Er Lu *An introduction to the*

Outline

- Purpose of RAMS
- Equations & Parameterized Terms
- Parameterization Schemes
- Model Structure
- Solution Technique
- Computational Speed

Purpose of RAMS

- Research

  used options as many as possible

  studied different meso-scale phenomena

  published many papers related to RAMS

- Forecast

Research – options used

- All parameterized components
- Time & spatial difference schemes
- (Non-)hydrostatic
- 2-D/3-D
- Map projections

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Research - phenomena studied

- winter storms
- supercell storms and tornadoes
- mesoscale convective systems
- sea breezes
- drylines
- small cumulus convection
- turbulent flow around buildings
- flow in wind tunnels
- flow in laboratory tornado simulator
- quantitative precipitation forecasting
- severe downslope winds
- operational forecasting
- transport and dispersion of pollutants
- effect of land-use change on weather and climate
- propagation of acoustic waves
- tropical cyclones
- large-eddy simulation of the convective boundary layer

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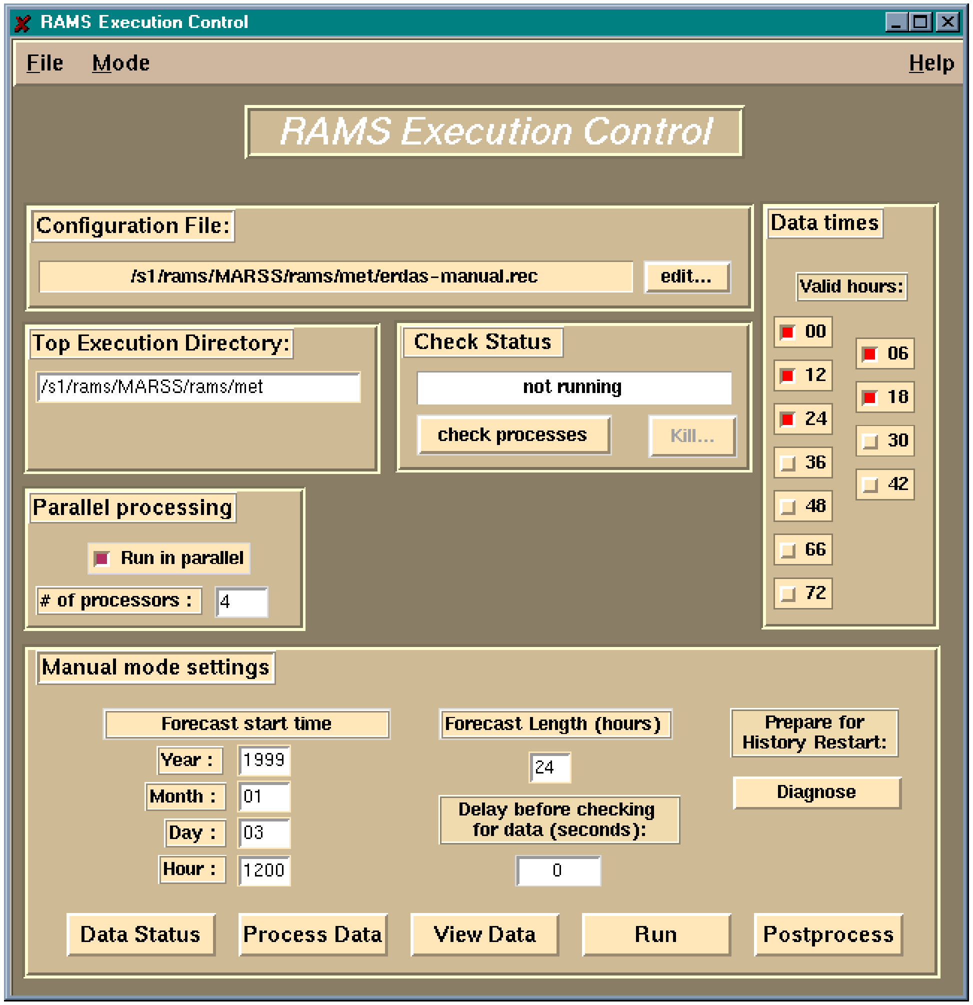
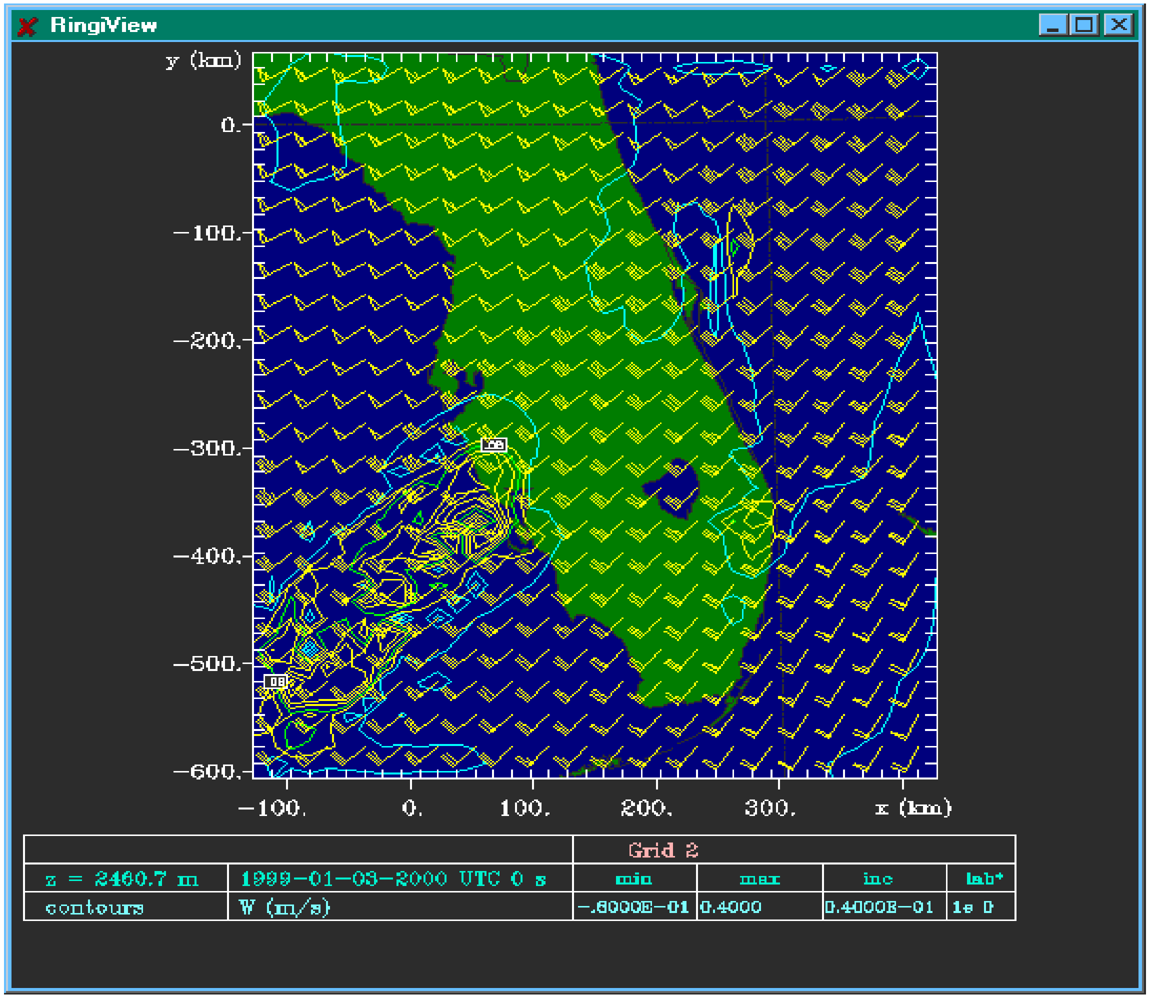
Operational Forecasting System

