Advanced Hurricane WRF (AHW) Physics

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1D Ocean Mixed-Layer Model

- 1d model based on Pollard, Rhines and Thompson (1973) was added for hurricane forecasts
- Purpose is to represent cooling of sea-surface temperature due to deep mixing of the oceanic boundary layer with stably-stratified cooler water below
- This has a negative feedback on hurricanes which helps to prevent over-prediction

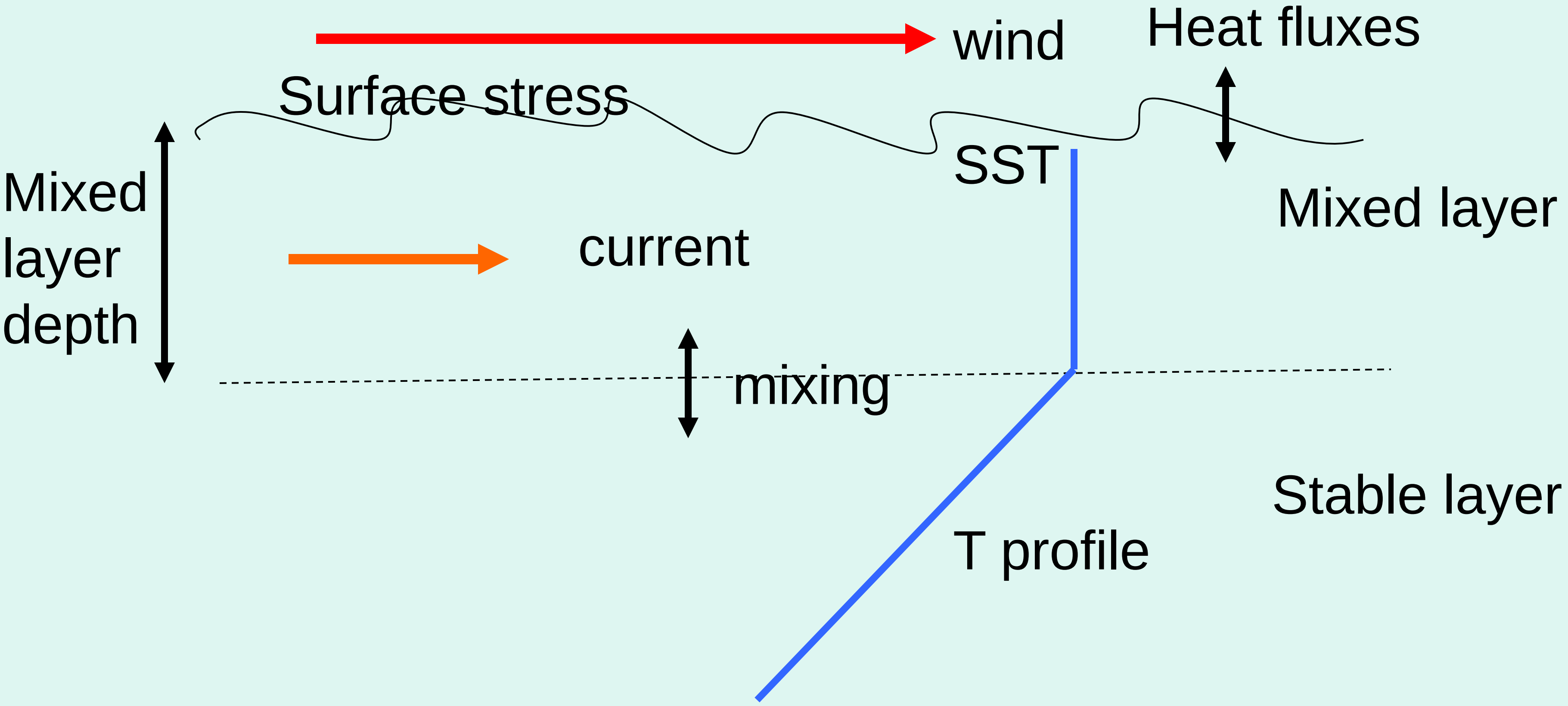
1D Ocean Mixed-Layer Model

- Mechanism
  - Stress from strong surface winds generates currents in the oceanic mixed layer (typically 30-100 m deep)
  - Currents lead to mixing with cooler water below when Richardson number becomes low enough
  - This cools the mixed layer, which changes the SST and hence surface fluxes

