Evaluation of Planetary Boundary Layer Schemes in Hurricanes Over Land Through Comparison of Surface Winds in Observations and Simulations of Hurricane Wilma (2005)

Brian D. McNoldy, David S. Nolan, and Jimmy Yunge

Department of Atmospheric Sciences
Rosenstiel School of Marine and Atmospheric Science
University of Miami

UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL of MARINE & ATMOSPHERIC SCIENCE

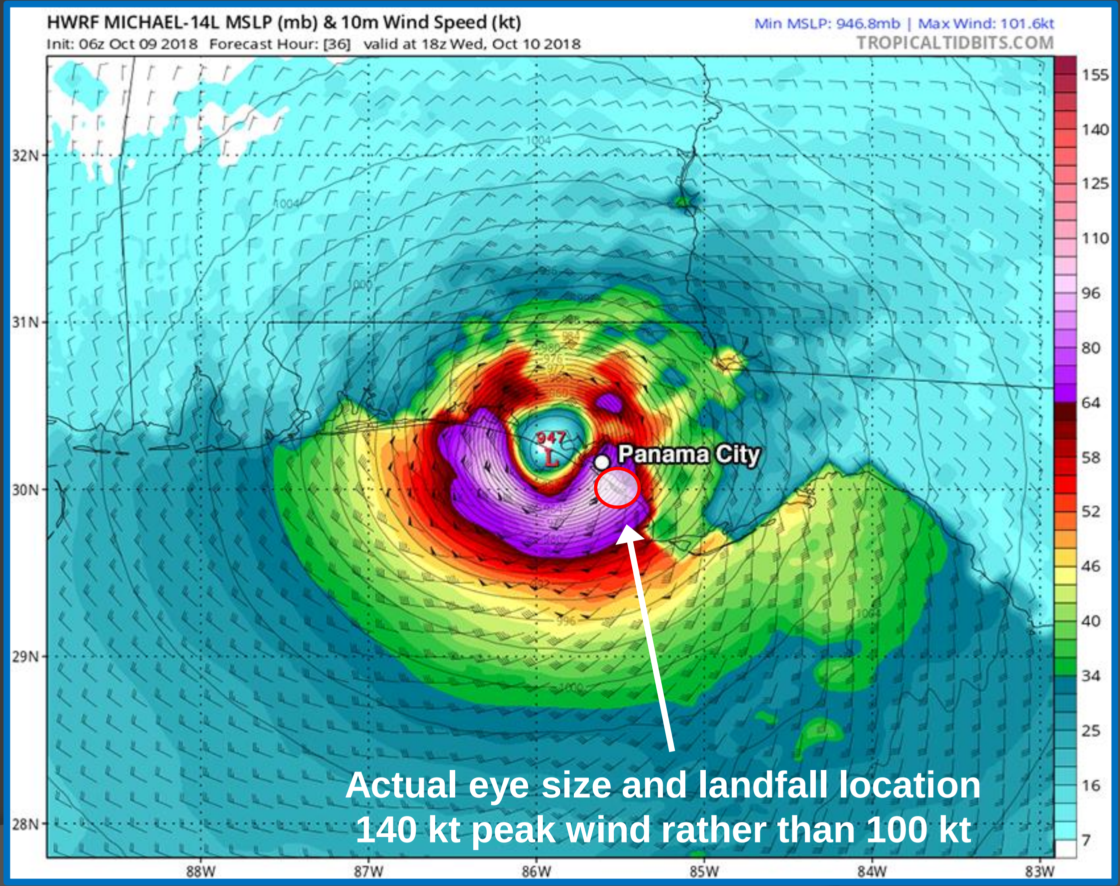
Thanks to Forrest Masters, John Knaff, and Jun Zhang for additional data sets.

This work is supported by the National Science Foundation through the ***PREEVENTS*** program.

AMS 100th Annual Meeting
15 January 2020, Boston MA

Motivation

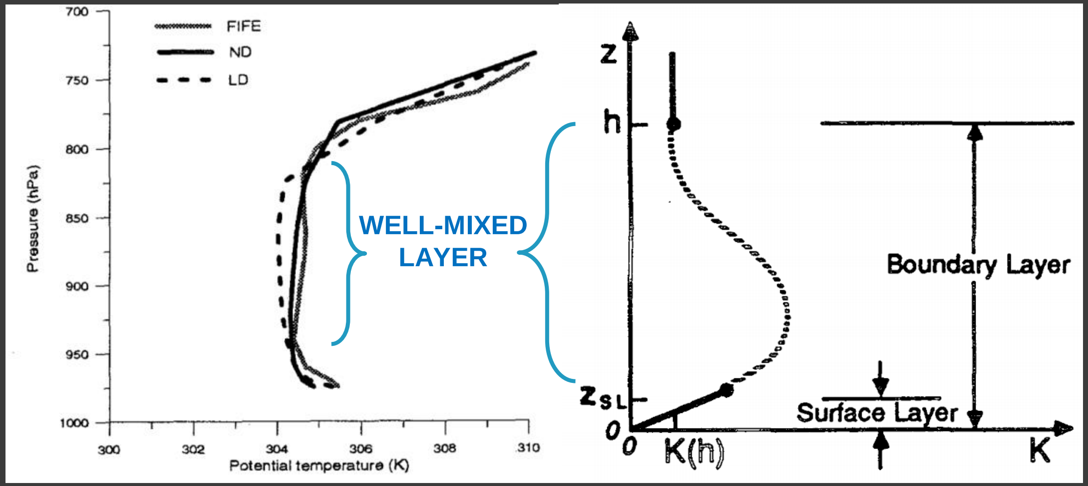
- Global and regional dynamical models are the primary tools for predicting the impacts of hurricanes.
- But, these are not used to predict the wind fields over land.
- Probably for two good reasons:
  - Typical forecast track and intensity errors could cause huge errors in local wind forecasts.
  - Forecast model over-land winds have not been validated, or improved.



Previous Work

- Nolan et al. (2009a,b) performed a comprehensive evaluation of the Yonsei University (***YSU***) and Mellor-Yamada-Janjic (***MYJ***) boundary layer parameterizations in WRF simulations of Hurricane Isabel (2003) against point observations and synthesized analyses.

YSU



MYJ

$$\frac{d}{dt}\left(\frac{q^2}{2}\right) - \frac{\partial}{\partial z}\left[lqS_q\frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right] = P_s + P_b - \varepsilon \quad \text{(TKE)}$$

$$l = l_0\kappa z(\kappa z + l_0)^{-1} \quad \text{(geometrically prescribed length scale varies from 0 to } l_0\text{)}$$

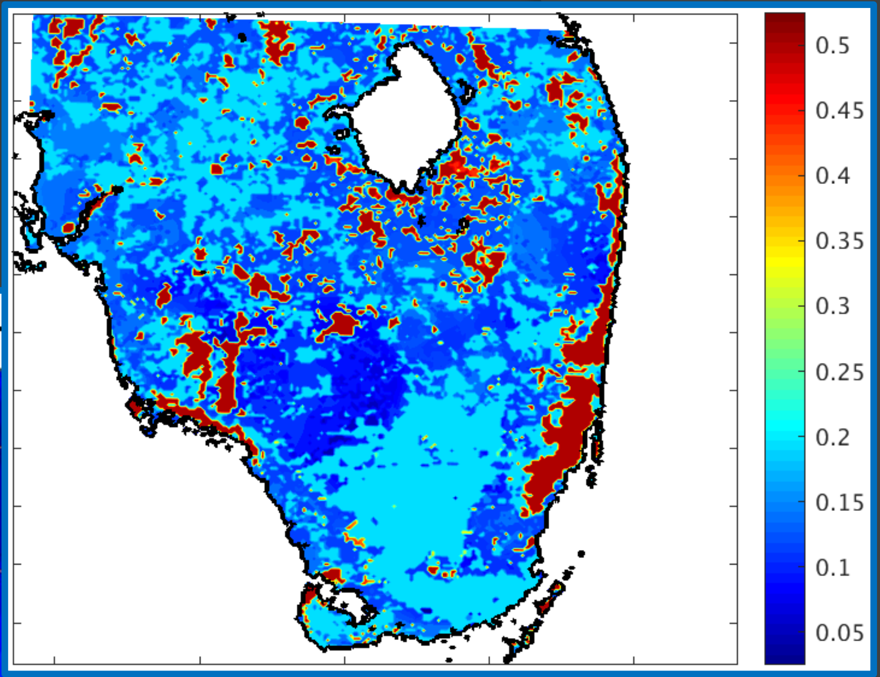
$$K_M = lqS_M, \text{ and } K_T = lqS_T \quad \text{(eddy diffusivities of momentum and temperature)}$$

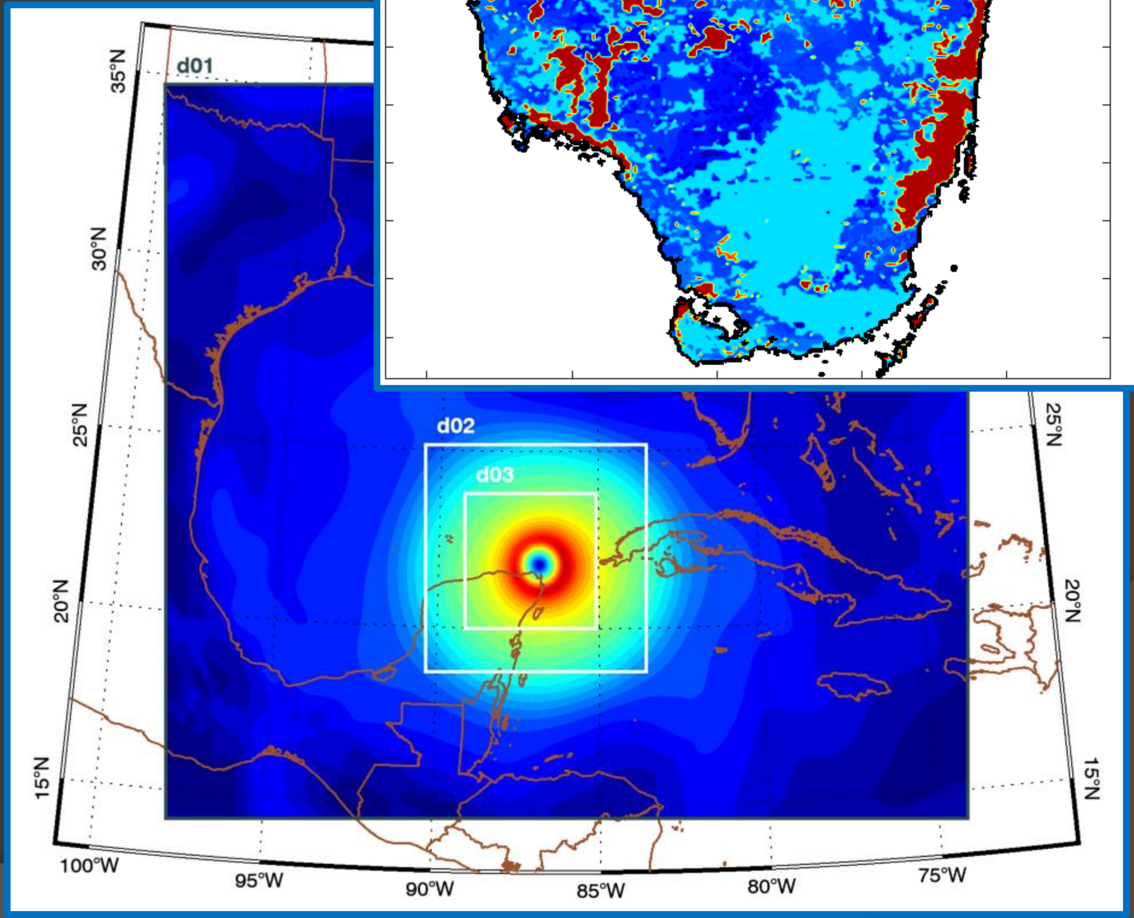
- Through fundamentally different approaches, both schemes reproduced the hurricane boundary layer quite well. YSU was a little better, as the MYJ caused too much loss of angular momentum causing an “exaggerated” secondary circulation.
- What about over land?

Modeling Parameters & Strategy

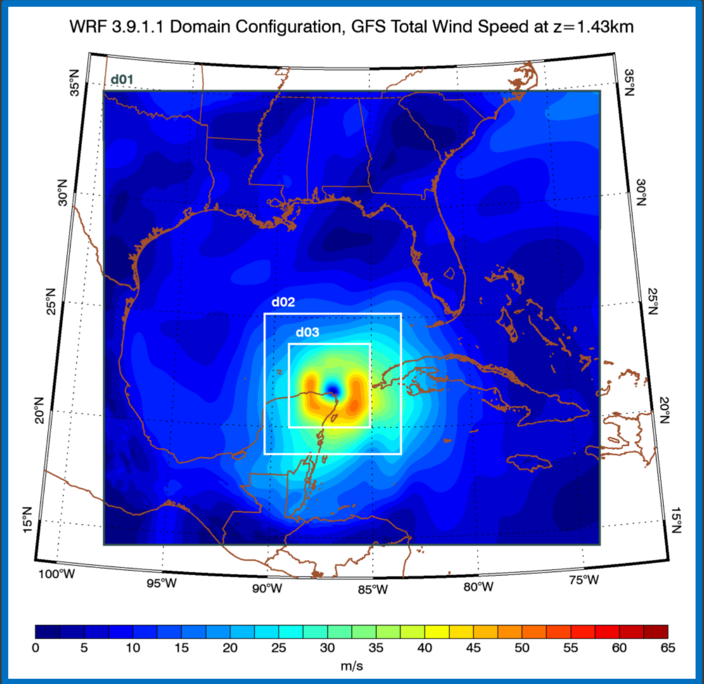
- WRF 3.9.1.1
  - 9 km / 3 km / 1 km domains
  - 60 vertical levels between 42 m - 20 km
  - YSU and MYJ boundary layer schemes
    - MYJ surface drag formula over water changed to match YSU formula
  - GFS initial and boundary conditions
    - Domain-scale grid nudging to GFS analyses at 1/12h timescale.
  - Surface winds on 1 km nest saved every 10 seconds
  - Simulation begins ~28 h before landfall
  - Interpolation of high-resolution terrain & land use data to 3 km and 1 km nested grids as they move (Chen et al. 2007)

