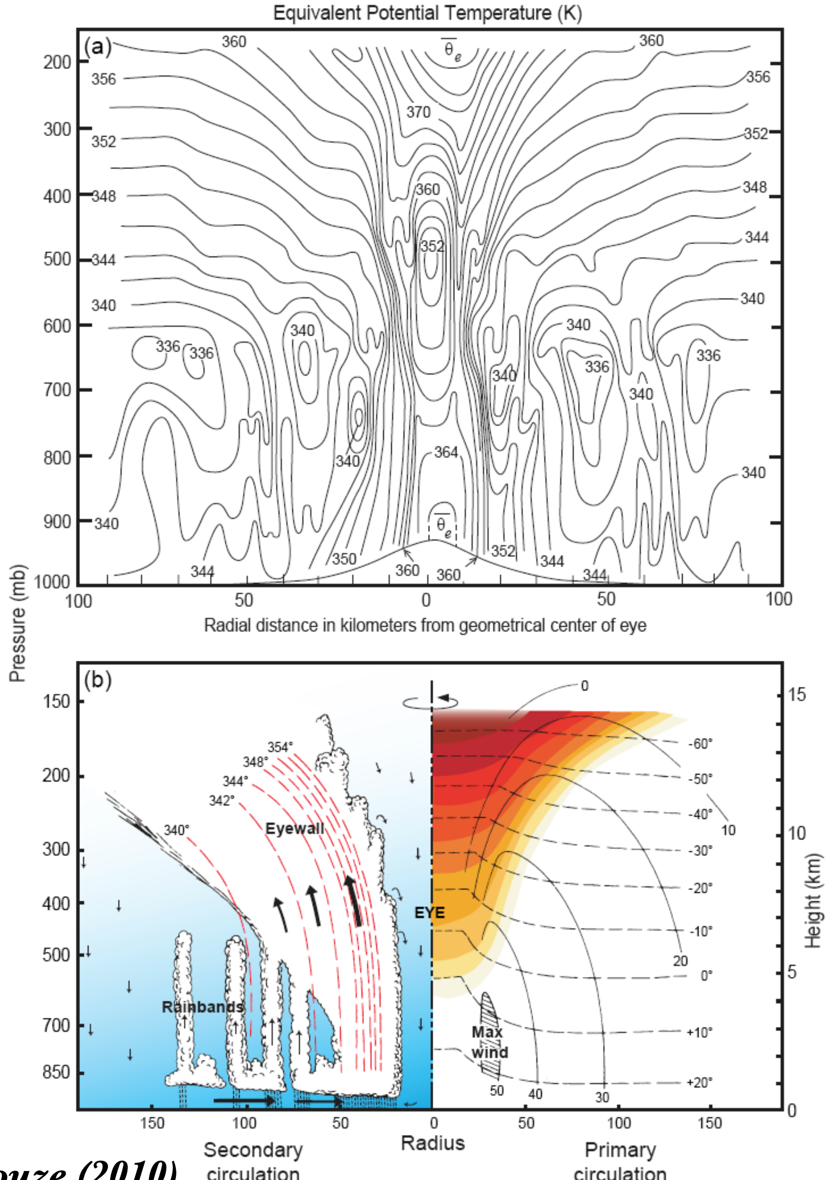
The distribution of Θ_e in TCs

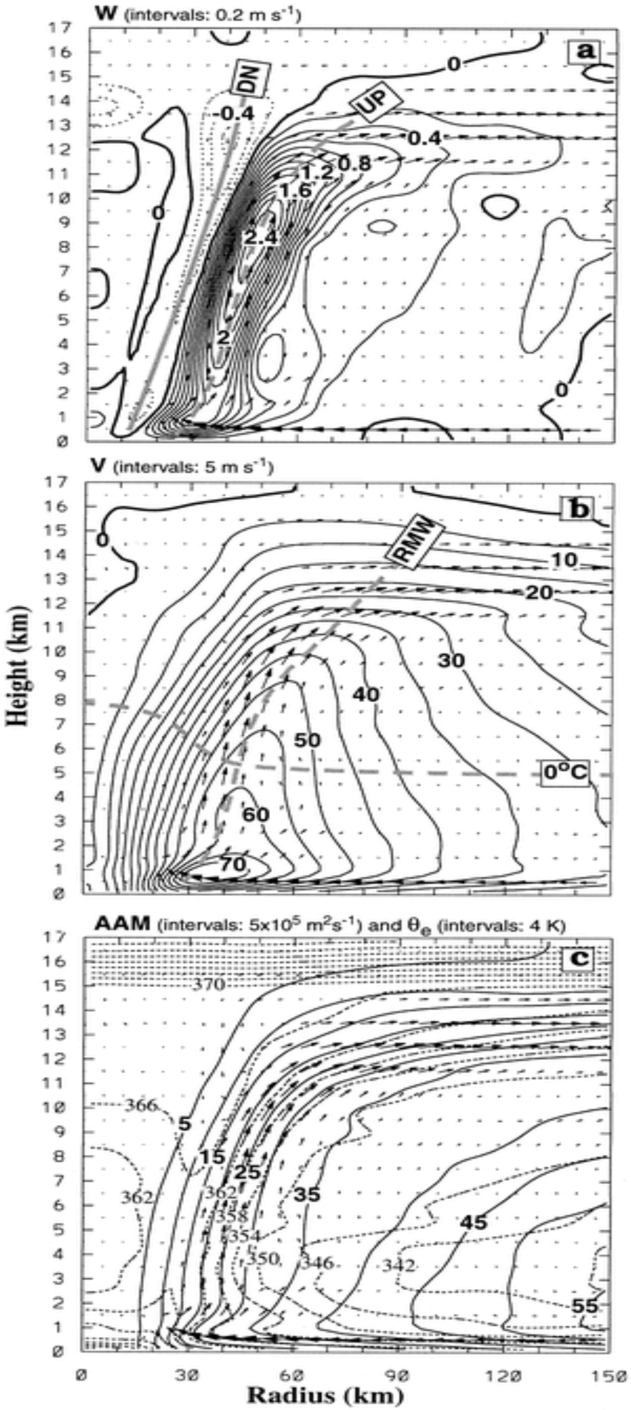


Houze (2010)

Lines of Θ_e look vertical, but are actually *sloped outward with height* in the eyewall.

Outside the core there is a distinct *minimum* in Θ_e at *midlevels*, similar to the *average tropical atmosphere* conditions.

The distribution of Θ_e in TCs

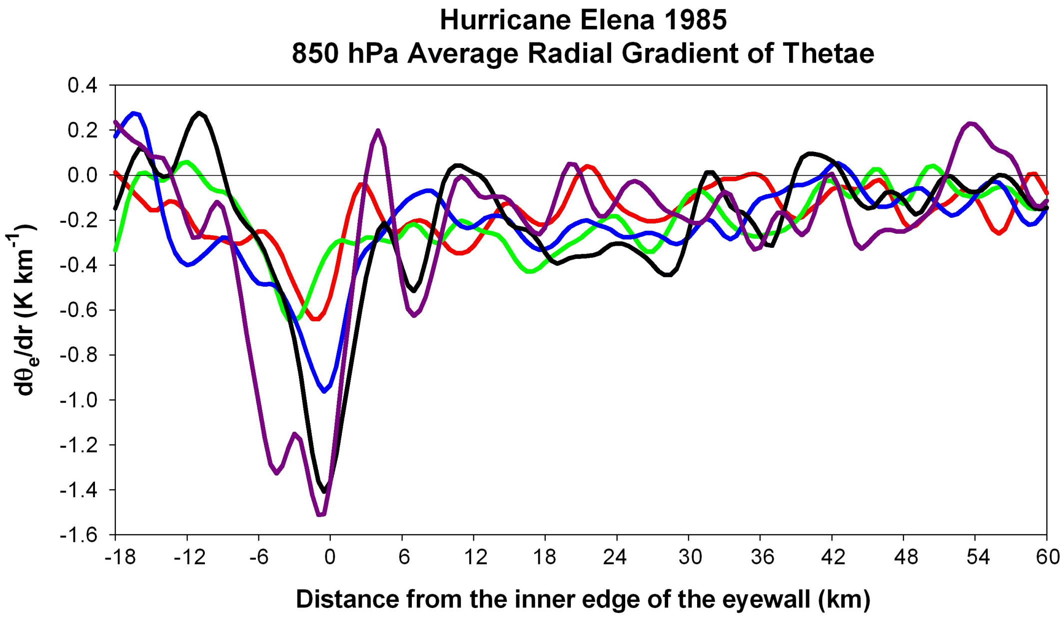


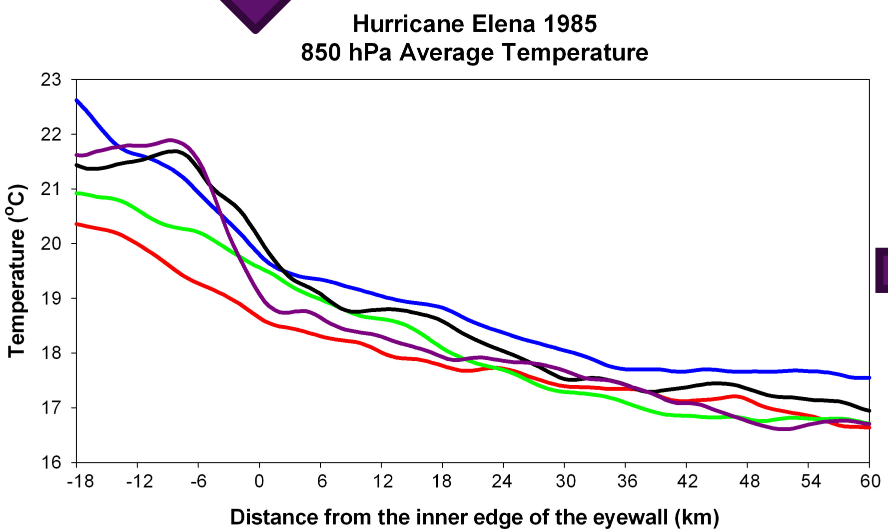
Lines of Θ_e are *sloped outward with height* in the eyewall (just like the *momentum* lines).

