Implementing a New Shallow Convection Scheme into WRF

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Outline

- Overview of the PSU Shallow Convection Scheme (SCP)
- WRF Implementation Plan
- Preliminary 1-D Results
- Summary and Conclusions

Technique Details of the PSU Shallow Convection Parameterization (SCP) *(Deng et al. 2003a, 2003b, JAS)*

- **<u>Triggering Function</u>**:
  1) Parcel T', Q'
  2) Parcel vertical lifting determined by factors including TKE
- **<u>Cloud model</u>**: K-F entraining/detraining cloud model
- **<u>Closure Assumption</u>**: Amount of total cloud-base mass flux or number of updrafts is determined with a hybrid of TKE and CAPE, depending on the updraft depth.

----- In addition -----

- Prognostic cloud scheme for cloud fraction and subgrid cloud water

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PSU SCP description- Parcel initial vertical velocity

$$w_B = \overline{w} + w_T + w_{NH}$$

1) Resolvable-scale vertical velocity: $\overline{w}$

2) Boundary layer turbulence:

$$w_T = \sqrt{\frac{2}{3} \cdot TKE_{MAX}}$$

3) Vertical "pumping" due to non-hydrostatic pressure effects for deep convection:

$$w_{NH} = \max\{0.15 \cdot [w(z_{1000})^{\tau-1} - (\overline{w} + w_T)], 0\}$$

PSU SCP description- T and Q perturbation and updraft radius

Parcel perturbation in **temperature** and **moisture**, averaged from the lowest 20% of the PBL ⇒ Cloud base (LCL)

Updraft radius:

in a range of 150 to 1500 m, as a function of PBL depth and cloud depth:

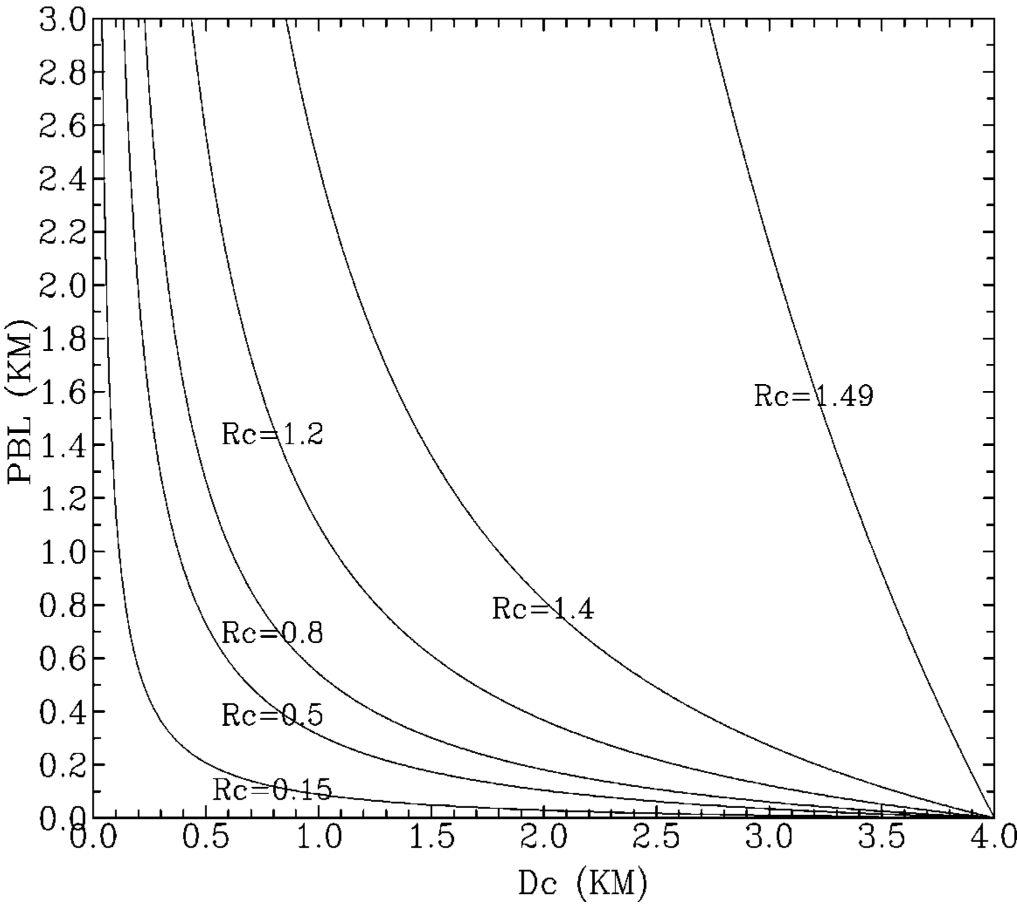
$$R_C = \frac{b - \sqrt{b^2 - 12\eta h_{PBL}}}{4}$$

where $b = \frac{7 + 2\eta h_{PBL}}{2}$

$$\eta = \frac{12 D_C}{4 - D_C}$$

D_C: Cloud depth (km)

h_{PBL}: PBL (km)



PSU SCP description- Closure assumption

Cloud-base mass flux:

$$\mu_B = N\mu_{BS} \quad \text{where} \quad \mu_{BS} = \pi R_C^2 w_B \rho$$

where the number of updrafts

$$N = \begin{cases} N_4 & z_T \le z_{LFC} \\ N_2 \quad \text{for} & D_C \ge 4\text{km} \\ N_3 & z_T > z_{LFC} \text{ and } D_C < 4\text{km} \end{cases}$$

where $N_4 = \varepsilon \cdot TKE_{\max} \cdot N_T$ → TKE-based closure

$$N_2 = \frac{\mu_B}{\mu_{BS}}$$ → CAPE-removal closure

$$N_3 = fN_2 + (1-f)N_4$$ → Hybrid closure

where $N_T = \dfrac{M_S}{\mu_{BS}\tau_C}$

$$\varepsilon = 0.15\,\text{kg J}^{-1}$$

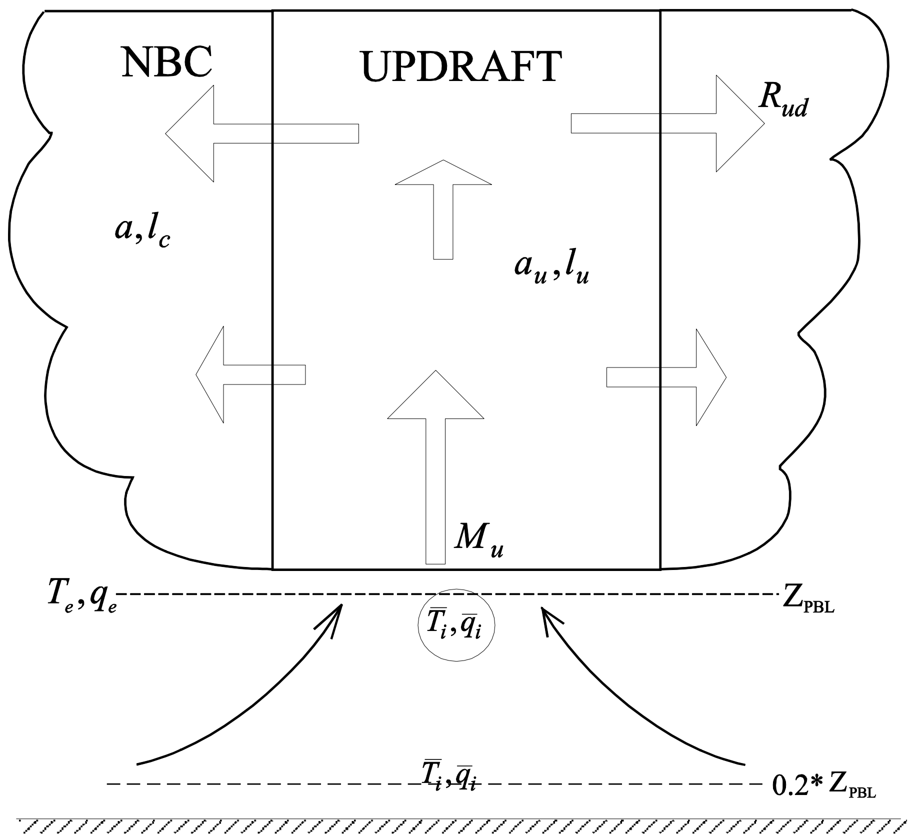
$f = h_3/h_1 \qquad h_3 = D_C - h_2$

$h_1 = 4 - h_2 \qquad h_2 = z_{LFC} - z_B$

M_S: mass of air in the model layer.

TKE_{MAX}: maximum TKE below the parcel-releasing level.

PSU SCP Schematic



Schematic of the prototype PSU SCP, where *a* is the neutrally-buoyant cloud (NBC) fraction, l_c is the NBC cloud water content, l_u is the cloud water content in the updraft denoted by subscript *u*, R_{ud} is the updraft detrainment rate; and Z_{pbl} is the depth of the PBL, etc.

PSU SCP description- A prognostic cloud scheme

$$\frac{\partial a}{\partial t} = S_a + D_a - \vec{v} \cdot \nabla a - w \frac{\partial a}{\partial z}$$

$$\frac{\partial l_c}{\partial t} = S_l + D_{mix} + D_{pre} + D_{ics} + D_{CTEI} - \vec{v} \cdot \nabla l_c - w \frac{\partial l_c}{\partial z}$$

a Cloud area

l_c Cloud water/ice content

S_a Source for cloud area due to updraft detrainment

D_a Dissipation of cloud area due to evaporation at cloud edge

S_l Source for cloud water due to updraft detrainment

D_{mix} Depletion of cloud water due to vertical mixing

D_{pre} Depletion of cloud water due to precipitation

D_{ics} Depletion of cloud ice due to ice settling

D_{CTEI} Depletion of cloud water due to CTEI

PSU SCP Interaction with Radiation Schemes

Effective cloud:

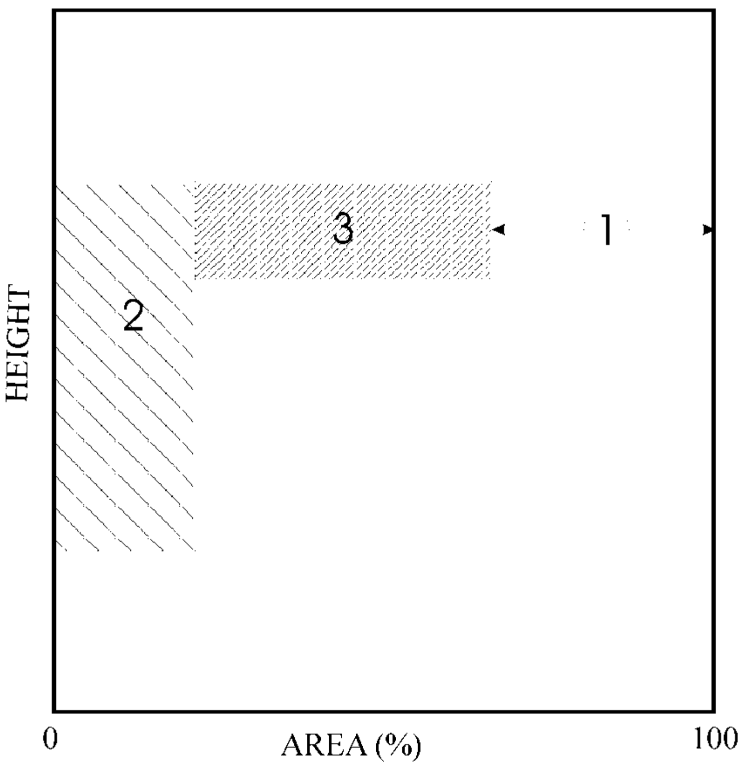
$$a_e = (1-a)a_S + a$$

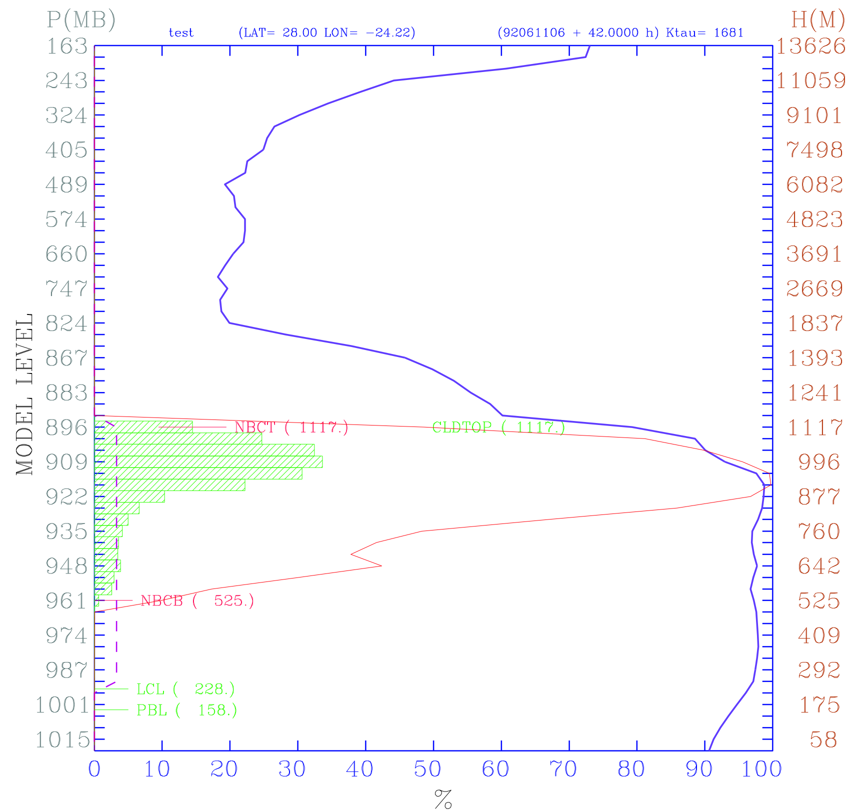
$$a_S = RH^{\alpha_1}[1-\exp(\frac{-\alpha_3(l_c+q_c)}{[(1-RH)q_S]^{\alpha_2}})] \quad \text{if RH} < 1$$

$\alpha_1, \alpha_2, \alpha_3$ Constants given by Xu and Randall (1996)

$$R_S = \bar{a}_{e2}R_2 + \bar{a}_{e3}R_3 + (1-\bar{a}_{e2}-\bar{a}_{e3})R_{clr}$$

$$\left.\frac{\partial T(z)}{\partial t}\right|_{rad} = [1-a_e(z)]\left.\frac{\partial T(z)}{\partial t}\right|_{clr} + a_e(z)\left.\frac{\partial T(z)}{\partial t}\right|_{cld}$$