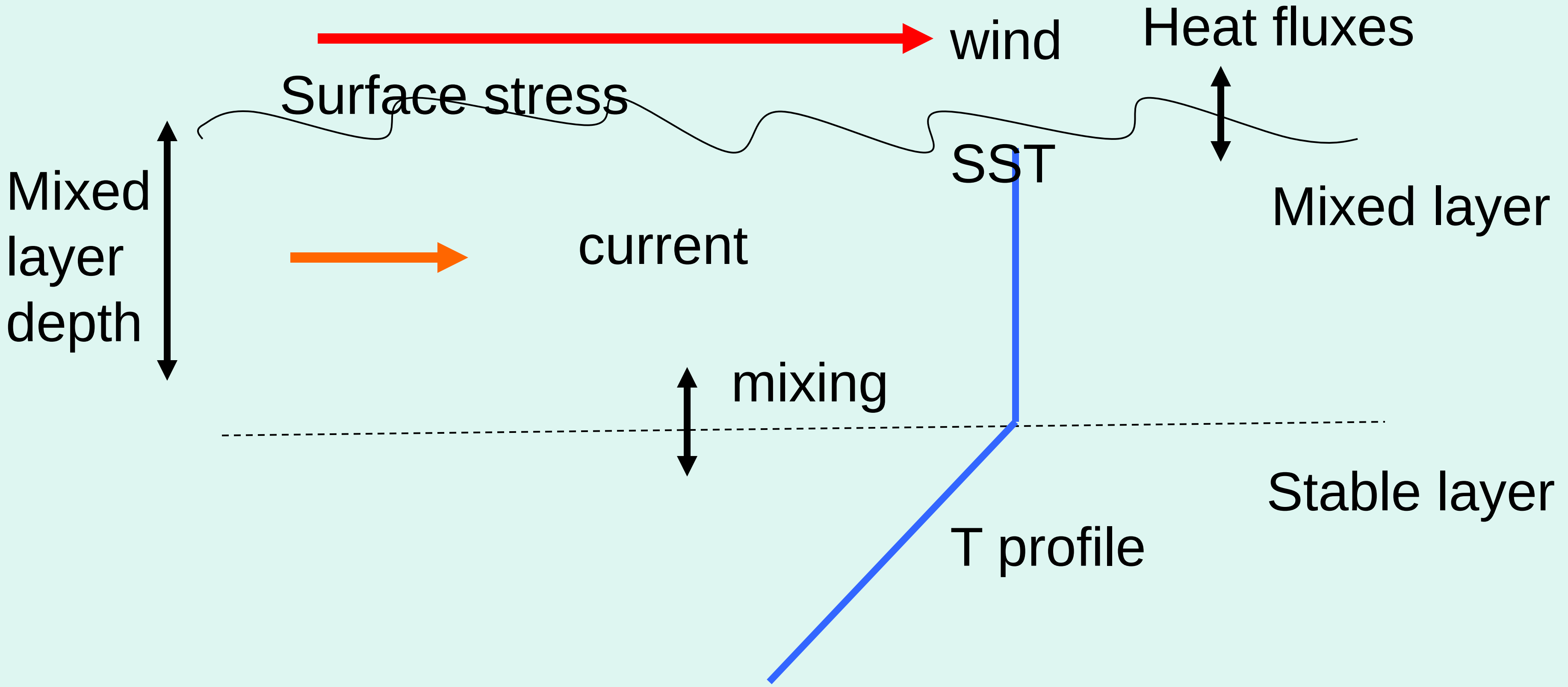
1D Ocean Mixed-Layer Model

- Model
  - Slab mixed layer
    - Predicts depth, vector current components, temperature
  - Initial depth specified from obs or climatology
  - Initial temperature is from SST or ocean heat content
  - Initial current is zero
    - hurricane induced currents are assumed to dominate over pre-existing currents
  - Lapse rate below mixed layer is specified from obs or climatology
  - Inertial turning effects from Coriolis are included
  - Thermal energy balance in mixed layer due to surface fluxes and radiation is included (small)

1D Ocean Mixed-Layer Model



1D Ocean Mixed-Layer Model



Surface Fluxes

- Heat, moisture and momentum

$$H = \rho c_p u_* \theta_* \qquad E = \rho u_* q_* \qquad \tau = \rho u_* u_*$$

$$u_* = \frac{kV_r}{\ln(z_r / z_0) - \psi_m} \qquad \theta_* = \frac{k\Delta\theta}{\ln(z_r / z_{0h}) - \psi_h} \qquad q_* = \frac{k\Delta q}{\ln(z_r / z_{0q}) - \psi_h}$$

Subscript *r* is reference level (lowest model level, or 2 m or 10 m)
z_0 are the roughness lengths

Roughness Lengths

- Roughness lengths are a measure of the “initial” length scale of surface eddies, and generally differ for velocity and scalars
- In earlier AHW $z_{0h}=z_{0q}$ are small constants (=10^{-4} m for water surfaces)
- z_0 for momentum is a function of wind speed following tank experiments of Donelan (this replaces the Charnock relation in WRF). This represents the effect of wave heights in a simple way.
- The Donelan formulation causes the drag coefficient to reach a maximum at about hurricane wind speeds, where Charnock’s drag continues to increase with wind speed with no limit.

Drag Coefficient

- C_{D10} is the 10 m drag coefficient, defined such that

$$\tau \equiv \rho C_{D10} V_{10}^2$$

It is related to the roughness length by (in neutral conditions)

$$C_{D10} = \left(\frac{k}{\ln(z_{10} / z_0)} \right)^2$$

Enthalpy Exchange Coefficient

- C_{E10} is the 10 m moisture exchange coefficient, defined such that

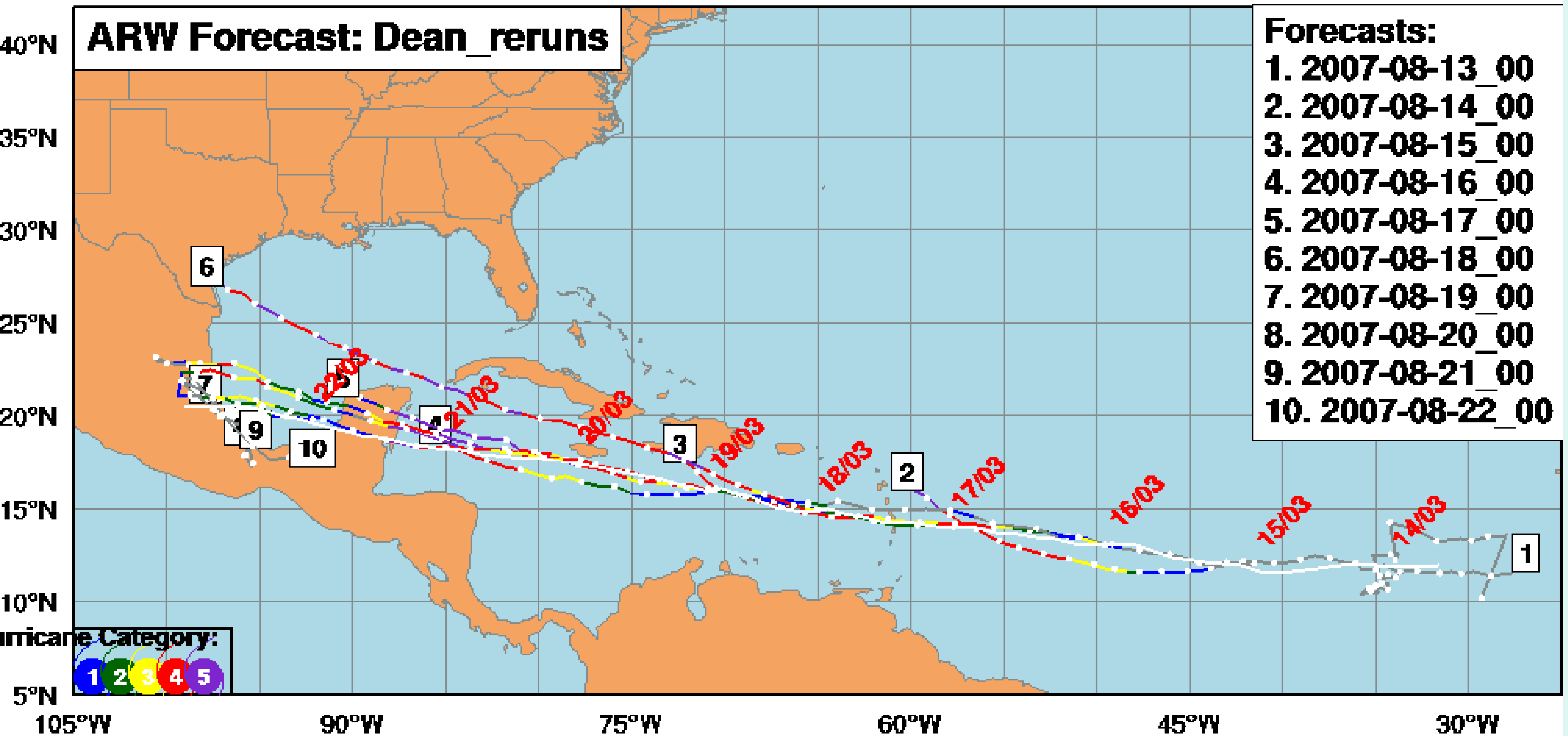
$$E \equiv \rho C_{E10} V_{10} \Delta q$$

