Urbanized WRF simulations of NYC: a heat wave, UHIs, and HRVs?

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Outline

- Two research goals
  - Simulation of summer 2010 interaction b/t a heat wave & NYC UHI with NCAR urbanized-WRF at horiz grid-resolutions less than 1 km
  - Impacts of horiz Δx- & Δt-magnitudes on formation & evolution of WRF "vortices" that appear in simulations
- Methodology
- Results
  - NYC: Heat wave + UHI
  - Vortices: real or not?
- Ways forward

Setup for 11 NYC (UHI+ heat-wave) WRF simulations:

- uWRF: our name for NCAR (led by F. Chen) urban-WRF
  - A. Martilli developed urban scheme in my TVM/URBMET
  - S. Dupont put it into MM5 for J. Ching at EPA
  - H. Taha and myself ran it for Houston
  - A. Martilli, E. Gutierrez, et al. are putting it into WRF

  - Momentum-adv: horiz (5th order) & vertical (3rd order)
  - Scalar-adv: moisture (Pos-definite); others (monotonic)

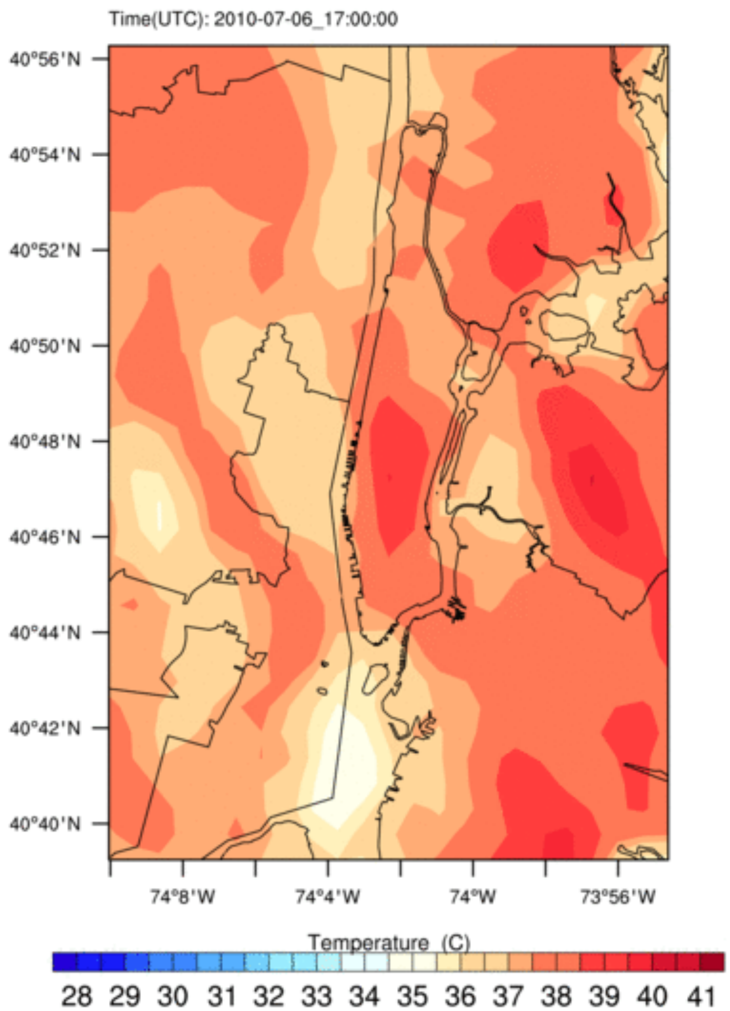
  - K_z: Boulac TKE (+Martilli multi-level urbanization)
  - K_h: Smagorinsky 2-D deformation (km_opt=4)
  - Gradients for K_h: simple, i.e., only adjacent-pts along co-ordinate directions (Diff_opt=1)

(continued on next slide)

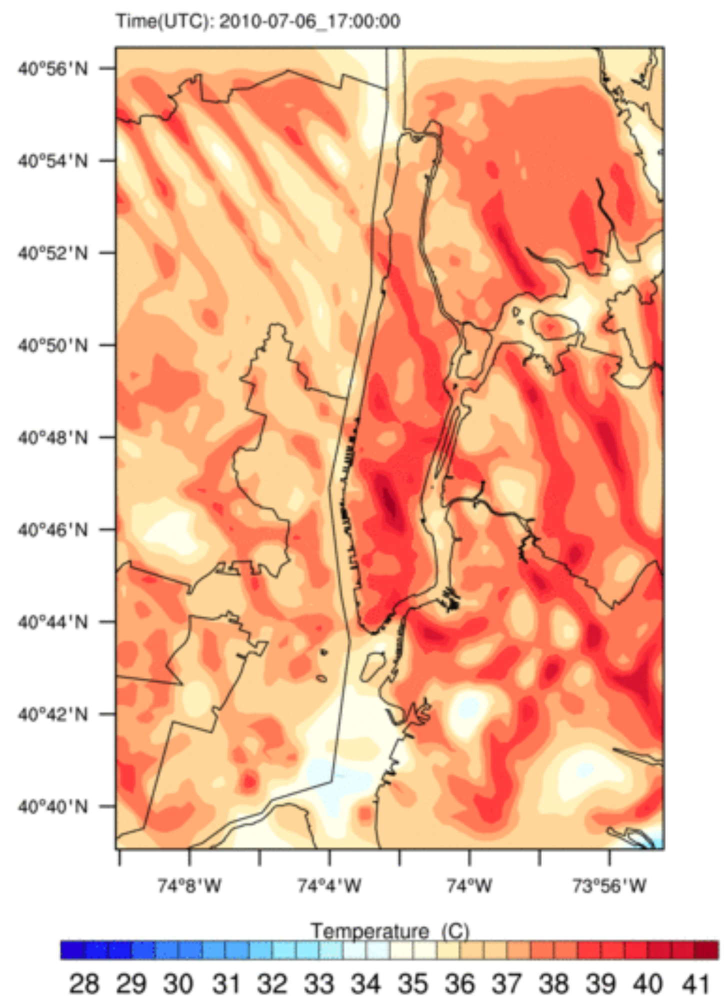
- Setup for 11 NYC (UHI+ heat-wave) WRF simulations (continued):
  - Land Surface Model: Noah
  - Building energy model: Martilli, w/ urban morphological data as f(x,y) from NUDAPT-database via J. Ching
  - Damping (on/at): upper BC, w, and/or divergence
  - Δx: 9, 3, 1, 0.333, 0.111 km
  - Δt: 27, 9, 3, 1, 0.1 s

– E. Gutierrez's MS (SJSU) & PhD (CCNY) work

Results: NYC Temp at z=12 m for 07/06/10, 13 EST, Δt=1 s
Δx =1 km: left, good UHI & Δx = 333 m: right, waves + convection??
Next slide: corresponding w-fields

