within the next year is forecast, although the possibility of more frequent occurrences of similar disruptions is projected for a warming climate.

Aside from those variations governed by the changing seasons or diurnal cycle, the quasi-biennial oscillation (QBO) is arguably the most repeatable mode of natural variability seen anywhere in the atmosphere. It was first discovered in the late 1950s (*1*, *2*) and features alternating eastward and westward wind jets descending through the equatorial stratosphere at roughly 1 km per month (*3*), from ~50 km (~1 hPa) down to ~16 km (~100 hPa), with the quasi-biennial periodicity being most evident in the ~20- to 40-km layer. Since the 1950s, the period of the oscillation has varied between 22 to 36 months. The oscillation is nearly zonally uniform and so is seen in both local observations and in longitudinally averaged data with roughly the same amplitude, at least for monthly means, and is confined to equatorial latitudes (*4*, *5*). On the other hand, its influence is felt throughout the atmosphere. For example, the fate of ash and sulfur from large volcanic eruptions in the tropics is affected by the QBO (*6*), and there are known surface weather and climate impacts resulting from the QBO's extratropical teleconnections (*7*–*9*); such teleconnections may provide an important source of predictability that can be exploited with seasonal and decadal prediction systems (*10*) owing to the regularity of the QBO. Disruption to the regular QBO behavior is therefore expected to have potentially far-reaching consequences.

In November 2015, the QBO winds were westward above 30 km (~15 hPa) and eastward beneath. During November and December 2015, the westward phase propagated downward as is typical (Fig. 1A), but by January 2016, its descent had stalled. Although by itself this was not unusual (Fig. 1A, during early 2009, just above 20 hPa), the stalling was followed by the unexpected formation of a second westward layer interrupting the lower stratospheric eastward phase (near 40 hPa). Subsequently, the descending westward phase in the upper stratosphere began to recede, while the anomalous westward jet below strengthened and began to descend. Here, we quantify the extent to which this behavior is anomalous compared with the previous six decades of observations containing 27 QBO cycles.

The state of the QBO is often characterized by using an updated time series of monthly mean balloon observations of near-equatorial zonal winds (*11*). This record spans essentially the entire era of operational tropical stratospheric wind soundings from January 1956 to present day and provides 724 monthly profiles of the equatorial zonal wind. For each of these profiles, we identified a "best match" month having the smallest root mean square (RMS) difference over seven levels spanning 70 to 10 hPa (Fig. 1B). For the vast majority of months, there is a close match with another month in the record, and RMS differences are typically 2 to 3 ms^{-1}. Before 2016, the month with the largest RMS difference with its best historical match was December 1988 (4.8 ms^{-1}). The unprecedented behavior in 2016 is apparent because February, March, and April 2016 have RMS differences of 6.7, 10.1, and 6.8 ms^{-1}, respectively.

Canonical theory describes the QBO as driven by the interaction of the zonal mean flow, with a spectrum of vertically propagating waves forced in the lower atmosphere and dissipated within the stratosphere (*12*, *13*). Mean-flow driving is proportional to local vertical wind shear so that where there is westward vertical shear, the mean flow is accelerated westward, and vice versa for eastward vertical shear. This leads to the downward phase propagation of the alternating QBO wind regimes seen throughout the observed record (Fig. 1A). The selective filtering of upward propagating waves by low-level jets then leads to opposite-sign acceleration at higher levels in a "shadowing effect." Climatological large-scale upwelling in the equatorial stratosphere (*14*) opposes the downward phase propagation (*15*) and can contribute to the descent stalling, whereas the forcing of the westward phase can be supplemented by horizontally propagating quasi-stationary planetary waves from the extratropics, particularly in boreal winter (*16*–*19*).