It is related to the roughness lengths (assuming neutral conditions) by

$$C_{E10} = \left(\frac{k}{\ln(z_{10} / z_0)} \right) \left(\frac{k}{\ln(z_{10} / z_{0q})} \right)$$

Often it is assumed that C_H=C_E=C_k where C_k is the enthalpy exchange coefficient. However, since 90% of the enthalpy flux is latent heat, the coefficient for sensible heat (C_H) matters less than that for moisture (C_E)

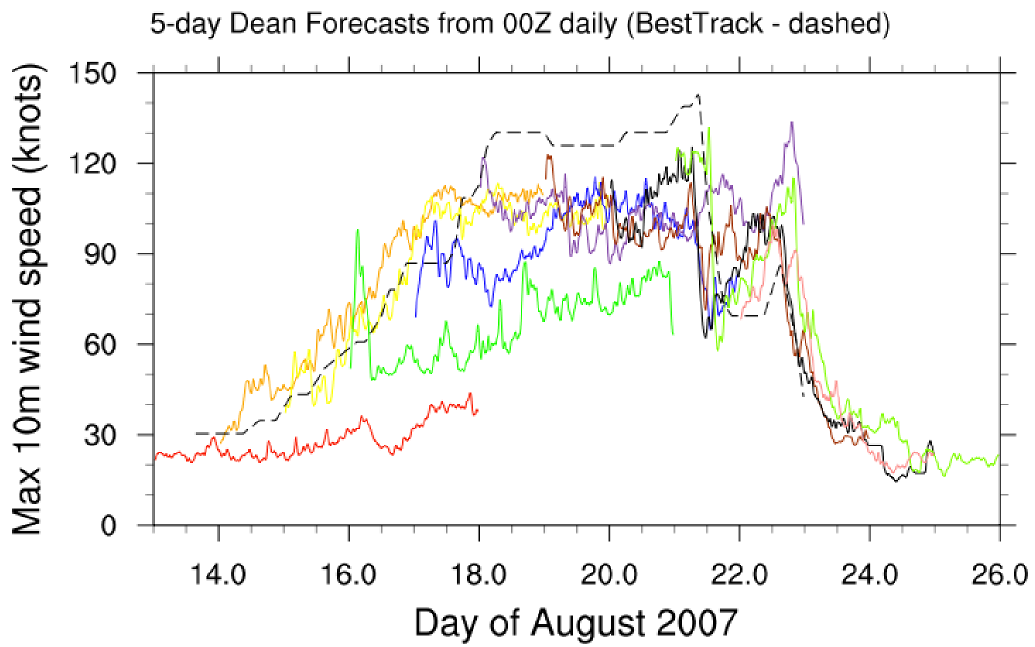
Dean track forecasts



Hurricane Dean

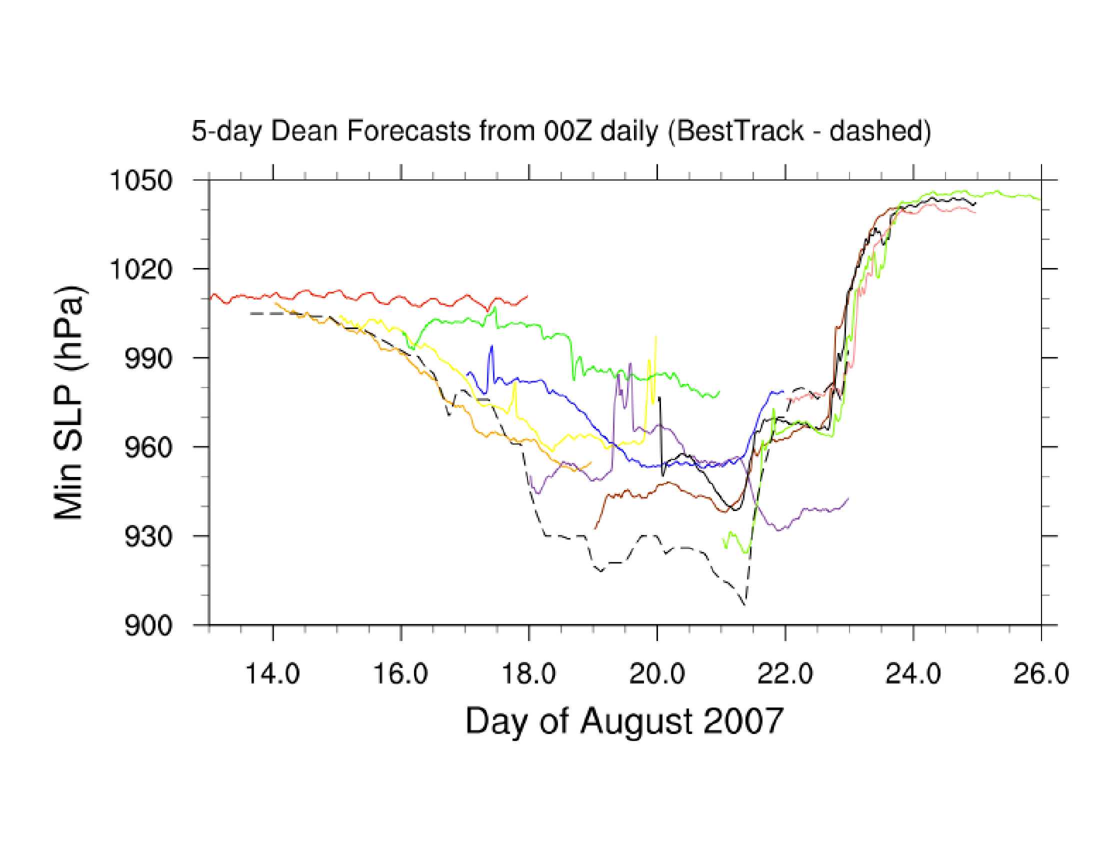
- Reached category 5 in Caribbean
- Minimum central pressure - 906 hPa
- Maximum wind - 165 mph
- Made landfall as category 5 in Belize and Mexican Yucatan
- Redeveloped over Gulf
- Second landfall in Mexico as category 2

Hurricane Dean (2007)



Note that forecasts underestimate maximum windspeed

Hurricane Dean (2007)