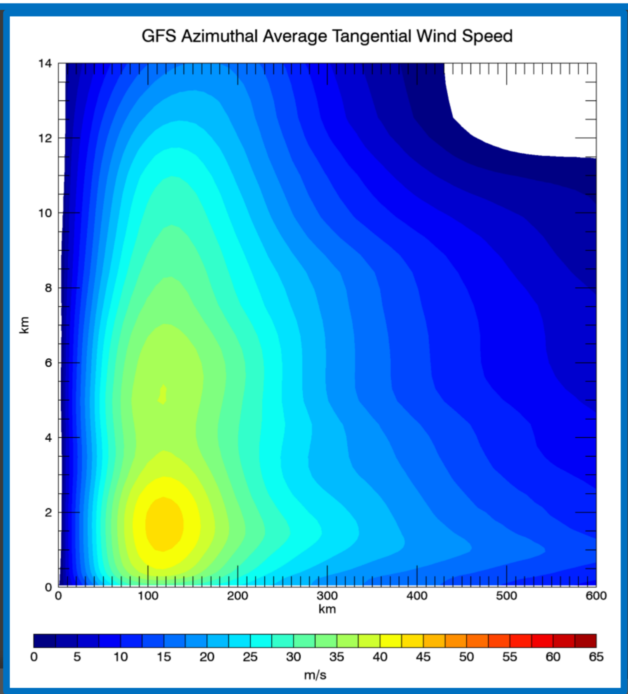
Roughness Length z_0 in d03



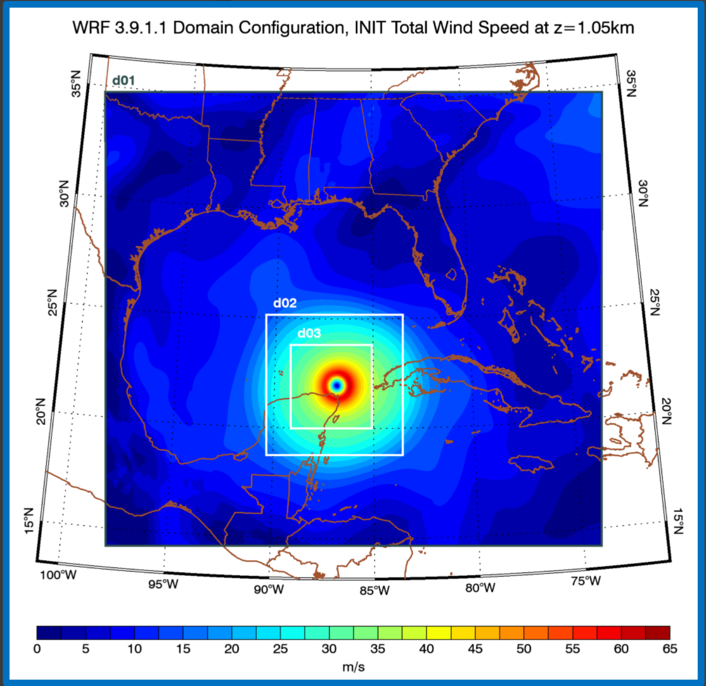


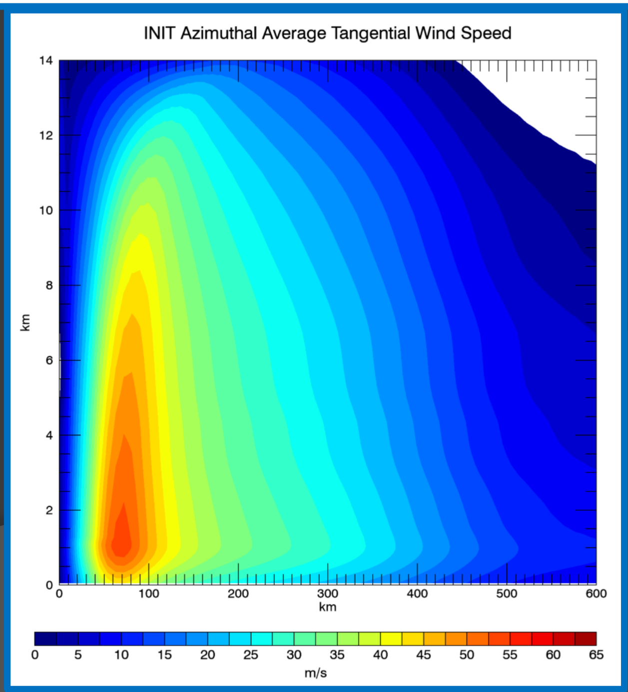
Vortex Bogussing



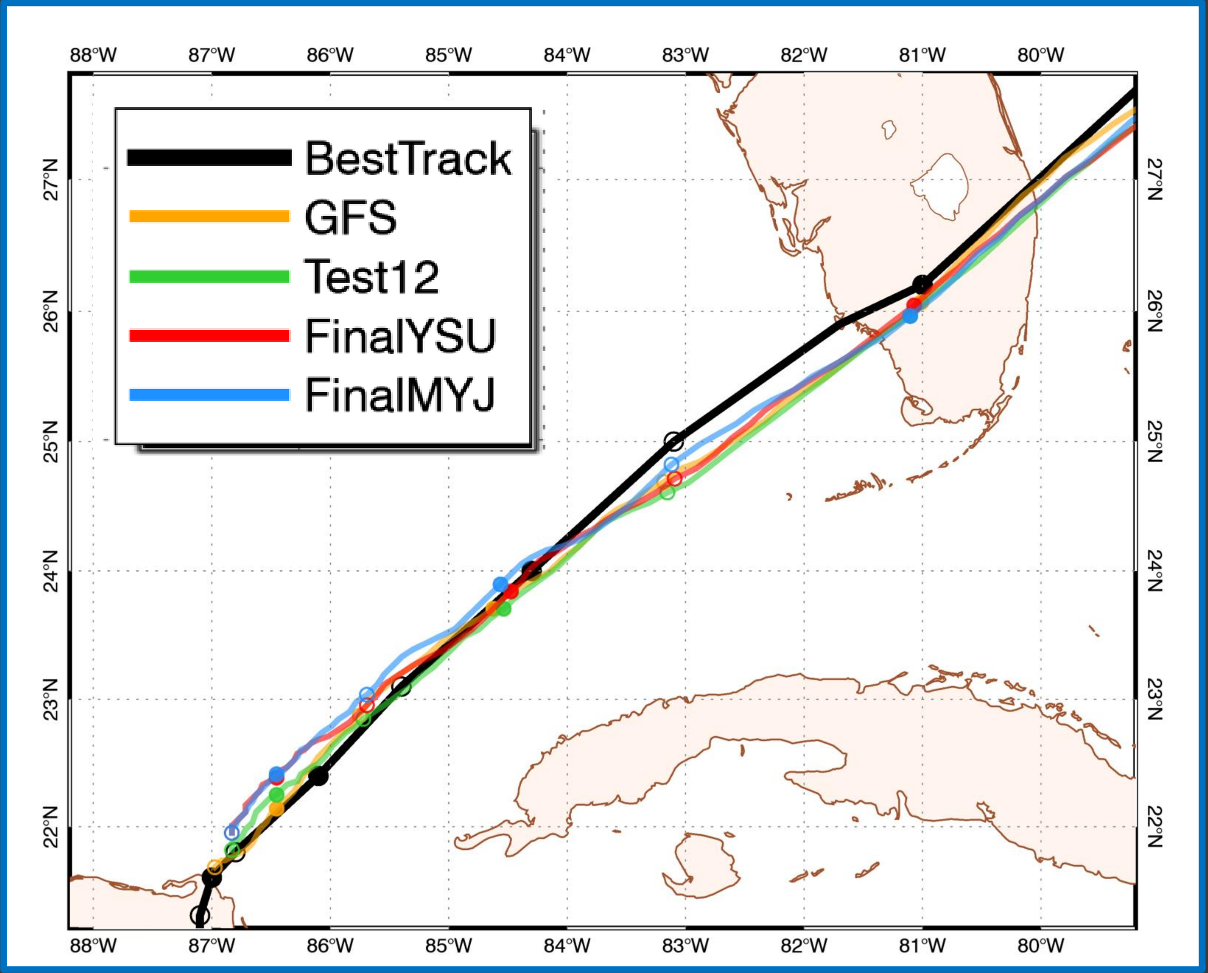


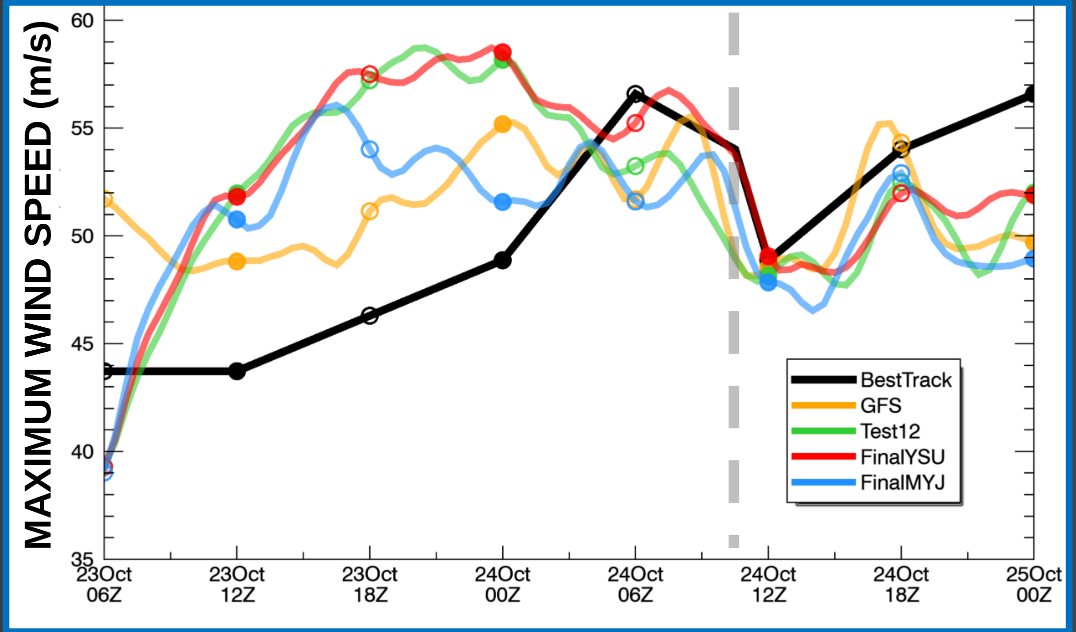
- Vortex “bogussing” method of Rappin et al. (2013) is used to replace the GFS vortex with a smaller, stronger vortex in a better location.
- Vortex removal technique modeled after GFDL system.
- Vertical structure of wind field built from MPI theory of Emanuel (1986).
- Trial-and-error to make a simulation with track, intensity, and size as close as possible to Wilma (2005).

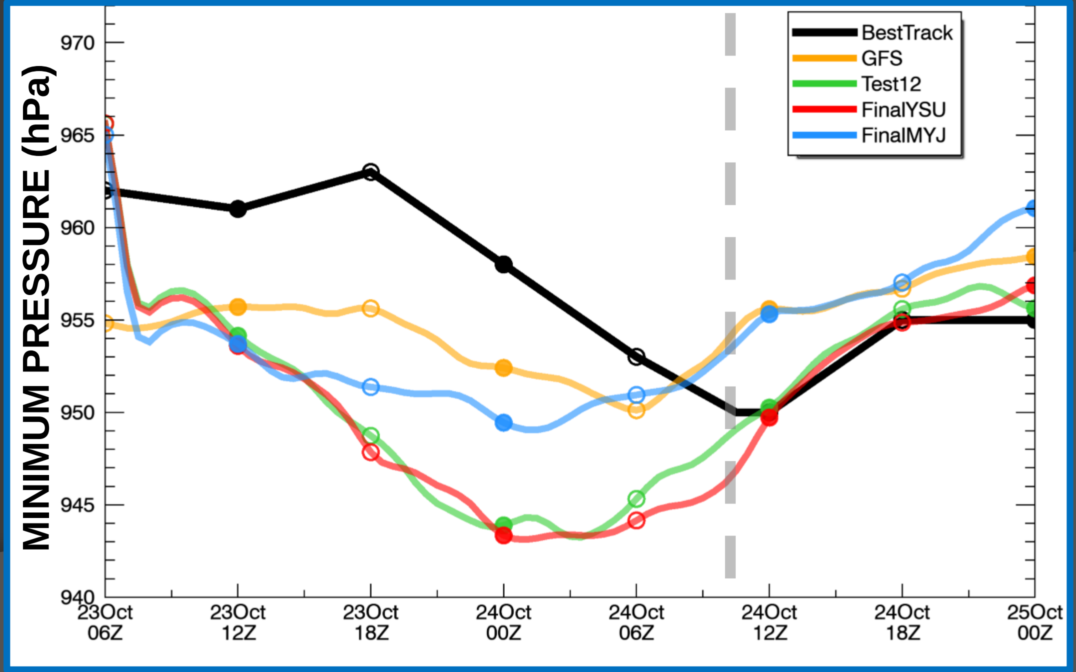




Track, Intensity, and Size



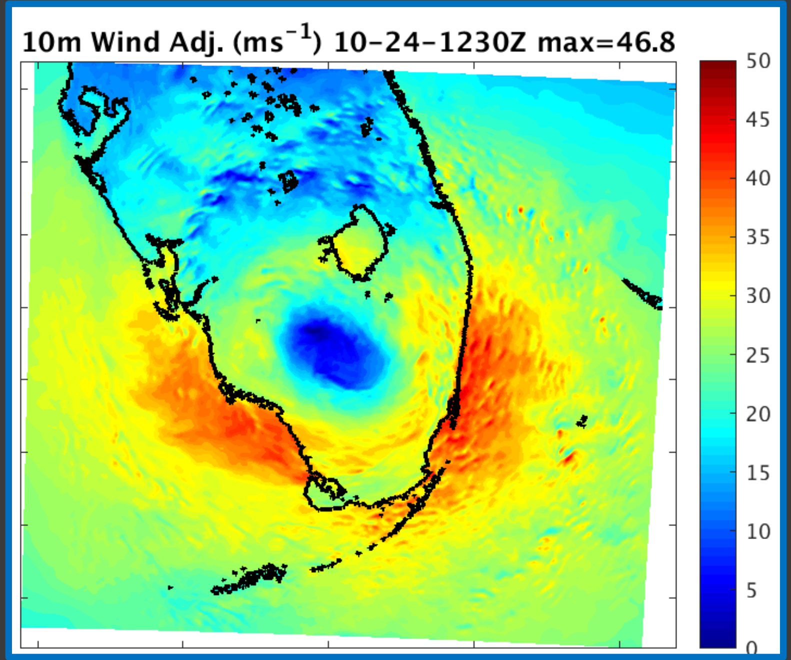


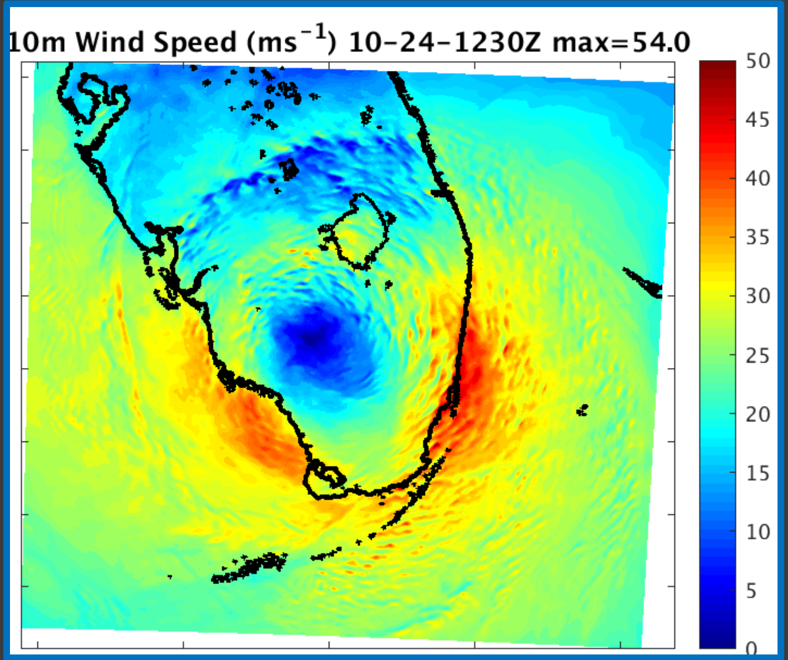


- GFS initial conditions produced excellent track & intensity.
- But the vortex size was too large.

