7 The Quasi-Biennial Oscillation (QBO)

(Reviewed by Baldwin et al., Rev. Geophys., 2001)

Previously we noted the remarkable quasi-periodic reversal of zonal winds in the tropical stratosphere, the quasi-biennial oscillation. The monthly mean zonal mean zonal winds at the equator are shown in Fig. 1. The QBO is centered on the equator; therefore during the westerly phase of the oscillation the equator is (locally) a region of maximum westerlies and therefore a maximum of relative angular momentum. Since total angular momentum is conserved by zonally-symmetric motions, it follows that a zonally-symmetric ring of air moved into the equatorial zone from higher altitudes would have reduced relative angular momentum (i.e. easterlies) on arrival. Therefore the observed westerly phase of the QBO requires the presence of eddies, i.e. departures from zonal symmetry, for its existence. In fact, it is thought probable that both easterly and westerly regimes are wave-driven.

In addition to the planetary scale waves of the winter hemisphere, the dominant large-scale wave motions of the tropical stratosphere are upward-propagating equatorial waves (synoptic scale motions trapped within about 10 degrees of the equator), in particular westerly Kelvin waves and easterly mixed Rossby-gravity wave; in addition there are the ubiquitous gravity waves. Development of a fully self-consistent, 2D, theory of the interaction between waves and mean zonal flow is a complicated business which (thus far at least) has only been done numerically. However, as a means of looking at the mechanisms involved in the generation of the QBO, therefore, we shall consider an analogue to the oscillation (which has been realized in the laboratory; we will see a movie of this) involving a pair of vertically-propagating internal gravity waves. (Increasingly, it is being recognised that gravity waves indeed are likely to be the dominant forcing, so this is in fact a reasonable thing to do.)
Consider two waves, generated at \( z = 0 \), which are equal and opposite in the sense that they have the same zonal wavenumber and amplitude but opposite zonal phase speeds:

<table>
<thead>
<tr>
<th>wave ( n )</th>
<th>zonal wave# ( k_n )</th>
<th>zonal phase vel ( c_n )</th>
<th>EP flux ( F_n(z = 0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( k )</td>
<td>( c )</td>
<td>( -F_0 )</td>
</tr>
<tr>
<td>2</td>
<td>( k )</td>
<td>( -c )</td>
<td>( F_0 )</td>
</tr>
</tbody>
</table>

We assume that these waves are dissipated by thermal dissipation (radiative cooling with rate \( \alpha \)) as they propagate upwards. (This is not very realistic — they likely dissipate by breaking and/or, in the lab experiment, by sidewall friction — but it renders the problem mathematically tractable. We just use thermal processes as our notional dissipation mechanism for convenience.)

Now, it was shown in the appendix to Section 5 of the class notes that the EP flux of each wave evolves with height according to

\[
F_n(z) = F_{0n} \exp \left( -\int_{z_0}^z \Lambda_n(z')dz' \right)
\]

where \( \Lambda_n \), the attenuation rate for the \( n^{th} \) component, is

\[
\Lambda_n = \frac{\alpha}{(\partial \omega / \partial m)_n} = \frac{\alpha N^2}{m_n k(\bar{u} - c_n)^3} \approx \frac{\alpha N}{k(\bar{u} - c_n)^2},
\]

for \( m^2 >> 1/4H^2 \). The implications of this dependence of \( \Lambda_n \) on \((\bar{u} - c_n)\) are that in westerly flow, a wave of westerly phase speed is selectively absorbed and gives enhanced westerly forcing of the mean flow, while the converse is true in easterly flow.

Now, the mean zonal momentum equation is

\[
\frac{\partial \bar{u}}{\partial t} = \frac{1}{\rho} \left[ \frac{\partial F_1}{\partial z} + \frac{\partial F_2}{\partial z} \right]
\]

If \( \bar{u} = 0 \) everywhere, then \( \Lambda_1 = \Lambda_2 \) (recall that the sign of \( m_n \) is opposite to that of \((\bar{u} - c_n)\) and therefore (2) gives us this result). Hence

\[
\frac{\partial F_1}{\partial z} = -\alpha_1 F_1
\]

while

\[
\frac{\partial F_2}{\partial z} = -\alpha_2 F_2 = -\alpha_1 F_2
\]
and, since $F_2 = -F_1$ on $z = 0$, it follows that $F_2 = -F_1$ everywhere. Then (3) tells us that

$$\frac{\partial \bar{u}}{\partial t} = 0$$

when $\bar{u} = 0$ everywhere. This result is in fact fairly obvious on the grounds of symmetry—the problem thus posed is invariant to a reversal of the zonal direction. However, if we break the symmetry by introducing a perturbation in the mean flow, we find that the perturbation is amplified and leads to a QBO-like oscillation.

The processes involved are as follows (cf. Fig 2). In the region of a (say)

![Figure 2: Wave propagation and the QBO.](image)

westerly zonal wind perturbation (Fig 2a), wave 1 is selectively absorbed and therefore generates a westerly force acting on the mean flow which reinforces the initial perturbation. Actually, the maximum force acting on $\bar{u}$ occurs just below the maximum flow (because $|F|$ decreases with height) and so the westerly regime descends as it amplifies. Above the level of the initial perturbation, wave 2 begins to dominate (because wave 1 has been selectively attenuated at lower levels) and so the acceleration becomes negative; an easterly wind regime is thus generated at high levels. These two wind regimes intensify and descend (Fig 2b), with wave 1 being absorbed in the westerlies and wave 2 in the easterlies, until (Fig 2c) the shear separating the two regimes becomes so strong that viscous effects come into play. Through this process, the easterly regime above “eats away” into the lower-level westerlies until (Fig 2d) the low-level westerlies are destroyed altogether. At this point, wave 1 is suddenly able to propagate to high levels, where it induces
westerly acceleration and hence the onset of a new westerly regime. Then the oscillation—for that is what it has now become—proceeds as (b)-(d) with a phase reversal and so on.

This process has been demonstrated in the laboratory\(^1\) and in simplified numerical models. (GCMs have mixed success in reproducing the QBO; high-resolution models produce a QBO-like oscillation, but most do not get the right period or amplitude. The GCMs are improving, however.) Unfortunately, wave climatologies are not known well enough for us to be able to give a good quantitative comparison between simple models and observations, beyond saying that characteristics such as the period of the QBO are consistent with what we do know.

Some basics are still poorly understood, such as the relative roles of the various wave types in the driving mechanism of the oscillation. An important aspect of the QBO is the existence of a significant signal at high latitudes. There appears to be a strong correlation between midwinter warmings in the northern hemisphere and the phase of the equatorial QBO. It seems likely that modulation of the subtropical zonal winds by the QBO has some impact on midlatitude planetary waves, which then communicate the signal to high latitudes, but as yet there is no tight theory of this. (There are even strong indications of a solar cycle influence on polar warmings; the influence changes sign according to the phase of the QBO.)

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\(^1\)Animations of experimental results can be found at: http://dennou-k.gaia.h.kyoto-u.ac.jp/library/gfd_exp/ (there are several GFD experiments here: go to “QBO”).