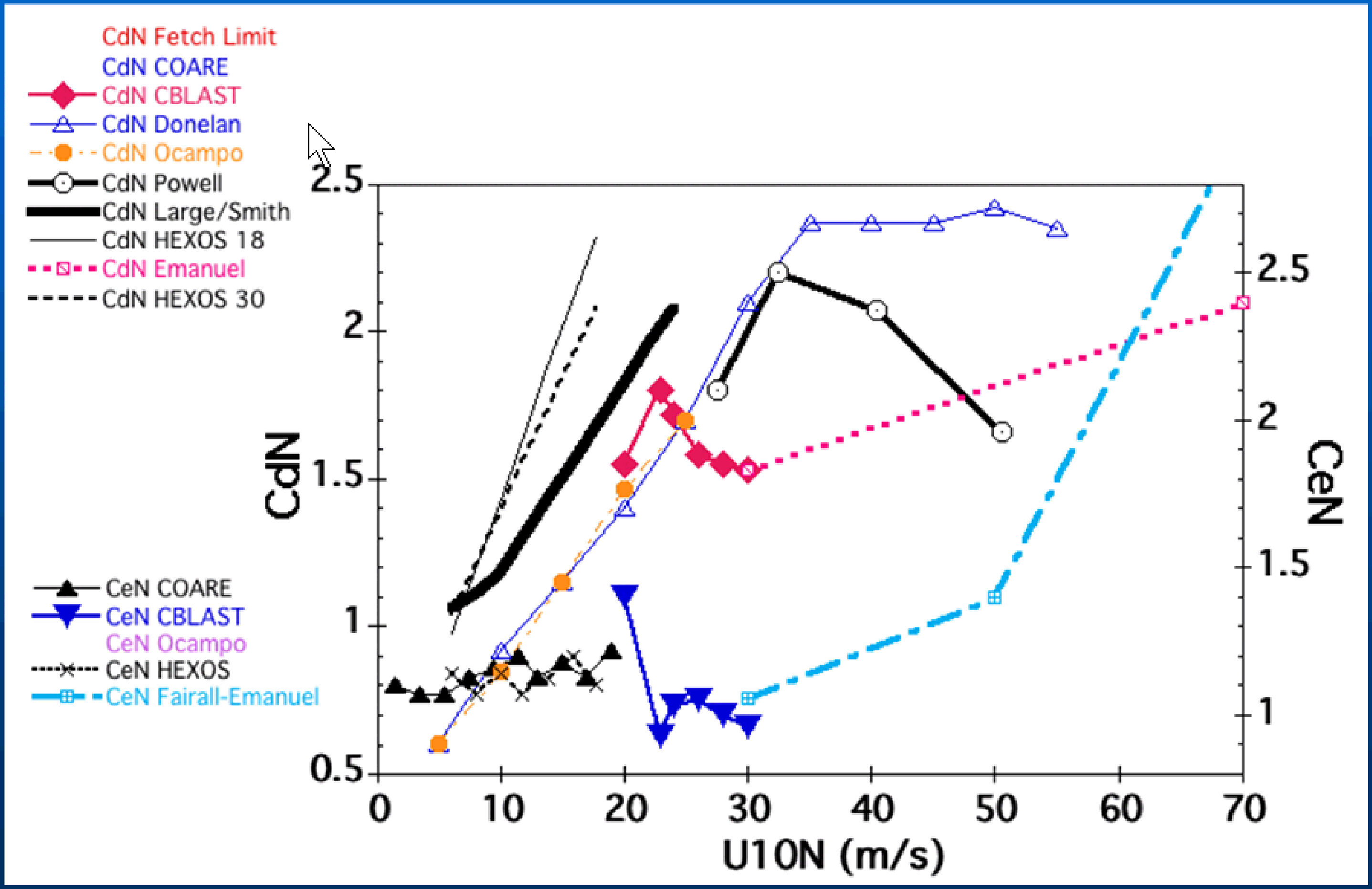
Forecasts also underestimate pressure drop

C_D and C_k

- From the works of Emanuel (1986), Braun and Tao (2001) and others the ratio of C_k to C_D is an important factor in hurricane intensity
- Observations give some idea of how these coefficients vary with wind speed but generally stop before hurricane intensity

27th AMS Hurricane conference

Black et al. (2006)