Data Ingest	*Observational data ingest and quality control*
Observational Data Viewer	*View upper air and surface observational data*
RAMS Execution Control	*Configure, control, and run RAMS forecast*
RAMS Forecast Viewer	*View RAMS forecast results*
Current Status	*Check current forecast status*

Operational Forecasting System



Operational Forecasting System



Equations & parameterized terms

Tendency Advection Subgrid

$$\frac{\partial u}{\partial t}=\left\{-u\frac{\partial u}{\partial x}-v\frac{\partial u}{\partial y}-w\frac{\partial u}{\partial z}\right\}+\left\{-\theta\frac{\partial \pi'}{\partial x}+fv\right\}+\left\{\frac{\partial}{\partial x}(-\overline{u'u'})+\frac{\partial}{\partial y}(-\overline{u'v'})+\frac{\partial}{\partial z}(-\overline{u'w'})\right\}$$

$$\frac{\partial v}{\partial t}=\left\{-u\frac{\partial v}{\partial x}-v\frac{\partial v}{\partial y}-w\frac{\partial v}{\partial z}\right\}+\left\{-\theta\frac{\partial \pi'}{\partial y}-fu\right\}+\left\{\frac{\partial}{\partial x}(-\overline{v'u'})+\frac{\partial}{\partial y}(-\overline{v'v'})+\frac{\partial}{\partial z}(-\overline{v'w'})\right\}$$

Ageostrophic

$$\frac{\partial w}{\partial t}=\left\{-u\frac{\partial w}{\partial x}-v\frac{\partial w}{\partial y}-w\frac{\partial w}{\partial z}\right\}+\left\{-\theta\frac{\partial \pi'}{\partial z}-\frac{g\theta_v'}{\theta_0}\right\}+\left\{\frac{\partial}{\partial x}(-\overline{w'u'})+\frac{\partial}{\partial y}(-\overline{w'v'})+\frac{\partial}{\partial z}(-\overline{w'w'})\right\}$$

Nonhydrostatic

$$\frac{\partial \theta}{\partial t}=\left\{-u\frac{\partial \theta}{\partial x}-v\frac{\partial \theta}{\partial y}-w\frac{\partial \theta}{\partial z}\right\}+\left\{\left(\frac{\partial \theta}{\partial t}\right)_{rad}\right\}+\left\{\frac{\partial}{\partial x}(-\overline{\theta'u'})+\frac{\partial}{\partial y}(-\overline{\theta'v'})+\frac{\partial}{\partial z}(-\overline{\theta'w'})\right\}$$

Diabatic

$$\frac{\partial r}{\partial t}=\left\{-u\frac{\partial r}{\partial x}-v\frac{\partial r}{\partial y}-w\frac{\partial r}{\partial z}\right\}+\left\{\frac{\partial}{\partial x}(-\overline{r'u'})+\frac{\partial}{\partial y}(-\overline{r'v'})+\frac{\partial}{\partial z}(-\overline{r'w'})\right\}$$

$$\frac{\partial \pi'}{\partial t}=-\frac{R\pi_0}{c_v\rho_0\theta_0}\left\{\frac{\partial \rho_0\theta_0 u}{\partial x}+\frac{\partial \rho_0\theta_0 v}{\partial y}+\frac{\partial \rho_0\theta_0 w}{\partial z}\right\}$$

- Surface fluxes
- Subgrid mixing

- Q1 profile
- SH at surface
- Q2 profile
- LH at surface

- Surface T & r

- SW & LW
  cloud
  albedo
  vegetation

- Convection

Subgrid mixing *(Smagorinsky 1963)*

Deformation-based

$$\left(\frac{\partial u_j}{\partial t}\right)_{turb} = \frac{\partial}{\partial x_i}(-\overline{u_i'u_j'})$$

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

K theory

Unresolved transport ~ gradient of transport quantity

Eddy mixing coefficient

$$K_{mi} = \rho(C_x\Delta x)(C_z\Delta z)\left\{S_3 + F_H\left[\max(0,-F_B)\right]^{0.5}\right\}\left[\max(0,1-R_{hm}R_i)\right]^{0.5}$$

