The counter-propagating Rossby wave perspective on baroclinic instability and its relevance to extra-tropical cyclone life cycle

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The goal of baroclinic instability theory is to predict how wave behaviour changes as the basic state is varied. For example, how might we expect weather system development to change in a future climate scenario? However, simplifications to the basic state and dynamic equations needed to solve the problem analytically also render it difficult to relate the results to the atmosphere. More complex idealised problems can be solved numerically but then it is hard to understand the results from a physical perspective. The gap can be bridged by viewing baroclinic growth in terms of the interaction of pairs of counter-propagating Rossby waves (CRWs). Typically, zonal wind speed is greater aloft and each pair consists of a lower CRW propagating along the ground in the direction of the upper level wind and an upper CRW propagating in the opposite direction aloft. This perspective applies to small amplitude waves described by the primitive equations growing on general zonal jets. The structures of the CRWs can only be found exactly by superposing a growing normal mode and its decaying conjugate, which are obtained numerically. However, once found it is possible to use physical propagation and interaction arguments to predict the evolution of each CRW pair.

The perspective also brings out some surprisingly robust results about baroclinic instability that could not be ascertained directly from the normal modes. If a jet has no surface shear then CRW pairs must approach a phase-locked configuration with a large westward tilt. This is related to the fact that the self-induced phase speed of the upper wave is always slower than that of the lower wave due to its strong propagation relative to the westerly jet. A positive meridional PV gradient within the troposphere is essential to this argument. In life cycle experiments, this predicts correctly that the system slows down as the lower wave saturates nonlinearly through frontogenesis and wave breaking. The dependence of CRW structure on jet shape also determines the direction of normal mode momentum fluxes which influence the modification of the basic state by the wave life cycle.