Dissipative Heating in the WRF Model

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Dissipation

- Dissipation: the removal of kinetic energy in a fluid due to viscosity (e.g., Batchelor 1967)

velocity equations:

$$\frac{\partial u}{\partial t} = \frac{\partial \tau_{xz}}{\partial z}$$
$$\frac{\partial v}{\partial t} = \frac{\partial \tau_{yz}}{\partial z}$$

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"dot" with velocity:

$$u \times \left[\frac{\partial u}{\partial t} = \frac{\partial \tau_{xz}}{\partial z}\right]$$
$$v \times \left[\frac{\partial v}{\partial t} = \frac{\partial \tau_{yz}}{\partial z}\right]$$

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kinetic-energy equation:

$$\frac{\partial k}{\partial t} = u\frac{\partial \tau_{xz}}{\partial z} + v\frac{\partial \tau_{yz}}{\partial z}$$

$$k \equiv (u^2 + v^2)/2$$

rearrange RHS:

$$\frac{\partial k}{\partial t} = \underbrace{\left(\frac{\partial (u\tau_{xz})}{\partial z} + \frac{\partial (v\tau_{yz})}{\partial z}\right)}_{\text{diffusion}} - \underbrace{\left(\tau_{xz}\frac{\partial u}{\partial z} + \tau_{yz}\frac{\partial v}{\partial z}\right)}_{\text{dissipation } (\varepsilon)}$$

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IF:

$$\tau_{xz} = K(\partial u/\partial z)$$

$$\tau_{yz} = K(\partial v/\partial z)$$

THEN:

$$\varepsilon = K\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]$$

In this case,
ε is positive-definite
(thus, removes k from fluid)

Dissipative Heating

- Dissipative Heating is the associated increase in internal energy:

$$\frac{\partial k}{\partial t} = \ldots - \underbrace{\varepsilon}_{\text{dissipation}}$$

$$\frac{\partial T}{\partial t} = \ldots + \underbrace{\frac{\varepsilon}{c_v}}_{\text{dissipative heating}}$$

Note: total energy equation

$$\frac{\partial E_t}{\partial t} = \frac{\partial k}{\partial t} + c_v \frac{\partial T}{\partial t}$$

$$= \ldots - \varepsilon + \varepsilon$$

- Things to remember about dissipative heating:
  - It is required for conservation of total energy (hence, it is typically included in Global Climate Models)
  - It is related to viscous modification of flow (u,v)

Dissipative Heating in NWP Models

- Dissipative Heating seems simple:

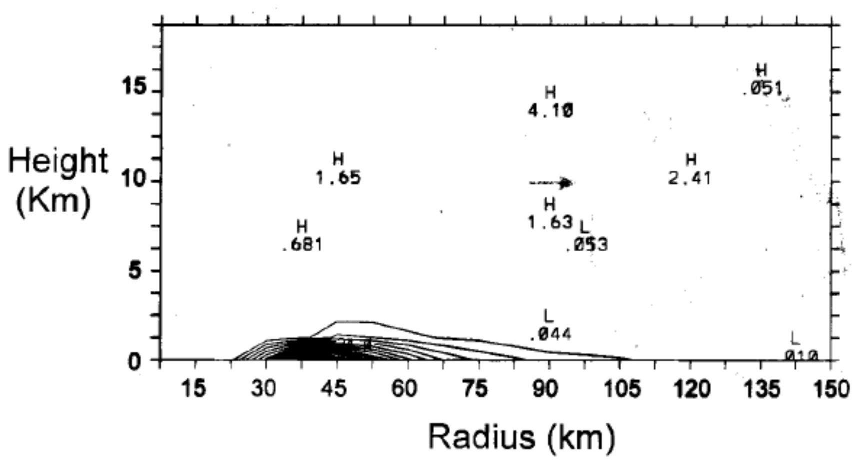
$$\frac{\partial T}{\partial t} = \ldots + \underbrace{\frac{\varepsilon}{c_v}}_{\text{dissipative heating}}$$

- But dissipative heating is not included in many NWP models
  - It's complicated! There can be several sources of dissipation (PBL, advection, upper-level damper, etc)
  - It is usually considered to be small in magnitude …

