Numerical Modeling of Atmospheric Processes Associated with Wildland Fires

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Part I

The Dynamics of Fire-Generated Dry Convection: Fundamental Processes and Complicating Factors

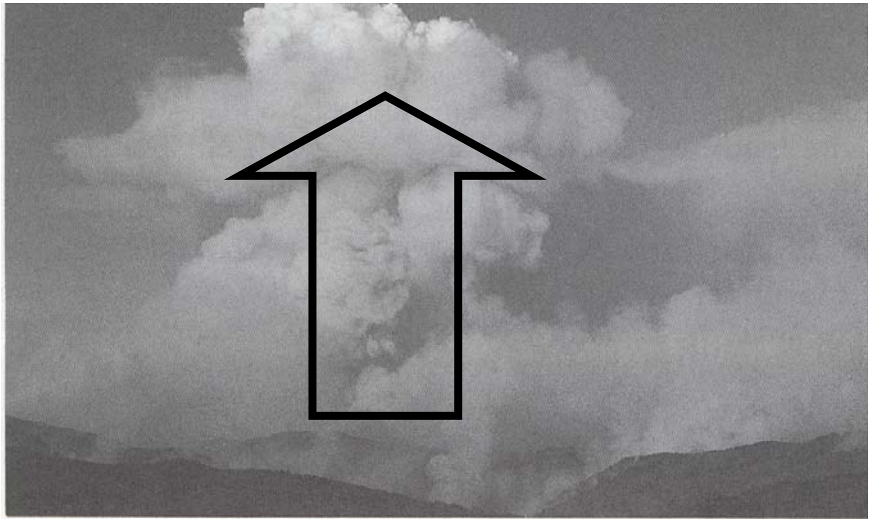
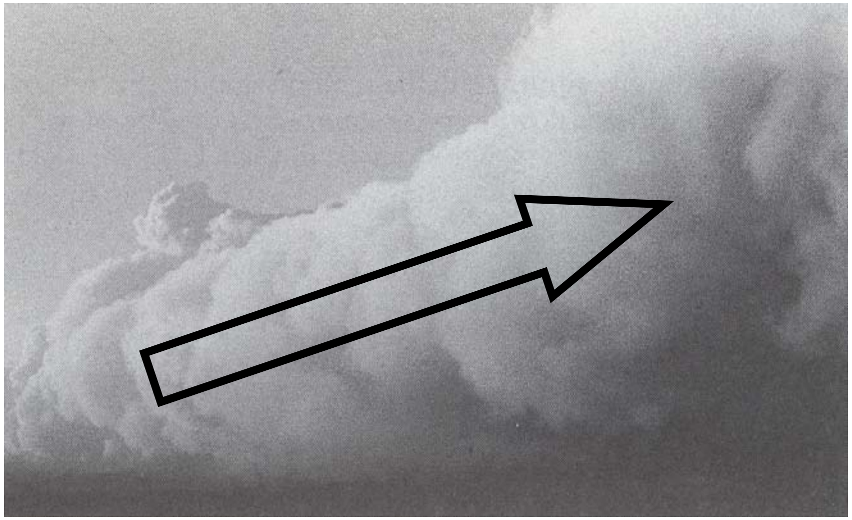
PhD Dissertation

Graduated North Carolina State University Aug 2009

Advisor: Dr. Matt Parker

Motivation

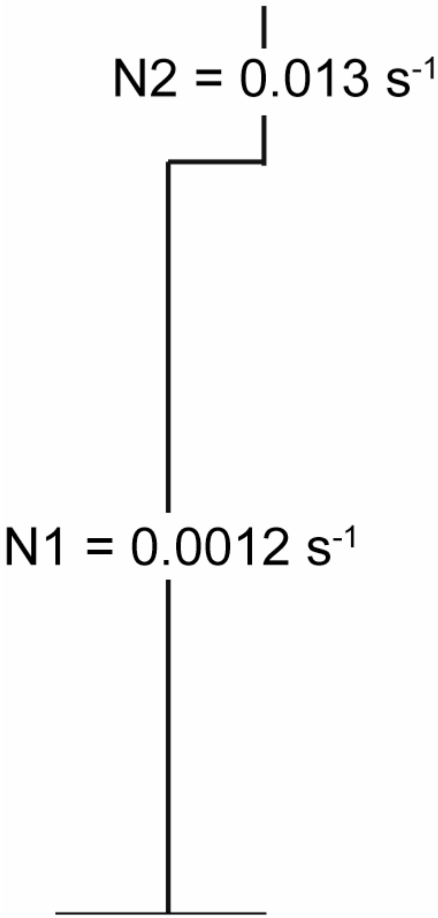
- The fundamental processes that yield different types of fire-generated convection are not well understood.