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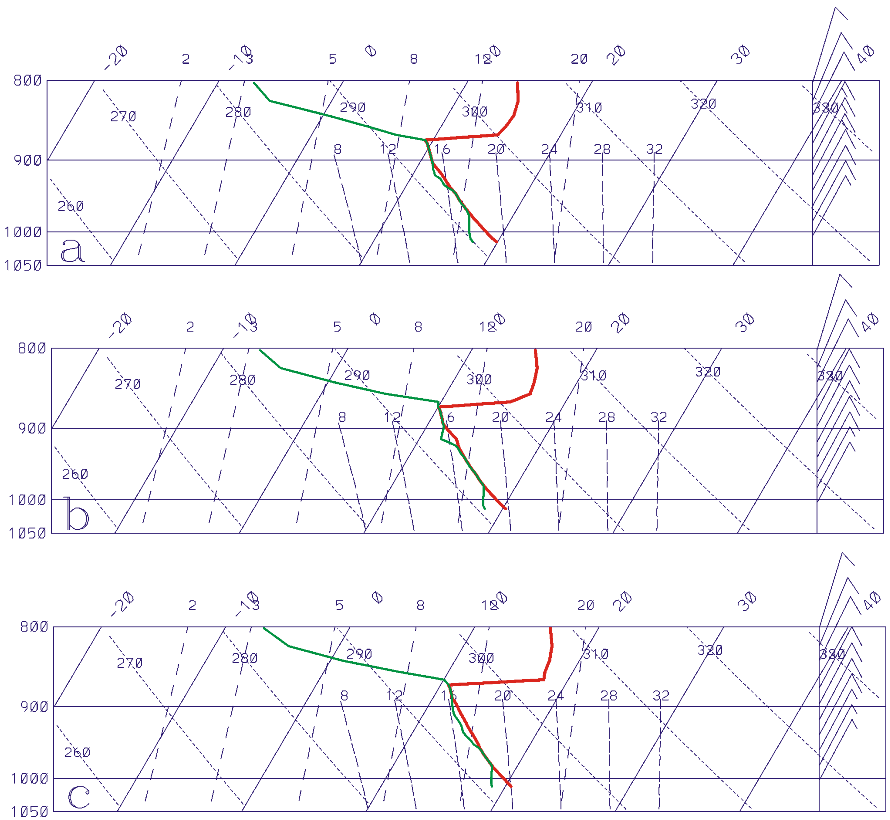
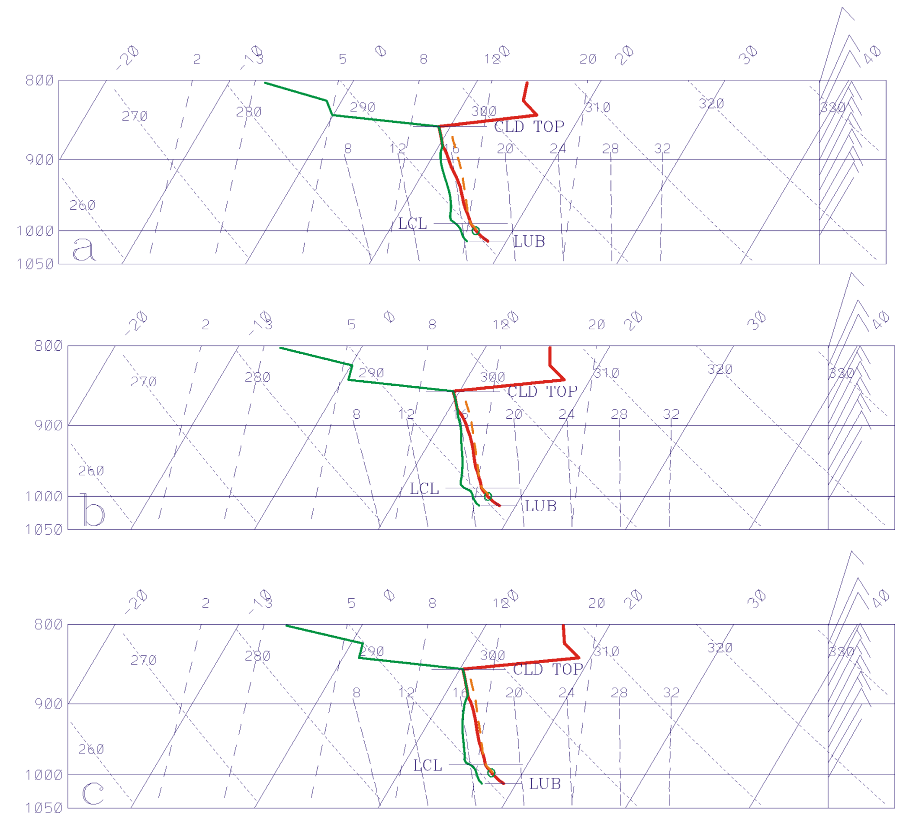
Effect of PSU SCP

Marine environment

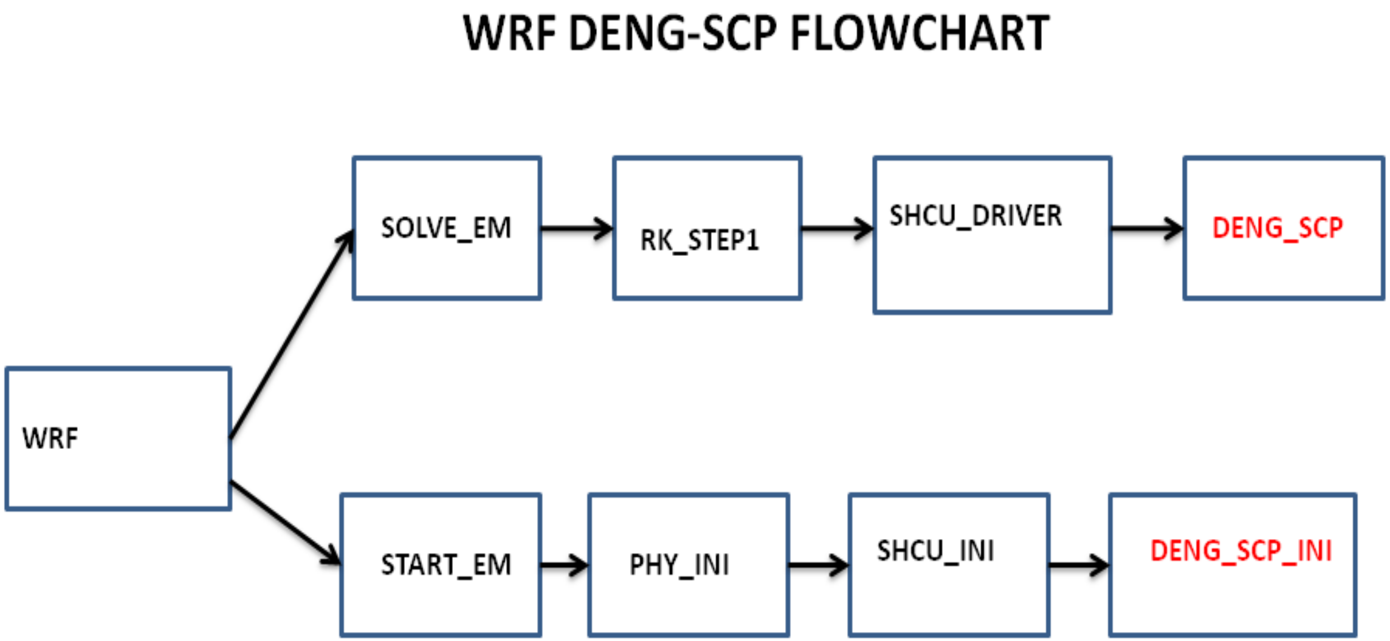
Simulated sounding (20h, 40h, 60h)

Without shallow convection   With shallow convection





WRF Implementation Plan



In addition, MM5 GS PBL scheme is implemented

PSU SCP 1-D WRF Test Cases

- **Case1 - Marine Shallow Stratus (Azores Islands, ASTEX)**
  - **1992.06.11.06Z – 1992.06.14.06Z (72-hour simulation)**
  - **Location: (20.0N, 24.22W)**

- **Case2 - Continental Shallow Stratocumulus**
  - **1998.06.08.12Z – 1998.06.09.12Z (24-hour simulation)**
  - **Location: Pittsburgh, Pennsylvania**

- **Case3 - Continental Deep Convection**
  - **1997.07.10.12Z – 1997.07.11.12Z (24-hour simulation)**
  - **Location: SGP ARM CART Site**

PSU SCP 1-D WRF Model Configuration

- DX=30 km, DT=90 S, 62 Eta layers
- WRF physics
  - Gayno-Seaman TKE-predicting PBL scheme (bl_pbl_physics =11) (newly implemented with the PSU SCP Scheme)
    - MM5 Monin-Obukhov scheme (sf_sfclay_physics =1)
    - 5-layer thermal diffusion scheme (sf_surface_physics =1)
  - PSU-Deng shallow convection scheme (shcu_physics 3)
  - RRTMG atmospheric radiation scheme (ra_lw_physics=4, ra_sw_physics=4)
  - WSM 3-class simple ice explicit moisture scheme (mp_physics=3)
- SCM initialization codes modified to allow pressure level sounding as in MM5

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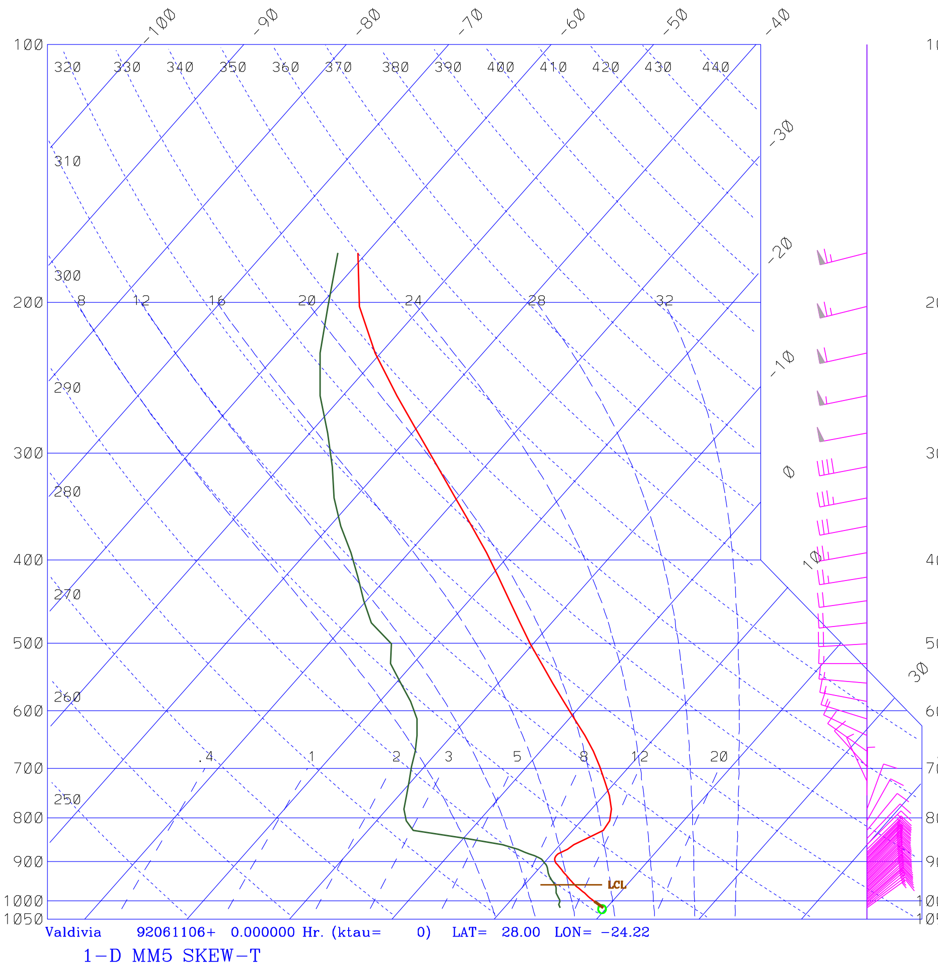
- **Case 1: Marine Shallow Stratus –Azores Islands, ASTEX, 06 UTC, 11-14 June 1992, 72-hour simulation**

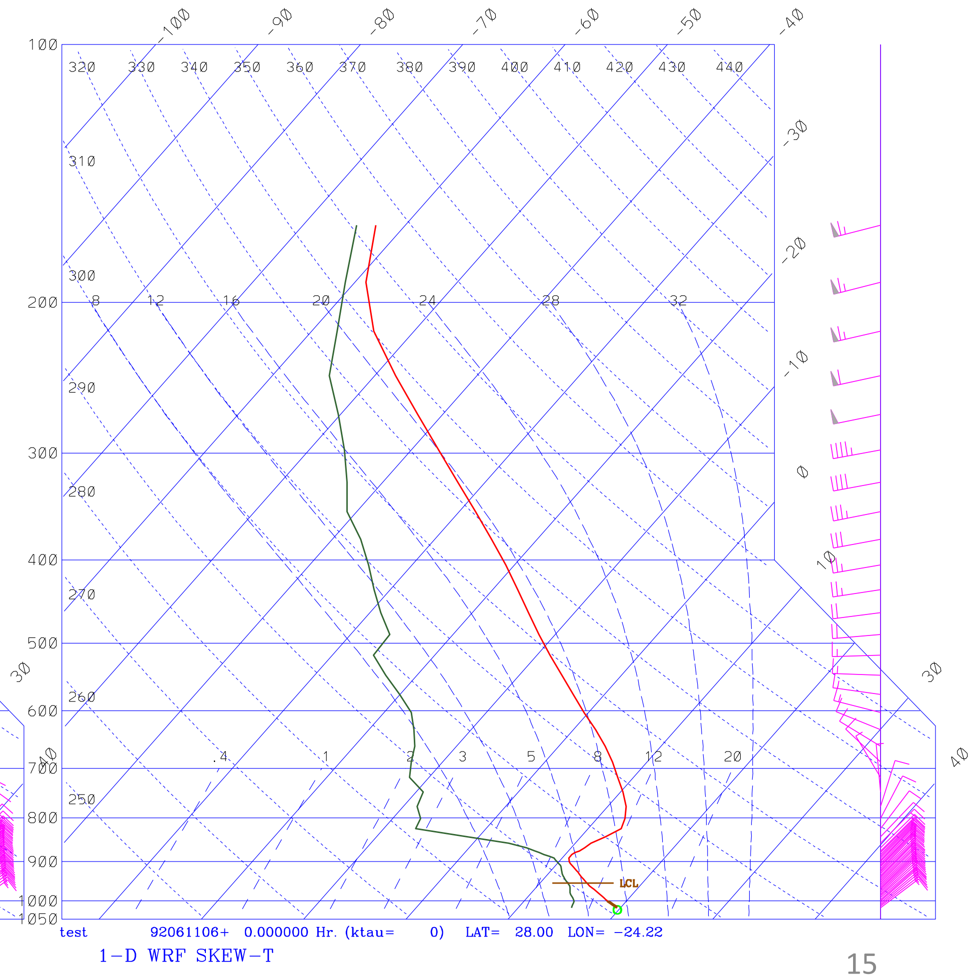
Dominated by the persistent Bermuda High, this region exhibits deep tropospheric subsidence and a moist marine atmospheric boundary layer that is often capped by a strong inversion and stratocumulus clouds, with a prescribed subsidence profile.