Because the strong westward accelerations near 30 to 50 hPa in late 2015 and early 2016 occur in a region of eastward mean flow shear, they cannot be accounted for by the canonical theory. On the other hand, fluxes of wave activity (Fig. 2A, arrows) averaged for February 2016 suggest that waves propagating from the Northern Hemisphere might be the most likely cause of the westward acceleration (planetary scale Rossby waves propagating from the extratropics can only transport westward momentum). Typically, during winter months upward wave activity fluxes enter the stratosphere at mid- to high latitudes then refract equatorward. In February 2016, the anomalously strong high-latitude eastward jet was unusually flanked by subtropical

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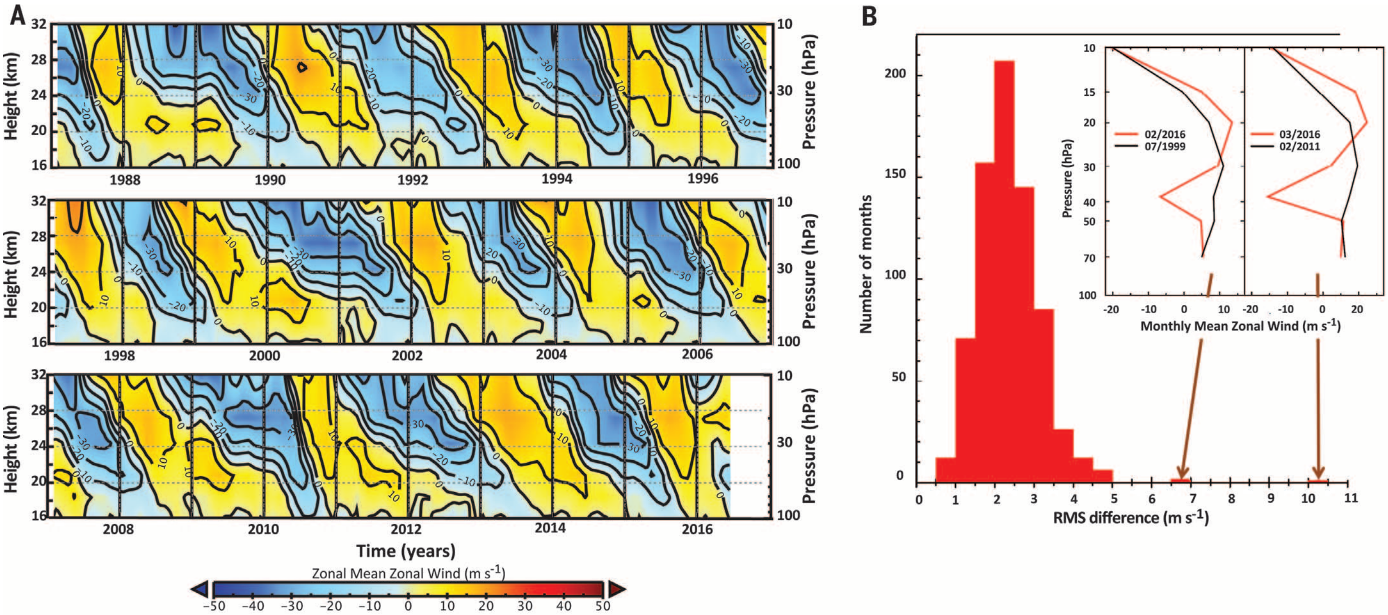

Fig. 1. Evolution of the QBO showing regular repeating wind structures and anomalous westward winds in 2016. (**A**) Vertical profile time series of monthly mean zonal mean eastward wind averaged over 5°S–5°N, showing descending eastward (yellow) and westward (blue) wind regimes (*25*) for the past 13 observed QBO cycles. (**B**) Histogram of RMS differences in monthly mean eastward wind averaged over the 70, 50, 40, 30, 20, 15, and 10 hPa levels between each of the 724 monthly profiles from all 27 observed QBO cycles and its closest match in the record (*11*). Only matches between profiles separated by more than 6 months were evaluated in order to ensure only matches from earlier or later QBO cycles were considered. (Insets) Monthly mean profiles together with their best matches for February and March 2016.