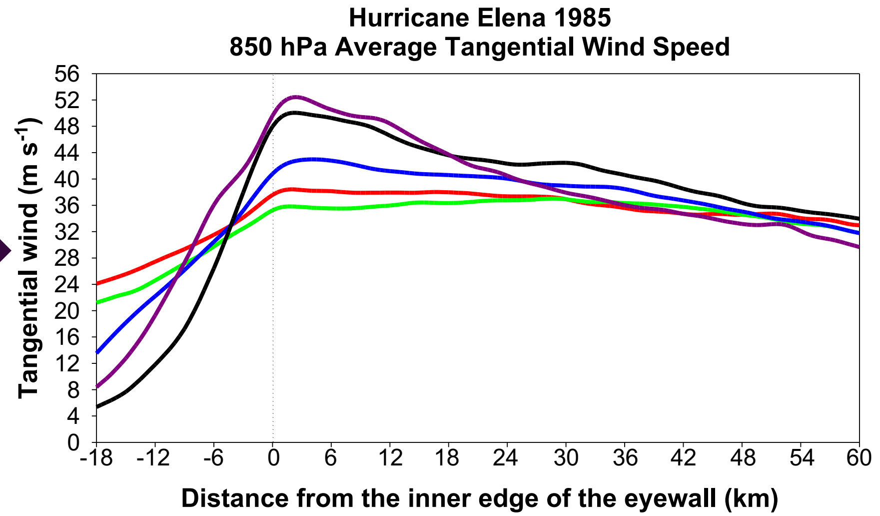
Outside the core the *minimum* in Θ_e at *midlevels is evident*.

Zhang et al.(2020)

Large $d\Theta_e/dr$ is necessary for strong TCs







Review of mature TC dynamics & thermodynamics

1) Cyclonic, convergent flow into a pre-existing disturbance is driven by friction in the boundary layer

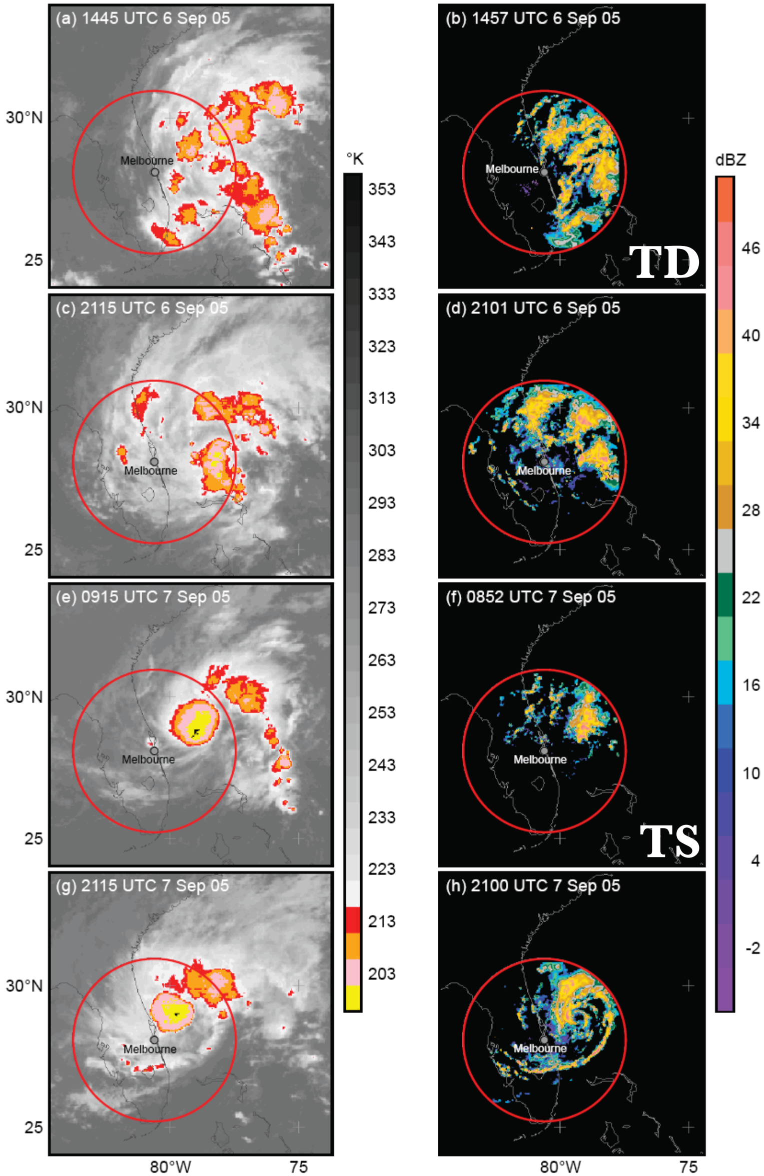
2) Cyclonic outflow near the center aloft turns anticyclonic due to momentum loss at the surface with diabatic outflow extending great distances from the center

3) Deep warm core caused by the lifting of high-Θ_e air in the eyewall and compensating subsidence in the eye

4) Strong radial gradient of Θ_e at the surface due to fluxes, which supports a strong radial gradient of temperature and surface pressure

5) Outward-sloping eyewall (Θ_e and m surfaces) required by thermal wind balance

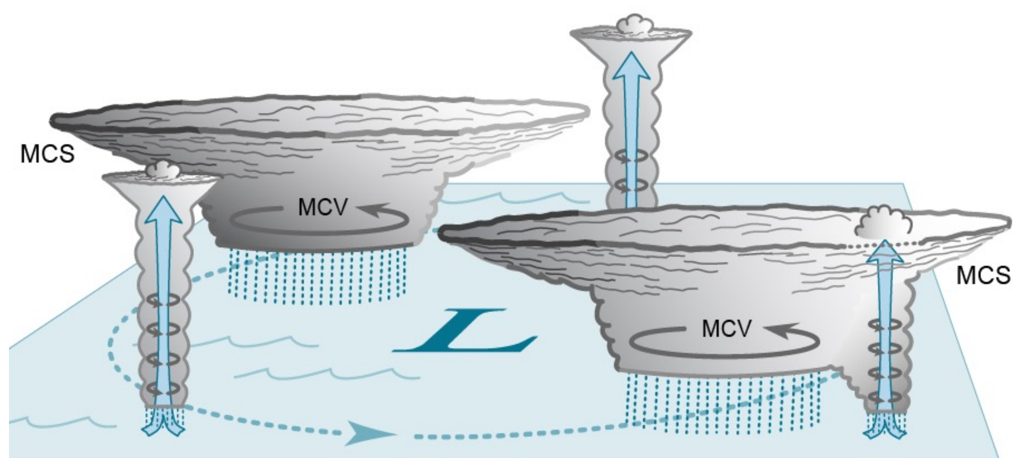
Eradicating the Θ_e minimum for TC genesis



Satellite and radar overview of the genesis of Ophelia

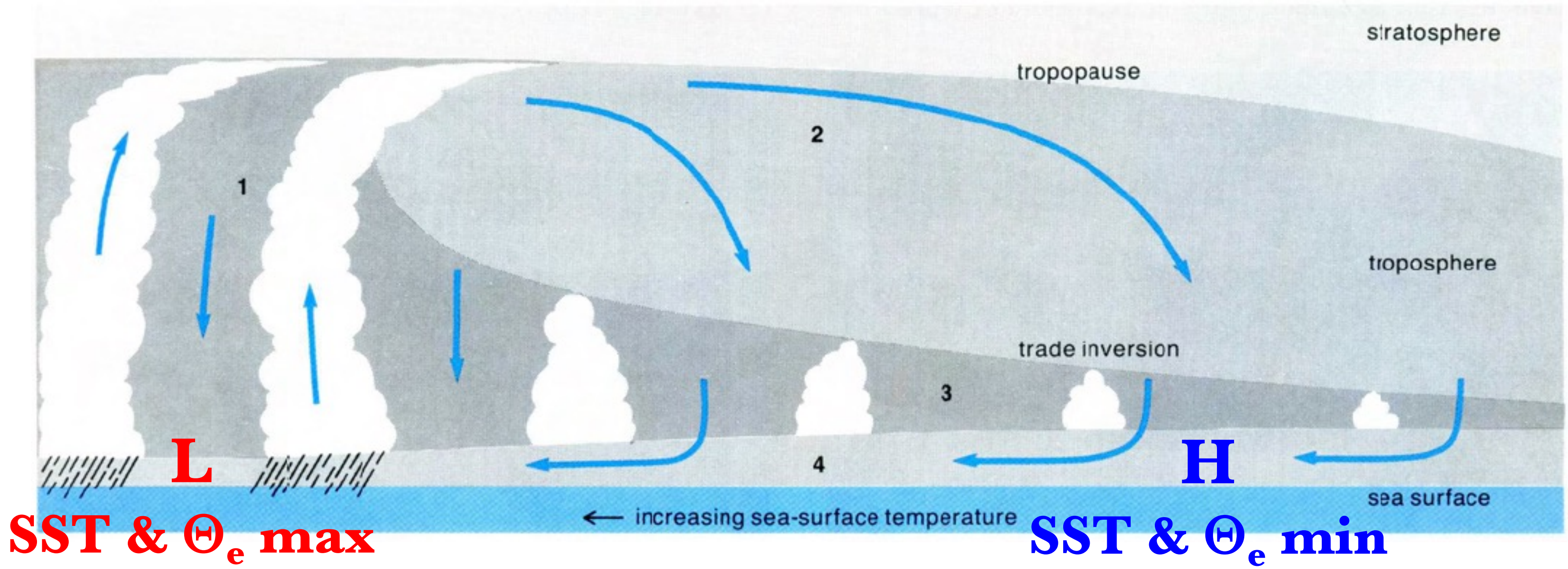
a. Synoptic History

Ophelia formed from a non-tropical weather system. A cold front moved off the eastern coast of the United States on 1 September. The front moved southeastward and became part of an elongated trough of low pressure that extended from Tropical Depression Lee east of Bermuda to near the Florida Peninsula. Two areas of low pressure formed in the trough on 4 September. The eastern low, south of Bermuda, eventually became Hurricane Nate. The western low, near the Bahamas, became Ophelia.



