Building a Weather-Ready Nation by Transitioning Academic Research to NOAA Operations
NCWCP
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Contributions to the HWRF modeling system

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Funding: NOAA/HFIP, NASA, NSF, DTC

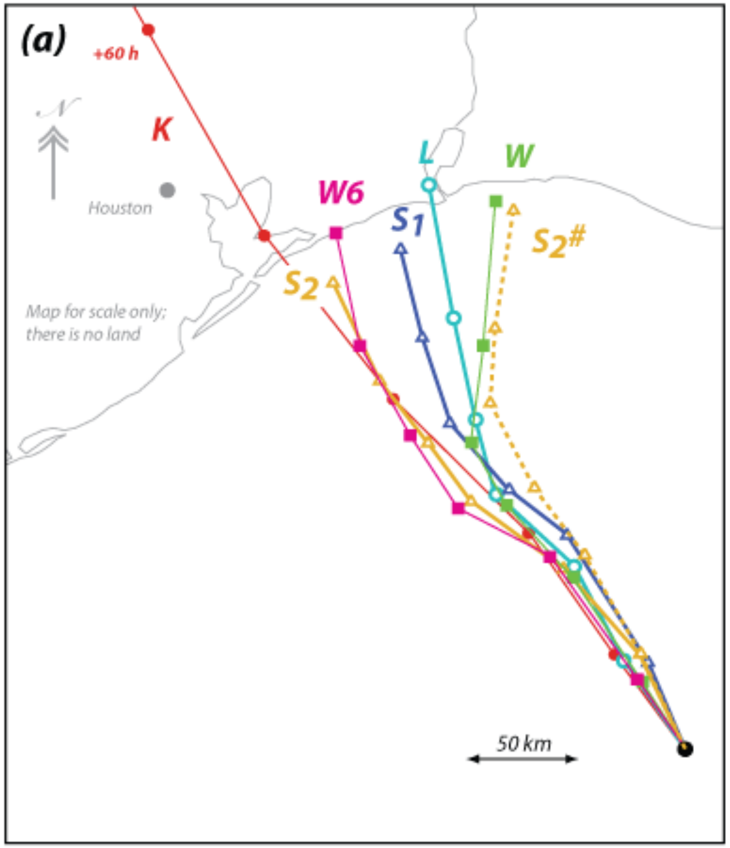
HWRF-related projects

- **Cloud-radiative forcing (CRF) in HWRF** (HFIP)
  - HWRF operational GFDL radiation scheme had issues with CRF
  - Demonstrated how and why CRF influences storm size (Bu, Fovell, and Corbosiero 2014, Fovell et al. 2016)
  - R2O: motivated adoption of modern radiation scheme (RRTMG)
  - Problem: RRTMG caused forecast skill to decrease
- **Planetary boundary layer (PBL) mixing in HWRF** (HFIP and DTC)
  - HWRF operational GFS PBL scheme performs excessive mixing, masked by CRF issue
  - Demonstrated how and why PBL mixing influences storm size (Bu, Fovell, and Corbosiero 2017)
  - R2O: contributed GFS PBL mixing improvements (Bu and Fovell 2015)
  - Opportunity: GFS PBL mixing possibly remains too deep
- **PBL depth in HWRF** (DTC and EMC)
  - R2O: Testing HWRF with YSU PBL with GFDL surface layer (ongoing)
  - Expected benefit: more realistic hurricane boundary layer structure

Background

Fovell and Su (2007), Fovell et al. (2009, 2010, 2016)

Microphysics experiment



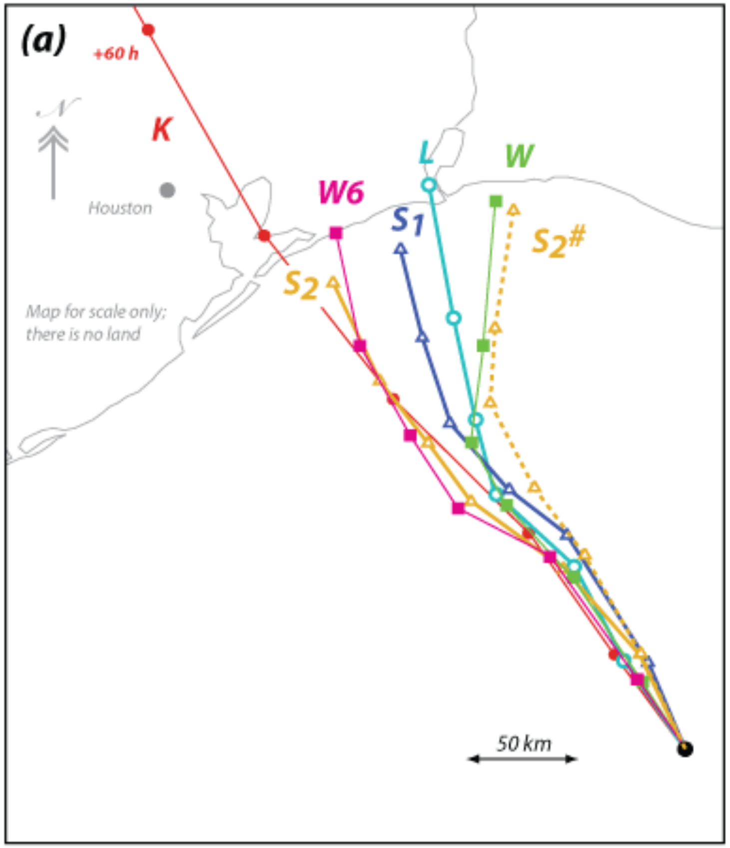
very small part of domain shown

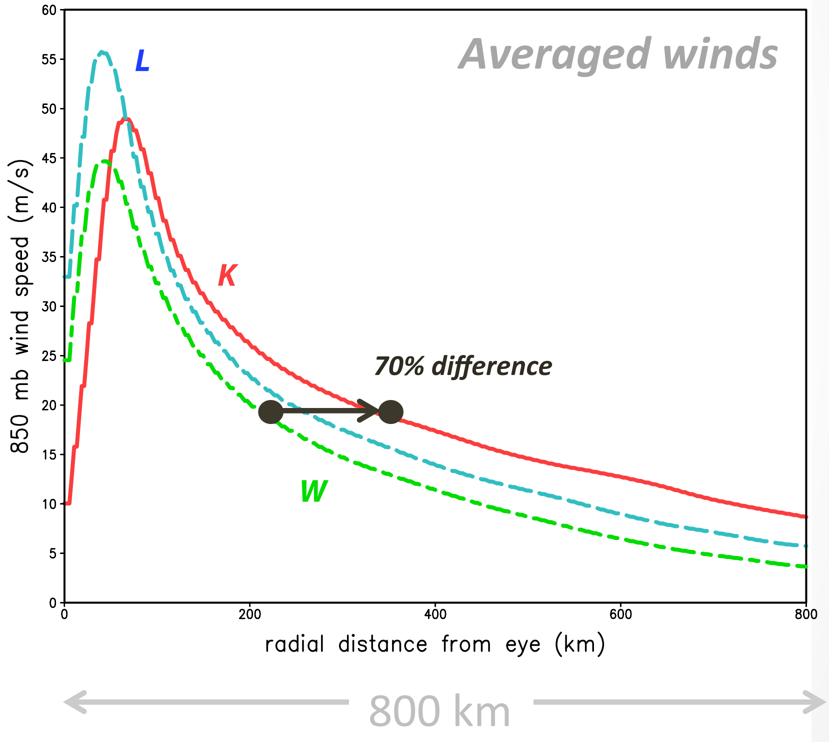
- WRF-ARW @3 km resolution, 72 h
- Uniform SST
- Single (tropical) sounding
- No initial flow
- **NO LAND**
- 7 microphysics (MPs)
- **One initial condition**

Fovell and Su (2007)
Fovell et al. (2009, 2010, 2016)

Microphysics experiment

very small part of domain shown



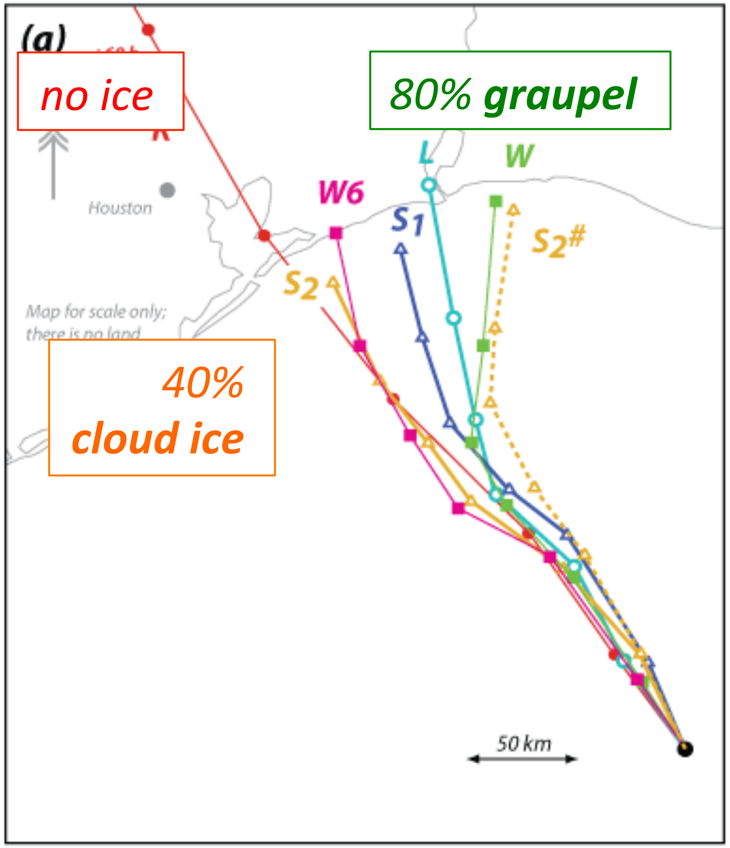


Radius of gale-force winds
(34 kt = 17.5 m/s)

Fovell and Su (2007)
Fovell et al. (2009, 2010, 2016)

Microphysics experiment

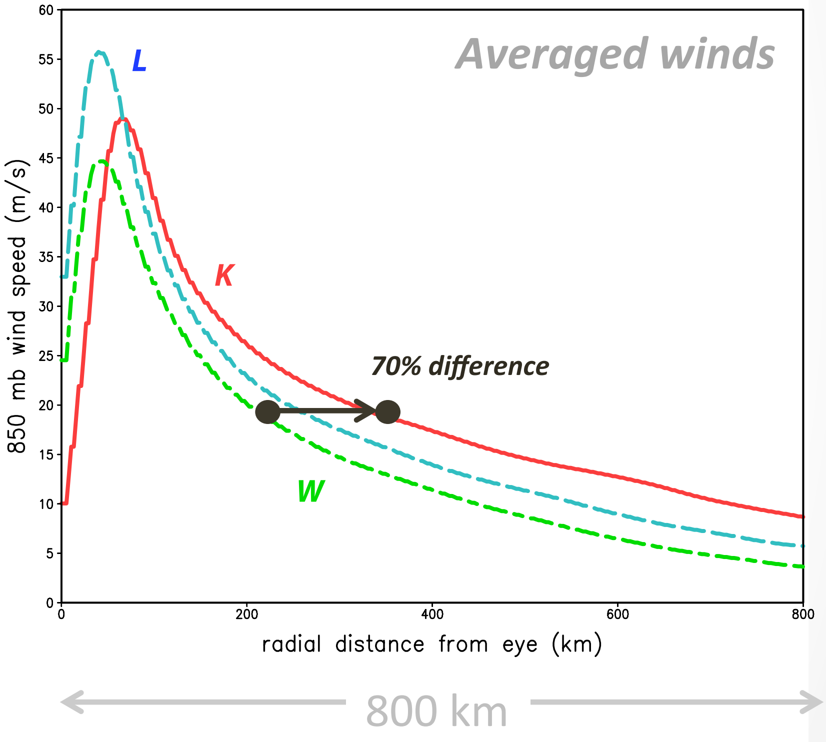
very small part of domain shown



no ice

80% **graupel**

40%
cloud ice



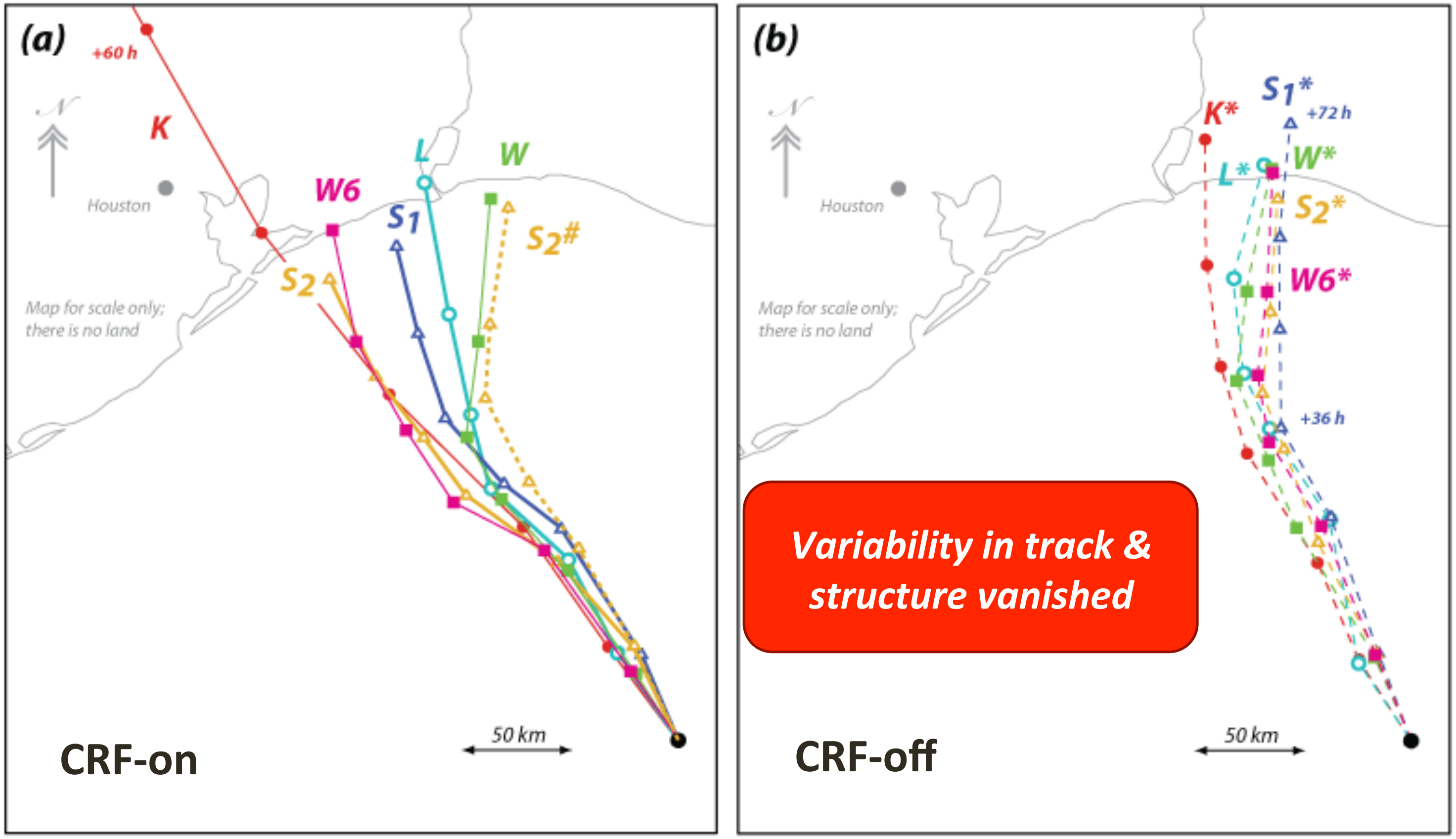
Averaged winds

70% difference

800 km

Fovell and Su (2007)
Fovell et al. (2009, 2010, 2016)

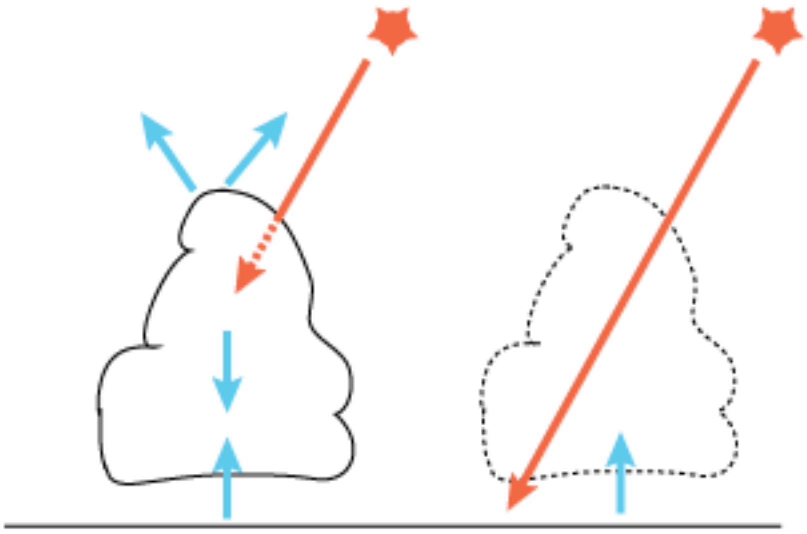
Influence of cloud-radiative forcing (CRF)



Variability in track & structure vanished

Retains clear-sky forcing
Makes clouds transparent

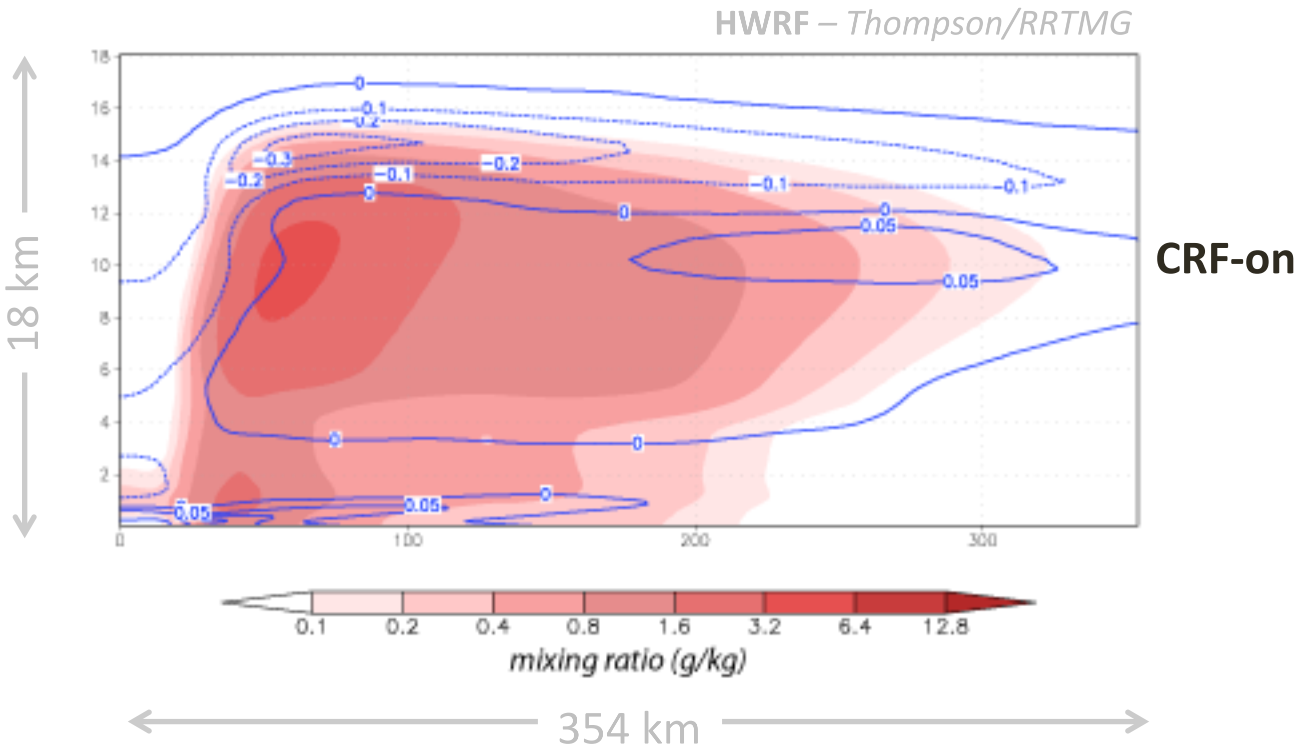
Fovell et al. (2010)



