The air-sea interaction process of tropical cyclones

Paradox

- How to maintain buoyancy in eyewall when a warm-core is developing aloft?
- How to overcome boundary layer cooling due to adiabatic expansion?

The answer

- Heat flux is proportional to $\rho C_D V^2(SST - T_{air})$
- Moisture flux is proportional to $\rho c_p C_D V^2(q_{SST} - q_{air})$
- Fluxes increase as storm intensifies, which mostly balances the adiabatic expansional cooling and also keeps boundary layer nearly saturated
- As long as the surface temperature stays relatively the same, and the boundary layer stays moist for a low LCL, lifting from a lower pressure surface essentially adds buoyancy to the eyewall, compensating against the increasingly warm temperatures aloft. The updraft is maintained in the eyewall.
- The inflow continues to concentrate angular moment in the storm, while the latent heat release and dynamically driven eye subsidence both contribute to a warmer core aloft.
- Winds increase, which also increase fluxes, and the pressure drop indirectly adds buoyancy to counter the warmer environment aloft.
- A nonlinear positive feedback process occurs. When the eye forms, rapid intensification is possible under ideal conditions (low shear, moist environment, deep warm water).
- A Maximum Potential Intensity is ultimately limited by SST. The reason is unknown, but most likely related to diminishing returns in eyewall buoyancy as the warm core develops. However, other theories have been invoked regarding frictional processes.

Holland MPI scheme --- physically based on eyewall temperature constraints on air parcel ascent

