RAMS 2002

ATMET's Recent Air Quality Applications

Craig J. Tremback
ATMET
ATmospheric, Meteorological and Environmental Technologies

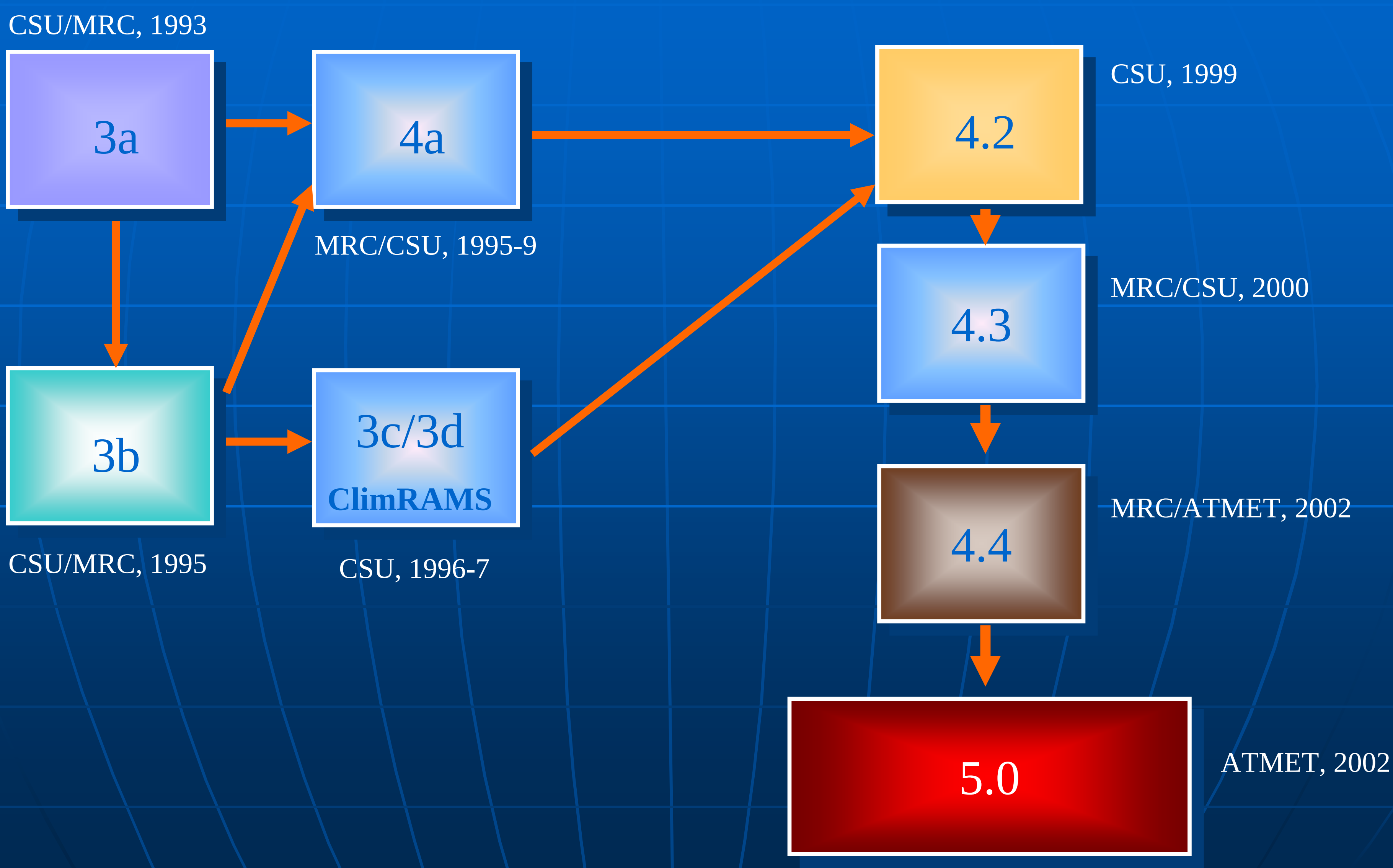
RAMS
Regional Atmospheric Modeling System

- RAMS developed primarily by Colorado State University, Mission Research Corporation/*ASTER Division, and ATMET.
- Large user base (over 160 sites in more than 30 countries) contribute with extensive testing and some development
- Changes over the past year:
  - RAMS distribution and support transferred to ATMET
  - RAMS available at no-cost to all US federal, state, and local government agencies and US universities
  - R. Walko moves to Duke University

RAMS Developments for 2001-2002

- New vertical coordinate
- Land surface scheme improvements
- Data assimilation schemes
- FDDA schemes
- History initialization option
- 1-way nest
- Continued transition to Fortran 90

RAMS Versions



Problems with Terrain-Following (σ) Coordinate Systems

- All terrain-following coordinate models have difficulty in handling "steep" topography
  - In σ_z systems, dependent on ratio $\Delta z_{topo} / \Delta z$
- Problems arise in taking horizontal gradients
- ETA coordinate model (Mesinger/Janjic) developed to address this problem for σ_p coordinate systems
- In σ_z systems, what we really want is a true Cartesian horizontal gradient.
- Horizontal diffusion was causing the majority of the "bad" effects in RAMS when topography became too steep.

A Permanent Solution ?

ETA-type step-coordinate model used successfully:

- Simple Cartesian grid easy to implement
- Eliminates all coordinate-induced, numerical truncation errors
- Runs faster per gridpoint, about 2x faster for basic numerics
- Allows arbitrarily steep topography (cliffs, buildings, etc.
- However…

ETA Disadvantages

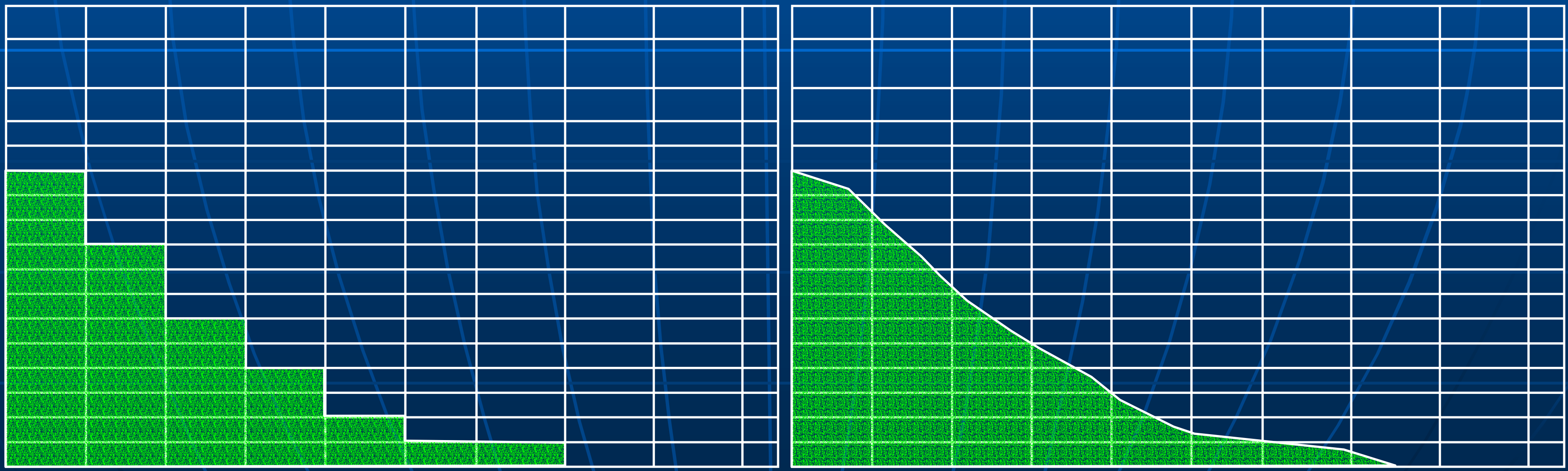
However, ETA-type model has drawbacks:

- Topography must jump in steps of Δz, even along smooth slopes.
- Need to numerically deal with "corners". W. Gallus showed ETA model generates noise.
- Usually needs more gridpoints (and memory/disk), hence slower physics
- Gridpoints underground can be blocked from computation relatively easily; not as easy to block from memory (could use "less-structured" grid)

Toward a Better Solution…

- ADAP (ADaptive APerature) coordinate
- Mostly following work of Adcroft, *et al* for oceanographic model
- "Shaved" ETA-type coordinate

Standard ETA coordinate ***ADAP coordinate***



ADAP Features

- Grid structure is a true Cartesian grid.
- The apertures of the grid cell faces are adapted to topography that would block the flow.
- Implemented as an option in RAMS; σ_z still supported because high-resolution slopes is still an issue. Vertically-nested grids can help.
- Same technique can be applied to other types of obstacles: buildings, vegetative canopy, etc.
- Allows very complex shapes (overhangs, tunnels, etc.)
- All components (topography, buildings, vegetation, etc.) can be present in simulation at same time.