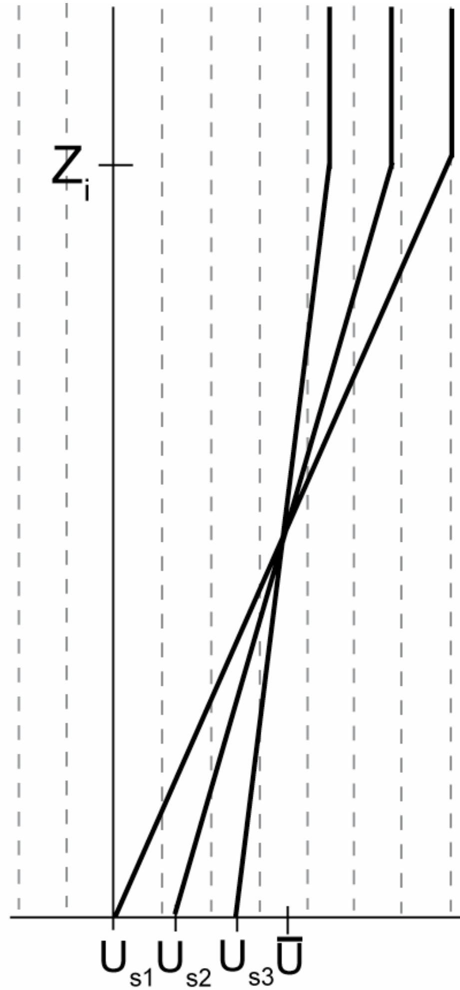
From Rothermel (1991)

Experiment Design

- Advanced Regional Prediction System (ARPS), ver. 5.1.0
- 2D and 3D idealized simulations
- Flat terrain
- Fire parameterized by steady heat flux into lowest model level (**D = 520 m, Qo = 28.8 kW/m^2**).



$$N^2 = \frac{g}{\theta_o}\frac{\partial\bar{\theta}}{\partial z}$$



From Kiefer et al. (2009), J. Atmos Sci., Vol 66, 806-836.

2D Experiment Design

	U_s	0	1.25	2.5	3.75	6.25	7.5	8.75	10.0	12.5
$\overline{U}$	A \ B	∞	3.4	1.7	1.1	0.7	0.6	0.5	0.4	0.3
0	0	A1B9	A1B8	A1B7	A1B6	A1B5	A1B4	A1B3	A1B2	A1B1
2.5	0.3	A2B9	A2B8	A2B7	A2B6	A2B5	A2B4	A2B3	A2B2	A2B1
3.75	0.6	A3B9	A3B8	A3B7	A3B6	A3B5	A3B4	A3B3	A3B2	A3B1
6.25	1.7	A4B9	A4B8	A4B7	A4B6S / A4B6	A4B5S / A4B5	A4B4	A4B3	A4B2	A4B1
10	4.3	A5B9	A5B8	A5B7	A5B6	A5B5	A5B4	A5B3	A5B2	A5B1
12.5	6.8	A6B9	A6B8	A6B7	A6B6	A6B5	A6B4	A6B3	A6B2	A6B1