YSU

MYJ


10m Wind Adj. (ms^{-1}) 10-24-1230Z max=46.8
50
45
40
35
30
25
20
15
10
5
0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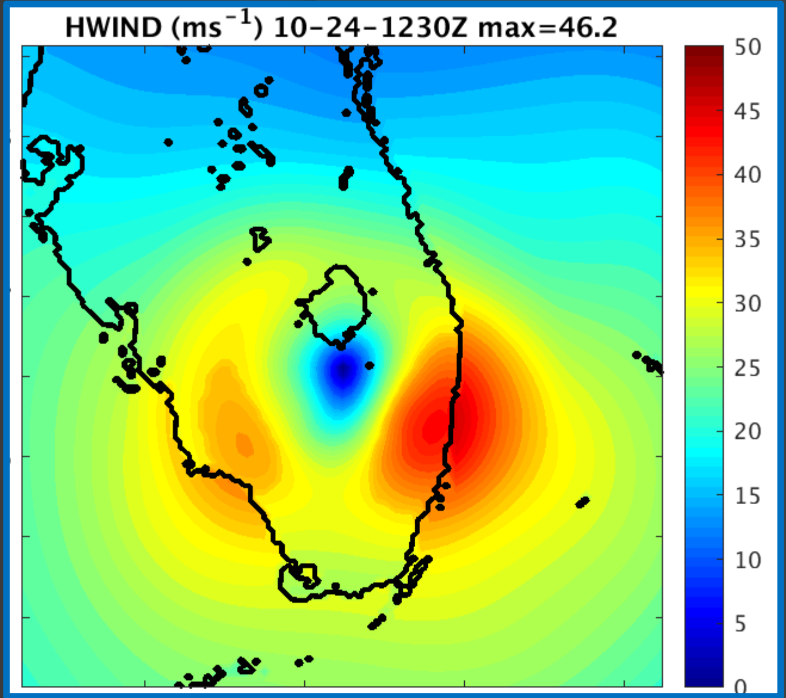
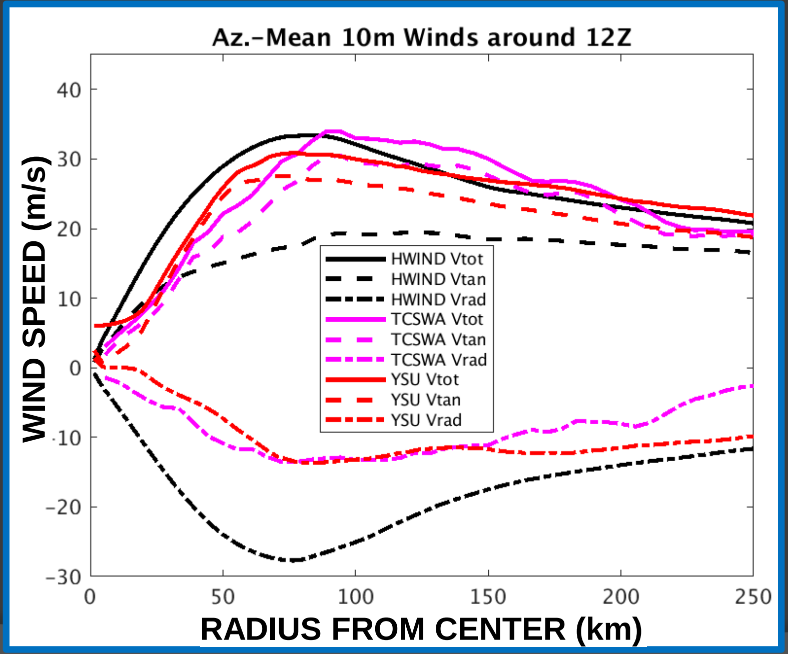
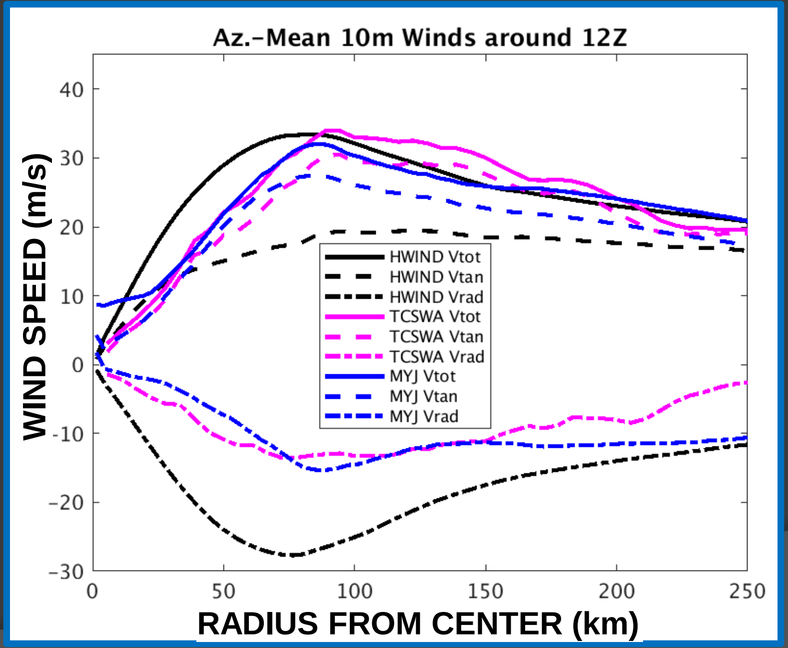
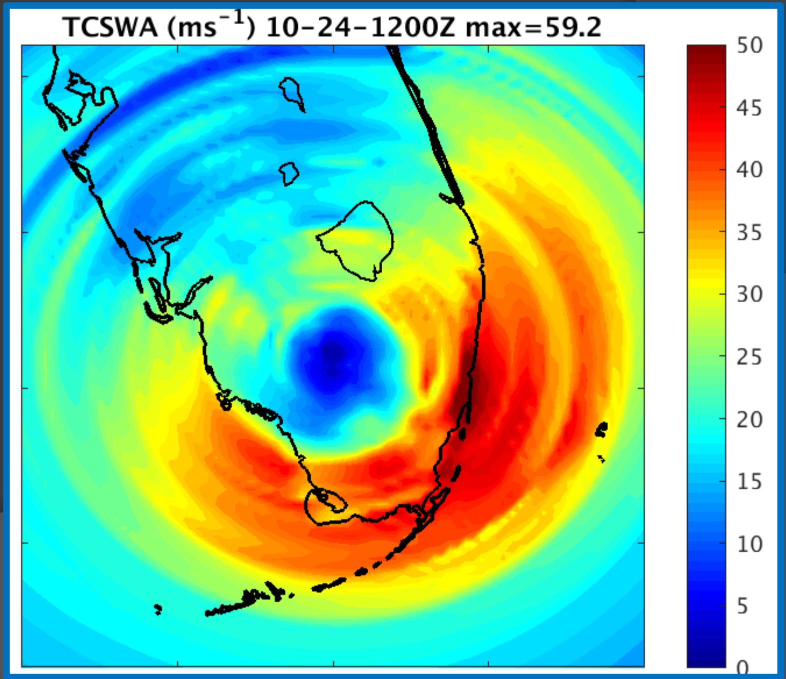
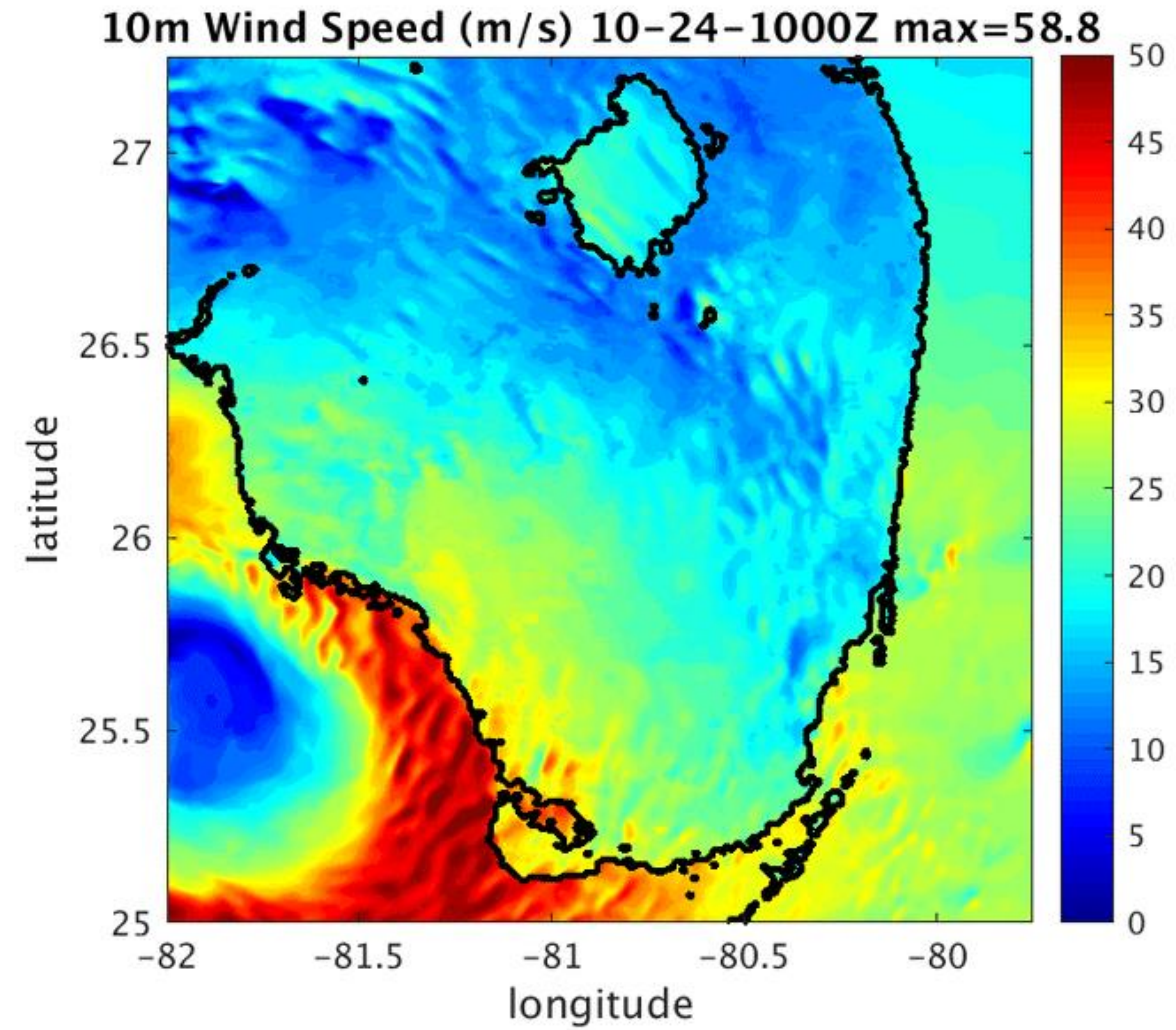
50
45
40
35
30
25
20
15
10
5
0


HWIND (ms^{-1}) 10-24-1230Z max=46.2
50
45
40
35
30
25
20
15
10
5
0

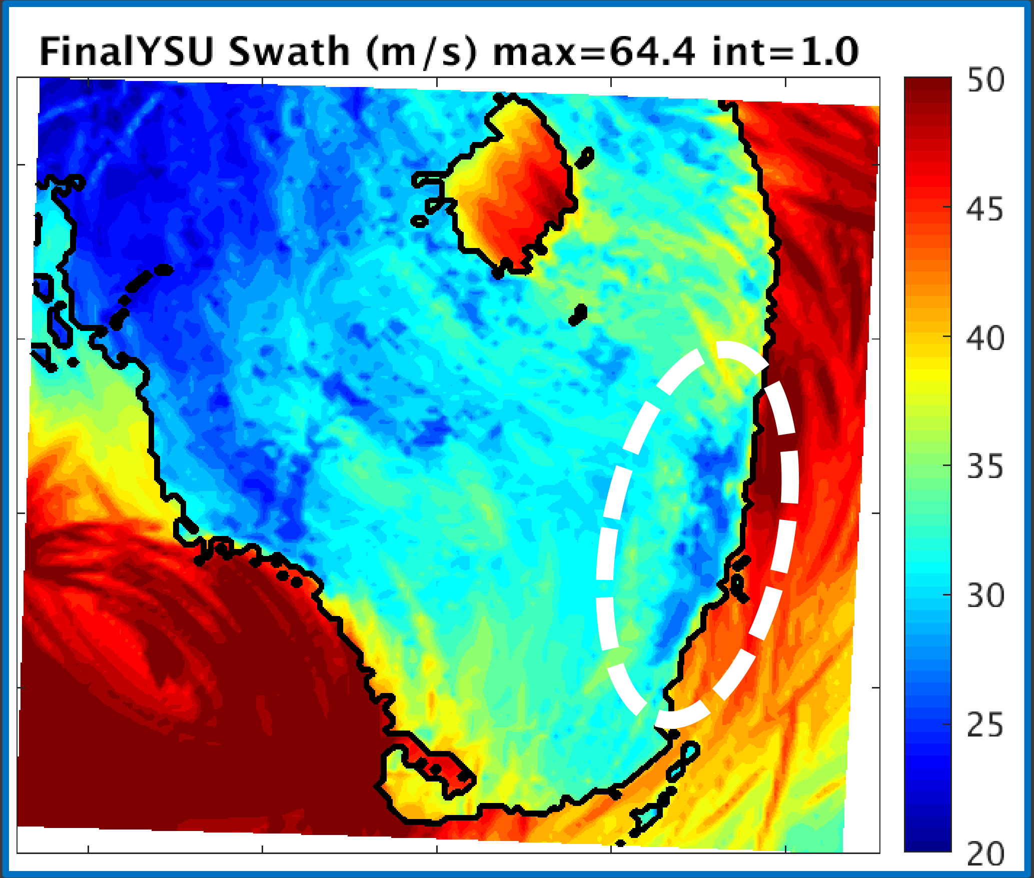

Az.-Mean 10m Winds around 12Z
WIND SPEED (m/s)
RADIUS FROM CENTER (km)
40
30
20
10
0
-10
-20
-30
0
50
100
150
200
250
HWIND Vtot
HWIND Vtan
HWIND Vrad
TCSWA Vtot
TCSWA Vtan
TCSWA Vrad
YSU Vtot
YSU Vtan
YSU Vrad

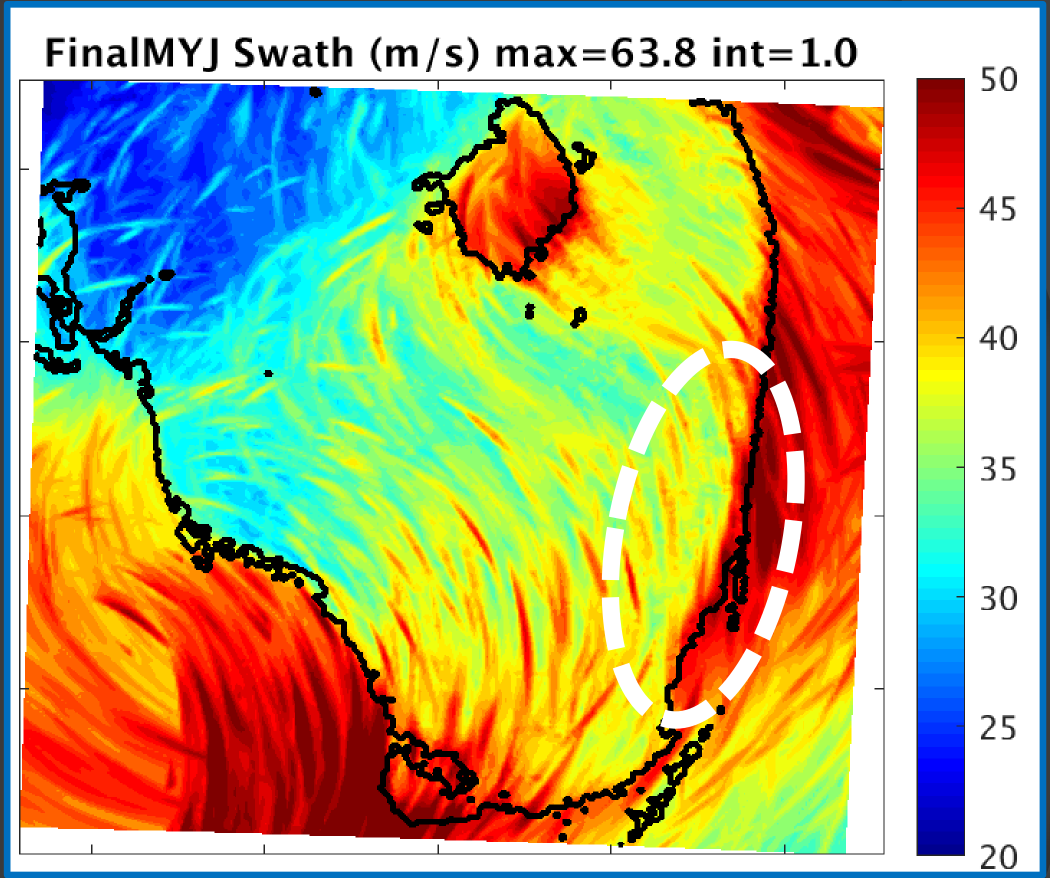

Az.-Mean 10m Winds around 12Z
WIND SPEED (m/s)
RADIUS FROM CENTER (km)
40
30
20
10
0
-10
-20
-30
0
50
100
150
200
250
HWIND Vtot
HWIND Vtan
HWIND Vrad
TCSWA Vtot
TCSWA Vtan
TCSWA Vrad
MYJ Vtot
MYJ Vtan
MYJ Vrad


TCSWA (ms^{-1}) 10-24-1200Z max=59.2
50
45
40
35
30
25
20
15
10
5
0


10m Wind Speed (m/s) 10-24-1000Z max=58.8
latitude
longitude
27
26.5
26
25.5
25
-82
-81.5
-81
-80.5
-80
50
45
40
35
30
25
20
15
10
5
0