RAMS/ADAP Modifications for Very High-Resolution Simulations

- Two-way nested grid communication allows building interaction with “real” weather
- Isotropic turbulence options:
  - Deardorff TKE available for a long time, used in LES runs
  - Recently implemented E-ε and E-l (S. Trini Castelli, CNR, Torino, Italy)
- All model terms must account for partially-closed apertures
- Complete transition of RAMS from finite-difference model to finite-volume model

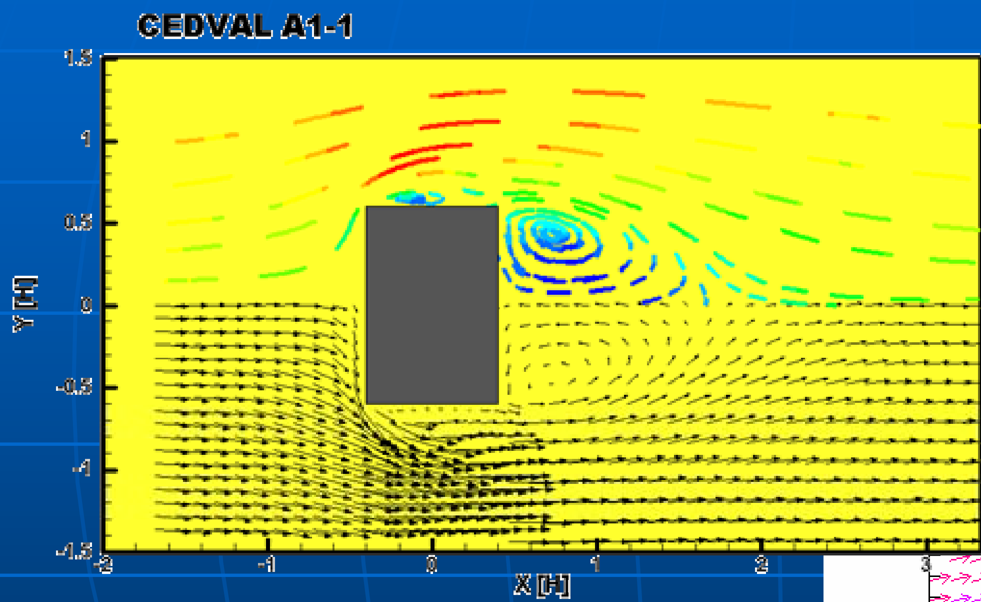
RAMS/ADAP Very High-Resolution Simulation Examples

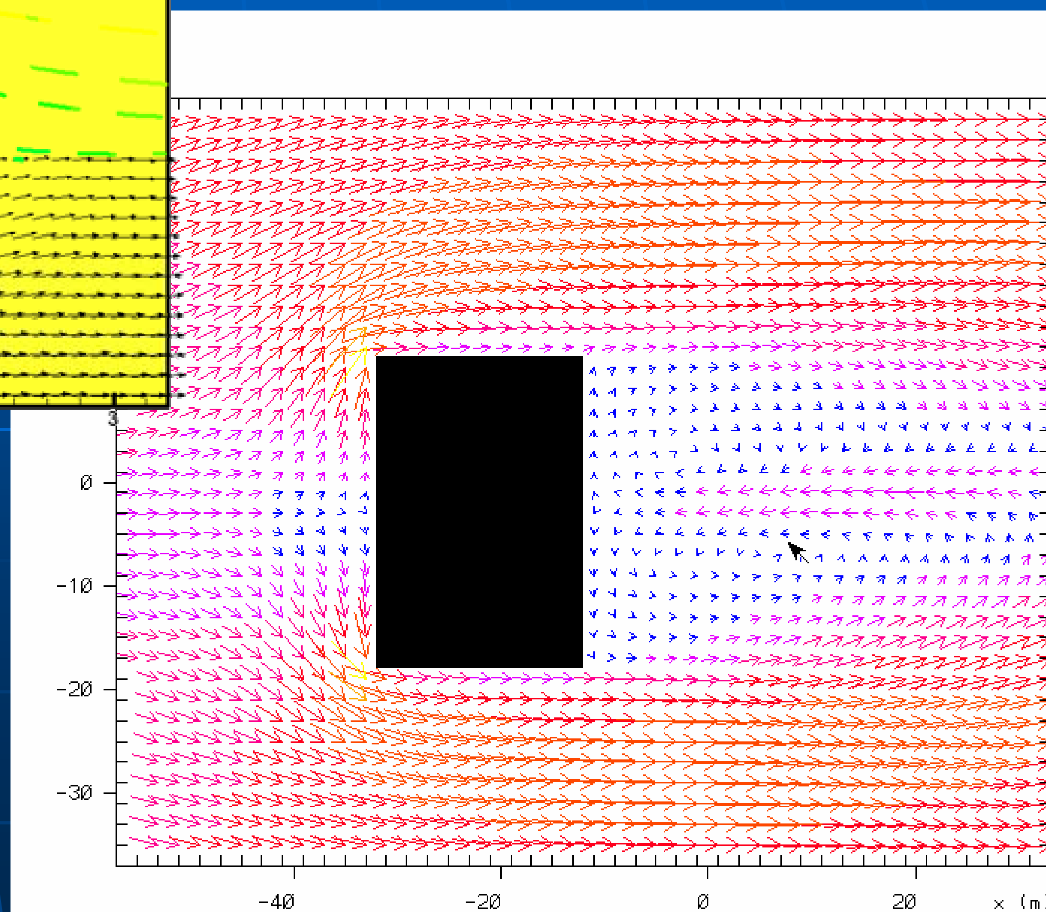
1) Flow around a single rectangular building (CEDVAL A1-1, Re = 32750)
2) Flow through an array of buildings (CEDVAL B1-1, Re = 56390)
3) Flow through an array of buildings on a slope

RAMS configuration

- Two grids: Δx = 10 m & 2 m; Δz = 2 m, stretched
- Neutral, horizontally homogeneous initialization
- 5 m/s initial flow; Re $\approx$ 100
- Deardorff isotropic TKE subgrid scheme