How and why CRF influences tropical cyclone size

Bu, Fovell, and Corbosiero (2014, JAS)

Azimuthally/temporally averaged structure

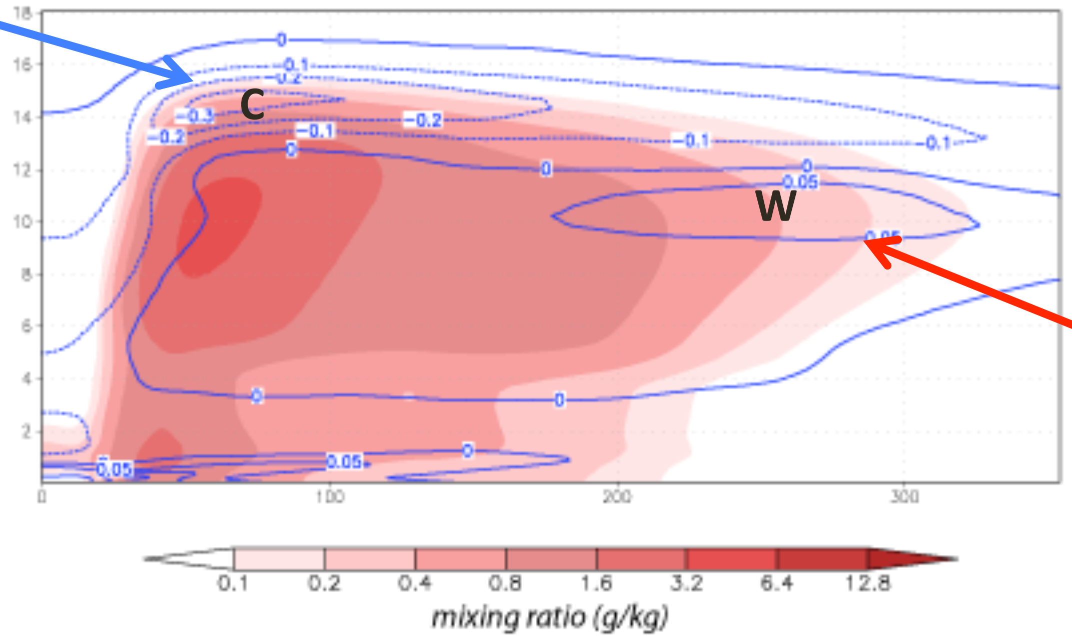


Condensate (shaded) and net radiative forcing (K/h)

Bu et al. (2014)

Azimuthally/temporally averaged structure

HWRF – *Thompson/RRTMG*



net cooling
~ 7 K/day

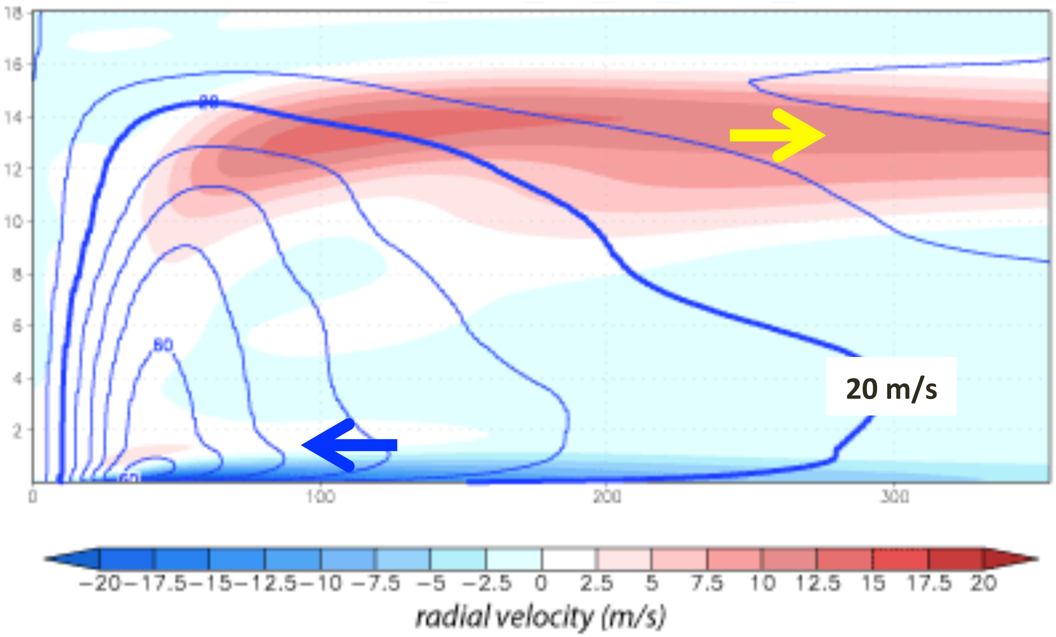
net warming
~ 1 K/day

Condensate (shaded) and net radiative forcing (K/h)

Net radiation = LW + SW and includes background (clear-sky) forcing
Radiation contour interval differs for positive and negative values

Cooling ci=0.1 K/h
Warming ci = 0.05 K/h

Azimuthally/temporally averaged structure



HWRF – *Thompson/RRTMG*

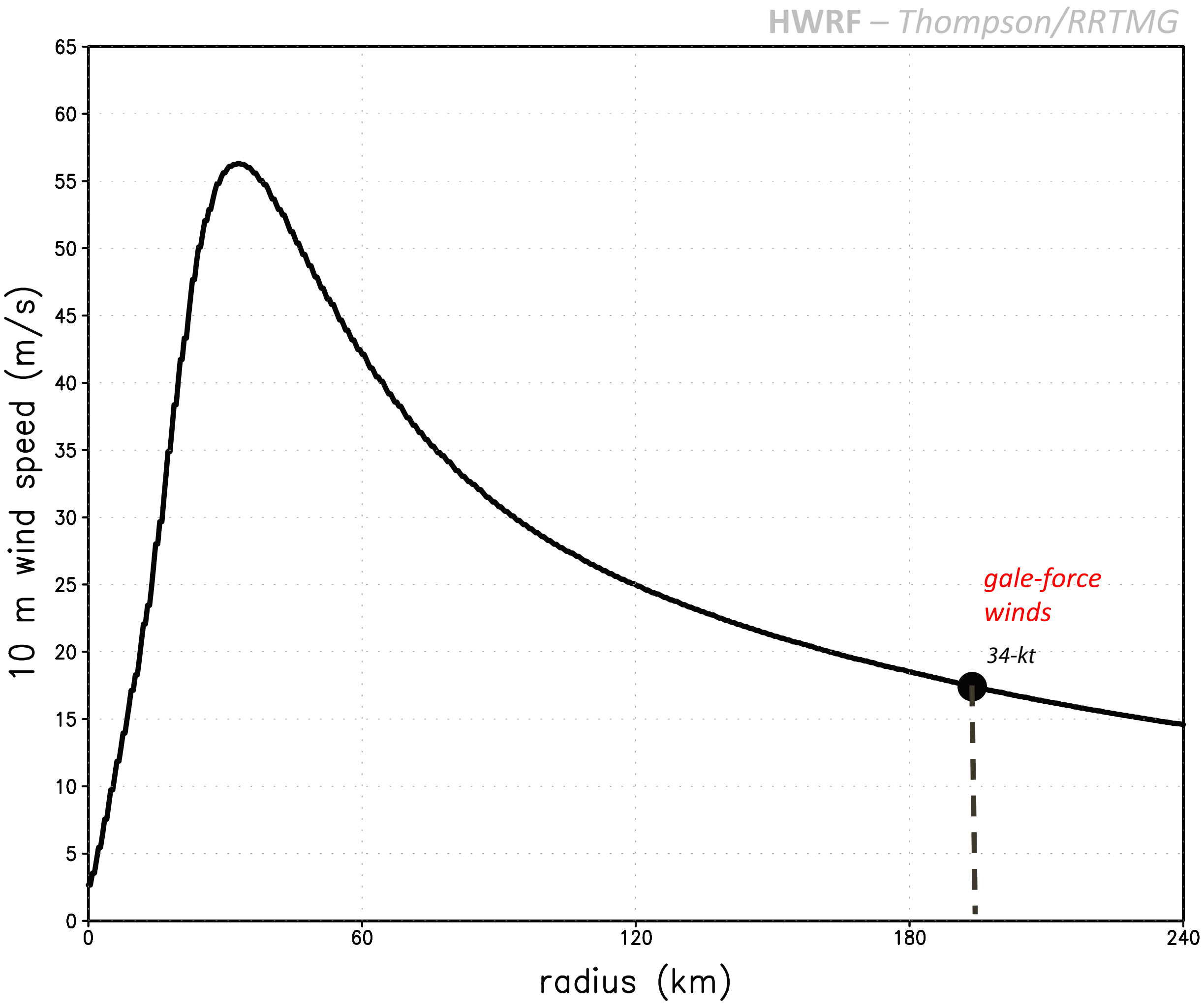
20 m/s

20 m/s
~ gale-force

Radial (shaded) and tangential velocity (m/s)
Temporally and azimuthally averaged

Bu et al. (2014)

Averaged 10-m winds

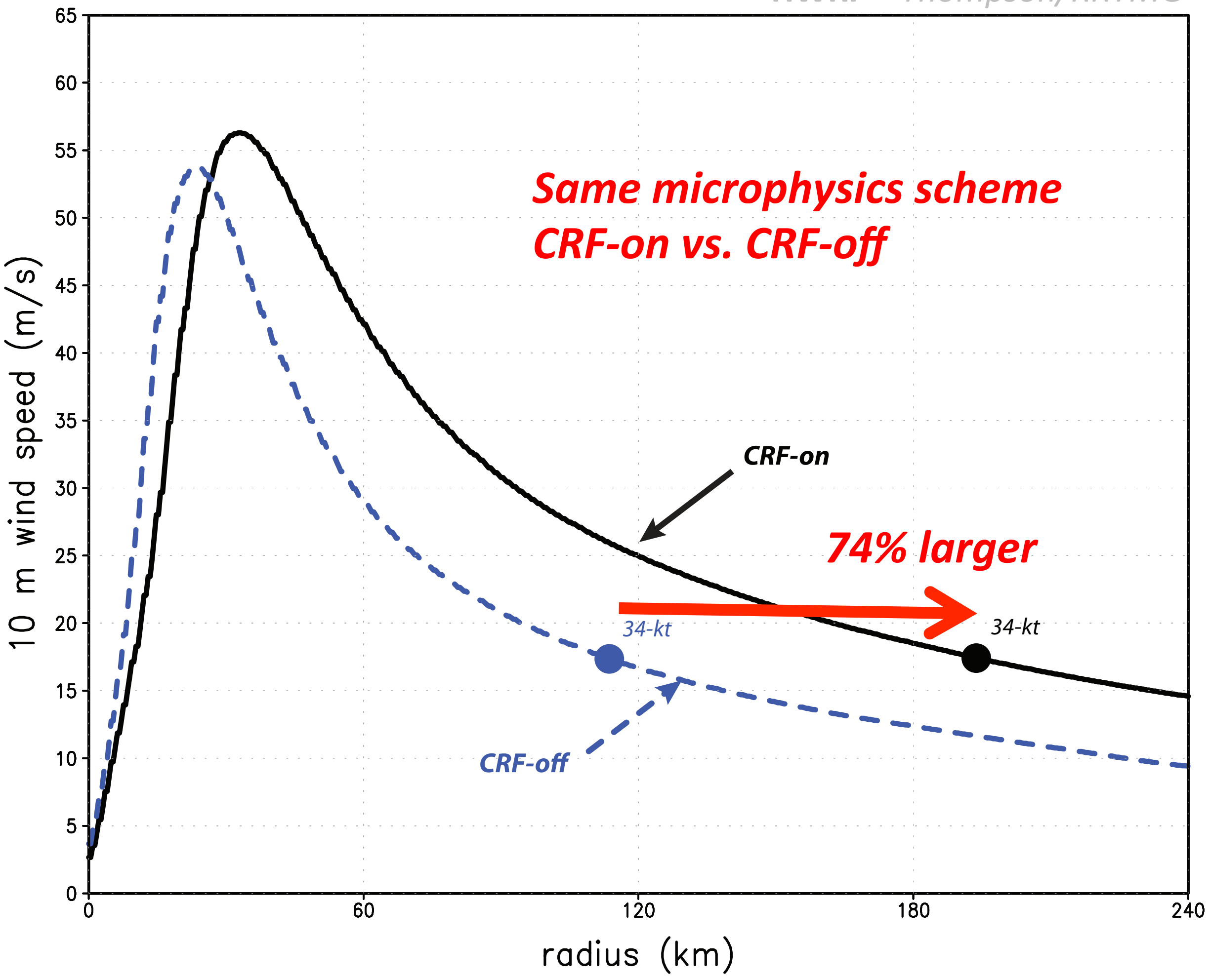


(Actually cat. 4-5 but asymmetric)

Bu et al. (2014)

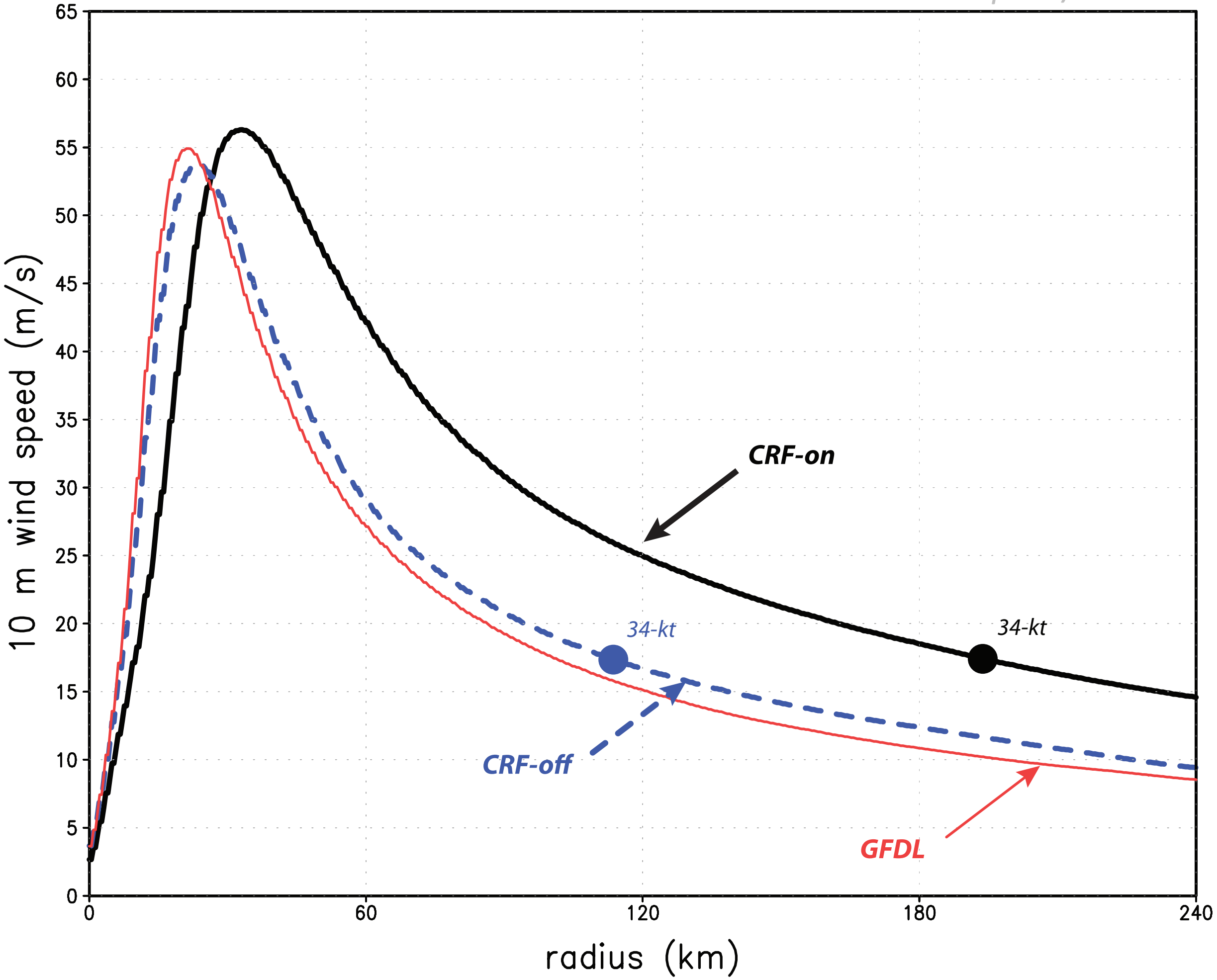
Averaged 10-m winds

HWRF – *Thompson/RRTMG*



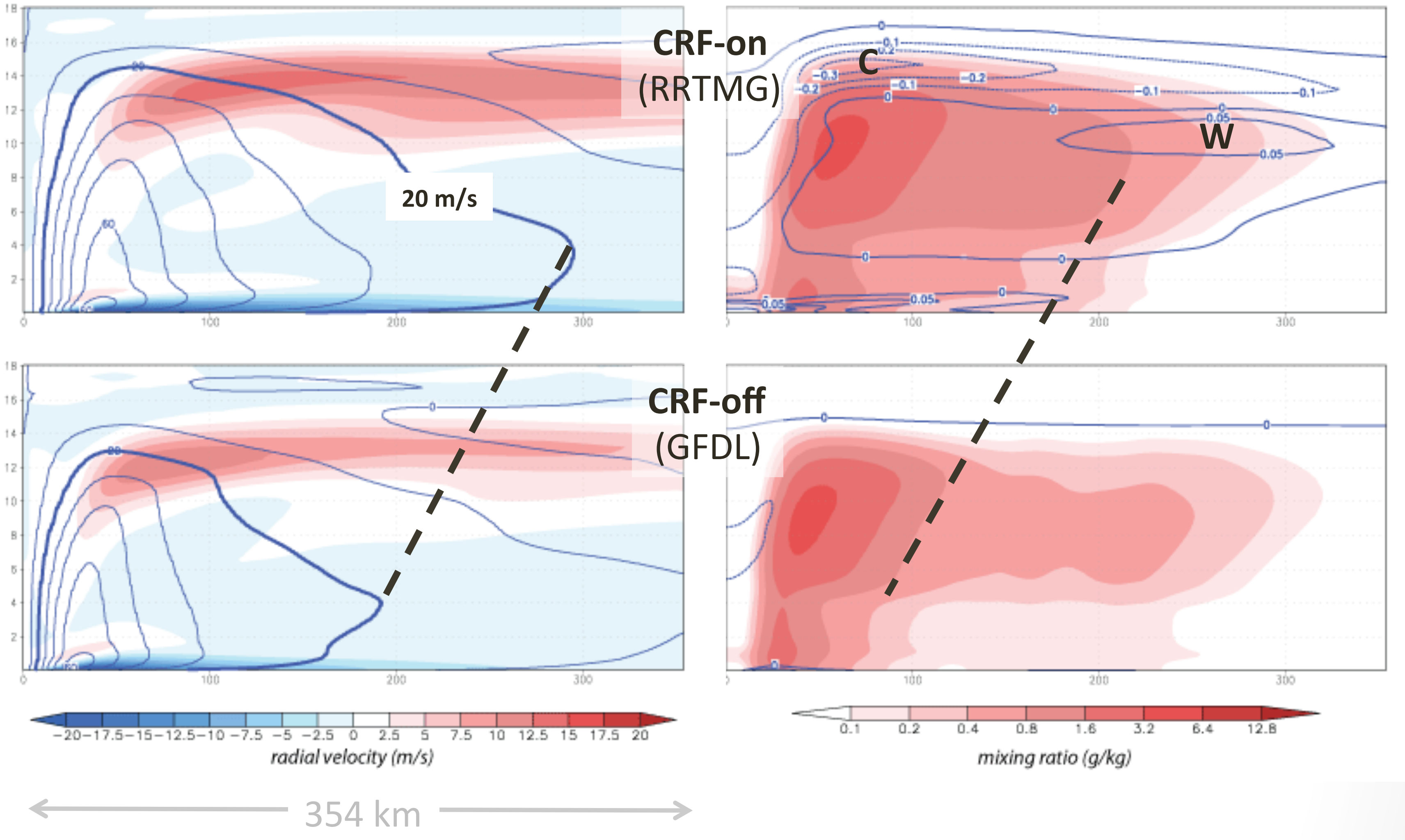
Averaged 10-m winds

HWRF – *Thompson/RRTMG*



Original HWRF radiation (no CRF)