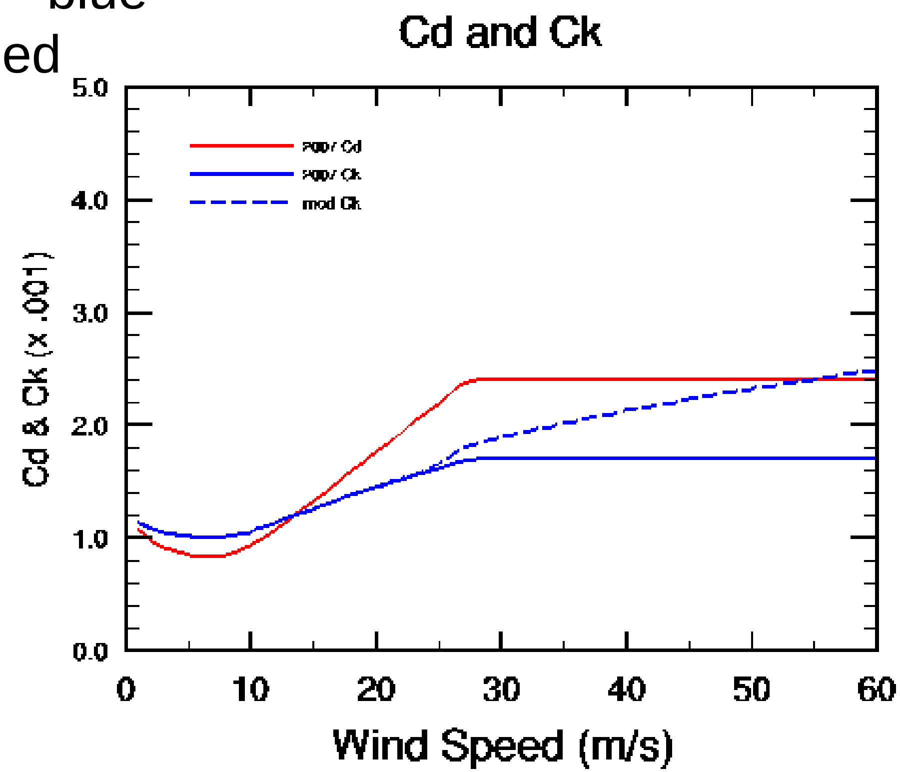


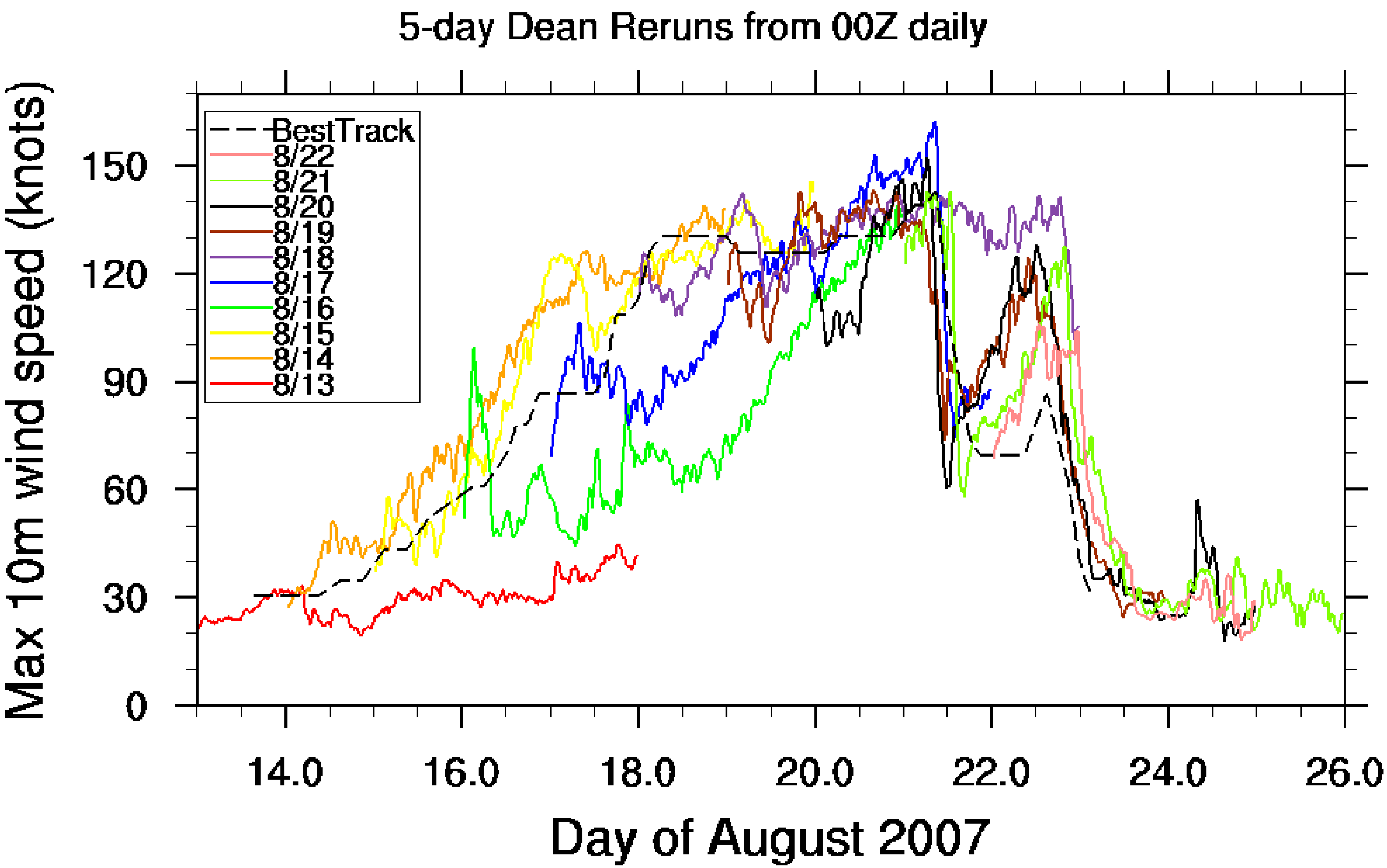
Modification to C_k in AHW

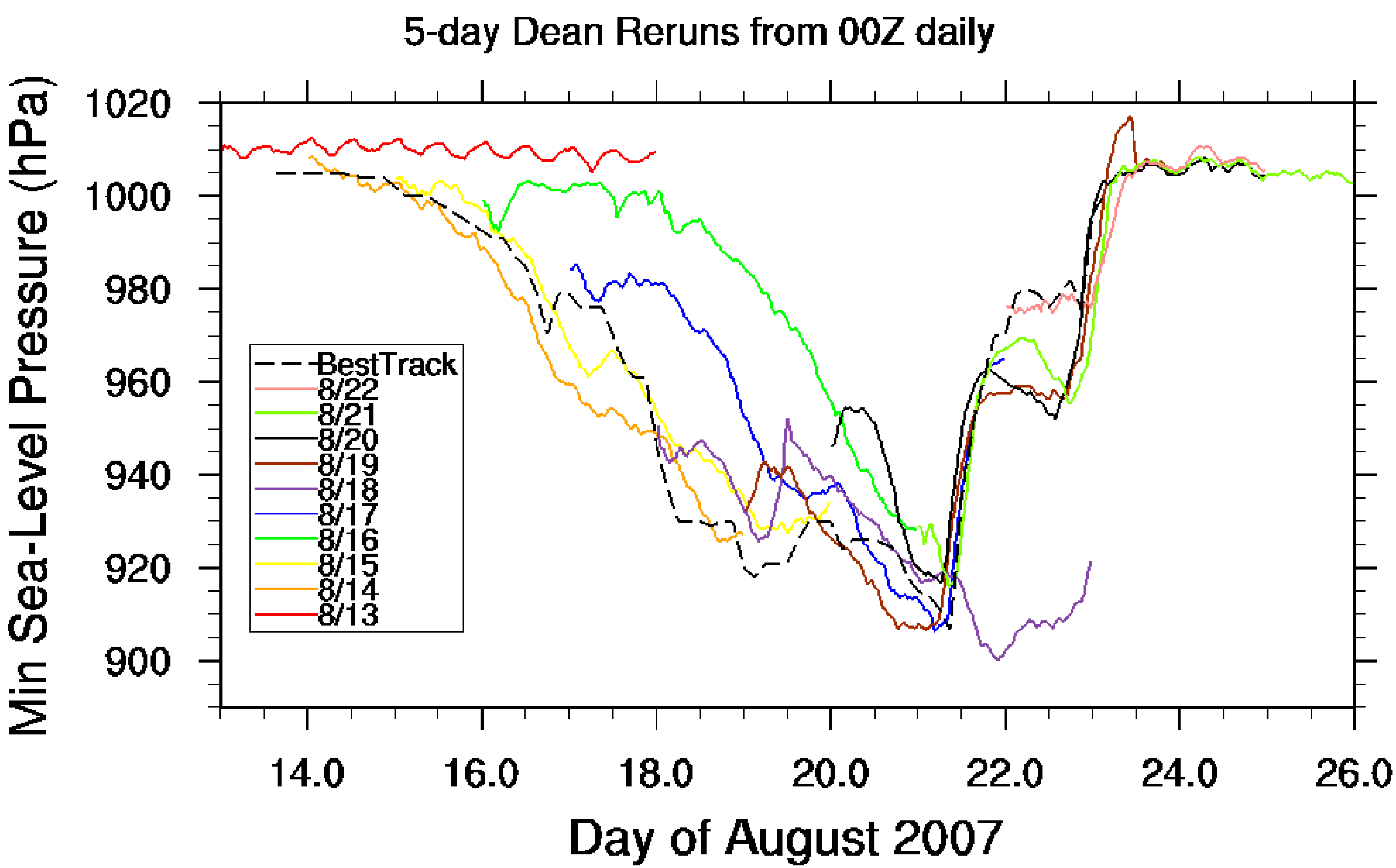
- Commonly z_{0q} is taken as a constant for all wind speeds
- However for winds greater than 25 m/s there is justification for increasing this to allow for sea-spray effects that may enhance the eddy length scales
- We modify z_{0q} in AHW to increase at wind speeds > ~25 m/s
- This impacts C_k as shown next

