UNIVERSITY OF OXFORD

# Synchronisation of the equatorial quasi-biennial oscillation by the annual cycle in a warming climate

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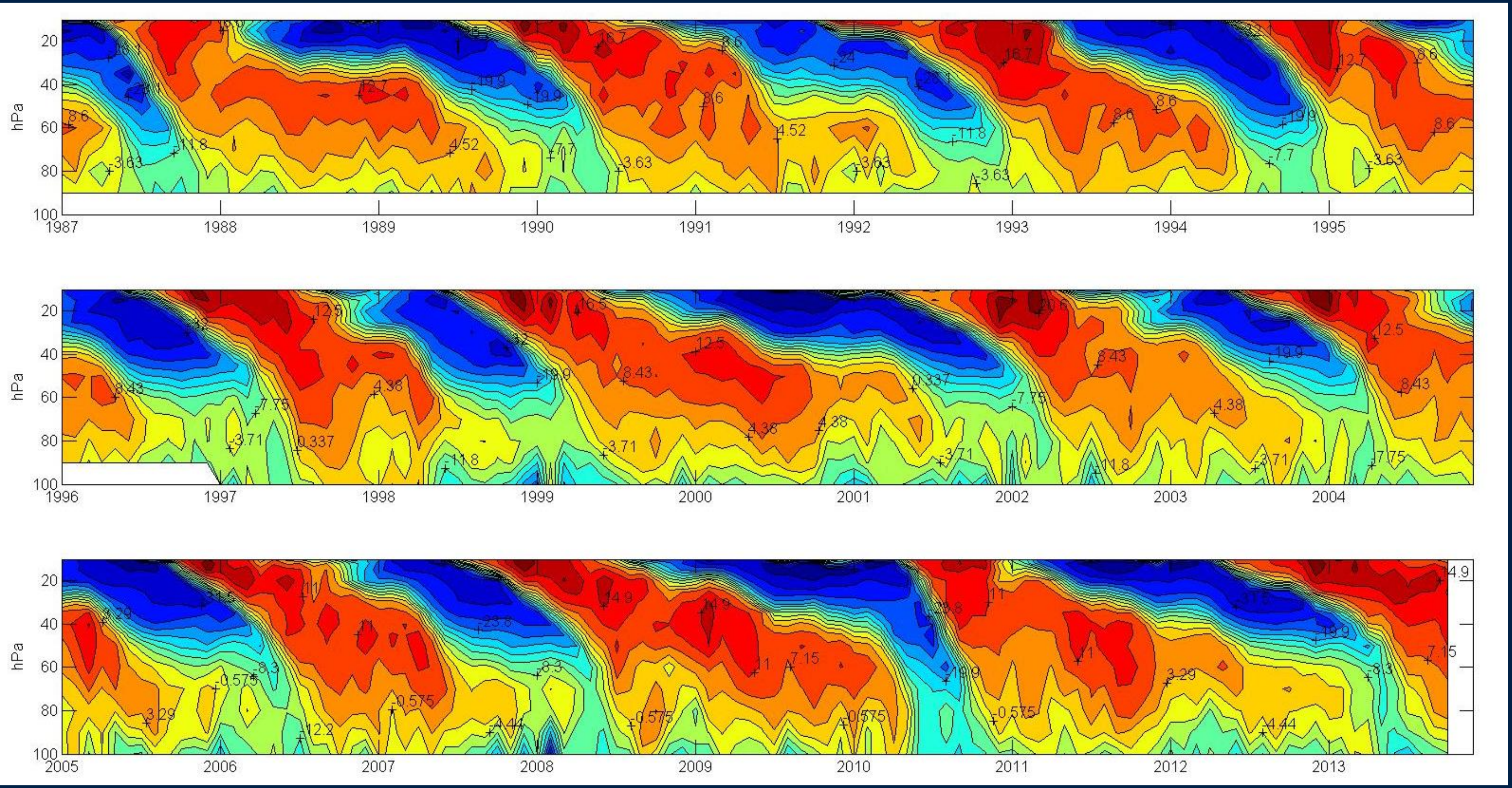
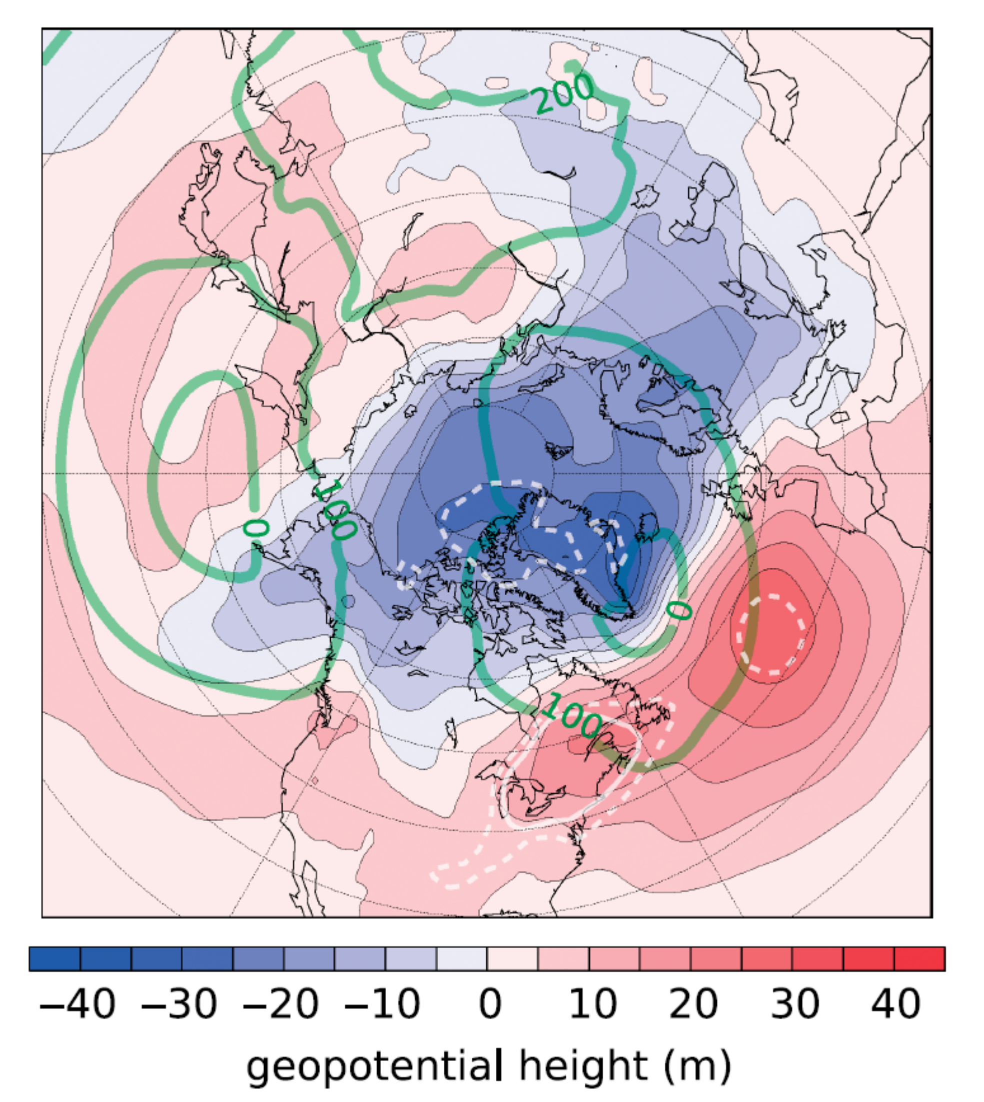
# The Quasi-Biennial Oscillation




*"Alternate bands of easterly and westerly winds which originate above 30km and which move downward through the stratosphere at a speed of about 1km per month" - Reed 1960*