Flow around a single building





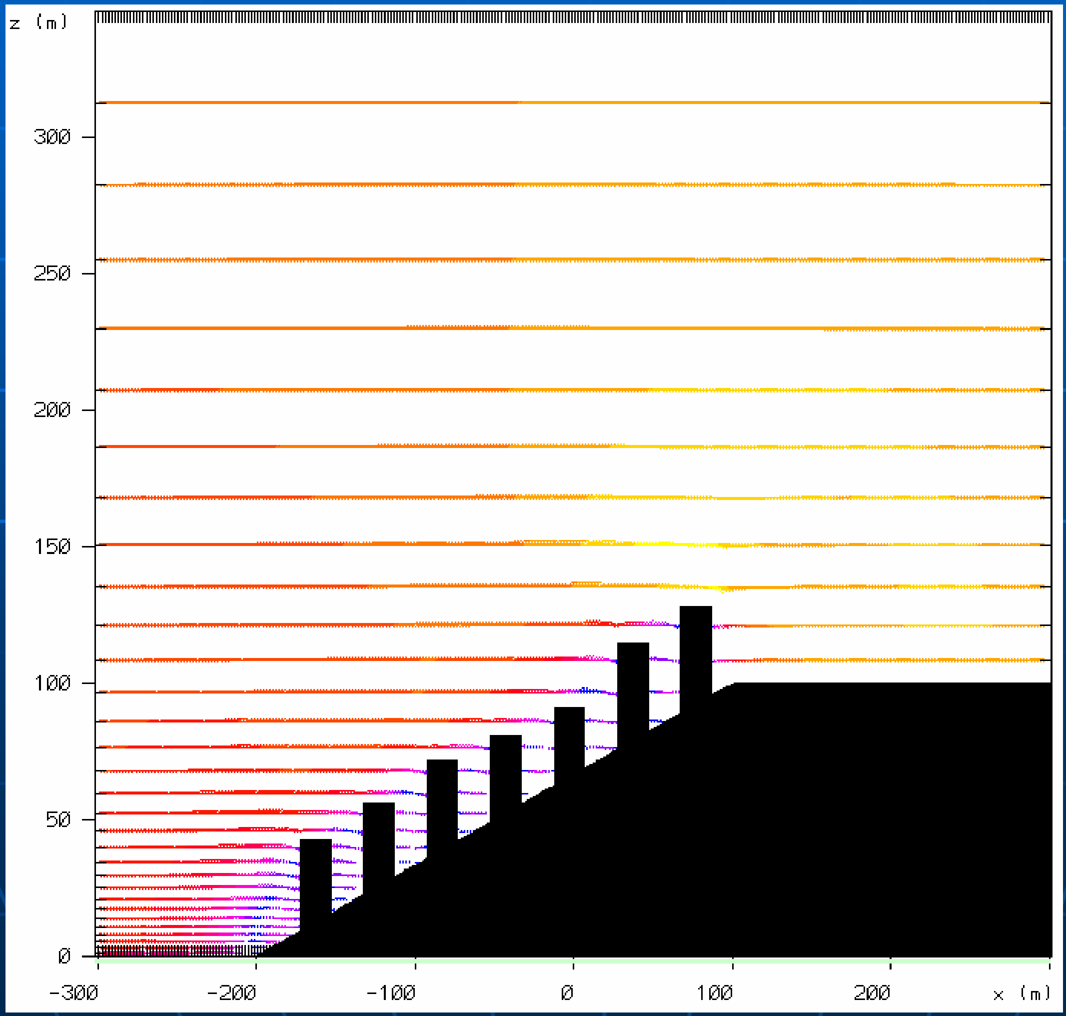
Z = 0.28H

Building size:

- x=20m
- y=30m
- z=25m

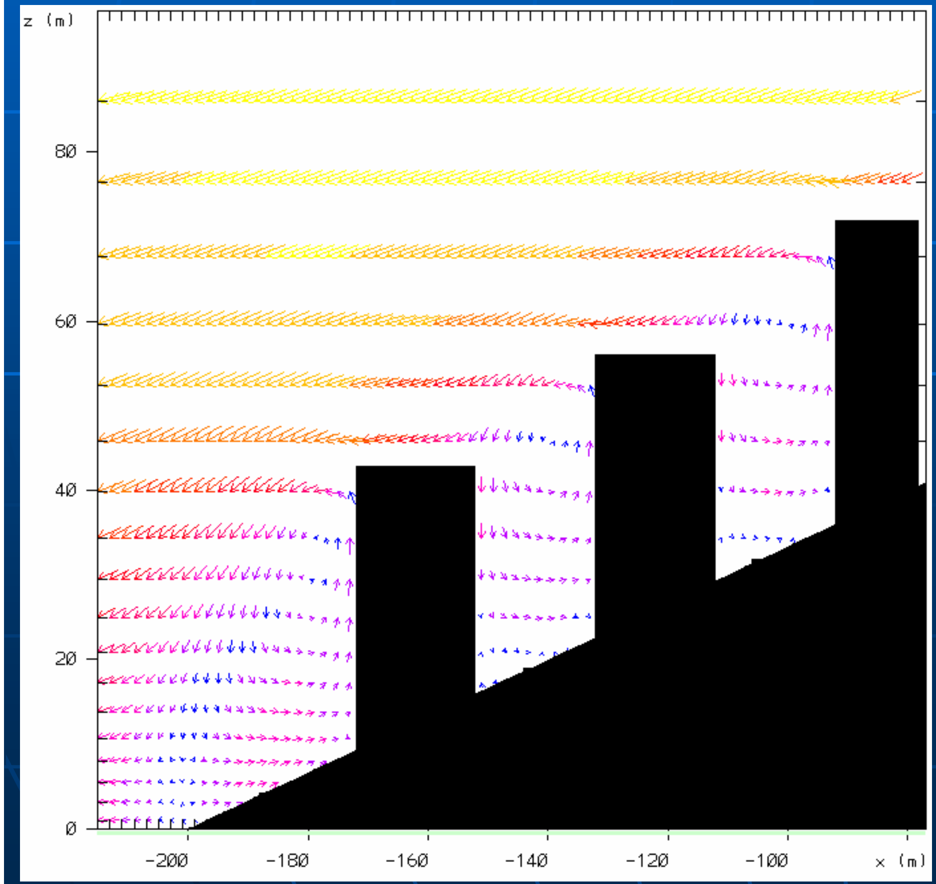
Cedval: 1:200

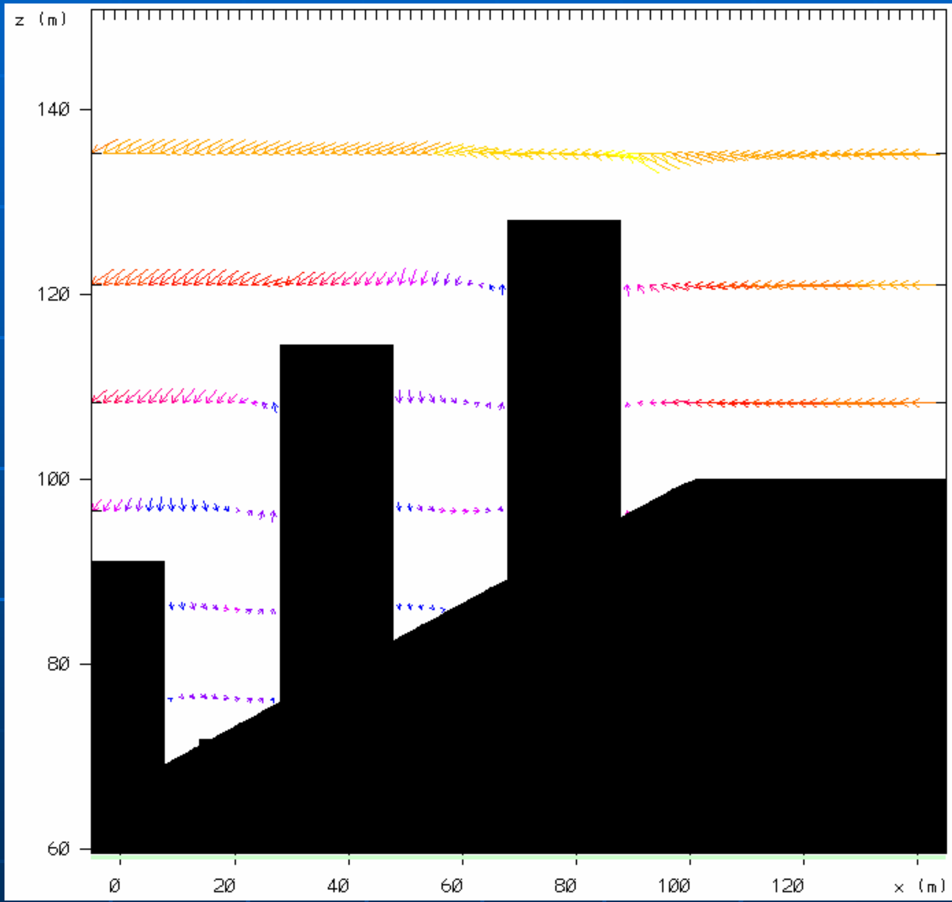
Flow through buildings on a slope



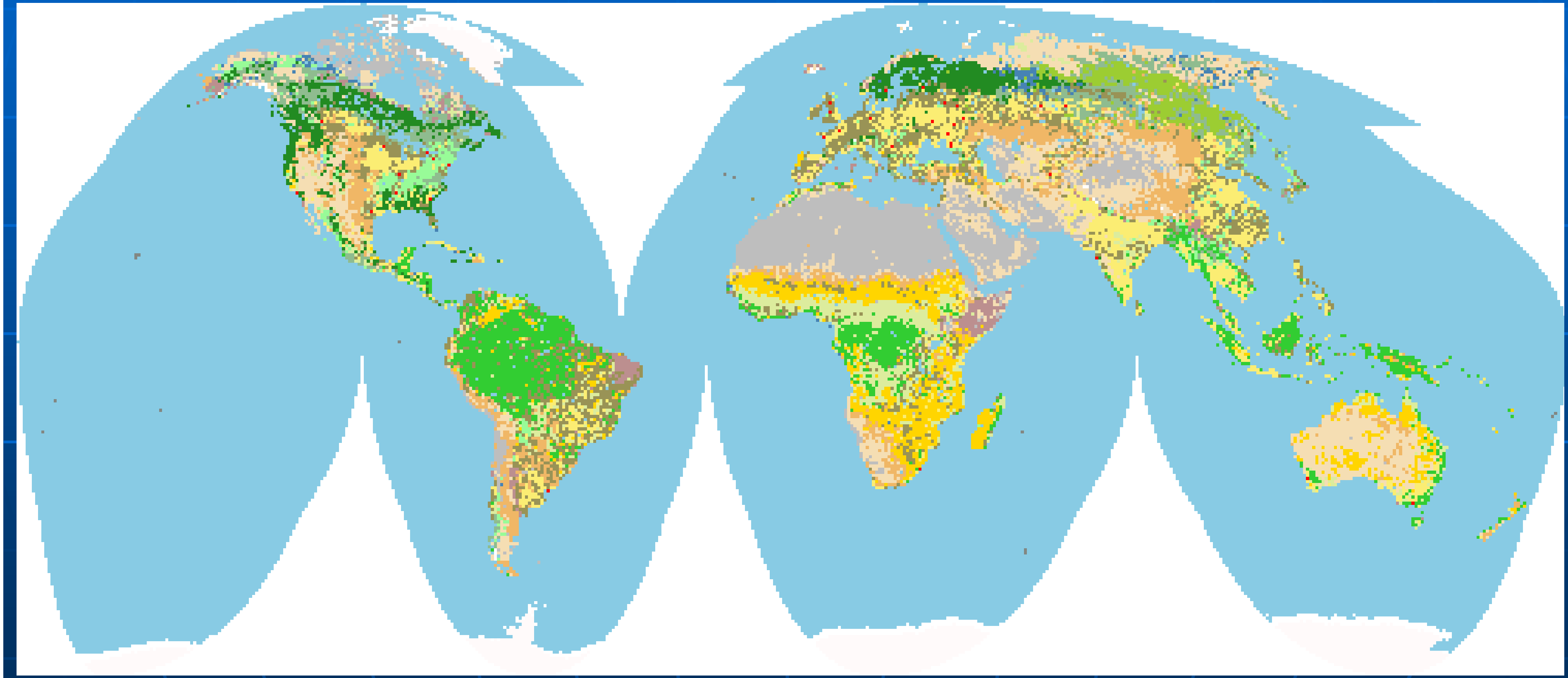
5 m/s

Flow through buildings on a slope





Normalized Difference Vegetation Index - NDVI



- Global 1 km data from USGS
- Monthly - April 1992 through March 1993
- Captures first-order seasonal effects

RAMS Land-surface Improvements

NDVI
Normalized Difference Vegetation Index

- Measure of "greenness" of vegetated surface, higher values indicate higher amount of growing vegetation
- Global 1km monthly historical dataset (Apr 1992 – Mar 1993) from USGS
- Not real-time, but captures most of first-order seasonal effects
- Now standard input dataset to Land Ecosystem Atmosphere Feedback (LEAF) model – RAMS land surface parameterization
- Implementation of SiB2 algorithms to convert NDVI to:
  - leaf area index
  - roughness length
  - vegetation fraction coverage
  - albedo

RAMS Data Assimilation Schemes

- Schemes designed to assist in initialization of model
- Based on previous model runs or "processed" observations
- Primarily intended for use in a operational forecast cycle, but can have some applications in historical reconstruction

RAMS Data Assimilation Schemes

Recycle

scheme which recycles prior forecast's fields of unobserved variables to initialize the current run

- Numerous variables required on initialization are not observed
- Ability to specify soil and vegetation properties from previous forecast fields
- Can be extended to any field (clouds, etc.)
- Has been used successfully for soil moisture by several users over the years, but now is a standard option

RAMS Data Assimilation Schemes

Antecedent Precipitation Index

scheme which uses past (observed) precipitation to assist in defining the initial soil conditions for the start of a model run

- "Stripped-down" RAMS with only soil/vegetation schemes executed
- All atmospheric parameters specified from previous forecast
- Precipitation data specified from observations/radar/satellite
- Example:
  - 0000 UTC forecast time on the 30th
  - Back up to 0000 UTC on the 29th
  - Run RAMS in API mode for 24 hours
  - Initial soil moisture field available for 0000 UTC on 30th
- Provides initial soil moisture and all other soil/vegetation properties
- Can be combined with soil moisture observation assimilation

RAMS Data Assimilation Schemes

Cumulus Inversion

scheme which uses past (observed) precipitation rates to compute convective heating and moistening rates

- All atmospheric parameters specified from previous forecast
- Precipitation data specified from observations/radar/satellite
- Convective parameterization is *"inverted"*
- Usually inputs atmospheric properties and outputs precipitation rate, heating and moistening profiles
- Inverted to input precipitation rate, still outputs heating and moistening profiles
- Intended for coarser grid spacings where convective parameterizations would be used
- Heating/moistening profiles are used in assimilation run (3-6 hours) prior to actual forecast start

RAMS Data Assimilation Schemes

Condensate Nudging

scheme which uses prior forecast's condensate to nudge fields during assimilation run

- Prior forecast results of condensate are used in assimilation run (3-6 hours) prior to actual forecast start
- Nudging done similarly to FDDA nudging
- Primarily intended for fog, low/mid-level stratus
- Of course, if forecast is very bad…

RAMS Data Assimilation Schemes

History Initialization

ability to start run by defining ALL fields from a previous run

- Designed to allow complete change of grid structure
- If grids match, direct copy of information; otherwise interpolation
- Primarily intended for use where a large difference exists between grids in original run and new run
- Example:
  - Emergency response system for Japanese nuclear plants
  - Collaboration with Mitsubishi Heavy Industries, Nagasaki
  - Mesoscale forecast run down to 2 km grid
  - High-resolution dispersion run at scale of plant
  - Coarse grid – 50m spacing

RAMS Data Assimilation Schemes

One-way nest

ability to define fine grid boundaries from a previous run of a coarse grid

- Not intended as replacement where two-way nest can be used
- Nested grid has no affect on coarse grid
- More boundary reflection, requires more smoothing in boundary region than two-way nest
- Example:
  - Emergency response system for Japanese nuclear plants

RAMS FDDA Schemes

Enhanced Analysis Nudging

nudges prognosed model fields to a gridded data analysis

- Previous options only allowed specification of nudging strength for all variables and all grids
- Option added to vary nudging strength:
  - on different nested grids
  - for different variables (wind, temperature, moisture, pressure)

RAMS FDDA Schemes

Observational Nudging

nudges prognosed model fields "directly" to the observations

- Designed to accommodate range of observations from 12-hour rawinsondes in large-scale runs to sonic anemometers in small-scale runs
- User-specified "update time" when observations are "analyzed" (typically every 15-30 minutes for standard obs)
- Each observation location is queried at update time
- If observation times are "close enough" in time, values are interpolated
- Observations are "analyzed" with 3-D Kriging interpolation scheme which produces variable and covariance fields
- Nudging proceeds with user-specified timescales which can vary by grid and variable

RAMS and Fortran 90

- Transition to many F90 features
  - free format source code
  - f90 memory allocation
  - explicit variable typing (IMPLICIT NONE)
  - use of MODULEs
  - careful use of pointers (some f90 features produce inefficient code)

Fortran 90 Data Types and the A array

- Old way – required for memory efficiency in F77 with nested grids….
- Compute total memory for all variables, all grids:

```
ALLOCATE ( A(tot_mem) )
```

- Compute separate variable indices:

```
IUP=f(nnxp,nnyp,etc…)
CALL COMPUTE_SUB(nzp,nxp,nyp,a(iup))


SUBROUTINE COMPUTE_SUB(n1,n2,n3,up)
REAL UP(N1,N2,N3)
```

Fortran 90 Data Types and the A array

- New way – F90 pointers and user-defined data types (similar to C structures)

- Define data types in an F90 module:

```
MODULE wind_arrays
    TYPE WIND_MEMORY
            integer, dimension(maxgrds) :: nnxp,nnyp,nnzp
            real, pointer, dimension(:,:,:) :: up,vp,wp
    END TYPE
END MODULE
```

- Declare new data type:

```
TYPE(wind_memory) :: winds(ngrids)
```

- Allocate pointer arrays:

```
ALLOCATE (winds(ngrid)%up(nnzp(ngrid),nnxp(ngrid),nnyp(ngrid)))
```