Magnitude of 3-D rate-of-strain tensor

$$S_3 = \left[\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2\right]^{0.5}$$

Subgrid mixing *(Mellor-Yamada 1974 & 1982)*

Turbulent Kinetic Energy (TKE)

$$e = \frac{1}{2}\overline{\left(u'^2 + v'^2 + w'^2\right)}$$

$$\frac{\partial e}{\partial t} = ...$$

Eddy diffusivities for momentum, heat, and TKE

$$K_m, K_h, K_e \sim \sqrt{e}$$

Surface fluxes *(Louis 1979)*

Surface fluxes of momentum, heat, and water vapor based on surface similarity theory

$$(-\overline{u'w'})_0 \equiv u_*^2 = a^2 u^2 F_m\left(\frac{z}{z_0}, R_{iB}\right)$$

$$R_{iB} = \frac{gz}{U^2}\frac{\theta - \theta_0}{\theta}$$

Bulk Richardson number

$$(-\overline{\theta'w'})_0 \equiv \theta_* u_* = \frac{a^2}{R} u \Delta\theta F_h\left(\frac{z}{z_0}, R_{iB}\right)$$

$$\Delta\theta = \theta - \theta_s$$

$$(-\overline{r'w'})_0 \equiv r_* u_* = \frac{a^2}{R} u \Delta r F_h\left(\frac{z}{z_0}, R_{iB}\right)$$

$$\Delta r = r - r_s$$

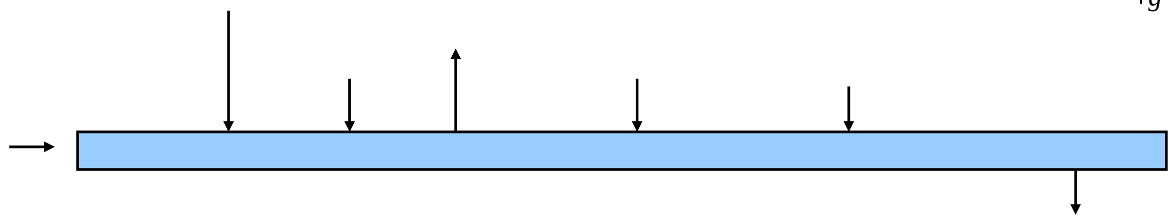
θ_s, r_s calculated from surface energy and water balance

Soil surface

- Heat diffusion in soil $\frac{\partial \theta_s}{\partial t} = \frac{\partial}{\partial z}\left[\lambda \frac{\partial \theta_s}{\partial z}\right]$ θ_s soil

- Ground surface potential temperature

$$C_s \Delta z_g \frac{\partial \theta_g}{\partial t} = \alpha_g R_s^{\downarrow} + R_l^{\downarrow} - \sigma T_g^{4} + \rho_a C_p u_* \theta_* + \rho_a C_p u_* r_* - C_s \lambda \left.\frac{\partial \theta_s}{\partial z}\right|_g$$



- Moisture of top soil layer

$$\frac{\partial \eta_s}{\partial t} = \frac{\left(\rho_a u_* r_* / \rho_w\right) - D_\eta \frac{\partial \eta}{\partial z} - K_\eta}{\Delta z_g}$$

- Mixing ratio at ground surface

$$r_g = e^{\left[\frac{g \psi_g}{R_v T_g}\right]} r_s\left(T_g P_g\right)$$

Vegetated surface

- "Big leaf" approach: shortwave transmissivity τ_{veg} T_{veg}

- Ground surface potential temperature

$$C_s \Delta z_g \frac{\partial \theta_g}{\partial t} = \tau_{veg} \alpha_g R_s^{\downarrow} + \sigma T_{veg}{}^4 - \sigma T_g{}^4 + \rho_a C_p u_* \theta_* + \rho_a C_p u_* r_* - C_s \lambda \frac{\partial \theta_s}{\partial z}\bigg|_g$$