HWRF – *Thompson/RRTMG*

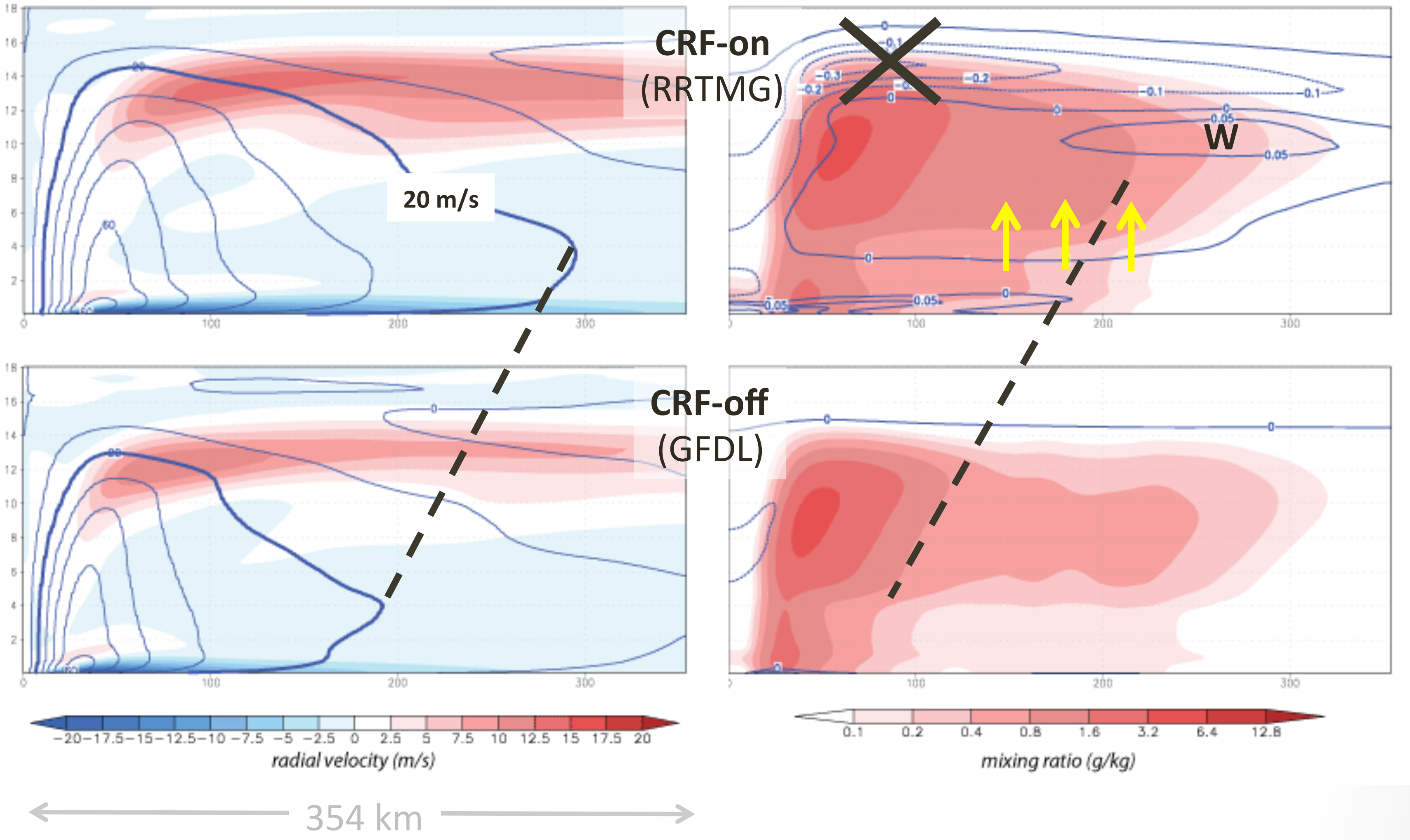


Radial & tangential velocity

Condensate & net radiative forcing

Bu et al. (2014)

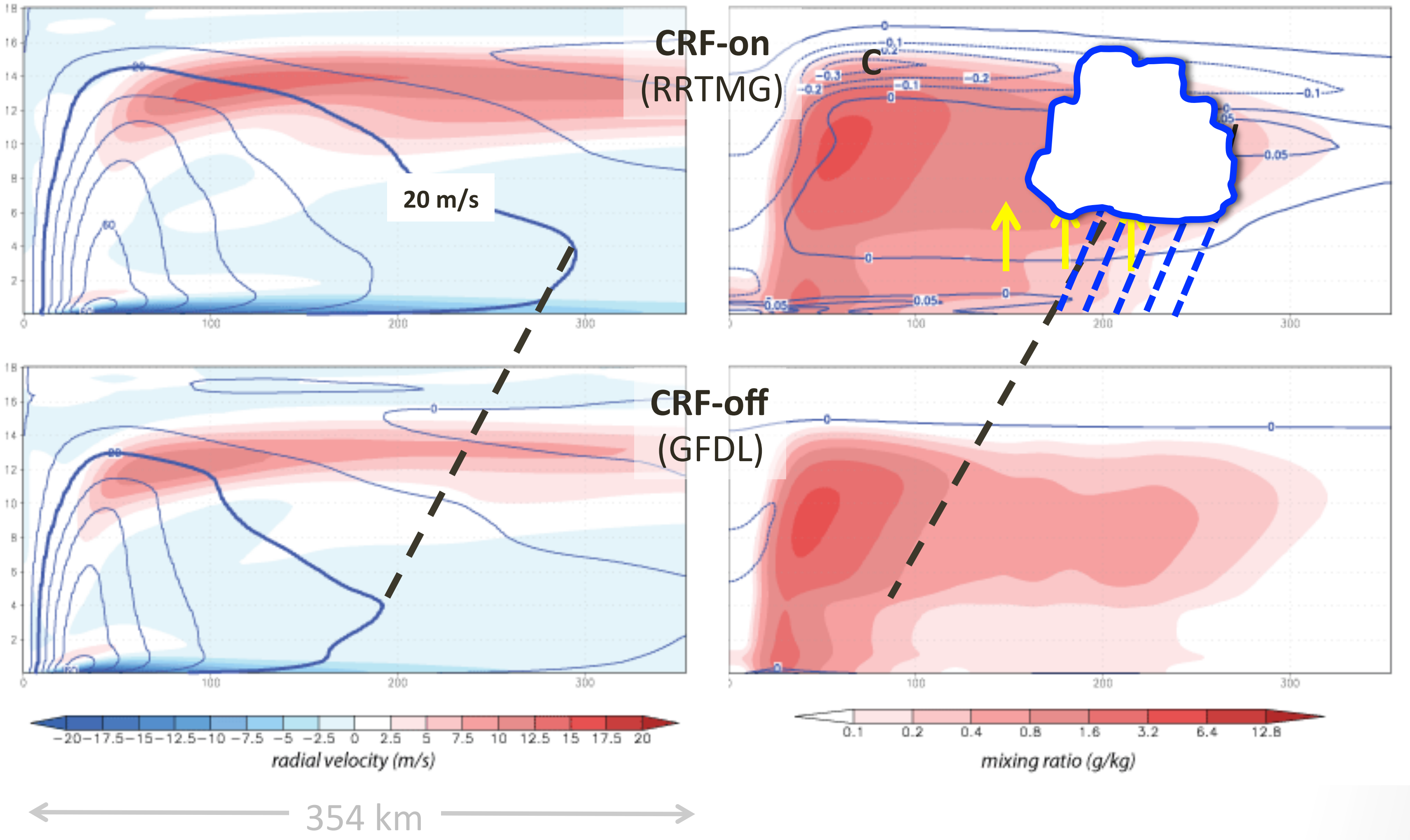
HWRF – *Thompson/RRTMG*



Radial & tangential velocity

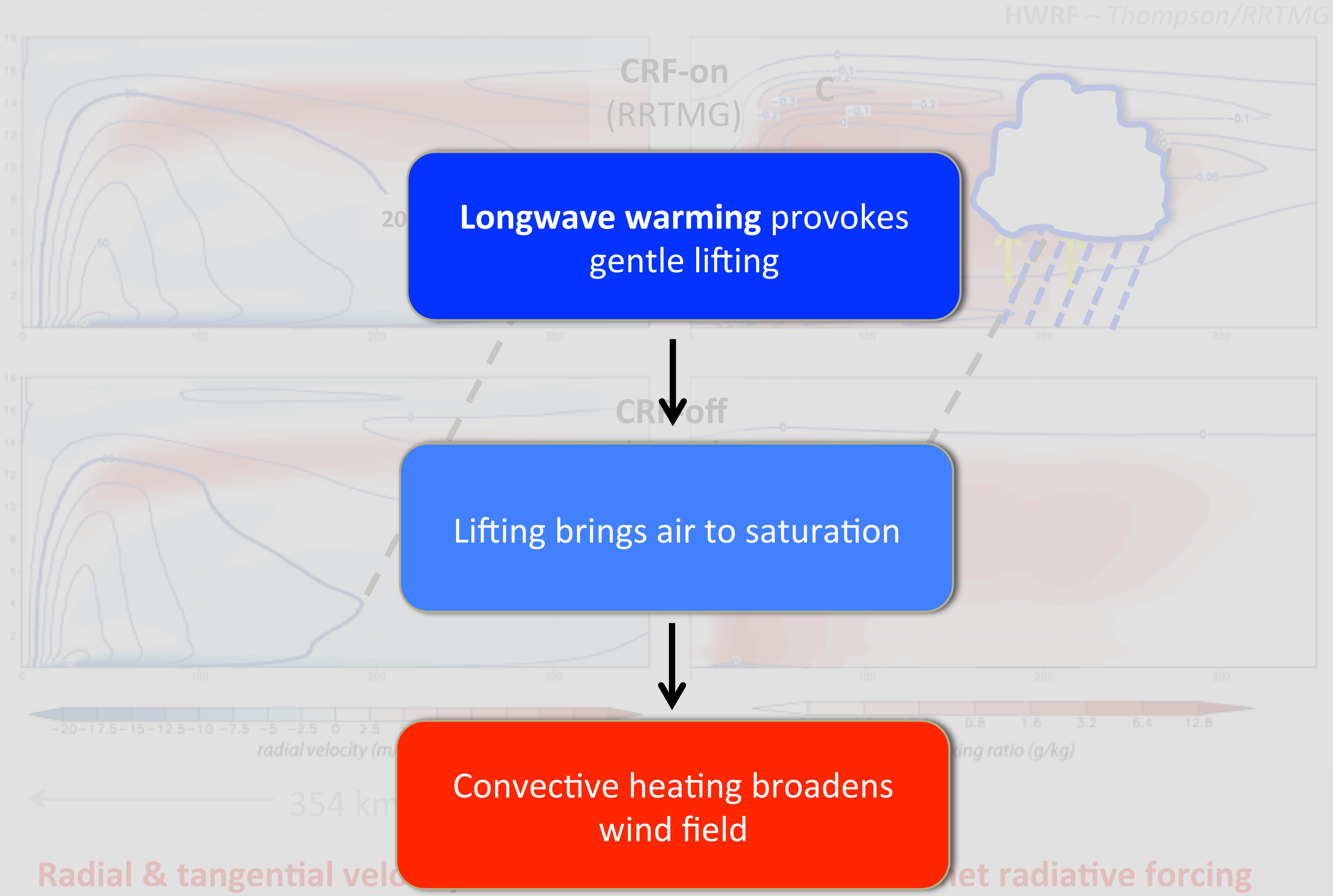
Condensate & net radiative forcing

HWRF – *Thompson/RRTMG*



Radial & tangential velocity

Condensate & net radiative forcing



Longwave warming provokes gentle lifting

↓

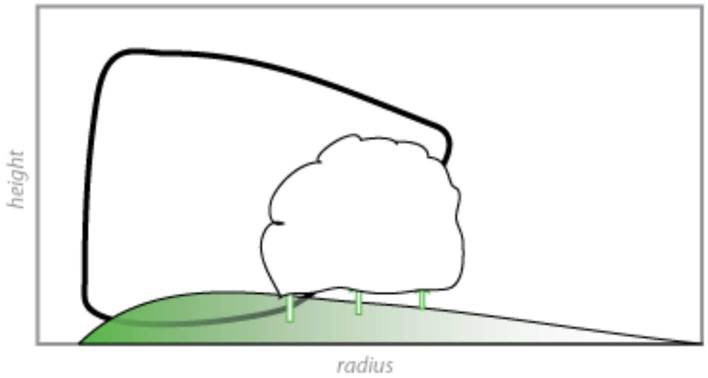
Lifting brings air to saturation

↓

Convective heating broadens wind field

CRF summary

- Longwave warming includes weak, persistent ascent, leading to enhanced outer convective activity, expanded size
- **Storm size** depends on **microphysics** because hydrometeor species result in different **radiative forcings**
  - Other factors being equal, more CRF (ice > snow > graupel) leads to wider storms
  - Bu, Fovell, and Corbosiero (2014) and Fovell et al. (2016)
- R2O: GFDL radiation had deficient cloud-radiative forcing
- GFDL ➔ RRTMG transition *decreased* forecast skill largely due to development of **positive storm size bias** in DTC tests
- Something else was working to horizontally expand storms: **PBL moisture mixing**



How and why PBL mixing influences tropical cyclone size

Bu, Fovell, and Corbosiero (2017, JAS)

A common PBL approach

Troen and Mahrt (1986)

$$K_m = \kappa w_s z \left(1 - \frac{z}{h}\right)^p$$

$$w_s = \frac{u_*}{\phi} \qquad p = 2$$

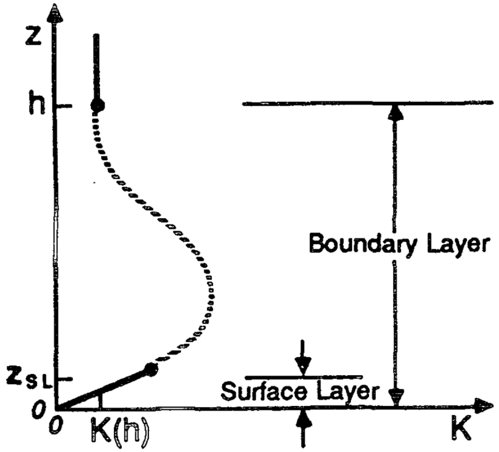


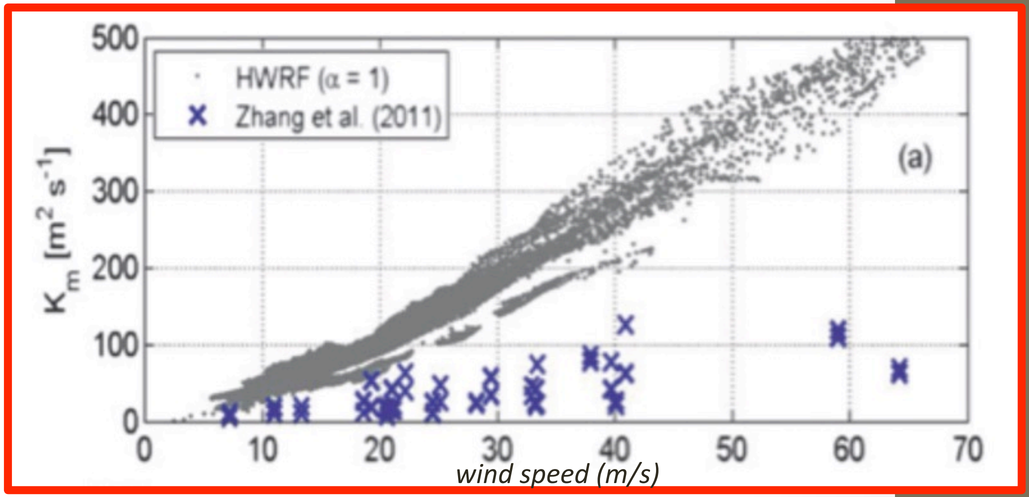
FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

Given PBL depth *h*,
scheme provides vertical mixing
magnitude and depth

GFS PBL scheme

Troen and Mahrt (1986)

GFS PBL scheme
(used by operational HWRF)



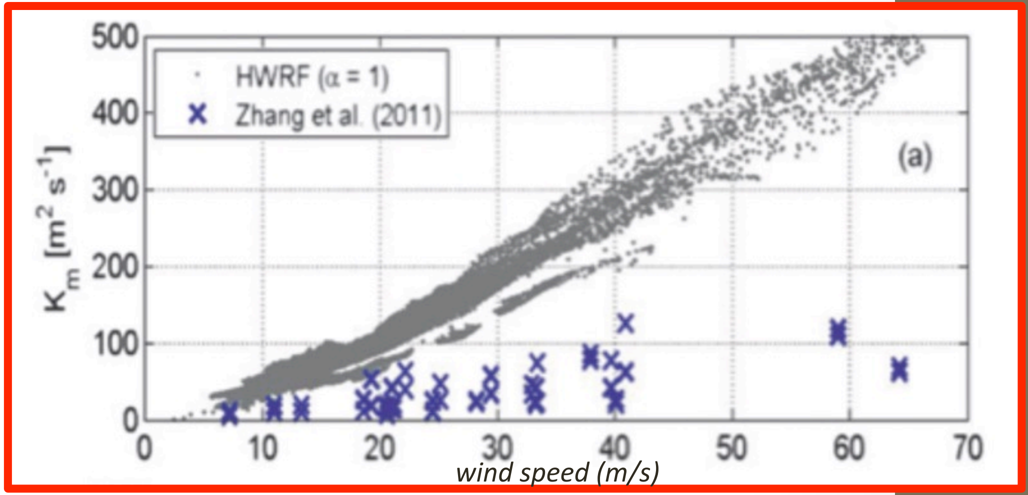
$$K_m = \kappa w_s z \left(1 - \frac{z}{h}\right)^p$$