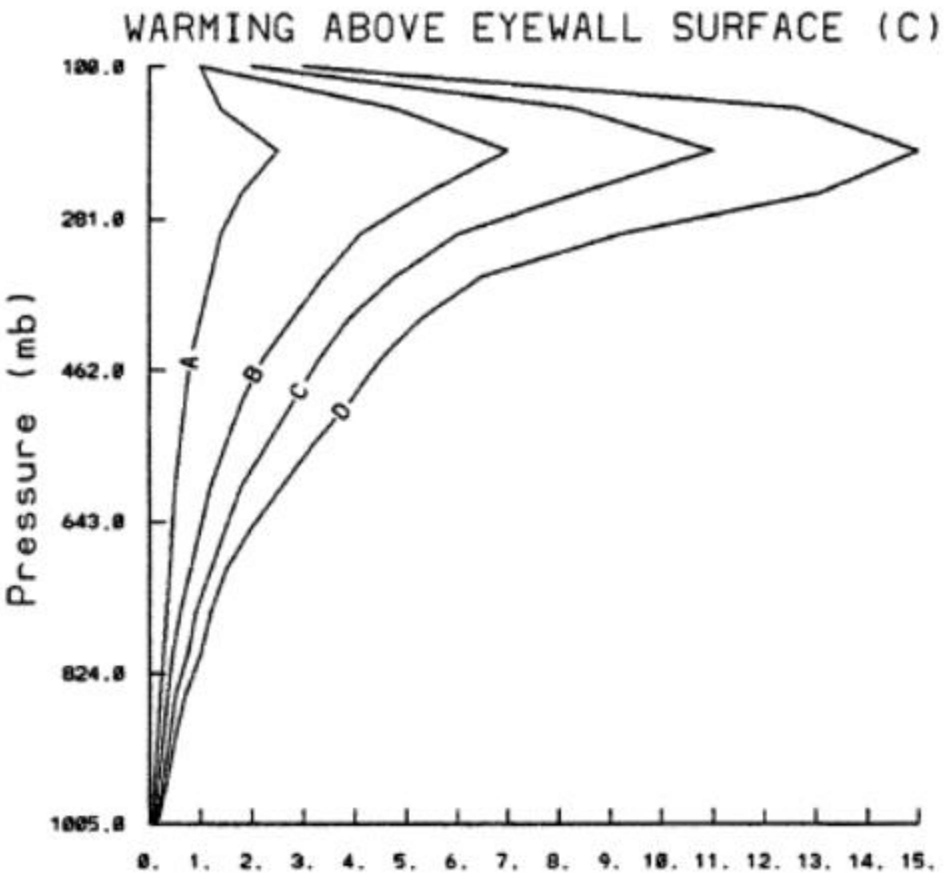


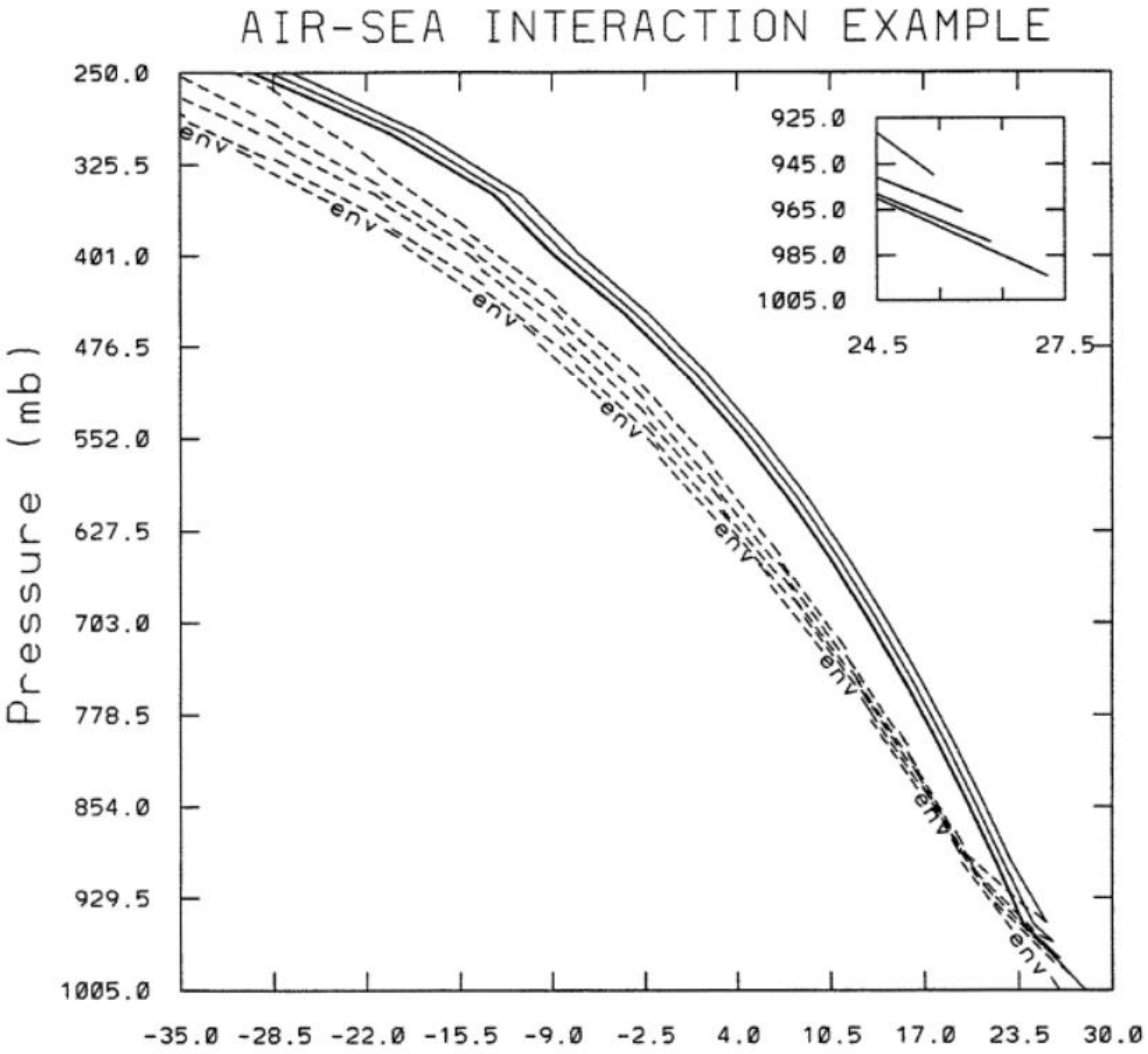
Figure 7.7: Hypothetical development of the eyewall temperature perturbation relative to the western North Pacific mean tropical sounding (Frank 1977b; Gray and Frank 1977). The corresponding surface pressures under the eyewall are 994.3 (A), 979.1 (B), 965.9 (C), and 949.7 mb (D). These temperature profiles represent the TC from its minimal tropical storm stage to its MPI stage.