- Vegetation temperature

$$C_{veg} \Delta z_{veg} \frac{\partial \theta_{veg}}{\partial t} = (1 - \tau_{veg}) \alpha_{veg} R_s^{\downarrow} + R_l^{\downarrow} + \sigma T_g{}^4 - 2\sigma T_{veg}{}^4 + 2\rho_a C_p u_* \theta_* + \rho_a C_p u_* r_*$$

- Effective vegetation mixing ratio

$$r_{veg} = \gamma r_{veg_s} + (1 - \gamma) r_a$$

SW radiation – no cloud *(Mahrer & Pielke 1977)*

Downward solar flux at ground $R_s^{\downarrow} = R_s \dfrac{\cos i}{\cos Z}$

Air T change due to absorption of water vapor $\left(\dfrac{\partial T}{\partial t}\right)_s = 0.0231 \dfrac{S}{\rho c_p} \left[\dfrac{\tau(z)}{\cos Z}\right]^{-0.7} \dfrac{\partial \tau}{\partial z}$

Incidence angle of solar rays on sloped surface $\cos i = \cos\alpha \cos Z + \sin\alpha \sin Z \cos(\beta - \eta)$

Zenith angle $\cos Z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\psi$

Net SW at surface $R_s = S(1 - A)(G - a_w)$

Solar flux at TOA $S = S_0 \cos Z$

Effect of oxygen, ozone, and carbon dioxide (Atwater & Brown 1974) $G(p, \cos Z)$

Water vapor absorption $a_w = 0.077 \left[\dfrac{\tau(z)}{\cos Z}\right]^{0.3}$

LW radiation – no cloud *(Mahrer & Pielke 1977)*

water vapor + carbon dioxide: Infrared emission & absorption

Downward LW flux at surface

$$R_L = \left(\sigma T_{top}^{\ 4} - \sigma T_N^{\ 4}\right)\left[\varepsilon(N+1, top) - \varepsilon(N, top)\right]$$

Air T change due to LW flux divergence at level N

$$\left(\frac{\partial T}{\partial t}\right)_L = -\frac{1}{\rho C_p \Delta z}\left\{\left(\sigma T_N^{\ 4} - \sigma T_g^{\ 4}\right)\left[\varepsilon(N+1,0) - \varepsilon(N,0)\right] + \left(\sigma T_{top}^{\ 4} - \sigma T_N^{\ 4}\right)\left[\varepsilon(N+1, top) - \varepsilon(N, top)\right]\right\}$$

$$\varepsilon = \varepsilon_v + \varepsilon_c$$

Emissivity of CO2 (Kondrat'yev 1969)

$$\varepsilon_c = 0.185\left[1 - \exp\left(-0.03919\tau_c^{\ 0.4}\right)\right]$$

ε_v emissivity of water vapor, is determined from its optical path based on the data of Jacobs et al (1974).

Stable precipitation - physical processes

nucleation of cloud droplets
nucleation of ice crystals by Brownian motion
thermophoersis
diffusiophoresis
contact freezing
deposition freezing
homogeneous nucleation of cloud droplets and haze
collisions between all pairs of hydrometeor species including self-collection
evaporation
condensation
sublimation
deposition
freezing
melting
shedding of water by hail
heat exchange in hydrometeor collisions
sedimentation
secondary ice production

Convective precipitation *(Kuo 1974, Molinari 1985)*

Terms in model equations due to moist convection

$$\left(\frac{\partial\theta}{\partial t}\right)_{con} = \frac{L}{\pi}(1-b)I\frac{Q_1}{\int_{z_g}^{z_{ct}} Q_1 dz} \qquad \left(\frac{\partial r_T}{\partial t}\right)_{con} = bI\frac{Q_2}{\int_{z_g}^{z_{ct}} Q_2 dz}$$

$$I = \int \frac{\pi}{L}\left(\frac{\partial\theta}{\partial t}\right)dz + \int\left(\frac{\partial r}{\partial t}\right)dz = \frac{1}{L}\int\frac{\partial}{\partial t}\left(c_p T + Lr\right)dz$$