Houze (2010)

Emanuel (1988): Normal state of the tropical maritime environment



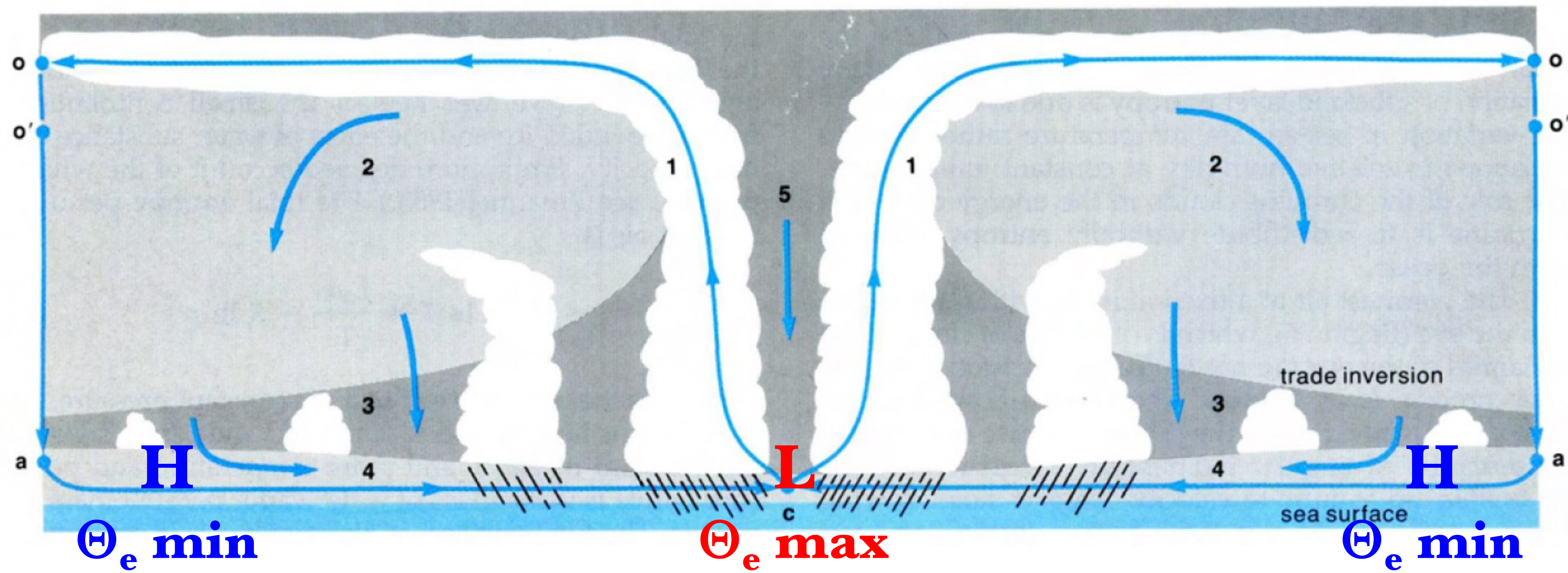
1: **Air ascends in deep cumulus convection**

2: **Air slowly subsides as it cools due to net longwave radiation loss to space**

3: **Trade wind inversion, moistened by trade cumuli**

4: **Increase of Θ_e due to boundary layer fluxes**

WISHE theory for TC development



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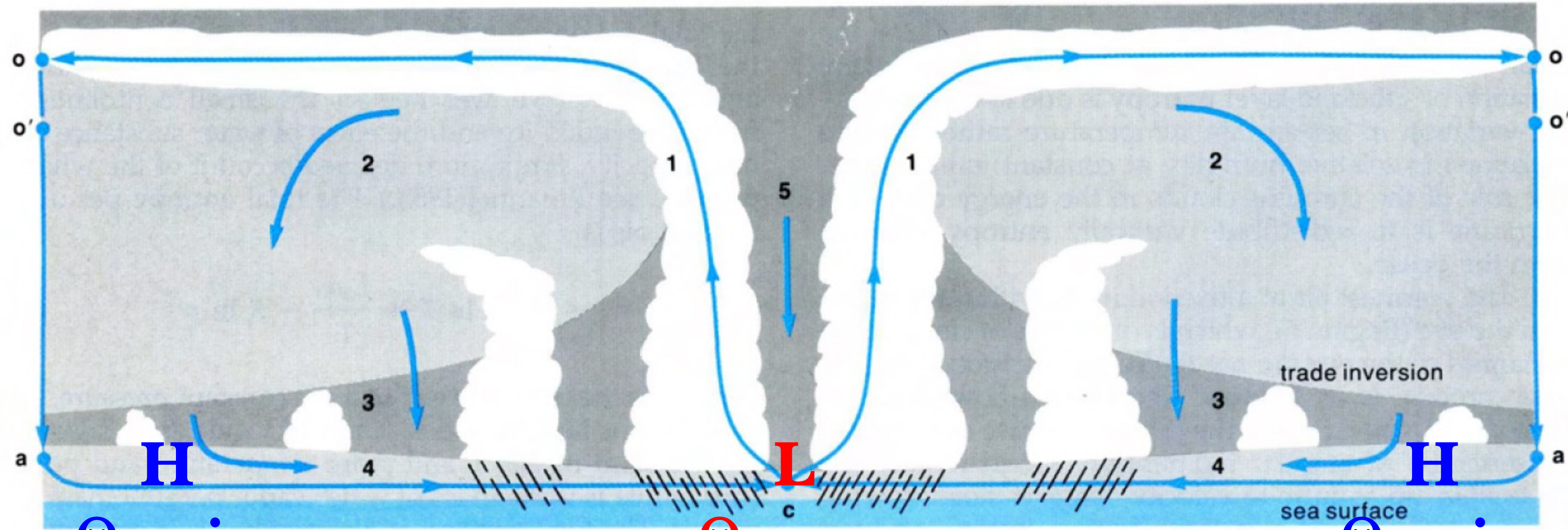
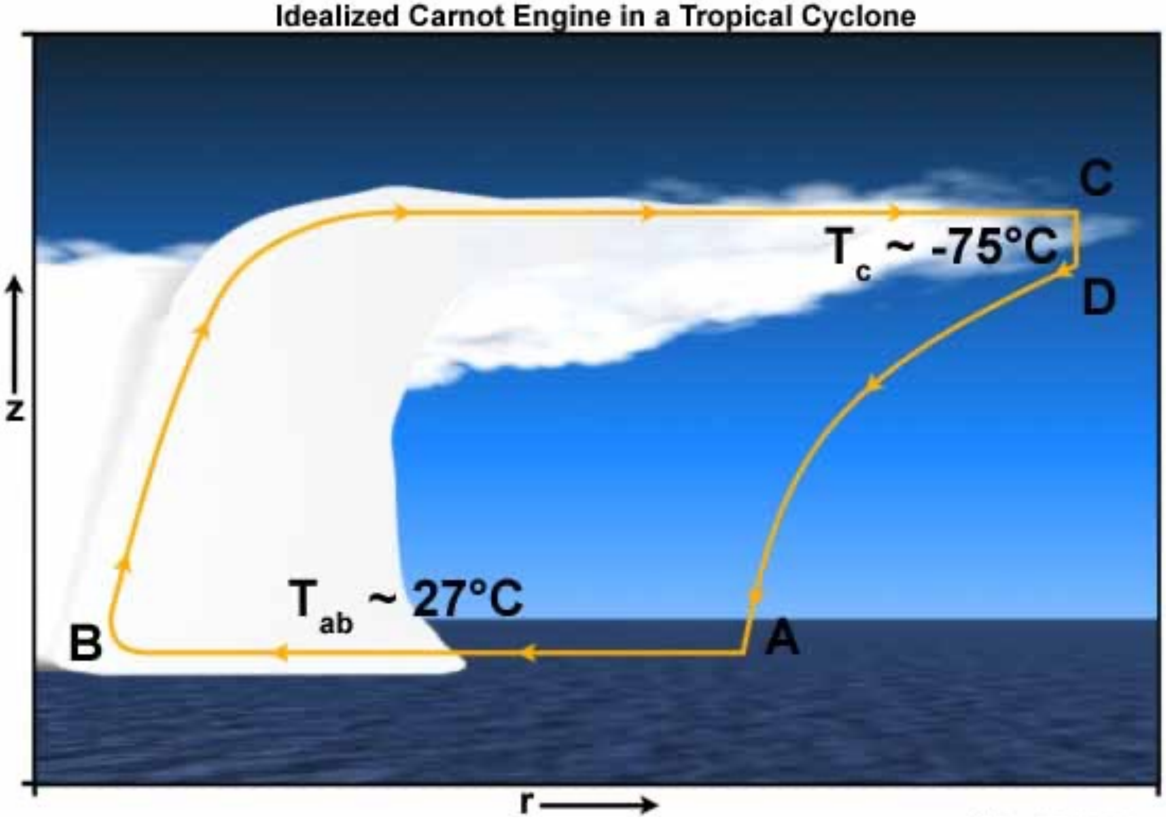


In a TC, versus the large-scale tropics, the *SST* is considered to be *constant*.