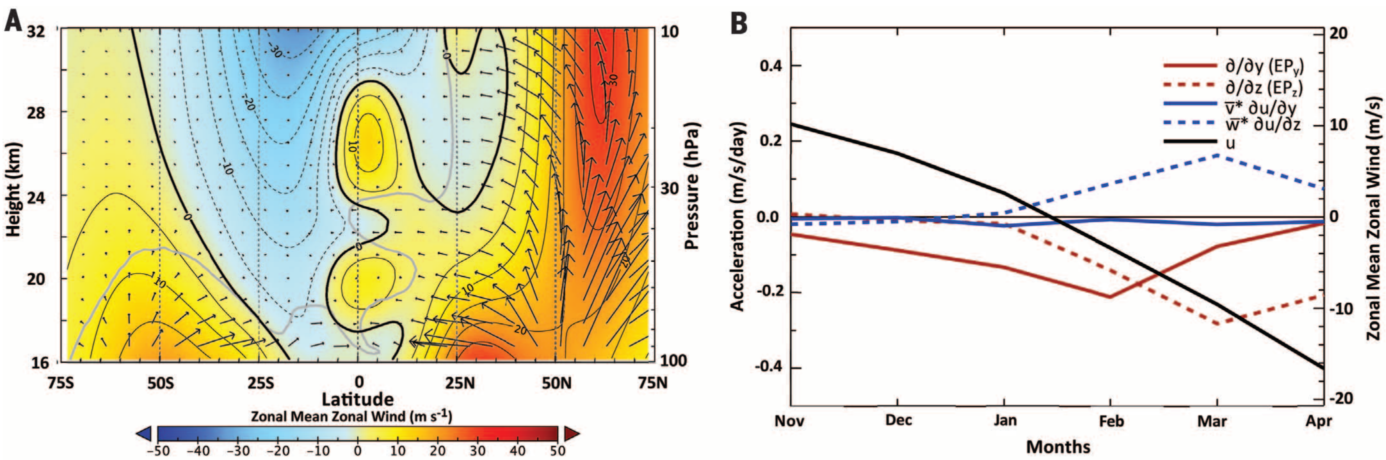

Fig. 2. Wave-driven circulation changes associated with the formation of 40-hPa westward *u* (where *u* is the zonal velocity field). (**A**) Latitude-log-pressure plot showing February 2016 mean zonal mean wind (solid and black contours), Eliassen-Palm (EP) flux (*26*) (black arrows), and their extent (gray contour). EP flux is indicative of wave propagation direction and shows wave activity leaving the troposphere near 50°N and entering the tropics near 40 hPa. (**B**) Monthly mean time series of horizontal (solid lines) and vertical (dotted lines) contributions of EP flux divergence (red) and *u*-advection (blue), averaged over 5°S–5°N. $\overline{v}^*$ and $\overline{w}^*$ are the northward and upward residual mean winds, respectively (*26*). Westward acceleration evident near 40 hPa started in November 2015 and continued during January–February 2016. Monthly mean *u* time series (solid black lines) indicates development of easterly anomaly. Diagnostics derived from 6-hourly global operational analysis data (*25*, *27*).

westward winds above ~30 hPa (Fig. 2A). Because these westward winds do not favor Rossby wave propagation (*21*), the wave flux is confined to the region below, turning horizontal and equatorward (Fig. 2A). The QBO so happened to be in its eastward phase at this level, which allows the waves to propagate all the way to the equator near 40 hPa. Summertime westward winds prevent further propagation across the equator into the Southern Hemisphere. The resultant wave dissipation causes a westward acceleration at the equator.