Results & Comparisons

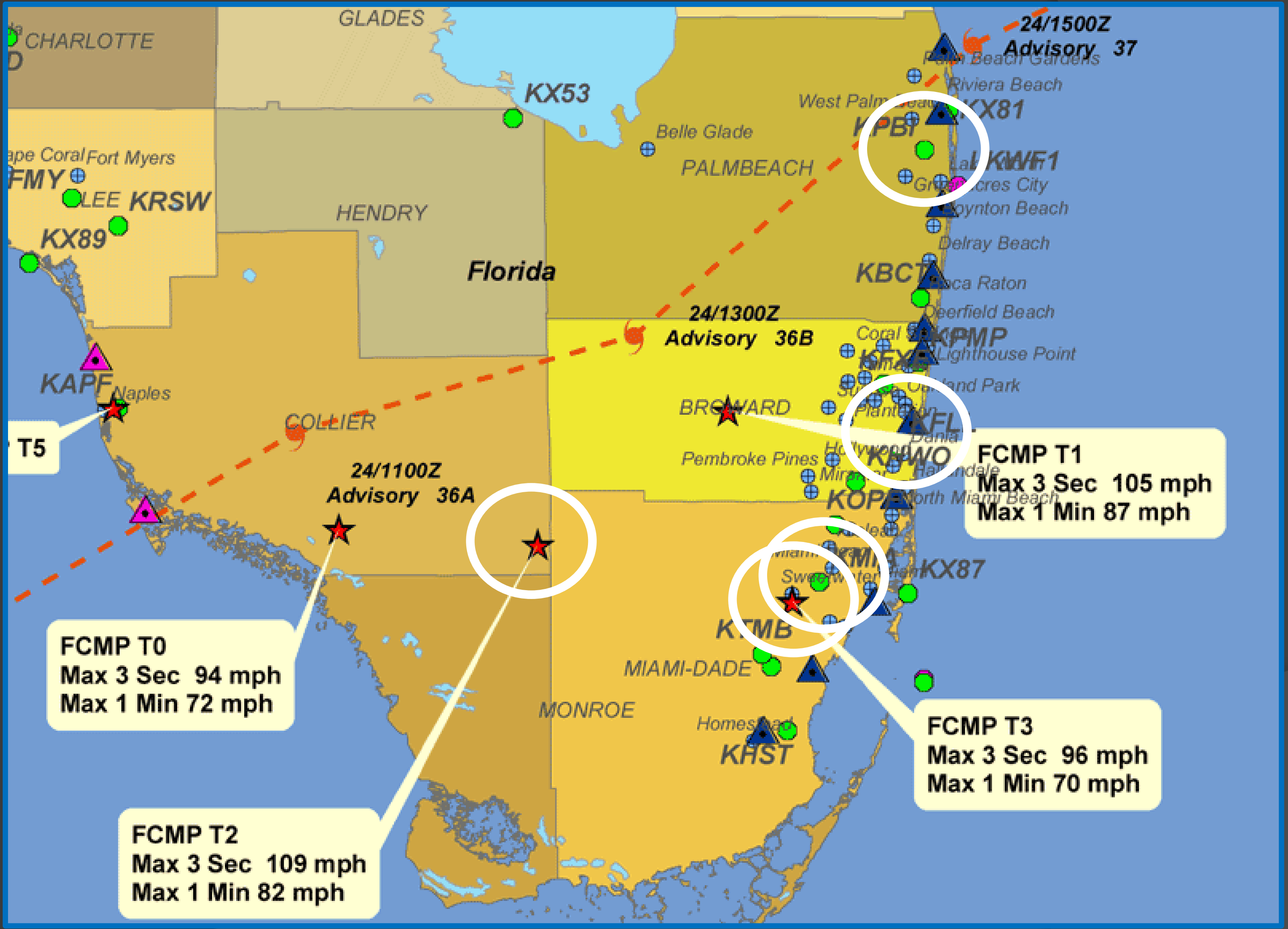


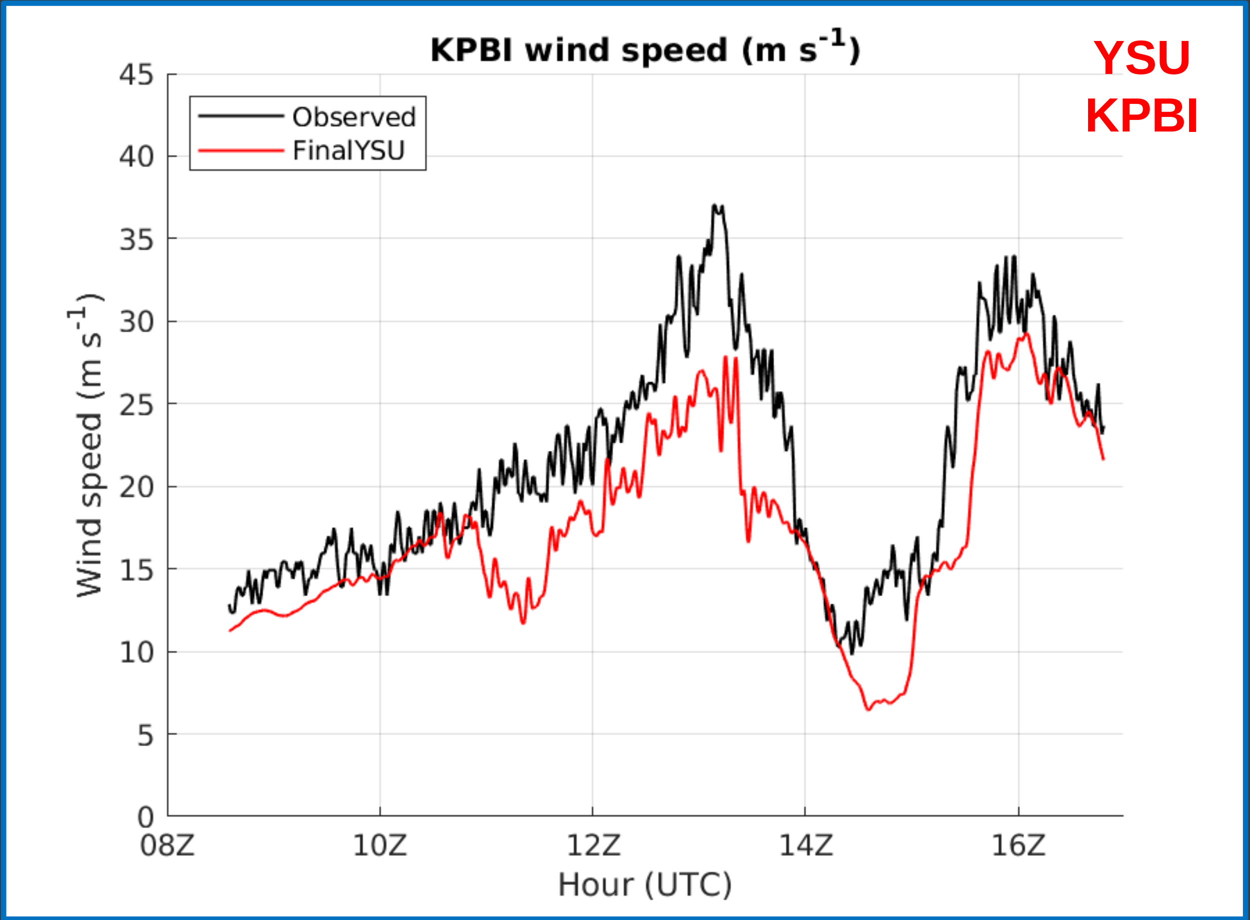


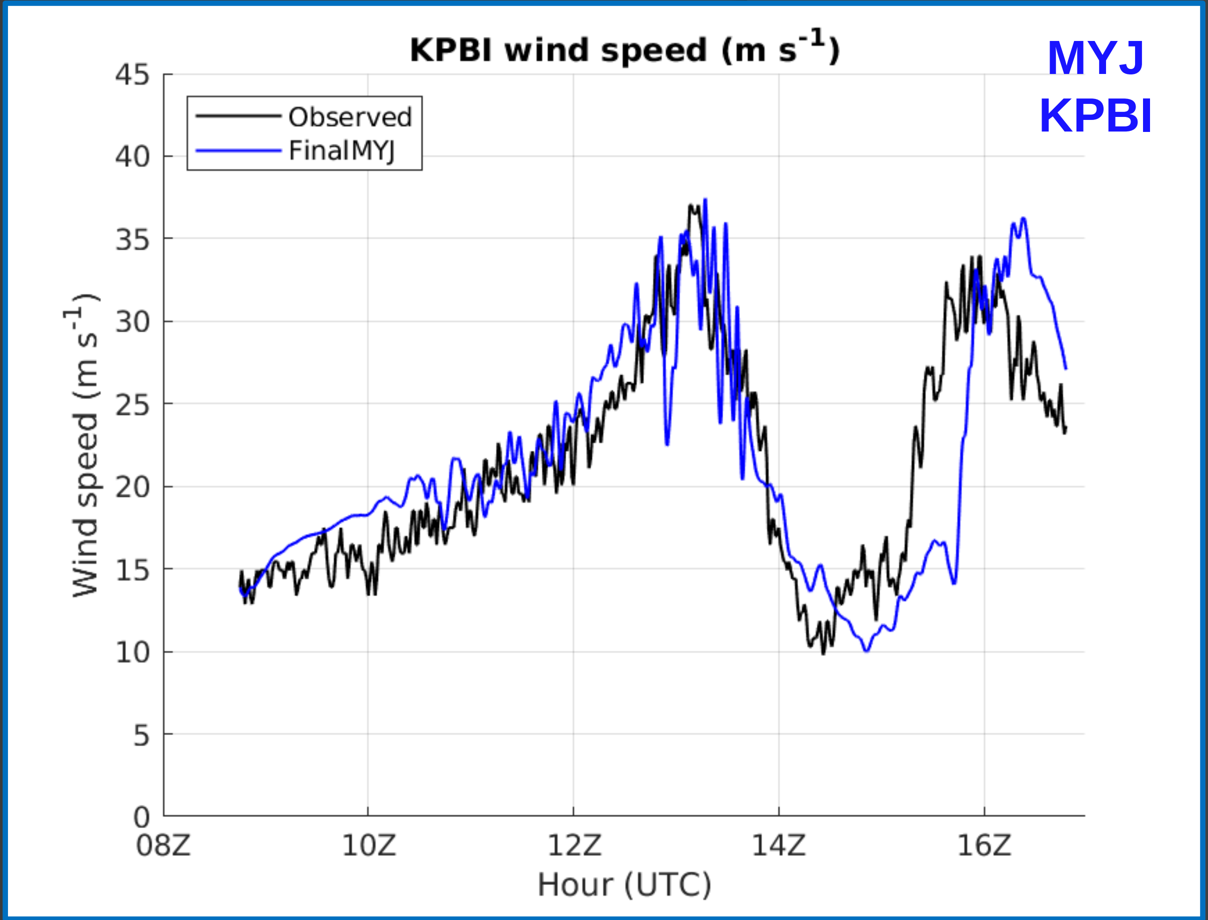
- Surface winds reduced over land in both models, but more in YSU
- YSU winds further reduced in urban areas; seems more correct
- Wind streaks are associated with mesoscale vortices 5-10 km in scale

Results & Comparisons

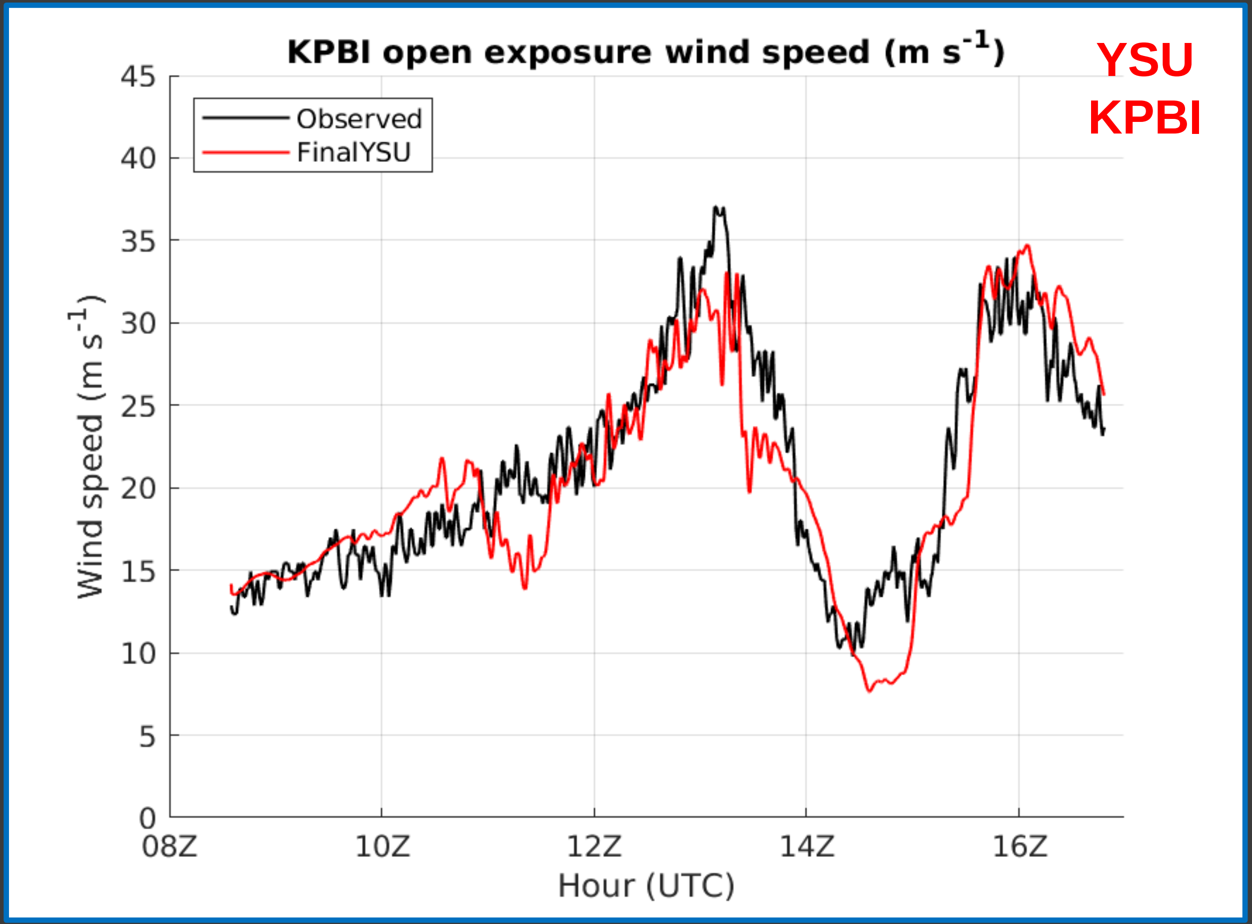
- The real test: Comparison to time series from point observations.
- Data from airports (MIA, FLL, PBI) and from mobile towers deployed by the *Florida Coastal Monitoring Program* (Masters et al. (2010), Balderrama et al. (2011))