Modification to C_k in AHW

C_d - red, C_k - blue
New - dashed
Old - solid




5-day Dean Reruns from 00Z daily
Max 10m wind speed (knots)
150
120
90
60
30
0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
Day of August 2007
BestTrack
8/22
8/21
8/20
8/19
8/18
8/17
8/16
8/15
8/14
8/13


5-day Dean Reruns from 00Z daily
Min Sea-Level Pressure (hPa)
1020
1000
980
960
940
920
900
BestTrack
8/22
8/21
8/20
8/19
8/18
8/17
8/16
8/15
8/14
8/13
14.0
16.0
18.0
20.0
22.0
24.0
26.0
Day of August 2007

Impact on Dean forecasts

- General improvement in both wind and pressure intensity measures. (Track not affected significantly.)
- This is consistent with enhanced ratio of C_k to C_D as expected from previous theoretical and modeling studies
- Impact of changing C_k in the case of Dean was greater than impact from increasing ocean mixed-layer depth

AHW Options

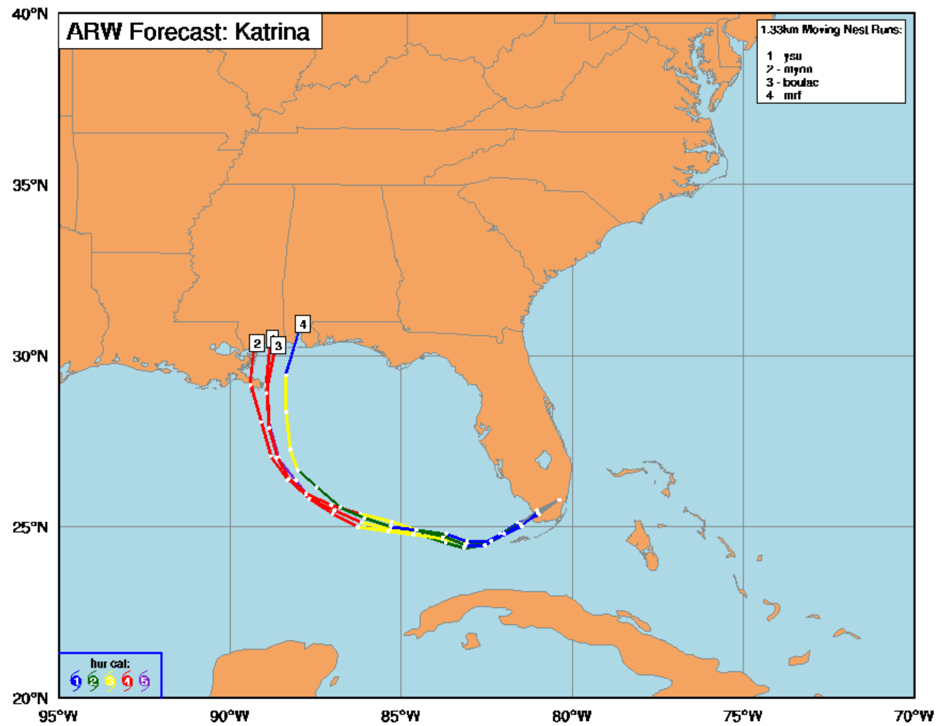
- Ocean Mixed Layer (omlcall=0,1)
  - In 3.2 can be used with any sf_surface_physics (land-surface) option
- Tropical Cyclone Surface Fluxes (isftcflx=0,1,2) for sf_sfclay_physics=1 only
  - 0: Charnock z_0 , Carlson-Boland z_{0q}
  - 1: Donelan z_0 , Ramped z_{0q}
  - 2: Donelan z_0 , Garratt z_{0q}
  - Options 1 and 2 for hurricanes also include dissipative heating in Version 3.2

PBL Options

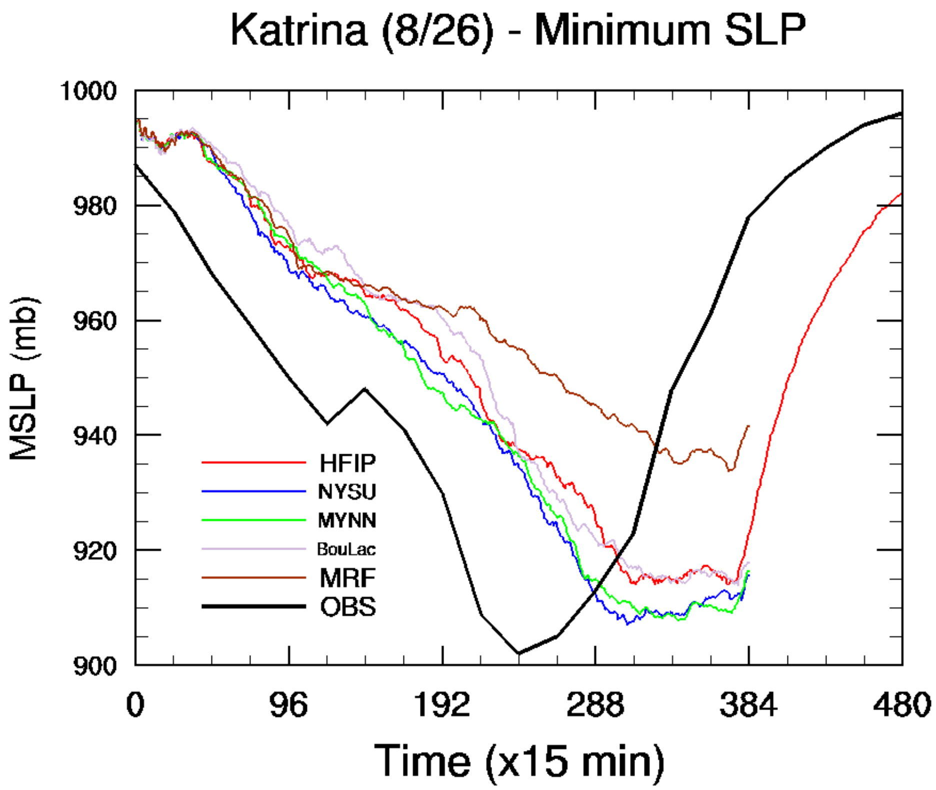
- YSU PBL (sf_sfclay_physics=1, bl_pbl_physics=1)
  - Nonlocal vertical mixing, allows use of isftcflx options
- MYJ PBL (sf_sfclay_physics=2, bl_pbl_physics=2)
  - TKE prediction local scheme
- ARW has several other PBL choices that can be run with sfclay option 1 (and isftcflx=1) (MYNN, BouLac, ACM2)
- All PBLs should use diff_opt=1, km_opt=4 for horizontal diffusion scheme