*[Data from FUB]*

# Extratropical influence of the QBO

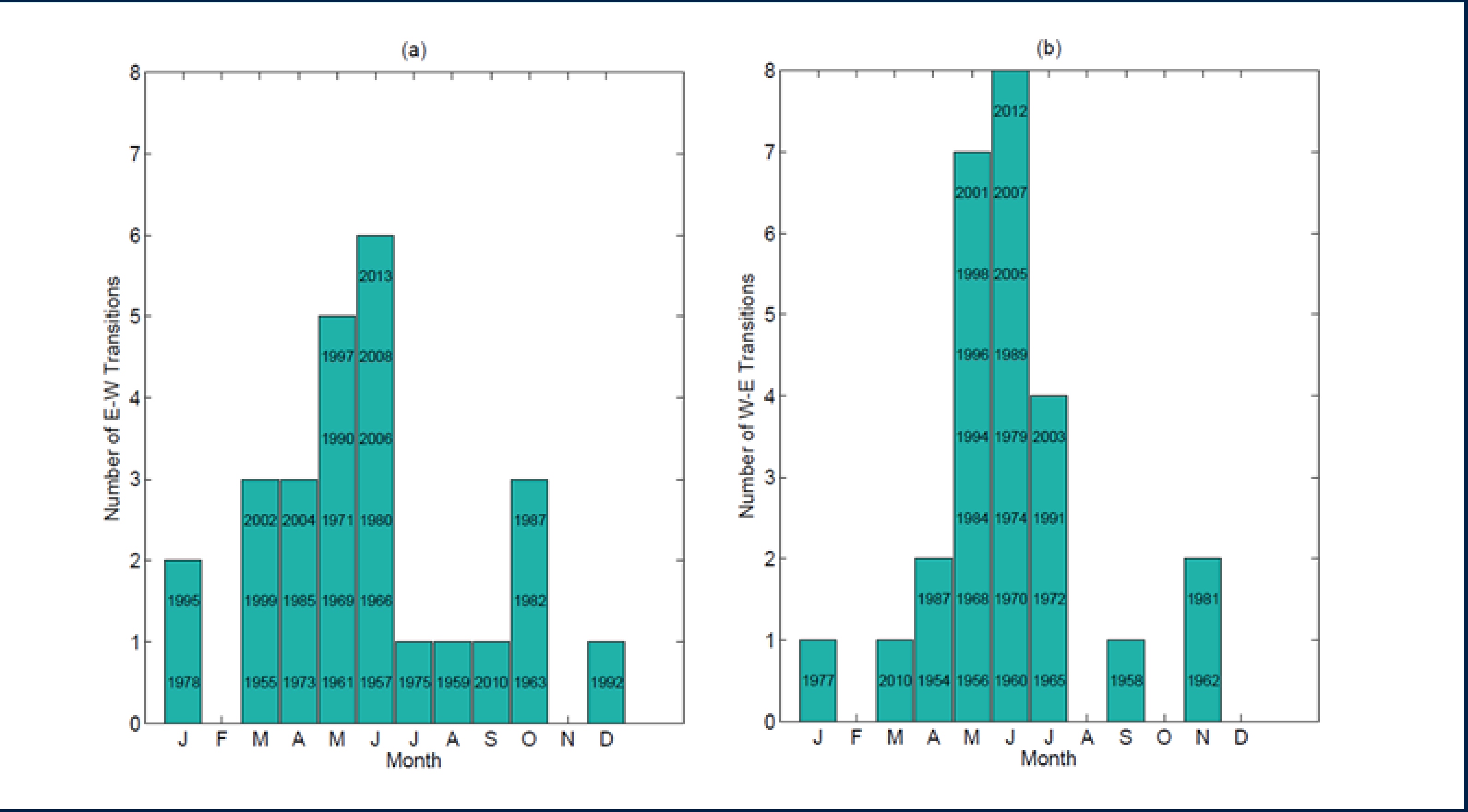



"…by modulating the latitudinal extent of the winter westerlies, the QBO may act either to focus planetary wave activity toward high latitudes or to allow its passage into the Tropics. Increased extratropical confinement of wave activity, corresponding to a poleward shift of the zero-wind line associated with the QBO easterly phase, is expected to weaken the vortex while the opposite situation during the QBO westerly phase is expected to strengthen it."

*- Anstey & Shepherd (2014)*

*[Source: Anstey and Shepherd 2014]*

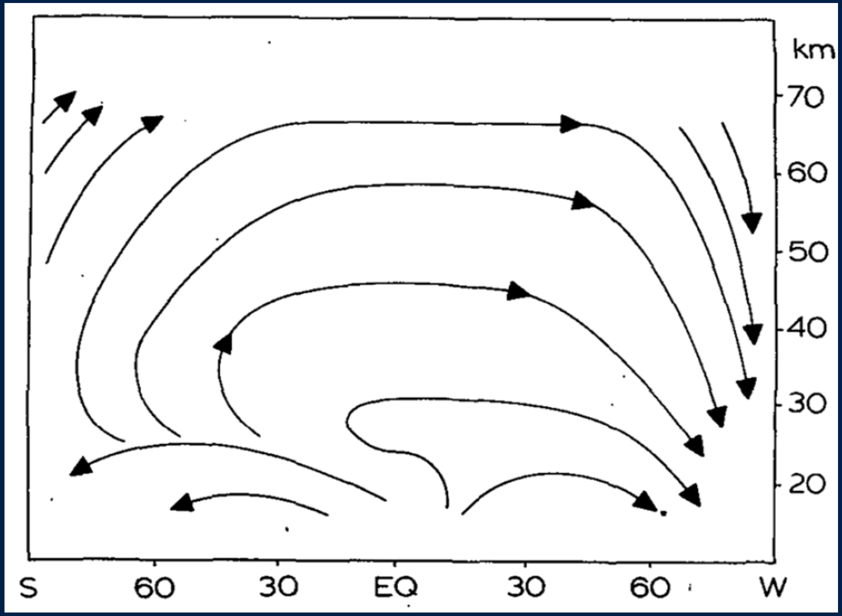
# Seasonal effects on QBO transitions



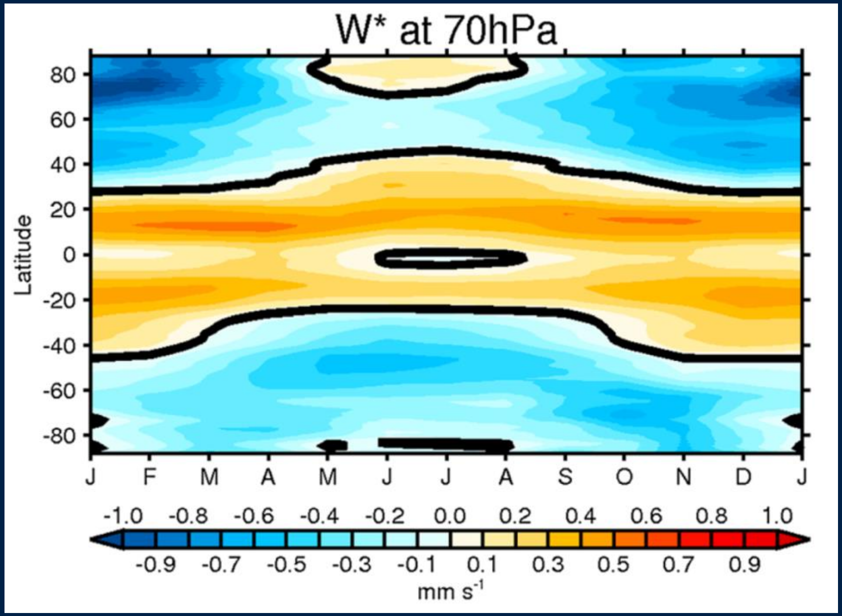

Histogram of the transitions of the QBO winds at 50hPa for each month, from (a) Easterlies to Westerlies, and (b) Westerlies to Easterlies.