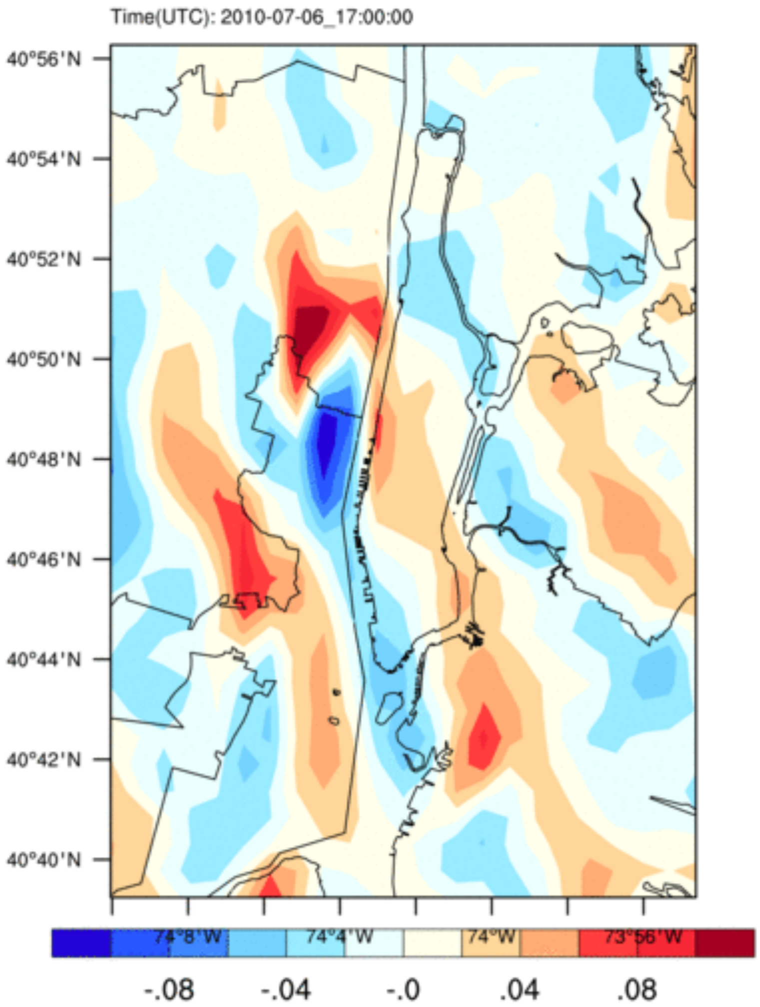


Run 2: ΔX=1 km, Δt=1 s

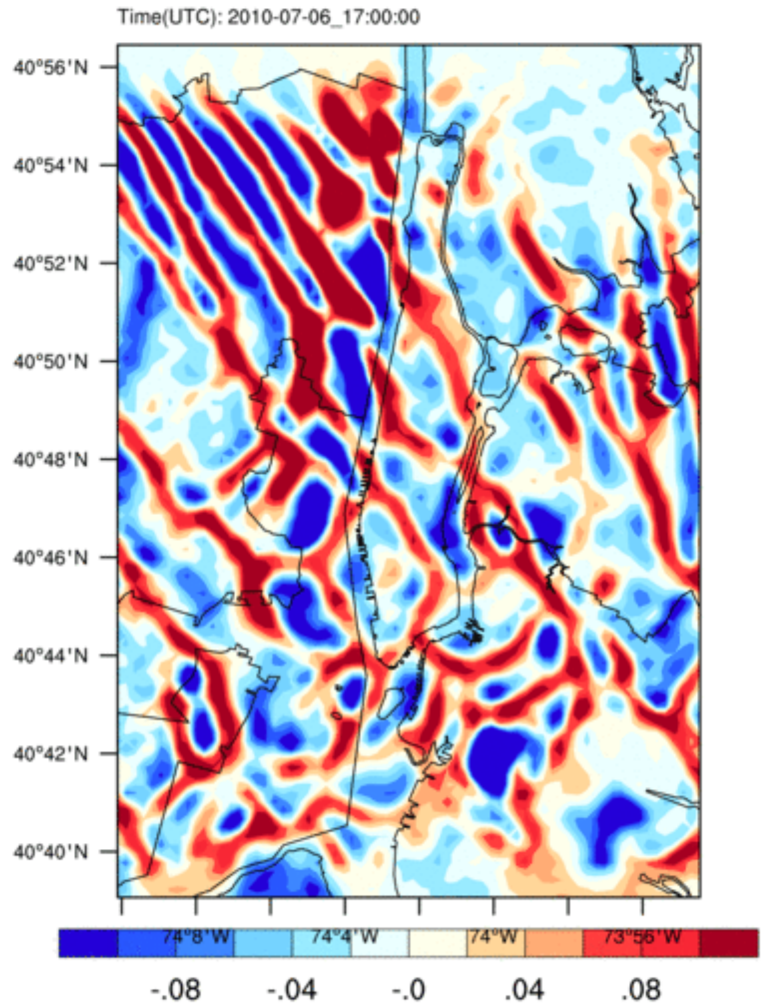


Run 4: ΔX=333 m, Δt=1 s

NYC w-velocity at z=12 m, 07/06/10, 13 EST, Δt=1 s
Δx =1-km (left): max at Palisades ridge west of NYC (OK)
& Δx = 333-m (right) waves + convection???



Run 2: ΔX=1 km, Δt=1 s

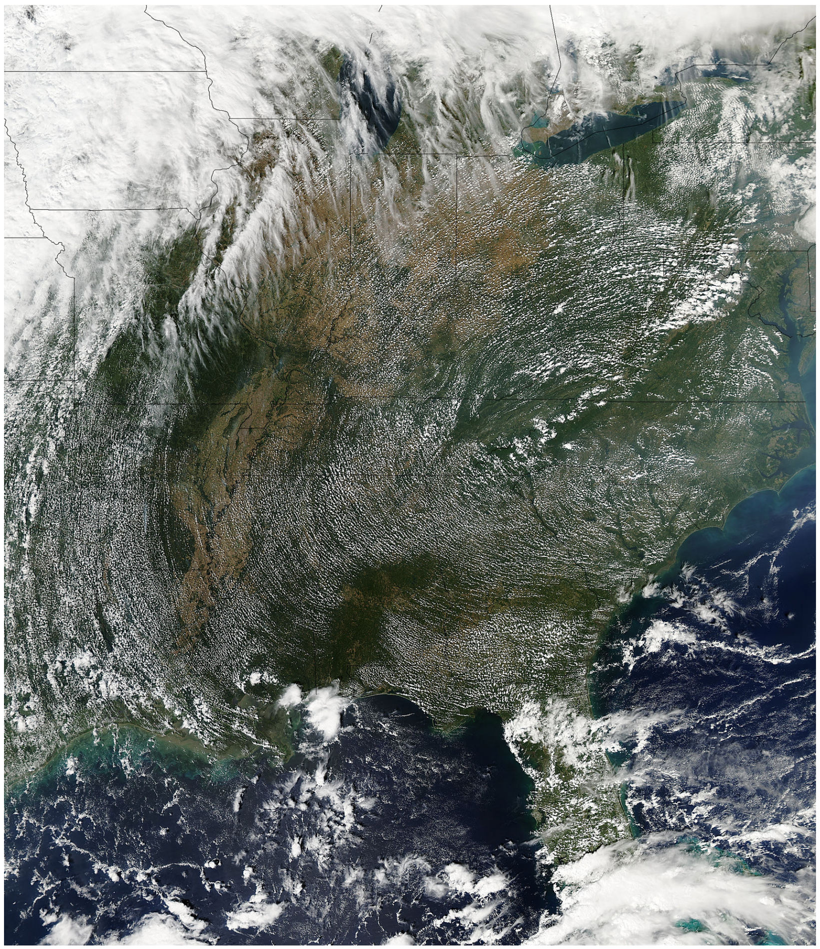


Run 4: ΔX=333 m, Δt=1 s

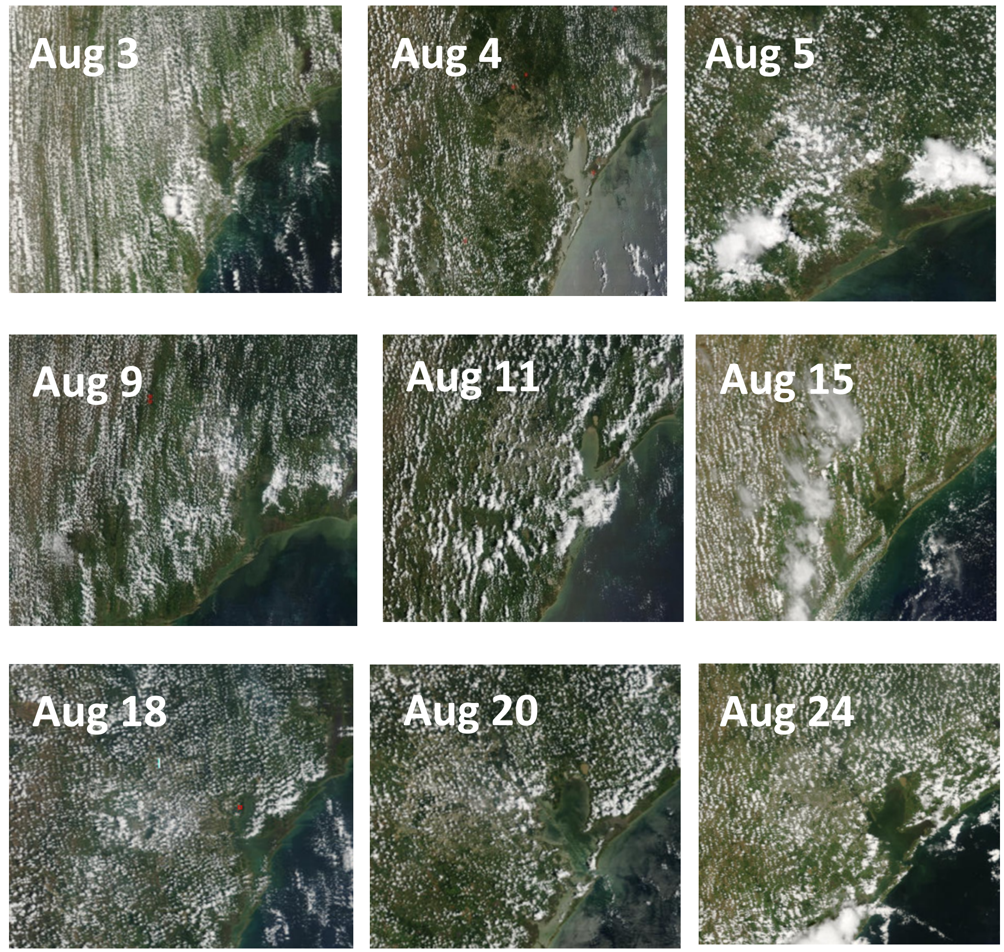
HRVs are sometimes seen in weakly-forced convective PBLs