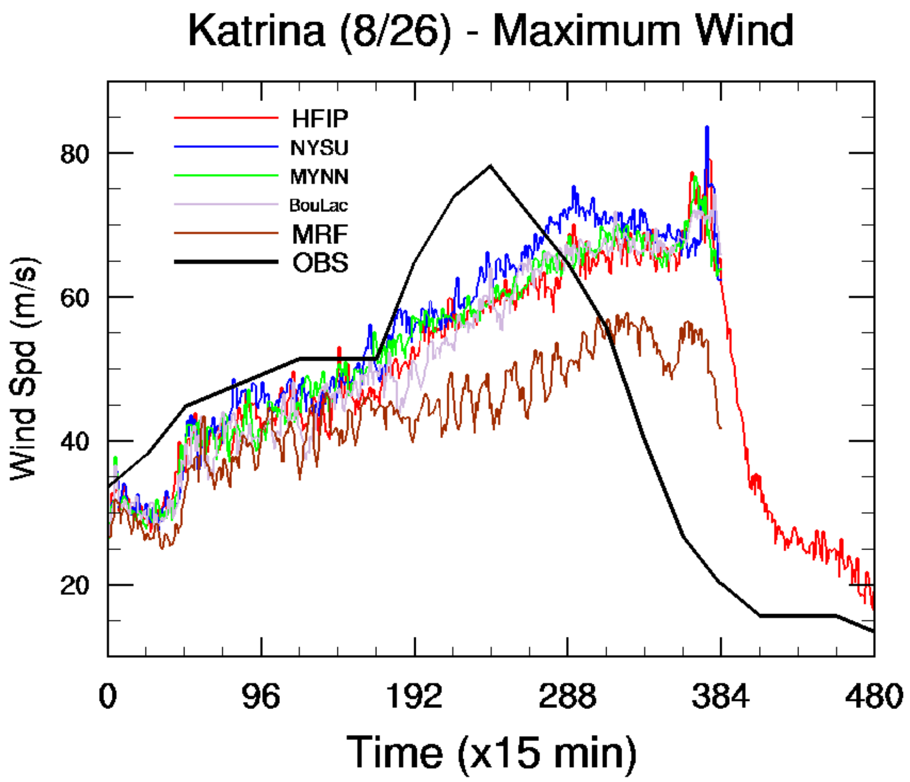
Katrina (2005) PBL Comparison

- Initialized August 26th (EnKF)
- GFS forecast boundaries
- 12/4/1.33 km moving nests
- 96 hours
- YSU default versus MYNN, BouLac and MRF



PBL Comparison





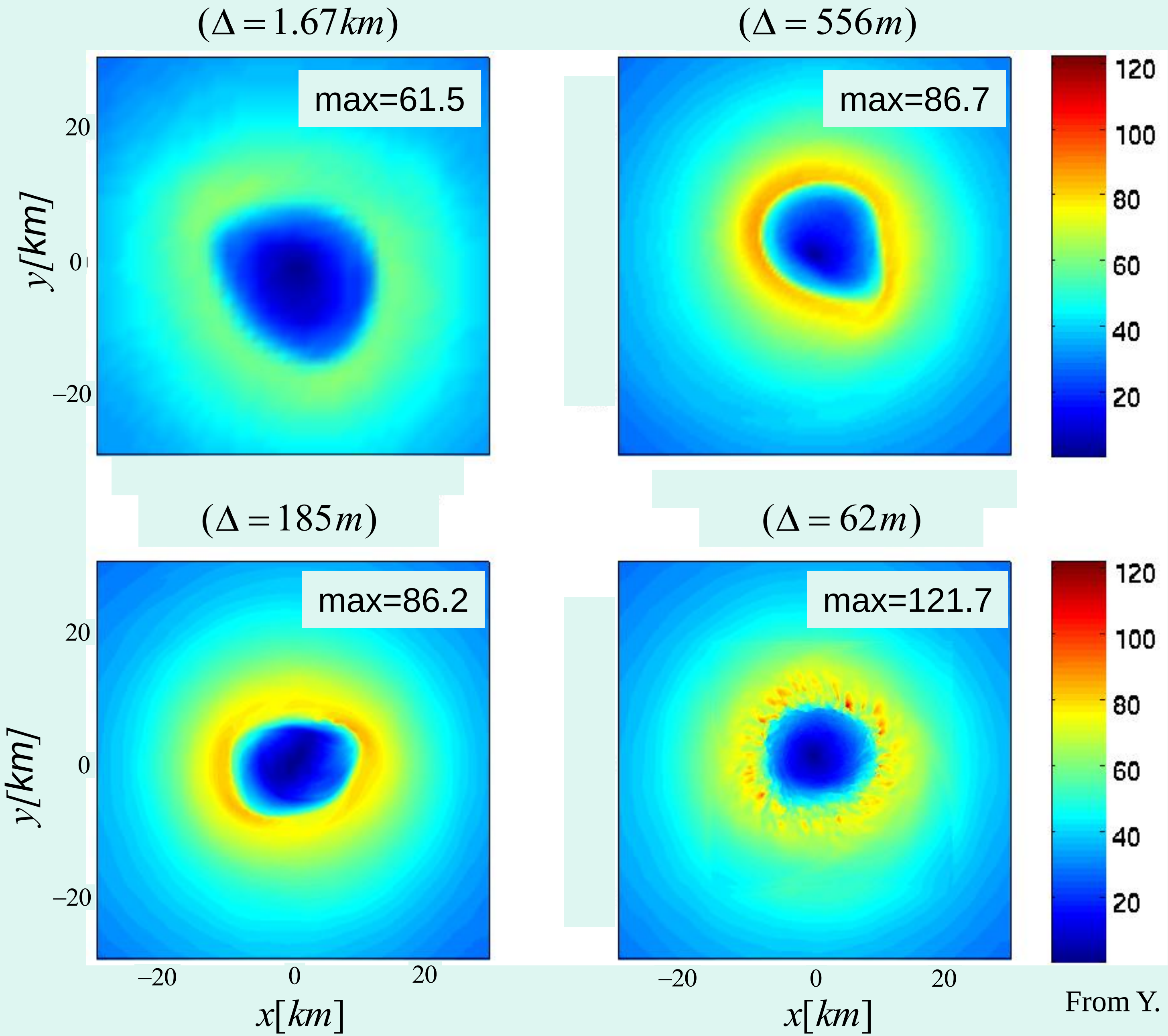
PBL Options

- LES PBL (bl_pbl_physics=0, diff_opt=2, km_opt=2,3)
- Only valid for high-resolution large-eddy simulations, e.g. dx=100 m or less
- Turning off PBL activates vertical diffusion which works using consistent sub-grid turbulence scheme (selected by km_opt) with horizontal diffusion
  - km_opt=2: subgrid 3d tke prediction scheme
  - km_opt=3: subgrid 3d diagnostic Smagorinsky scheme