Note how the moist adiabatic shifts to the right when lifted from lower pressure if adiabatic temperature cooling is compensated by heat fluxes, and RH stays high.

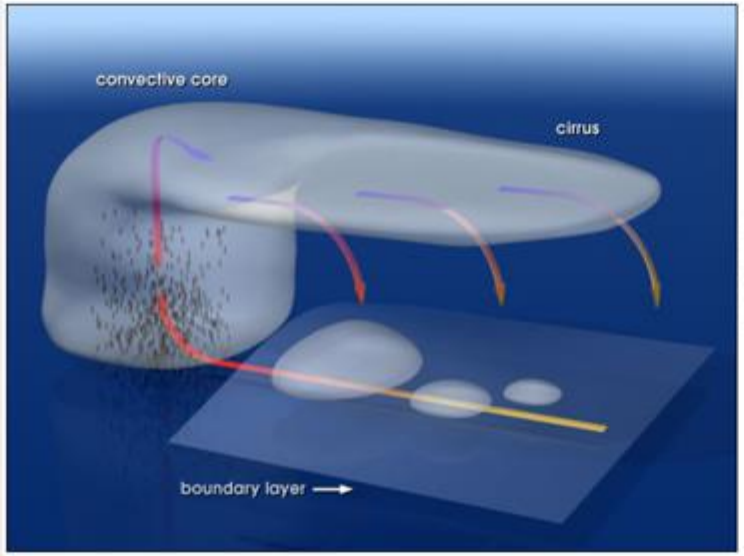
Stated another way, the reduction in pressure for relatively constant RH and temperature adds moist entropy to the system. In other words, θ_e increases.

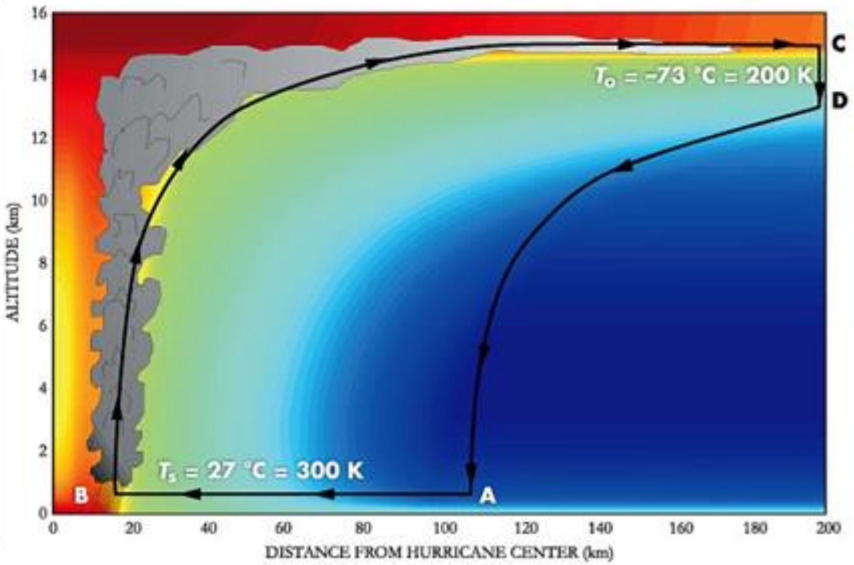
Over cooler water, the heat flux is reduced, and a mature tropical cyclone slowly weakens….sometimes quickly weakens.

Over land, the heat flux and moisture flux are lost. The eyewall collapses. Even a major hurricane will be a tropical depression in 24-36 hours.



Emanuel MPI scheme --- mathematically based on Carnot Engine abstraction





A→B: isothermal expansion as air flows toward lower pressure. Temperature stays constant from flux compensations

B→ C: Adiabatic expansion during ascent

C→ D: Air flow out in isothermal compression

D→ A: Adiabatic compression during descent

There are many questionable mathematical assumptions in branches B→ C, C→ D, and D→ A. But this formulation gives a reasonable MPI because A→ B captures the essence of how a hurricane functions, while the others merely close the system of equations with clever parameterizations.

Branch A→ B mathematically is represented by moist static energy ($h = c_p T + gz + L_V q$). But $h \approx c_p T ln \theta_e$. This branch is the same process as described before, just hidden in murky math and questionable assumptions in the other branches!