Hands-on activities: Rossby waves, barotropic instability, and baroclinic instability

Purdue EAPS 53600 Spring 2020, Prof. Dan Chavas

What is this? Rossby waves and their associated instabilities are difficult theoretical concepts and are taught as such – without walking through a basic mechanistic understanding. You can understand these mechanistic steps – all you need is two pieces of paper and some pens!

Materials:

- A few different colored pencils or pens
- Two pieces of paper, preferably long in one direction and narrow in another (e.g. fold a regular 8.5”x11” piece of paper in half along the long axis)
- Optional: a gray pencil

Activity 1: the Rossby wave

Rossby waves form in the presence of a PV gradient. Can you understand *mechanistically* why they form and move?

1. Take one piece of paper and orient it so the long side runs left to right (landscape). Draw an arrow denoting the Northward direction.
2. Suppose PV increases to the north (positive meridional PV gradient). Draw three contours of constant PV and label them q_1, q_2, q_3 (q3 largest).
3. Draw a new q_2 contour (dashed line) that includes a longwave undulation (so alternating regions displaced north and south). Try to make the wave have a constant wavelength, like a single sine wave. Assume this new contour was created because the original was displaced with PV conserved.
4. Using a different color, mark the sign of the **relative vorticity** you expect within each displaced region. Also draw arrows depicting the fluid flow you expect around these relative vorticity anomalies.
5. Using a different color, draw contours of constant positive (solid) and negative (dashed) streamfunction associated with these anomalies. Note that the magnitudes are arbitrary. (How are streamfunction related to geopotential height in pressure coordinates or pressure in height coordinates?)
6. Using the first color (or a totally new one), draw how the displaced contour would be expected to change with time based on the advection of the contour itself by the north/south portion of the flow field. In what direction does a Rossby wave propagate?
7. Consider everything you just did, but with a southward-pointing PV gradient. How would each step change? In what direction will the Rossby wave propagate?
8. Now generalize: in what direction do Rossby waves propagate relative to the direction of the PV gradient?

Activity 2: Barotropic instability

Barotropic instability is a horizontal (2D) instability that involves the unstable growth (amplification) of two Rossby waves displaced <u>horizontally</u> from one another. Specifically, this instability occurs due to the **mutual amplification of two counter-propagating Rossby waves** that cause both of them to grow unstably at the same time. Note: if these Rossby waves occur at boundaries with a PV discontinuity, they are called Rossby edge waves (Rayleigh problem).

Can you understand *mechanistically* why this mutual amplification occurs? And why, e.g., two Rossby waves moving in the same direction will *not* mutually amplify?

1. Repeat steps 1-5 in Activity 1 on a second piece of paper (you might label the contours q_4, q_5, q_6). This gives you two Rossby waves to play with.
2. Place them flat on the table with the second wave to the north of the first. Move them close enough together that you can imagine the flow of one wave interacting with (i.e. advecting) the other wave contour, and vice versa. Note: it may help to fold either/both pieces of paper.
3. Try keeping one wave stationary while shifting the other to the west/east. Try shifting ¼ wavelength at a time. At each phase shift, stop and examine: how does the north/south flow field affect the *other* wave – would it act to amplify the wave or suppress it? Is this true at all phases? Between both waves? Try using a gray pencil to mark the effects of flow from one wave on the other wave (then you can erase so it doesn't get too messy).
4. Is there a specific phase shift in which the flow field of each wave is acting to amplify the other wave at all phases? How would you characterize this phase shift in terms of PV (e.g. "PV contours tilt westward with X")? How about in terms of streamfunction? Northward flow? Relative vorticity?

<u>Activity 3: Baroclinic instability</u>

Baroclinic instability is fundamentally equivalent to barotropic instability, except that it is a fully-3D process in which the two Rossby waves are displaced <u>vertically</u> from one another rather than horizontally. The waves may be at the surface and tropopause boundaries (Eady problem) or at the surface boundary and in the interior (Charney problem).

Can you understand *mechanistically* how this vertical orientation can also produce this same mutual amplification?

1. Take your two Rossby waves and place one above the other. (One way to do this is to tape the tops of the sheets to a wall above one another, then you can lift the bottoms out from the wall to go between 2D and 3D!)
2. Go through exactly the same steps as Activity 2, only here the anomalous flow field *projects upwards/downwards* from one wave towards the other.
3. Is there a specific phase shift in which the flow field of each wave is acting to amplify the other wave at all phases? How would you characterize this phase shift in terms of PV

(e.g. “PV contours tilt westward with height”)? How about in terms of streamfunction? Northward flow? Relative vorticity?