GFS PBL scheme generates **excessive mixing** relative to available observations (Gopal et al. 2012; Zhang et al. 2011)

GFS PBL scheme

Troen and Mahrt (1986)

GFS PBL scheme
(used by operational HWRF)



GFS PBL scheme generates **excessive mixing** relative to available observations (Gopal et al. 2012; Zhang et al. 2011)

$$K_m = \boxed{\alpha}\kappa w_s z\left(1-\frac{z}{h}\right)^p$$

Gopal et al. (2012)

α parameter added to constrain mixing

Sensitivity to α

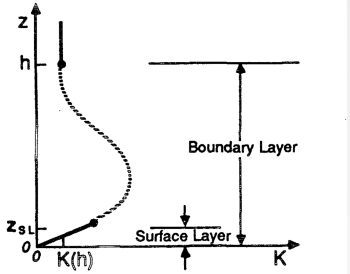
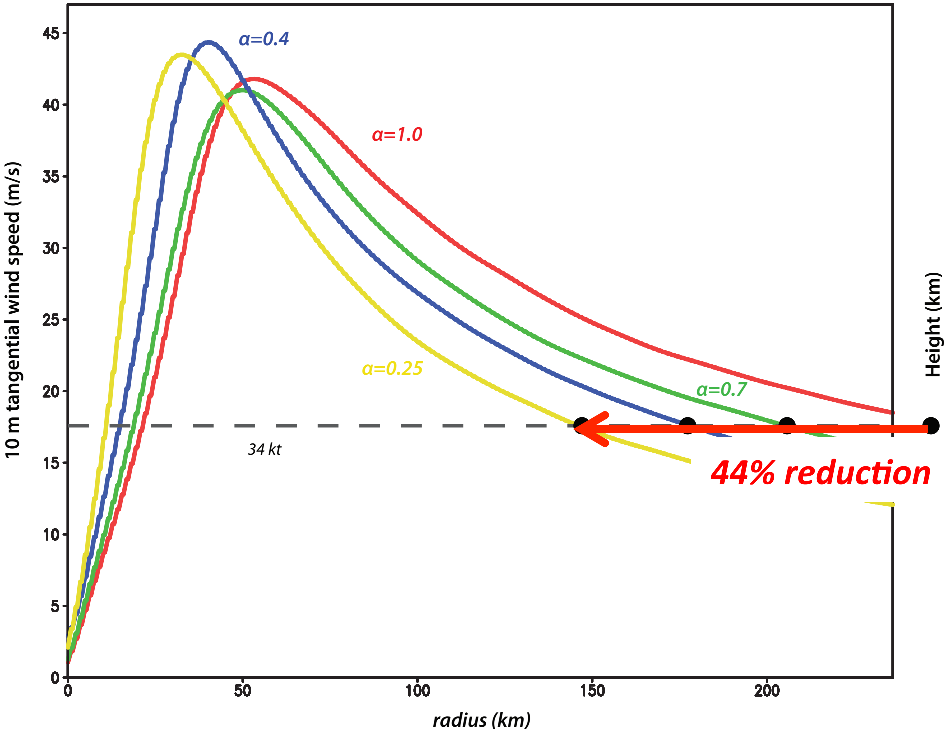


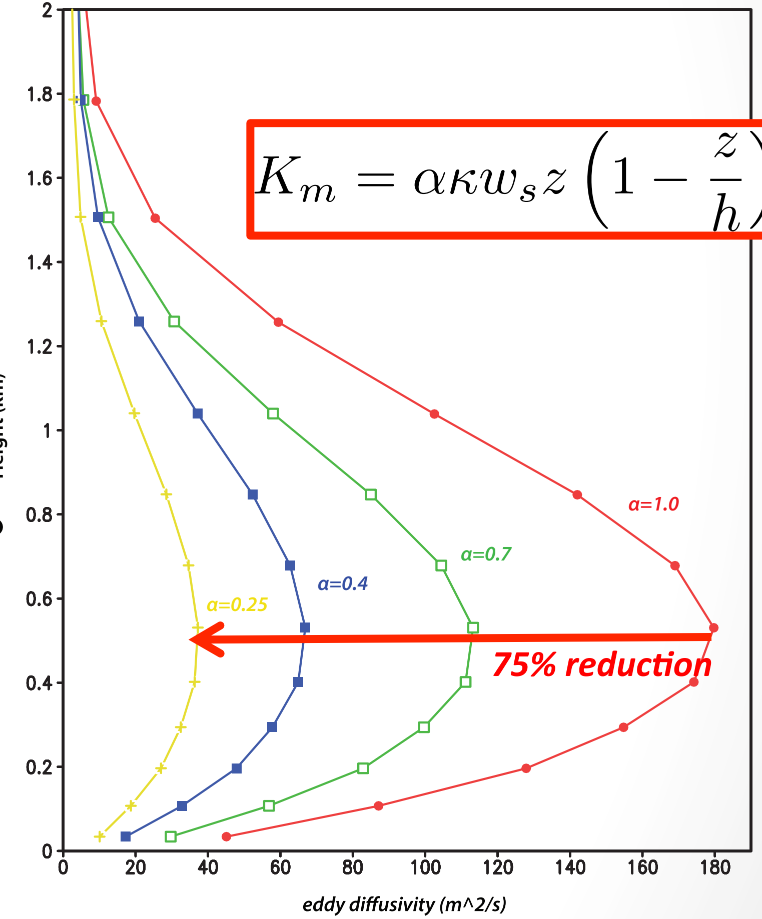
FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

10-m winds



44% reduction

K_m profiles

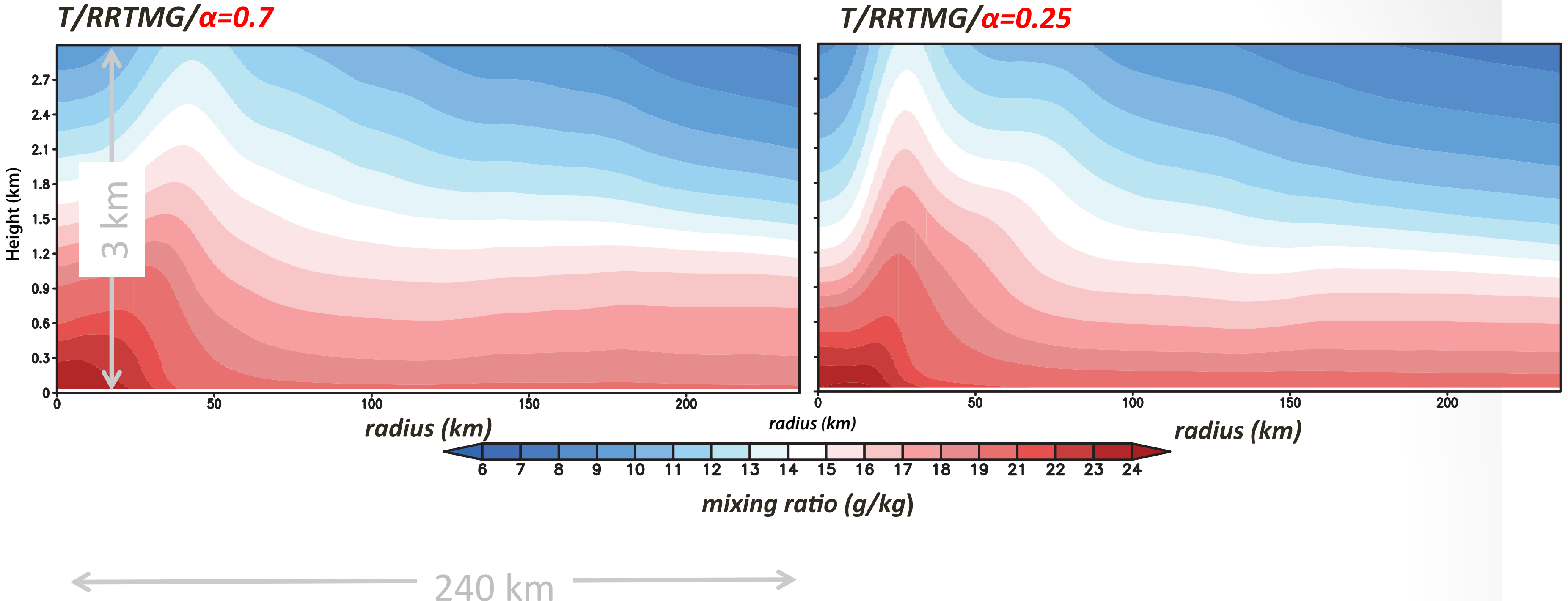


$$K_m = \alpha \kappa w_s z \left(1 - \frac{z}{h}\right)^p$$

75% reduction

Bu et al. (2017)

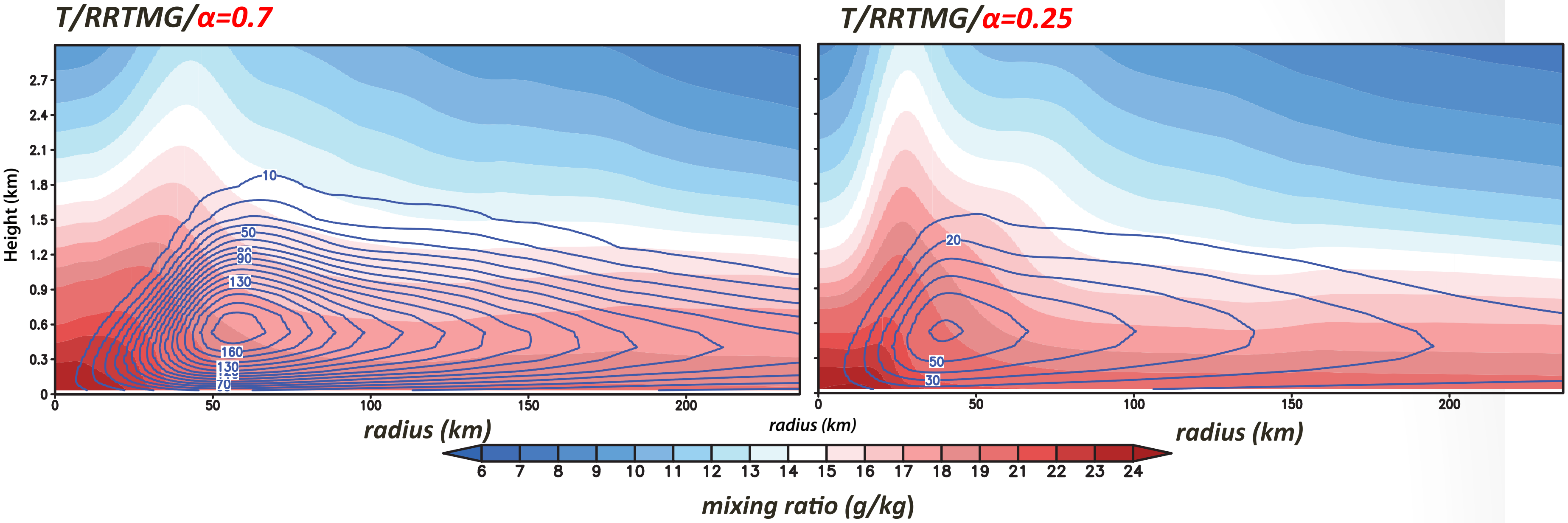
HWRF – *Thompson/RRTMG*


T/RRTMG/α=0.7

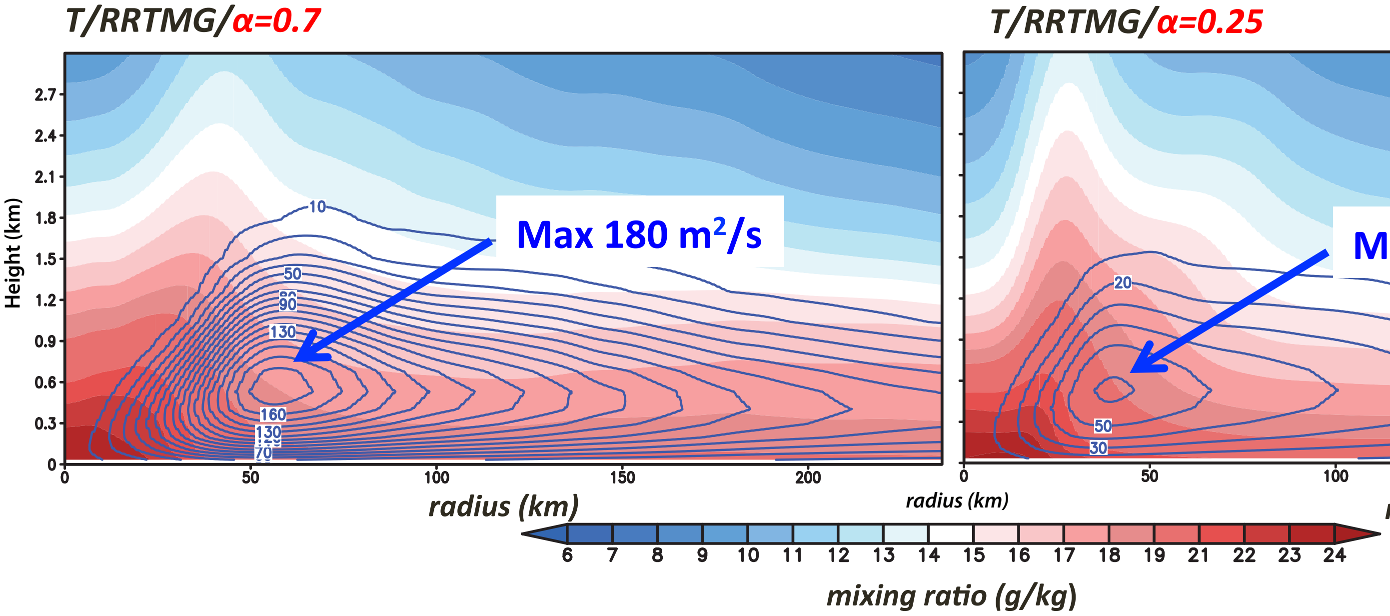
T/RRTMG/α=0.25

Water vapor
(colored, g/kg)

Bu et al. (2017)



Water vapor
(colored, g/kg) &
eddy diffusivity
(contour)



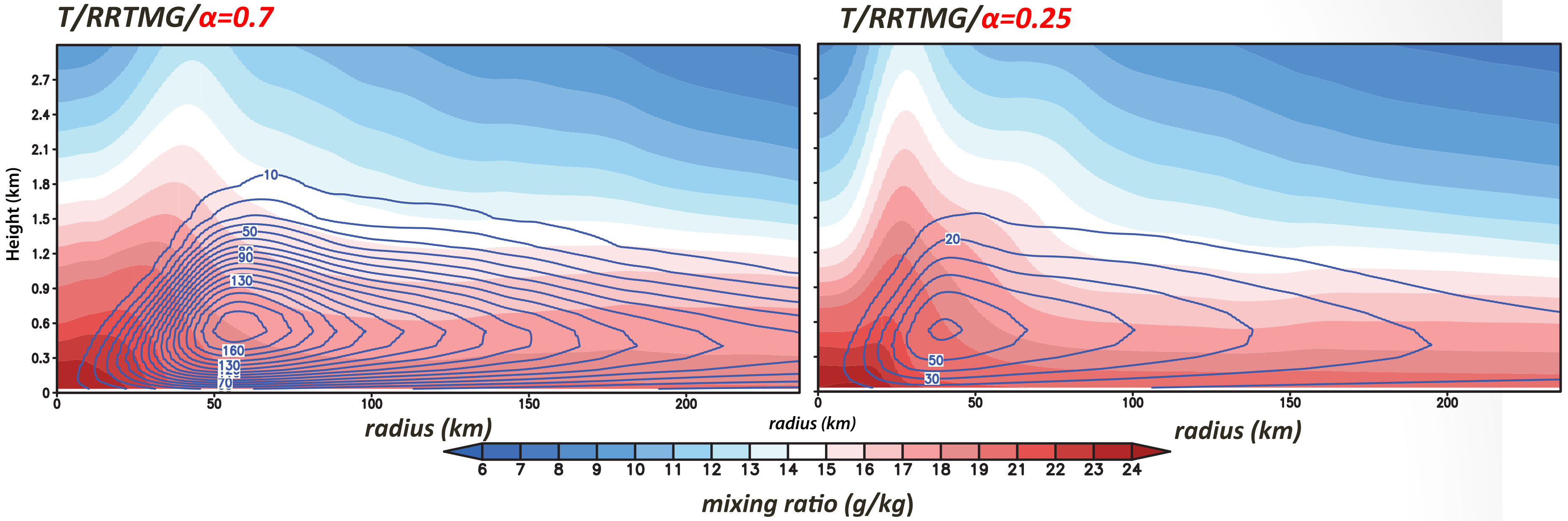
T/RRTMG/α=0.7

T/RRTMG/α=0.25

Max 180 m^2/s

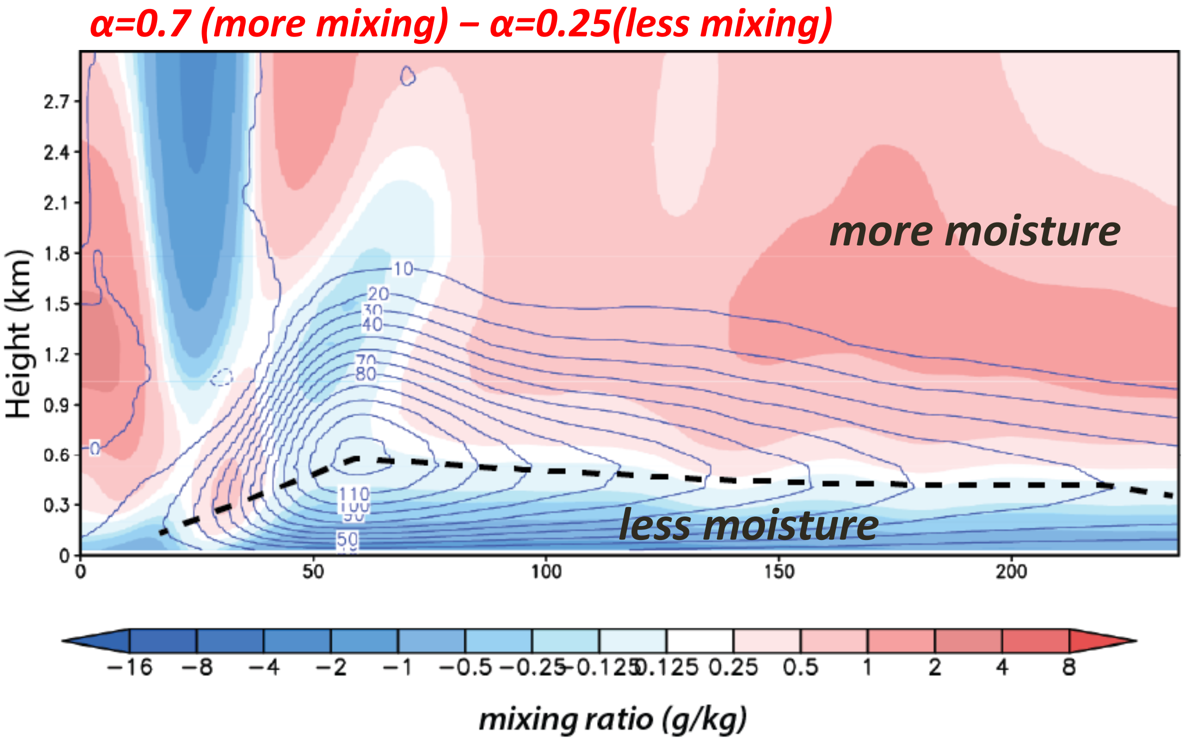
Max 60 m^2/s

Water vapor
(colored, g/kg) &
eddy diffusivity
(contour)