*[Data from FUB]*

# The Brewer-Dobson circulation




Streamlines of the Lagrangian-mean velocities
*[Source: Dunkerton 1978]*

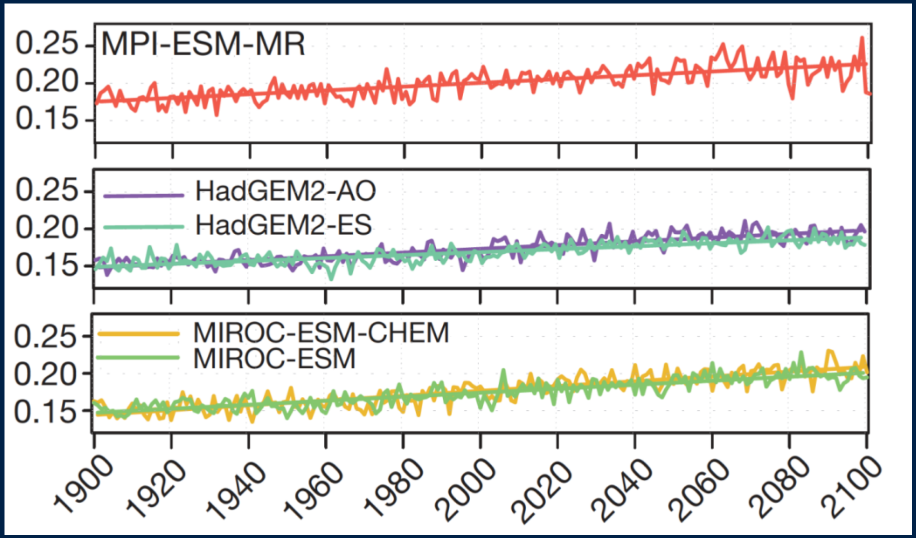



Mean residual vertical velocities $w^*$ at 70 hPa
*[Source: Butchart 2014]*

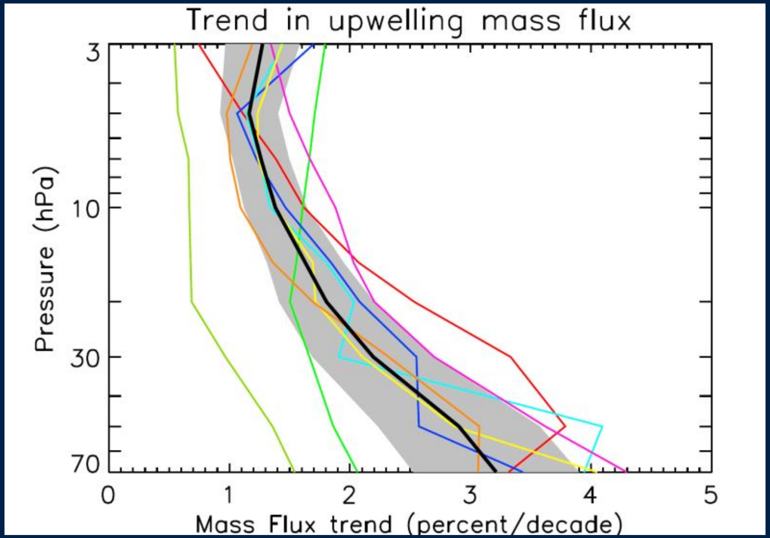
The vertical upwelling of tropical air affects the period of the QBO by impeding the descent of QBO shear zones.

Since the strength of w* varies along with the annual cycle, it would be interesting to investigate how this modulation might affect the period of the QBO.

# Projected acceleration of Brewer-Dobson upwelling under climate change scenarios




Time variation in modelled annual mean upward velocity at 70 hPa. *[Source: Kawatani & Hamilton 2013]*




Projected upwelling trends from RCP8.5 scenario simulations of 8 stratosphere-resolving GCMs. *[Source: Hardiman et al 2013]*

Motivation: The strength of the polar vortex in winter is modulated by the phase of the QBO. A better understanding of the QBO period and phase would improve forecasting skill.

Observation: The transition between QBO phases exhibits a seasonal dependence, possibly modulated by the seasonal cycle in the upwelling of the Brewer-Dobson circulation.

GCM studies in warming scenarios indicate that the strength of this upwelling will increase by ~3% per decade.

Aim: To systematically investigate the influence of the annual cycle in tropical upwelling on the QBO period, using a simple 1D model.

# Model Description

Wave forcing

Diffusion

$$\frac{\partial \bar{u}}{\partial t} + w\frac{\partial \bar{u}}{\partial z} = -\frac{1}{\rho}\sum_i \frac{\partial \mathcal{F}_i}{\partial z} + \kappa \frac{\partial^2 \bar{u}}{\partial z^2}$$

Governing Equation

Vertical advection
(tropical upwelling)

Forcing amplitude

Dissipation rate

Buoyancy frequency

$$\frac{1}{\rho_0}\mathcal{F}_i(z,t) = F_i \exp\left\{-\int_{z_l}^{z} \frac{\mu N \alpha(z)}{k_i(\bar{u}(z',t)-c_i)^2}dz'\right\}$$

Wave forcing

Wavenumber

Phase speed of wave

We use the simplest 1D model of the QBO due to Holton & Lindzen (1972) (see also Plumb 1977), extended to include vertical advection.

The zonal wind is forced by two identical vertically propagating gravity waves travelling in opposite directions.

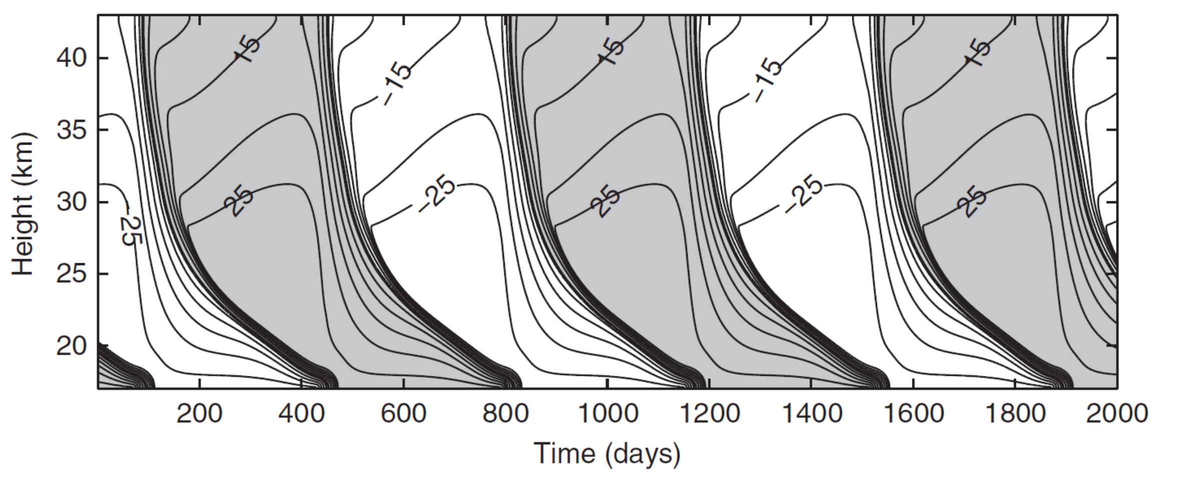
# Model Description

$$w(z,t) = \left[ w_c + w_a \cos\left(\frac{2\pi t}{360}\right)\right] \exp\left\{\frac{z - z_t}{z_t - z_l}\right\}$$