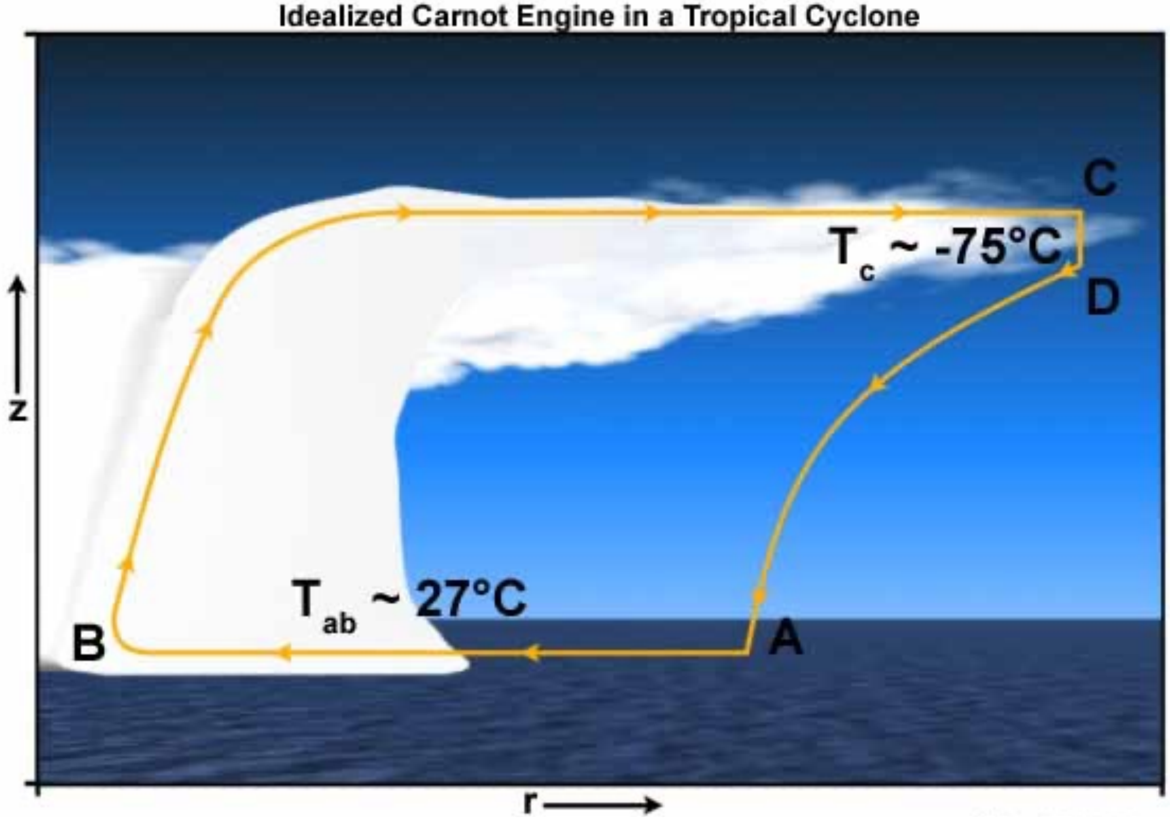
Thus, the increase of Θ_e from point (a) to point (c) is due to *larger* *surface fluxes* due to *faster* *wind speeds* towards the storm *core*.

The TC as a Carnot (heat) engine



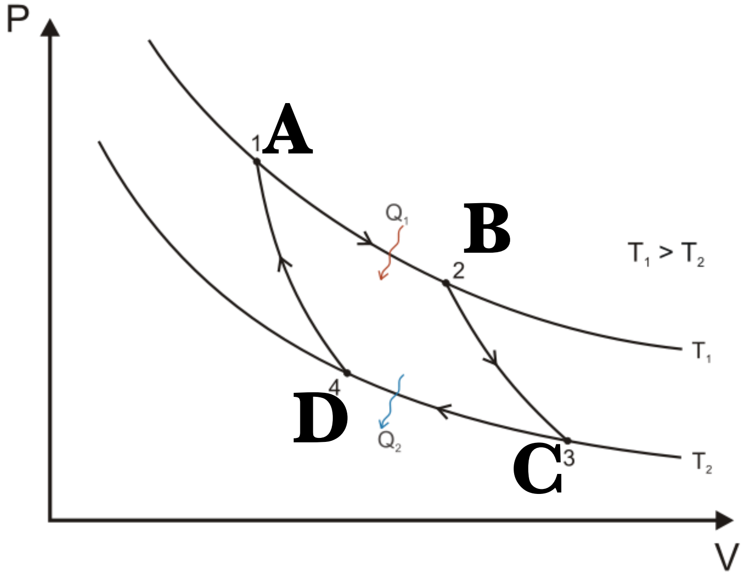
Emanuel (1986) conceptualized a TC as a Carnot (heat) engine, in which *heat energy* (extracted *from* the *ocean*) is *converted into mechanical energy*.

The TC as a Carnot (heat) engine



The *cycle* is composed of two *isothermal* (AB and CD) and two (moist) *adiabatic* (BC and DA) legs.

Emanuel's Carnot cycle & TC heat engine

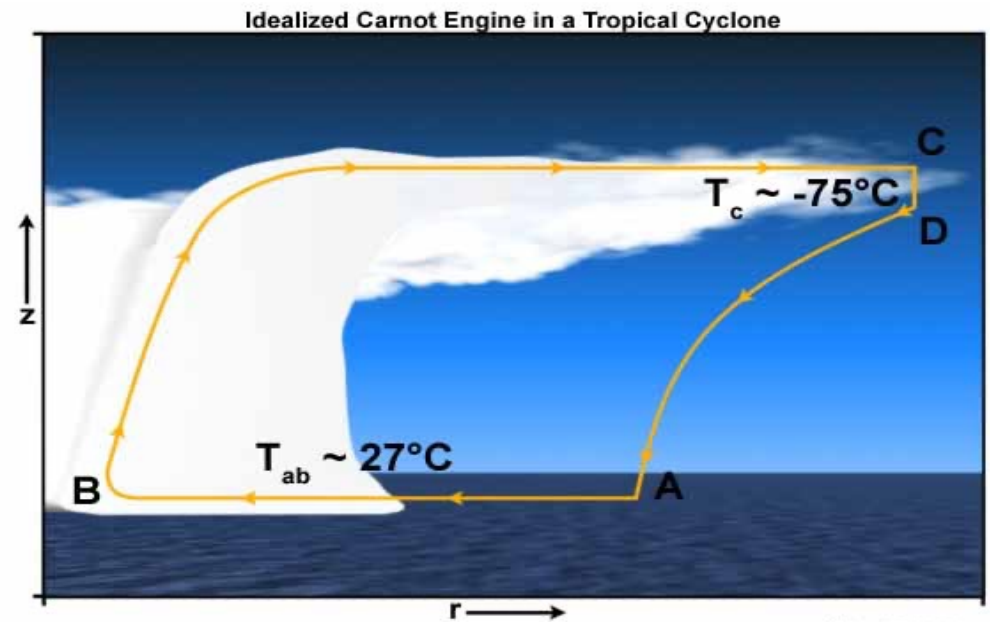


AB Isothermal Expansion (adiabatic and evaporative cooling + heat flux)

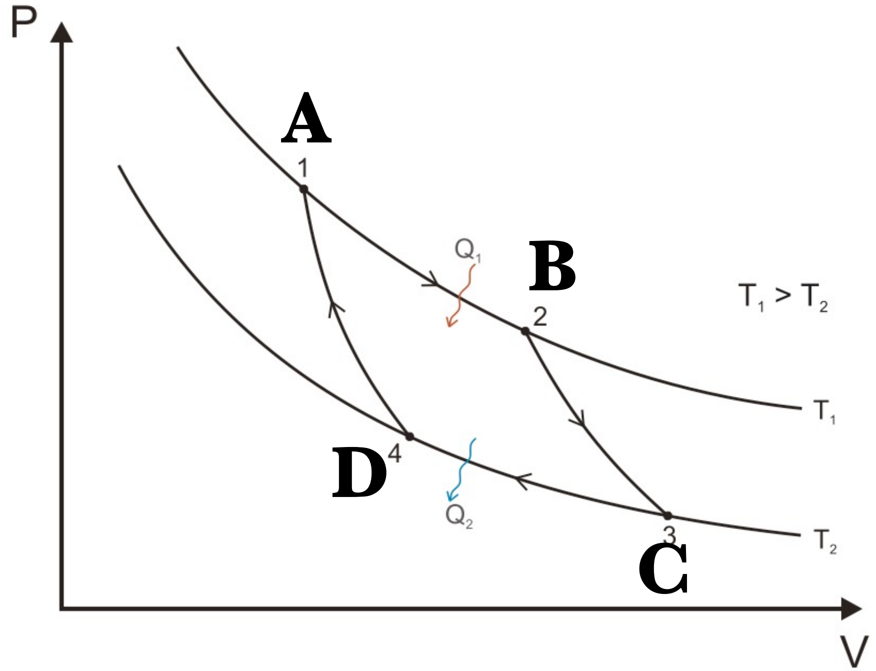
BC Adiabatic Expansion (cooling partially offset by latent heat release)

