AFRICAN EASTERLY WAVES IN CURRENT AND FUTURE CLIMATES

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Introduction

Rossby waves and barotropic instability

Easterly waves in current climate

Easterly waves in future climate

Easterly waves in idealized simulations

Conclusion
Westward propagating wave disturbances observed in West Africa that occur from instabilities of the African Easterly Jet (AEJ)

- Period: 3-5 days
- Wavelength: 2500-3500 kilometers
- Identified from meridional winds at 850hPa

Occurs during the African monsoon season (summer/early autumn)

Could bring an increase of rainfall and potentially trigger tropical storms/hurricanes in the Atlantic
Introduction: Rossby Waves

- Large scale, planetary waves that occur as a result of the rotation of the Earth (Coriolis Force)
  - Westward propagating
  - Propagate along a circle of latitude
  - Absolute vorticity conservation

- Generation mechanism
  - Large scale thermal and topographic forcing
  - Barotropic instabilities (Perturbations in pressure field -2D)
  - Baroclinic instabilities (Perturbations in both temperature and pressure field -3D)
The beta-plane approximation: the sphere is approximated by the tangent plane at a latitude $\phi_0$. The Coriolis parameter is:

$$f = 2\Omega \sin \phi \approx 2\Omega \sin \phi_0 + 2a^{-1}\Omega \cos \phi_0 a(\phi - \phi_0) = f_o + \beta y$$

$\Omega$ and $a$ are the angular velocity and the radius of Earth; $y = a(\phi - \phi_0)$ is the northward distance and $\beta = 2a^{-1}\Omega \cos \phi_0$

In the beta-plane, the barotropic vorticity equation is:

$$\frac{\partial \eta}{\partial t} + u \frac{\partial \eta}{\partial x} + v \frac{\partial \eta}{\partial y} + \beta v = 0$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$\eta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$ is vorticity
If we let $u = U(y) + u'(x, y, t)$, $v = v'(x, y, t)$ and $\eta = -U_y + \eta'(x, y, t)$, the equation becomes:

$$\frac{\partial \eta'}{\partial t} + U \frac{\partial \eta'}{\partial x} + u' \frac{\partial \eta'}{\partial x} + v' \frac{\partial \eta'}{\partial y} + (\beta - U_{yy}) v' = 0,$$

$$\eta' = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2}$$

where $(u', v') = (-\psi_y, \psi_x)$ and $\psi$ is a streamfunction. Neglect the nonlinear terms, assume a constant basic flow $U$, and use $\psi = Ae^{i(kx+ly-\omega t)}$ where $k$ and $l$ are the wavenumbers; the dispersion relation for Rossby waves can be obtained:

$$c = \frac{\omega}{k} = U - \frac{\beta}{k^2 + l^2}$$

The waves propagate westward with respect to the basic flow.
Barotropic Vorticity Equation: Barotropic instability

- In the presence of a shear flow $U = U(y)$, the linearized equation becomes:

$$\left( \frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) \Delta \psi + (\beta - U_{yy}) \frac{\partial \psi}{\partial x} = 0$$

- Letting $\psi = A(y)e^{i(kx-\omega t)}$ where $\omega = \omega_r + i\omega_i$ gives:

$$A_{yy} - k^2 A + \frac{\beta - U_{yy}}{U - c} A = 0$$

- If we multiply by the complex conjugate $A^*$, impose a channeled flow: $\psi(y = -L) = \psi(y = L) = 0$, and integrate we get:
The imaginary part of this equation is:

\[ c_i \int_{-L}^{L} \frac{\beta - U_{yy}}{|U - c|^2} |A|^2 dy = 0 \]

This condition is satisfied if the flow is stable \((c_i = 0)\). If the flow is unstable \((c_i \neq 0)\), then \(\beta - U_{yy}\) must change sign.

Thus, the necessary condition for barotropic instability is

\[ \beta - U_{yy} = 0 \]

somewhere in the domain.
Data and Method

- **Data for Current Climate: 2008-2017**
  - Global Analyses from the National Center for Environmental Prediction (NCEP)
  - Archived at the frequency of 6 hours
  - Available on a $1^\circ \times 1^\circ$ longitude-latitude grid
  - Distributed on 26 pressure levels from 1000 hPa to 10 hPa (30 km)
  - Variables include temperature, zonal and meridional winds, etc.