Upwelling

Constant Upwelling component

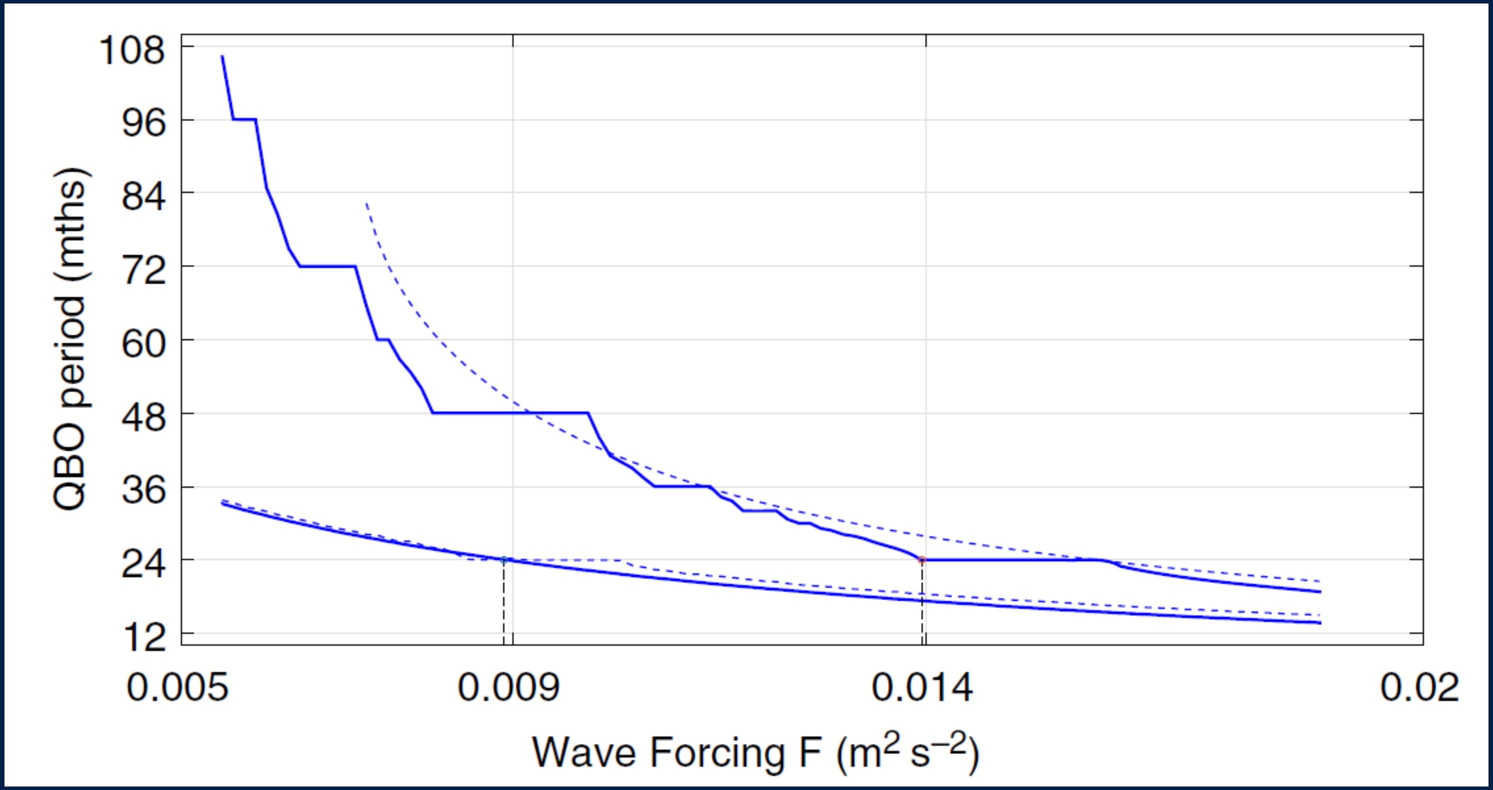
Periodic Upwelling component




Sample Output

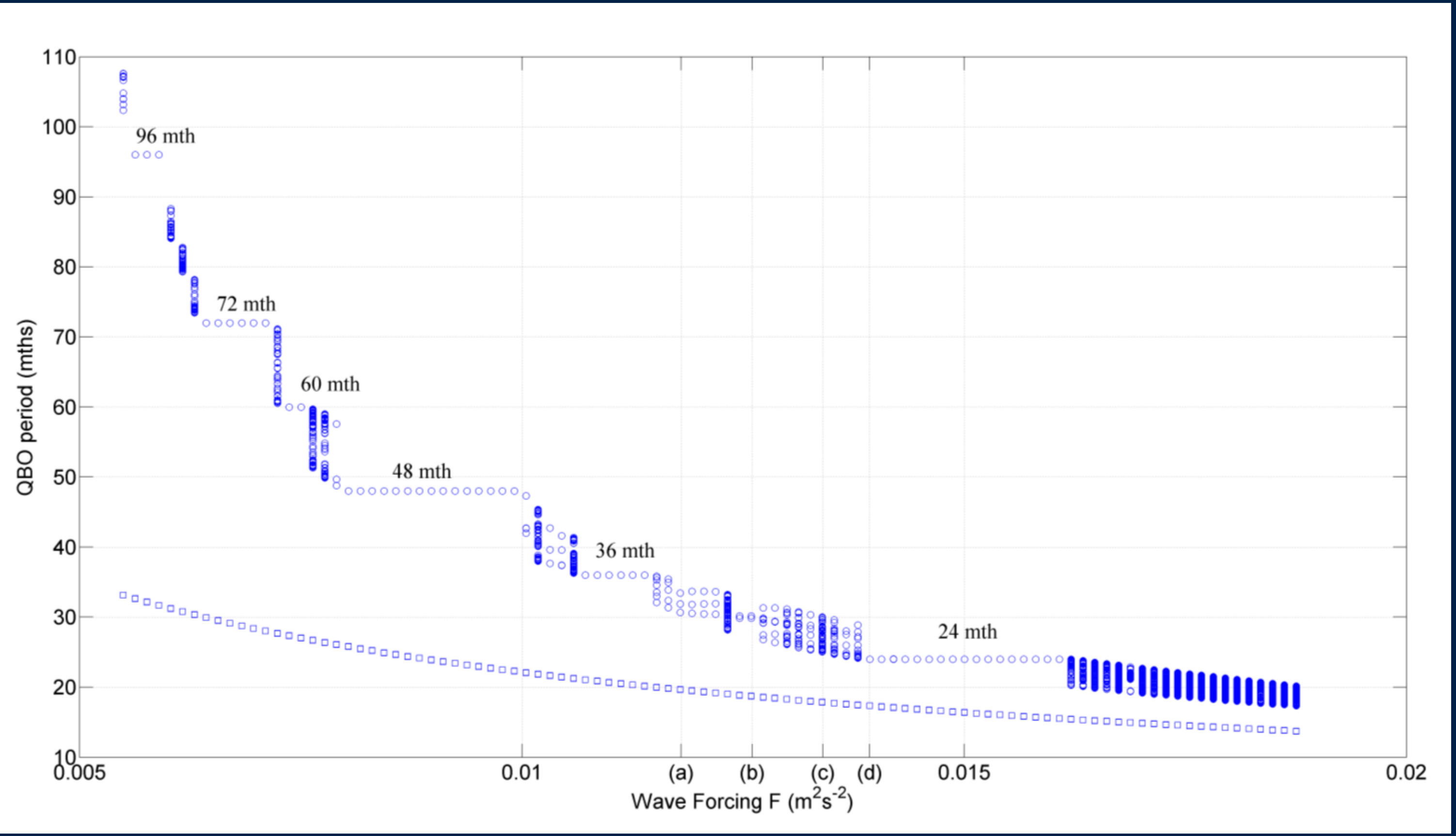
In the following studies we vary the wave forcing strength F as well as the strength of the two upwelling terms. All other parameters are fixed.