Initial Condition

MM5

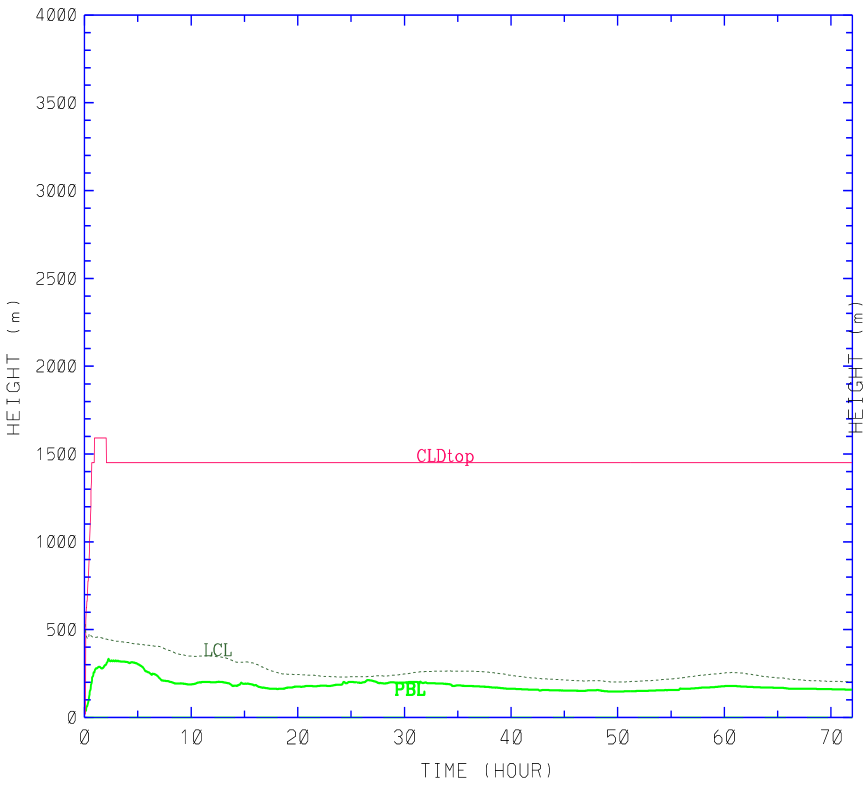


WRF

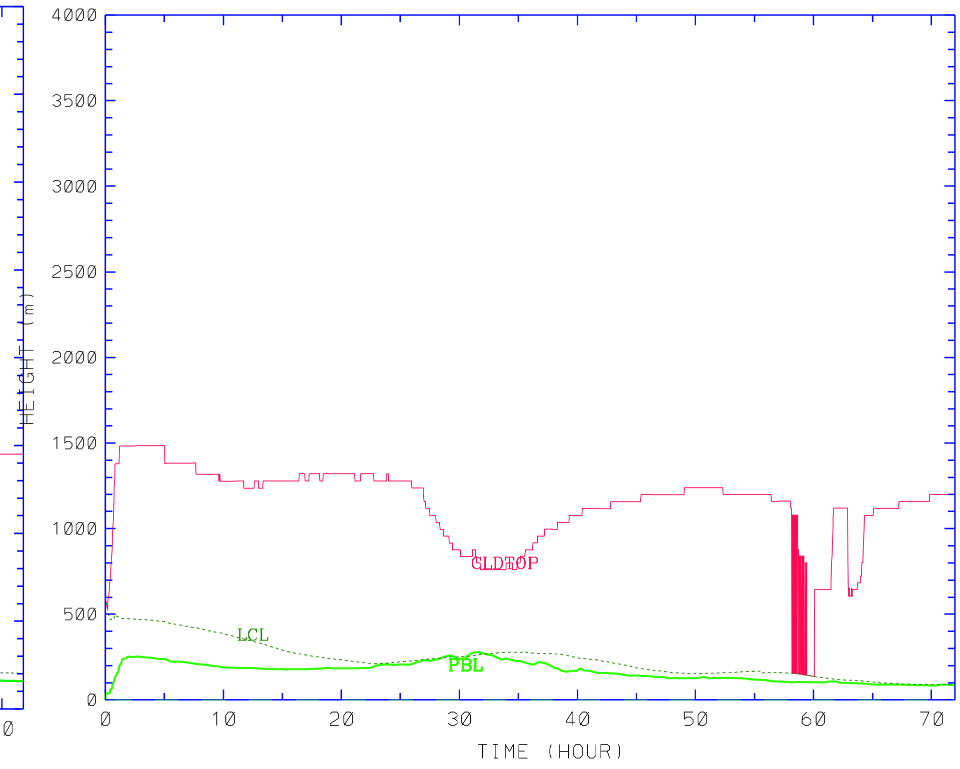


Model-predicted Cloud Updraft Top, LCL and PBL Depth

MM5

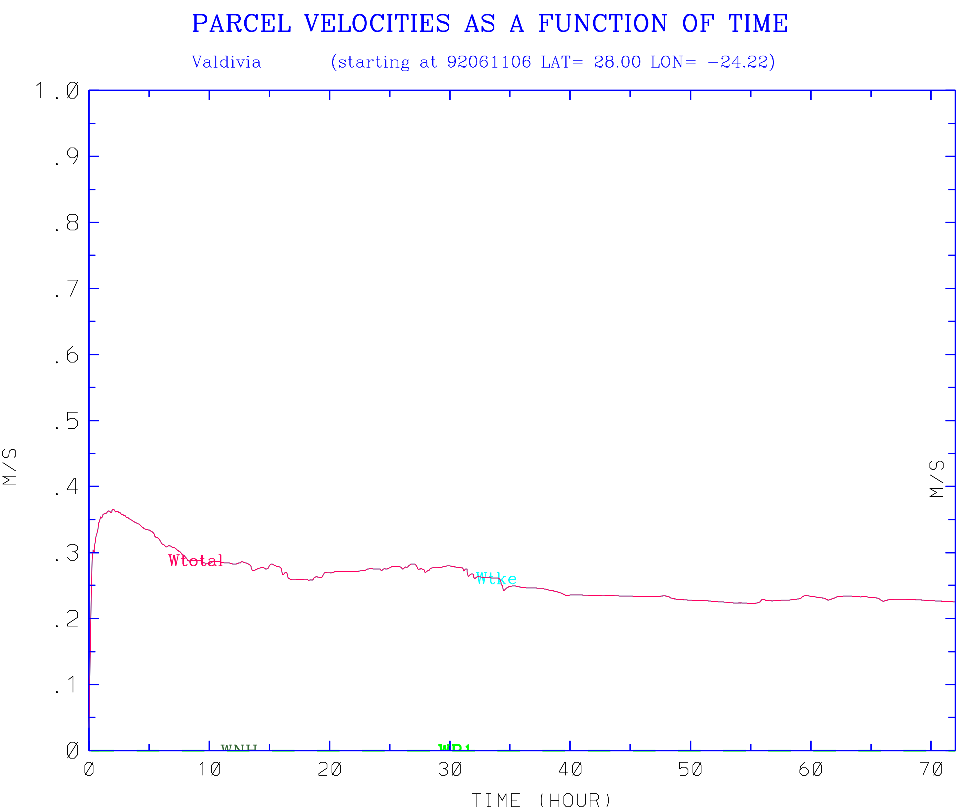


WRF

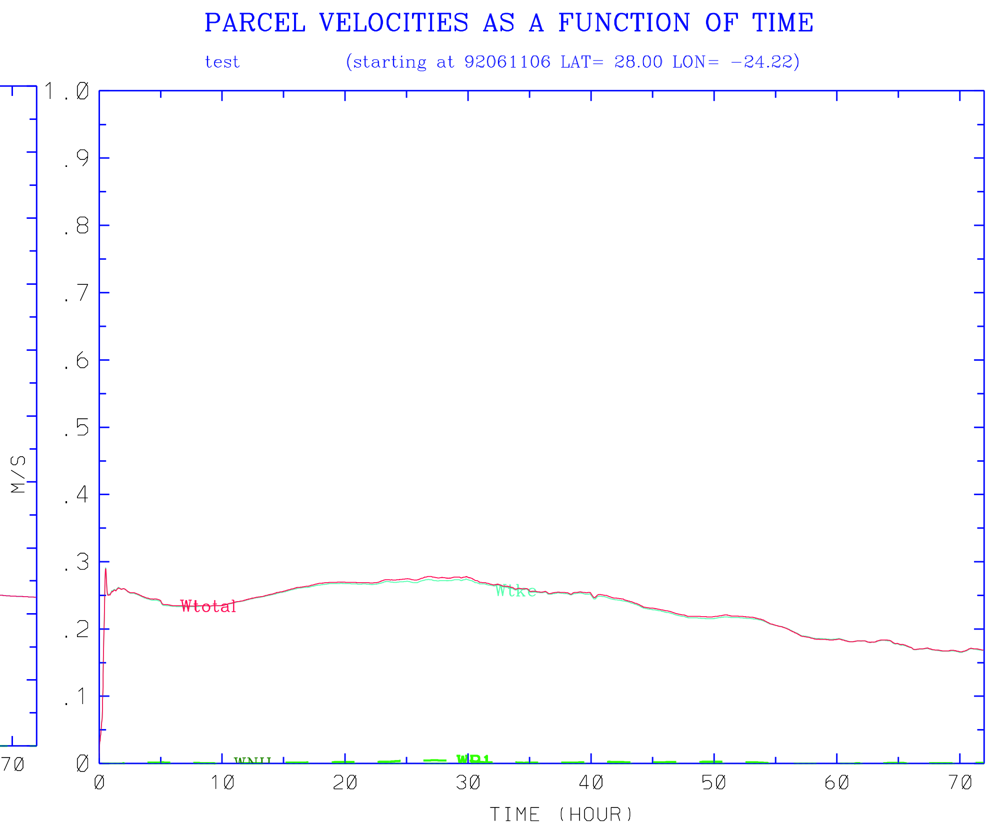


Cloud Parcel Initial Vertical Velocity

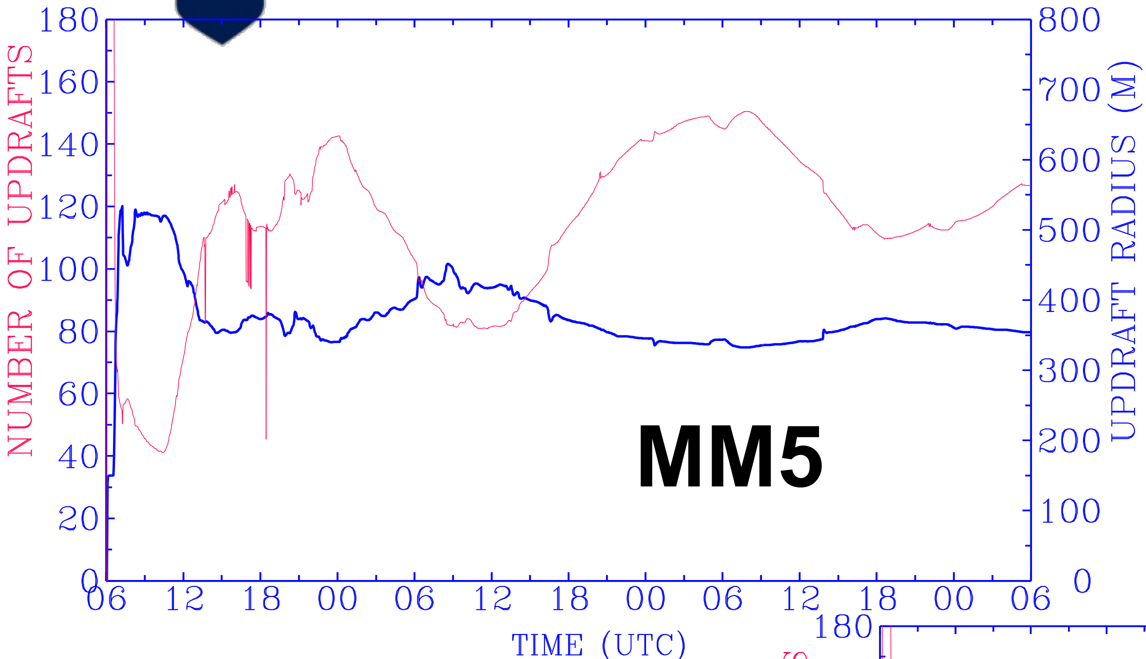
MM5

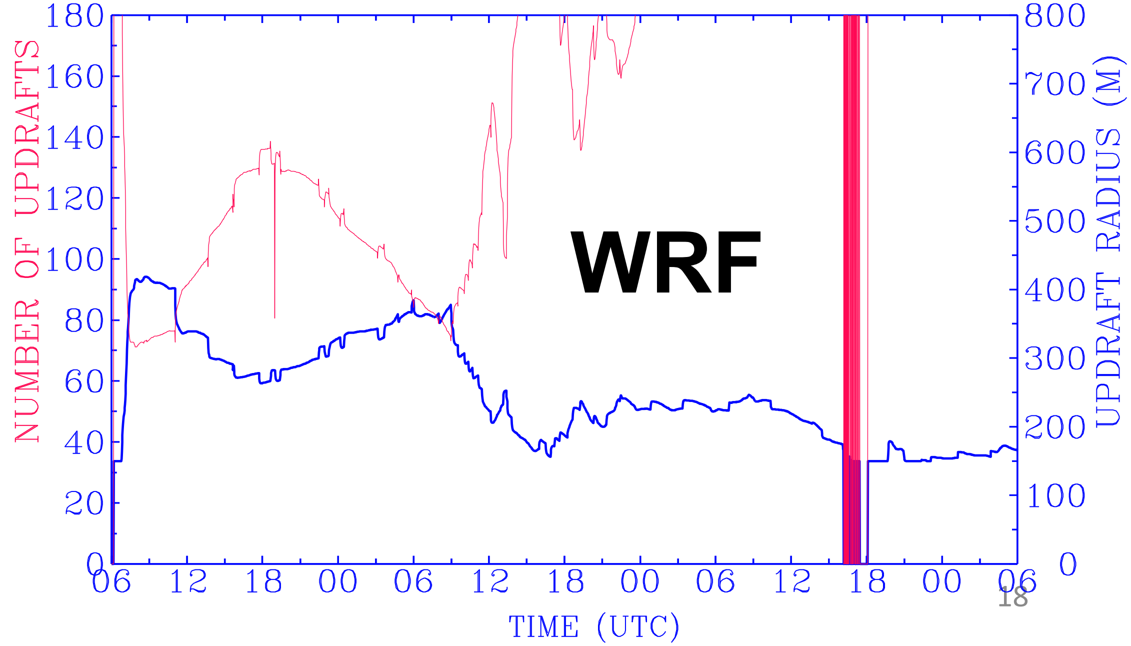


WRF

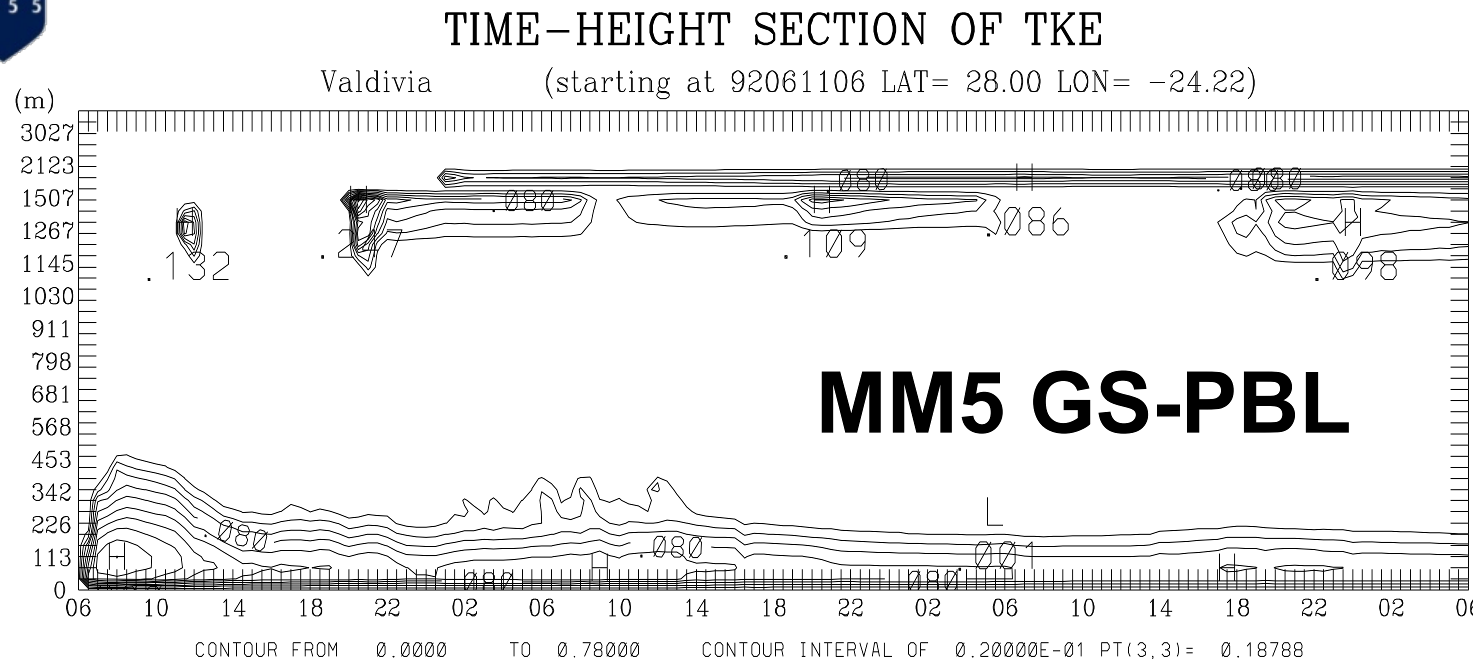


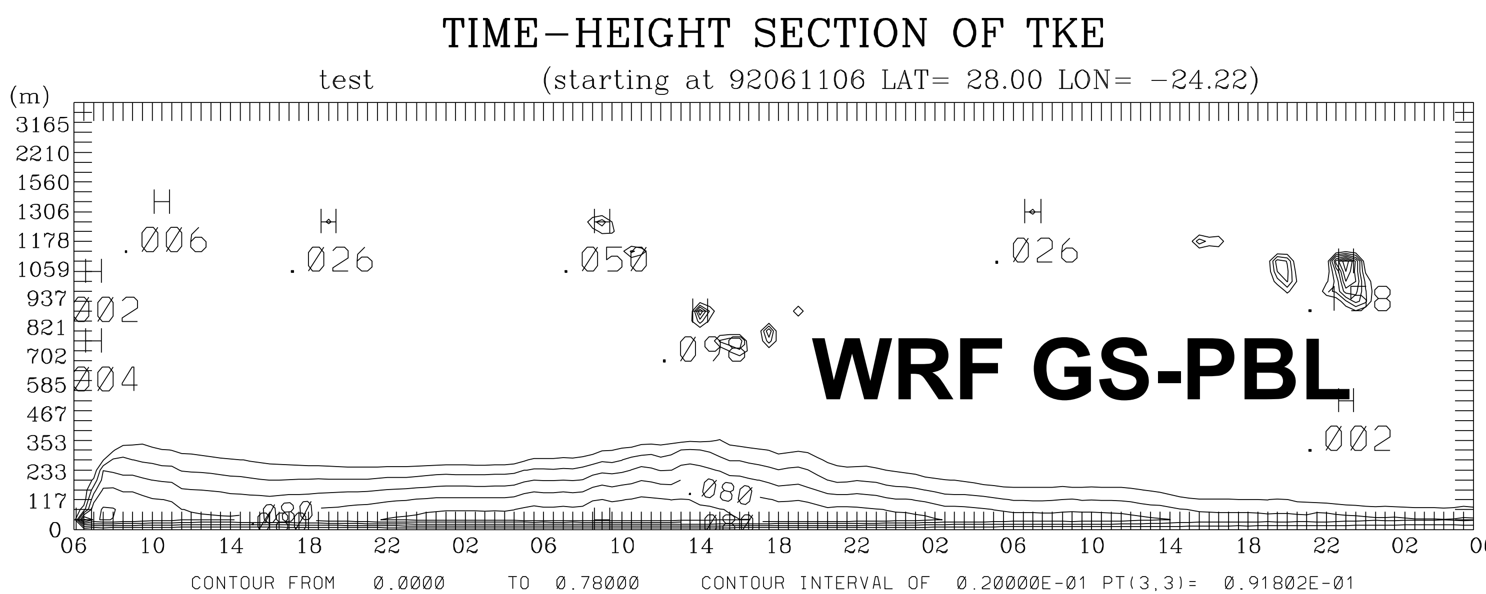
Model-predicted Number of Updrafts and Size