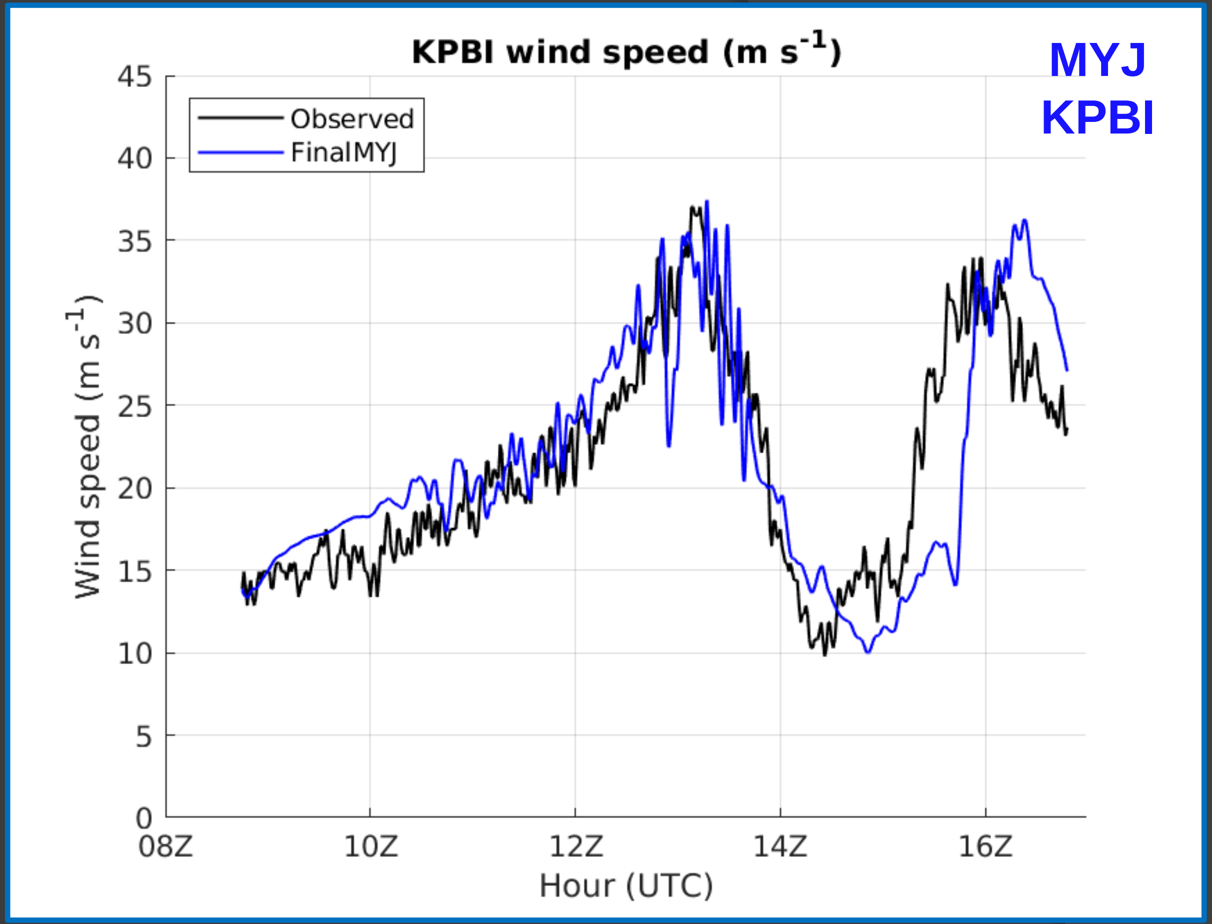




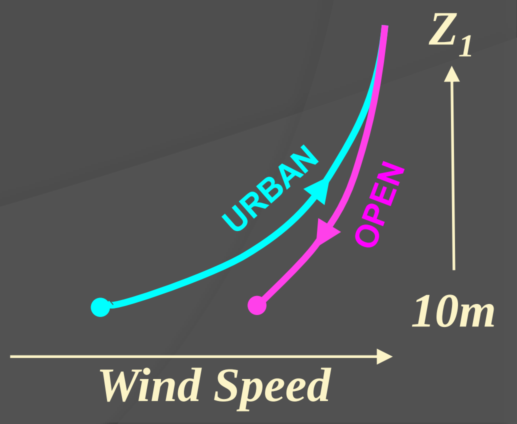


- Model winds are 2-minute means, like ASOS at airports.
- MYJ is nearly perfect!   YSU is much less. Why?
- The land use data set has the airport location designated as "urban". But airport measurements are often in "open exposure".

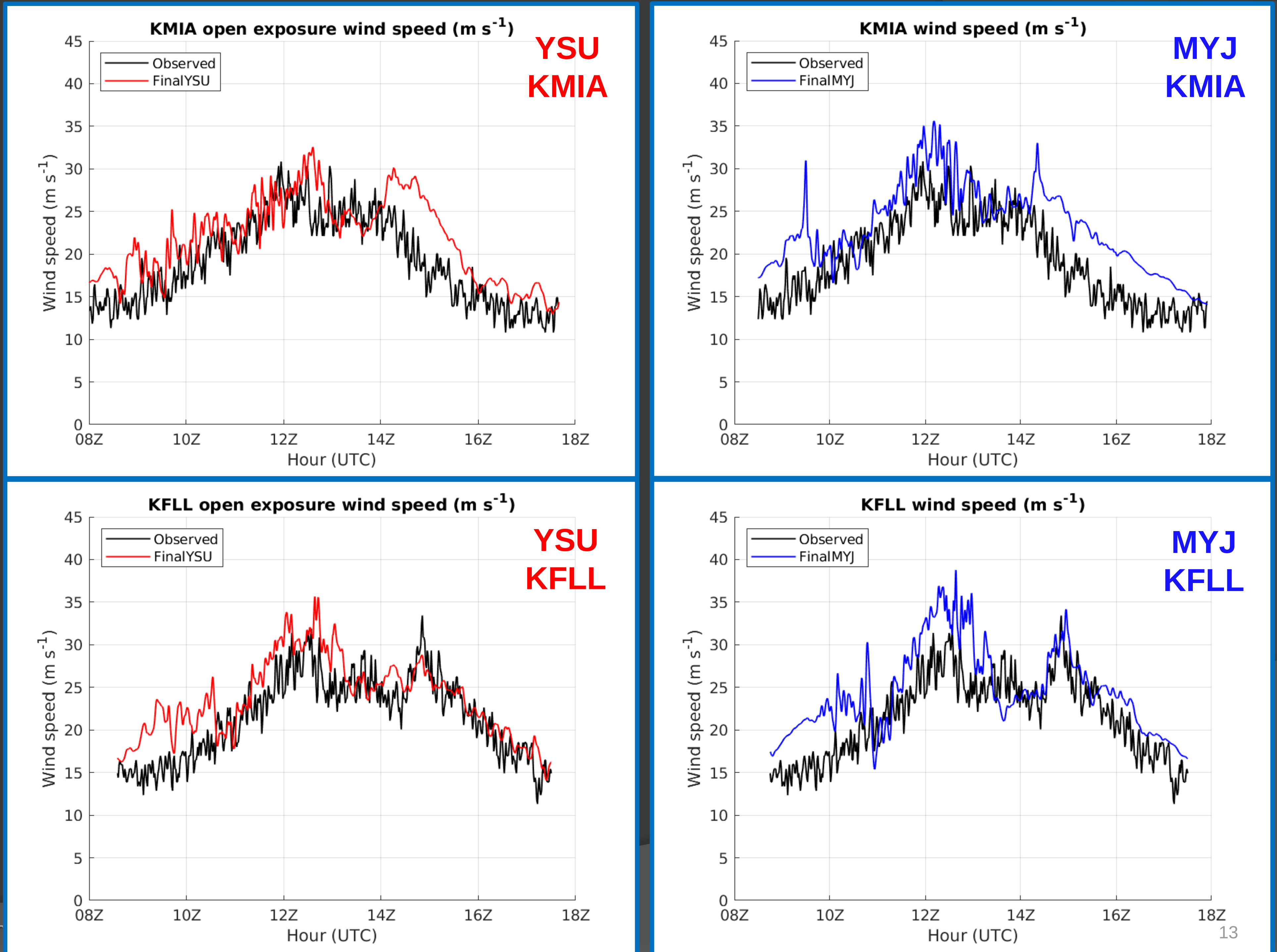




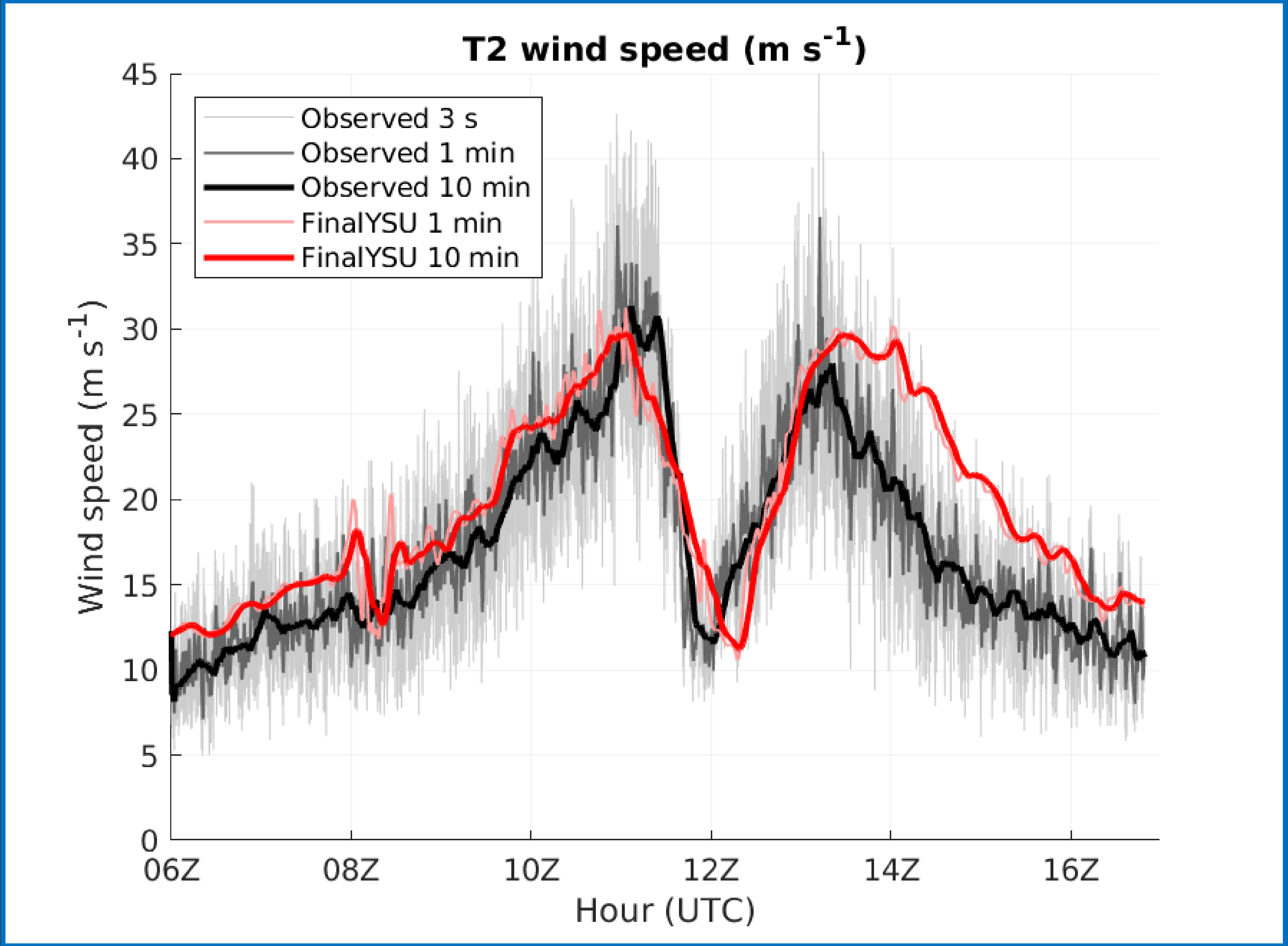
- YSU time series corrected to Z_{open} = 0.03 m using the logarithmic law:
  - $S10_{open} = S10 \times \frac{\log(Z_1/Z_0)}{\log(10/Z_0)} \times \frac{\log(10/Z_{open})}{\log(Z_1/Z_{open})}$ where Z_1 = lowest model level
- MYJ does not seem to recognize rougher surfaces, so this correction causes overestimates…do not apply it.



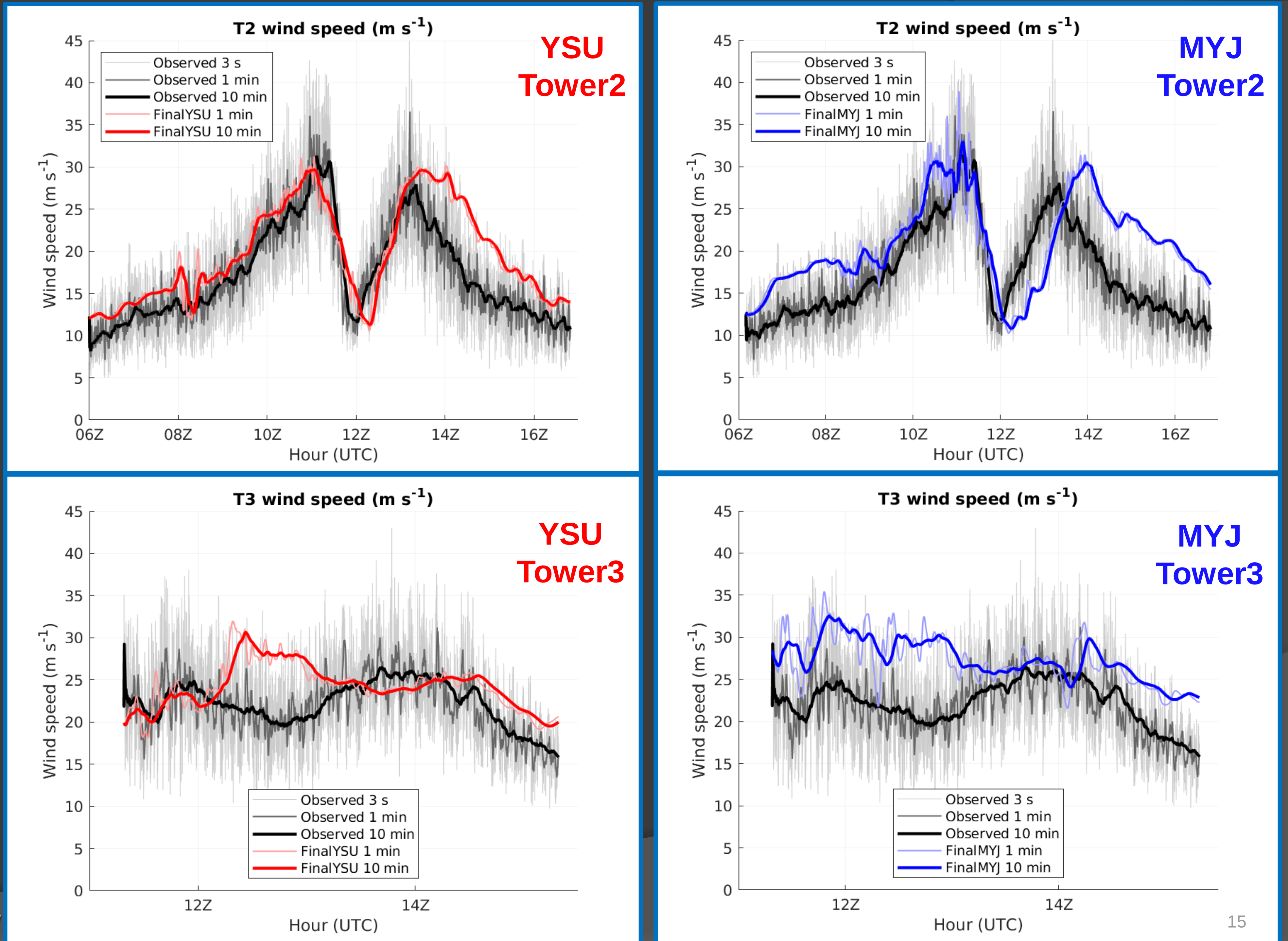
- Similar agreement from both schemes at Miami (top) and Fort Lauderdale (bottom) airports



