The momentum budget of the QBO in WACCM

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a few model details

- Simulations use **WACCM-5** at 1° horizontal resolution and 110 vertical levels
- NB: model top is 140 km; resolution vs. altitude are shown below only up to 60 km

- Tropical GW are parameterized by the Beres convective scheme (Beres et al., *JAS*, 2005): Spectral properties depend on the depth and intensity of convective heating in WACCM
$U_{eq}(t)$: WACCM vs. FU Berlin data

- Excellent agreement in most respects
- Observed period = 28 months (1952-2016); simulated period = 27.5 months (1980-2010)
- West phase slightly too strong compared to observations (Singapore radiosondes)
$U_{eq}(t,z)$ (contours) vs. wave forcing (color)

- parameterized GW drag and $\text{div}(F)$ contribute comparably to both east and west phases, esp. below 30 km
- easterly and westerly forcing are concentrated along the respective vertical shear zones
- accelerations are of order $1 \text{ m s}^{-1} \text{ day}^{-1}$

Monthly means averaged over $\pm 2^\circ$ shown over one decade (1990-2000)
\( \text{div}(F)_k \) acceleration (m s\(^{-1}\) day\(^{-1}\)) (color)

- Fourier decomposition of \( \text{div}(F) \) in wavenumber, \( k = 0-15 \)
- 30-day running means
- shown for the decade 1990-2000, averaged over ±2°

- planetary scale waves, \( k = 1-4 \), provide nearly all westerly forcing
- smaller-scale waves, \( k > 4 \), provide nearly all easterly forcing

look in detail at one west phase and one east phase
Forcing due to $\text{div}(\mathbf{F})$ and GW drag is positive (westerly)

Total forcing is smoother in latitude than either $\text{div}(\mathbf{F})$ or GW drag alone (compensation; Cohen et al., 2013, 2014)

Total forcing is about 1 m s$^{-1}$ day$^{-1}$; $\text{div}(\mathbf{F})$ and GW drag are each $\sim 1/2$ of the total

take a closer look at $\text{div}(\mathbf{F})$
\[ \text{div}(F)_k \ (\text{m s}^{-1} \text{ day}^{-1}) : \text{west phase (color)} \]

October 1995 monthly mean; \( U \) contours superimposed

- as noted earlier, \( k = 1-4 \) provide most of the \( \text{div}(F) \) in the descending westerly phase (especially within ±5° of the Equator)

what waves are involved?
**equatorial spectrum (±2°), west phase**

- Power at the Equator is dominated by eastward-traveling $u'$ component
- relatively little power in $v'$ (note much smaller scale on right panel)
- consistent with Kelvin waves

WAWG 2017
wave structure: west phase

\(k = 1\), eastward traveling component (color)
contours of \(U\) superimposed, October 1995

- symmetric structure in \(u'\)
- small \(v'\) (not shown)
- similar for \(k = 2, 3, 4, \ldots\)
- \(\rightarrow\) Kelvin waves
- \(c \sim 30\) m s\(^{-1}\)
descending east phase: October 1996

monthly mean accelerations (color); $U$ contours superimposed

- GW drag is negative (easterly)
- note again the tendency for compensation of $\text{div}(\mathbf{F})$ and GW drag
- $\text{div}(\mathbf{F})$ is negative near the Equator but positive beyond about ±5°
div($\mathbf{F}$)$_k$ (m s$^{-1}$ day$^{-1}$): east phase (color)

October 1996; $U$ contours superimposed

- $k > 4$ provide over 80% of the total div($\mathbf{F}$) in the descending easterly phase, on and off the Equator

what kind of waves?
Equatorial spectrum($\pm$2°), east phase

- Comparable power in $u'$ and $v'$ components
- Note high wavenumber, westward traveling (easterly) waves, especially $k = 8$ in this particular example (in general, there is power over a broad range of westward wavenumbers)
- Location in the spectrum is consistent with RG waves

look at structure of $k=8$
wave structure: east phase

-k = 8, westward traveling component (color)
-contours of $U$ superimposed, October 1996

-antisymmetric structure in $u'$ symmetric in $v'$ \(\rightarrow\) RG waves
-\(f \sim 0.1\) cpd westward \(\rightarrow\) \(c \sim -5\) m s\(^{-1}\)
-note “pancake” structures centered atop westerly jet, suggestive of instability

what kind?
east phase: barotropic instability

- the criterion for barotropic instability,
  
  \[ \frac{\partial \zeta}{\partial y} < 0, \quad \zeta = (f - \overline{U}_y) \]

  is met over a narrow range of latitude centered near ±10° (negative contours)

- div(F) decelerates \( \overline{U} \) at the Equator and accelerates it at ±10°

- this acts to decrease \( \overline{U}_y \) and stabilize the jet

Summary

• high resolution WACCM simulations allow studies of previously inaccessible features of tropical dynamics: model-generated QBO

• the simulated QBO compares well with observations

• resolved $\text{div}(\mathbf{F})$ and parameterized GW play comparable roles

• $\text{div}(\mathbf{F})$ in the descending west phase is due to planetary-scale ($k = 1-4$) Kelvin waves

• $\text{div}(\mathbf{F})$ in the descending east phase is due to smaller-scale ($k > 4$) RG waves, excited by barotropic instability