Model-predicted TKE





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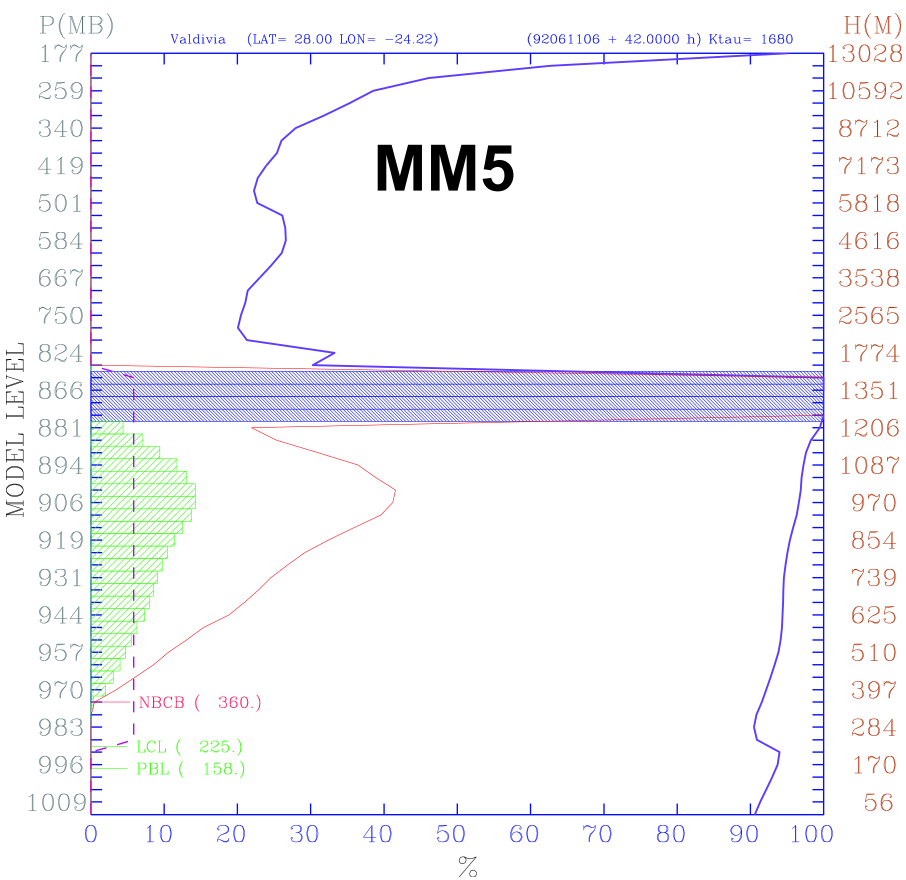
Model-predicted Cloud Fraction at 42 h

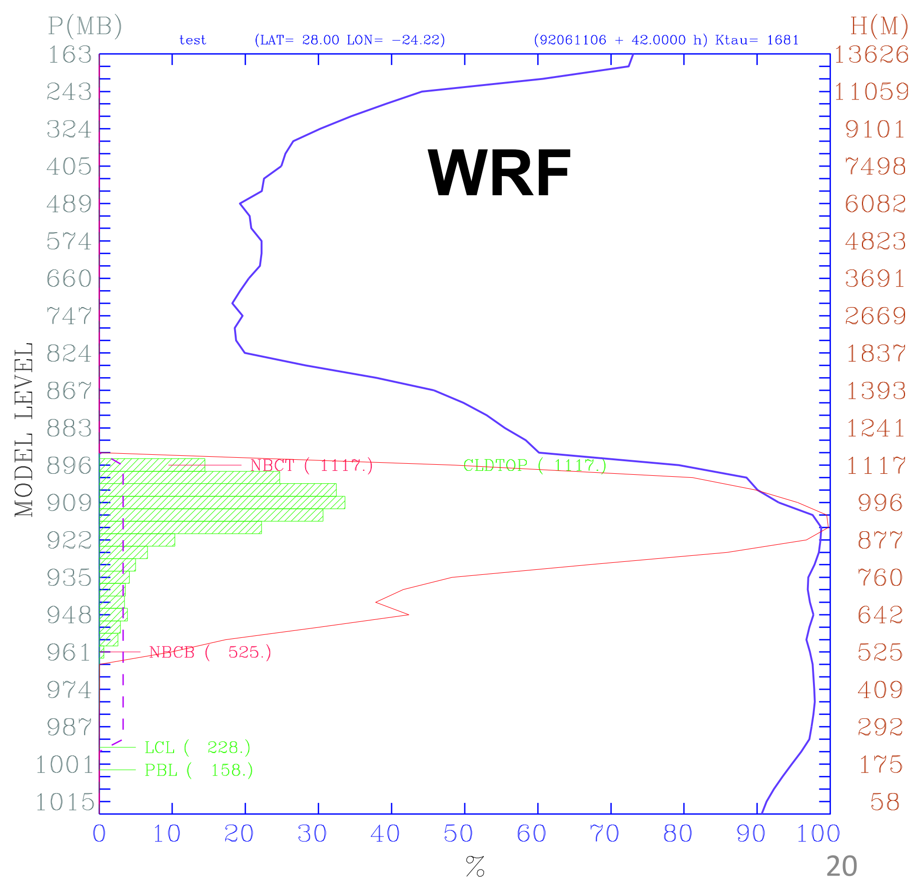
Dashed: Updraft

Shaded: NBC

Red Solid: Effective Cloud

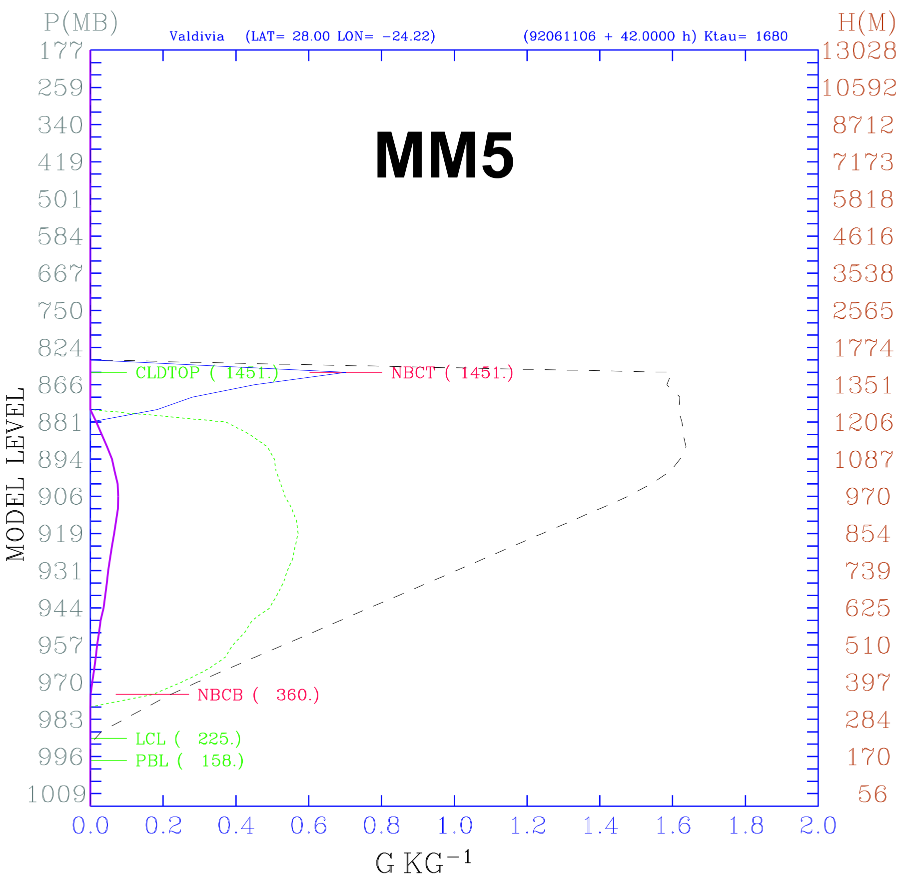
Blue Solid: RH

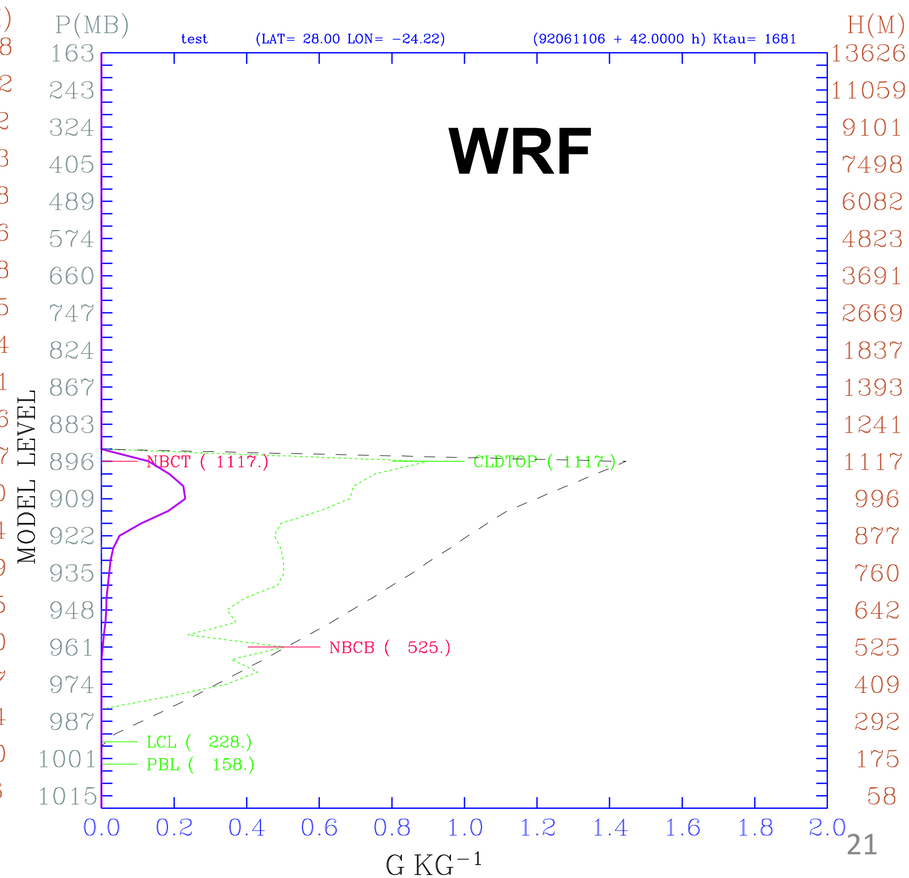




Model-predicted Cloud Water Content at 42 h

Dashed: Updraft
Heavy Solid: NBC avg. to grid
Green dotted: NBC
Thin Solid: Resolved



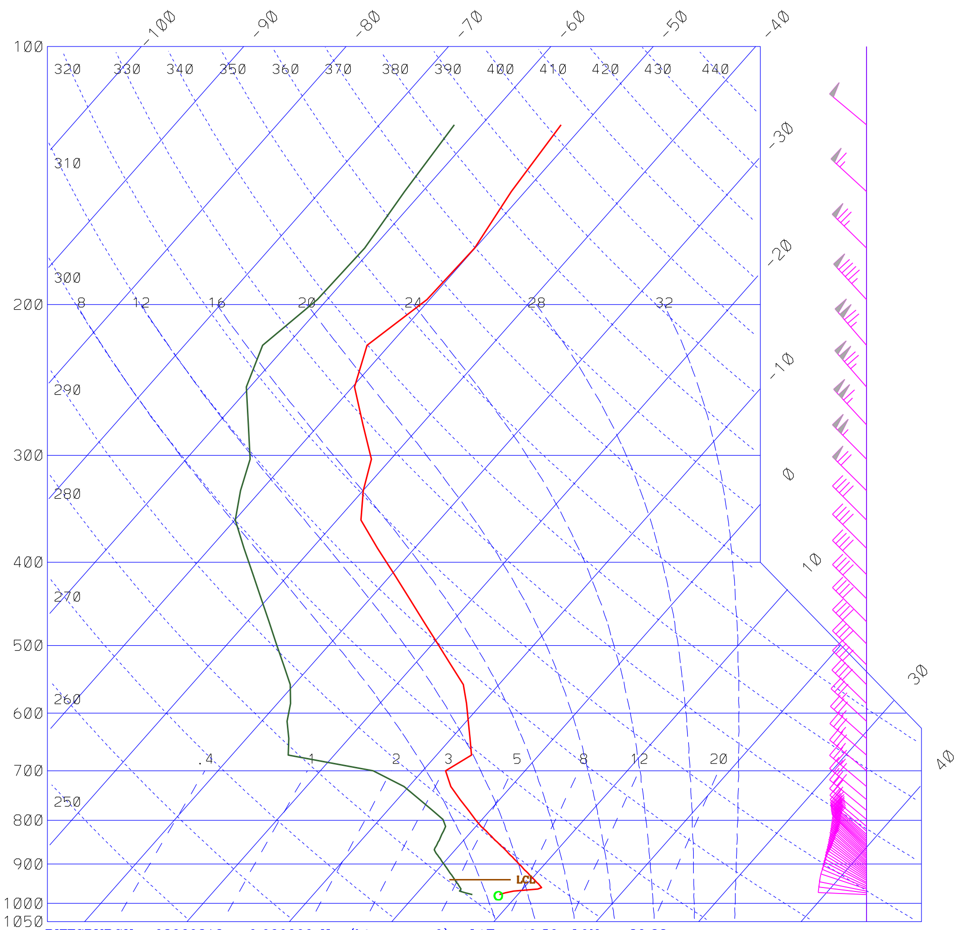


- **Case 2: Continental Shallow Stratocumulus - Pittsburgh, PA: 12 UTC, 8 June 1998 - 12 UTC, 9 June 1998, 24-hour simulation**

Cool northwesterly winds prevailed over western PA beneath the mid-level subsidence inversion associated with the ridge, shallow cloud generation during the daytime and evening hours was dominated by the local surface fluxes.