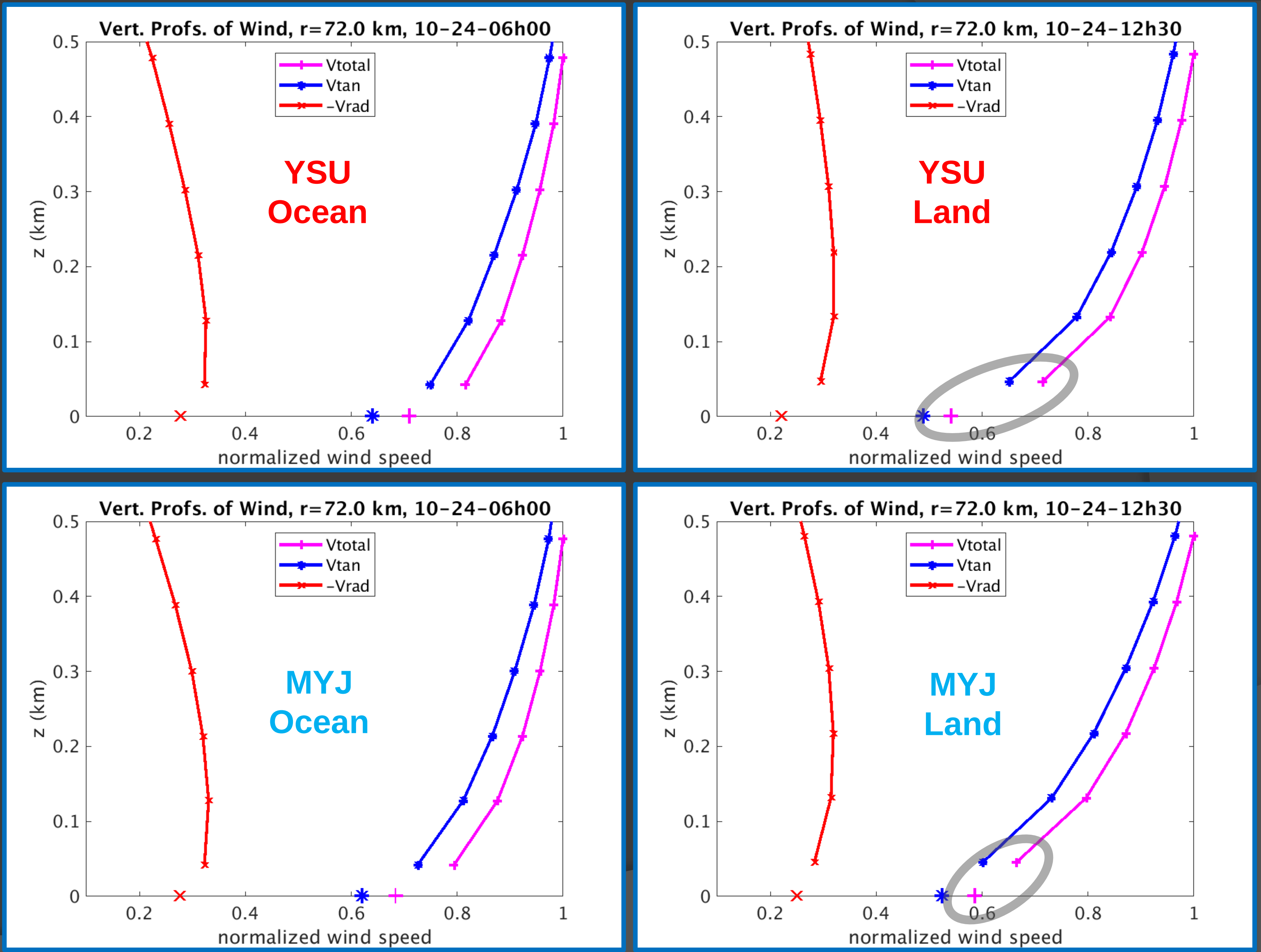
- 10 Hz FCMP tower data converted to 3-s gusts, 1-min winds, and 10-min winds.
- Model cannot reproduce the variability of the 1-min winds.
- But it can reproduce the variability of 10-min winds.



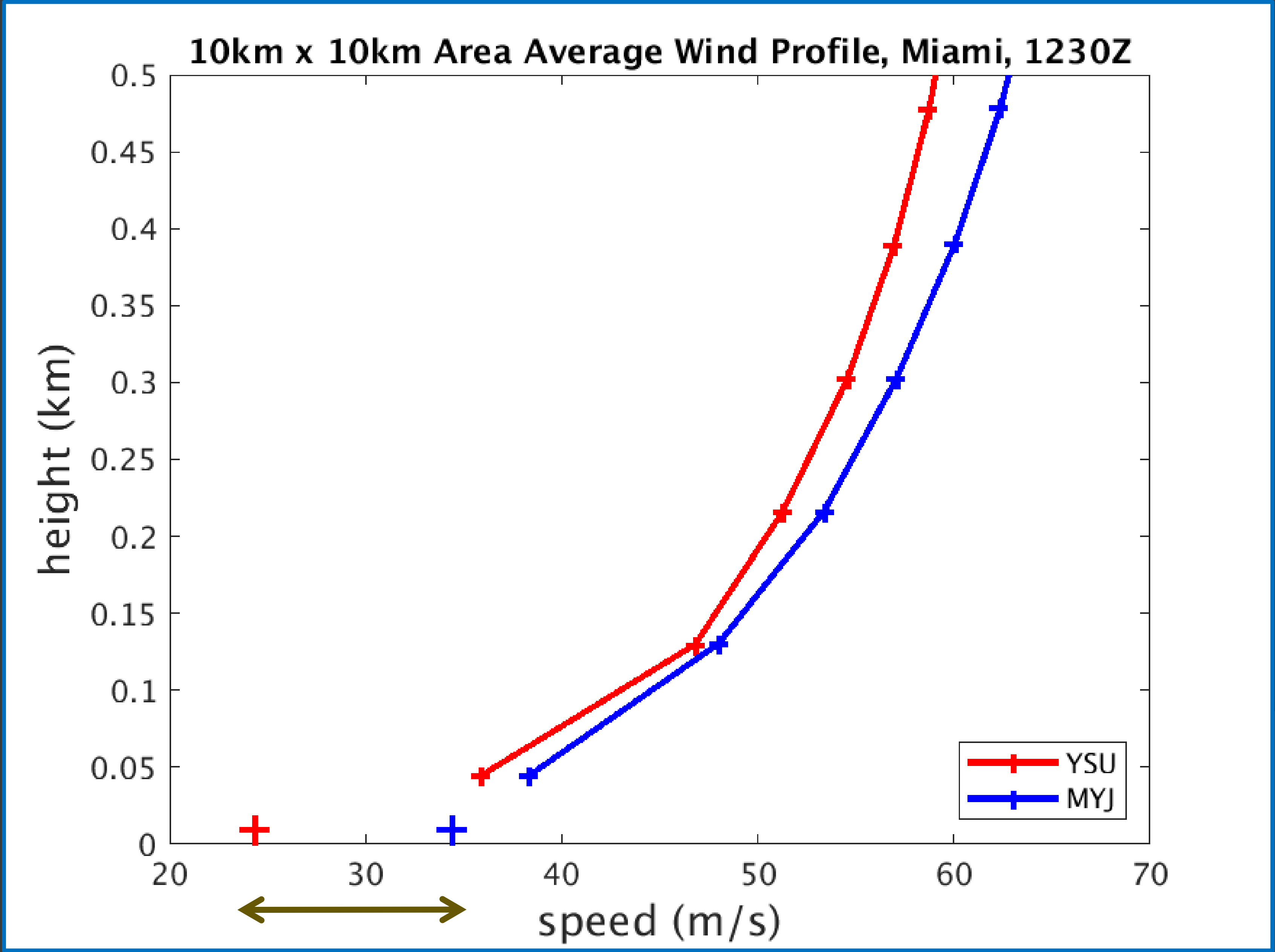
- Similar agreement from both schemes at Tower2 (top), but a bit high at Tower3 (bottom)
  - Miami's FIU campus… $z_0 > 0.5$m?



- Normalized azimuthal-mean vertical profiles of wind over land and water.
  - Nearly identical over water (left)
  - Over land, YSU has reduced surface winds (upper right)
  - Over land, MYJ has reduced winds in lowest model level (lower right)



- Compare vertical wind profiles in hurricane conditions over “urban” area…
  - 2-8% different at model levels in lowest 500 m
  - About 30% different at the surface
- **WHY?**



YSU

```fortran
        dqx   = min(qx(i,k+1)-qx(i,k),0.0)
        hfxpbl(i) = we(i)*dthx
        qfxpbl(i) = we(i)*dqx
!
        dux = ux(i,k+1)-ux(i,k)
        dvx = vx(i,k+1)-vx(i,k)
        if(dux.gt.tmin) then
          ufxpbl(i) = max(prpbl(i)*we(i)*dux,-ust(i)*ust(i))
        elseif(dux.lt.-tmin) then
          ufxpbl(i) = min(prpbl(i)*we(i)*dux,ust(i)*ust(i))
        else
          ufxpbl(i) = 0.0
        endif
        if(dvx.gt.tmin) then
          vfxpbl(i) = max(prpbl(i)*we(i)*dvx,-ust(i)*ust(i))
        elseif(dvx.lt.-tmin) then
          vfxpbl(i) = min(prpbl(i)*we(i)*dvx,ust(i)*ust(i))
        else
          vfxpbl(i) = 0.0
        endif
        delb  = govrth(i)*d3*hpbl(i)
        delta(i) = min(d1*hpbl(i) + d2*wm2(i)/delb,100.)
      endif
    enddo
!
    do k = kts,klpbl
      do i = its,ite
        if(pblflg(i).and.k.ge.kpbl(i))then
          entfac(i,k) = ((zq(i,k+1)-hpbl(i))/delta(i))**2.
        else
          entfac(i,k) = 1.e30
        endif
      enddo
    enddo
!
!     compute diffusion coefficients below pbl
!
    do k = kts,klpbl
      do i = its,ite
        if(k.lt.kpbl(i)) then
          zfac(i,k) = min(max((1.-(zq(i,k+1)-zl1(i))/(hpbl(i)-zl1(i))),zfmin),1.)
          zfacent(i,k) = (1.-zfac(i,k))**3.
          wscalek(i,k) = (ust3(i)+phifac*karman*wstar3(i)*(1.-zfac(i,k)))**h1
          wscalek2(i,k) = (phifac*karman*wstar3_2(i)*(zfac(i,k)))**h1
          if(sfcflg(i)) then
            prfac = conpr
            prfac2 = 15.9*(wstar3(i)+wstar3_2(i))/ust3(i)/(1.+4.*karman*(wstar3(i)+wstar3_2(i))/ust3(i))
            prnumfac = -3.*(max(zq(i,k+1)-sfcfrac*hpbl(i),0.))**2./hpbl(i)**2.
          else
            prfac = 0.
            prfac2 = 0.
            prnumfac = 0.
            phim8z = 1.+aphi5*zol1(i)*zq(i,k+1)/zl1(i)
            wscalek(i,k) = ust(i)/phim8z
            wscalek(i,k) = max(wscalek(i,k),0.001)
          endif
          prnum0 = (phih(i)/phim(i)+prfac)
          prnum0 = max(min(prnum0,prmax),prmin)
            xkzm(i,k) = wscalek(i,k) *karman*    zq(i,k+1)      *    zfac(i,k)**pfac+ &
                        wscalek2(i,k)*karman*(hpbl(i)-zq(i,k+1))*(1-zfac(i,k))**pfac
          !Do not include xkzm at kpbl-1 since it changes entrainment
          if (k.eq.kpbl(i)-1.and.cloudflg(i).and.we(i).lt.0.0) then
            xkzm(i,k) = 0.0
          endif
          prnum =  1. + (prnum0-1.)*exp(prnumfac)
          xkzq(i,k) = xkzm(i,k)/prnum*zfac(i,k)**(pfac_q-pfac)
          prnum0 = prnum0/(1.+prfac2*karman*sfcfrac)
          prnum =  1. + (prnum0-1.)*exp(prnumfac)
          xkzh(i,k) = xkzm(i,k)/prnum
          xkzm(i,k) = xkzm(i,k)+xkzom(i,k)
          xkzh(i,k) = xkzh(i,k)+xkzoh(i,k)
          xkzq(i,k) = xkzq(i,k)+xkzoh(i,k)
          xkzm(i,k) = min(xkzm(i,k),xkzmax)
          xkzh(i,k) = min(xkzh(i,k),xkzmax)
          xkzq(i,k) = min(xkzq(i,k),xkzmax)
        endif
      enddo
```

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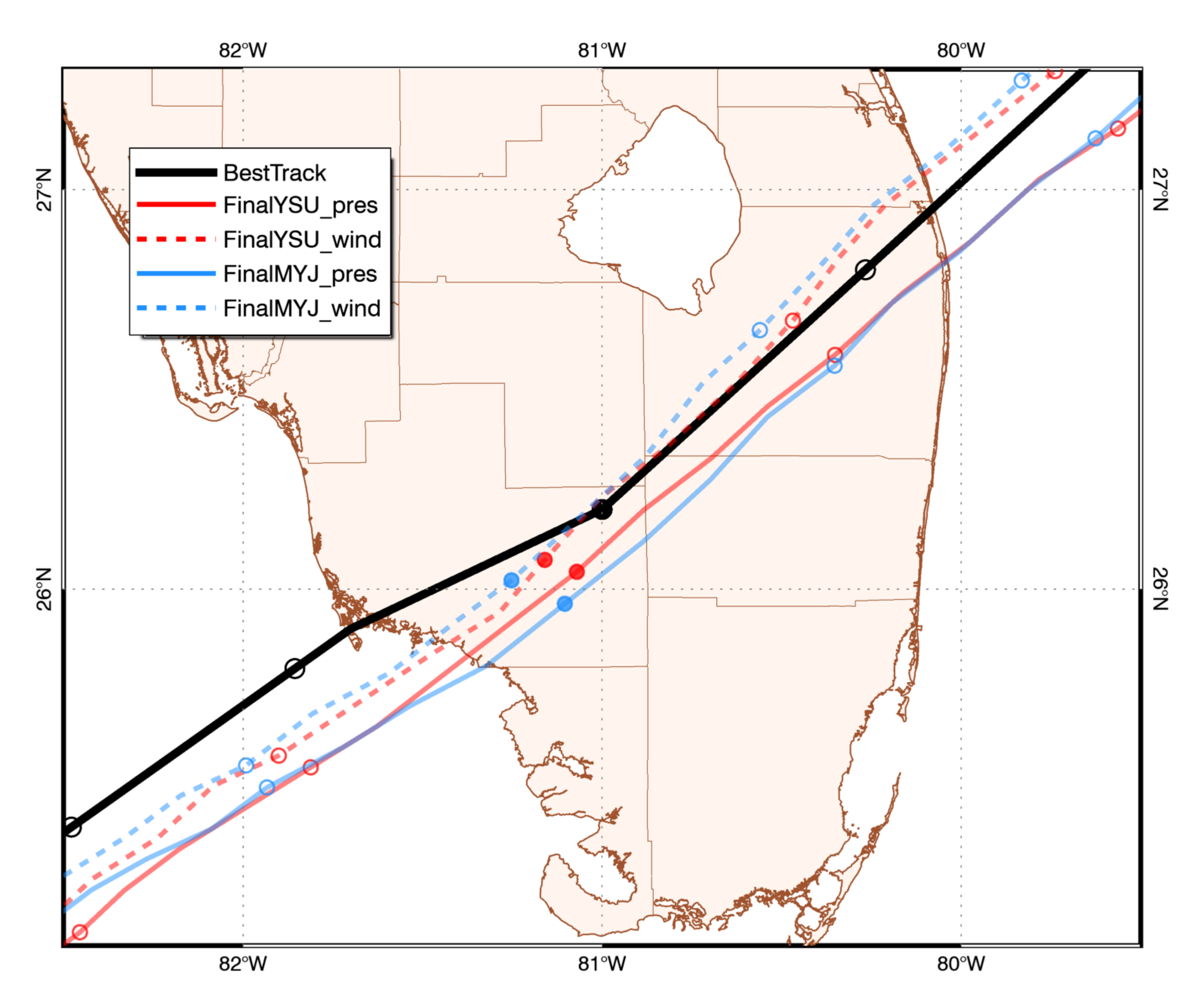
MYJ

```fortran
      REAL,DIMENSION(MSS:MSE,KTS:KTE),INTENT(INOUT):: SPECIES
!
!----------------------------------------------------------------------
!***
!***  LOCAL VARIABLES
!***
      INTEGER:: K,M
!
      REAL:: CF,CMB,CMSB,DTOZL,DTOZS,RCML,RHOK,RKHH,RKHZ,RKSS,RSSB
!
      REAL,DIMENSION(KTS:KTE-1):: CM,CR,DTOZ
!
      REAL,DIMENSION(MSS:MSE,KTS:KTE-1):: RKCT,RSS
!
!----------------------------------------------------------------------
!**********************************************************************
!---PREPARATIONS-------------------------------------------------------
      DO K=KTS,LMH-1
        DTOZ(K)=DTDIF/(ZHK(K)-ZHK(K+1))
        CR(K)=-DTOZ(K)*RKH(K)
        IF(K.LT.LPBL) THEN
          DO M=MSS,NSPEC
            RKCT(M,K)=0.
          ENDDO
        ELSE
          RKHZ=RKH(K)*(ZHK(K)-ZHK(K+2))
          DO M=MSS,NSPEC
            RKCT(M,K)=RKHZ*CTS(M)*0.5
          ENDDO
        ENDIF
      ENDDO
!---TOP LEVEL----------------------------------------------------------
      RHOK=RHO(KTS)
      CM(KTS)=DTOZ(KTS)*RKH(KTS)+RHOK
      DO M=MSS,NSPEC
        RSS(M,KTS)=-RKCT(M,KTS)*DTOZ(KTS)+SPECIES(M,KTS)*RHOK
      ENDDO
!---INTERMEDIATE LEVELS------------------------------------------------
      DO K=KTS+1,LMH-1
        DTOZL=DTOZ(K)
        CF=-DTOZL*RKH(K-1)/CM(K-1)
        RHOK=RHO(K)
        CM(K)=-CR(K-1)*CF+(RKH(K-1)+RKH(K))*DTOZL+RHOK
        DO M=MSS,NSPEC
          RSS(M,K)=-RSS(M,K-1)*CF &
                   +(RKCT(M,K-1)-RKCT(M,K))*DTOZL+SPECIES(M,K)*RHOK
        ENDDO
      ENDDO
!---BOTTOM LEVEL-------------------------------------------------------
      DTOZS=DTDIF/(ZHK(LMH)-ZHK(LMH+1))
      RKHH=RKH(LMH-1)
!
      CF=-DTOZS*RKHH/CM(LMH-1)
      CMB=CR(LMH-1)*CF
      RHOK=RHO(LMH)
!
      DO M=MSS,NSPEC
        RKSS=RKHS*CLOW(M)
        CMSB=-CMB+(RKHH+RKSS)*DTOZS+RHOK
        RSSB=-RSS(M,LMH-1)*CF+RKCT(M,LMH-1)*DTOZS+SPECIES(M,LMH)*RHOK
        SPECIES(M,LMH)=(DTOZS*RKSS*SZ0(M)+RSSB)/CMSB
      ENDDO
!---BACKSUBSTITUTION---------------------------------------------------
      DO K=LMH-1,KTS,-1
        RCML=1./CM(K)
        DO M=MSS,NSPEC
          SPECIES(M,K)=(-CR(K)*SPECIES(M,K+1)+RSS(M,K))*RCML
        ENDDO
      ENDDO
!----------------------------------------------------------------------
!
      END SUBROUTINE VDIFH
!
!----------------------------------------------------------------------
!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
!----------------------------------------------------------------------
      SUBROUTINE VDIFX(DTDIF,LMH,RKHS,CT                              &
```