Near Future Plans

- Continued F90 transition
- Additional convective parameterizations (Kain-Fritsch, Grell)
- RRTM longwave radiation scheme
- TEB urban canopy?
- Integrated dispersion model (online and offline HYPACT)
- Various chemical modules (mercury, sulphur, etc.)
- Biomass burning source model
- Global capabilities being transferred to companion model
  - OLAM (Ocean-Land-Atmosphere Model) under development at Duke
  - Difficult to covert mesoscale model to global model directly
  - Numerics must conserve everything exactly for long-term simulation
  - OLAM has different formulation for numerics, unstructured adaptive grid
  - Will use same RAMS physics code
  - Farther future – RAMS will covert to OLAM grid structure

ATMET's Current and Recent Air Quality Related Projects

- With ENVIRON
  - TNRCC – Houston/Galveston, Sep 1993
    - Several projects with MM5 and RAMS comparisons down to 1.33 km grids. Detailed MM5 sensitivity tests.
  - BAAQMD – Bay Area, CCOS, Jun-Aug, 2000
    - RAMS simulations for two CCOS episodes down to 1 km grid, along with sensitivity tests. Delivery of hardware/software system.
  - HARC - Houston/Galveston, TexAQS, Aug 2000
    - MM5 runs for the Aug episode, with extensions of our sensitivity tests we performed for 1993 episode.

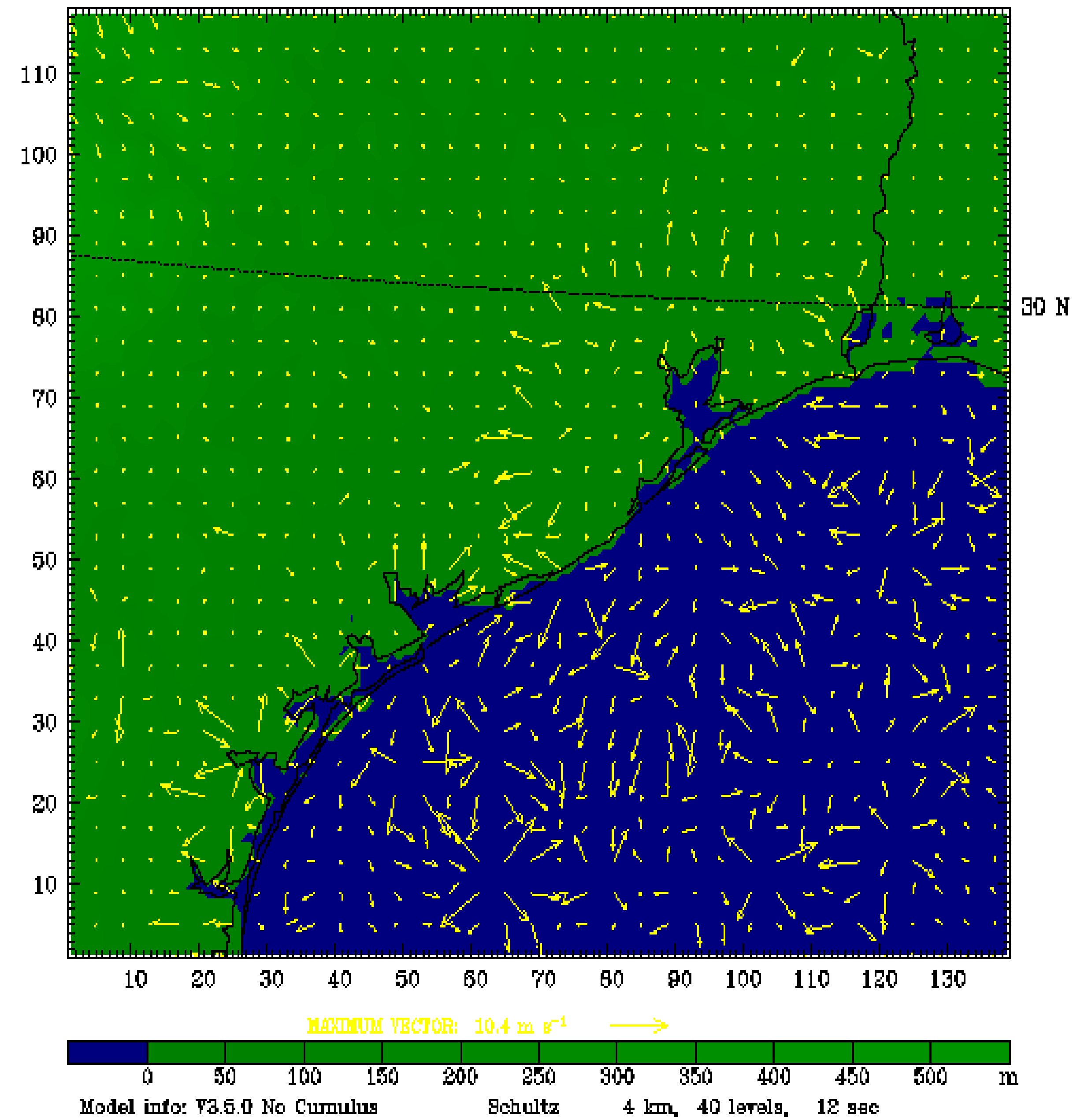
ATMET's Current and Recent Air Quality Related Projects

- With Alpine Geophysics
  - EPA – annual/episodic runs for 2001
    - MM5 runs for episodic regional simulations with some sensitivity tests
- TNRCC
  - Houston/Galveston, TexAQS, Aug 2000
    - RAMS runs for TexAQS Aug episode with various sensitivity tests to compare with previous and ongoing MM5 simulations.

MM5 Sensitivity Tests

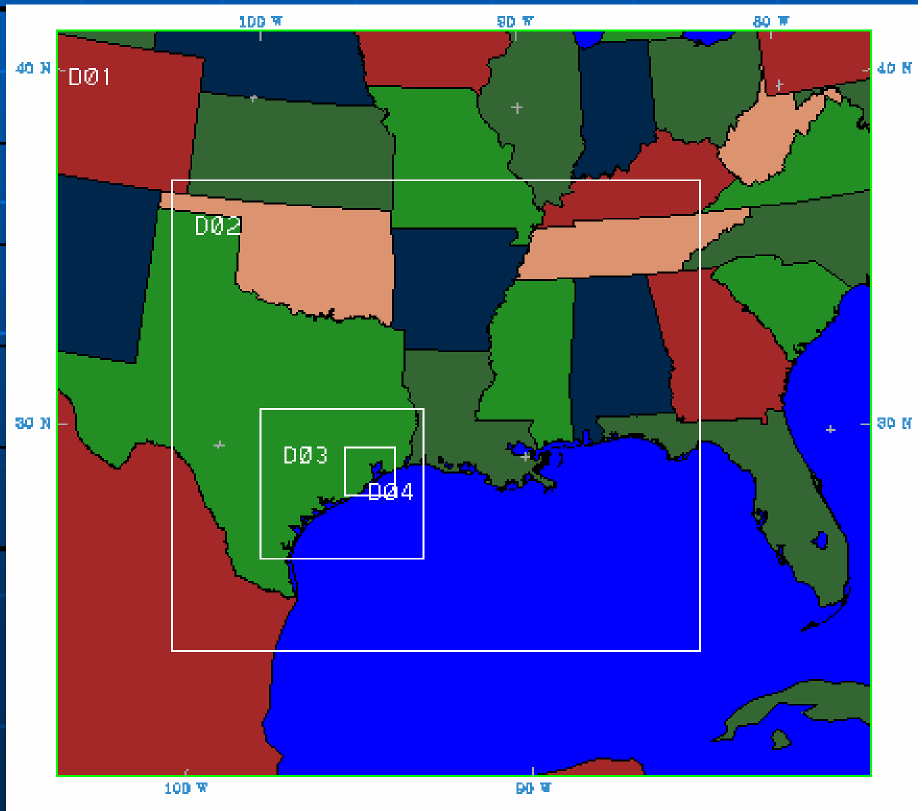
- In conjunction with ENVIRON under TNRCC funding, RAMS and MM5 meteorological simulations were performed for the period 6-11 September 1993 for Houston/Galveston
  - MM5 was run in both:
    - 3-grid configuration (4 km finest grid)
    - 4-grid configuration (1.33 km finest grid).
- Statistical verification results of MM5 were acceptable
- Examination of the MM5 meteorological fields, several undesirable features were apparent. The most notable of these features were:
  - Consistent under-prediction of the sea breeze development
  - Under-prediction of surface wind speeds over land during the day
  - Creation of explicit, grid-scale thunderstorms (even on a 4km grid) which generated very strong outflows. These outflows were so strong at times that the low-level wind field was completely disrupted.