Initial Condition

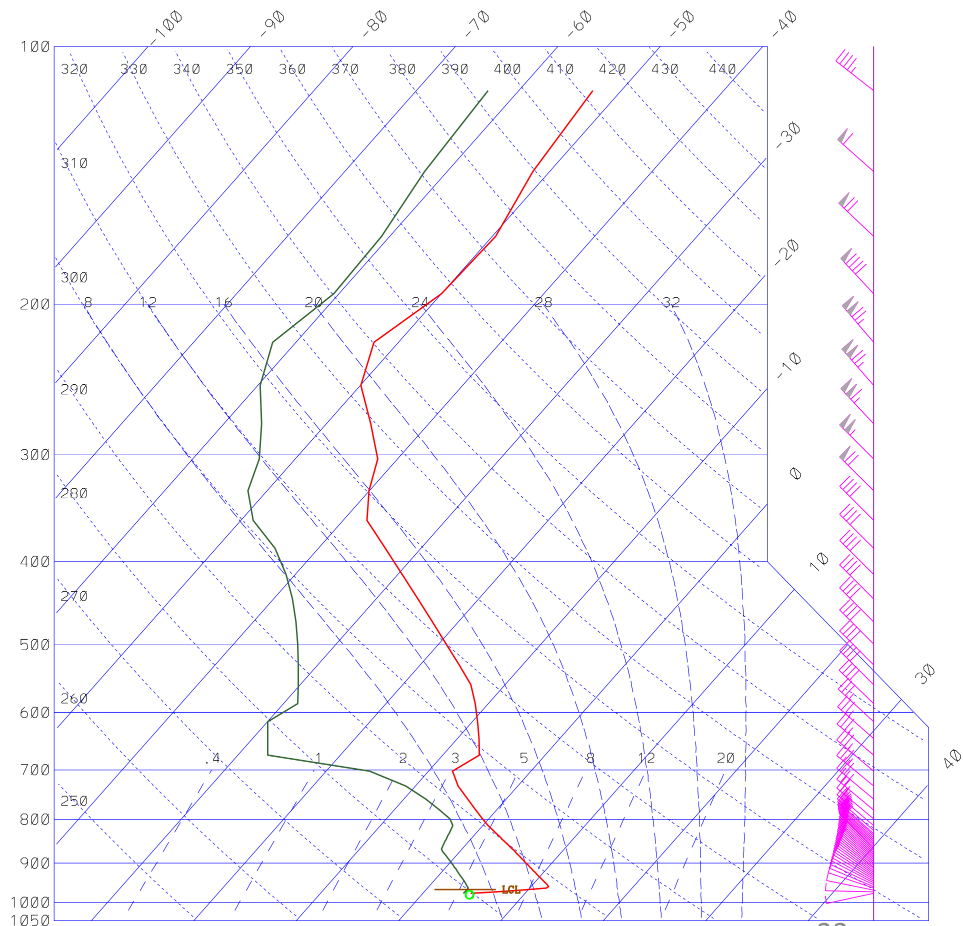
MM5



PITTSBURGH 98060812+ 0.000000 Hr. (ktau= 0) LAT= 40.50 LON= -80.22

1-D MM5 SKEW-T

WRF

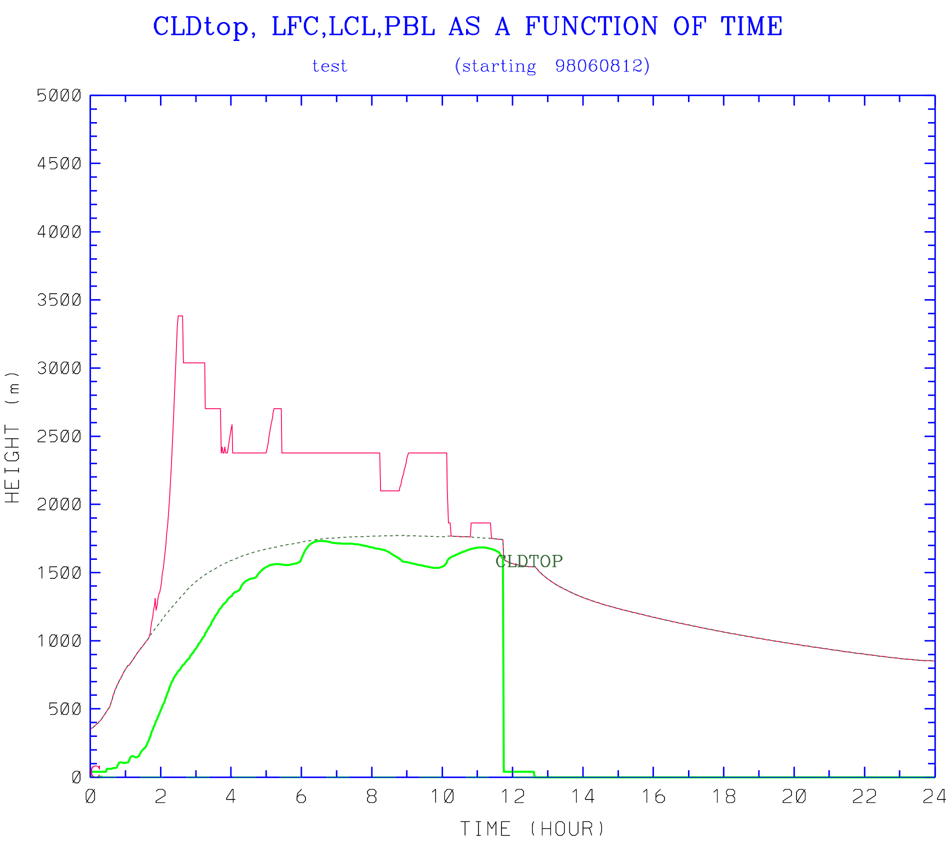


test 92061106+ 0.000000 Hr. (ktau= 0) LAT= 28.00 LON= -24.22

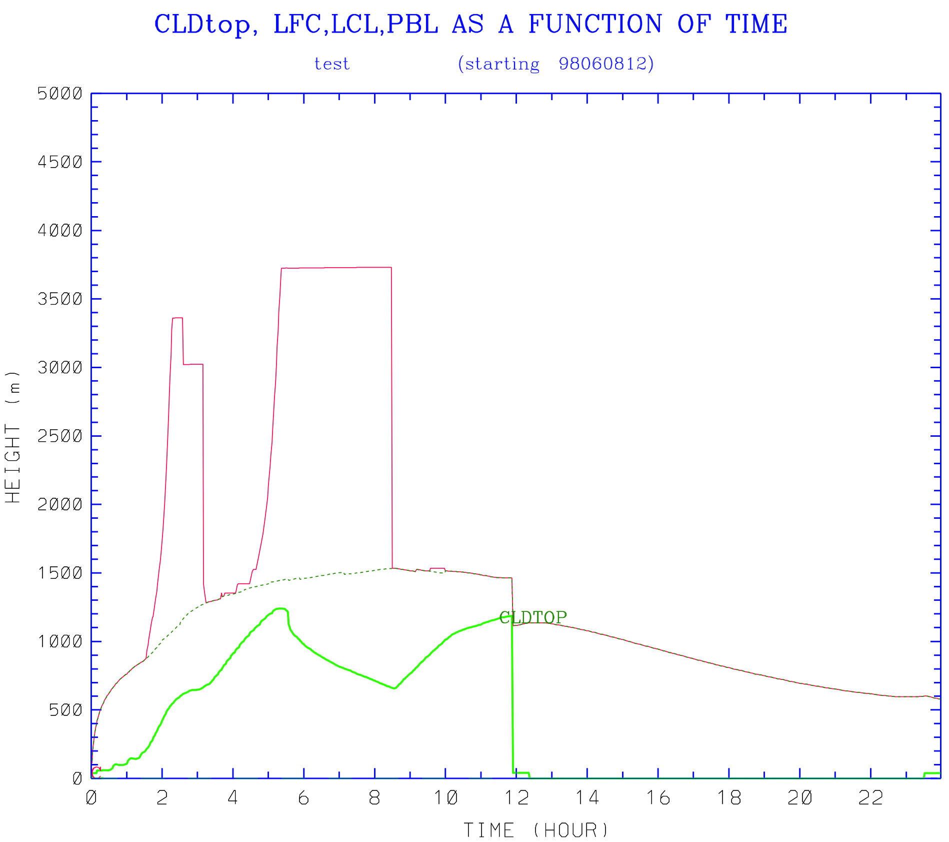
1-D WRF SKEW-T

Model-predicted Cloud Updraft Top, LCL and PBL Depth

MM5

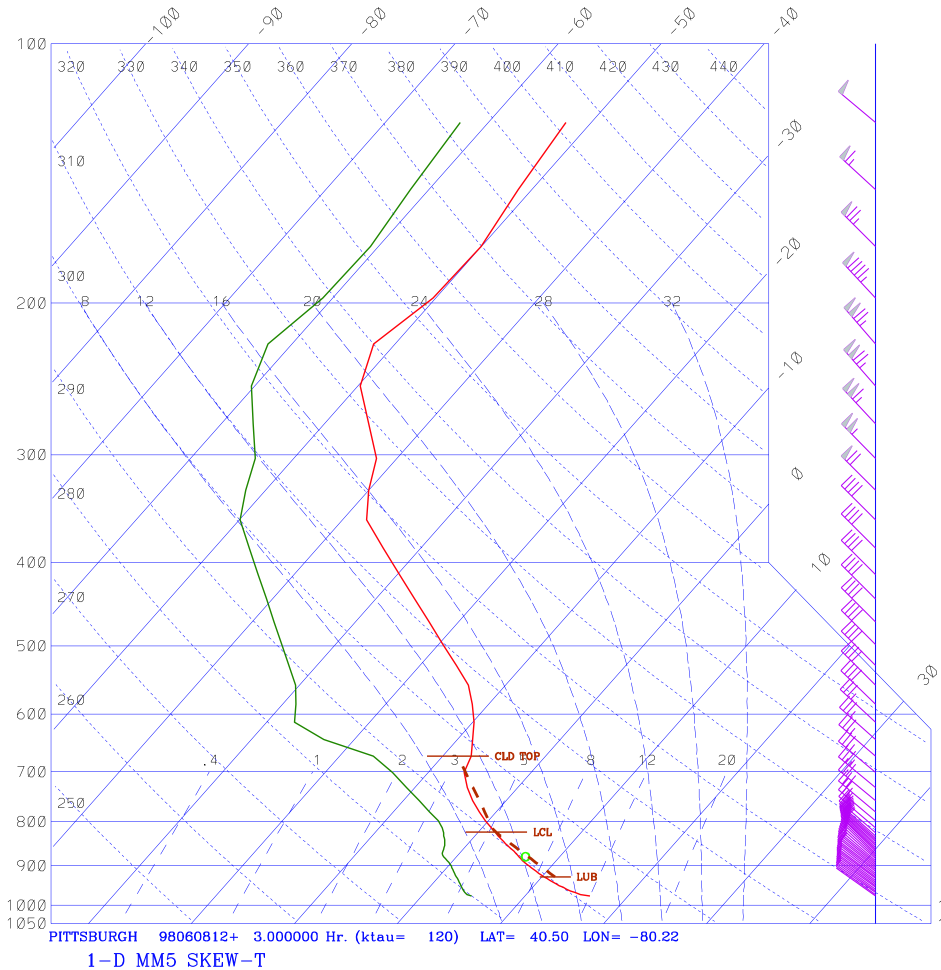


WRF

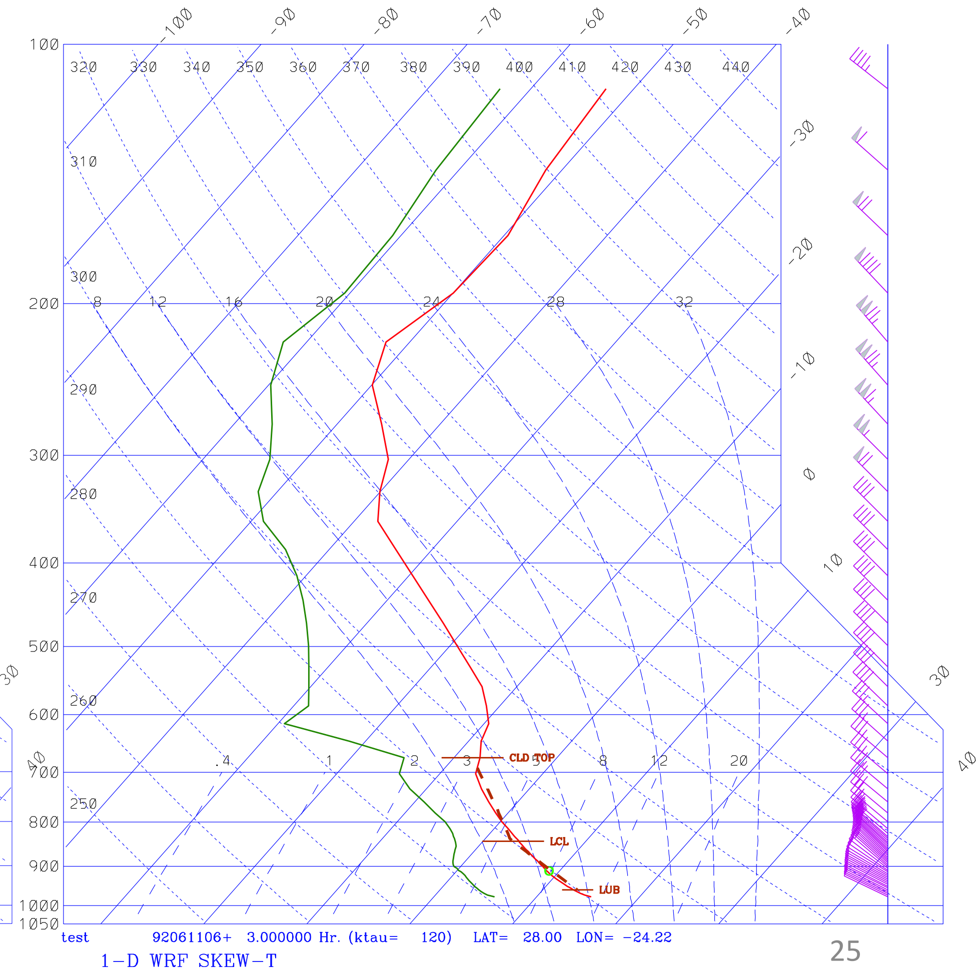


Model-predicted Condition at 3h

MM5



WRF



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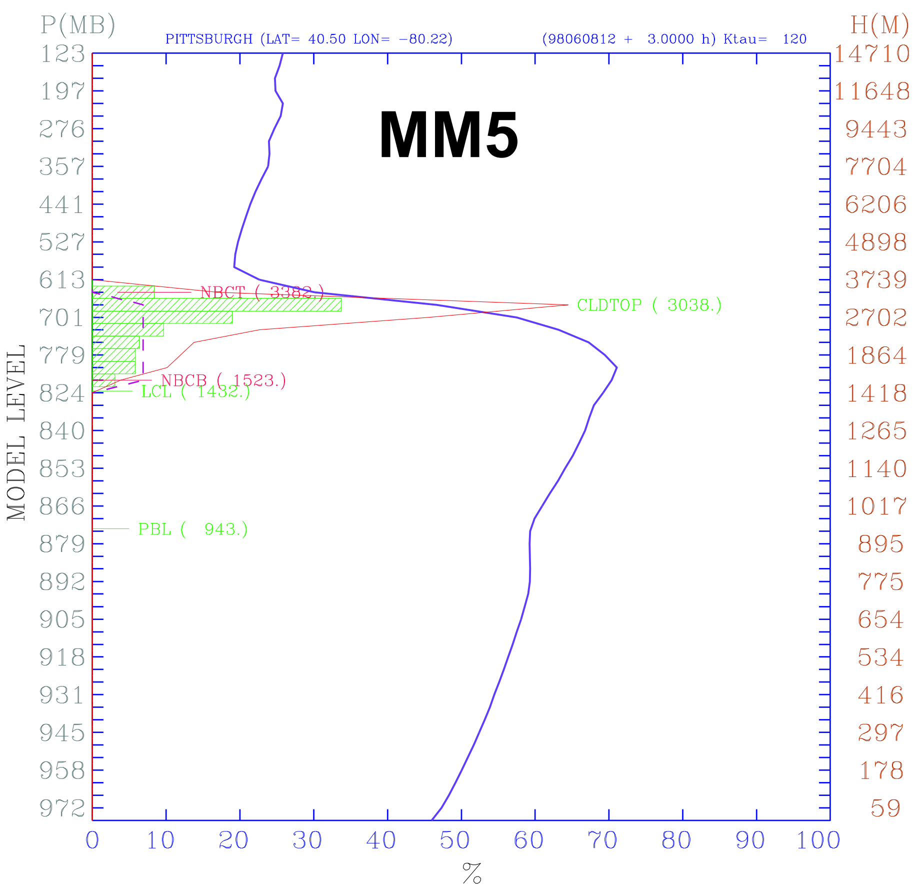
Model-predicted Cloud Fraction at 3 h