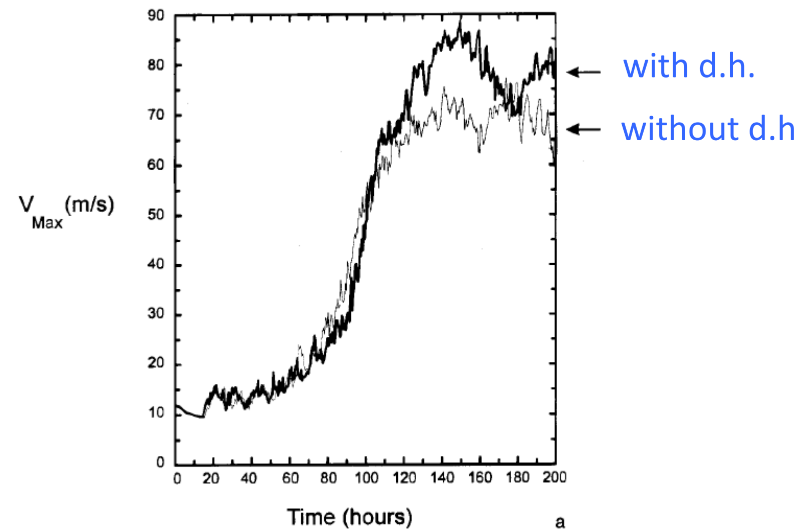
Dissipative Heating in Hurricanes

- Bister and Emanuel (1998, Meteor. Atmos. Phys.) found:
  - Dissipative heating can be quite large (>100 K day^{-1}) in hurricanes
  - Dissipative heating can increase maximum hurricane intensity (MPI) by 20%

Dissipative heating rate:



Max. windspeed vs. time



  - Other modeling studies found similar results:
    - Zhang and Altshuler (1999, MWR): MM5, Hurricane Andrew (1992): ~10% increase in V_{max}
    - Jin et al. (2007, WAF): COAMPS, Hurricane Isabel (2003): up to 20% increase in V_{max}

Dissipative Heating in the WRF Model

- Dissipative Heating *is* included in two physical parameterization schemes in WRF:
  - MM5/WRF surface layer scheme (sf_sfclay_physics = 1) [only if isftcflx ≥ 1]
  - GFS PBL scheme (bl_pbl_physics = 3) [used for HWRF]

- But, both formulations are unusual …

Dissipative Heating for sf_sfclay_physics = 1

- For sf_sfclay_physics = 1 (the "MM5-WRF Monin-Obhukov scheme"; more recently, the Revised MM5/WRF scheme (Jimenez et al., 2012):

- a portion of dissipative heating *was* included in WRF for, but …
  - Only at the lowest model level
  - Only over water
  - Only for isftcflx ≥ 1
  - But it was commented-out in WRF 3.6.1

Dissipative Heating for sf_sfclay_physics = 1

- The heating tendency is (was) added to the surface sensible heat flux
  - Perhaps convenient, but….
  - … sensible heat flux (temperature flux) and dissipative heating (viscous flow modification) are two different physical processes

sensible heat flux

$$F = H + \rho u^* u^* U_1$$

extra term to account for dissipative heating

u^* is surface friction velocity
U_1 is windspeed at lowest model level ($z = \Delta z/2$)

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$$\frac{\partial \theta}{\partial t} = -\frac{1}{(\rho c_p \pi)} \frac{\partial F}{\partial z}$$

neglect

$$\frac{\partial \theta}{\partial t} = -\frac{1}{(\rho c_p \pi)} \frac{F_\Delta - F_0}{\Delta z}$$

$$= +\frac{1}{(\rho c_p \pi)} \frac{F_0}{\Delta z}$$

$$= +\frac{1}{(c_p \pi)} u^* u^* \frac{U_1}{\Delta z}$$

$$\frac{\partial k}{\partial t} = \ldots \underbrace{\left(\tau_{xz} \frac{\partial u}{\partial z}\right)}_{\text{dissipation } (\varepsilon)}$$

surface stress magn. (τ)

Shear near the surface

Dissipative Heating in HWRF

- GFS PBL: included at every grid point (not just lowest model level)
- But, formulated incorrectly: uses both terms in kinetic-energy equation

$$\frac{\partial k}{\partial t} = u\frac{\partial \tau_{xz}}{\partial z} + v\frac{\partial \tau_{yz}}{\partial z}$$

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The entire RHS of this equation is used for calculation of d.h. in HWRF

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```
!=========================================================================
!    ADD  IN  DISSIPATIVE HEATING .... v*dv. This is Bob's doing
!=========================================================================