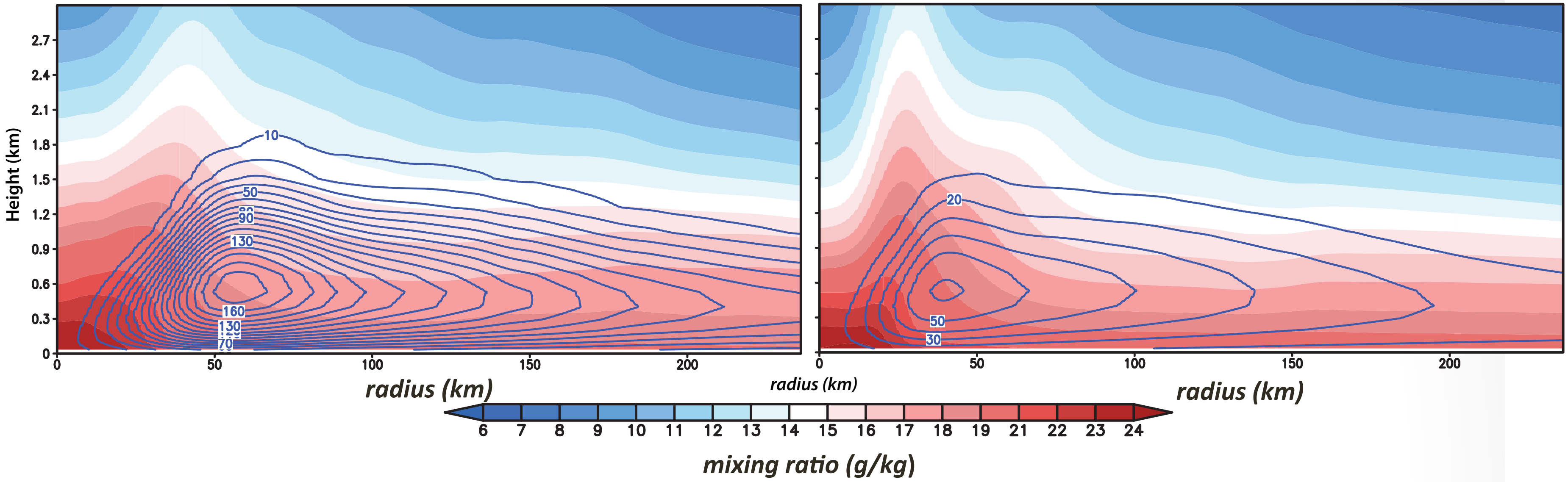
T/RRTMG/α=0.7

T/RRTMG/α=0.25



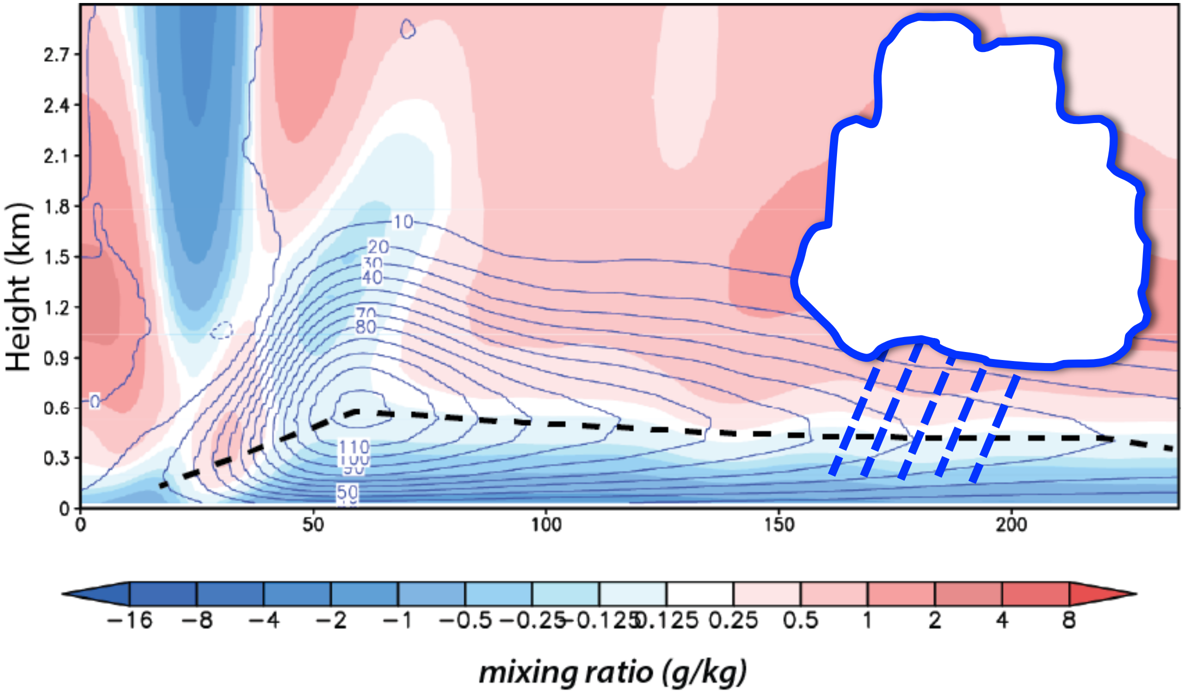
α=0.7 (more mixing) − α=0.25(less mixing)

Water vapor (colored, g/kg) & ***eddy diffusivity*** (contour) difference fields due to α

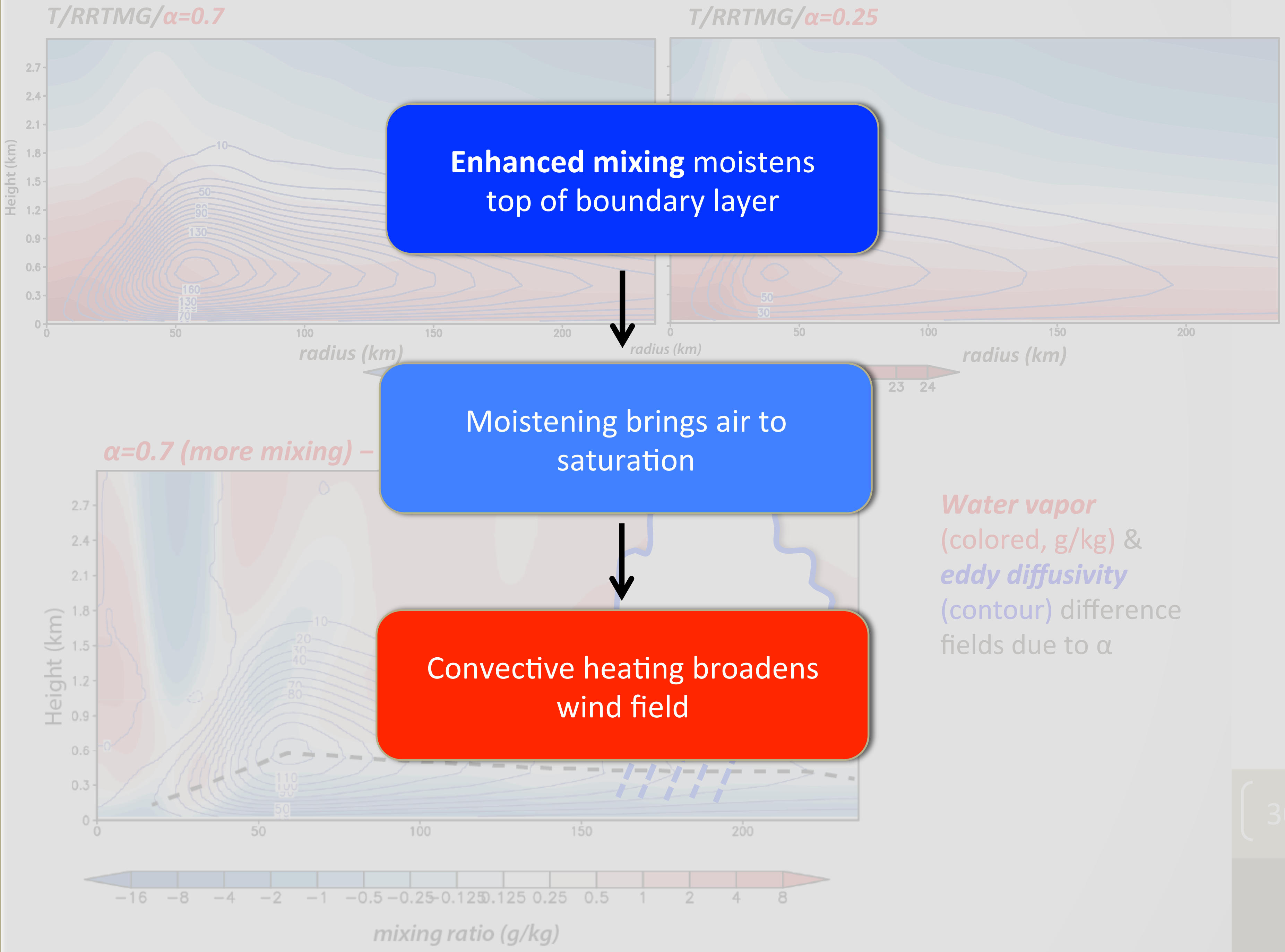

T/RRTMG/α=0.7

T/RRTMG/α=0.25

α=0.7 (more mixing) – α=0.25(less mixing)



Water vapor (colored, g/kg) & ***eddy diffusivity*** (contour) difference fields due to α



Enhanced mixing moistens top of boundary layer

↓

Moistening brings air to saturation

↓

Convective heating broadens wind field

Water vapor (colored, g/kg) & *eddy diffusivity* (contour) difference fields due to α

PBL summary

- Mixing moisture upward raises absolute and relative humidity, leading to enhanced outer convective activity, expanded size
- Excessive mixing in GFS scheme was masking CRF problem!
  - Although Gopal et al.'s α reduced mixing… *still* too large in HWRF
- **Storm size** depends on **PBL schemes** because they result in **different PBL depths and mixing strengths**
  - Other factors being equal, more mixing leads to wider storms
  - Bu, Fovell, and Corbosiero (2017)
- Problem: α has no correct value, applied everywhere (outside hurricane, even over land)
  - R20: we contributed fundamentally different way of limiting mixing via observations and confine it to hurricane core (Bu and Fovell 2015)
- Opportunity: GFS PBL's cousin, YSU, produces **very different results**

GFS vs. YSU

Troen and Mahrt (1986)

GFS PBL scheme
(used by operational HWRF)

YSU PBL scheme
(often used in WRF-ARW)

Differ in how they determine
PBL depth *h*

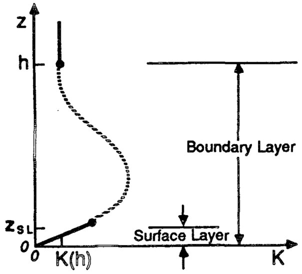
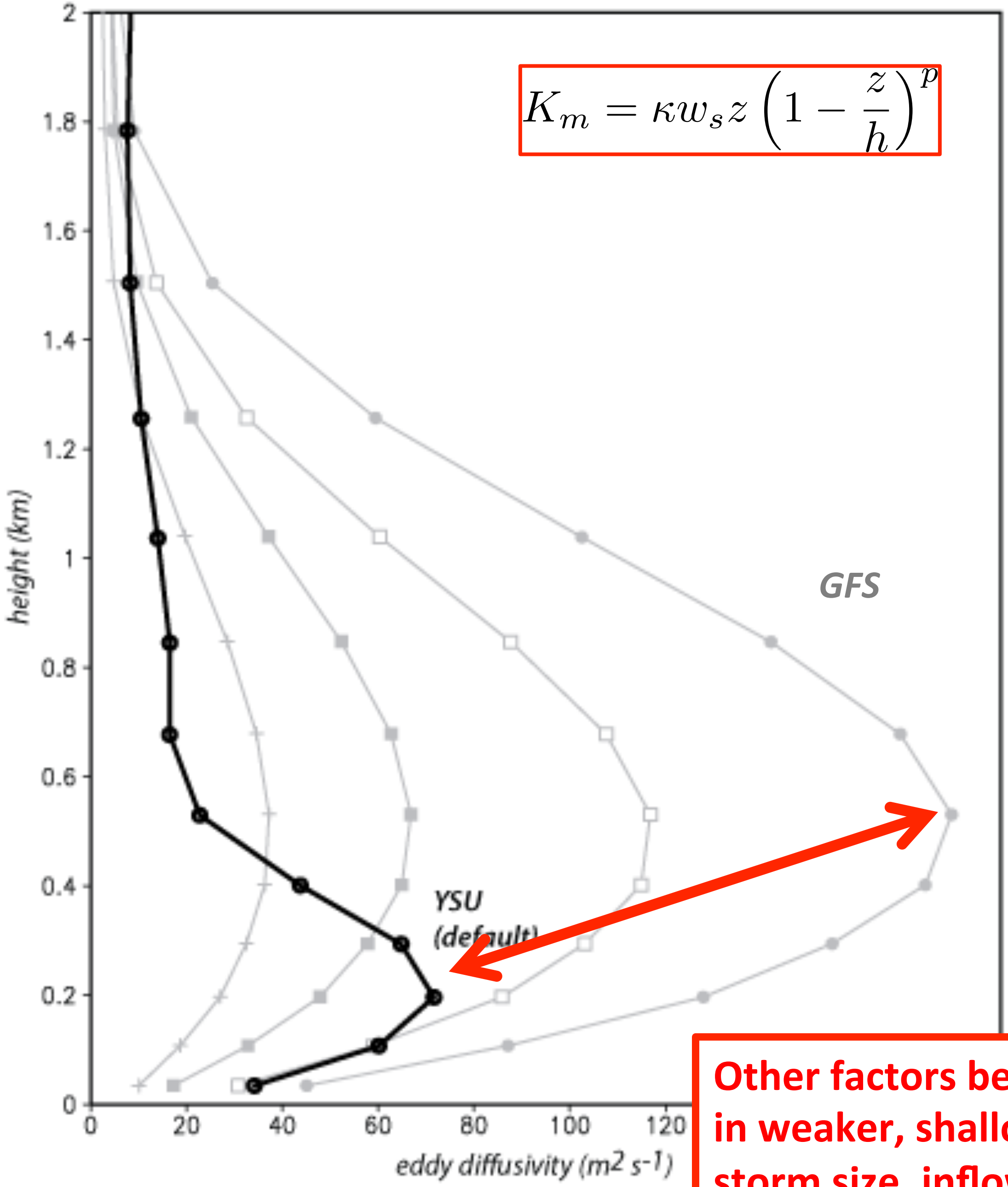


FIG. 1. Typical variation of eddy viscosity *K* with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).



$$K_m = \kappa w_s z \left(1 - \frac{z}{h}\right)^p$$

HWRF GFS vs. YSU

Eddy mixing

Variation of Critical Richardson number

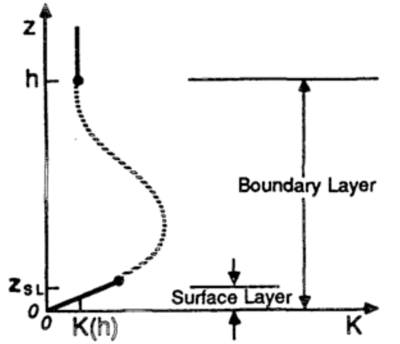
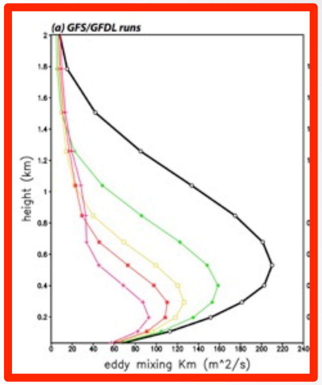


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

Other factors being equal, YSU results in weaker, shallower mixing, which influences storm size, inflow strength, and intensity

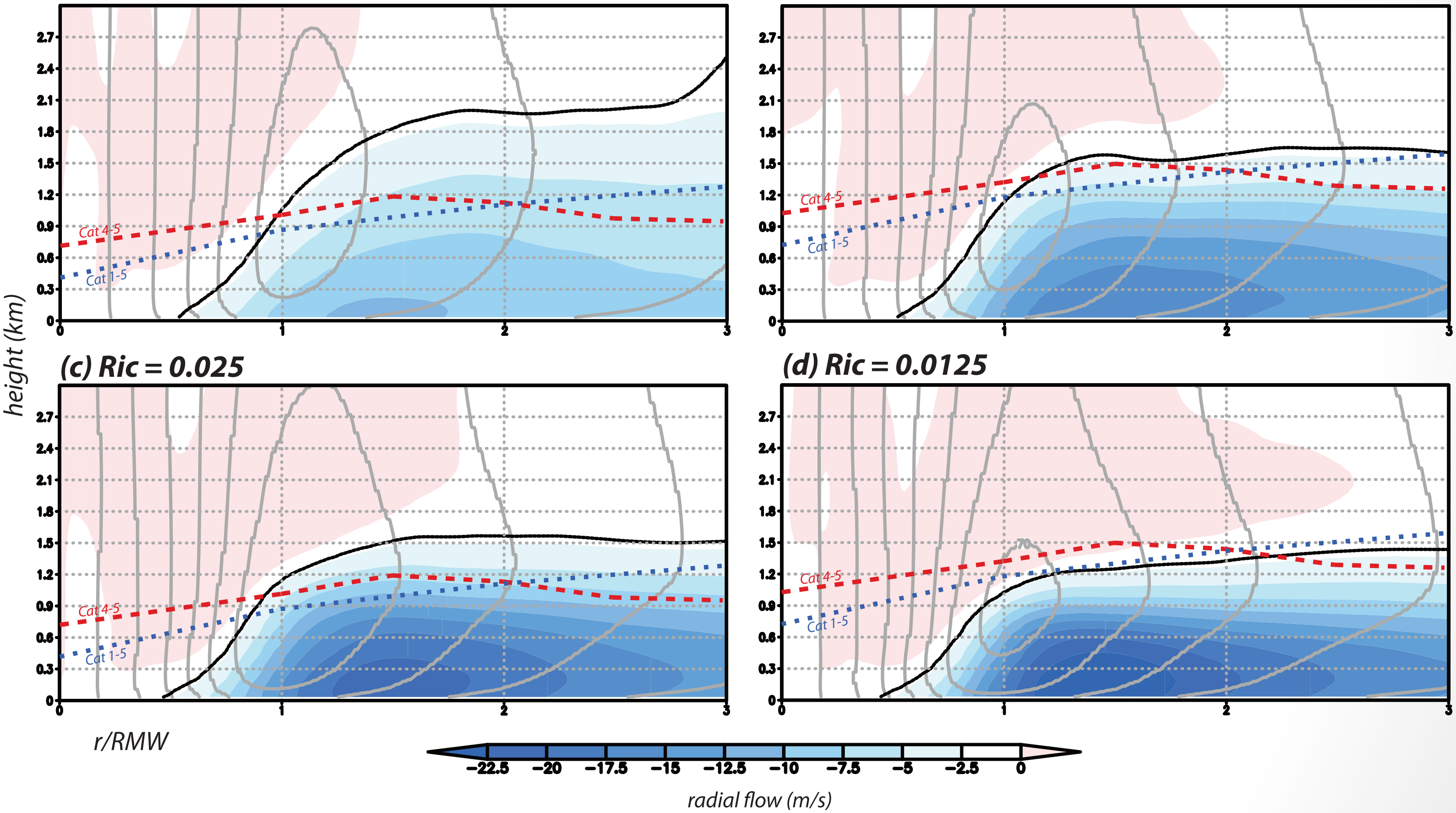
GFS with different Ri_c



(a) Ric = 0.25

unmodified

(b) Ric = 0.05



Zhang et al. (2011) composite inflow layer depths also shown

Current work summary

- Other factors being equal, YSU PBL results in weaker/ shallower mixing than GFS PBL, even with α adjustment
- Principal difference: **how PBL depth is determined** (Ri_c)
- R2O: Made YSU compatible with GFDL surface layer, so we can do head-to-head GFS vs. YSU testing
- Ongoing: **comparison with observations** (Zhang et al. 2011a K_m, Zhang et al. 2011b inflow profiles, Vickery et al. 2009 wind profiles, etc..)
- Ongoing: **retrospective hurricane tests** with versions of YSU: track, intensity, size (with Sergio Abarca of EMC), supported by DTC
  - Plan on looking at TKE-based schemes (e.g., MYNN)