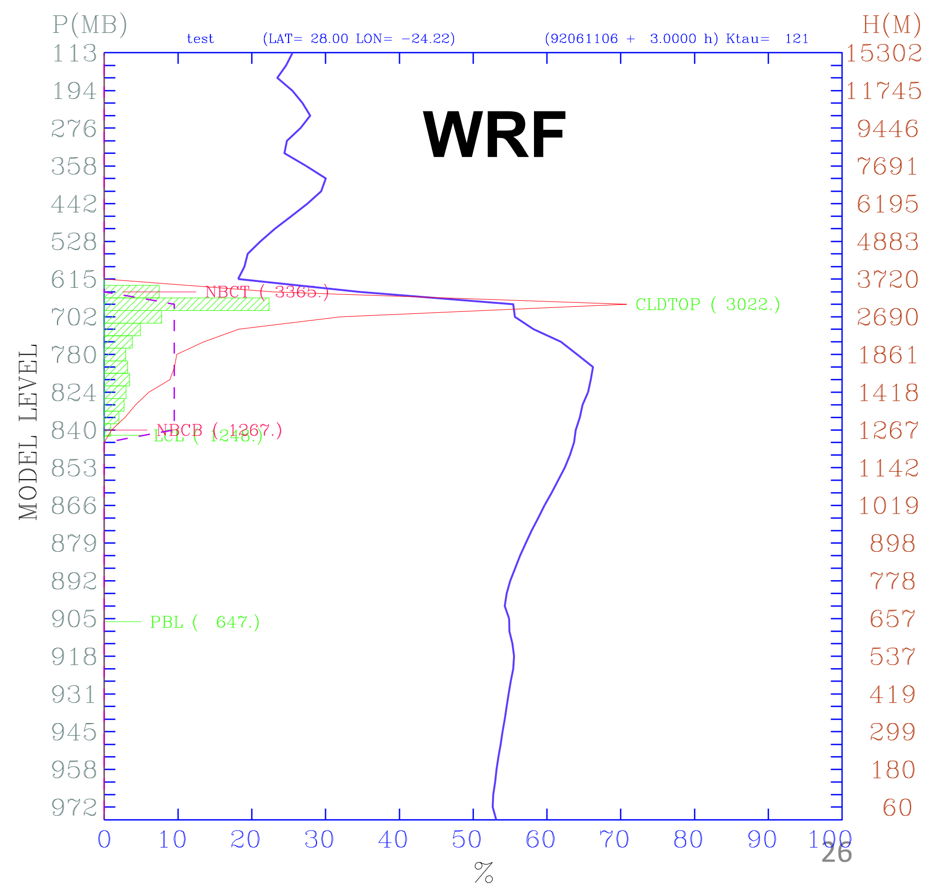
Dashed: Updraft

Red Solid: Effective Cloud

Shaded: NBC

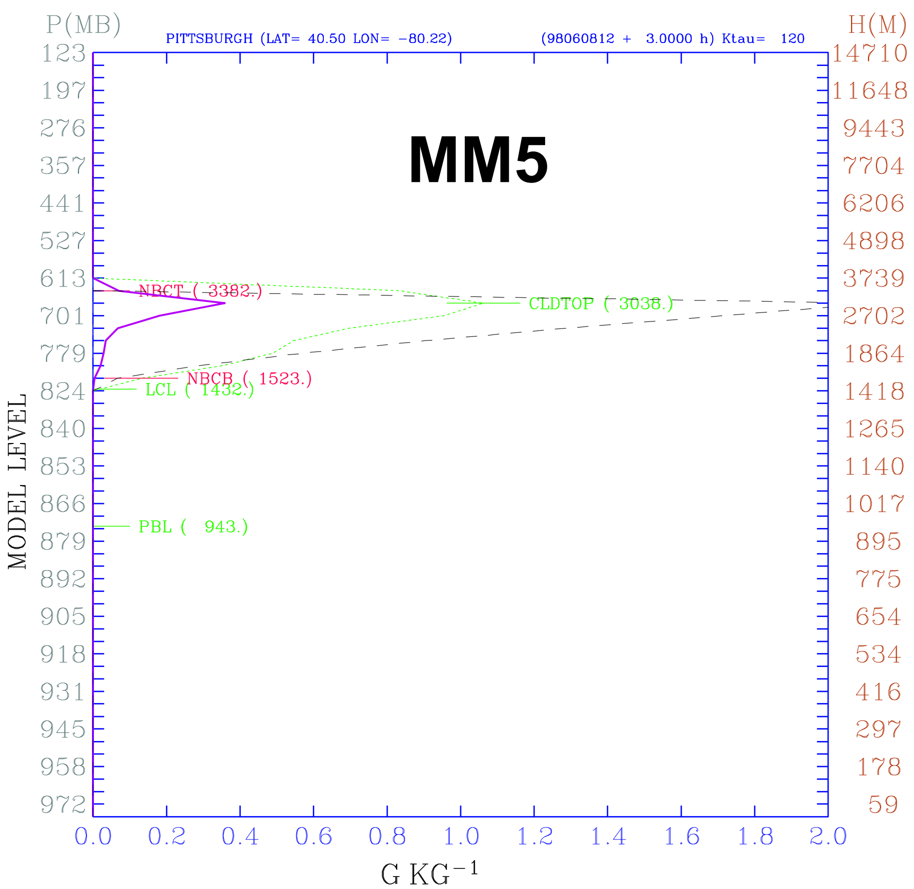
Blue Solid: RH

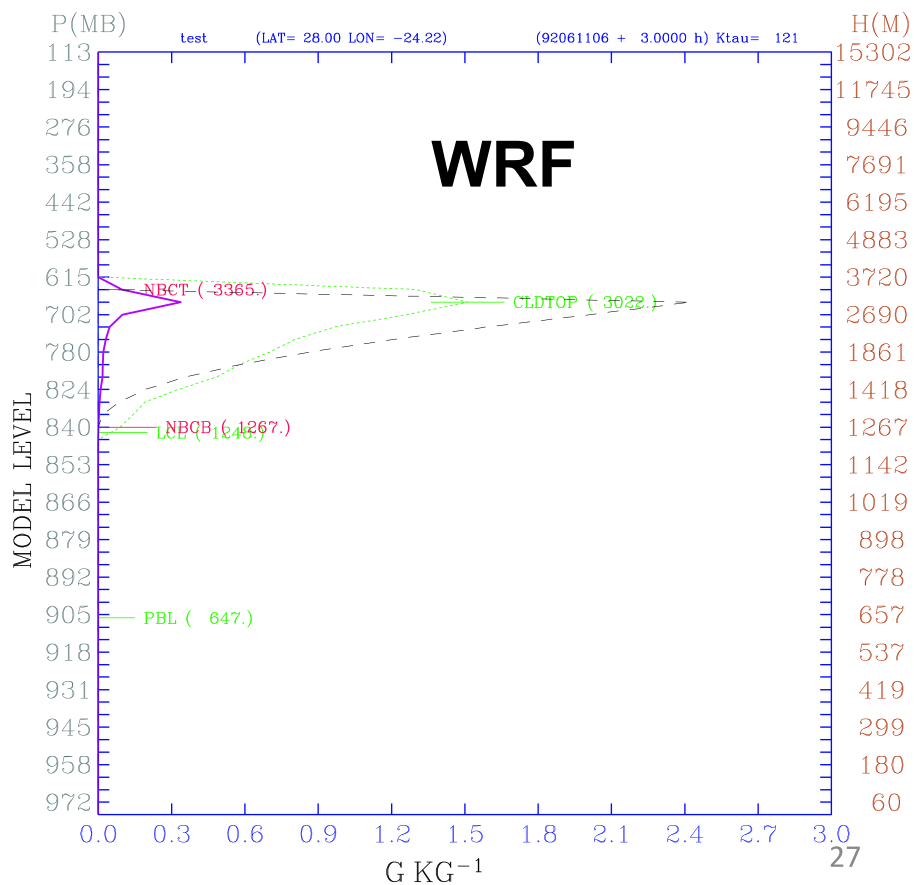




Model-predicted Cloud Water Content at 3 h

Dashed: Updraft
Green dotted: NBC
Heavy Solid: NBC avg. to grid
Thin Solid: Resolved



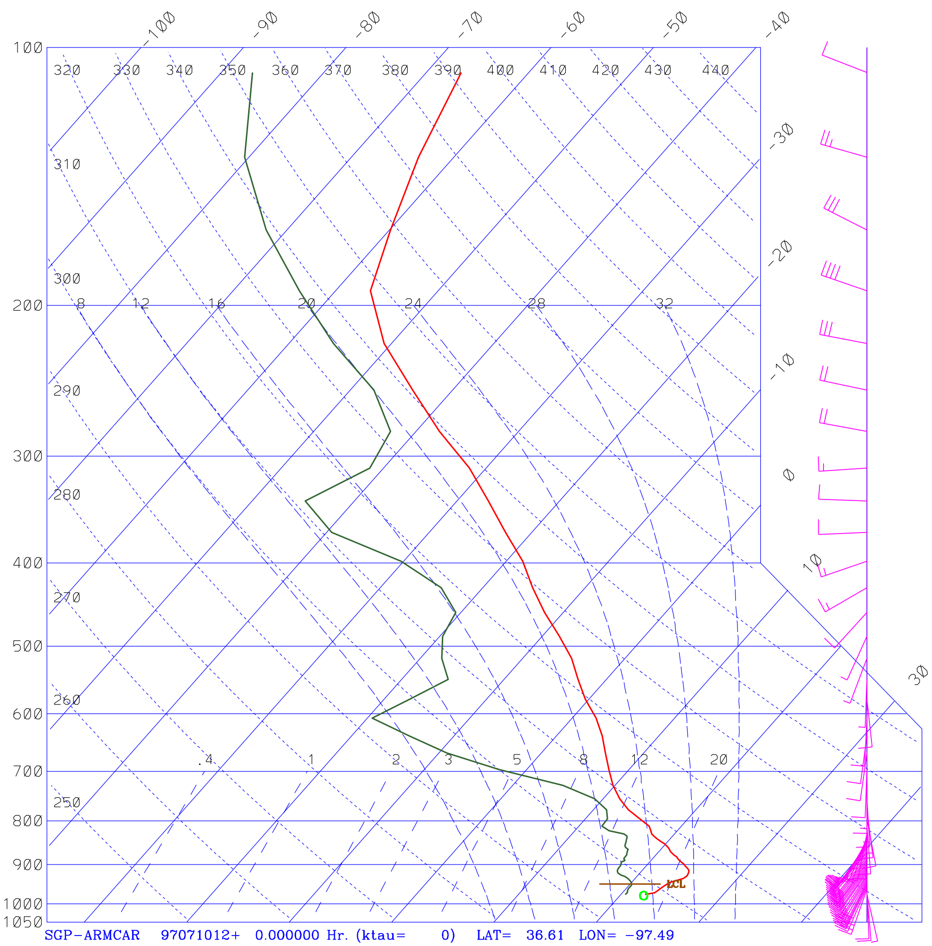


- **Case 3: Continental Deep Convection - SGP ARM CART Site: 12 UTC, 10 July - 12 UTC, 11 July 1997, 24-hour simulation**

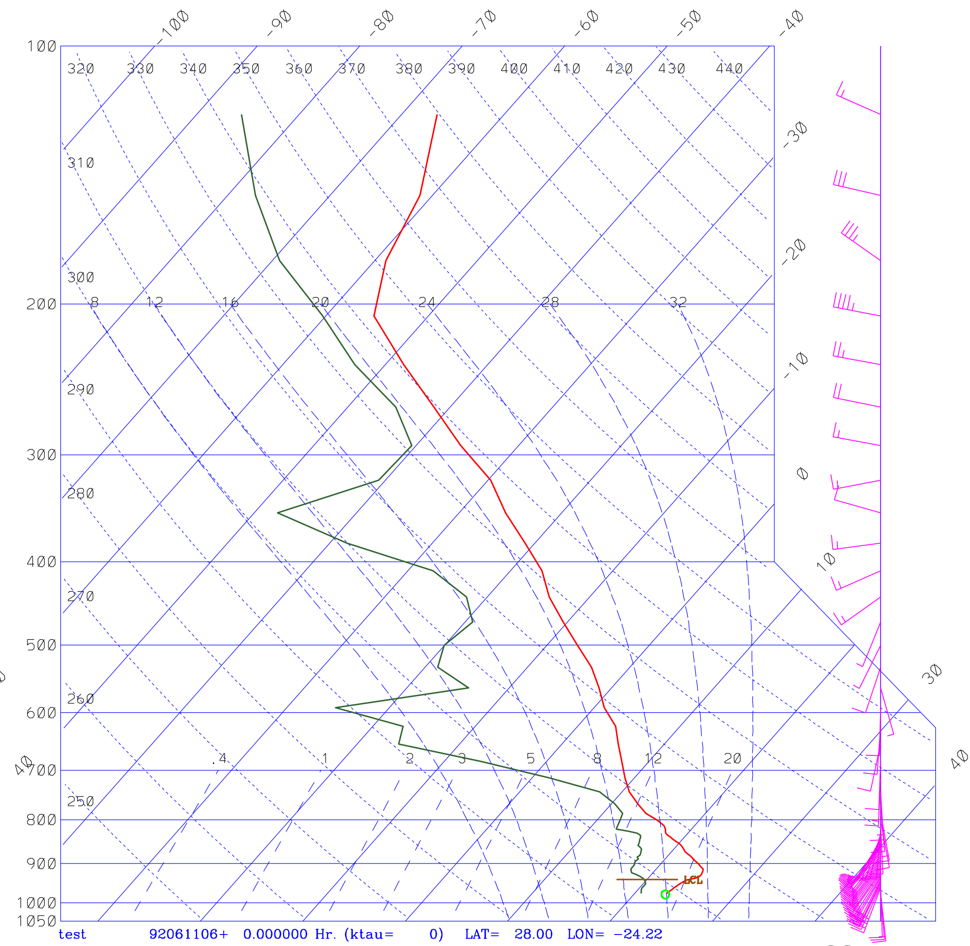
Warm south-southeasterly flow on the west side of the high advected warm moist air from the Gulf of Mexico to the region of interest, which supported deep convection later that day.

Initial Condition

MM5

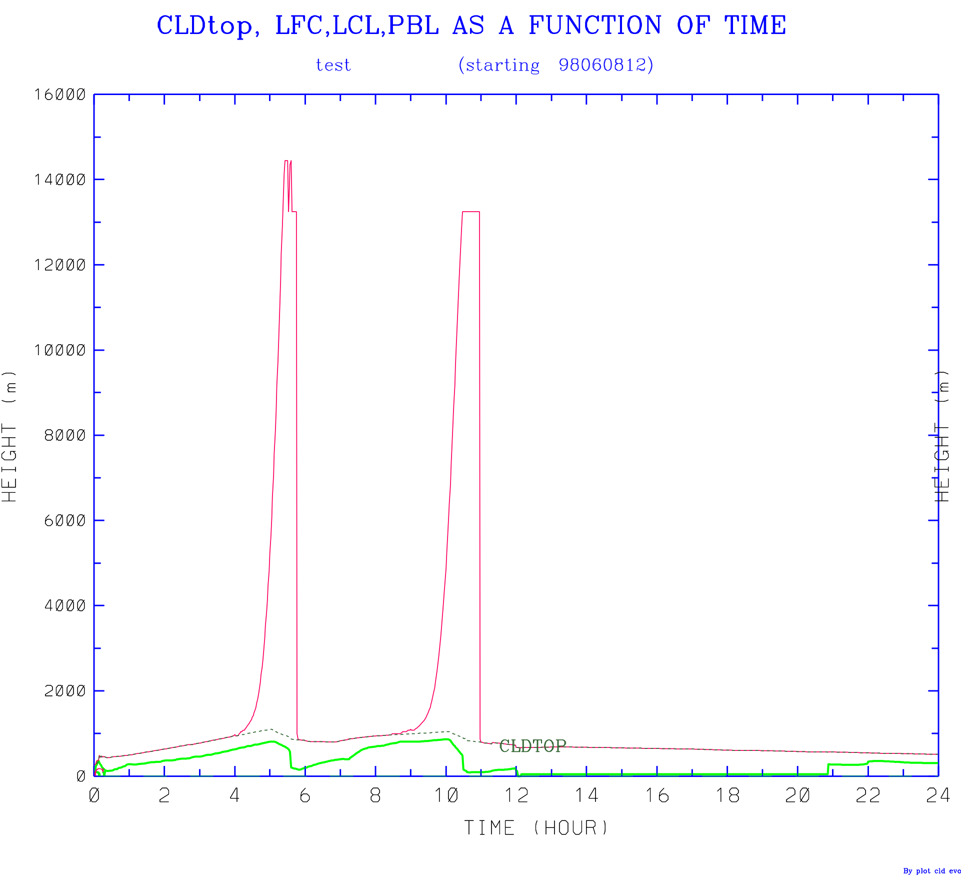


WRF

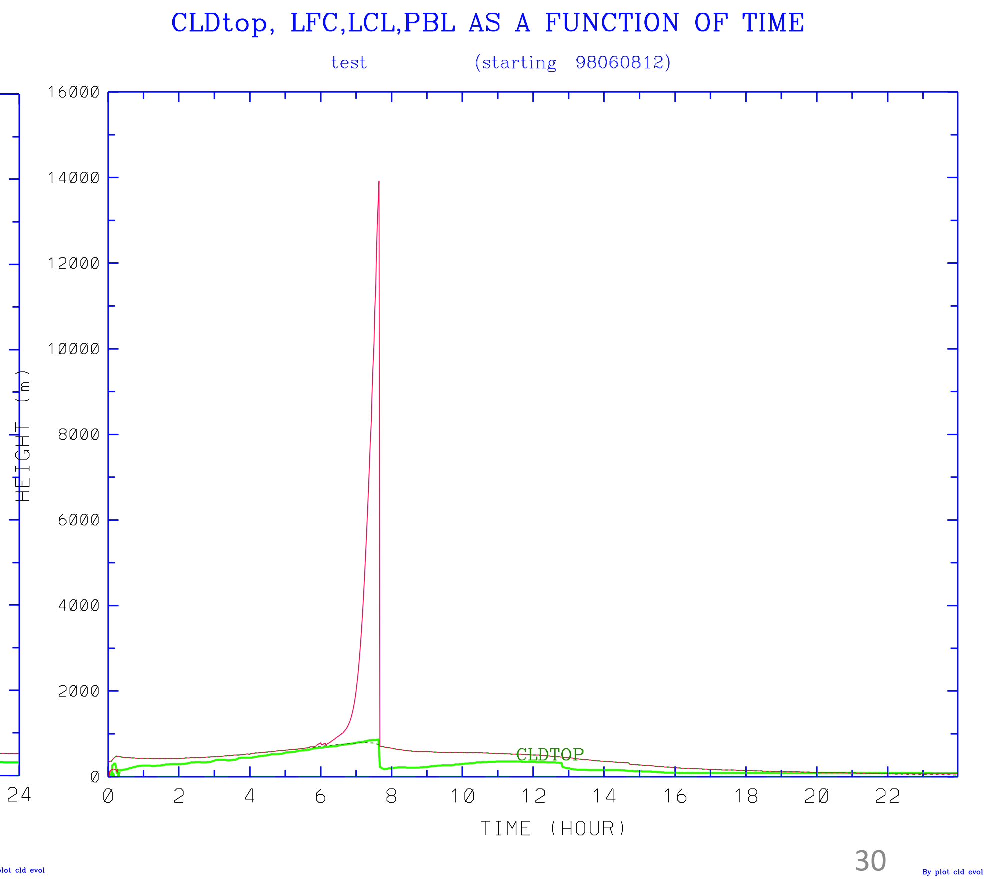


Model-predicted Cloud Updraft Top, LCL and PBL Depth

MM5



WRF



Summary and Conclusions

- **The PSU-Deng SCP scheme that was developed in MM5 is currently being implemented into the WRF modeling system, along with the PSU GS PBL scheme.**