- **Data for Future Climate: 2090-2099**
  - Projections from the Community Earth System Model (CESM)
  - Participated in phase 5 of the Coupled Model Intercomparison Experiment (CMIP5) and supported the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report
  - Emission scenario: RCP 8.5 greenhouse gas emissions pathway

- **Method**
  - Multi-taper spectral analysis to compute the spectra of AEWs
  - Temporal filter with a Kaiser window to reduce the Gibbs phenomenon.
  - Variances are computed from filtered data between 3 and 5 days.
African Easterly Waves in Current Climate

- Averaged power spectral density from global FNL-GFS/NCEP analyses for the decade 2008-2017. Each spectrum is computed over summer: June-September.
African Easterly Waves in Current Climate

- Averaged Yearly variance of filtered northward wind from global FNL-GFS/NCEP analyses for the decade 2008-2017. The filter employed spans the range between 3 and 5 days.
Power spectral density from global FNL-GFS/NCEP analyses for 2008 (black) and 2015 (blue). Each spectrum is computed over summer: June-September.
Yearly variance of filtered northward wind from global FNL-GFS/NCEP analyses for 2008 (left) and 2015 (right). The filter spans the range between 3 and 5 days.
- Monthly averaged zonal wind from global FNL-GFS/NCEP analyses for July 2008 (right) and July 2015 (left).
- Hovmoller diagram of filtered northward wind from global FNL-GFS/NCEP analyses for 2008 (right) and 2015 (left).
African Easterly Waves in Future Climate

- Power spectral density from global CESM/CMIP5 projections for 2094 (red) and 2099 (black). Each spectrum is computed over summer: June-September.
Yearly variance of filtered northward wind from global CESM/CMIP5 projections for 2094 (left) and 2099 (right). The filter spans the range between 3 and 5 days.
Monthly averaged zonal wind from global CESM/CMIP5 projections for July 2099 (right) and July 2094 (left).
Comparison between Current and Future Climates

- Averaged Power spectral density from FNL-GFS/NCEP: 2008-2017 (blue) and CESM/CMIP5: 2090-2099 (red). Each spectrum is computed over summer: June-September.
Averaged Yearly variance of filtered northward wind from FNL-GFS/NCEP: 2008-2017 (left) and CESM/CMIP5: 2090-2099 (right). The filter spans the range between 3 and 5 days.
Averaged Monthly zonal wind from FNL-GFS/NCEP: 2008-2017 (left) and CESM/CMIP5: 2090-2099 (right).
Easterly Waves in Idealized Simulations

- The jet considered in these simulations has the form:

\[ U = U_0 e^{-y^2/d^2} \]

- Two jets are used with \( U_0 = -8 \text{ ms}^{-1} \) and \( U_0 = -14 \text{ ms}^{-1} \)

- The beta-plane approximation is evaluated at \( \phi_0 = 15^\circ \text{N} \).

- The domain is \(-1000 \text{ km} < x, y < 1000 \text{ km} \) with a grid spacing of \( dx = dy = 10 \text{ km} \).

- The time step is \( \Delta t = 15 \text{ min} \), and the numerical integrations use 10,000 time steps.

- The space differencing employs fourth-order finite difference approximations, and the temporal scheme uses the RK3 method.
Illustration of the northward profiles of the basic flow $U(y)$ (blue) and normalized $\beta - U_{yy}$ (red) for the stronger jet: $-U_o = 14 \text{ ms}^{-1}$
Easterly Waves in Idealized Simulations

- Time series of the maximum northward velocity generated by the stronger jet: $U_o = -14 \text{ ms}^{-1}$ (red) and the weaker jet: $U_o = -8 \text{ ms}^{-1}$ (red)
Hovmoller \((x, t)\) diagram for the northward velocity generated by the weaker jet: \(U_o = -8 \text{ ms}^{-1}\) (left) and the stronger jet: \(U_o = -14 \text{ ms}^{-1}\) (right).
Conclusion

- Strong interannual variability of AEW’s activity identified at 850hPa and 15° N during summer.
- The AEW’s are Rossby waves and are generated by Barotropic and baroclinic instabilities of the AEJ.
- The wave activity is closely related to the intensity of the AEJ.
- Comparison of AEW’s activity between current (2008-2017) and future (2090-2099) climates shows a shift in the averaged spectrum towards low frequencies.
- Idealized simulations using strong and weak jets demonstrate that waves are controlled by barotropic instabilities.

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