TITLE: Eddy-Zonal Flow Feedback in the Southern Hemisphere

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Reasons for Review:

- The leading EOF of the zonal-mean zonal wind represents north-south movement of the midlatitude jet.
- Positive feedback between zonal-mean wind anomalies and eddy-momentum fluxes.
- EOF2 describes strengthening/weakening of the midlatitude jet, but has no feedback associated with it

Abbreviations/Symbols:

- ML Mid-Latitude
- N/S North/South
- ST Subtropical
- T Temperature

Data Details:

- NCEP Reanalysis
- 10-day cutoff Lanczos filter
- EOF analysis

Notes:

- Structure of the dominant mode of interannual variability of the zonal-mean wind is an equivalent barotropic dipole with maximum anomalies at 40°S and 60°S
    - N/S fluctuations in the jet around 50°S
    - Also true for daily, 10-day low-pass, and monthly mean

    - Observed in every season
- Zonal Index
    - Describes where the jet is located with respect to its mean position
    - "high index state" when jet is poleward of mean position
    - Same phenomenon as the leading mode of geopotential height on a constant pressure surface
        - Karoly (1990)
    - Found in quasigeostrophic and primitive equation models
    - Mean-wind-eddy feedback increases the persistence and low-frequency variance of zonal index
    - Eddy momentum fluxes cause a poleward propagation in the zonal-mean wind anomalies.
        - Feldstein (1998)

- Annual Mean Wind
    - Different dynamical processes govern the ST and ML jets
    - ST Jet (30°S)
        - Stronger than ML jet in July
        - Almost nonexistent in January
        - Observed at 200 mb
        - Not visible at 850 mb
        - Driven by differential heating between the tropics and ST
        - Pressure gradient forces air poleward at upper levels and equatorward at lower levels
        - The Result → westerlies at upper levels and easterlies at lower levels
            - Due to Coriolis
        - Jet is strong in winter (sharper T gradient) and weak in summer
    - ML Jet (50°S)
        - Persistent in strength and location through the year
        - Extends throughout troposphere
        - Eddies transport westerly momentum from ST upper levels to ML lower levels
        - Eddy activity is caused by baroclinic instability
            - Instability associated with T gradient
        - In Southern Hemisphere, relatively constant SSTs maintain T gradient
            - Seasonal cycle is small
            - Most of variability is due to internal atmospheric processes

- Zonal Wind-Eddy Feedback
    - Leading EOF

        - Explains 36% of variance
        - Barotropic dipole
        - Represents N/S fluctuations in ML jet
    - Eddies converge vertically averaged eddy momentum flux to influence zonal-mean wind:

$$\frac{\partial\langle[u]\rangle}{\partial t} = -\frac{1}{cos^2\varphi}\frac{\partial\left(\langle[u'v']\rangle cos^2\varphi\right)}{a\partial\varphi} - F \qquad (1)$$

    - How are the zonal index *z(t)* and the eddy forcing of the zonal index *m(t)* related?

$$\frac{dz}{dt} = m - \frac{z}{\tau} \qquad (2)$$

        - Phase relationship between eddy forcing and zonal wind constrained my momentum conservation.
        - High coherence squared → good approx.
        - *z(t)* and *m(t)* have a phase difference of 90° that approaches 0 at low frequencies
        - Zonal-mean momentum fluxes at high or low zonal index state will show reinforcing momentum fluxes.
        - Eddy forcing always leads zonal wind by 0° to 90°
        - *z(t)* is a much lower frequency than *m(t)*
        - Strongest correlations between *z(t)* and *m(t)* occur at short lags when *m(t)* leads *z(t)* (eddy forcing leads zonal wind).
        - Positive feedback is deduced by nonzero correlations at large (negative) lags
    - Feedback from observations
        - *Do the correlations at large positive lags in Fig. 5 result from intrinsic eddy variability or do they result from a positive zonal wind-eddy feedback?*
        - Synoptic-eddies consist of high frequency variations in *u'* and *v'*, yet their forcing is strongest at the lowest frequencies
            - Indicates a forcing by zonal-mean wind back on total eddy forcing

- Simple Model of Feedback
    - Define an equation that is independent of the feedback:

$$m = \widetilde{m} + bz \qquad (3)$$

$$\frac{d\tilde{z}}{dt} = \widetilde{m} - \frac{\tilde{z}}{\tau} \quad (4)$$

- $\tilde{z}$ represents zonal index without feedback
- $\widetilde{m}$ represents random eddy forcing independent of zonal wind anomalies
- *b* measures the strength of the feedback
  - If *b=0*, then zonal-mean wind does not communicate back to the eddy forcing
  - *b* = 0.0354 day^{-1}

- Feedback increased variance of *z* and *m* at lowest frequencies
- The feedback has a small effect on eddy forcing variability
  - Most of variability in *m* is at higher frequencies
- Seasonality of the feedback
  - Stronger feedback in winter than in summer
    - Not sure if this is significant
- Simultaneous regressions are not ideal for diagnosing the effect of zonal-mean wind anomalies on eddies
  - Only 31% of simultaneous eddy momentum forcing anomalies are caused by changes in the zonal-mean flow
  - Most of *m* is caused by $\widetilde{m}$
  - Must look at positive lags greater than a week to diagnose the effect of zonal-mean wind on eddy momentum flux

- Dynamics of the Feedback
  - Isolate part of eddy forcing that is responding to zonal wind anomalies from the burst of eddy forcing that initially created the zonal wind anomalies
    - This is the positive feedback
  - Baroclinic wave generation at the surface follows the N/S movement in the ML jet at upper levels
    - Wave generation follows max ∇T
  - **Wave Growth Rate** = **Meridional T Gradient** divided by **Buoyancy Frequency**
    - Waves propagate upwards and equatorwards
      - Equivalent to poleward momentum fluxes
    - Due to spherical geometry
  - Mechanism for feedback
    - The source of baroclinic wave activity follows the N/S movement of baroclinicity that, by thermal wind, generally corresponds to the latitude of strongest upper-level jet.
    - As wave propagate away, momentum fluxes reinforce jet, which allows for more wave growth

- Much of the variability of eddy activity in independent of zonal-mean flow and starts the entire process
- Direct Effect
  - Anomalies eddy fluxes
- Indirect Effect
  - Eddies on meridional circulation via anomalous friction and diabatic heating
  - Creates low-level baroclinicity
- Residual eddy momentum fluxes act to decay zonal wind anomalies
- Residual eddies are mostly external Rossby waves
  - Net propagation of Rossby waves into ML jet and momentum fluxes out of the jet
- High index
  - Eddies transport less momentum out of the subtropics
  - Weaker meridional circulation
  - Less subsidence in subtropics
  - Cooler mid-level T in subtropics

- EOF2
  - Strengthening and sharpening of ML jet
  - No wind-eddy feedback
    - Due to the horizontal shear of EOF2 coinciding with the horizontal shear of the time-mean ML jet
      - Not true for EOF1
    - Changes in barotropic shear oppose changed in baroclinicity
    - Horizontal shear weakens baroclinic positive feedback
  - N/S movement is more important than strengthening and sharpening
  - Poleward propagation of wind anomalies
    - 20 days after wind maximum, anomalies drift poleward by 10°

- Feedback consists of 2 parts:
  - Positive feedback that projects onto EOF1
    - Unique to EOF1
  - A propagating feedback that is in quadrature with EOF1 and implies poleward propagation of the wind anomalies
    - Witnessed in both EOF1 and EOF2