# Result 1: Synchronisation of the QBO



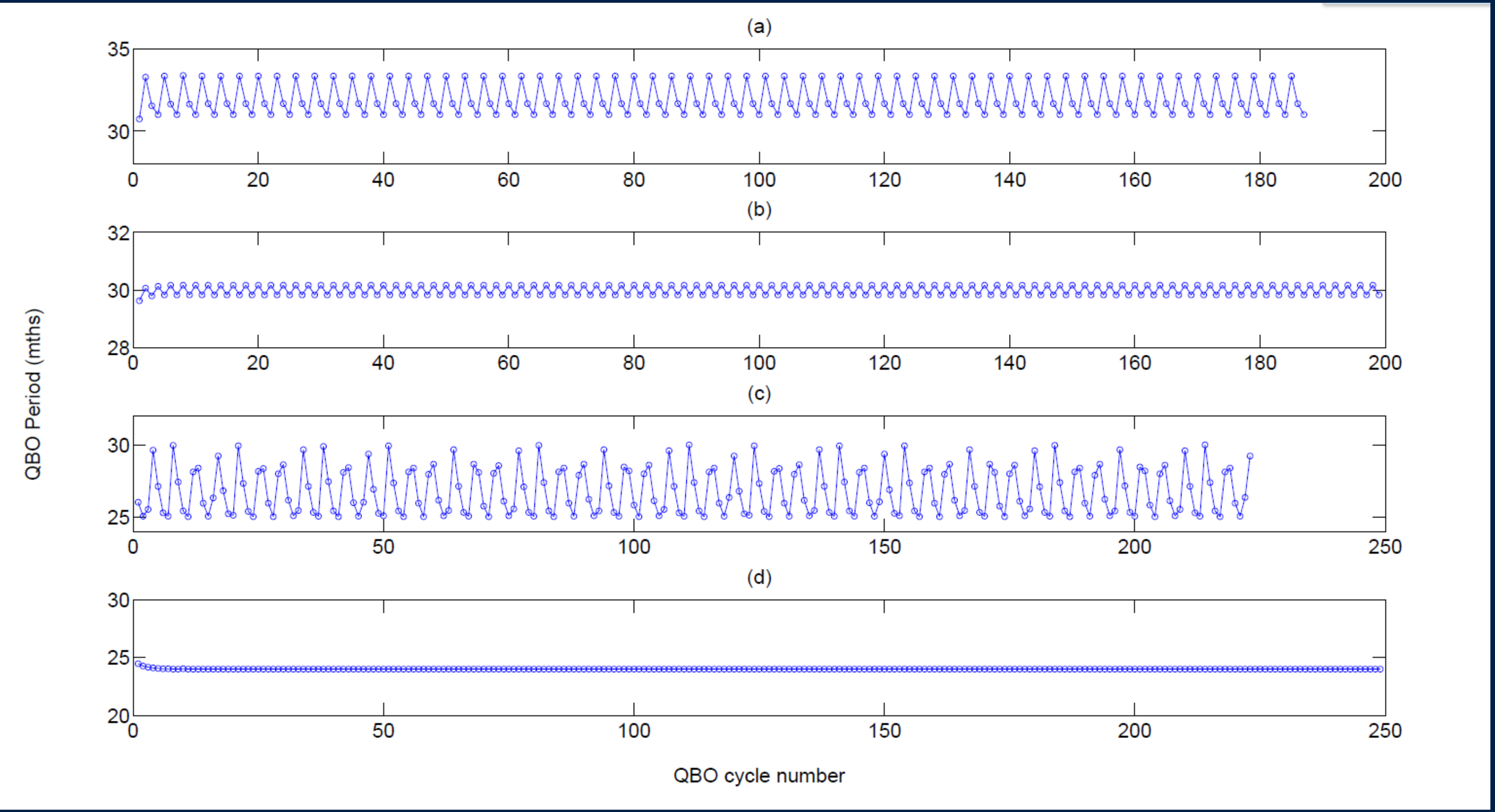

Average QBO period as wave forcing $F$ is varied in two sets of 100 simulations with (top, solid line) and without (bottom, solid line) tropical upwelling. In the upwelling run we set $w_c$ = 0.3mms−1 and $w_a$ = 0.2mms−1; in the no-upwelling comparison we set both to 0. The dashed curves correspond to upwelling simulations where just one of $w_a$ (top, dashed line) or $w_c$ (bottom, dashed line) are set to 0 (with the other parameter retaining its non-zero value).

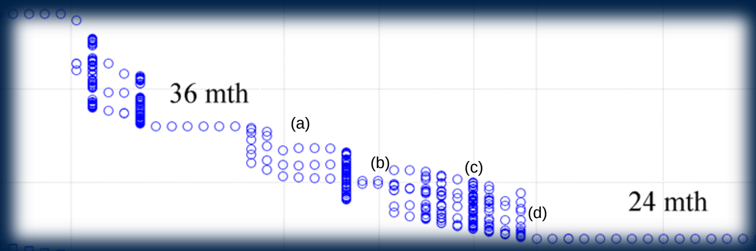
# Result 1: Synchronisation of the QBO




Individual QBO cycle lengths plotted against wave forcing, in the presence and absence of tropical upwelling. Each cycle length is defined by the time between the onset of westerly wind regimes at 40 hPa. Data points from the simulations with upwelling are plotted as circles, while those from simulations without upwelling are plotted as squares.