ATmospheric, Meteorological, and Environmental Technologies



MM5 Sensitivity Tests

Grid	# of X points	# of Y Points	Vertical Levels	Δx/Δy (km)
1	72	66	41	36
2	139	124	41	12
3	139	118	41	4
4	127	118	41	1.33



MM5 Sensitivity Tests

- Sensitivity simulations for the 24-hour period of 0000 UTC 8 September 1993 to 0000 UTC 9 September 1993.
- More than 20 different simulations were performed in the process of investigating the sensitivity of the MM5 results to various parameterizations, options, and grid resolution.
- Series of experiments categorized as:
  - control simulations
  - PBL tests
  - microphysics tests
  - FDDA tests
- *FDDA not used on most of these runs. 24 hour runs should not need it!*

MM5 Sensitivity Tests

Run tag	No. grids	Dura-tion	Micro-physics	Cu parm	PBL	Bucket scheme	Shal-low cu	Iz0topt	Imvdif	FDDA grid ndgng
Runorig4	4	4 days	Schultz	Grell	G-S MY	NO	NO	NA	NA	YES BL, UA
Runold2	2	24 hrs	Schultz	Grell	G-S MY	NO	NO	NA	NA	NO
Runa	2	24 hrs	Simple ice	KF2	MRF	YES	NO	0	1	NO
Runa4	4	24 hrs	Simple ice	KF2	MRF	YES	NO	0	1	NO
Runb	2	24 hrs	Reis1	KF2	MRF	YES	NO	0	1	NO
Runc	2	24 hrs	Reis 1	KF2	G-S MY	YES	NO	NA	NA	NO
Rund	2	24 hrs	Reis1	KF2	ETA MY	YES	NO	NA	NA	NO
Runold4	4	24 hrs	Schultz	Grell	G-S MY	NO	NO	NA	NA	NO
Rune	3	24 hrs	Reis1	KF2	ETA MY	YES	NO	NA	NA	NO
Runf	3	24 hrs	Reis1	KF2	MRF	YES	YES	0	1	NO
Runf2	3	24 hrs	Reis1	KF2	MRF	YES	NO	0	1	NO
Rung	3	24 hrs	Reis1	KF2	MRF	YES	YES	2	0	NO
Runh	3	24 hrs	Reis1	KF2	MRF	YES	YES	2	1	NO
Runi	3	24 hrs	Reis1	KF2	ETA MY	YES	YES	NA	NA	NO

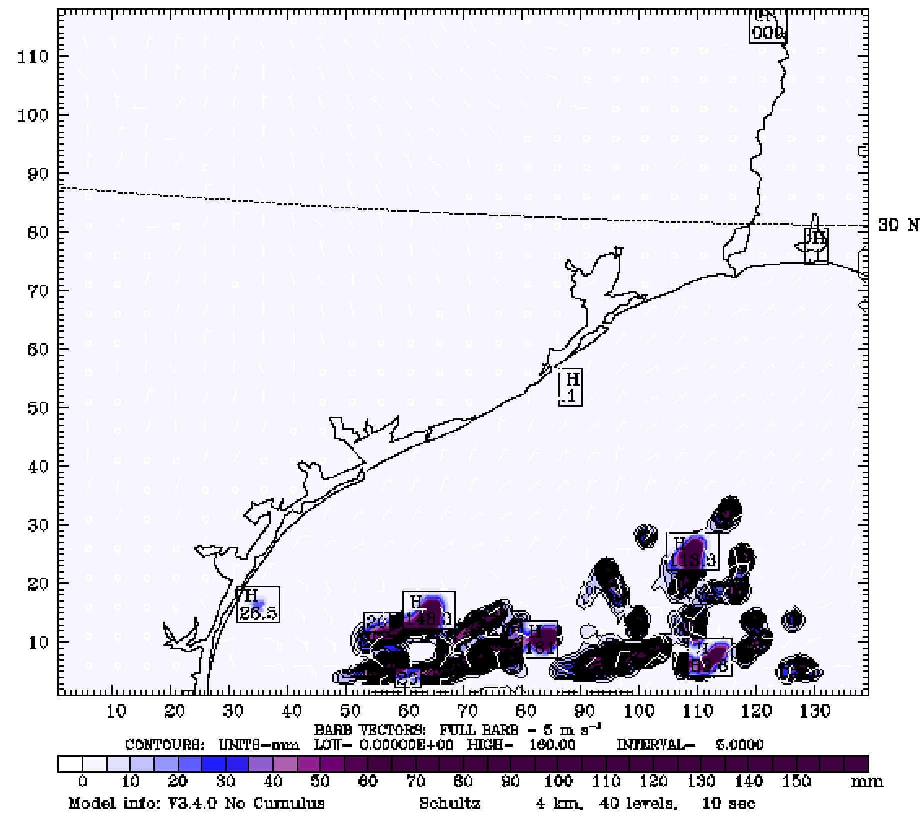
MM5 Sensitivity Tests

Run tag	No. grids	Duration	Microphysics	Cu parm	PBL	Bucket scheme	Shallow cu	Iz0topt	Imvdif	FDDA grid ndgng
Runj	3	24 hrs	Reis 1	KF2	G-S MY	YES	NO	NA	NA	NO
Runj2	3	24 hrs	Reis 1	KF2	G-S MY modified	YES	NO	NA	NA	NO
Runk	3	24 hrs	Reis 1	KF2	Blackadar	YES	NO	NA	NA	NO
Runl	3	24 hrs	Simple ice	KF2	MRF	YES	NO	0	1	NO
Runm	3	24 hrs	Reis 2	KF2	MRF	YES	NO	0	1	NO
Runn	3	24 hrs	Schultz	KF2	MRF	YES	NO	0	1	NO
Runo	3	24 hrs	Reis 1	KF2	G-S MY	YES	NO	NA	NA	YES BL, UA
Runnew4	4	4 days	Reis 1	KF2	MRF	YES	NO	0	1	YES UA ONLY
Runnew3	3	4 days	Reis 1	KF2	MRF	YES	NO	0	1	YES UA ONLY
Runnew4b	4	4 days	Reis 1	KF2	MRF	YES	NO	0	1	YES UA>.85

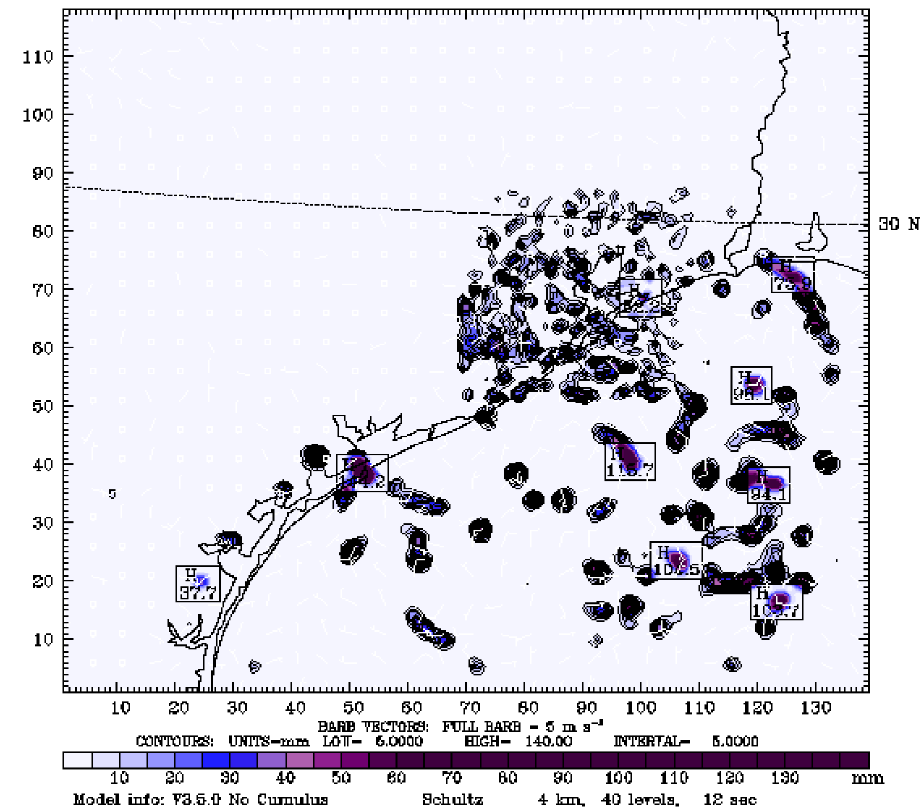
MM5 Sensitivity Tests

6 hr precipitation over grid 3 valid at 1800 UTC 8 September for:

a) with FDDA and GS

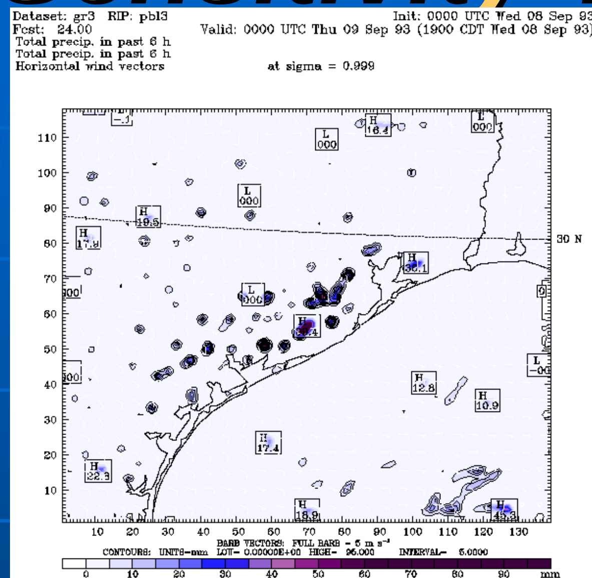


b) no FDDA and GS.

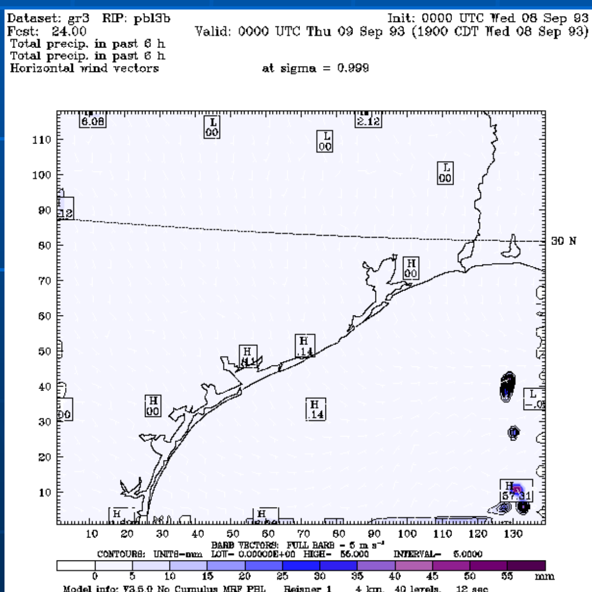


MM5 Sensitivity Tests

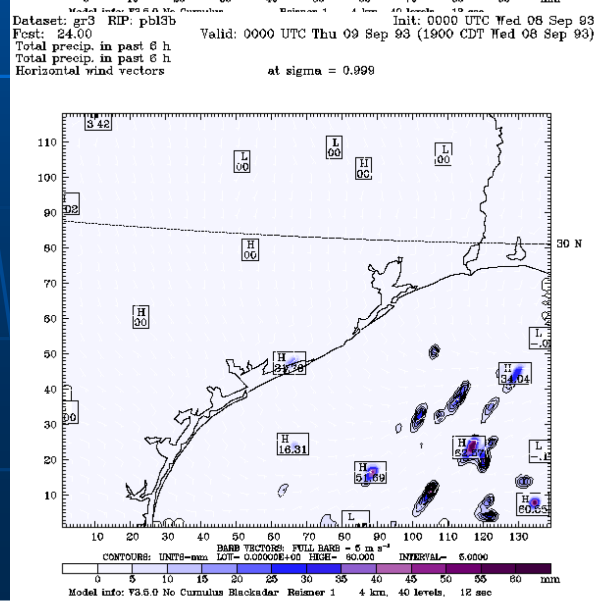
6-hr precipitation on grid 3 at 0000 UTC 9 September