CD Isothermal Compression (adiabatic warming + radiational cooling)

DA Adiabatic Compression (adiabatic warming)



Work done by the TC heat engine



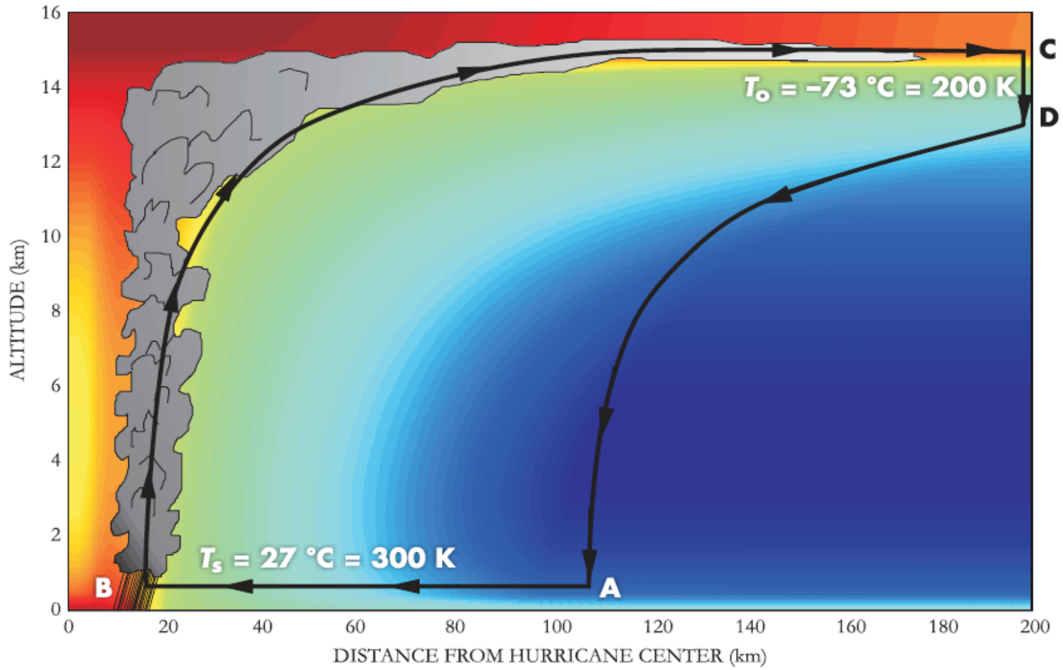
~ The ***work*** **done is** $\delta q = \delta w = Q_1 - |Q_2|$

~ **The *efficiency* (fraction of *heat* that can be *used to do work*) is:**

$$E = \text{Work done} / Q_1 = (Q_1 - |Q_2|) / Q_1$$

~ **The engine has done work by *transferring heat* from a *warmer to* a *cooler body*.**

Fuel for the TC heat engine



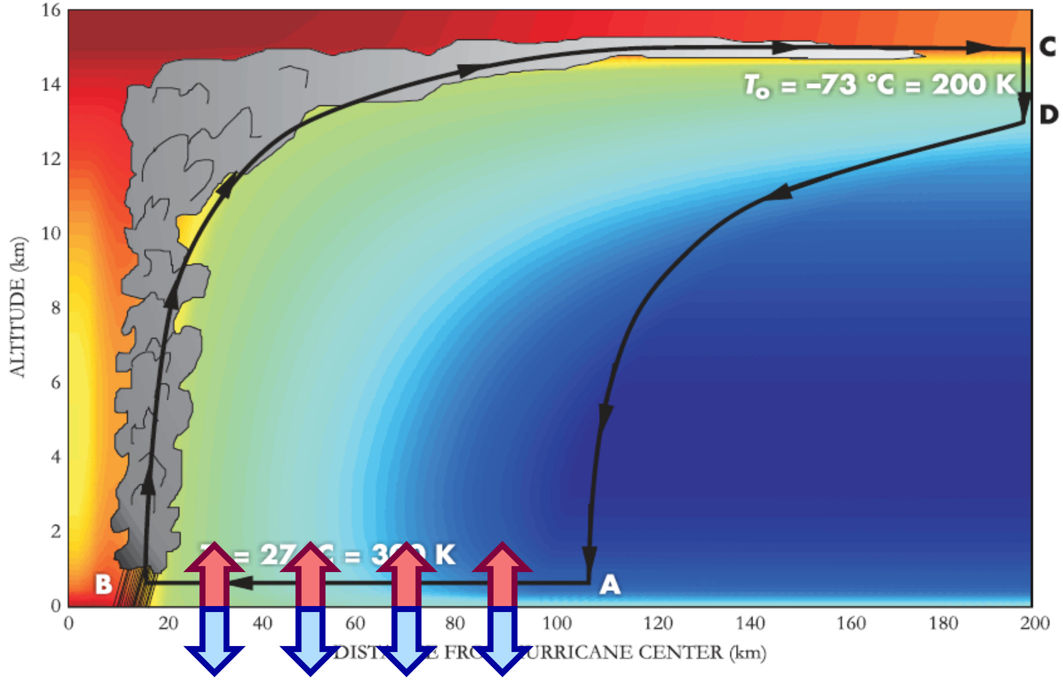
The *temperature difference* between the *ocean surface* and the *tropopause* provides the *thermodynamic energy* to *drive* the *system* and provides a measure of *heat engine* *efficiency*:

Temperature of "Hot" Reservoir (SST) →

$$E = \frac{T_S - T_O}{T_S}$$

← **Temperature of "Cold" Reservoir (outflow level)**

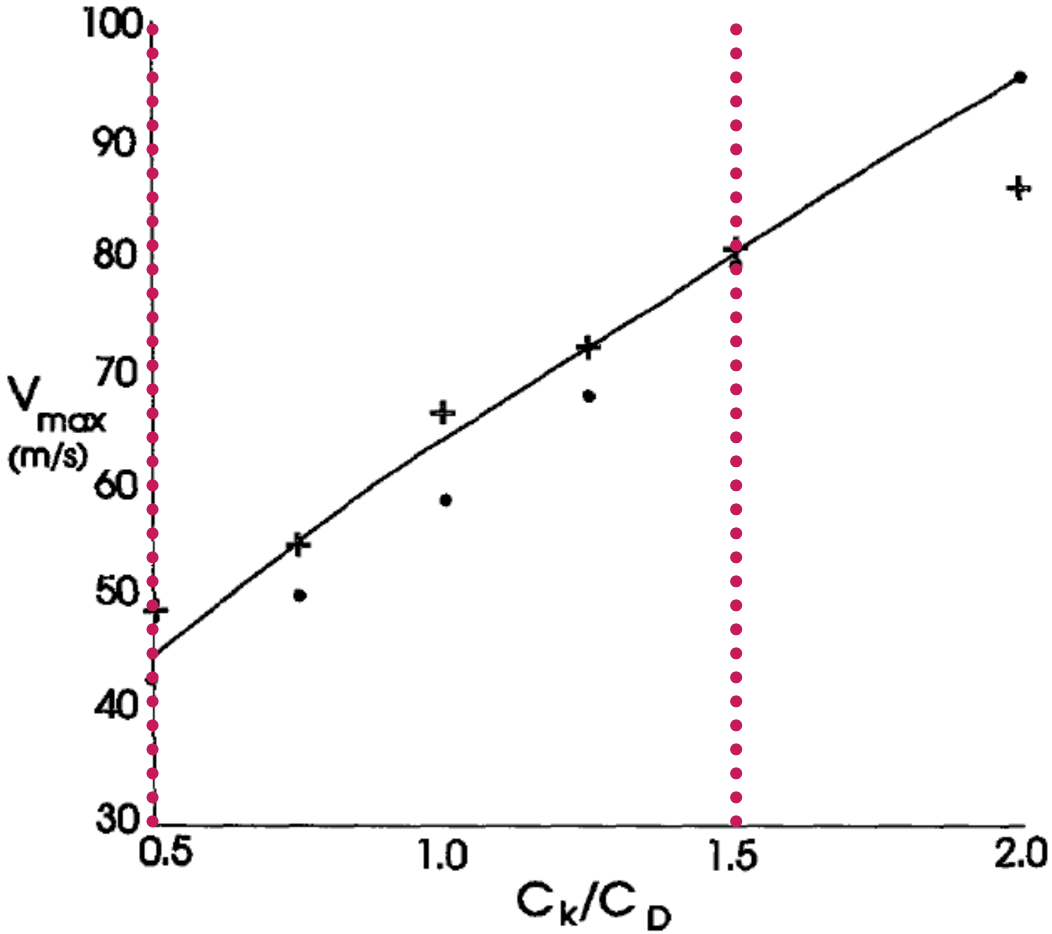
Maximum intensity of the TC heat engine



The *maximum intensity* a TC can achieve is related to the *efficiency* (*E*; the thermal disequilibrium) multiplied times the *ratio* of *two empirical coefficients* (*enthalpy* and *drag*):