Confirmation of the above analysis is provided by the monthly mean momentum budget at 40 hPa for late 2015 and early 2016 (Fig. 2B). Dominating the westward acceleration of the equatorial winds at this level up to February 2016 is the contribution from the horizontally propagating waves. This contribution declines once the winds at this level become westward (negative) in February, leaving a balance between the driving from the vertically propagating waves and the opposing upwelling and a return to the standard QBO paradigm. As this westward jet develops near 40 hPa, eastward acceleration appears near 20 to 30 hPa in the familiar "shadowing" pattern predicted by the canonical theory.

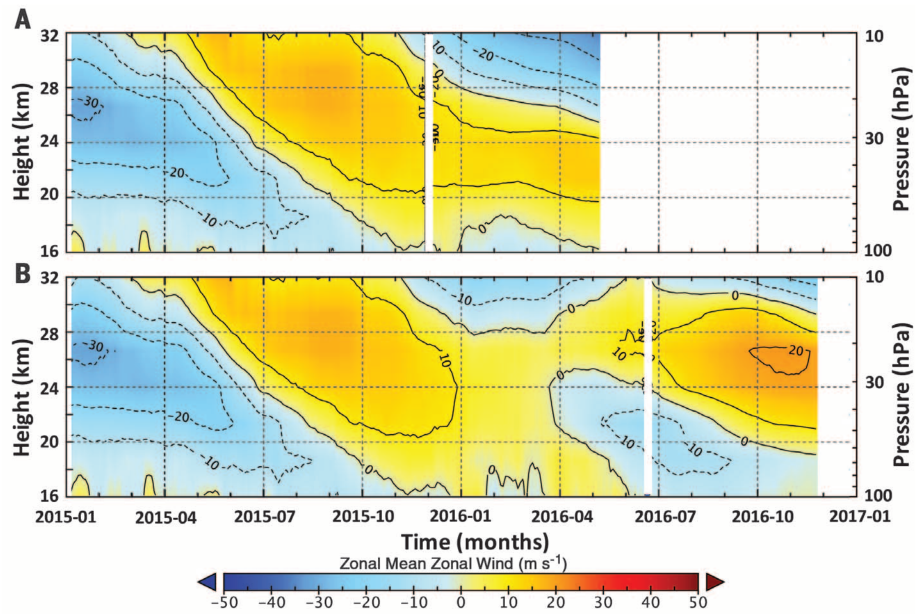

Fig. 3. Long-range forecasts of the QBO from before and during the 2016 disruption. (**A**) Forecasts from 1 December show the usual phase progression of descending eastward wind in the lower stratosphere. (**B**) Forecasts from June show growth, descent, and decay of the anomalies in westward wind near 50 hPa and a second period of eastward QBO winds in late 2016.

The QBO's long period and great regularity make it the most predictable long-term atmospheric variation after the annual cycle. Tests over many past cycles of the QBO confirm that this normally allows skilful predictions out to a few years ahead (*10*), yet the recent disruption of the oscillation shows very different characteristics. A seasonal climate prediction made in December 2015 and initialized with the atmospheric and oceanic state at the time (*20*) showed over the subsequent months a clear continuation and descent of the eastward phase of the QBO into the lower stratosphere, with no sign of the spontaneous appearance of westward flow in the lower stratosphere as occurred in observations (Fig. 3A). This is in sharp contrast to the usual skillful predictions of the QBO out to years ahead (*10*), and therefore the recent disruption of the QBO cycle was not predicted, even just 1 month in advance.