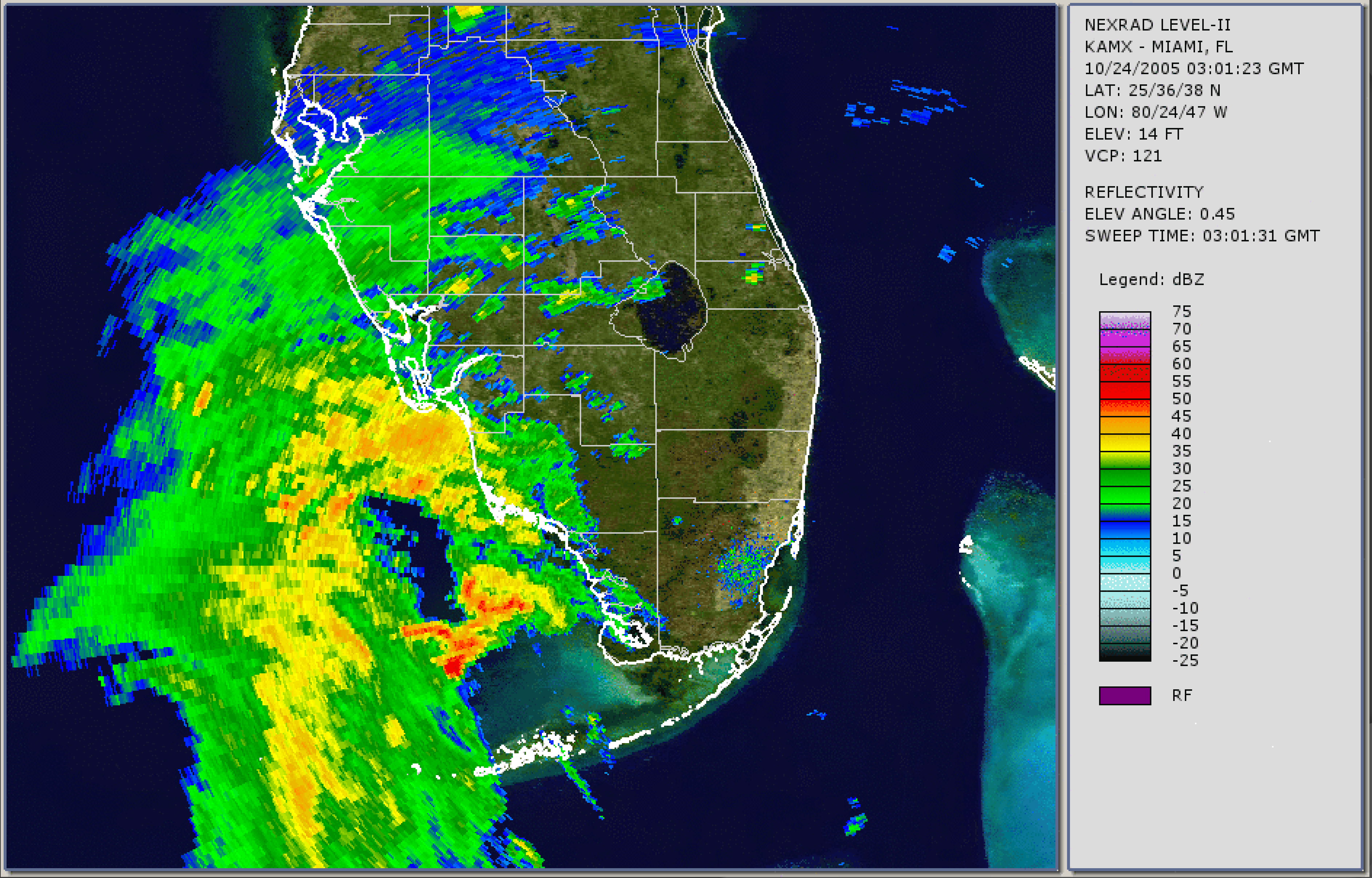
1524,7   86%

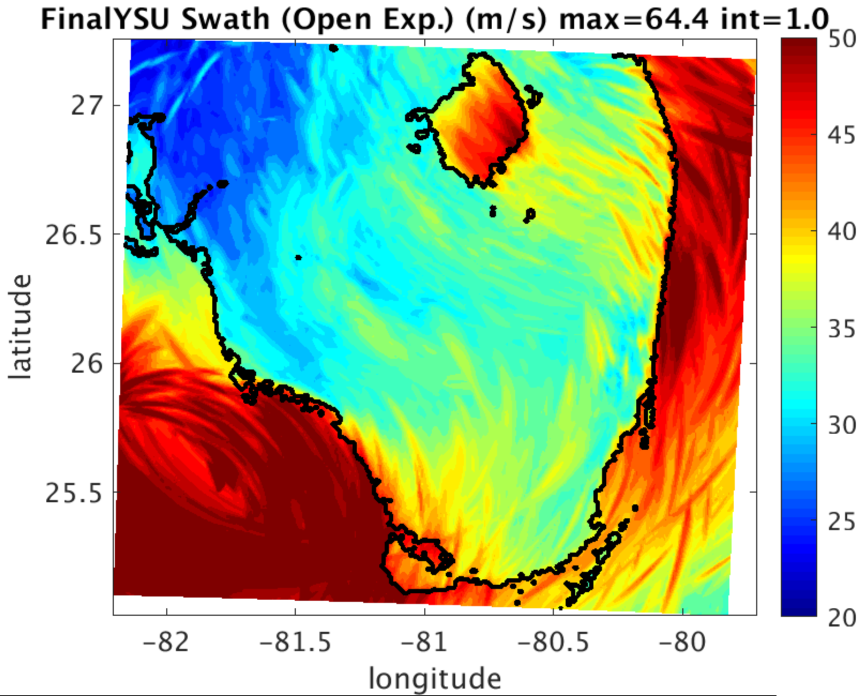
Summary

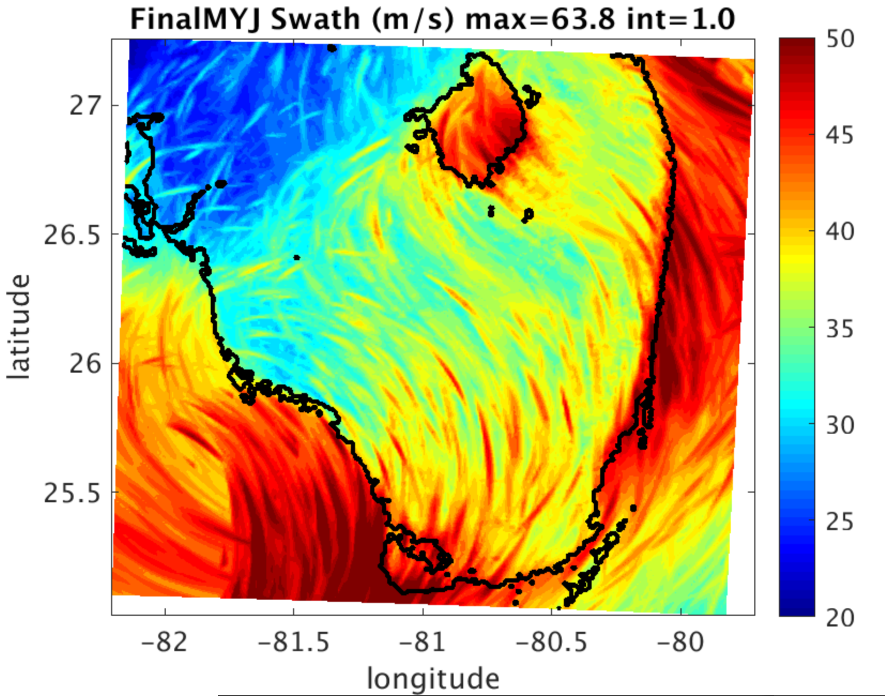
- The vortex bogussing technique and other modeling tricks were used to produce landfall simulations of Wilma (2005) with the correct track, intensity, and size.
- Under these conditions, a mesoscale model can produce time series of local wind speeds in good agreement with observations. (Make sure to correct for open exposure when needed.)
- Over water, the boundary layers and surface wind fields produced by the YSU and MYJ schemes are very similar.
- Over land, the MYJ does not appear to recognize further increases in roughness length associated with land surface types. YSU may overestimate the effect.
- The causes for these differences remain to be understood.

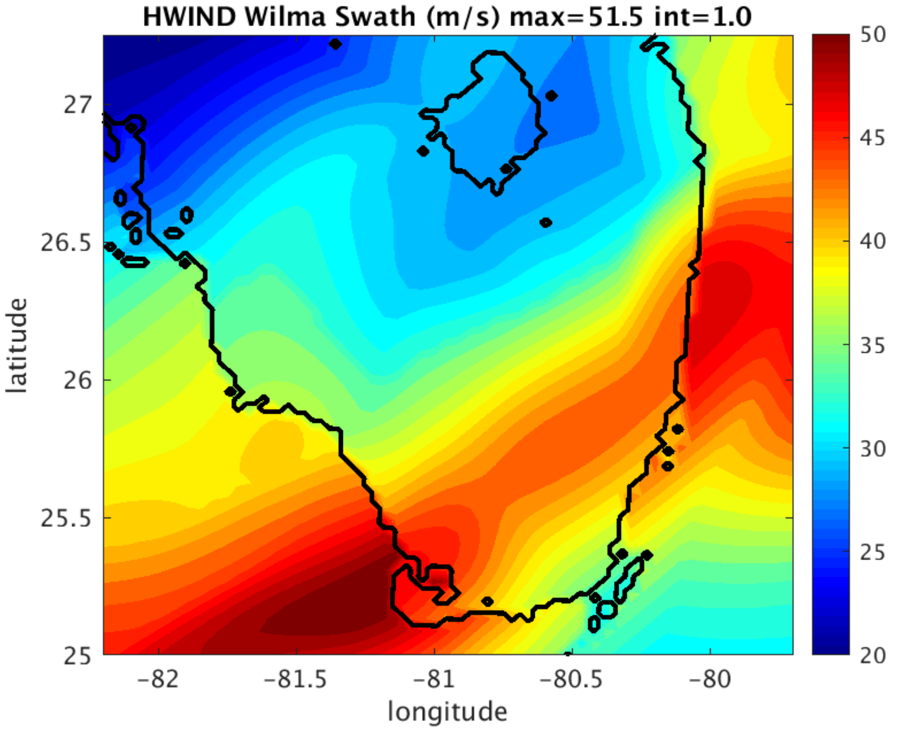


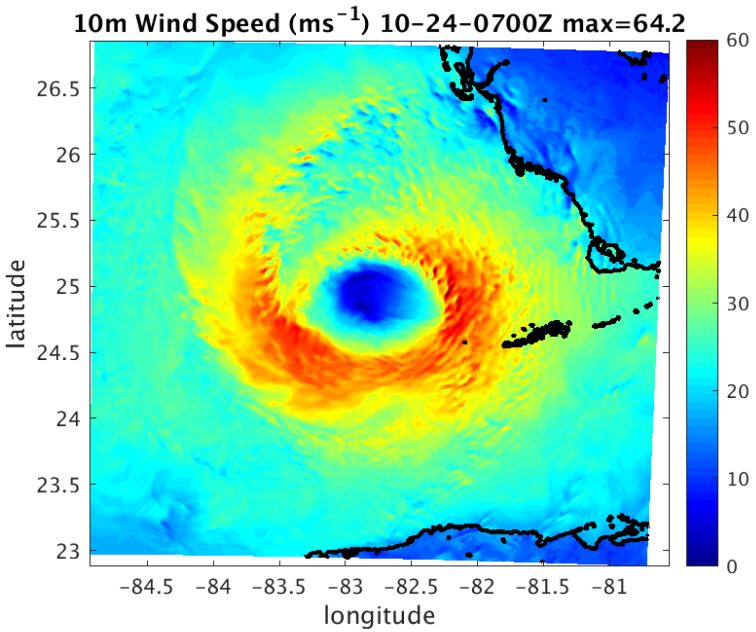
82°W
81°W
80°W
27°N
26°N
BestTrack
FinalYSU_pres
FinalYSU_wind
FinalMYJ_pres
FinalMYJ_wind

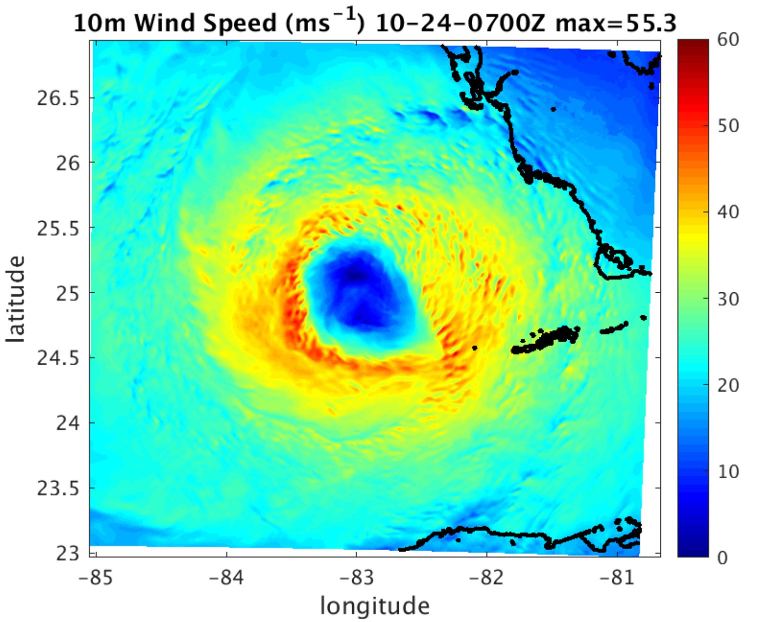

NEXRAD LEVEL-II
KAMX - MIAMI, FL
10/24/2005 03:01:23 GMT
LAT: 25/36/38 N
LON: 80/24/47 W
ELEV: 14 FT
VCP: 121
REFLECTIVITY
ELEV ANGLE: 0.45
SWEEP TIME: 03:01:31 GMT
Legend: dBZ
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
RF