I	Supply rate of moisture from resolvable scale to a grid column
bI	The part used to increase the moisture of the column
$(1-b)I$	The precipitated part, and its latent heat warms the column
$Q1$	Vertical profile of convective heating
$Q2$	Vertical profile of convective moistening

$I = ?$ $\qquad$ $b = ?$

Dimensionality & model domain

Dimension

- 2-D (x - z)
- 3-D

Domain

- No lower limit
- Global domain

Vertical coordinate & layers & resolution

- Coordinate

  terrain-following sigma-z

$$z^* = H\left(\frac{z - z_g}{H - z_g}\right)$$

- Layer

  grid spacing

  stretched

  increase resolution near ground

  grid nest ratio

  number of grid points within a parent grid point

  vary with height

- Resolution

  no limit

Horizontal coordinate & grid

- Horizontal coordinate
  - polar stereographic
  - Cartesian
- Grid
  - Arakawa-C staggered
    - moisture & thermodynamic variables are at grid point
    - u, v, w are at half delta x, y, z, respectively

Horizontal grid nesting & resolution

- Grid nesting
  - two-way interactive
    - any number of nested grids
- Resolution
  - no minimum
  - low as 2 cm

Time difference

- Leapfrog
  - velocity components
  - Exner function
- Forward
  - scalar quantities other than Exner function
- Time-split
  - smaller time step for fast waves

CFL $U\frac{\Delta t}{\Delta x}<1$ $\Delta t < \frac{\Delta x}{U}$

Non-hydrostatic: acoustic + gravity

hydrostatic: external gravity + Lamb

Leapfrog advection

Centered-in-time & centered-in-space (Tremback et al. 1987)

Second-order fluxes

Fourth-order fluxes

$$F_{j+\frac{1}{2}} = u_{j+\frac{1}{2}}\left(-\frac{1}{12}\phi_{j-1} + \frac{7}{12}\phi_j + \frac{7}{12}\phi_{j+1} - \frac{1}{12}\phi_{j+2}\right)$$

Forward upstream advection

Derivations and tests: Tremback et al. (1987)

Second-order fluxes

$$F_{j+\frac{1}{2}}\frac{\Delta t}{\Delta x} = \frac{\alpha}{2}\left(\phi_j + \phi_{j+1}\right) + \frac{\alpha^2}{2}\left(\phi_j - \phi_{j+1}\right)$$

Sixth-order integrated fluxes

Sixth-order constant grid fluxes

Initialization

- Horizontally homogenous interpolation

  single sounding

- Barnes objective analysis

  gridded pressure level data

  rawinsonde data

  surface observations

Lateral boundary condition

- normal velocity component
  - Klemp-Wilhelmson (1977)
  - Klemp-Lilly (1978)
  - Orlanski (1976)
  - cyclic
- other variables
  - zero gradient
  - zero divergence of gradient
  - cyclic

Top boundary condition

- Wall on top

  W=0

- Newtonian relaxation

  sounding or observed fields

  upper layers

  absorb gravity waves

Computational speed

- run time
  - number of grid cells
  - number of nested grids
  - grid resolution
  - physics complexity
  - simulation time
- model speed evaluation
  - update 50,000 grid cell per second
  - without bulk microphysics
- single PC processor (500 MHz)
  - 1 wall (CPU) clock second = 50,000 grid cells x 1 step
- parallel processing (MPI)
  - 16-processor SP-2 = 14 times faster than single processor

Other model options

- surface and subsoil hydrology model
  - transports water downslope
- prognostic scalar quantities
  - study transport and dispersion
- coupled with
  - microphysics model (CENTURY)
  - dynamic vegetation models (GEMTM)
- nested grids may move
  - follow moving system

References

- Tripoli and Cotton (1982)
- Tremback et al. (1987, 1994)
- Meyers et al. (1992,1997)
- Pielke et al. (1992)
- Nicholls et al. (1993,1995)
- Lyons et al. (1994)
- Harrington et al. (1995)
- Walko et al. (1995a, b, 2000a, b)
- Pielke and Nicholls (1997)
- Olsson (2000)
- Abbs (1999)