http://lance.nasa.gov/imagery/rapid-response/

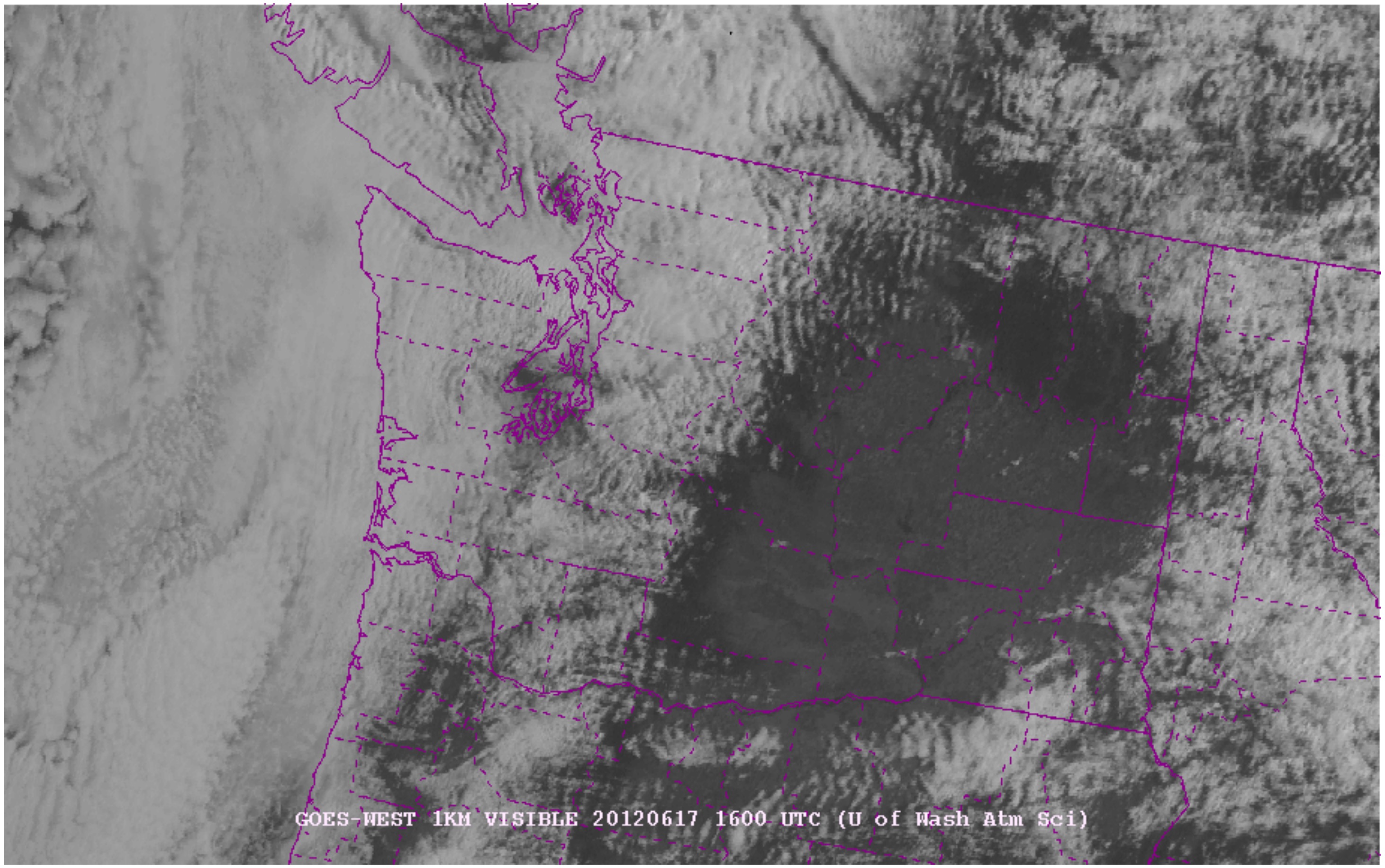
Eastern USA, October 2010
From J. Ching



Daily summer, flat Houston area (2006): Terra/Aqua Satellite ~ local noon



From C. Mass: US Pacific NW
Note: waves downwind of Mts,
but not offshore nor in basin

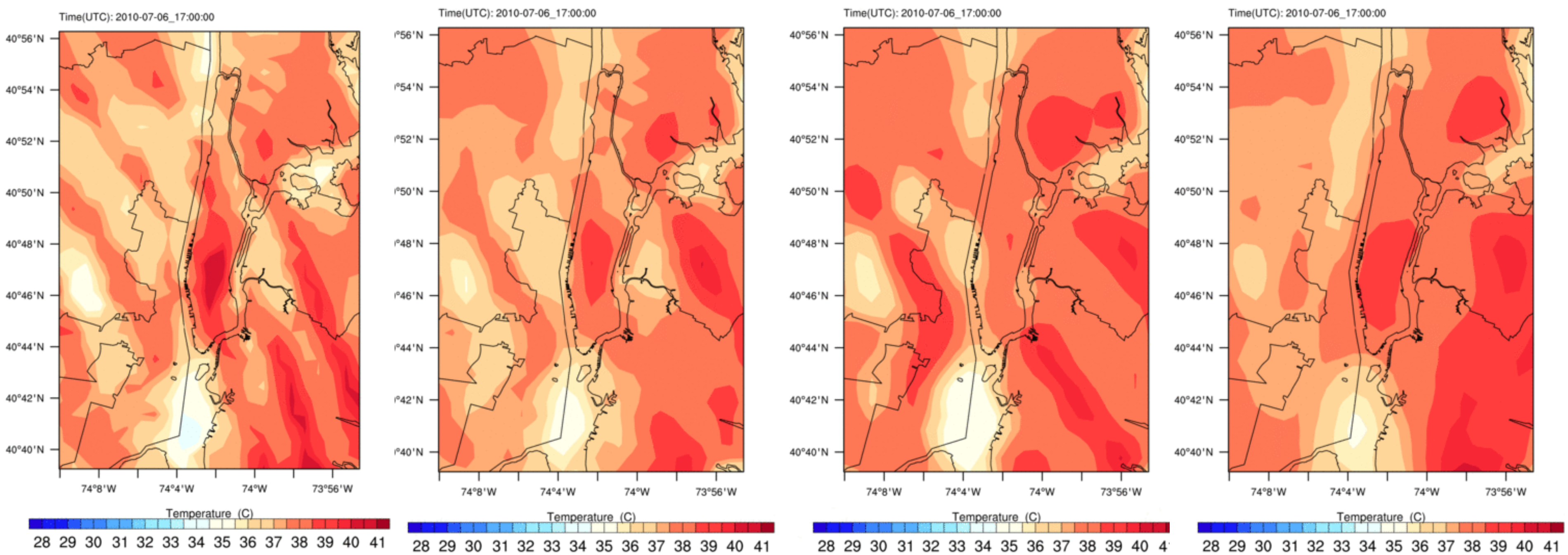


But, does WRF simulate "waves/HRVs" for correct reasons?

- WRF "always" shows them for $\Delta x < 500$ m during daytime windy hours,
- but their "form" depends on WRF-options (as shown in following slides)
  - Δx–magnitude by CCNY/SJSU for NYC
  - Δt-magnitude by CCNY/SJSU for NYC
  - Upwind lateral-boundary location by C. Mass for US-NW
  - Upper boundary absorbing layer by C. Mass for US-NW
  - Advection scheme by H. Kusaka et al. for China Sea
  - PBL scheme by J. Ching for Houston
  - K_{HOR} schemes by A. Martilli for Madrid

NYC Temp at z=12 m for 07/06/10, 13 EST for Δx = 333 m as function of Δt = 6, 1, 0.66, & 0.11 s

Rolls dissipate when Δt decreased (rightmost, good UHI; Δt = 0.11 s is 1/54 recommended value of 6 s for 3rd domain. WRF recommends Δt = 6Δx for coarsest domain, reduced by factor of 3 for each inner nest. Next slide: w-fields



Run 3: Δt=6 s | Run 4: Δt=1 s | Run 5: Δt=0.66 s | Run 6: Δt=0.11 s

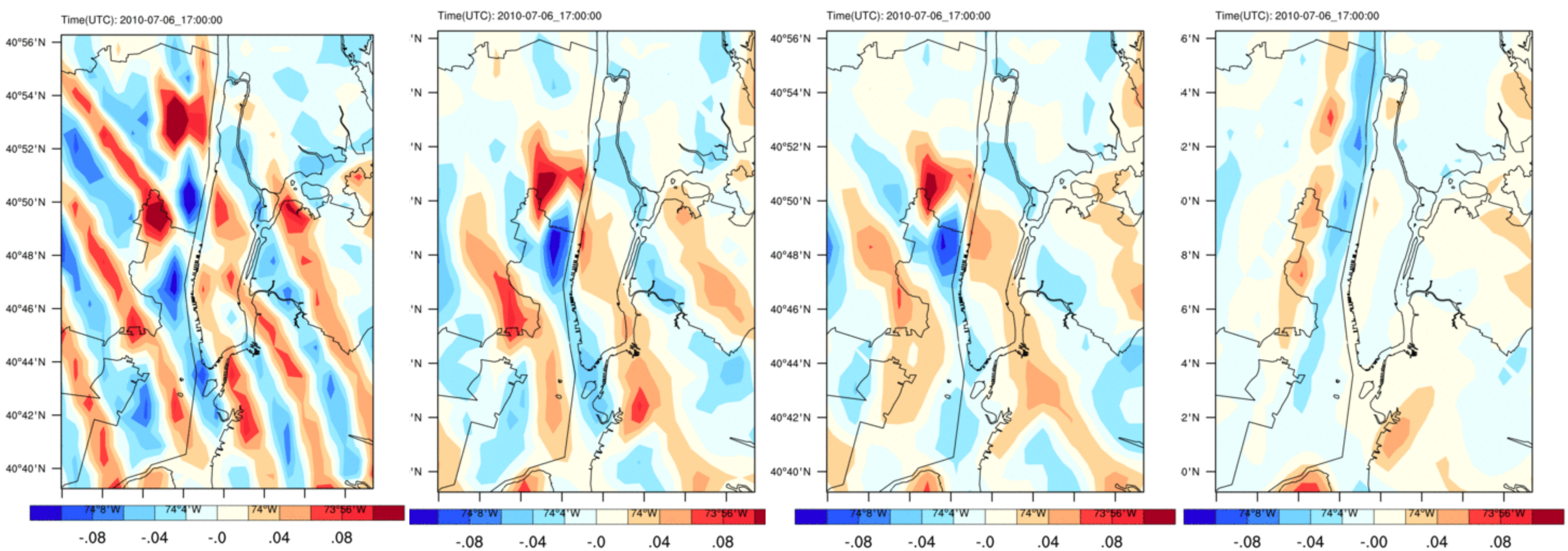
Results: T-waves decrease as Δt decreases, as K_{NUM} is $\sim(\Delta t)^{-2}$