A < 1, B > 1

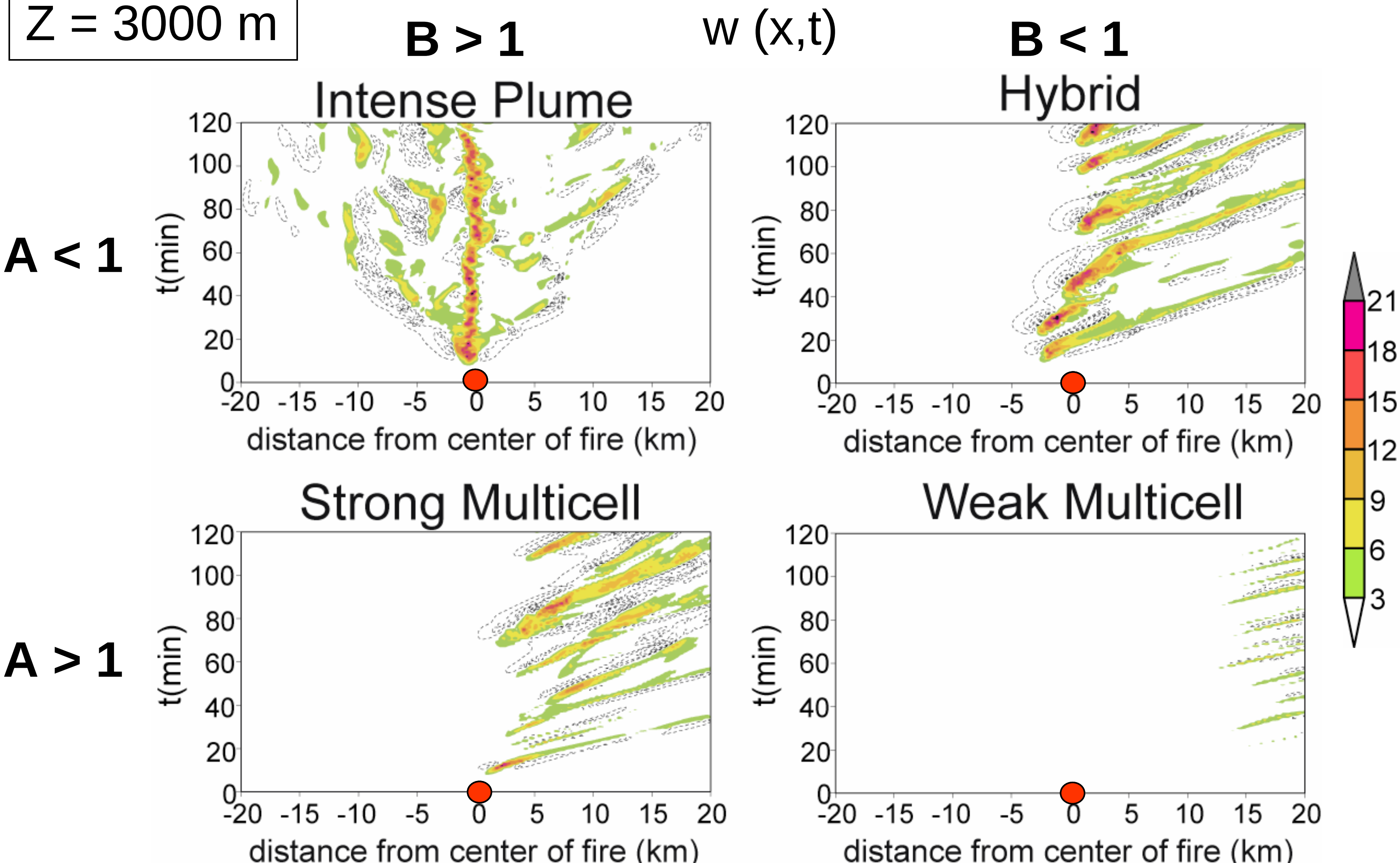
A < 1, B < 1

A > 1, B > 1

A > 1, B < 1

Organizational Modes

Z = 3000 m



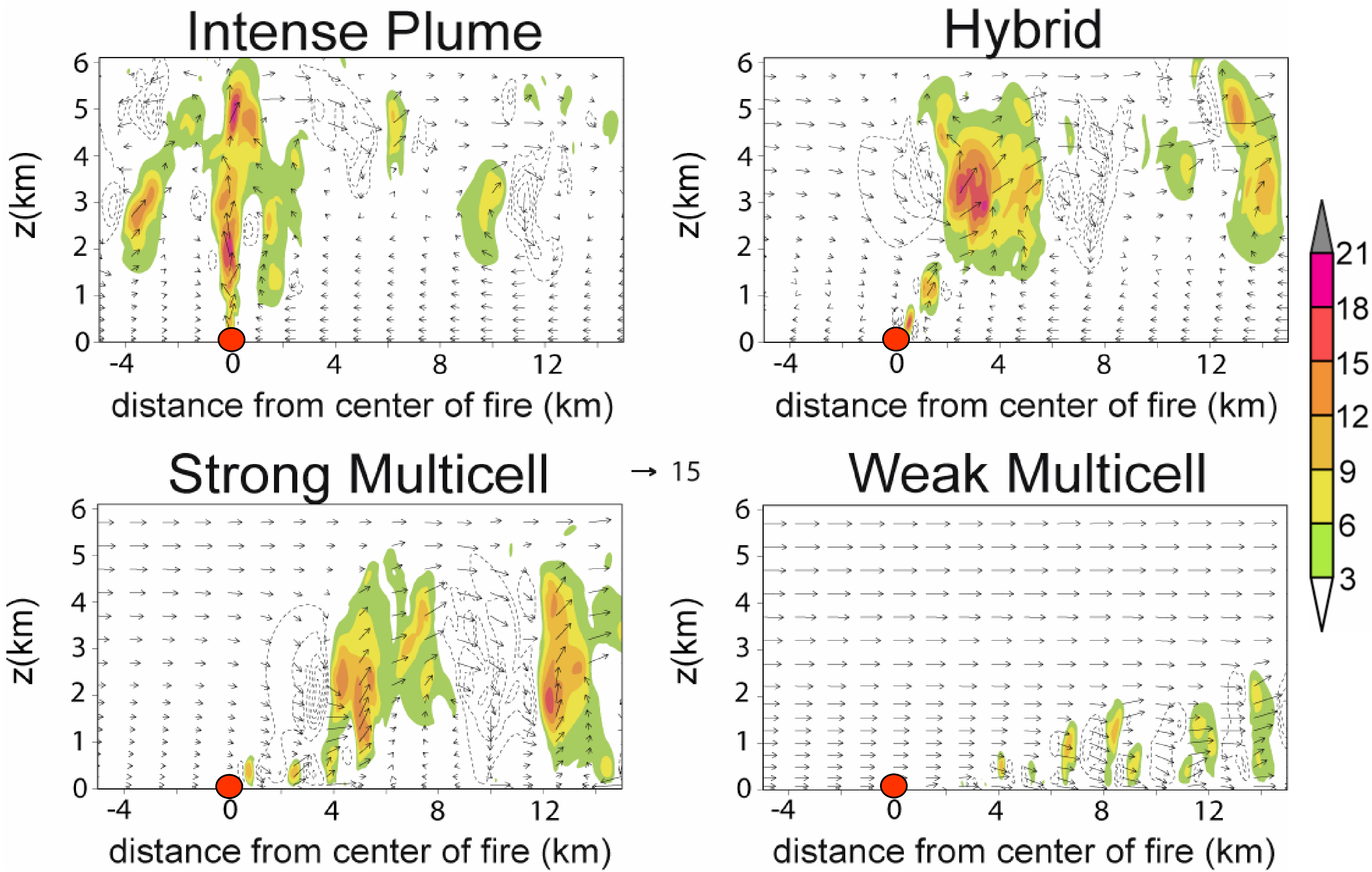
Organizational Modes

t = 80 min

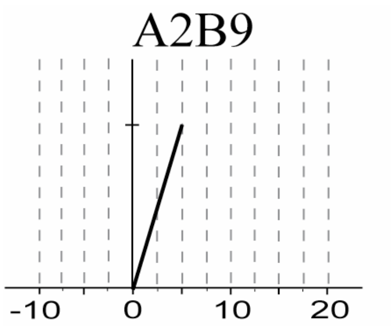
B > 1 w (x,z) **B < 1**

A < 1

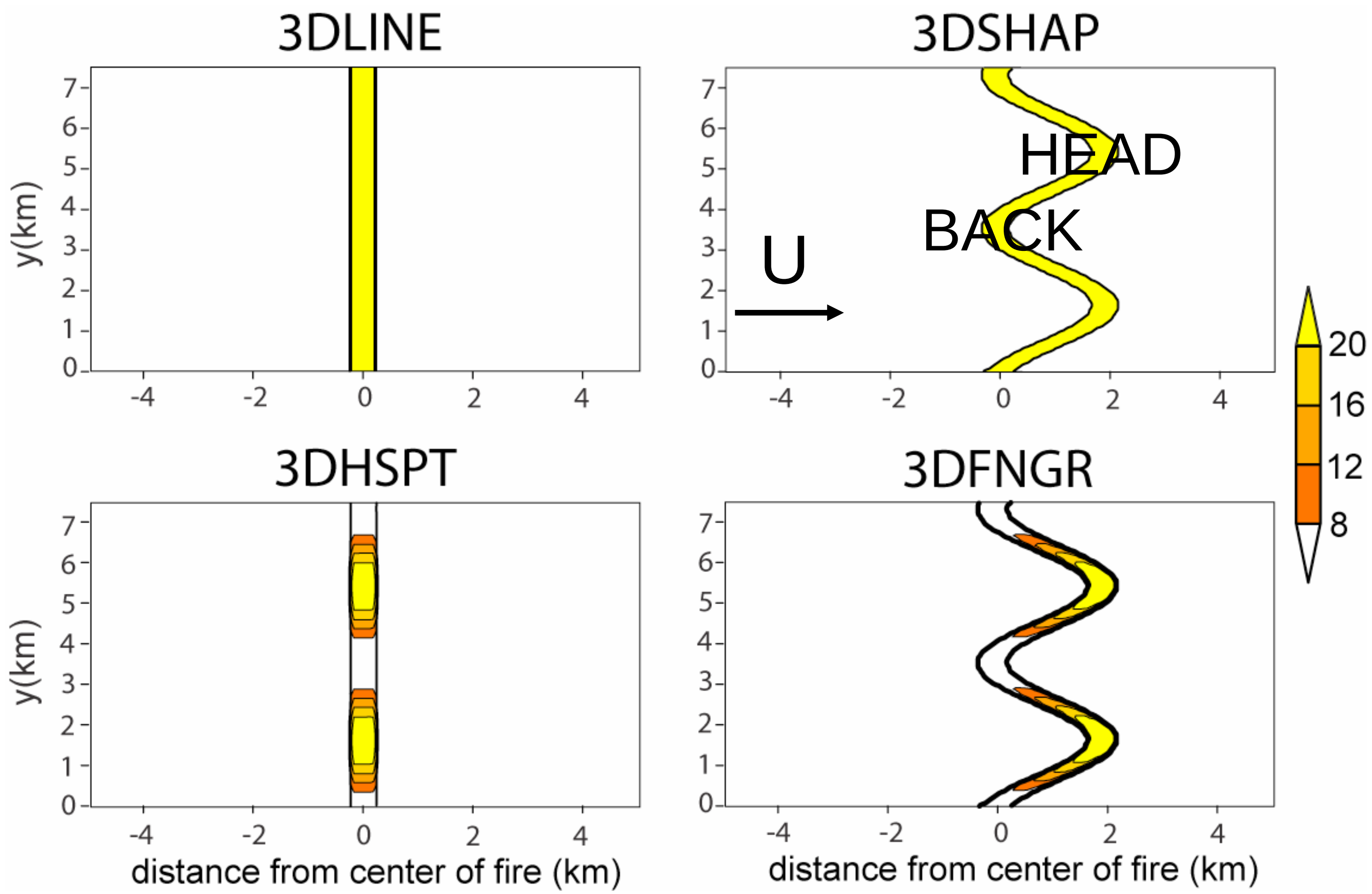
A > 1



3D - Fireline Experiment Design

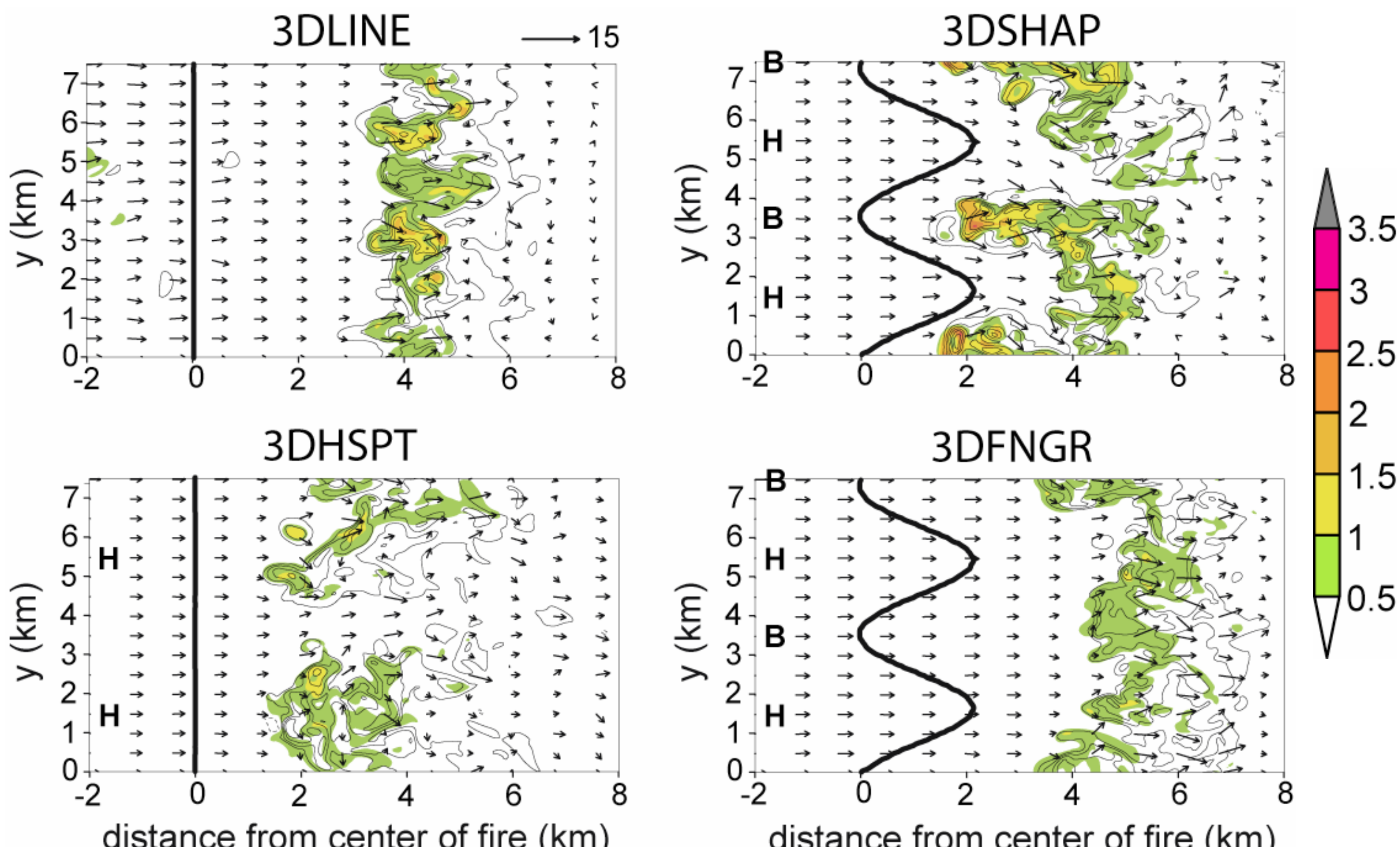


Surface Kinematic Heat Flux (K m/s)