$$V^2 \propto \frac{C_K}{C_D} E$$

Intensity dependence on C_K / C_D

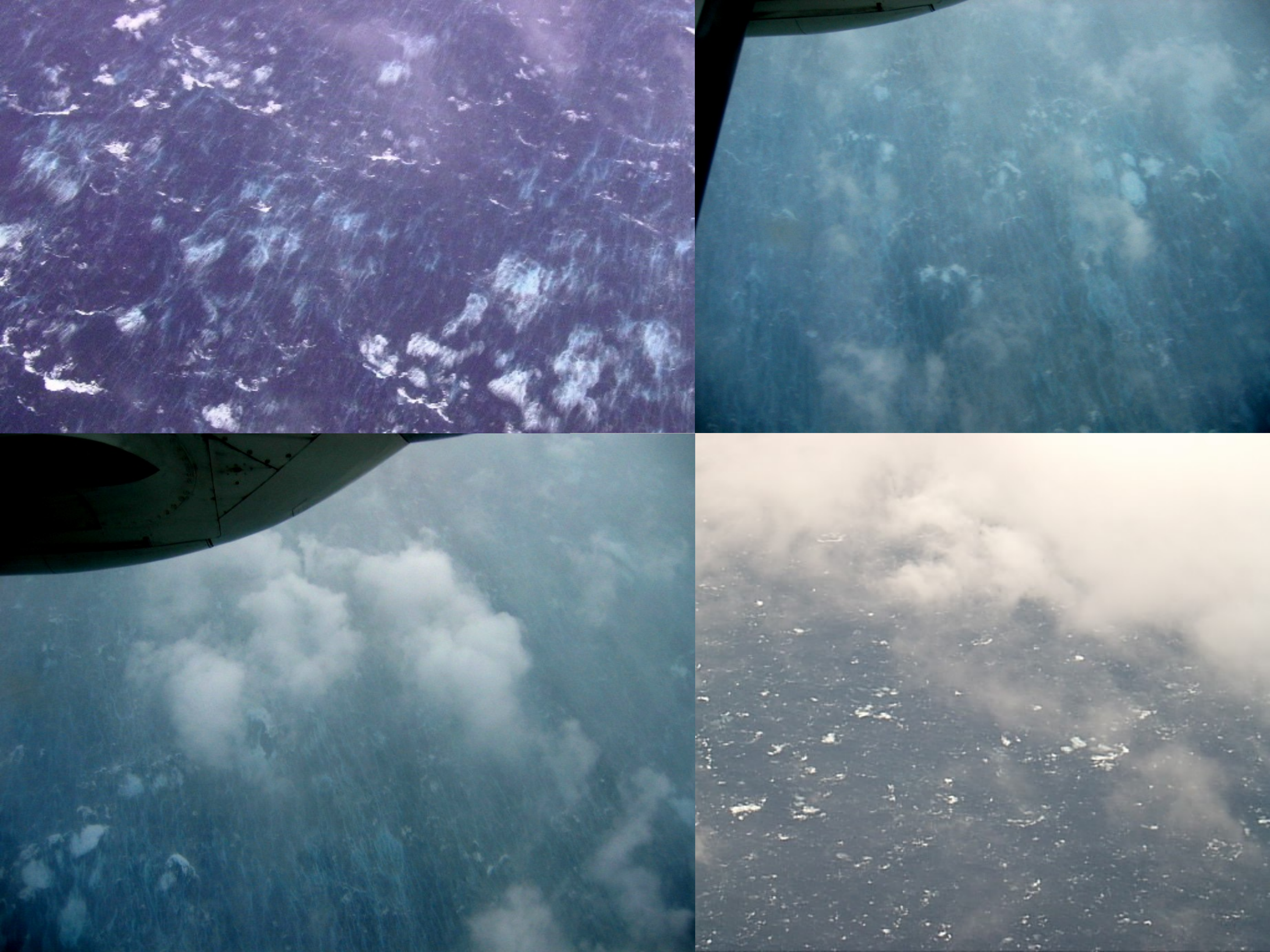


Emanuel's (1986)

TC as a Carnot heat engine / WISHE theory:

$$E = \frac{T_{SST} - T_{OUT}}{T_{SST}}$$

$$V^2{}_{\max} \propto \frac{C_K}{C_D} E$$



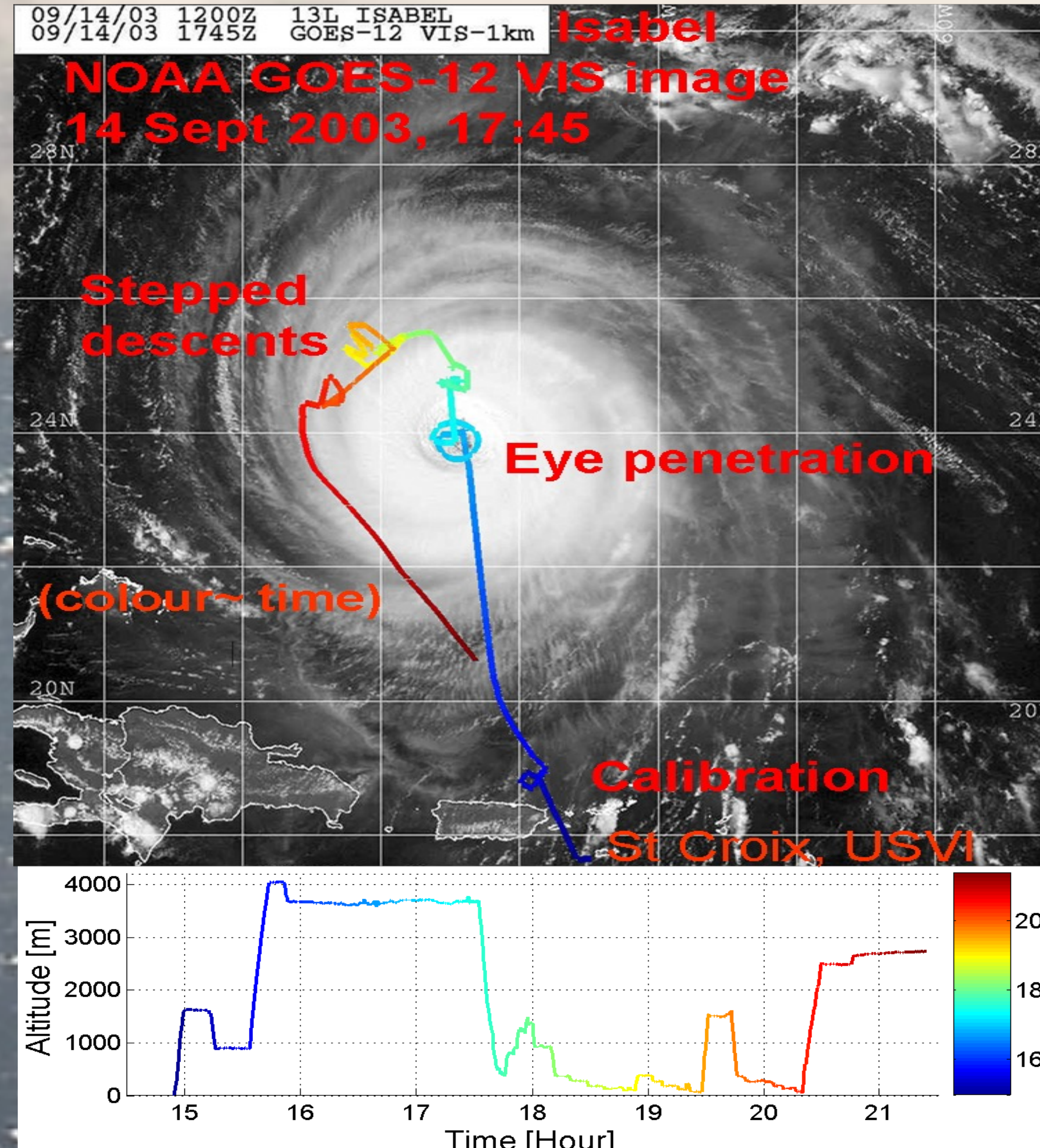
The Coupled Boundary Layer Air-sea Transfer Experiment (CBLAST)