Final comments

- Practical/operational vs. curiosity-driven research
- DTC resources were crucial to our HWRF work
    - documentation, code support, scientific expertise, retrospective experiments and tests, training, test data sets, visitor support, and much more
    - Went from never having used HWRF to finding a serious flaw in < 1 week ("different eyes")
- I wish the operational side weren't so "opaque"
    - Never met those people, didn't know what they were doing or what their priorities were
    - Working at cross purposes?
- Combining operational AND curiosity-driven research can be beneficial

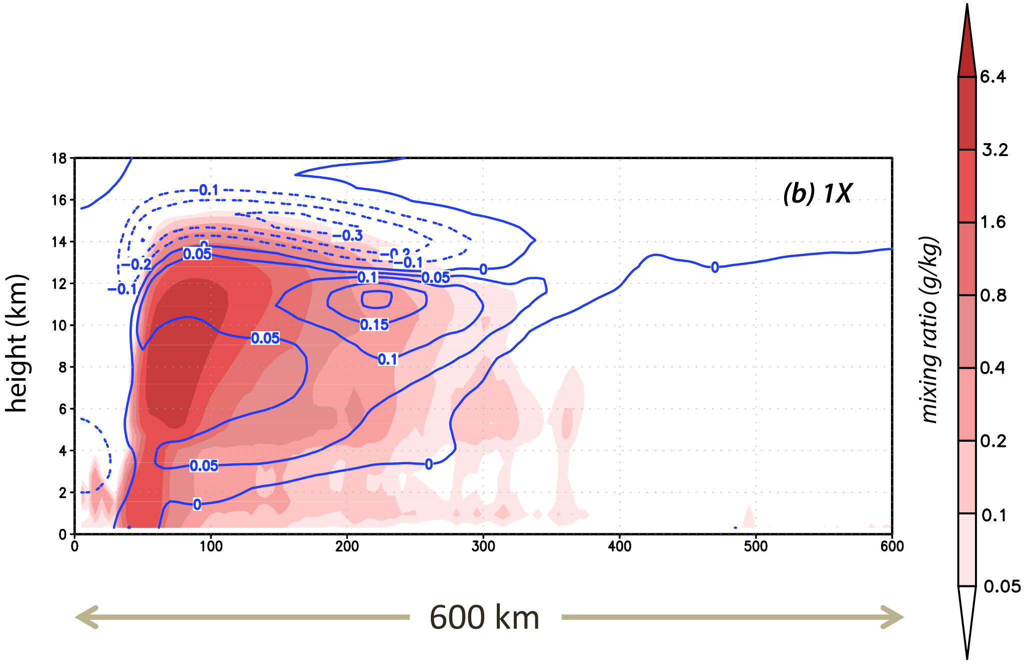
Thanks to…

- Hurricane Forecast Improvement Program for funding
- Developmental Testbed Center for two visitor projects
- Workshop organizers for invitation
- You for listening

[end]

CM1 – *Thompson/Goddard* - axisymmetric

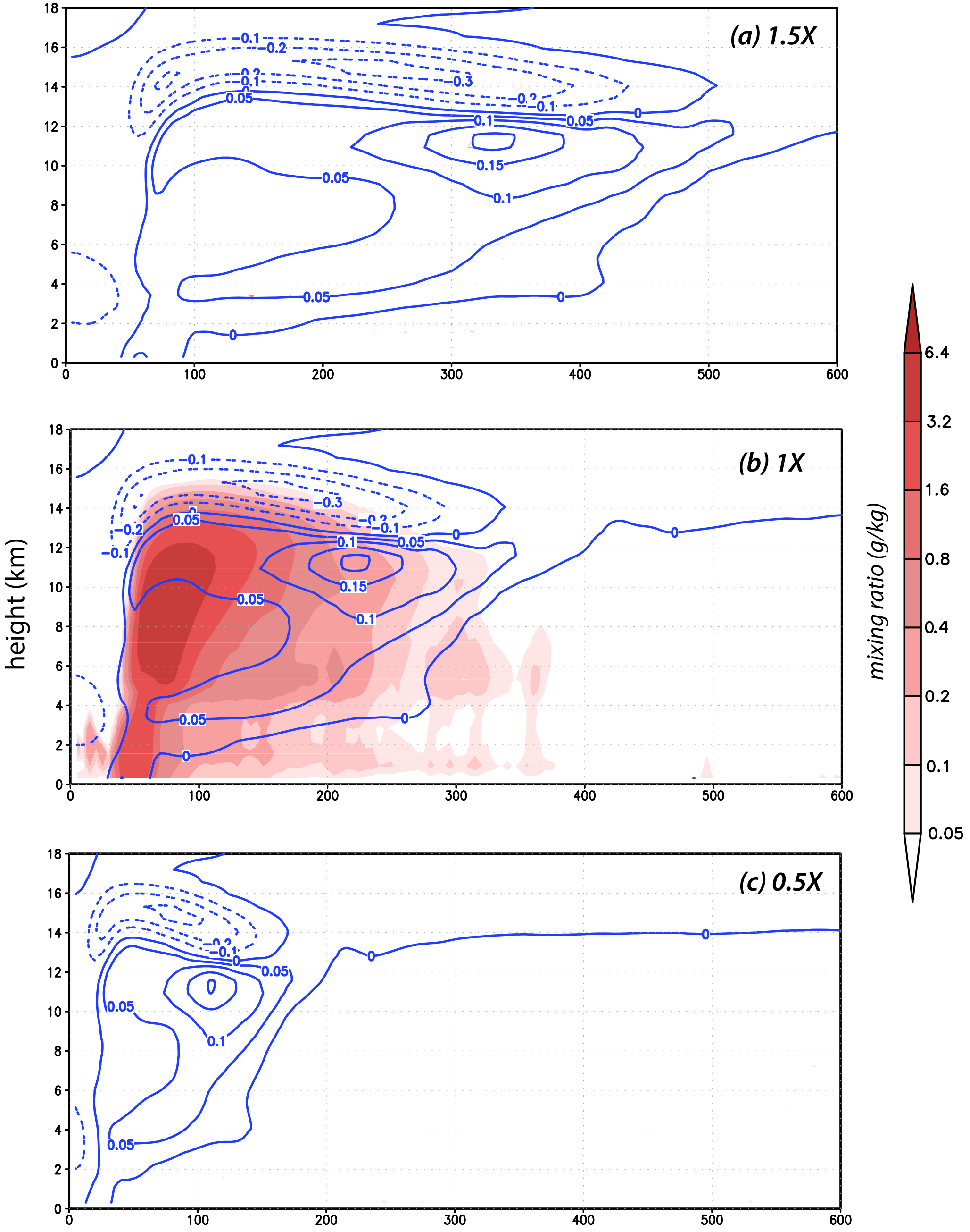
Does CRF *actively* control storm size?



- **CRF: fixed, external forcing**

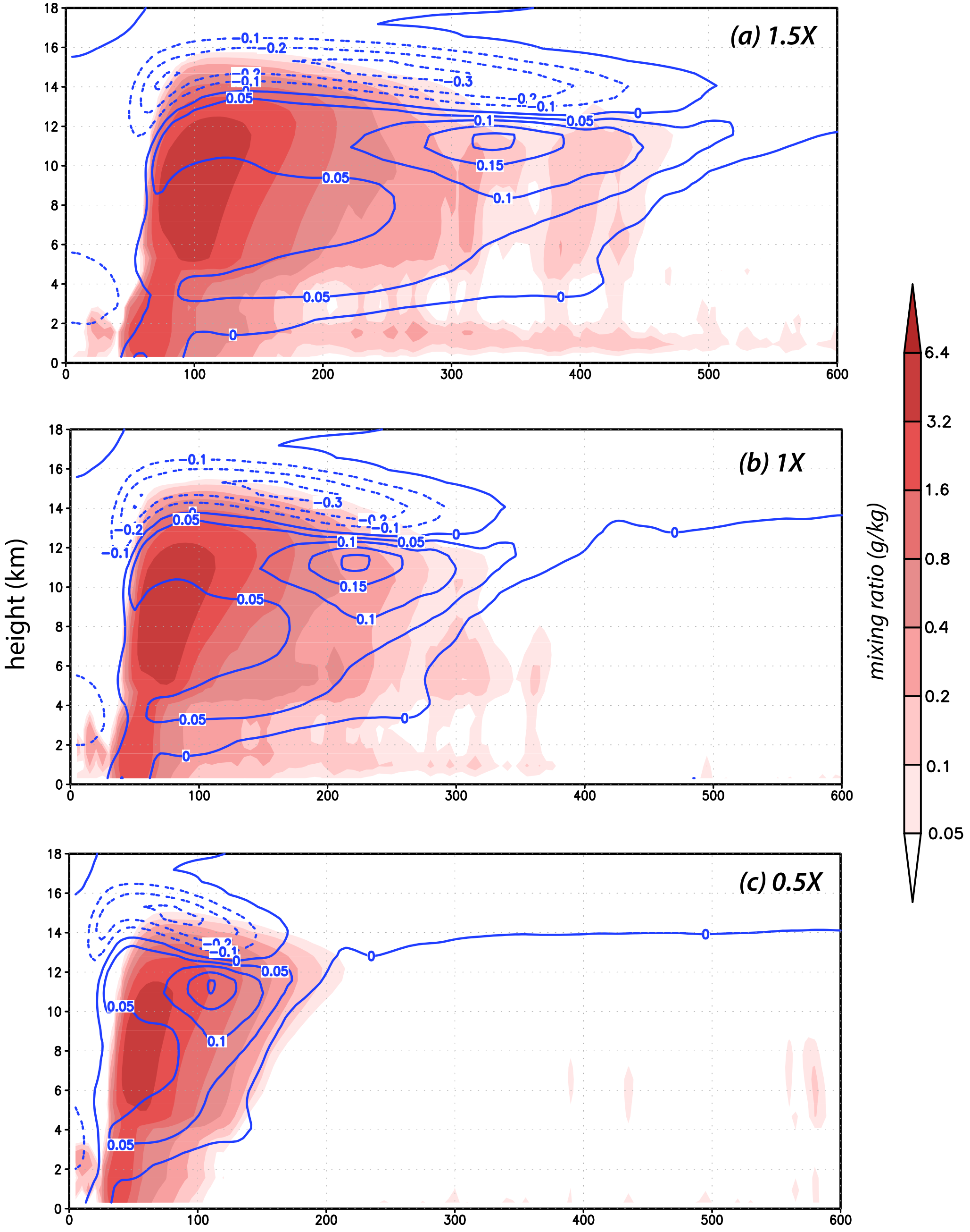
Fovell et al. (2016)

CM1 – *Thompson/Goddard* - axisymmetric



- **Expanded** radiation field
- **CRF: fixed, external forcing**
- **Contracted** radiation field

CM1 – *Thompson/Goddard* - axisymmetric



- **Expanded** radiation field

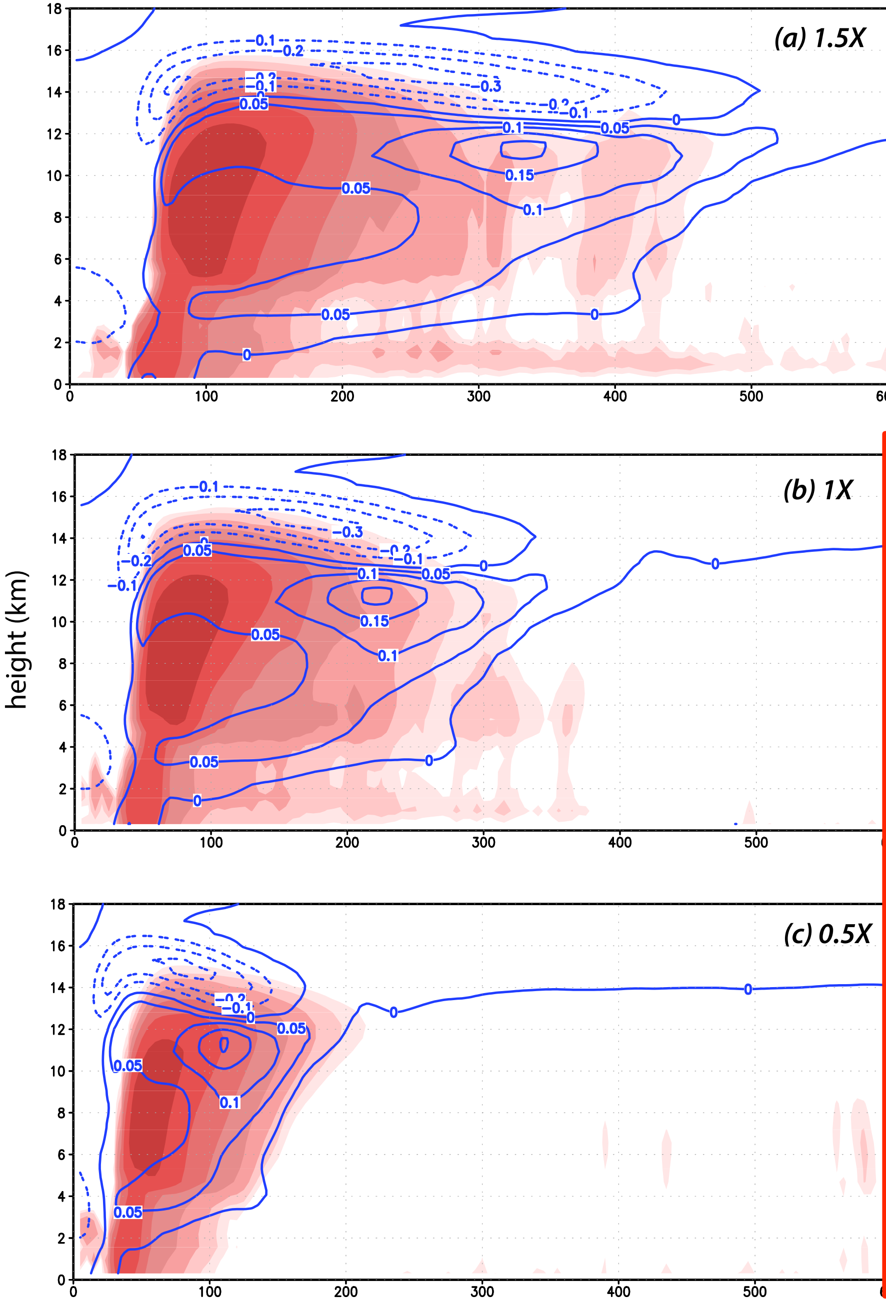
- **CRF: fixed, external forcing**

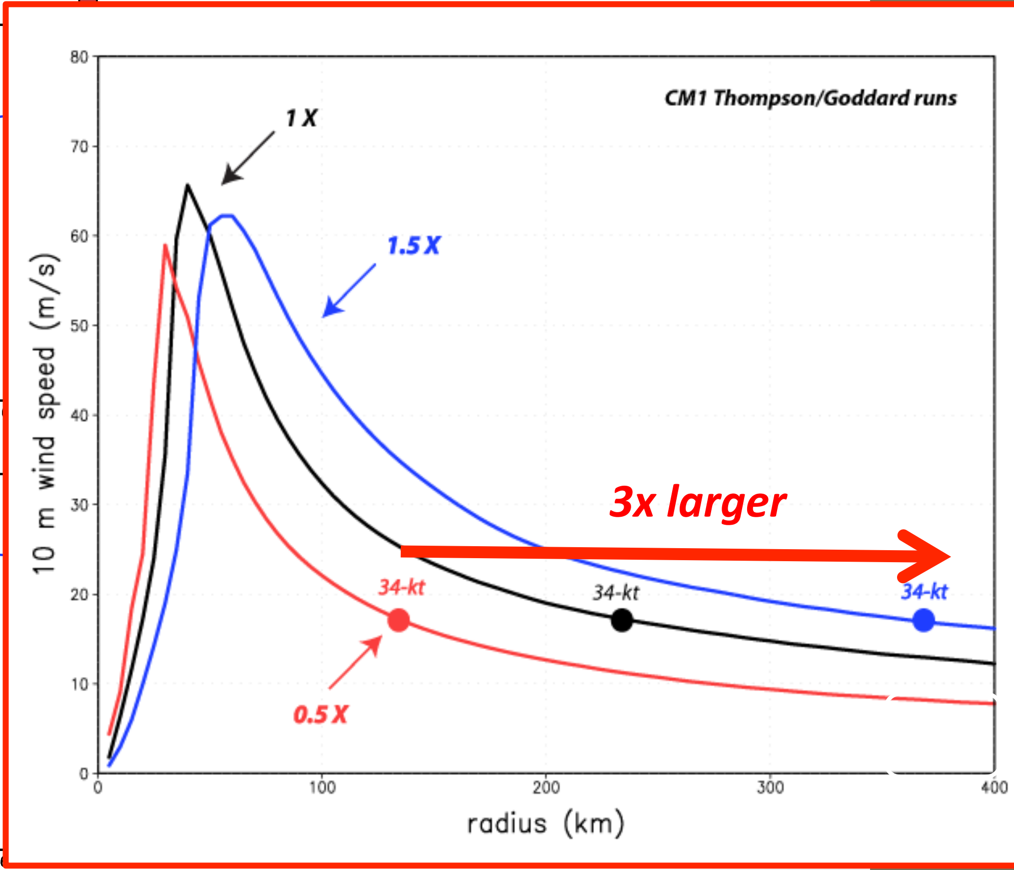
CRF actively controls storm size as a positive feedback