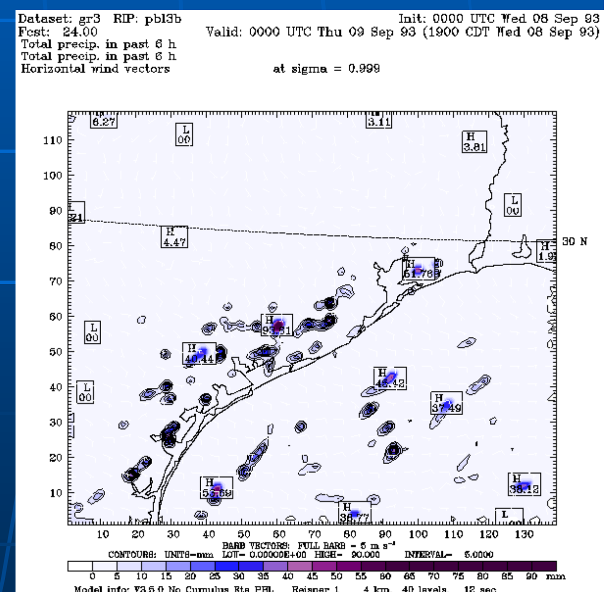
b) **GS pbl**



a) **MRF pbl**



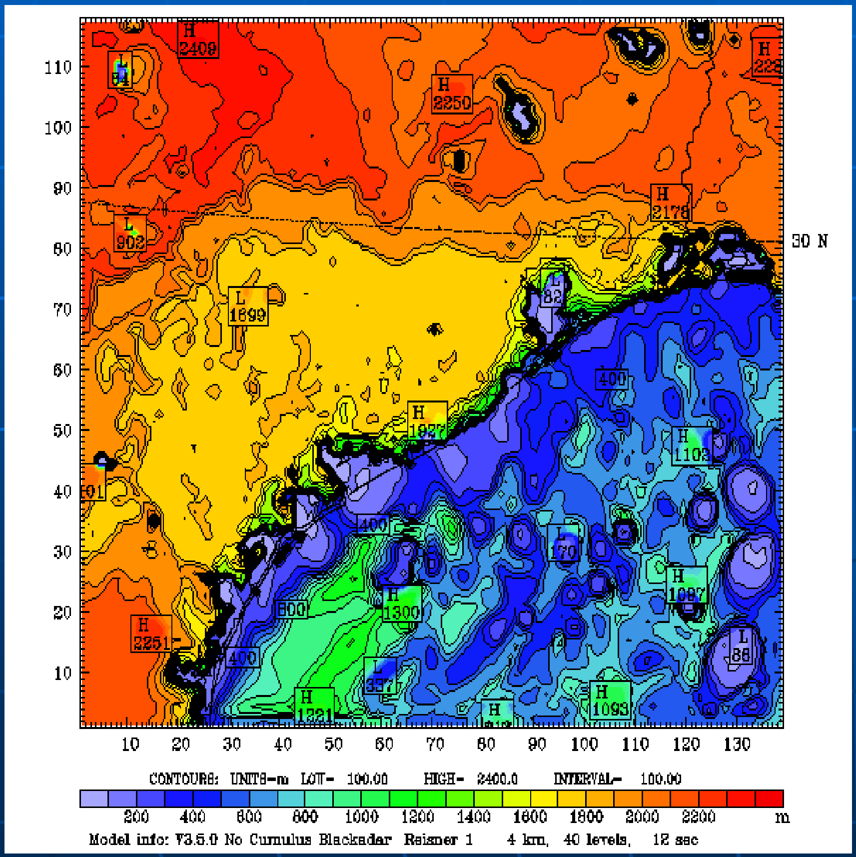
c) **Blackadar pbl**



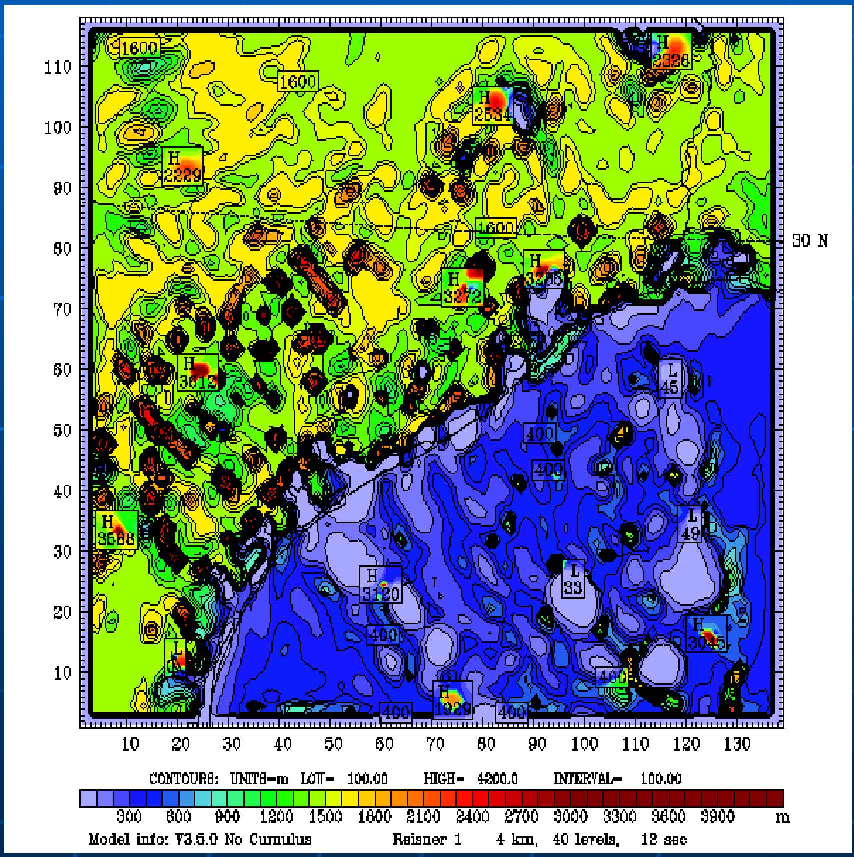
d) **ETA MY pbl**

MM5 Sensitivity Tests

PBL height – 1800 UTC



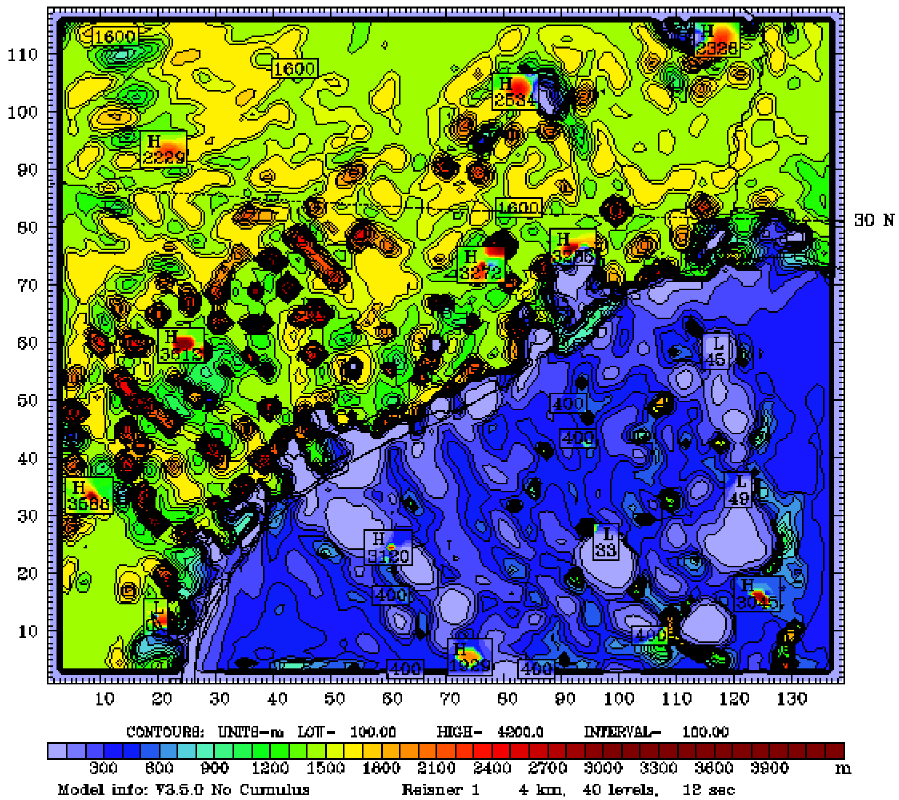
MRF



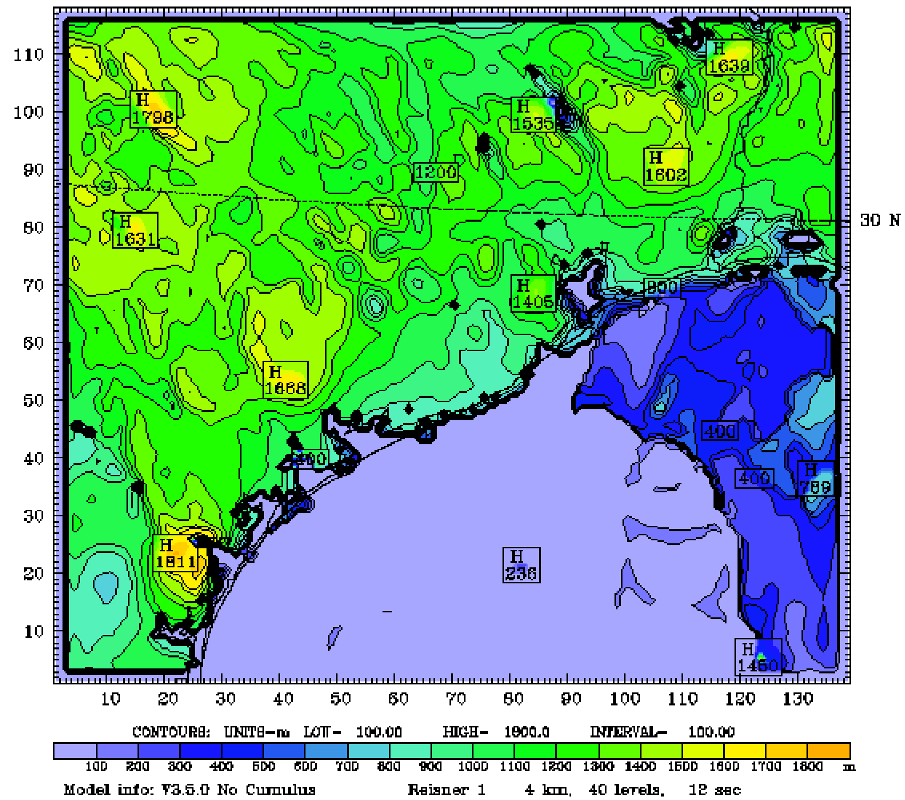
GS

MM5 Sensitivity Tests

PBL height – 1800 UTC



GS/no FDDA



GS/FDDA

MM5 Sensitivity Tests

- The cause of the convection:
  - GS and ETA TKE schemes not mixing heat upward from the surface fast enough.
  - Larger than realistic superadiabatic layer near surface was maintained.
  - Non-hydrostatic dynamics creates positive buoyancy tendency.
  - If boundary layer depth reaches significant fraction of horizontal grid spacing, grid-scale "thermals" develop. These are larger and stronger than realistic.
  - FDDA nudging acts as horizontal numeric filter, forcing circulations to even larger scale.
  - Resolved deep convection is produced.

MM5 Sensitivity Tests

- Under-prediction of surface wind speed: Low bias for the surface wind speed is primarily controlled by the PBL scheme as it interacts with the land surface scheme.
- Lack of sea breeze circulations: The lack of good sea breeze development in the previous simulations was caused by a combination of three things:
  - estimating the sea surface temperature from the lowest atmospheric level temperature
  - the over-development of grid-scale convective cells whose cold surface outflow both overwhelmed and thermally suppressed any developing sea breeze circulations
  - using the FDDA analysis nudging through the entire depth of the atmosphere.

MM5 Sensitivity Tests

- Recommendations:
  - Gayno-Seaman scheme should not be used at higher resolutions without further testing
  - Non-hydrostatic dynamics should be further tested in situations where non-hydrostatic effects are *expected* to occur.
  - Testing of the OSU/NCEP ETA and Pleim-Xu Land Surface Model (LSM) schemes.
  - FDDA should be used with caution.
  - The grid nudging parameters should be tested and adjusted for the smaller grid scales.
  - Use of the FDDA observation nudging scheme should be considered. Observation nudging may be more appropriate for smaller scales. But still, many parameters should be tested and adjusted.