2002: 3 Test flights in Hurricanes Edouard, Isidore, and Lili

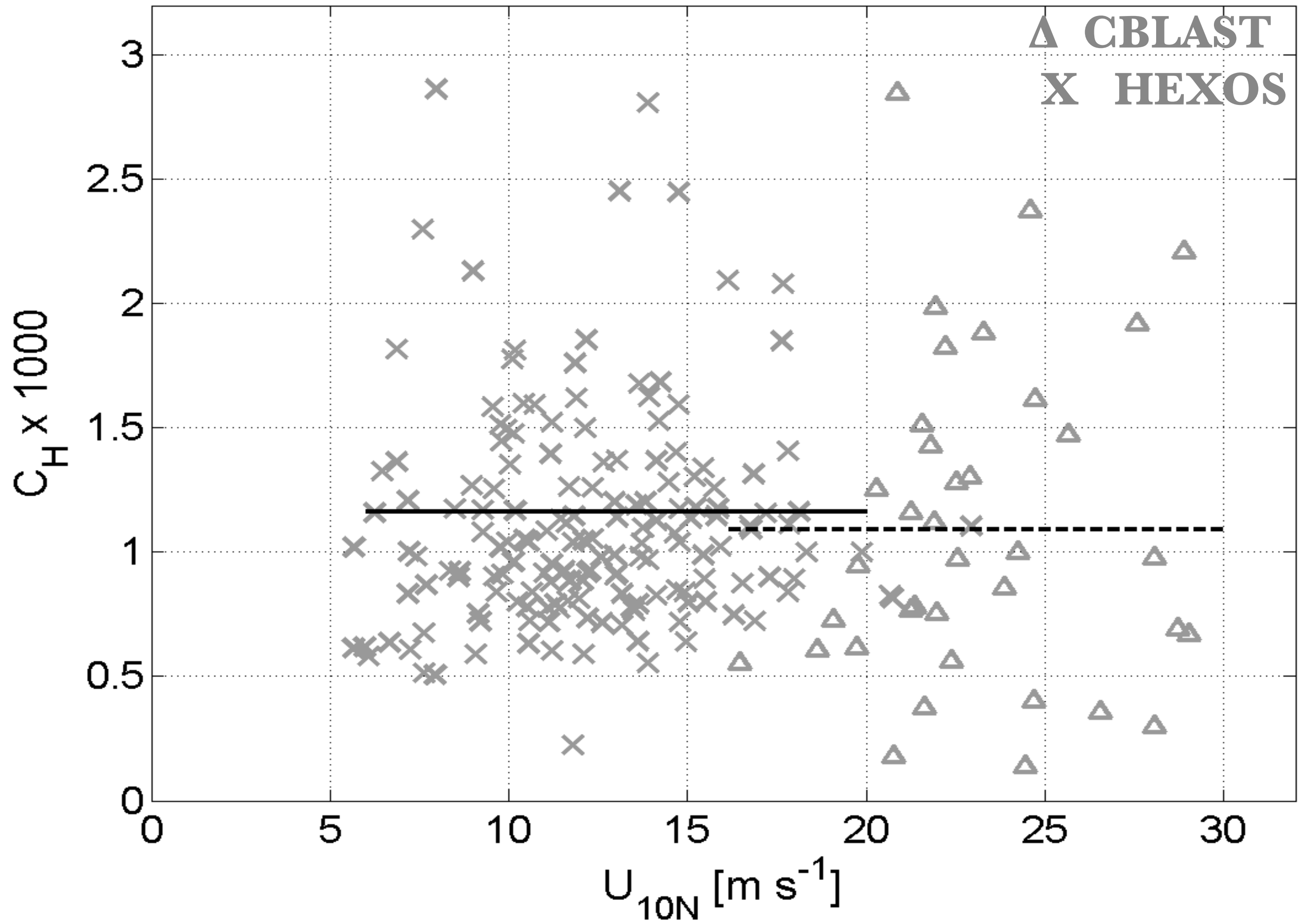
2003: 6 flights in Hurricanes Fabian and Isabel

2004: Flights at top of boundary layer, only 2 flux flights in Hurricanes Frances and Jeanne

Black et al. (2007), BAMS
Drennan et al. (2007), JAS
French et al. (2007), JAS
Zhang et al. (2008), GRL

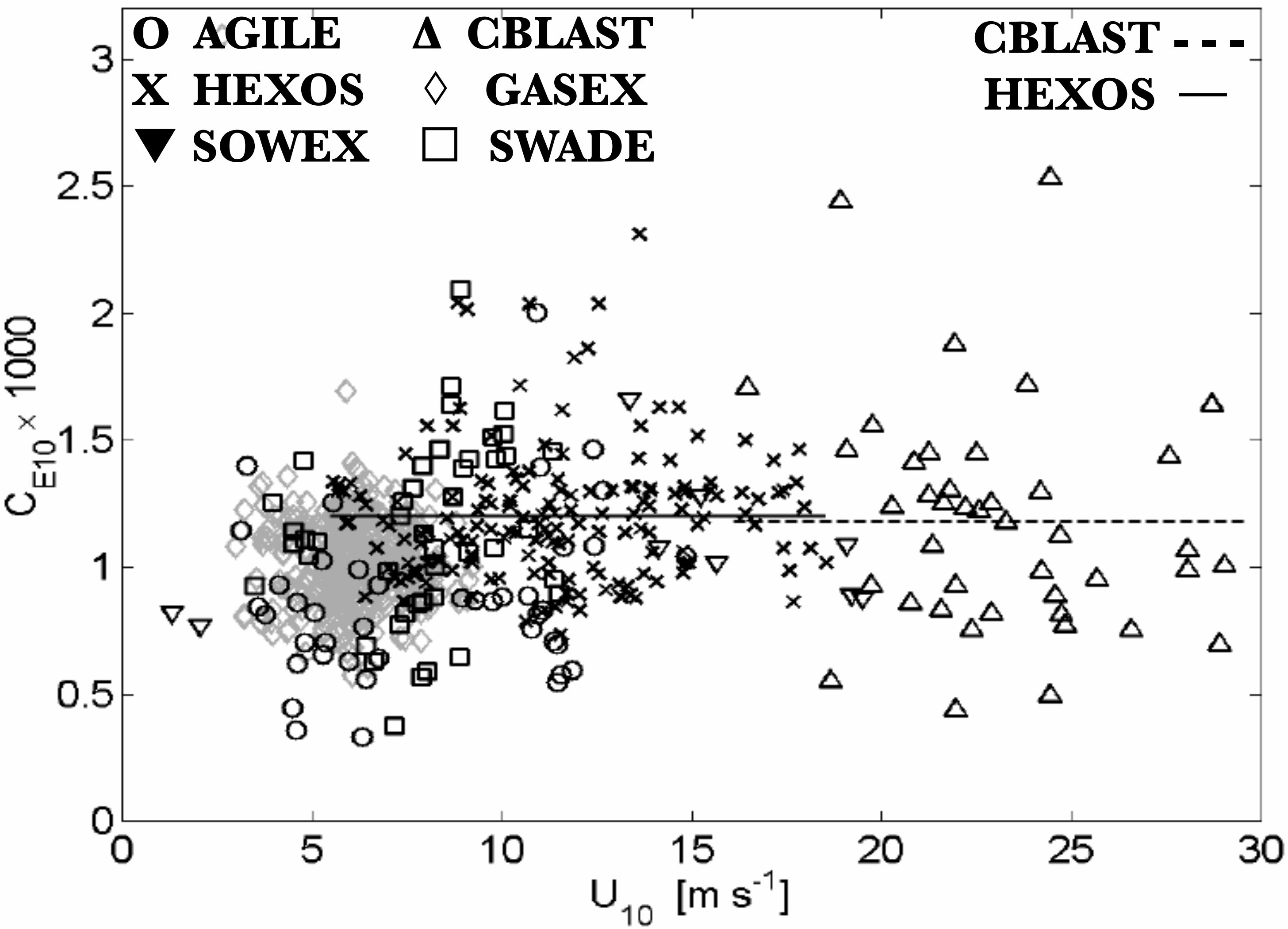


Heat exchange: Stanton numbers



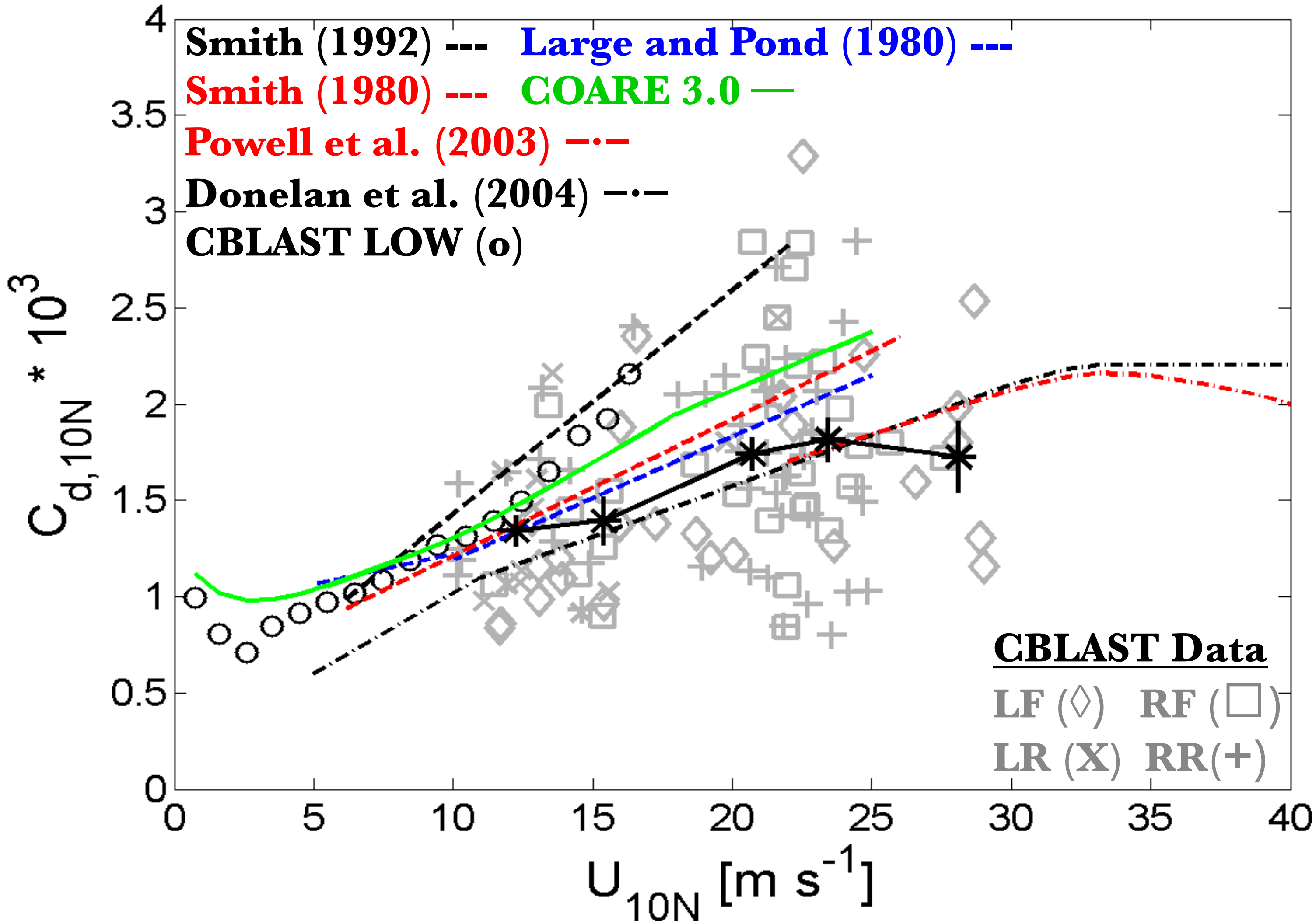
Zhang (2009)