#if (NMM_CORE==1)

      IF(DISHEAT)THEN
       DO k=kts,kte
         DO i=its,ite
          dishx(i,k)=u1(i,k)*du(i,k) + v1(i,k)*dv(i,k)
          cpmikj=CP*(1.+0.8*QV3D(i,k,j))
          dishx(i,k)=-dishx(i,k)/cpmikj
!         IF(k==1)WRITE(0,*)'ADDITIONAL DISSIPATIVE HEATING',tau(i,k),dishx(i,k)
          tau(i,k)=tau(i,k)+dishx(i,k)
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If anybody knows who Bob is, please let me know.

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```

This formulation can produce negative tendencies (i.e., cooling)!

Dissipation from PBL schemes

- An alternative method (if stress terms, e.g., τ_{xz} and τ_{yz}, are not known):

$$\frac{\partial u}{\partial t} = \frac{\partial \tau}{\partial z}$$

  – Assume stress is zero at model top, integrate downward to get $\tau(z)$
  – Then, using $\tau(z)$ and $u(z)$, calculate ε:

$$\frac{\partial k}{\partial t} = \ldots \underbrace{\left(\tau_{xz}\frac{\partial u}{\partial z}\right)}_{\text{dissipation } (\varepsilon)}$$

- About 10 lines of code
- A caveat … perhaps not applicable to schemes with counter-gradient fluxes, backscatter, etc.

Simulations

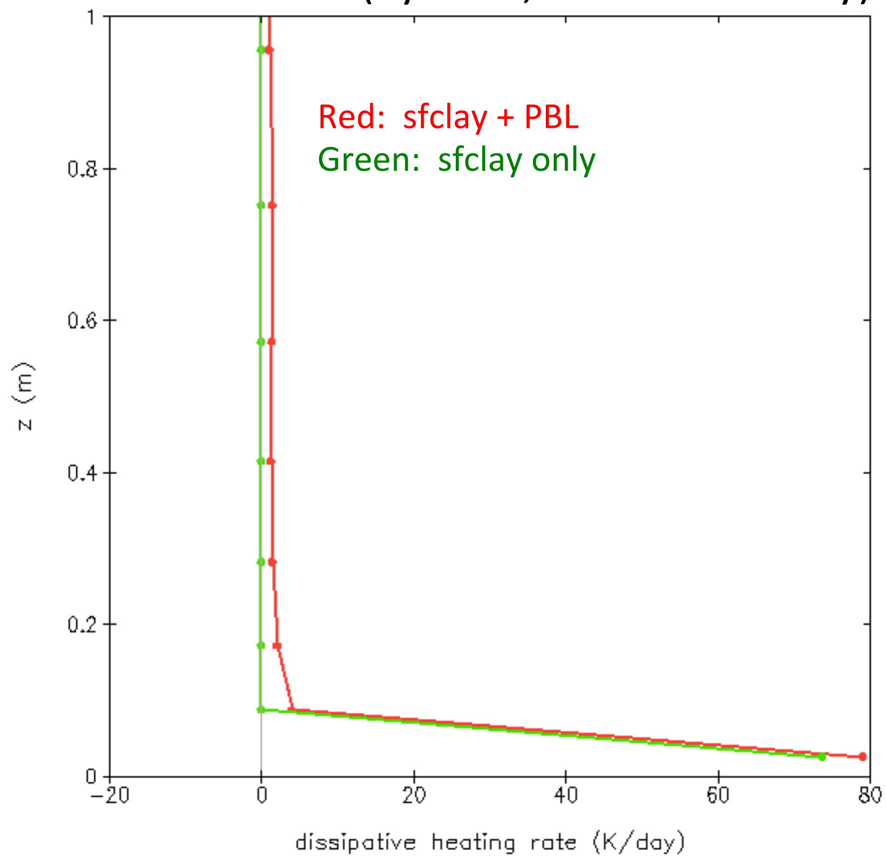
- Under development / testing: a generalized code for WRF
  - Uses u_*, z_0 near surface
  - Uses PBL tendencies to retrieve τ
    - Note: PBL schemes with TKE equations typically calculate ε

- Here: axisymmetric model simulations
  - Setup 1: MM5-WRF surface layer + YSU PBL (ARW)
  - Setup 2: GFDL surface layer + GFS PBL (HWRF)
  - TC test case setup: SST = 28 C, $f = 5\times10^{-5}\ s^{-1}$ (20 N), avg. tropical sounding
  - Δx = 3 km, 62 vertical levels (Δz = 20 m near surface)