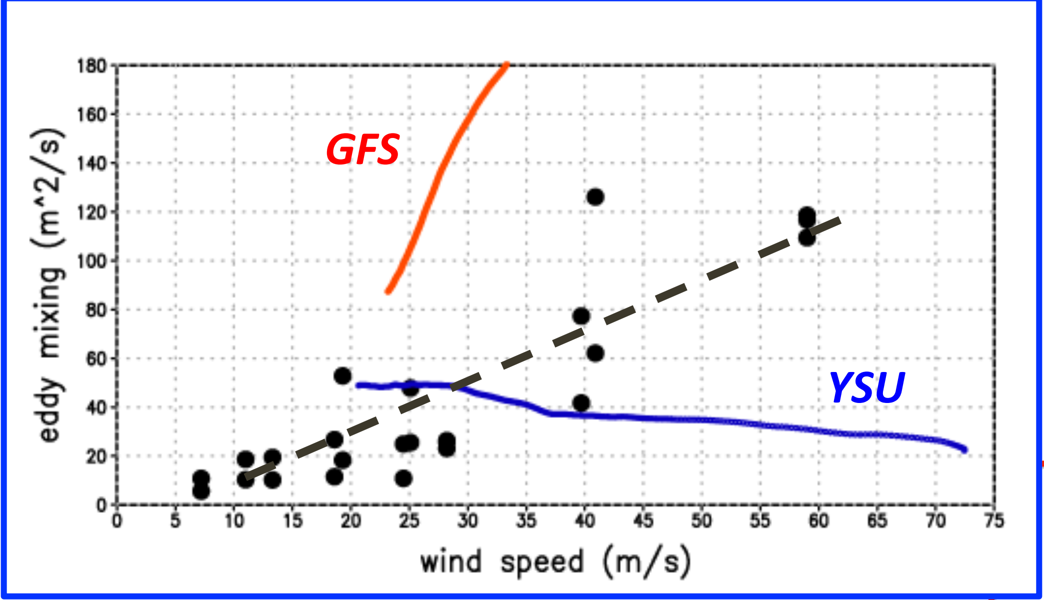
- **Contracted** radiation field

CM1 – *Thompson/Goddard* - axisymmetric

- **Expanded** radiation field





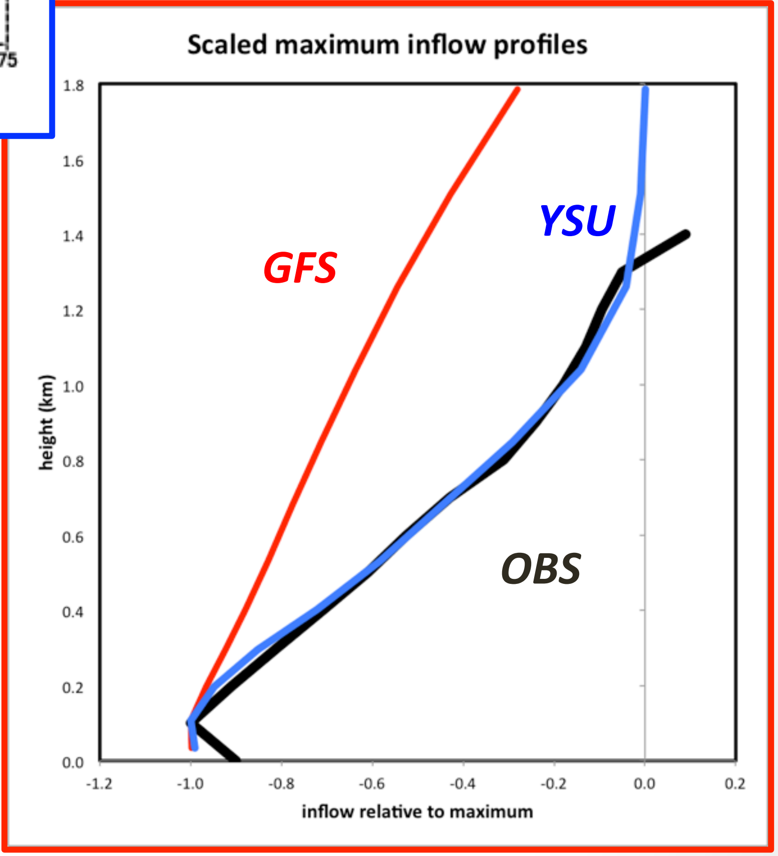


Eddy mixing estimates for 500 m MSL

(Zhang et al. 2011a)

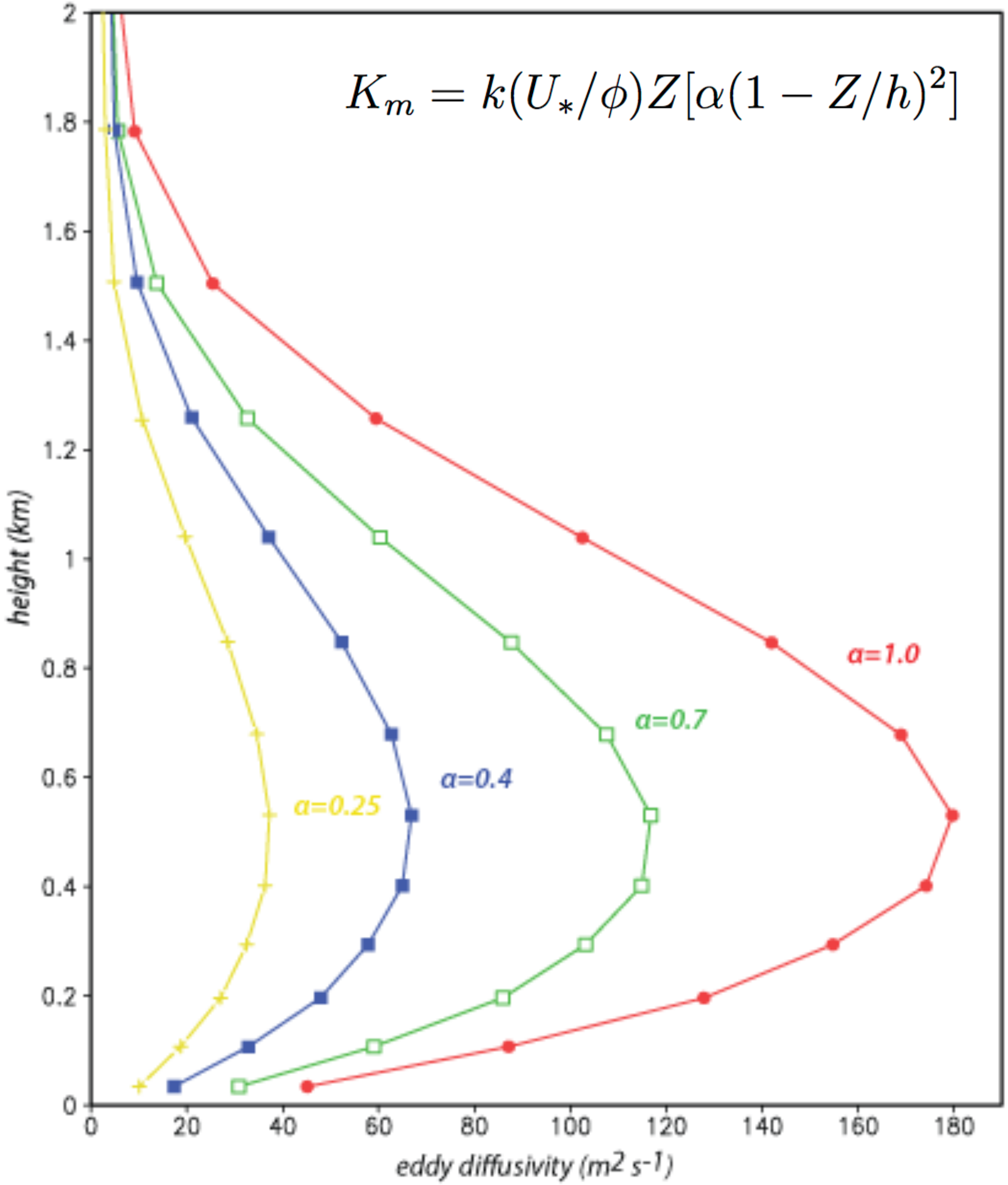
Inflow profile composites for major hurricanes

(Zhang et al. 2011b)



YSU+SFCLAYREV

GFS = unmodified by α parameter



HWRF simulations with GFS PBL

Eddy mixing applied to water vapor K_h

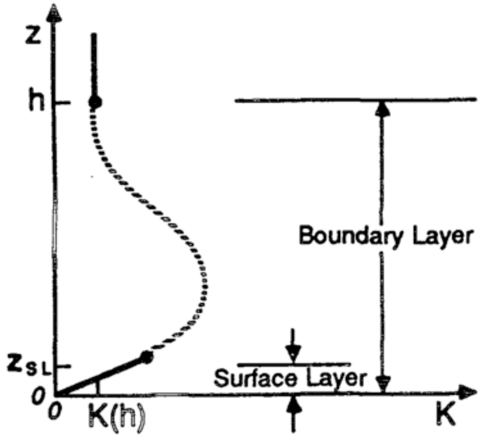
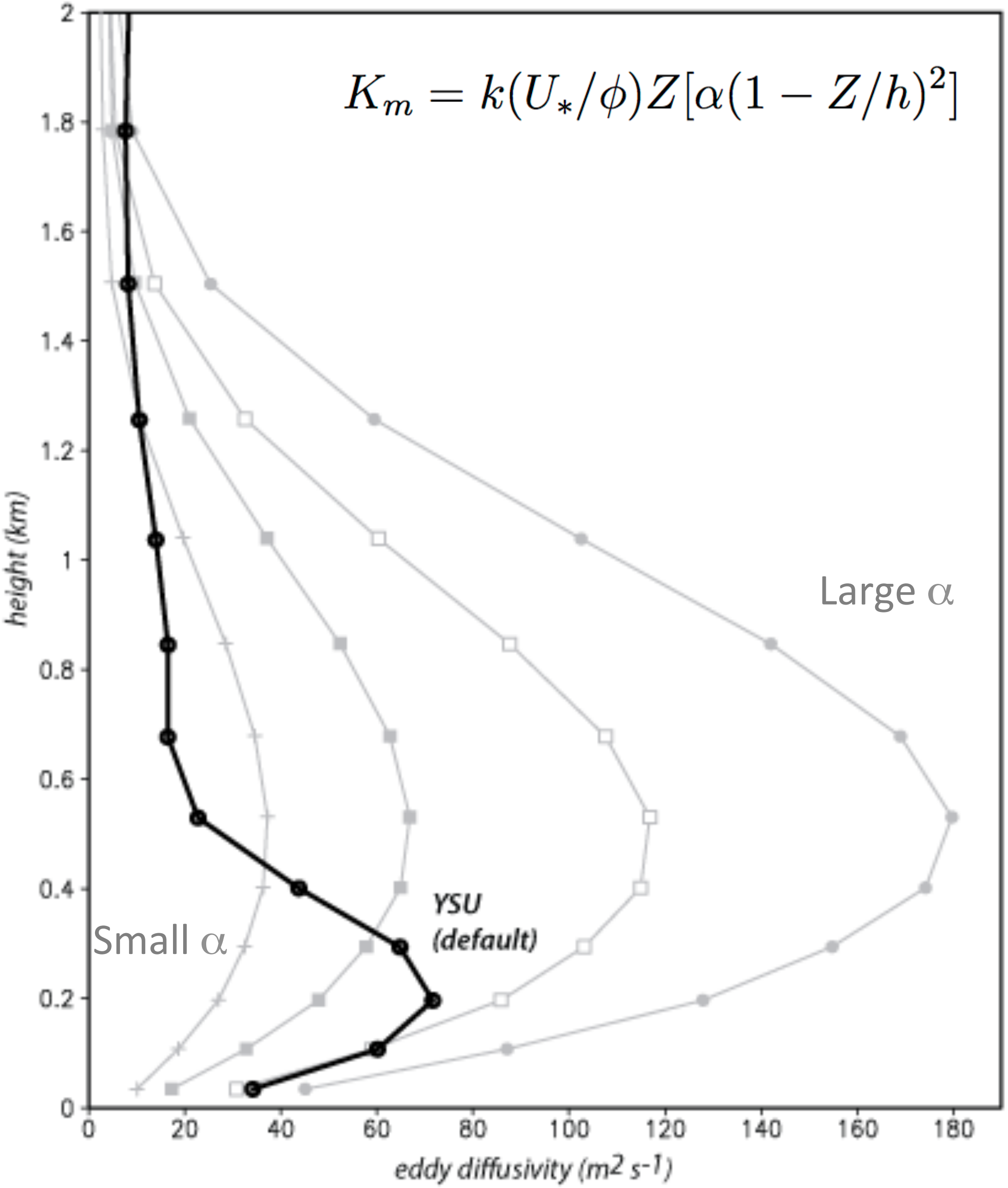


FIG. 1. Typical variation of eddy viscosity *K* with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

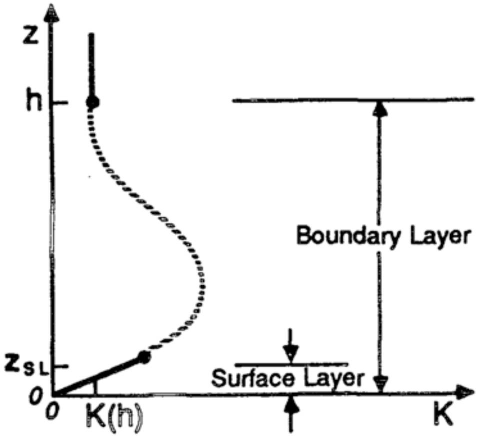


$$K_m = k(U_*/\phi)Z[\alpha(1 - Z/h)^2]$$

HWRF simulations with YSU PBL

(critical Ri = 0 unstable)

Eddy mixing applied to water vapor K_h



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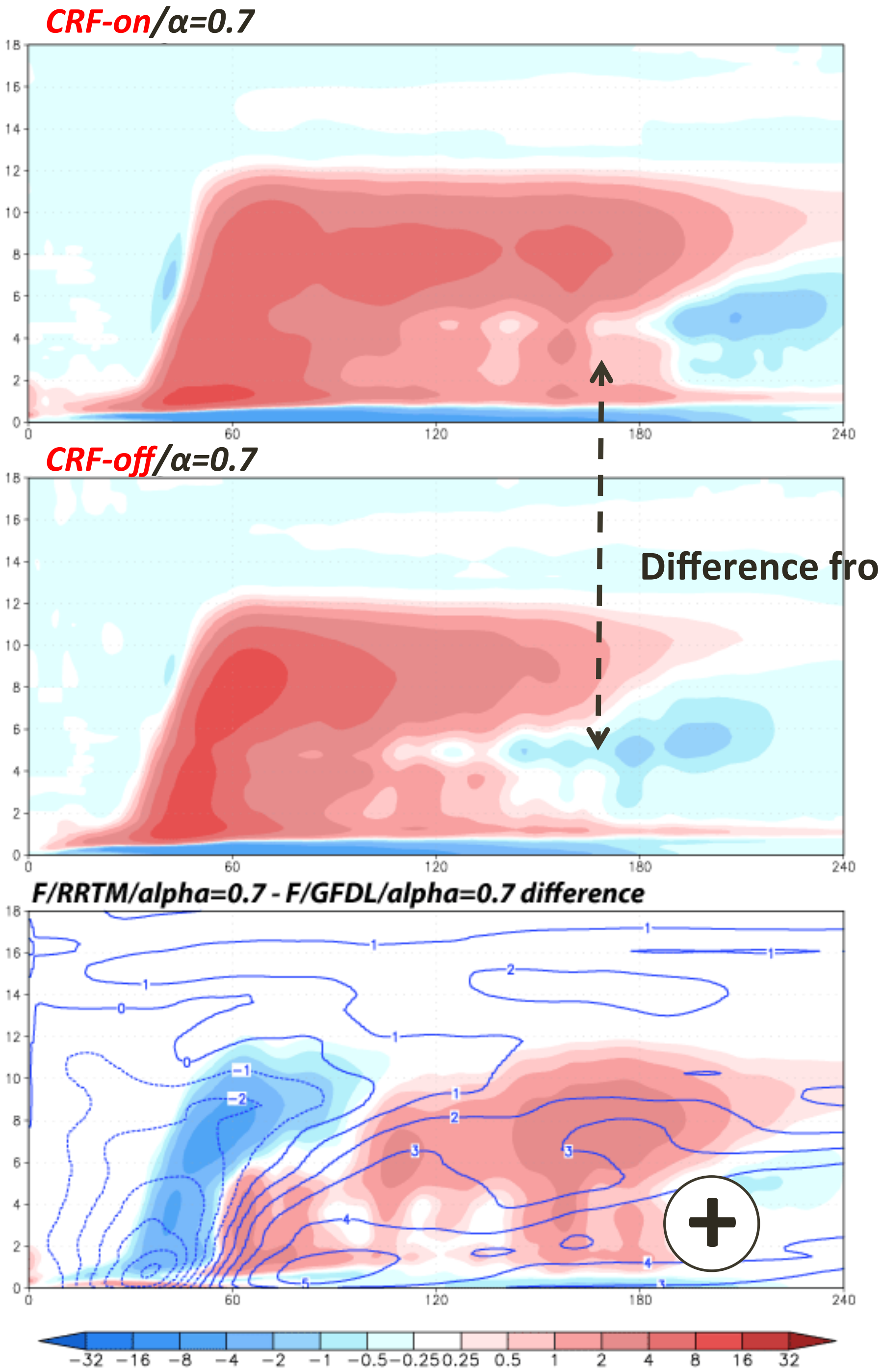


CRF-on/α=0.7

CRF-off/α=0.7

F/RRTM/alpha=0.7 - F/GFDL/alpha=0.7 difference

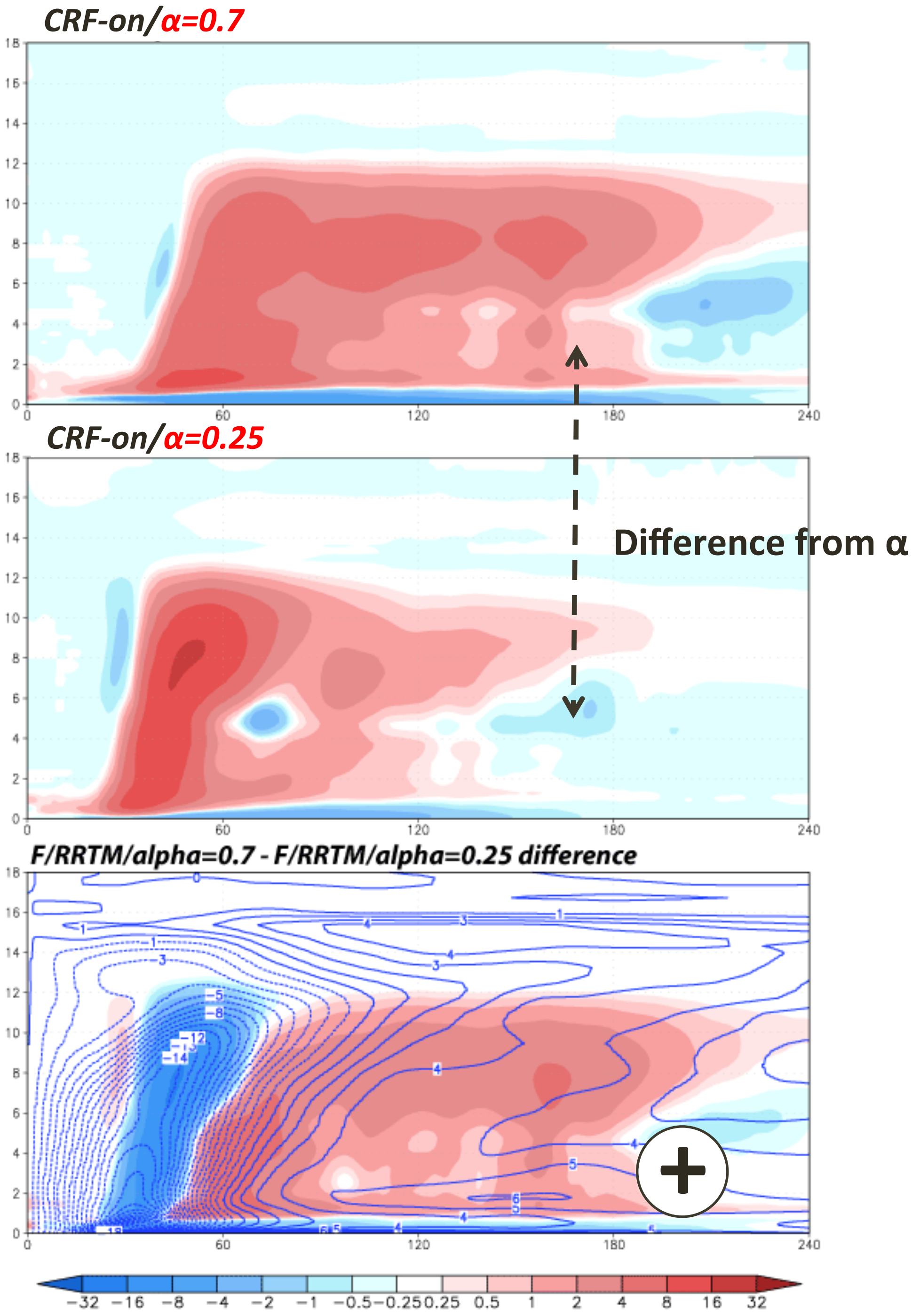
Difference from CRF

- Modified configuration
  GFS_alpha (α= 0.7)
  RRTMG radiation (CRF-on)