# Result 2: Length of each QBO cycle



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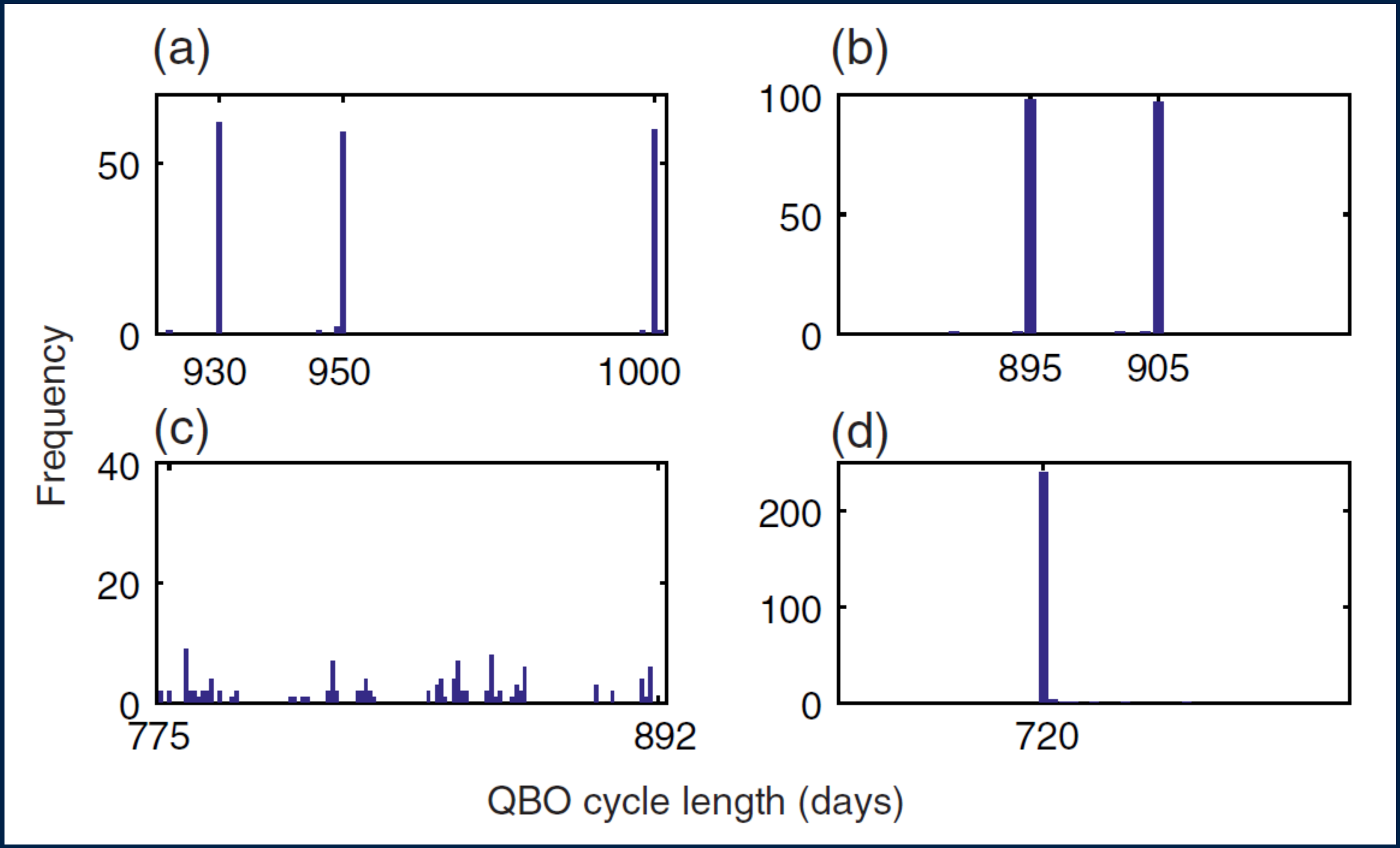
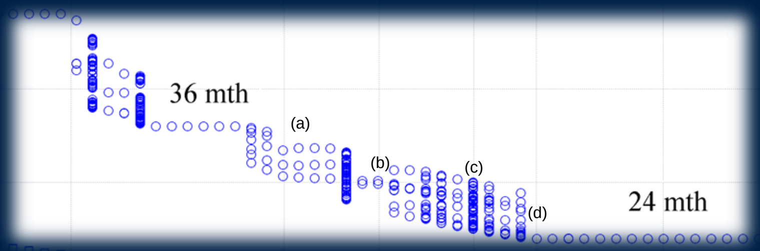
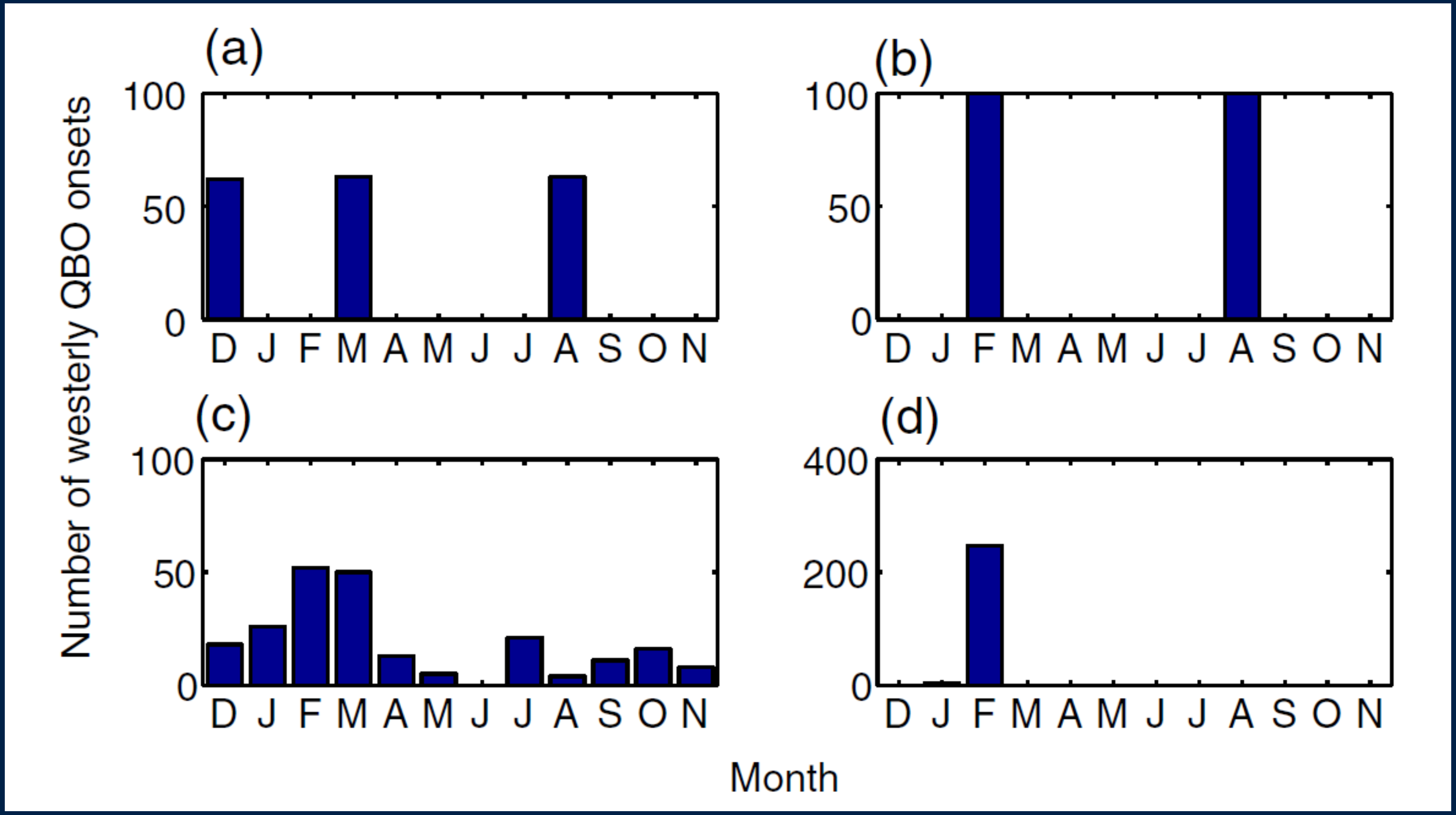
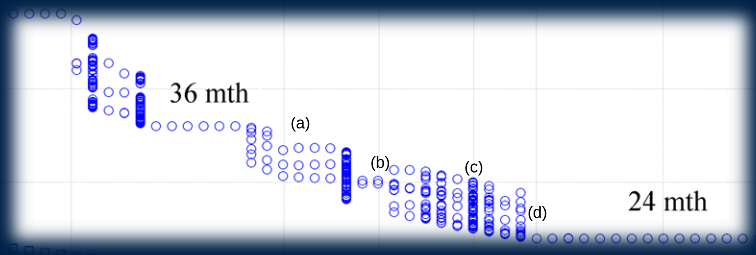