Next slide: corresponding w-fields

NYC w-velocity at z = 12 m on 07/06/10 at 13 EST for Δx=333-m, Δt = 6, 1, 0.66, & 0.11 s

Results: > w-waves decrease as Δt decreases, with rightmost field most reasonable (has max along Palisades ridge west of NYC)

> Decrease is expected, whether or not waves are real



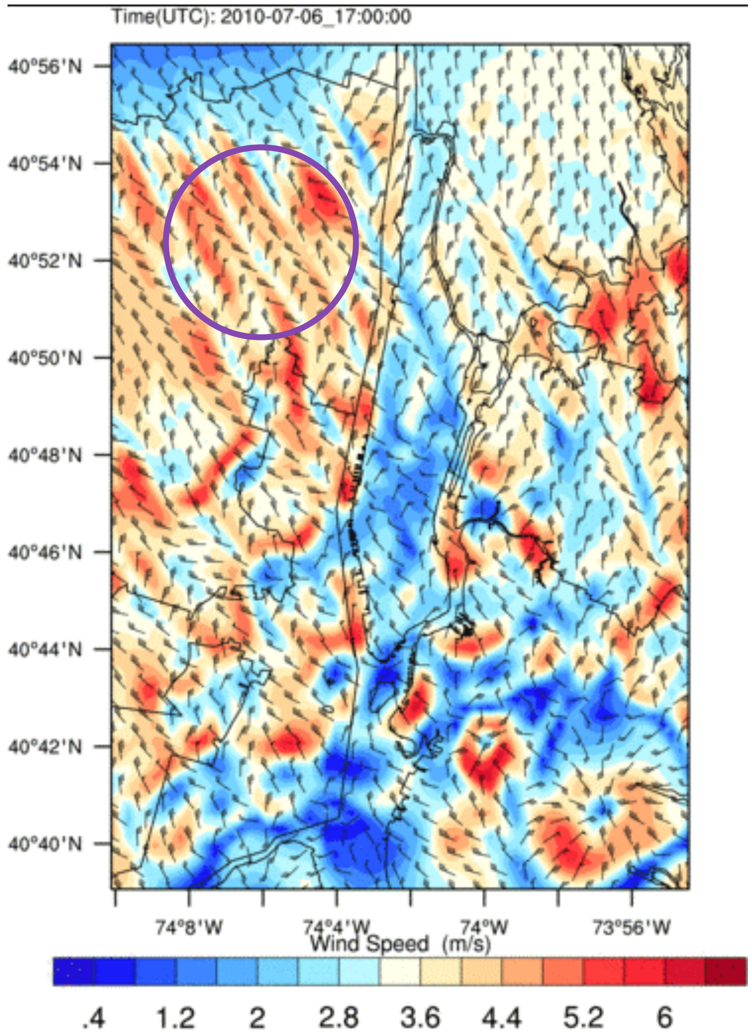
Run 3: Δt=6 s

Run 4: Δt=1 s

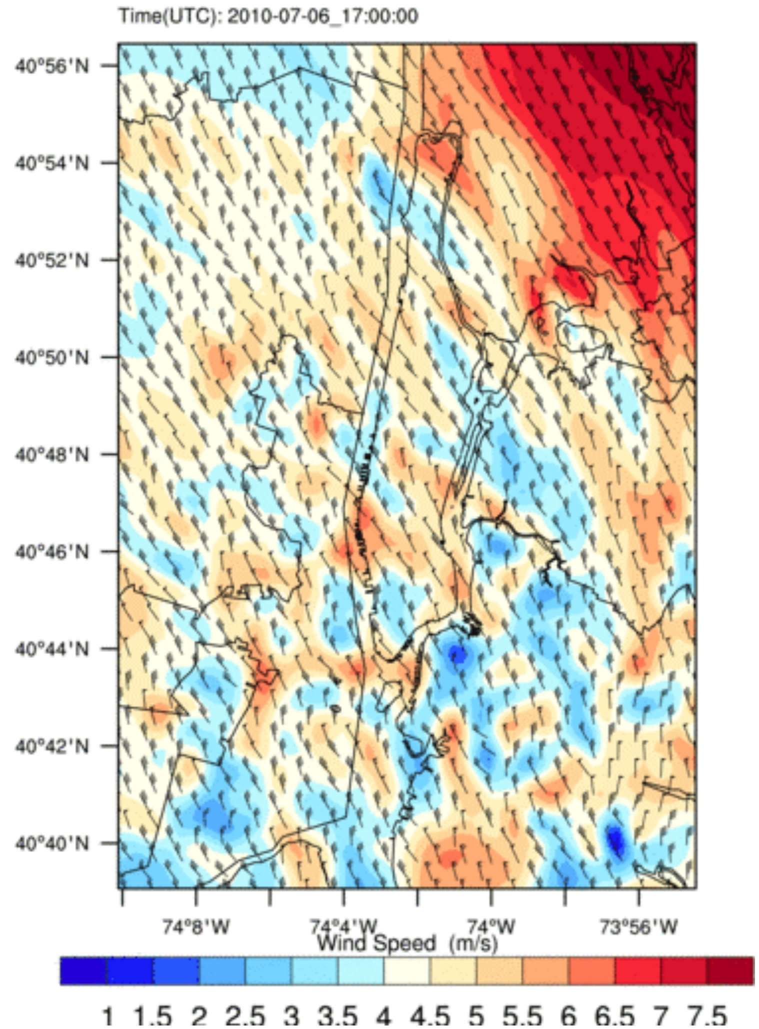
Run 5: Δt=0.66 s

Run 6: Δt=0.11 s

How V-wind ”lines-up” with waves at 2 levels: Δx=333 km

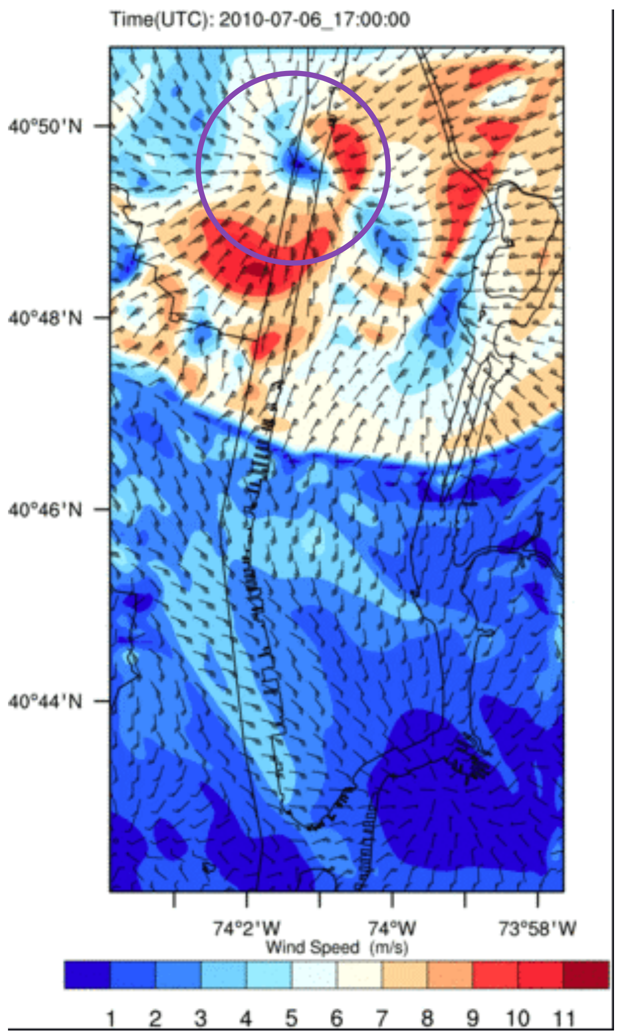


z= 1st V-level above sfc
(odd?, weak-div in waves)

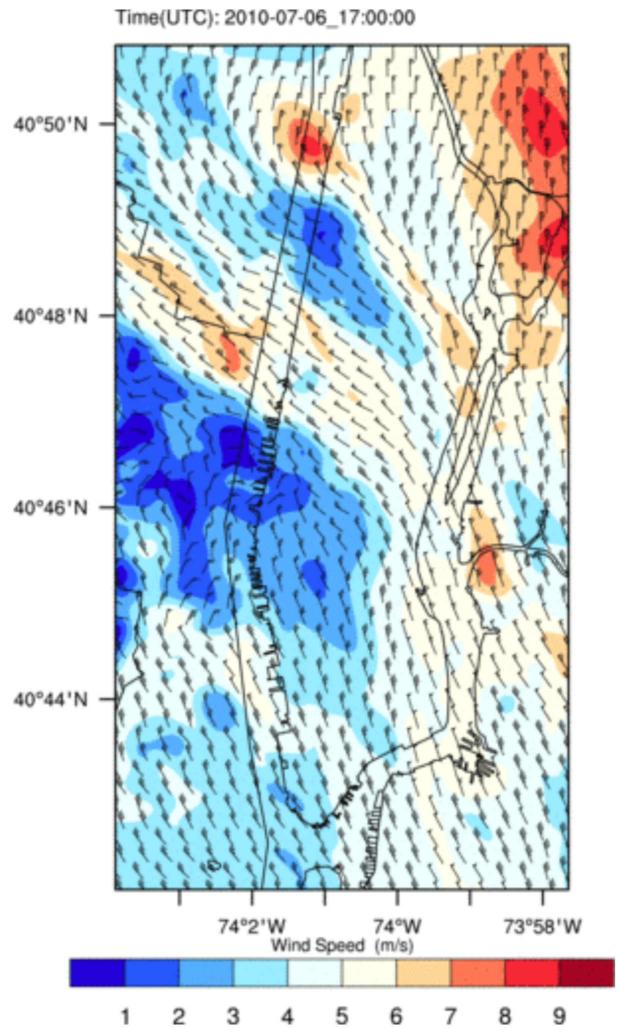


z = 1 km
(not much urban effect)