- **Operational configuration**
  GFS_alpha (α= 0.7)
  GFDL radiation (no CRF)

…and wind field difference

Diabatic forcing (colored, K/hr)
from microphysics


CRF-on/α=0.7

CRF-on/α=0.25

Difference from α

F/RRTM/alpha=0.7 - F/RRTM/alpha=0.25 difference

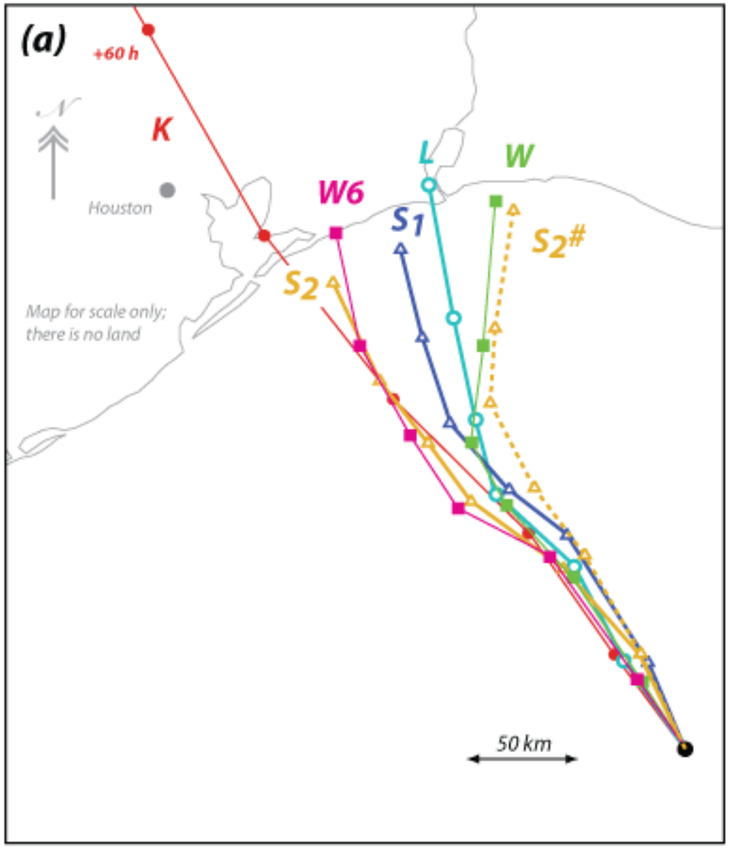
- Modified configuration
  GFS_alpha (α)= 0.7
  RRTMG radiation

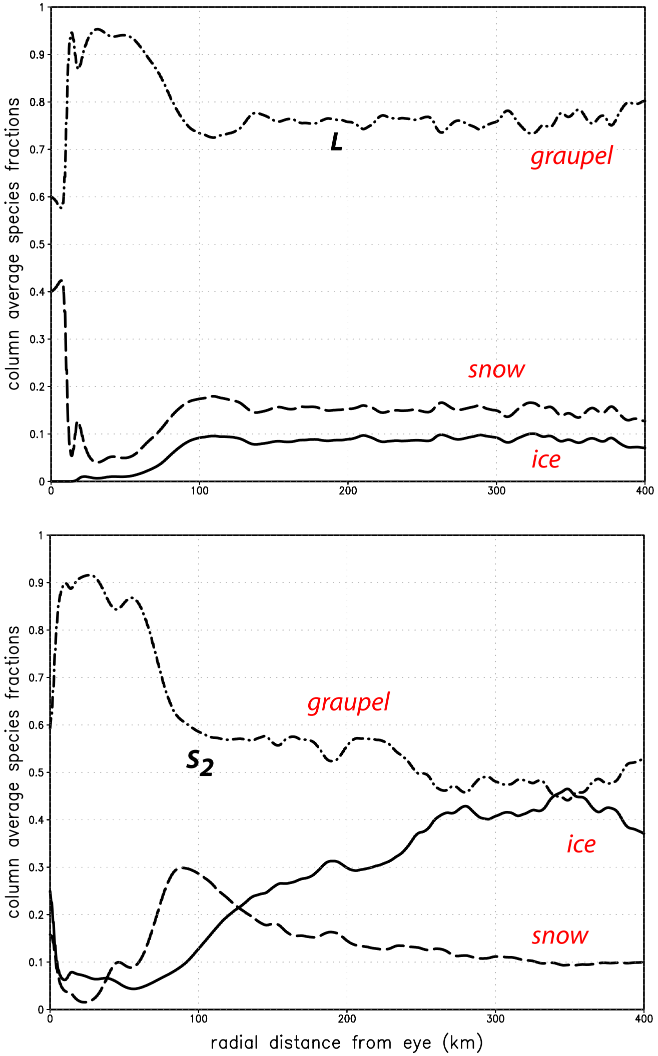
- Modified configuration
  GFS_alpha (α)= 0.25
  RRTMG radiation

Diabatic forcing (colored, K/hr)
from microphysics

“Semi-idealized” experiment

very small part of domain shown





80%

12%

8%

50%

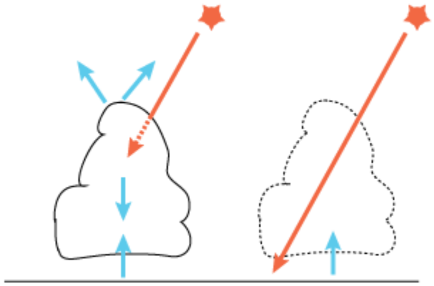
40%

10%

Fovell and Su (2007)
Fovell et al. (2009, 2010, 2016)

HWRF experimental design

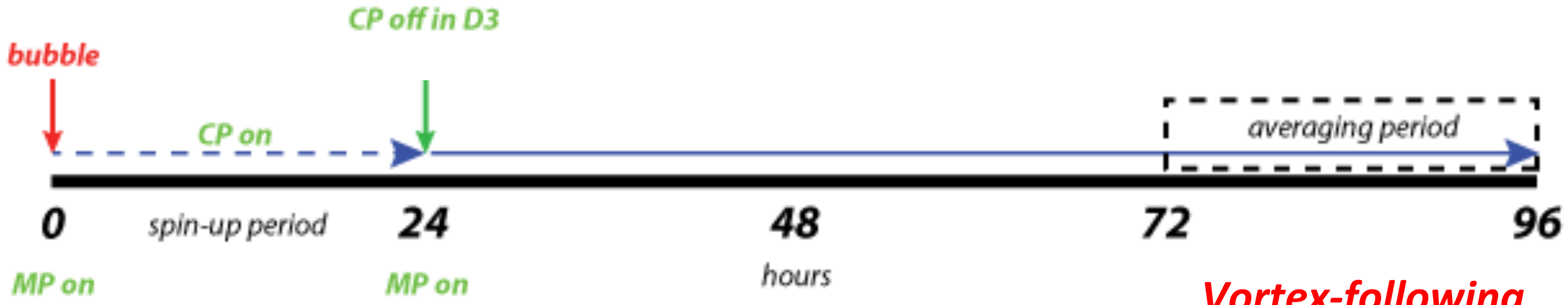
- 2013 HWRF semi-idealized
  - Thompson microphysics, RRTMG radiation, GFS PBL scheme
  - 3 telescoping domains (27/9/3 km) used operationally in 2012
  - NO LAND, uniform SST, Jordan sounding
  - Equinox conditions
- Focus on structure



* For 2014 and earlier seasons

HWRF simulation strategy

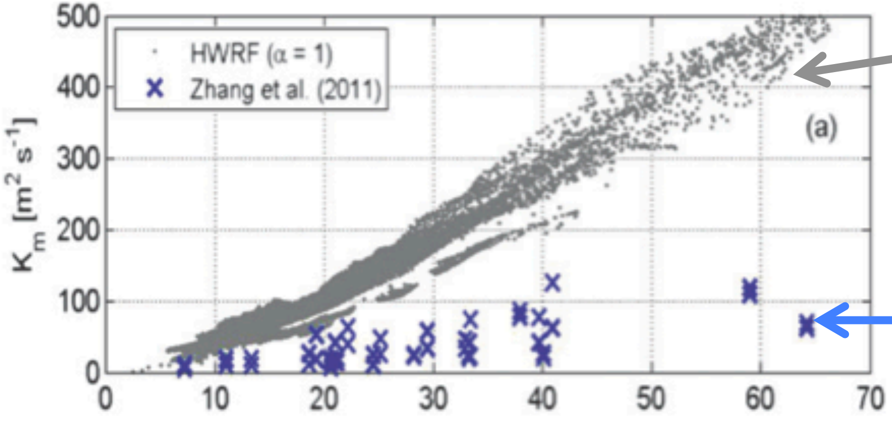
for semi-idealized experiments



Vortex-following
1 full diurnal cycle

D3 = Domain 3

Eddy mixing K_m



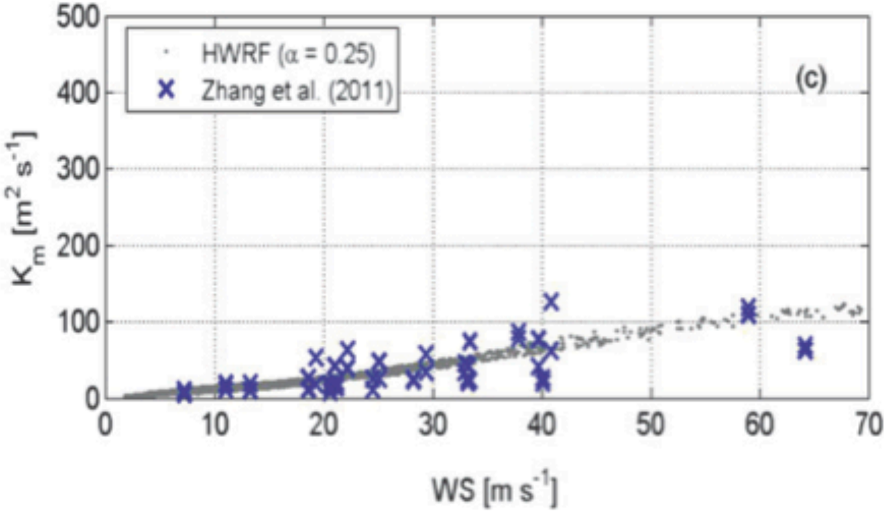
Wind speed

HWRF GFS PBL scheme

Observations @ 500 m MSL

$$K_m = k(U_*/\phi)Z[\alpha(1 - Z/h)^2]$$

α parameter ("gfs_alpha")

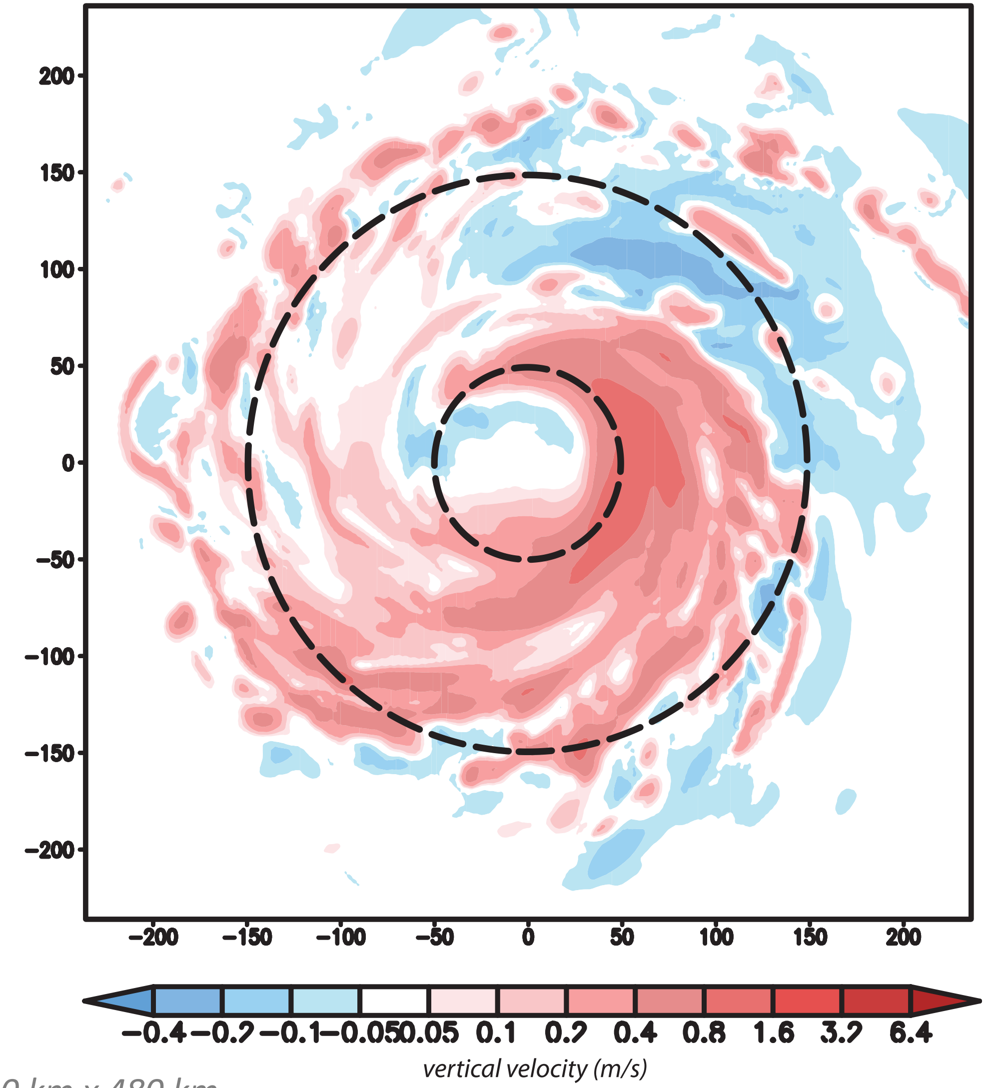


α = 0.25

α = 0.7 selected for operational model

Gopalakrishnan et al. (2012)

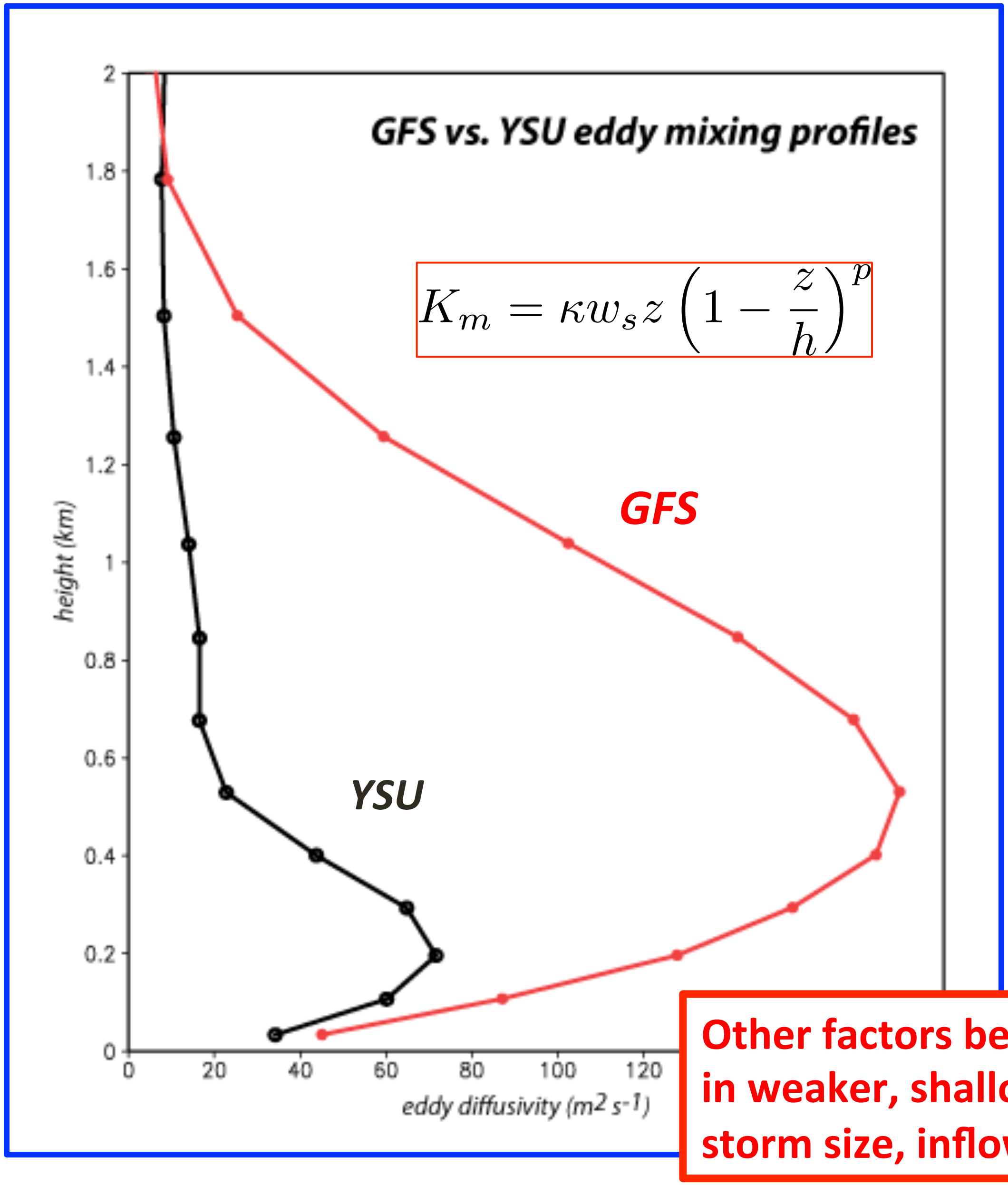
Temporally averaged *w*



480 km x 480 km

HWRF (2013)
GFS PBL scheme (α = 0.7)
Thompson microphysics
RRTMG radiation

"Semi-idealized"
(operational configuration for idealized simulation)



$$K_m = \kappa w_s z \left(1 - \frac{z}{h}\right)^p$$

Eddy mixing

Principal difference: critical Richardson Numbers (Ri_c)

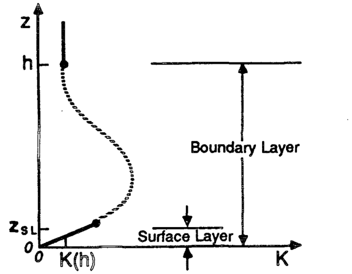


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

Other factors being equal, YSU results in weaker, shallower mixing, which influences storm size, inflow strength, and intensity

Bu et al. (2017)

GFS = unmodified by α parameter

Key difference: critical Richardson number (Ri_c)