- **Preliminary 1-D testing based on three convective cases showed that WRF with PSU-Deng SCP is able to reproduce the majority features of the MM5 results, including the cloud depth, fraction and cloud water.**

- **Future work include 1) addition of NBC advection terms, 2) extend to use with other PBL schemes, both TKE and none-TKE based; 3) 3-D evaluation; 4) comparison with existing shallow convection scheme in WRF; and 5) update and further improvement (e.g., allow more sophisticated microphysics, aerosol, tracer mixing, etc.).**

Acknowledgement

- **This research is supported by U. S. Environmental Protection Agency.**

Supplementary Slides

Shallow cloud model description- Convective-cloud sub-model

Parcel buoyancy equation used in KF scheme, except

$$\frac{dz_T}{dt} = 0.2 \cdot W_{max}$$

Shallow Conv. Scheme:	20-30 min.
KF scheme:	instantaneous

Source Layer:

Upper part of the PBL, a function of cloud width,
Min 10 mb to Max. 60 mb when transfer to K-F scheme

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Shallow cloud model description- Formation of NBCs

$$S_a = -\tilde{w}\frac{\partial a}{\partial z} + \frac{R_{ud}}{M_L}$$

$$S_l = \left(\frac{\partial l}{\partial t} - l_c S_a\right) \Big/ a$$

where $$\frac{\partial l}{\partial t} = -\tilde{w}\frac{\partial l}{\partial z} + \frac{R_{ud}}{M_L} l_u$$

R_{ud}	Updraft detrainment rate of (kg cloudy air/s)
M_L	Mass of air in the grid cell at a specific layer
$\tilde{w}$	Convective-induced subgrid-scale subsidence
l_u	Cloud liquid/ice content in updrafts
$l = al_c$	Grid-averaged cloud water/ice

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Shallow cloud model description- Dissipation of NBCs

Dissipation by evaporation:

$$D_a = -\frac{a}{l_c} K(q_s - q)$$

K: Diffusion coefficient ($10^{-5} s^{-1}$)

q: Water vapor mixing ratio

q_s: Saturation mixing ratio

Depletion by vertical mixing:

$$D_{mix} = \frac{1}{a}\frac{\partial}{\partial z}[(K_v + K_r)\frac{\partial(al_c)}{\partial z}]$$

K_v: Turbulent transport coefficient determined by TKE

K_r: Diffusion coefficient determined by cloud-top radiative forcing

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Shallow cloud model description- Dissipation of NBCs

Depletion by precipitation:

$$D_{pre} = -C_1(l_c - l_{cr}) - C_2(\rho q_r)^{0.25} l_c$$

l_{cr}	Critical value for liquid/ice water content at which auto conversion is activated (0.5 g/kg)
ρ	Air density
q_r	Rain water mixing ratio
C_1, C_2	Dimensional constants

Depletion by ice settling:

$$D_{ics} = -C_3(\rho l_c)^{1.16} / a$$

Ice settling process when $T < 0^{\circ}C$

C_3: Dimensional constant

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Shallow cloud model description- Dissipation of NBCs based on Randal 1980 and Del Genio et al. (1996)

Depletion by CTEI:

$$D_{CTEI} = -10^{-4} \frac{r - r_{\min}}{r_{\max} - r_{\min}} l_c$$

$$r = \Delta h / L\Delta(q + l_c)$$

$$r_{\min} = \frac{\kappa}{\beta} \quad (\approx 0.23)$$

$$r_{\max} = \frac{(1+\gamma)[1+\kappa(1-\delta)]}{2+\gamma[1+\kappa(1+\delta)]} \quad (\approx 0.7)$$

$$\kappa = \frac{C_P T}{L}$$

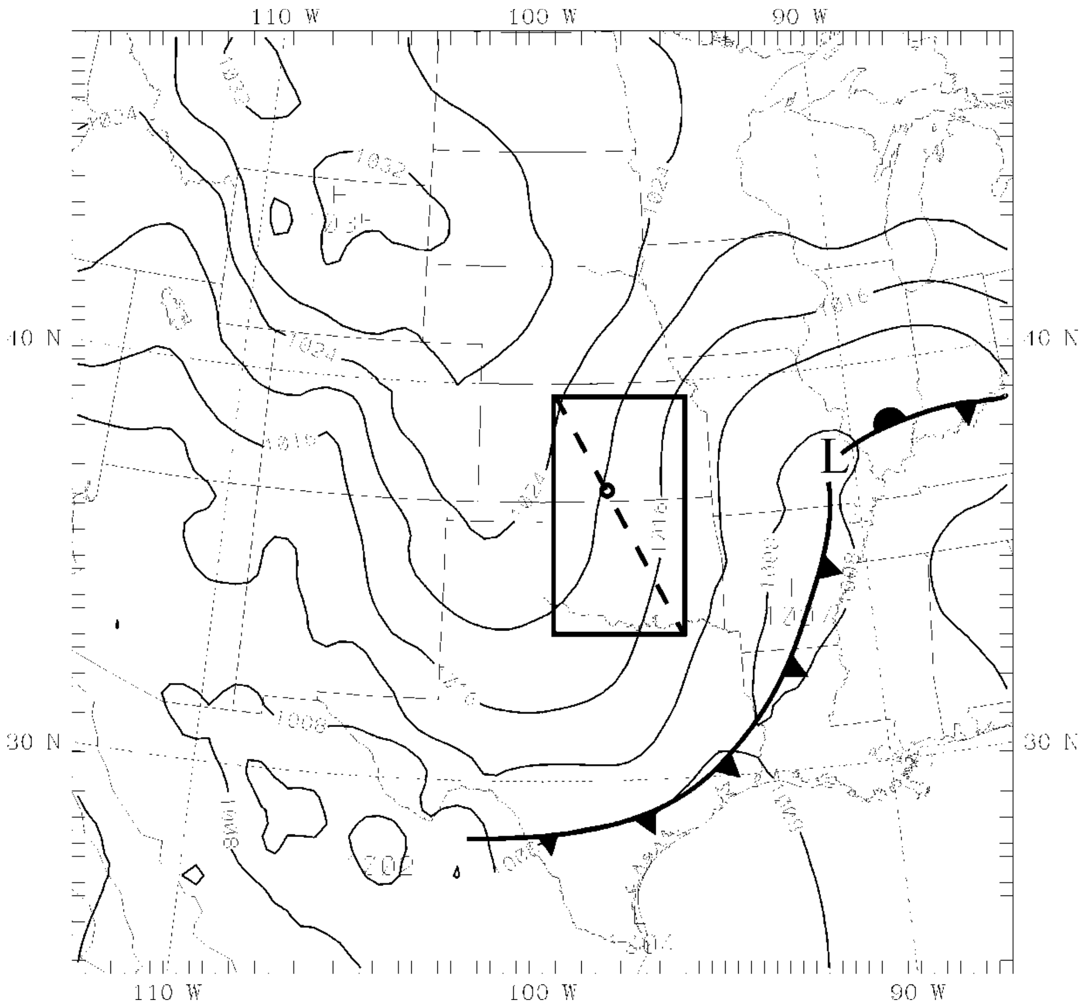
$$\gamma = \frac{L}{C_P} \left(\frac{\partial q_S}{\partial T}\right)_P$$

$$\beta = \frac{[1+\gamma\kappa(1+\delta)]}{1+\gamma}$$

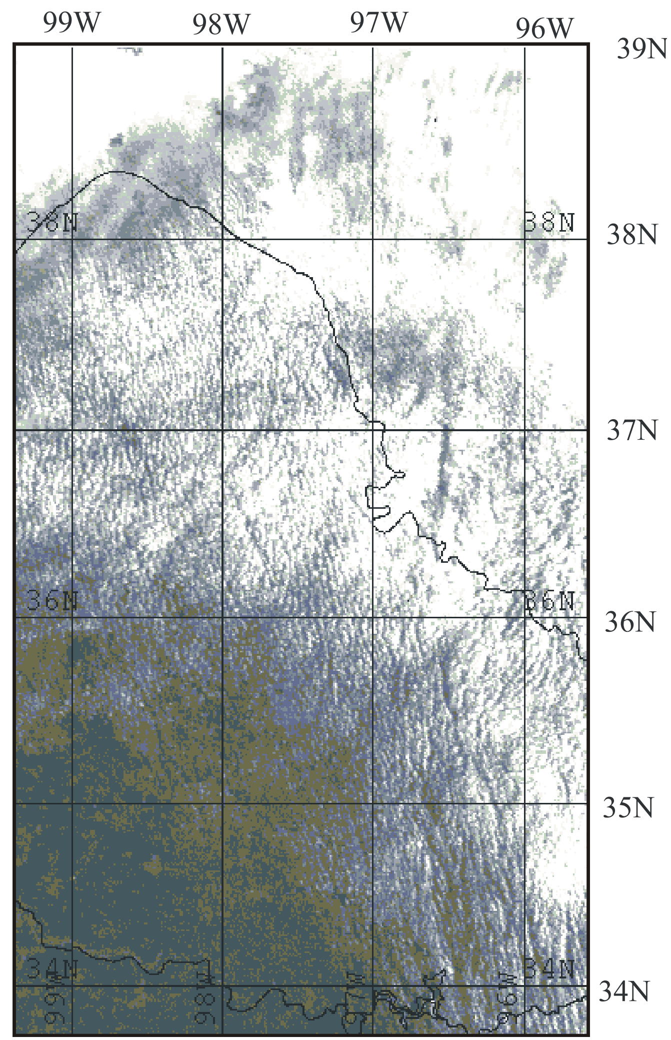
$$\delta = 0.608$$

Effect of PSU SCP

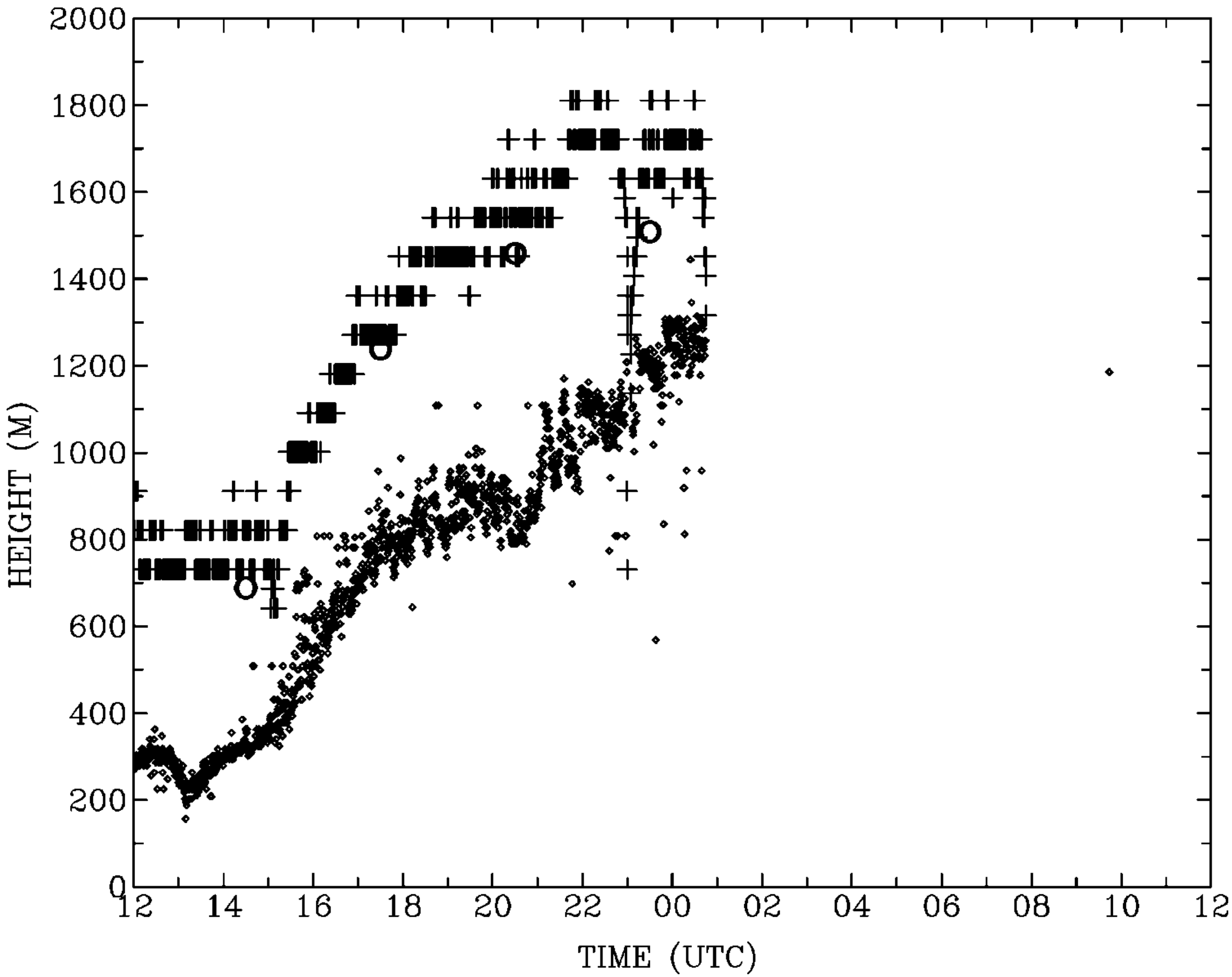
Sea Level Pressure Analysis 1997.04.12.00Z +0h



Satellite Image 1997.04.12.1709Z

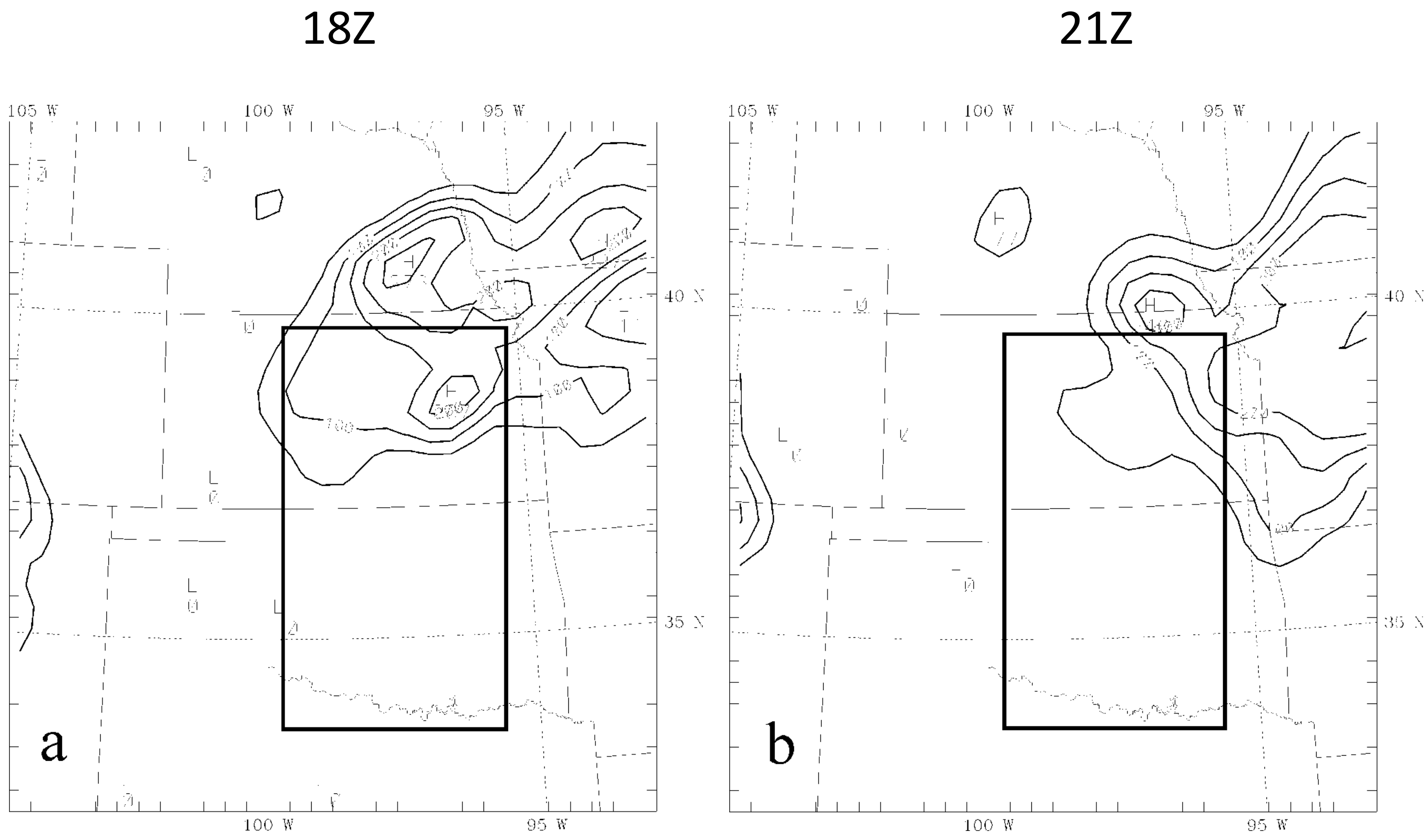


Observed cloud top, base and PBL top



MM5 simulated cloud water content (No shallow convection)