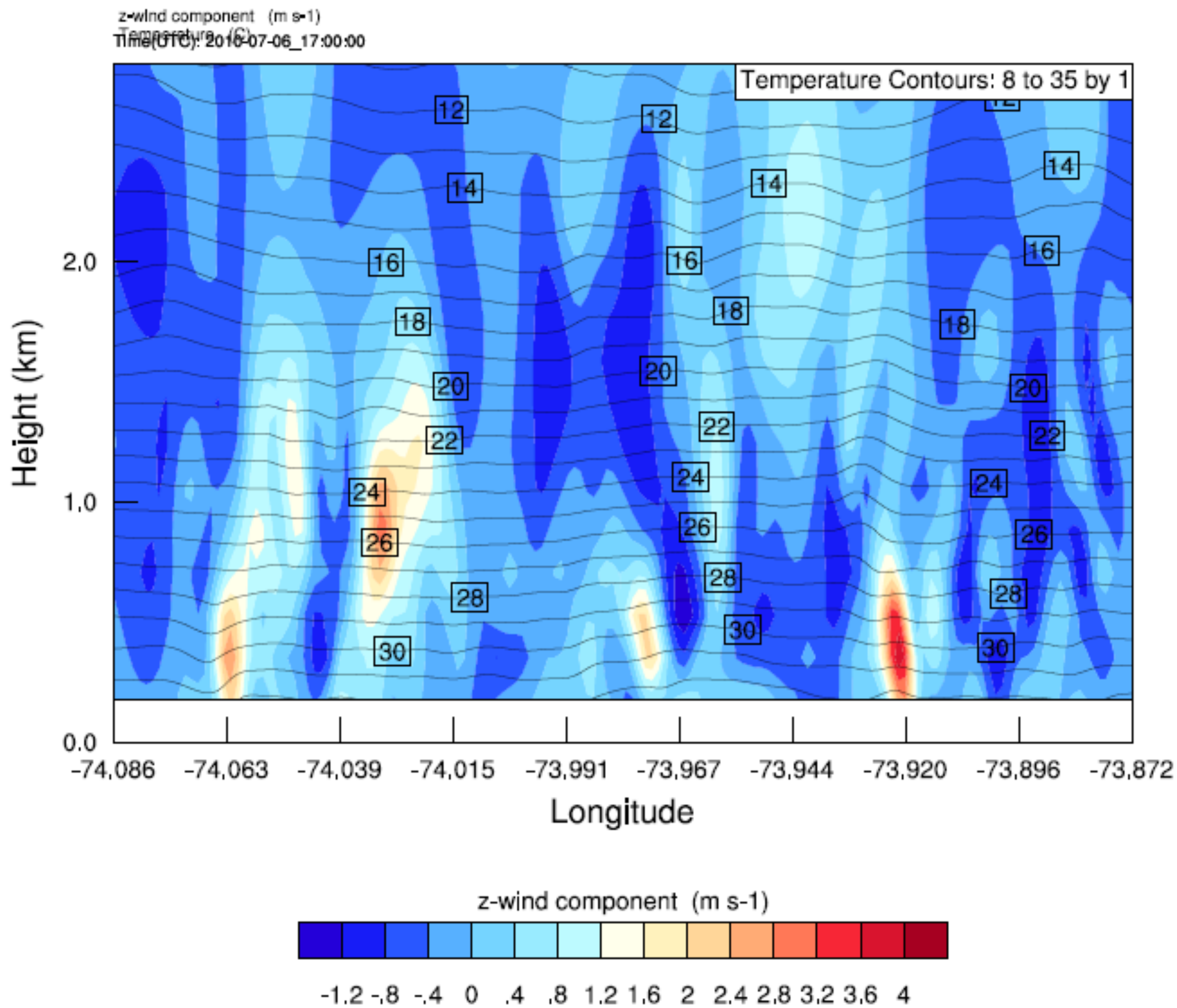
How V-wind ”lines- up” with waves at 2 levels: Δx= 111 m



z= 1st V-level above sfc
(strong-div, from a cell?)



z= 1 km
Nice urban effects

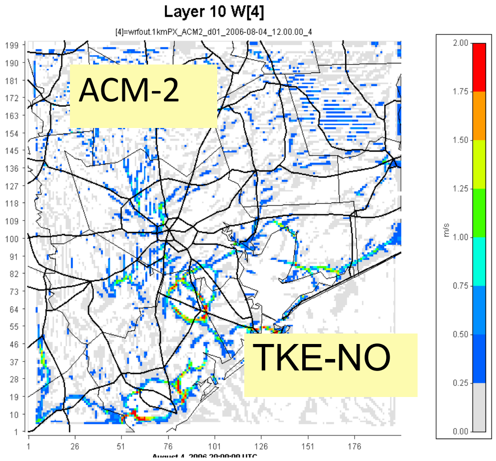


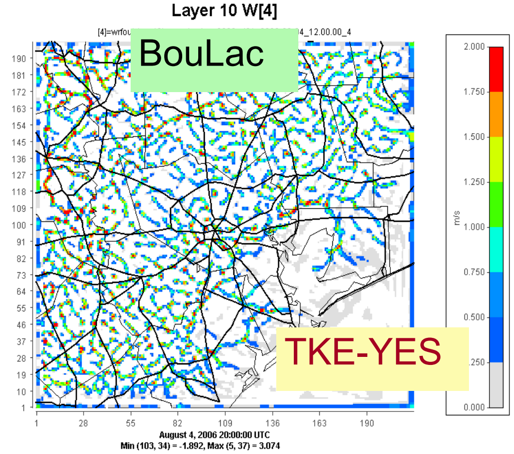
V-T z-section

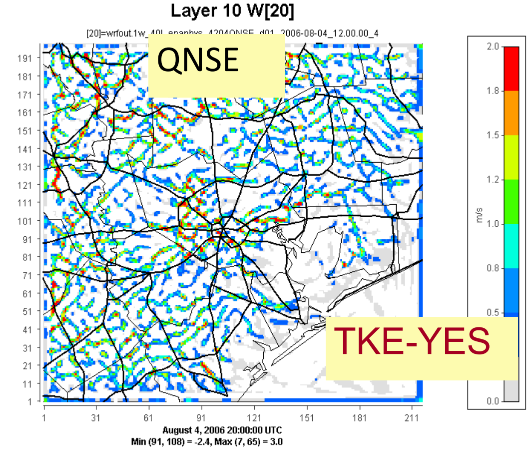
- Δx = 111 m
- Δt = 0.333 s
- wave is about 27Δx or 3 km
- This is half their size (bad news) in the 333 m simulation (not shown)
- Note: isothems are not greatly distorted
- Note: max-w = several m/s, which could create numerical instabilies

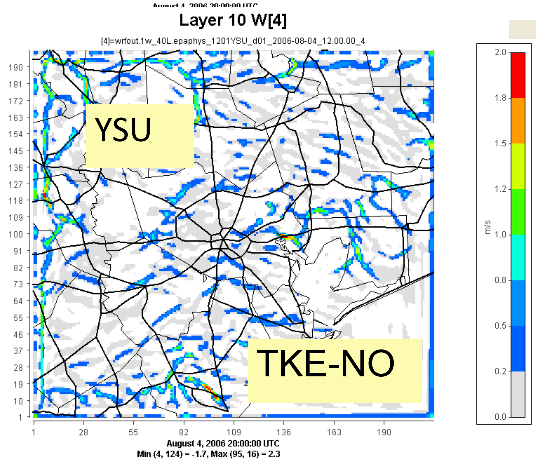
Summary of NYC Results

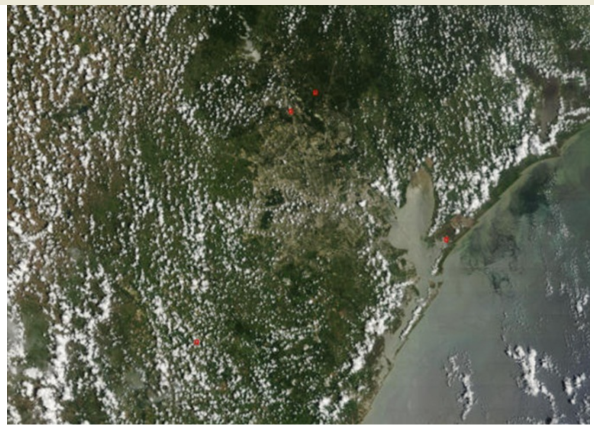
- Waves develop
  - with Δx=333 & 111 m (not shown), but not with 1 km
  - Start mid-morning, reach max strength in midafter-noon, break down into convection in late afternoon, & dissipate at night
  - Thus they are not computationally-unstable (or they would blow up)
- Wave size
  - f(Δx), for Δx = 333 & 111 m
  - from z-sections, somewhat hard to determine: more work needed
  - their size should not be f(Δx)