LES test

- Idealized case with LES on inner domains (< 1km dx), YSU on outer domains.
- Rotunno et al. (BAMS, December 2009)

Surface Wind ~ Resolution

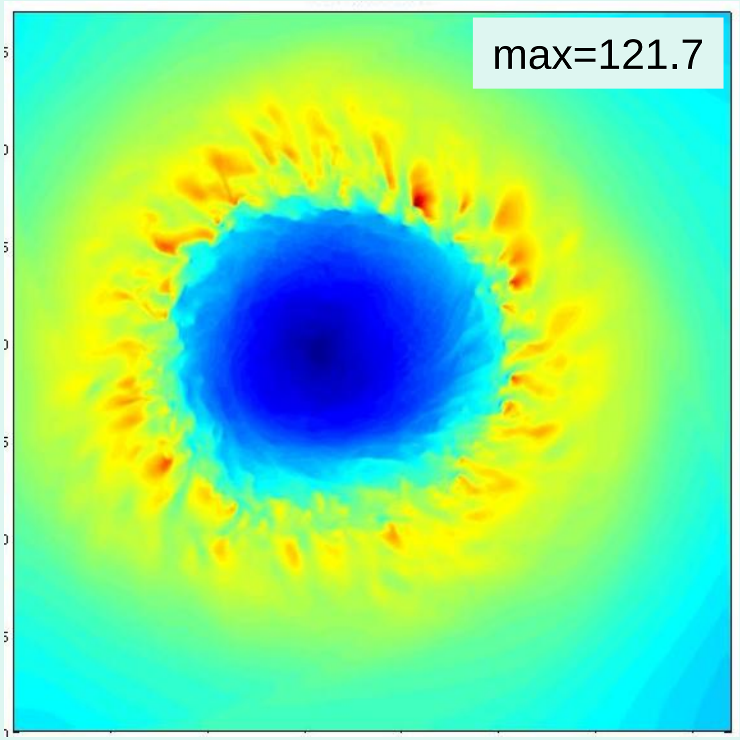


LES

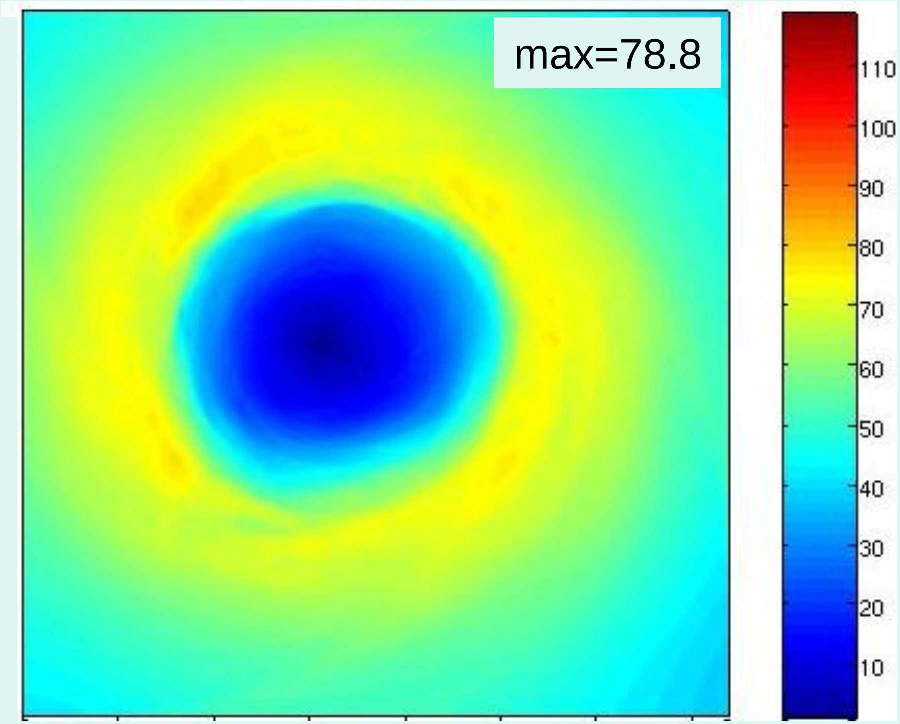
From Y. Chen et al. 2008

1-min Averaged Surface Wind

instantaneous



1-min average



37km

37 km

LES

From Y. Chen et al. 2008

LES test

- Rotunno et al. (BAMS, December 2009)
  - At less than 100 m dx gusts are resolved
  - 1-minute averages are not so dependent on resolution and actually show decrease at < 100 m compared to lower resolutions

Microphysics Options

- WSM3, WSM5, WSM6 are examples of the WRF schemes that can be used for hurricanes
- WSM3 and WSM5 have no graupel, but rimed particles seem not important to hurricanes, so such schemes are adequate
- There is significant sensitivity in intensity and track to microphysics choice
- Amount of moisture suspended in cloud versus precipitating out affects pressure field through drag terms, and this feeds back to dynamics (e.g. Bryan and Rotunno 2009, MWR)
- Work by Fovell et al. (UCLA) shows cloud/radiation interaction may affect track too

Katrina (2005) Microphysics Comparison

- Initialized August 26th (EnKF)
- GFS forecast boundaries
- 12/4/1.33 km moving nests
- 96 hours
- WSM5 default versus WSM3 and WSM6

QuickTime™ and a
decompressor
are needed to see this picture.

Microphysics Comparison

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Radiation Options

- For high model tops and multi-day simulations, shortwave schemes with ozone recommended (e.g. Goddard, RRTMG)
- Longwave options: RRTM in V3.2 will have a fix to work better with tops above 50 hPa than other schemes. RRTM also gives stronger outgoing longwave radiation (OLR) than other options currently
- There may be some sensitivity to longwave radiation (Fovell, personal communication)

Katrina (2005) Shortwave Comparison

- •Initialized August 26th (EnKF)
- •GFS forecast boundaries
- •12/4/1.33 km moving nests
- •96 hours
- •Dudhia shortwave default versus Goddard

QuickTime™ and a
decompressor
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Shortwave Radiation Comparison

QuickTime™ and a
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Cumulus Options

- For dx > 10 km, probably need a cumulus scheme.
- For hurricanes KF (cu_physics=1) is recommended in AHW. Tends to activate in outer bands, not in core region.
- For dx < 10 km, no cumulus scheme is needed, but may be used down to about 5 km.
- Cumulus schemes should be run with microphysics.

Land Surface

- Any land-surface scheme can be combined with the ocean-mixed layer model since V3.2
- No particular land-model preference for hurricane situations

Ongoing work

- Coupling with ocean models: HYCOM, POM, ROM, 3dPWP, etc.
- Coupling with wave models: SWAN, WaveWatch 3, WAM, etc.
- Improving surface flux formulations
  - Sea-spray, wave-model directional drag
- Hurricanes in climate change research
- LES idealized hurricane structure (Rotunno et al., 2009, BAMS)