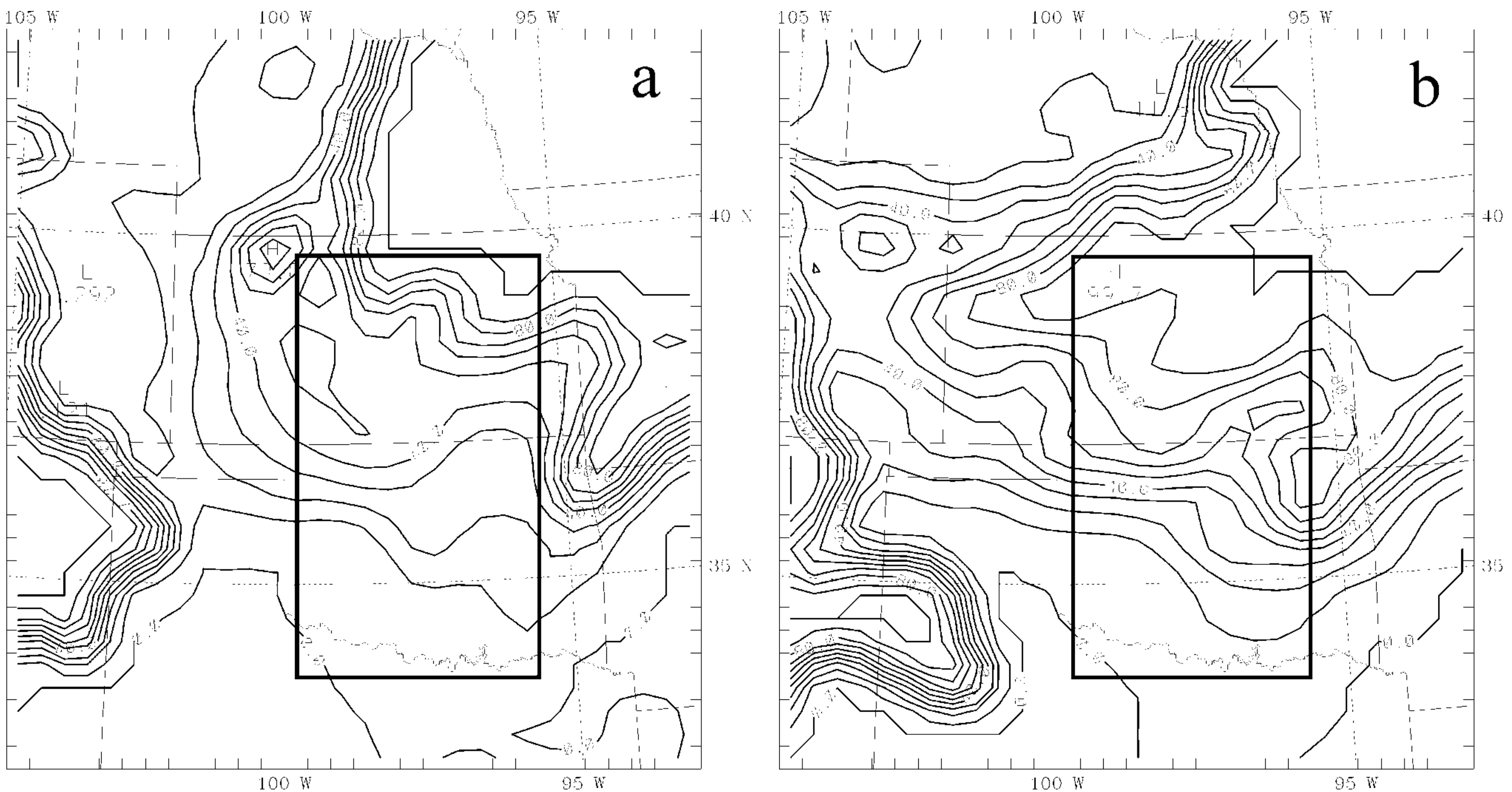
1997.04.12



MM5 simulated cloud fraction (with shallow convection)

1997.04.12

18Z 21Z



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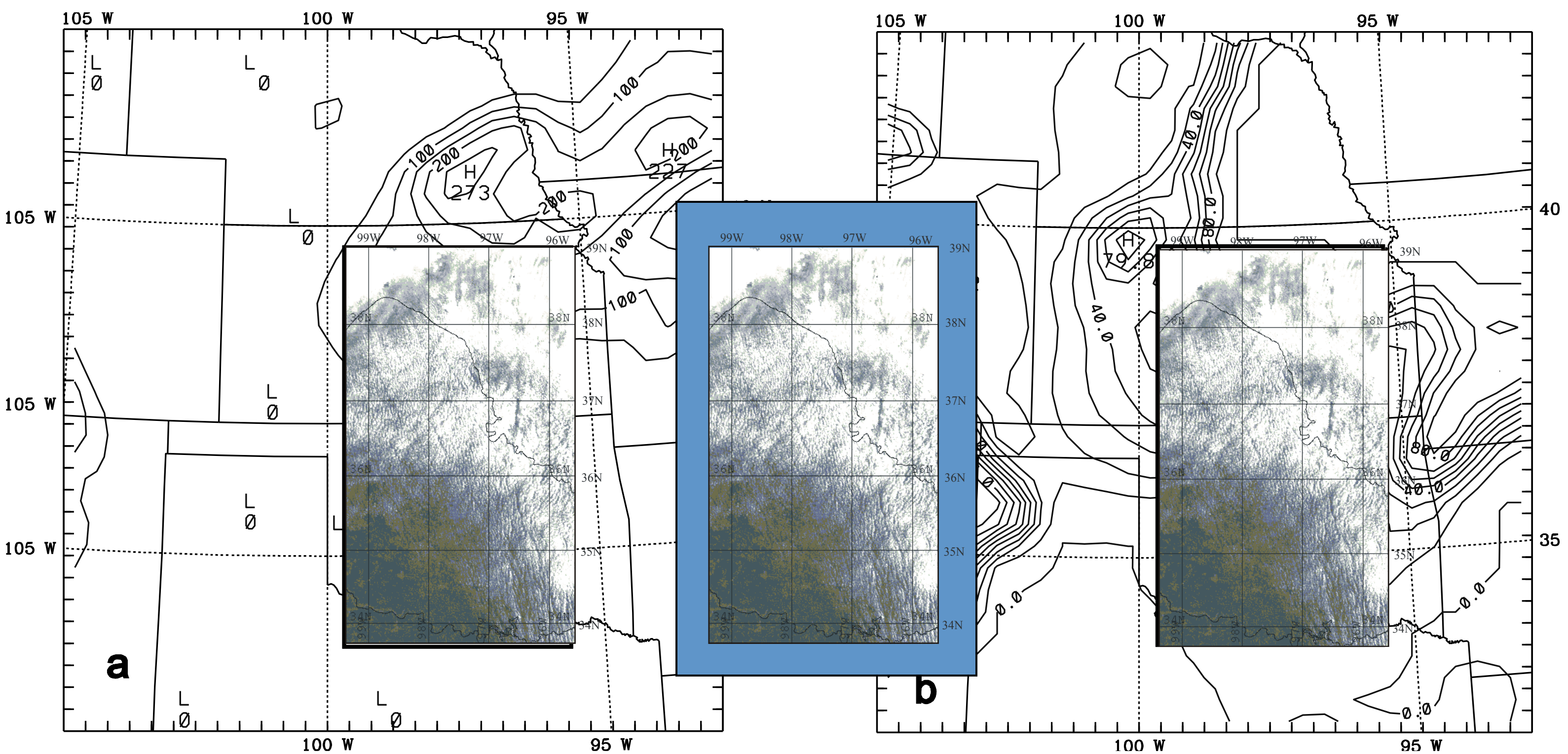
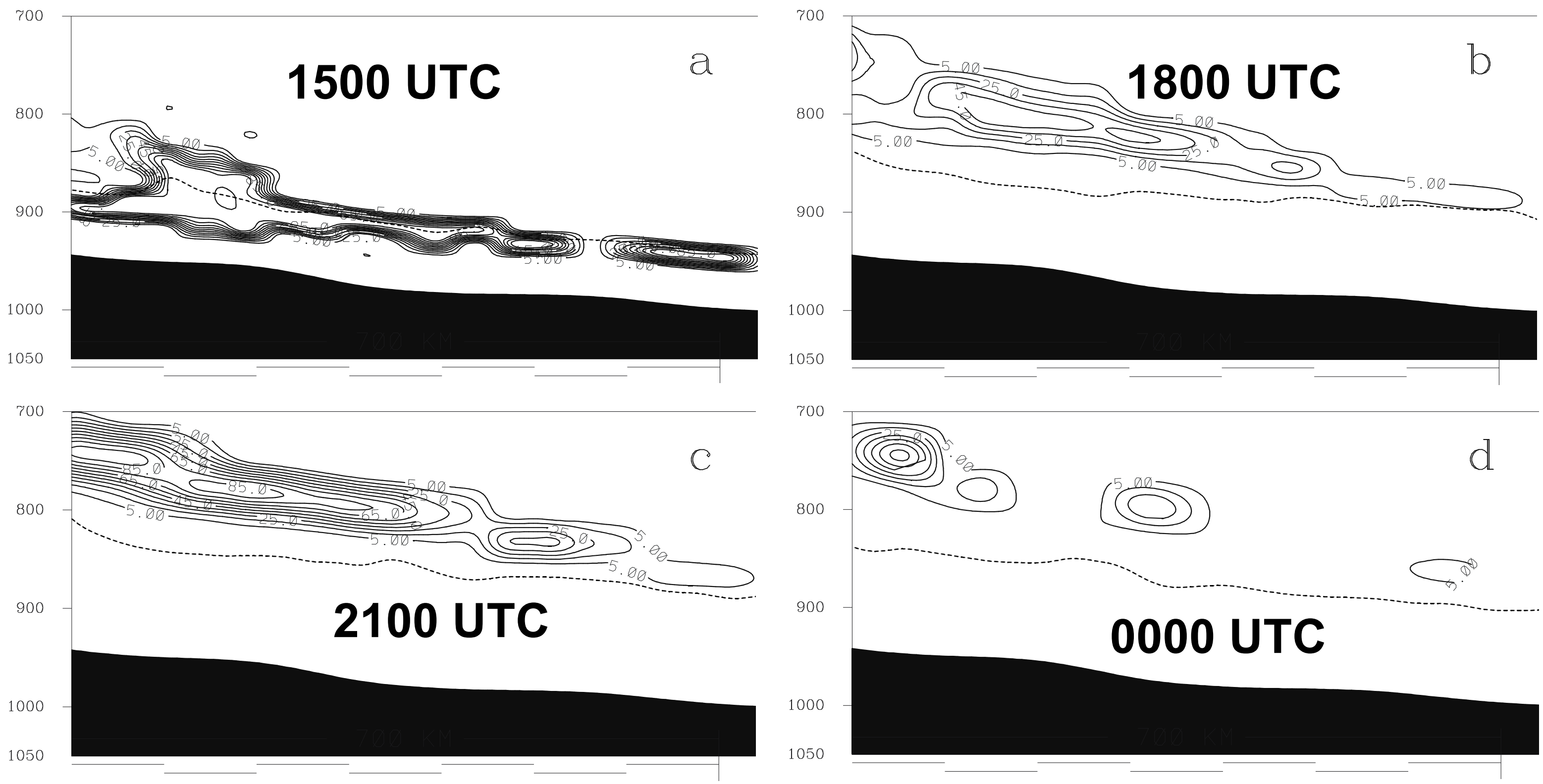
Effect of PSU SCP

MM5 Cloud Water Content **MM5 Cloud Fraction**

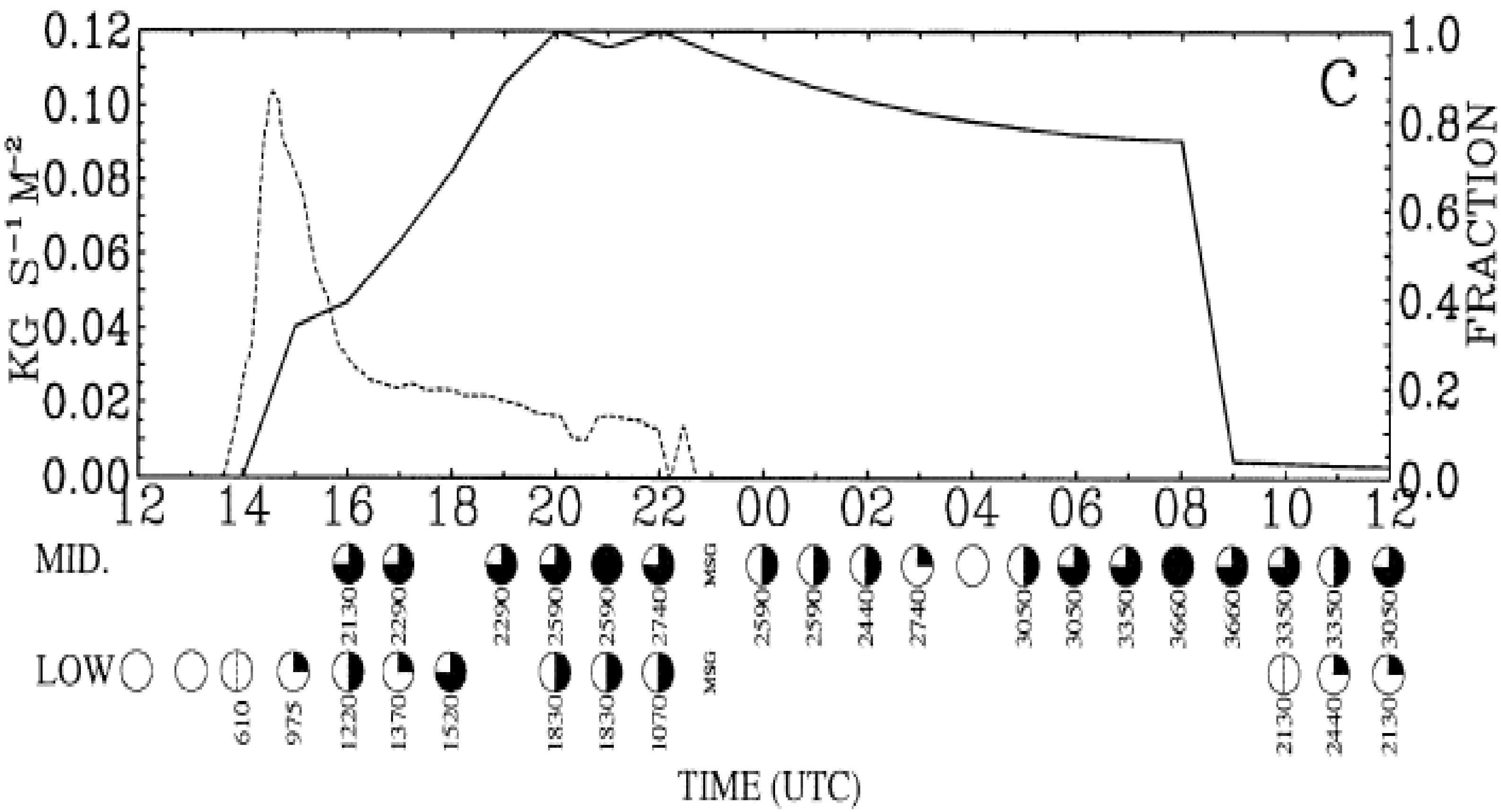


The 3-D model sensitivity to SCP. a) MM5-predicted liquid/ice water content (g kg^{-1}) of explicit cloud (scaled by 10000), at 1 km AGL at 1800 UTC 12 April 1997 in the experiment without the PSU shallow convection scheme. Contour interval is 0.005 g kg^{-1}. b) MM5-predicted fractional cloud area (%) for low clouds predicted with the PSU shallow convection scheme at the same time and height level. Contour interval is 10%. The rectangular area corresponds to the area covered by the satellite image.

Effect of PSU SCP
MM5-Predicted Cloud Fraction



MM5 north-south cross section of predicted fractional cloud area (%) versus pressure (hPa) with the PSU shallow convection scheme: a) 1500 UTC, b) 1800 UTC, c) 2100 UTC (this and the preceding from 12 April 1997), d) 0000 UTC 13 April 1997. Contour interval is 10%. Dashed curve is the MM5-predicted PBL depth.


0.12
0.10
0.08
0.06
0.04
0.02
0.00
KG S^{-1} M^{-2}
1.0
0.8
0.6
0.4
0.2
0.0
FRACTION
C
12 14 16 18 20 22 00 02 04 06 08 10 12
MID.
2130 2290 2290 2590 2590 2740 MSG 2590 2590 2440 2740 3050 3050 3350 3660 3600 3350 3350 3050
LOW
610 975 1220 1370 1520 1830 1830 1070 MSG 2130 2440 2130
TIME (UTC)