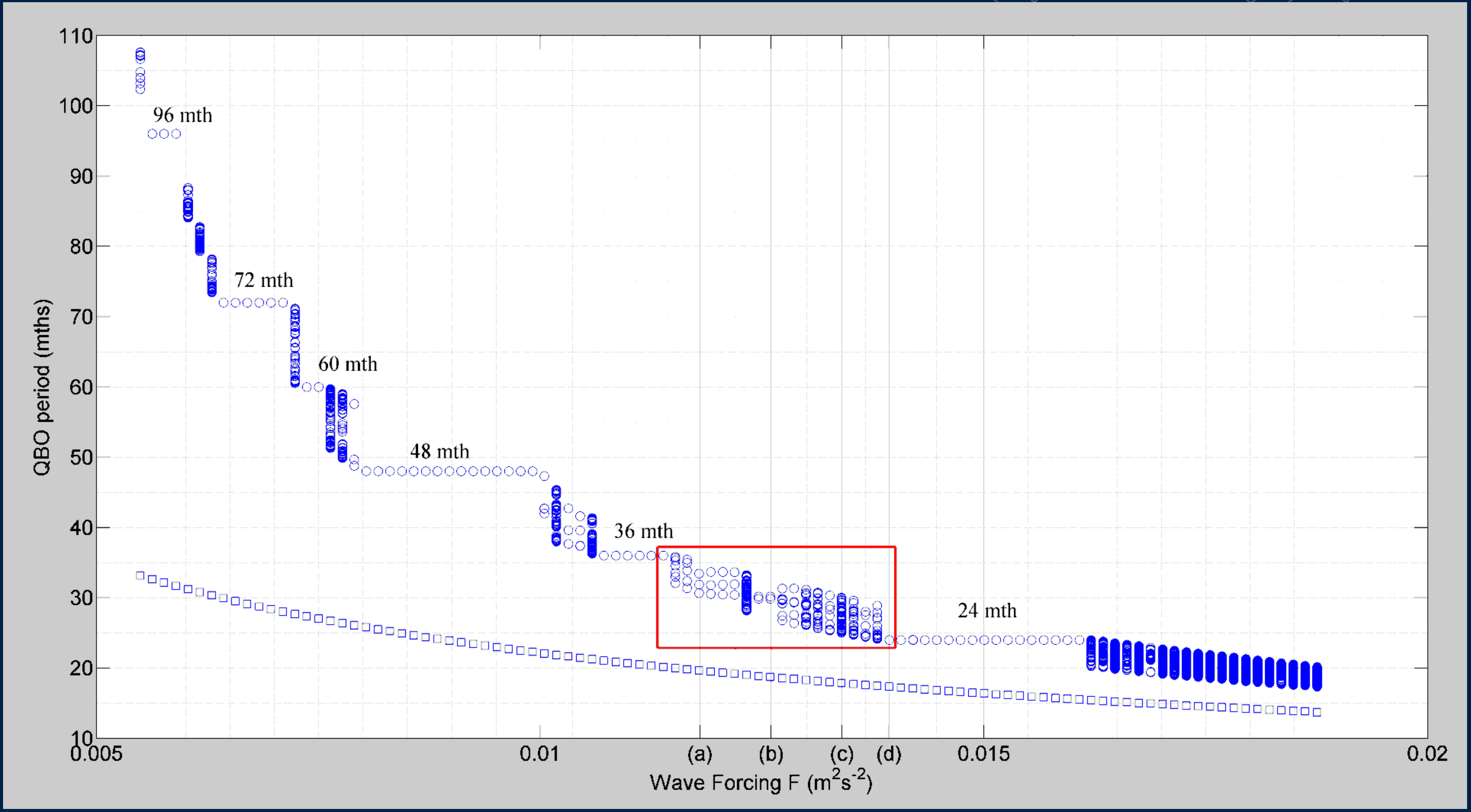



# Result 2: Length of each QBO cycle



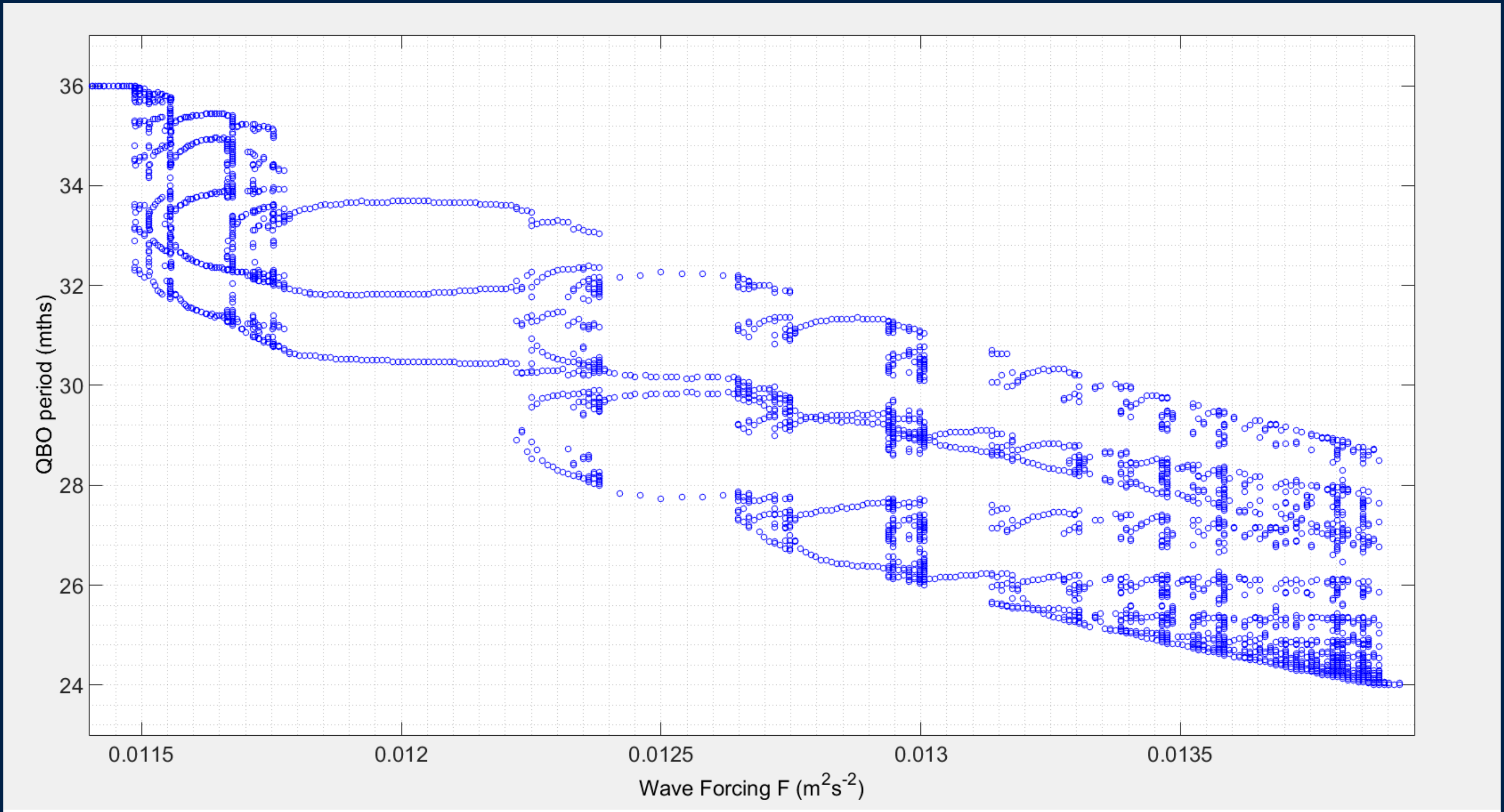



# Result 3: High resolution run

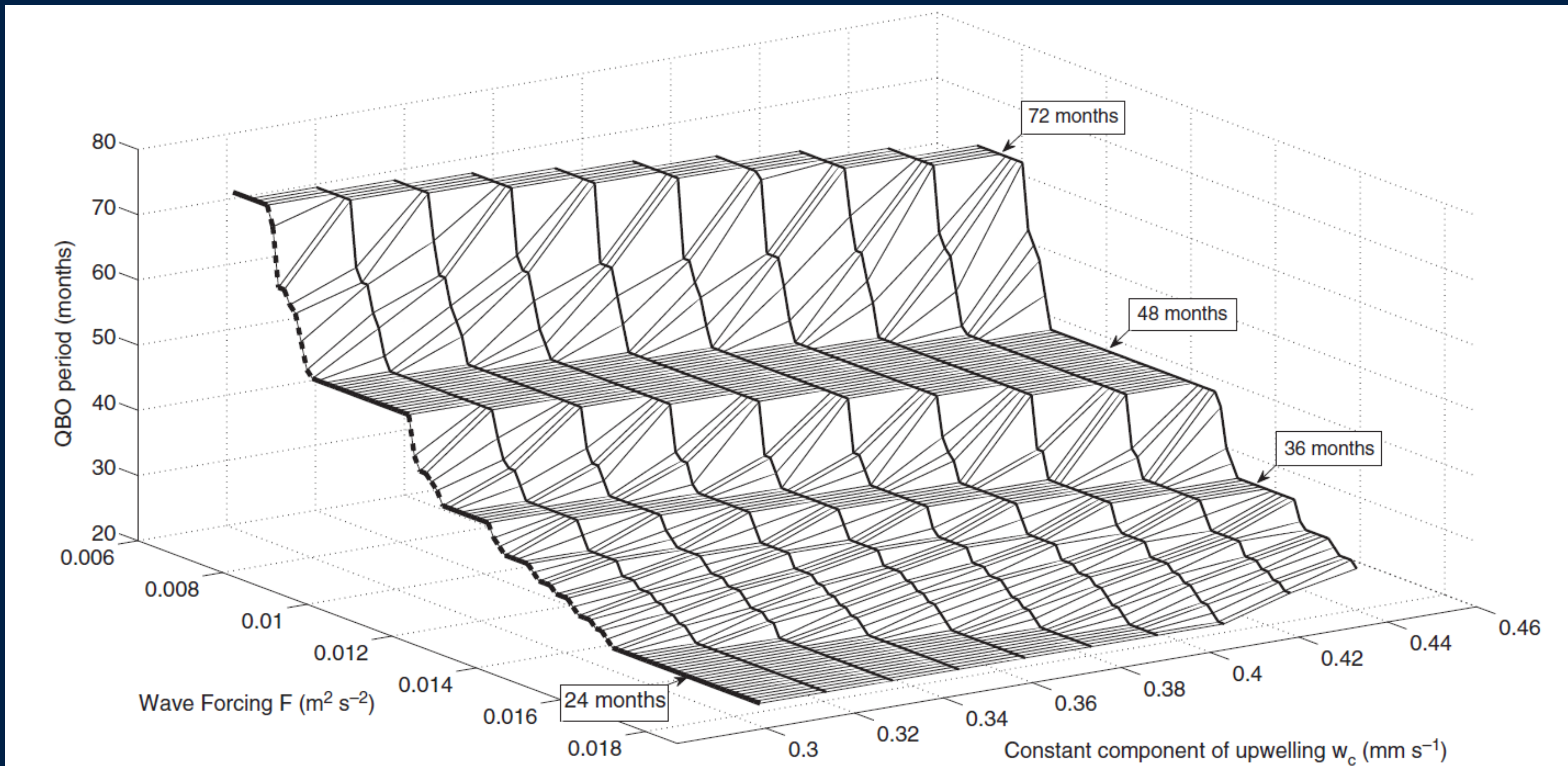



Rerun the section bounded by the red box, using 15 times the usual resolution along the wave forcing axis.

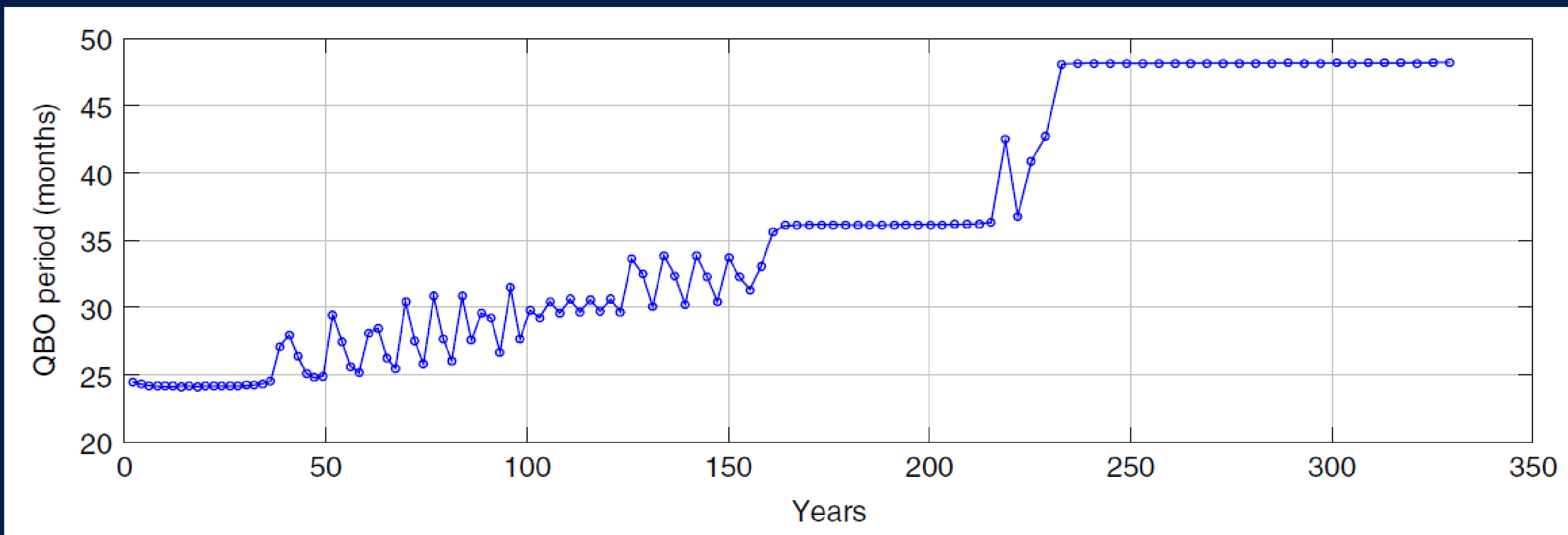
# Result 3: High resolution run



# Result 4: Influence of increasing $w_c$



# Result 5: QBO period evolution in a warming climate




The changing length of individual QBO cycles over a span of ≈330 years as a result of continuously increasing upwelling. Wave forcing is fixed at $F = 14.6\times10^{-3}$ m$^2$ s$^{-2}$, and $w_a = 0.2$mms$^{-}$1. The constant component of upwelling $w_c$ is allowed to change dynamically during the model run, increasing over present-day values at a rate of 3% per decade.

# Summary

We study the response of the QBO period to the annual cycle in tropical upwelling, using a simple 1d model.

The imposition of tropical upwelling causes the QBO period to increase, and the annual cycle of upwelling induces regions of synchronisation in the QBO.

The cycle-to-cycle change of the QBO period can be quite dramatic, with the sum of QBO cycle lengths often (though not always) summing to an integer multiple of the forcing period.

The sequence of cycle lengths can be quite sensitive to the value of the wave forcing (implications for predictability?)