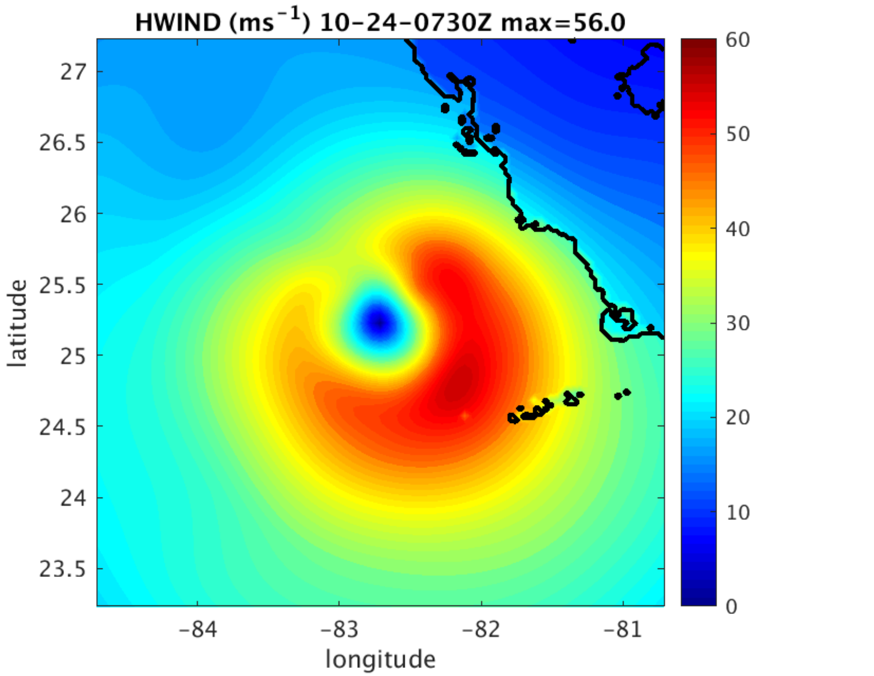

FinalYSU Swath (Open Exp.) (m/s) max=64.4 int=1.0
latitude
longitude
27
26.5
26
25.5
-82
-81.5
-81
-80.5
-80
50
45
40
35
30
25
20

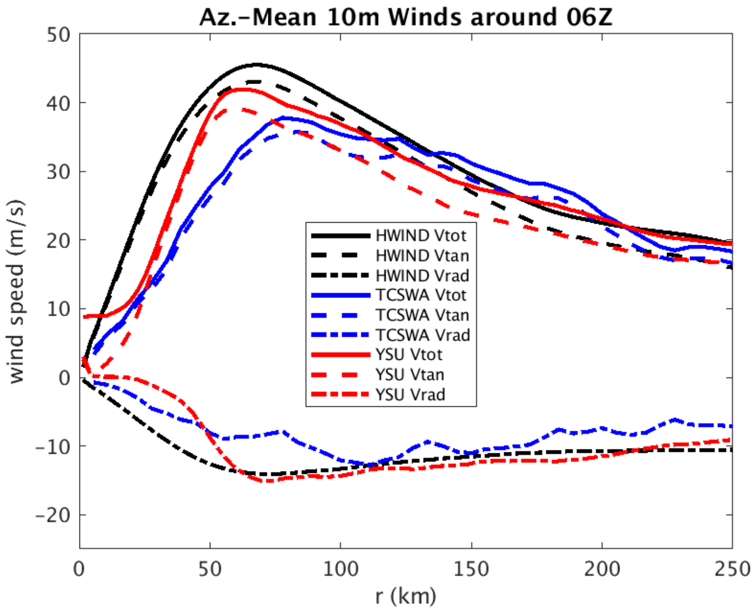

FinalMYJ Swath (m/s) max=63.8 int=1.0
latitude
longitude
27
26.5
26
25.5
-82
-81.5
-81
-80.5
-80
50
45
40
35
30
25
20

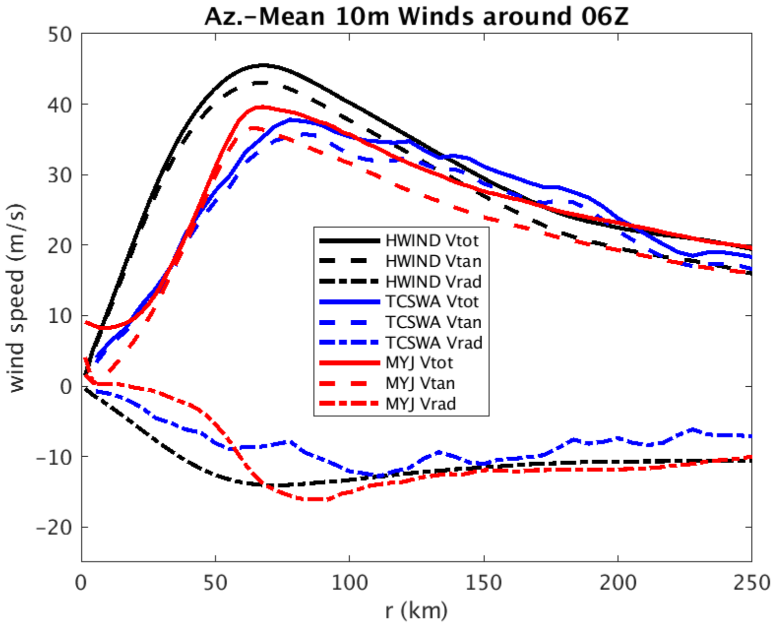

HWIND Wilma Swath (m/s) max=51.5 int=1.0
latitude
longitude
27
26.5
26
25.5
25
-82
-81.5
-81
-80.5
-80
50
45
40
35
30
25
20

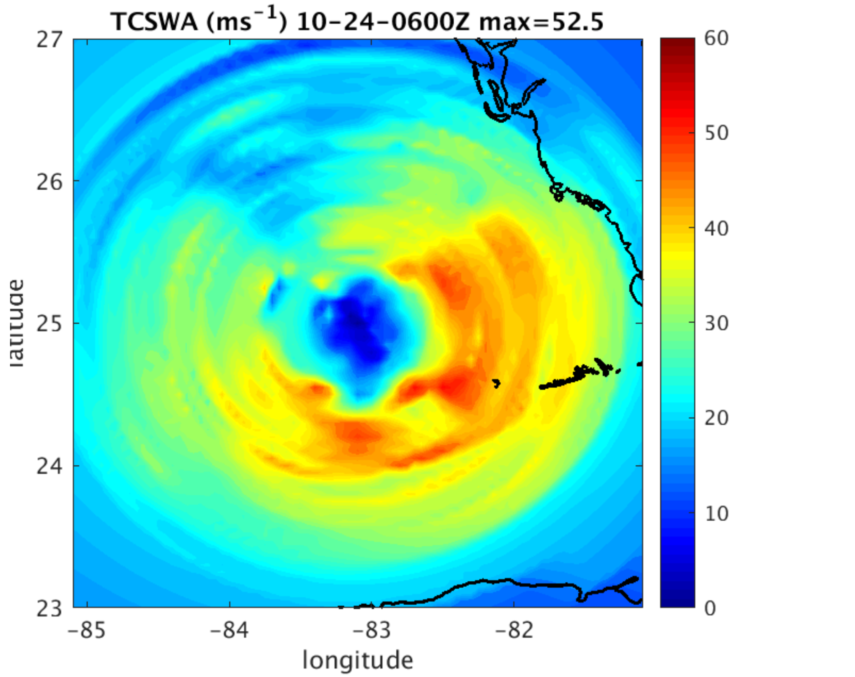

10m Wind Speed (ms^{-1}) 10-24-0700Z max=64.2
latitude
longitude

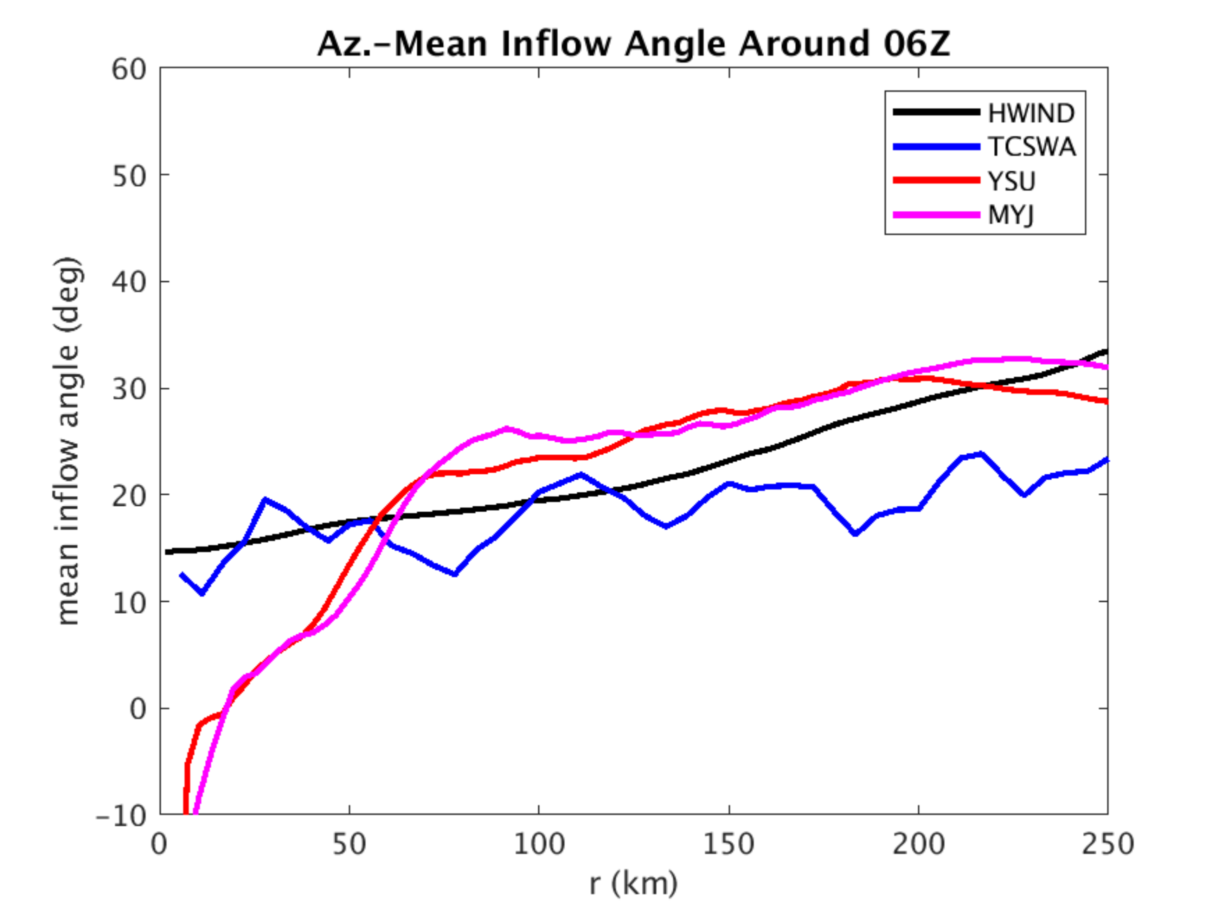

10m Wind Speed (ms^{-1}) 10-24-0700Z max=55.3
latitude
longitude

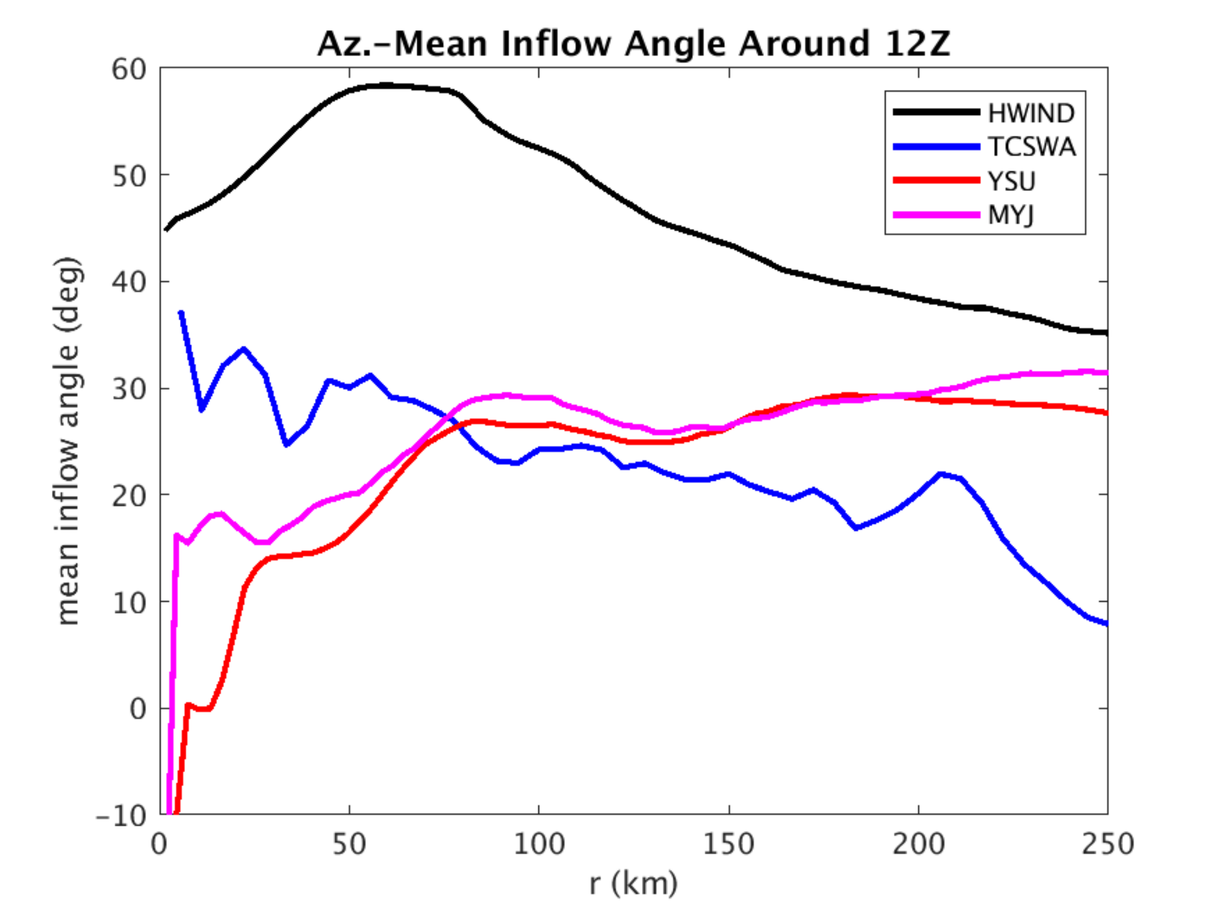

HWIND (ms^{-1}) 10-24-0730Z max=56.0
latitude
longitude


Az.-Mean 10m Winds around 06Z
wind speed (m/s)
r (km)
HWIND Vtot
HWIND Vtan
HWIND Vrad
TCSWA Vtot
TCSWA Vtan
TCSWA Vrad
YSU Vtot
YSU Vtan
YSU Vrad


Az.-Mean 10m Winds around 06Z
wind speed (m/s)
r (km)
HWIND Vtot
HWIND Vtan
HWIND Vrad
TCSWA Vtot
TCSWA Vtan
TCSWA Vrad
MYJ Vtot
MYJ Vtan
MYJ Vrad


TCSWA (ms^{-1}) 10-24-0600Z max=52.5
latitude
longitude


Az.-Mean Inflow Angle Around 06Z
HWIND
TCSWA
YSU
MYJ
mean inflow angle (deg)
r (km)


Az.-Mean Inflow Angle Around 12Z
HWIND
TCSWA
YSU
MYJ
mean inflow angle (deg)
r (km)