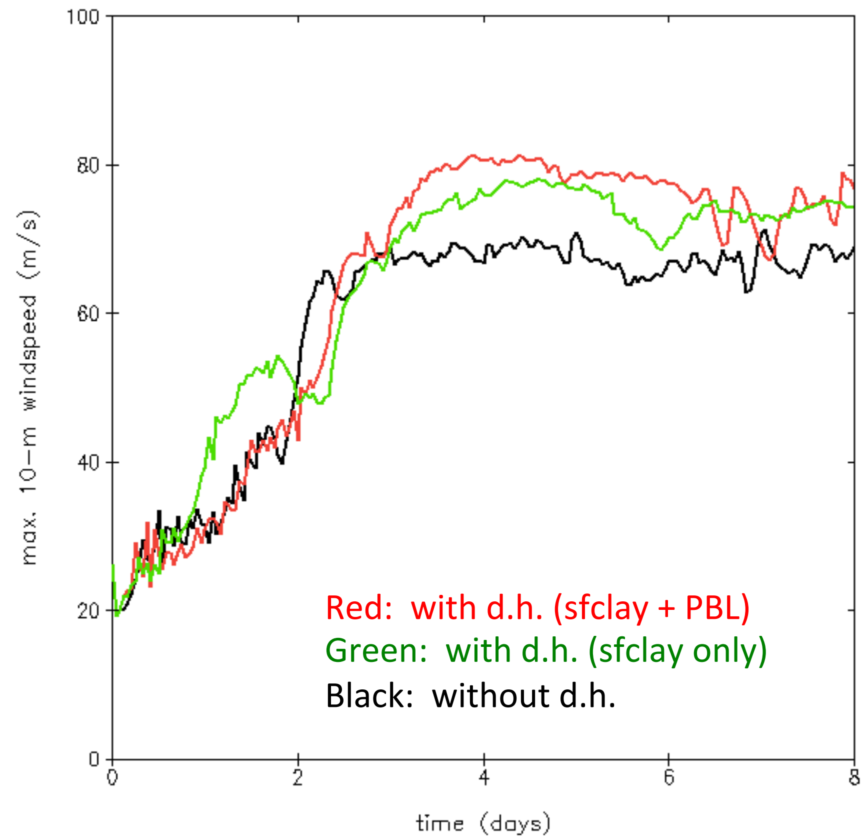
- Questions:
  - What is magnitude of dissipative heating with WRF physics?
  - Is it sufficient to only calculate dissipative heating at lowest model level?

Setup 1 (ARW physics)

Dissipative heating rate (K/day)
at r = 30 km (eyewall, at max intensity)