In the context of a warming climate, the model QBO period tends to increase in an unsteady manner, jumping through several cycles and passing through locking regions.

Rajendran, Kylash, et al. "Synchronisation of the equatorial QBO by the annual cycle in tropical upwelling in a warming climate."
*Quarterly Journal of the Royal Meteorological Society* (2015).

# References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Holton, James R., and Richard S. Lindzen. "An updated theory for the quasi-biennial cycle of the tropical stratosphere." *Journal of the Atmospheric Sciences* 29.6 (1972): 1076-1080.

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Kawatani, Yoshio, and Kevin Hamilton. "Weakened stratospheric quasibiennial oscillation driven by increased tropical mean upwelling." *Nature* 497.7450 (2013): 478-481.

Anstey, James A., and Theodore G. Shepherd. "High-latitude influence of the quasi-biennial oscillation." *Quarterly Journal of the Royal Meteorological Society* 140.678 (2014): 1-21.

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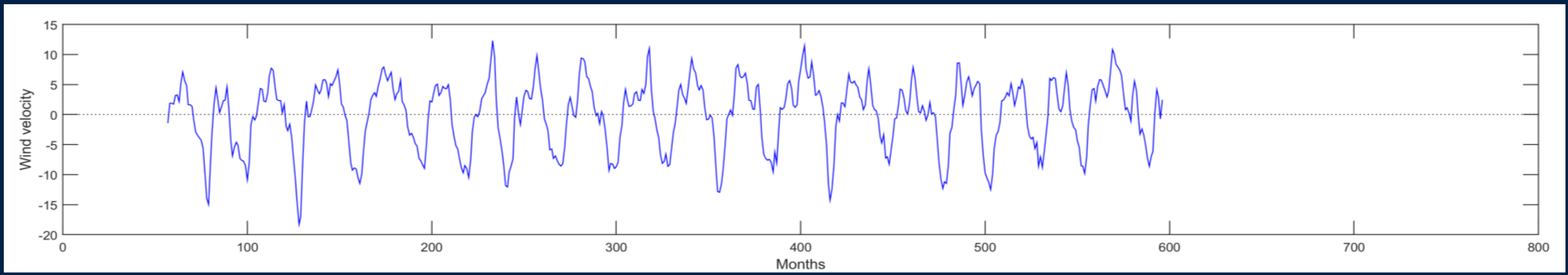
# Reanalysis: ERA-40, 1957 – 2002




| Westerly onset period (mths) | | | | Row Sum |
|---|---|---|---|---|
| 24, | | | | 24 |
| 24, | | | | 24 |
| 26, | 34, | | | 60 |
| 33, | 27, | | | 60 |
| 19, | 29, | | | 48 |
| 30, | 29, | | | 59 |
| 28, | 28, | 31, | 33, | 120 |
| 30, | 26, | 26, | | 82 |
| 22, | 35, | | | 57 |

- The sum of each row is within two months of a multiple of 12, (except for the last row).

- There is some ambiguity in the choice of onset month