This low predictability is consistent with the origin of the QBO's disruption being found in the extratropical atmosphere, where variability is inherently less predictable. The occurrence of a disruption to the eastward phase of the oscillation is also consistent with an extratropical origin from the winter hemisphere because transient Rossby waves occurring in the winter stratosphere can only propagate into eastward flow and

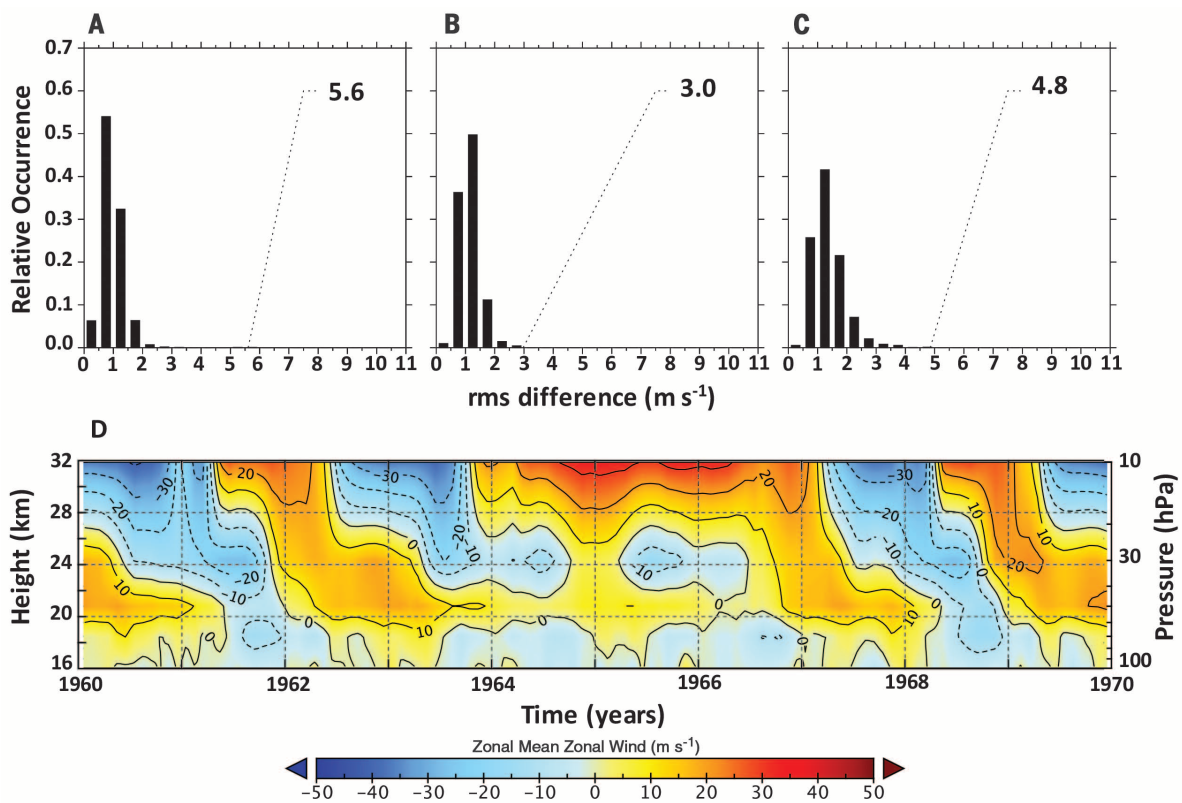

Fig. 4. Extreme QBO activity diagnosed in contributions to the Coupled Model Intercomparison Project Phase 5 (CMIP5). (**A** to **C**) Best-match RMS differences for (A) HadGEM2-CCS, (B) MIROC-ESM-CHEM, and (C) MPI-ESM-MR (*28*). Although outliers occur in the three model simulations, only one model produced analogous westward jet formation seen in observations. (**D**) The formation of westward *u* within a descending eastward jet is seen during 1964 in run r1i1p1 of MPI-ESM-MR. Anomalous westward *u* is seen near 100 hPa, and strengthened 10 hPa eastward *u* last until 1967. Only one event occurred during the 145-year run.

deliver westward acceleration to the mean flow. Furthermore, the stronger tropical upwelling during Boreal winter slows down the QBO's descent, allowing more time for the extratropical waves to impact during this particular phase.