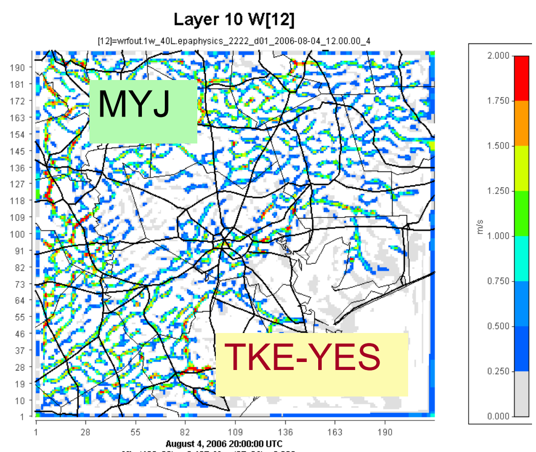


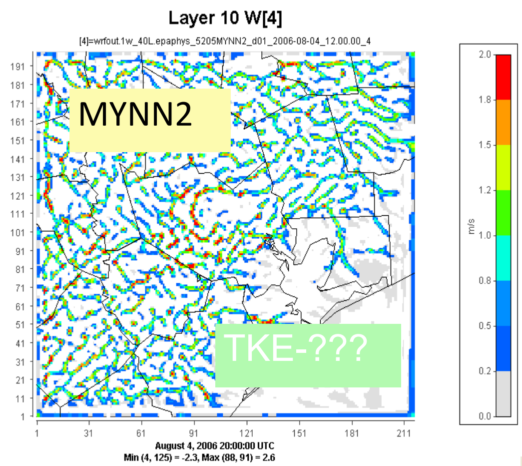


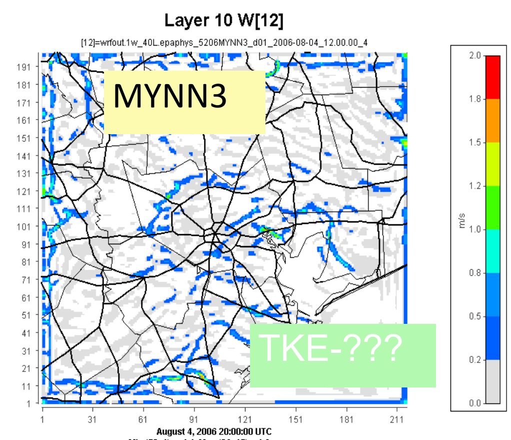
Results: sensitive to WRF PBL scheme

> (to R) TERRA: Pixel Size 500 m
On 4 Aug 2006, 12 LT

- 6 WRF-runs at 15 LT from J. Ching







Numerical Considerations: Horizontal Diffusion

Standard WRF configuration: K_h from **Smagorinsky deformation-scheme**

$$K_h = C_s^2 \Delta x^2 \left[0.25 \left(2\frac{\partial \bar{u}}{\partial x} - 2\frac{\partial \bar{v}}{\partial y} \right)^2 + \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right)^2 \right]$$

$$C_s = 0.4$$

In Martilli's simulations, Δ x *=1 km gives* K_h *of order of* ***100-200 m²/s***

Standard MM5

$$K_h = K_{H0} + C_s^2 \Delta x^2 \left[0.25 \left(2\frac{\partial \bar{u}}{\partial x} - 2\frac{\partial \bar{v}}{\partial y} \right)^2 + \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right)^2 \right]$$

$$K_{H0} = 3.\times 10^{-3} \frac{\Delta x^2}{\Delta t} = \mathbf{600\ m^2/s}$$

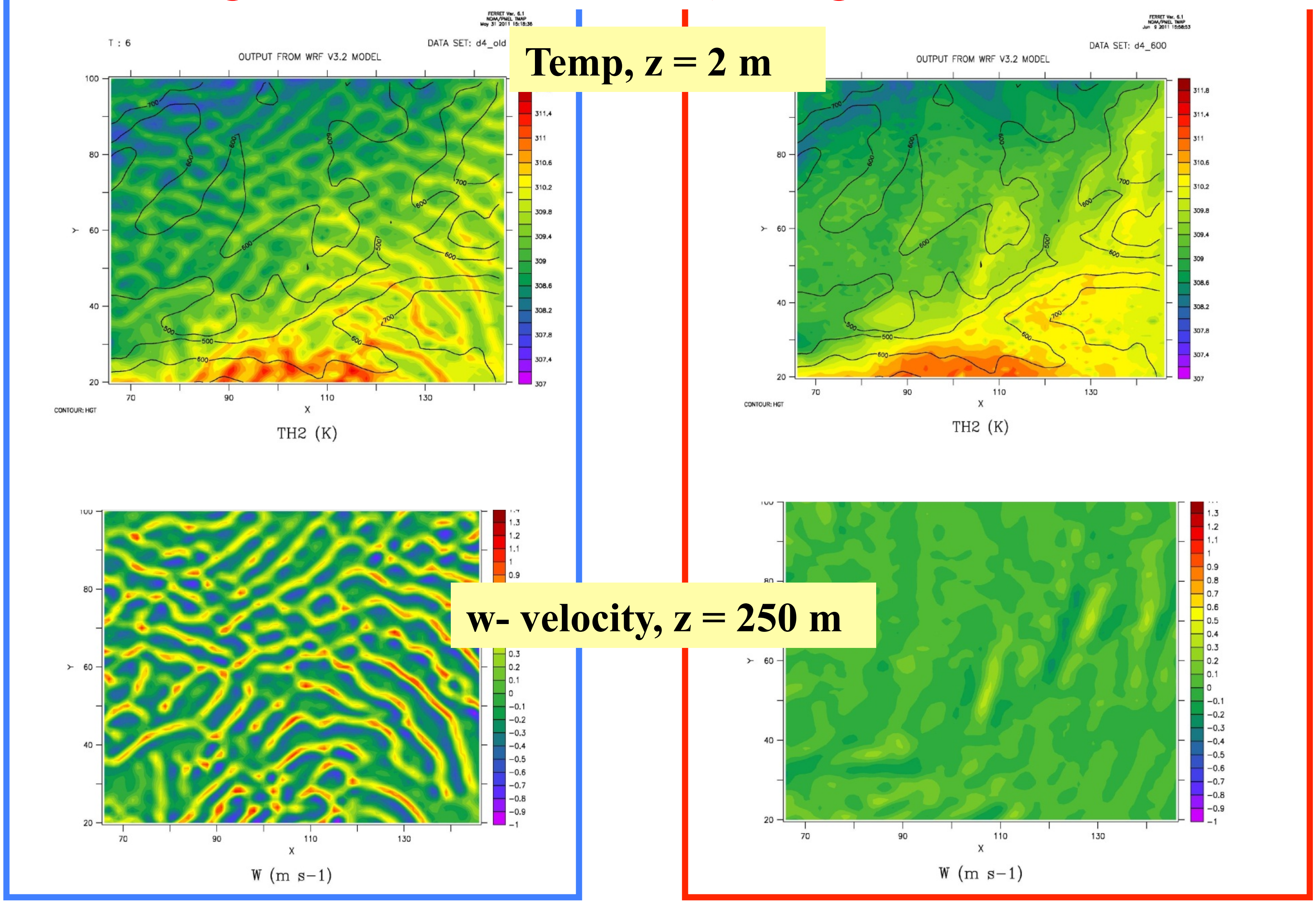
For Δx = 1000 m & Δt=5 s (Martilli case), [ ] = 0, as

"background K_{H0} is always dominant (Xu et al., 2001, MWR)

A. Martilli: WRF for Madrid: Δx =1 km, 12 UTC

WRF K_H : "Smagorinsk waves" acording to Tina Chow

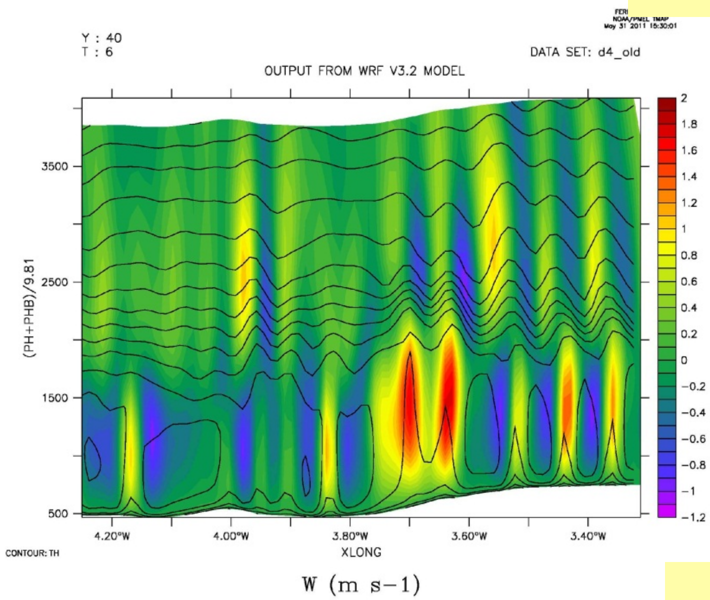
MM5-type **$(K_H)_0$ =6 00 m^2/s (too large, but worked; see next slide)**