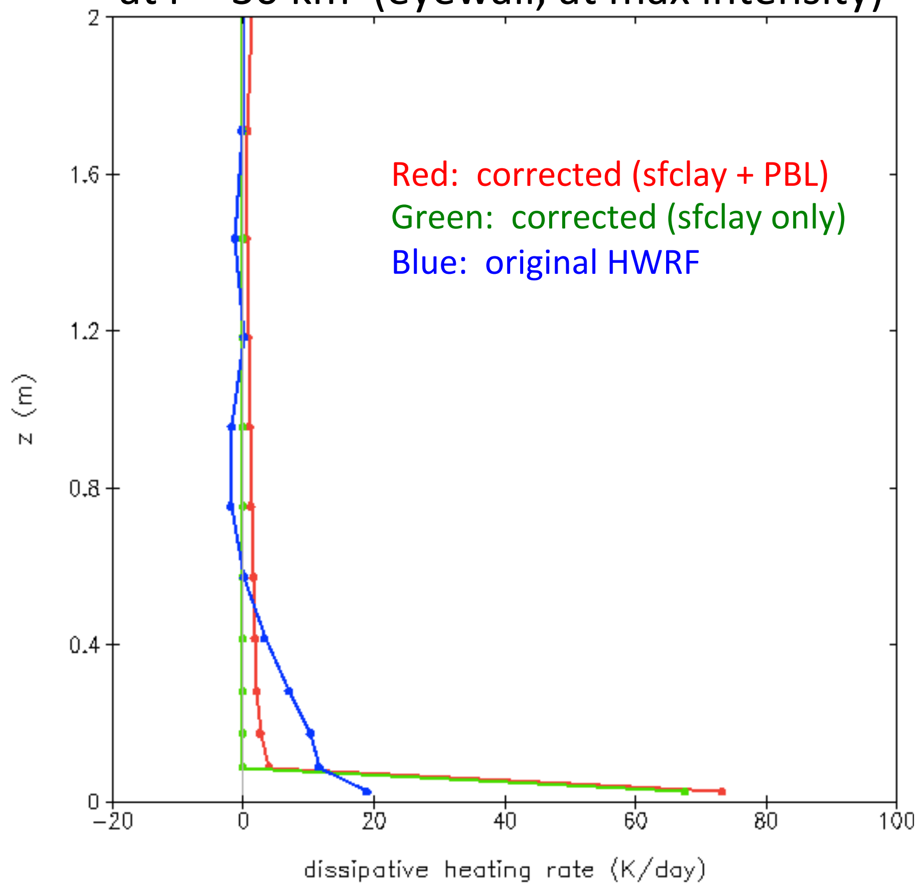


Maximum 10-m windspeed (m/s)



Setup 2 (HWRF physics)

Dissipative heating rate (K/day)
at r = 30 km (eyewall, at max intensity)



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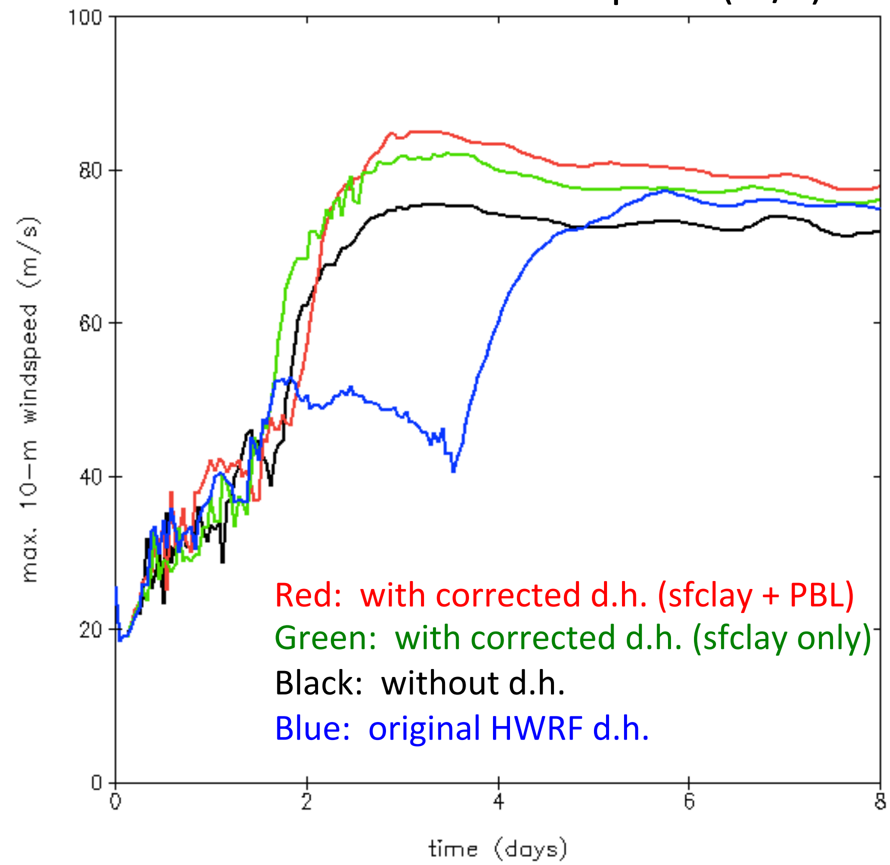

Summary

- Proposed modifications to dissipative heating (d.h.) in WRF:
  - For sfclay_physics=1: separate d.h. calculation from surface heat flux
    - Also: include d.h. over land
    - Add a namelist option (separate d.h. calculation from hurricane-windspeed flux mods)
  - For pbl_physics=3 (HWRF): isolate dissipation (i.e., exclude diffusion)

- In idealized hurricane simulations with WRF physics:
  - Heating rates of nearly 100 K/day near surface; 5 K/day above surface
  - Increase maximum winds by 10% (sfclay only) or 15% (sfclay + PBL)