Of course, it is also possible that our current numerical models can not properly represent the processes disrupting the QBO. To investigate this, the foregoing RMS analysis that was applied to the observational record was applied to historical global climate model runs so as to identify possible analogous events (Fig. 4, A to C). Among the available models that produce a QBO internally, only one rarely produced behavior similar to the observed disruption, with an example shown in Fig. 4D. The extreme profiles resemble those observed during 2016 with a thin layer of westward wind appearing within an otherwise eastward QBO phase.

What will happen next? The recent disruption of the QBO is a rare event that occurs in the northern winter. The forecast initialized after the disruption (Fig. 3B) suggests that the QBO will return to more regular phase progression over the coming year. The westward jet that suddenly appeared in the lower stratosphere is predicted to amplify in the summer of 2016 and progress downward with time. Eastward flow then descends from the 20-hPa level and dominates the lower stratospheric flow toward the end of 2016, returning the QBO to its typical behavior. We then expect regular and predictable QBO cycling to continue from 2017, as occurs in the available climate models (Fig. 4D). Nonetheless, as the climate warms in the future, climate models that simulate these events suggest that similar disruptions will occur up to three times every 100 years for the more extreme of the standard climate change scenarios. This is consistent with a projected strengthening of the Brewer-Dobson circulation due to increasing stratospheric wave activity (*14*) and the recently observed weakening of the QBO amplitude in the lower stratosphere (*21*) under climate change. However, robustly modeling how the QBO and its underlying processes and external influences will change in the future remains elusive.

There is a further outcome of the 2016 disruption of the QBO. After an eastward QBO at the onset of the 2015–2016 winter, the QBO at the onset of the coming winter of 2016–2017 was expected to be westward. The disruption of early 2016 means that an eastward QBO phase is now again expected in the lower stratosphere. Because of the expected QBO influence on the Atlantic jet stream, this increases the risk of a strong jet, winter storms, and heavy rainfall over northern Europe in the coming winter (*22*, *23*).

Note added in proof: A similar finding was published by Newman *et al.* (*24*) during the final revision period of the present study.

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SUPPLEMENTARY MATERIALS

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Table S1

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ATMOSPHERIC OXYGEN

A Pleistocene ice core record of atmospheric O_2 concentrations

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The history of atmospheric O_2 partial pressures (Po_2) is inextricably linked to the coevolution of life and Earth's biogeochemical cycles. Reconstructions of past Po_2 rely on models and proxies but often markedly disagree. We present a record of Po_2 reconstructed using O_2/N_2 ratios from ancient air trapped in ice. This record indicates that Po_2 declined by 7 per mil (0.7%) over the past 800,000 years, requiring that O_2 sinks were ~2% larger than sources. This decline is consistent with changes in burial and weathering fluxes of organic carbon and pyrite driven by either Neogene cooling or increasing Pleistocene erosion rates. The 800,000-year record of steady average carbon dioxide partial pressures (Pco_2) but declining Po_2 provides distinctive evidence that a silicate weathering feedback stabilizes Pco_2 on million-year time scales.

The importance of O_2 to biological and geochemical processes has led to a long-standing interest in reconstructing past atmospheric O_2 partial pressures (Po_2, reported at standard temperature and pressure) (*1*–*12*). However, there is no consensus on the history of Phanerozoic Po_2, with reconstructions disagreeing by as much as 0.2 atm, the present-day pressure of O_2 in the atmosphere (e.g., *7*, *10*). Even over the past million years, it is not known whether atmospheric O_2 concentrations varied or whether the O_2 cycle was in steady state (Fig. 1A). Knowledge of Po_2 over the past million years could provide new insights into the O_2 cycle on geologic time scales and serve as a test for models and proxies of past Po_2. Here we present a primary record of Po_2 over the past 800,000 years, reconstructed using measured O_2/N_2 ratios of ancient air trapped in polar ice.

O_2/N_2 ratios of this kind have been extensively used to date ice cores on the basis of the correlation between O_2/N_2 and local summertime

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Science

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