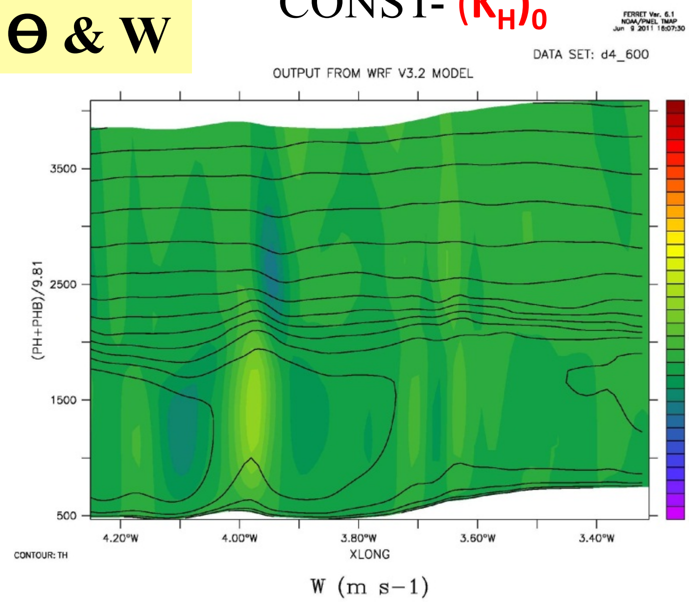


Smagorinsky-K_H

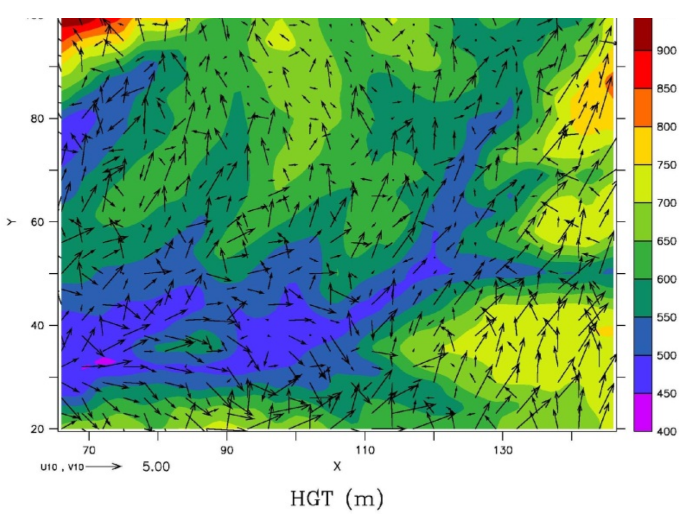
z-Section: Θ & W

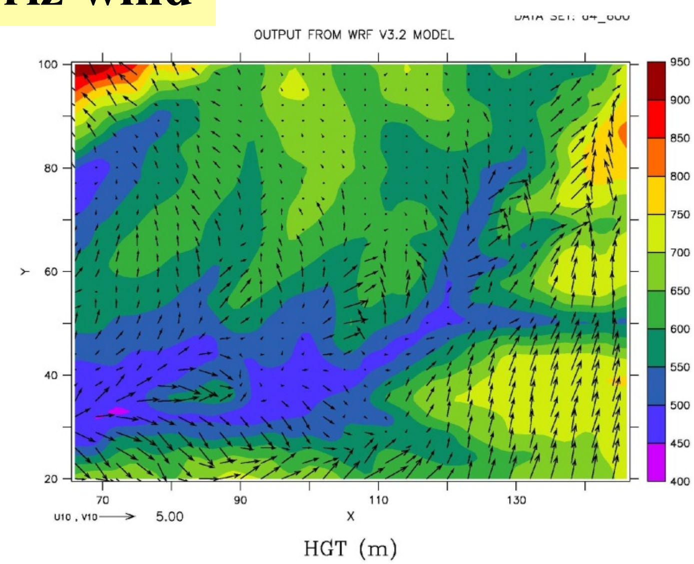
CONST- $(K_H)_0$





z = 10 m horiz-wind





Sensitivity of WRF to Adv- & Diff -chemes for Heavy Rain along Baiu Front

H. Kusaka, A. Crook, J. Knievel, & J. Dudhia

Results: even-order adv schemes (b & d): (dispersive; but no K_{NUM} diff) →waves

Dynamics	Advanced research core with mass coordinate system
Time integration	Time-split method using 3rd-order Runge-Kutta scheme with smaller time step for acoustic and gravity wave modes
Spatial discritization	Table 1 (horizontal) 3rd-order upwind (vertical)
Land surface	Noah-LSM
Planetary boundary layer	MRF
Horizontal diffusion	2D-Smagorinsky or constant
Shortwave radiation	Dudhia
Longwave radiation	RRTM
Cloud microphysics	Lin
Cumulus parameterization	Kain-Fritch (d01)
Time step	60 sec (d01), 20 sec (d02)
Initial and boundary conditions	NCEP Final Analysis Data

Case	Advection Scheme	Numerical Diffusion
3S	3rd-order upwind	4th-order (Implicit)
4S	4th-order centered	
5S	5th-order upwind	6th-order (Implicit)
6S	6th-order centered	
4C	4th-order centered	2nd-order (Explicit)
6C	6th-order centered	2nd-order (Explicit)
4F	4th-order centered	4th-order (Explicit)
6F	6th-order centered	6th-order (Explicit)

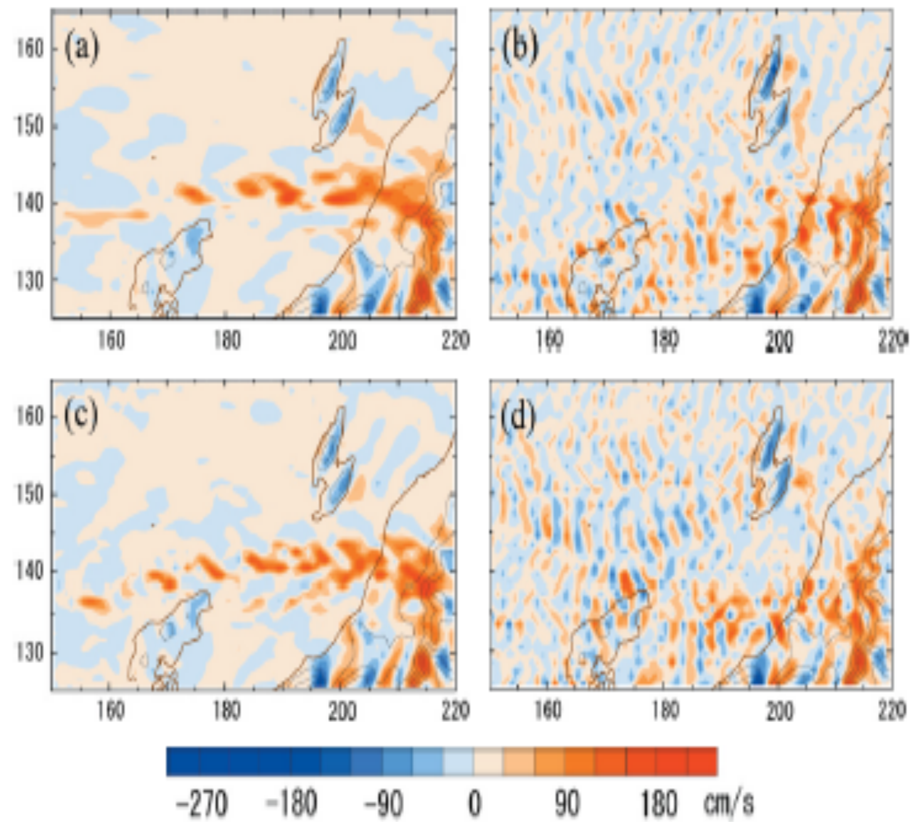


Fig. 5. Vertical velocity at 850hPa at 0600 JST. (a) Case 3S, (b) Case 4S, (c) Case 5S, and (d) Case 6S. Axis is grid point of domain 2.

WRF-ARW Advection Scheme

- Runge Kutta (RK3): 3rd-order in time for linear-Eqs only (Wicker & Skamarock, 2002), (W&S)
- *W&S: 2nd to 6th orders (f. d.)*
  - *Even orders: no numerical/implicit diff (reduces peaks), but dispersive (causes waves)*
  - *Odd orders: numerical diff proportional to Cr, but not dispersive (NYC used 5th)*
- *Adv-scheme for scalars: could be positive-definite or monatomic, i.e., W&S with filter*
- *Four Skamarock WRF-Adv ref*
- *See next slides*

5th-order adv-scheme uses 6th-order approx. for $\partial q/\partial x$

$$F^{5\text{th}}_{i-1/2} = F^{6\text{th}}_{i-1/2} - \frac{|u_{i-1/2}|}{60}[10(q_i - q_{i-1}) - 5(q_{i+1} - q_{i-2}) + (q_{i+2} - q_{i-3})], \tag{4c}$$

$$F^{6\text{th}}_{i-1/2} = \frac{u_{i-1/2}}{60}[37(q_i + q_{i-1}) - 8(q_{i+1} + q_{i-2}) + (q_{i+2} + q_{i-3})] \tag{4d}$$

Advection Scheme Stability

- Stability Condition: $(\alpha^{2}+\beta^2+\gamma^2)^{1/2} < \Omega$ (1)

$\alpha = u\Delta t/\Delta x$, $\beta = v\Delta t/\Delta y$, $\gamma = w\Delta t/\Delta z$ (2a,b,c)

Recommended Ω-values

Time Scheme	Spatial order			
	3rd	4th	5th	6th
Leapfrog	*Unstable*	0.72	*Unstable*	0.62
RK2	0.88	*Unstable*	0.30	*Unstable*
RK3	1.61	1.26	1.42	1.08

Use:(1)&(2c) to compare: 3-D WRF & (2c) Δt's

- From (2c): $\Delta t < \Omega * (\Delta z)_{min} / [(\sqrt{3}) * w_{max}]$ or

  $\Delta t < 1.42 * \underline{12\text{-m}} / [1.732x(\underline{2\text{-m/s}})] < 6$ s

- WRF recommended: Δt = 6*9-m/(3*3)=6 s!
- Maybe g-wave speed not correct stability-criterion

Questions

- How common are HRVs in the atm & from models
- Do RAMS, COAMPS, MM5, etc. also produce HRVs
- What is Eq. for mag of K_{NUM} for WRF adv-scheme(s)
- Why does WRF need filters for (upper, w, &/or divergence) damping
- What are effects of following on HRV simulations:
  - Δx– & Δt-magnitudes
  - upwind lateral-boundary location
  - upper boundary absorbing layer
  - advection, PBL, & K_{HOR} schemes

Ways Forward: via conf. calls w/ NCAR, etc.