Moisture exchange: Dalton numbers



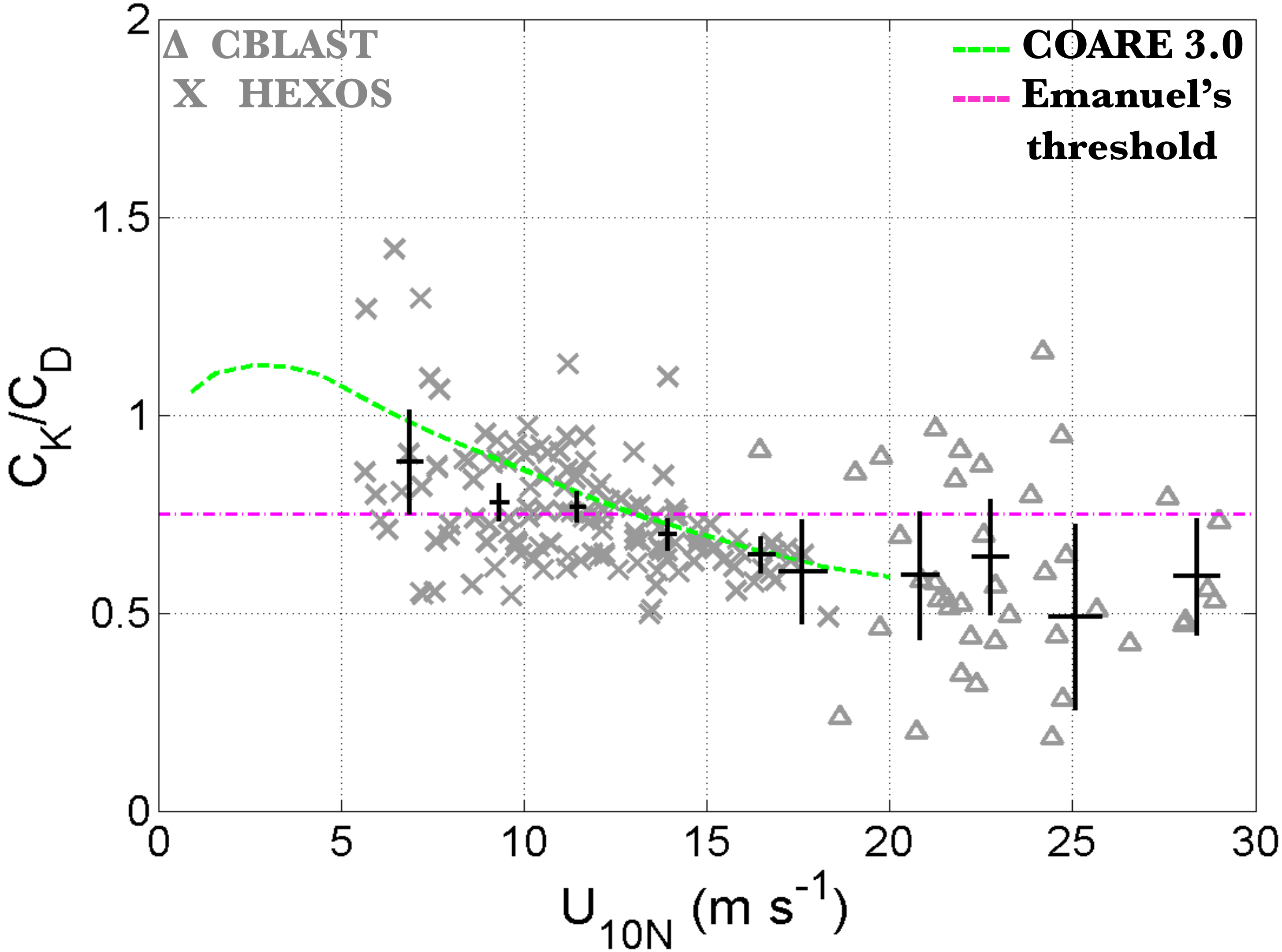
Zhang (2009)

Friction: Drag coefficient



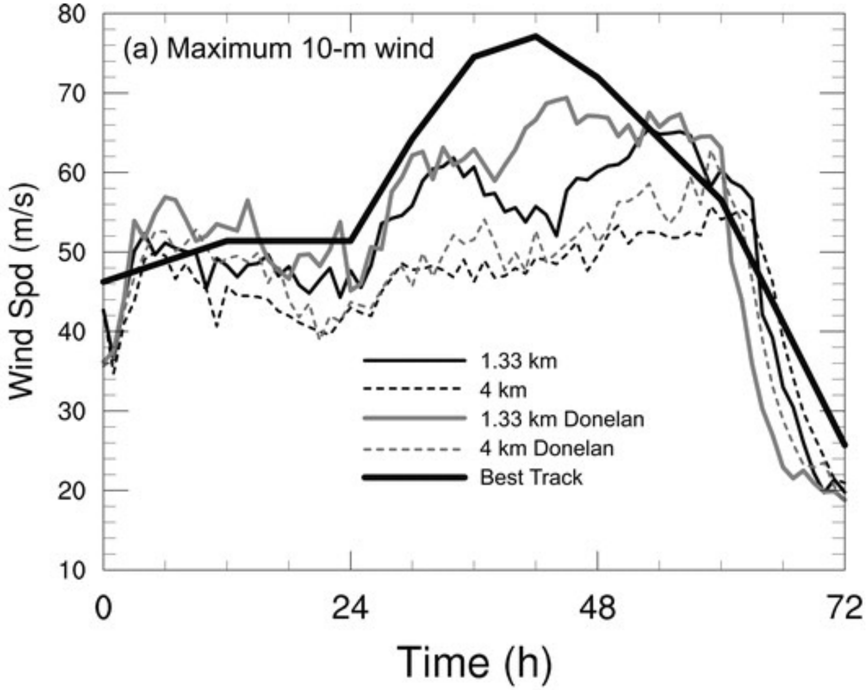
Black et al.(2007)

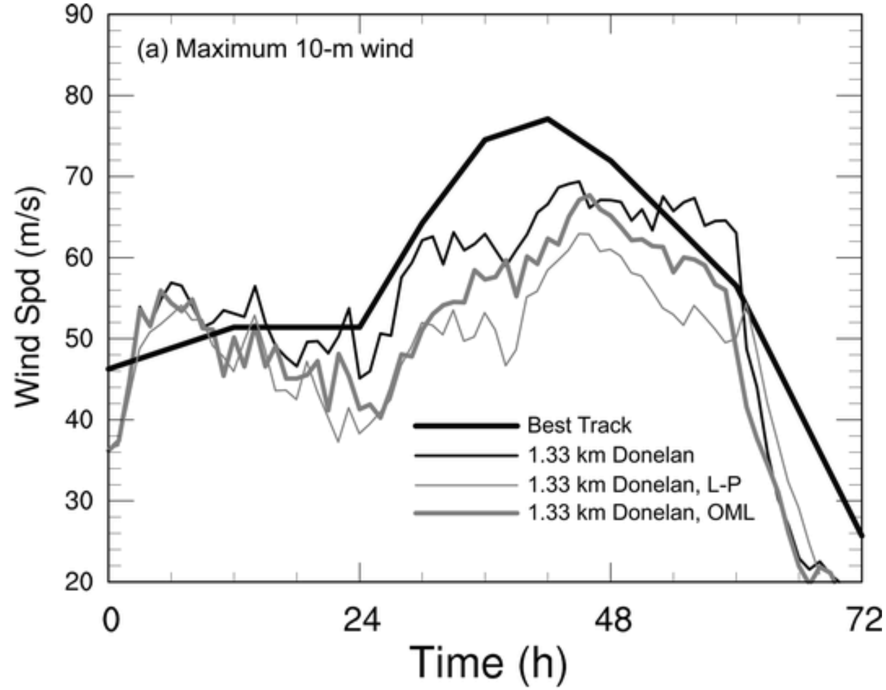
C_K / C_D



Zhang (2009)

Davis et al. (2008): Testing C_K and C_D formulations





NCAR AHW simulations of Hurricane Katrina (2005)

Left plot:

Donelan smaller C_D than control; C_K increases for high winds

Right plot:

L-P constant C_K for strong winds

Davis et al.(2008)