- At NCAR
  - Analysis of IHOPS data (P. LeMone)
  - LES simulations into J. Wyngaard's *terra incognita* > from increasing-Δx end

    > RANS models come from decreasing-Δx end

    > *terra incognita* arises from need to have "spectral gap" b/t mean & turbulent quantities
  - But HRVs, Cu-convection, 2-D (horiz) waves in stable BLs, etc. are all meso-phenomena within gap
- At CIEMT
  - New $\mathbf{K_H}$-formulation: as f(TKE)
  - See next 3 slides

Suggested (Martilli) K_h-parameterization

Best option would be to use : $\overline{u_i' u_j'} = -K\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \frac{2}{3}\delta_{ij} tke$

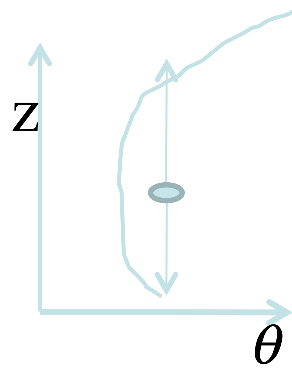
But, as 1st step, he assumes

$$\overline{u_i' u_j'} = -K\frac{\partial \overline{u_i}}{\partial x_j}$$

(relatively easy to implement in WRF)

As he uses Bougeault & Lacarrere, so K_z is

$$K_z = c\, l_{boulac}\sqrt{tke}$$



$$\int_z^{z+l_{up}} \frac{g}{\theta_o}\left(\theta(z) - \theta(z')\right)dz' = tke(z)$$

$$\int_z^{z+l_{down}} \frac{g}{\theta_o}\left(\theta(z') - \theta(z)\right)dz' = tke(z)$$

$$l_\varepsilon = \left(l_{up} l_{down}\right)^{1/2}$$

$$l_{boulac} = min\left(l_{up}, l_{down}\right)$$

By analogy, in horiz:

$$K_x = c\, max\left(l_{boulac}, \Delta x\right)\sqrt{tke}$$

Cmax =3Cz ? Invoke Lenschow?

l_{up} & l_{down} are distances that parcel from level z, & having the TKE of level z, can travel up- & down-ward due (to buoyancy effects) b/f coming to rest

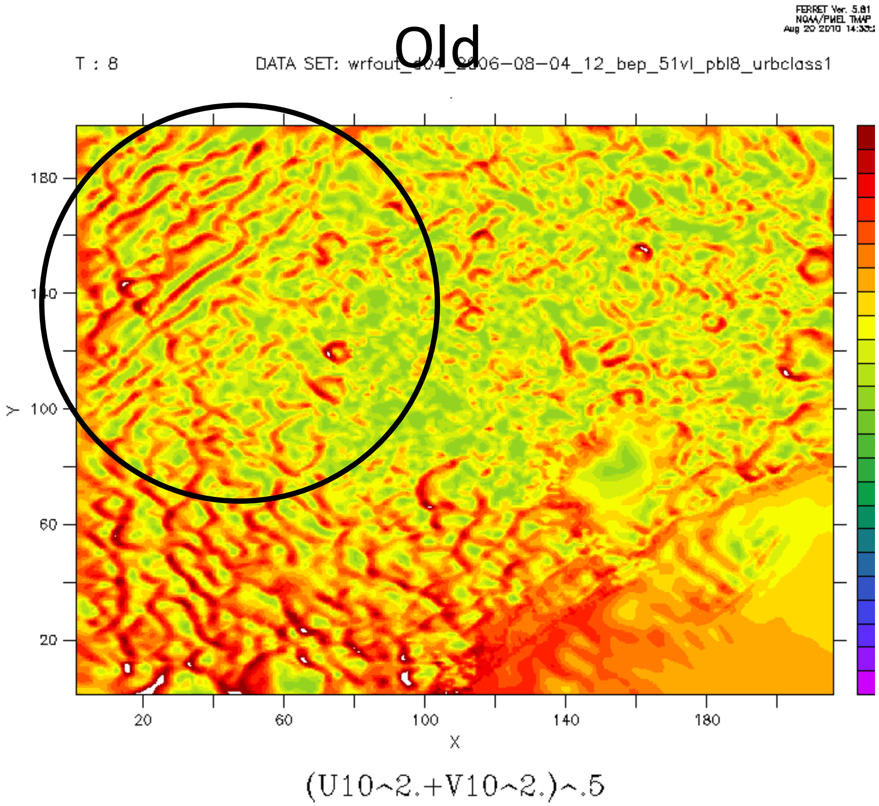
This is similar to TKE 1.5-closure in WRF-LES (space-average), with anisotropic-mixing option

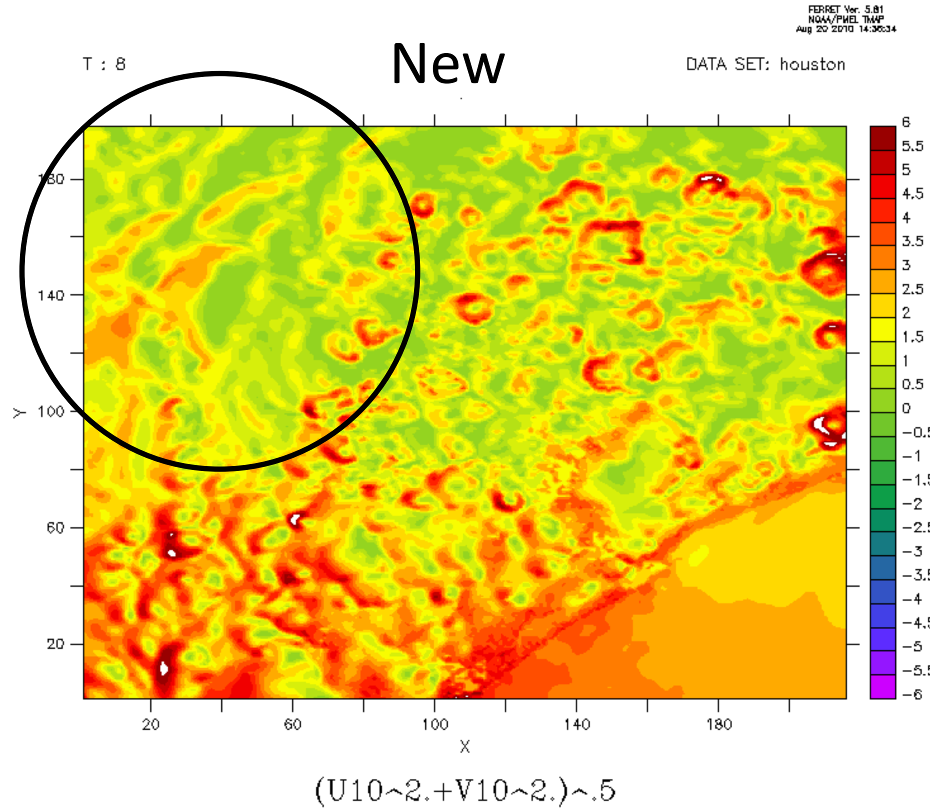
	TKE 1.5 prognostic LES	3-D Bougeault & Lacarrere	
	$K_z = c\Delta z\sqrt{tke}, if\ N^2 > 0$ $K_z = c\,min\left(\Delta z, 0.76\frac{\sqrt{tke}}{N}\right)\sqrt{tke}, if\ N^2 \le 0$	$K_z = c l_{boulac}\sqrt{tke}$	vertical
	$K_x = c\Delta x\sqrt{tke}$	$K_x = c\,max(l_{boulac}, \Delta x)\sqrt{tke}$	horiz

But, instead of filtering only structures smaller than a grid cell, we also filter those smaller than the size of the most energetic eddies (l_boulac),

b/c, as we run in RANS (t-average) mode, all turbulence should be filtered out by turbulence closure scheme

Original structures are now smoothed (filtered)





Ways Forward (cont.)

- At SJSU/CCNY
  - Runs with various Δt's & Δx's
  - Develop algebraic-stress model for (divergence of) horizontal turbulent-fluxes, which bypasses $\mathbf{K_H}$
    - but need to re-derive Mellor & Yamada's Level 2.5 Eqs. for a non-hydro/compressible model
    - K is 4th order tensor, with 81 components
- Who else would like to join us??

Urbanized WRF simulations of NYC: a heat wave, UHIs, and HRVs?

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Questions and suggestions?