3D Shape/Inhomogeneity Assessment

w(x,y) at z = 3000 m, t = 80 min



Part II

Development of Modeling Tools for Predicting Smoke Dispersion from Low Intensity Fires

JFSP project 09-1-04-1

PI: Warren Heilman

Co-Pi: Jay Charney, Sharon Zhong, John Hom

Strategy

- Incorporate canopy parameterization into ARPS model
- Parameterize heat from fire (1-way interaction)
- Test out modeling strategy on test case: Double Trouble State Park Wildfire (2 June 2002)
- Run simulation of prescribed burn in Silas Little Experimental Forest (planned Feb-Mar 2011)
- Ultimately: Pass meteorological fields to smoke dispersion model (Flexpart)

Canopy Parameterization: Dupont and Brunet (2008) (J. Agr. Forest Met., V148, 976-990)

Momentum Equation

PGF

CORIOLIS

$$\overline{\rho}\left(\frac{\partial \widetilde{u}_i}{\partial t} + \widetilde{u}_j \frac{\partial \widetilde{u}_i}{\partial x_j}\right) = -\frac{\partial}{\partial x_i}\left(\widetilde{p}'' - \alpha_{div}\frac{\partial \overline{\rho}\widetilde{u}_j}{\partial x_j}\right) - 2\overline{\rho}\omega_j \epsilon_{ijk}(\widetilde{u}_k - \overline{u}_k)$$

$$-\overline{\rho}g\left(\frac{\widetilde{\theta}''}{\overline{\theta}} - \frac{c_p}{c_v}\frac{\widetilde{p}''}{\overline{p}}\right)\delta_{i3} - \overline{\rho}\frac{\partial \boldsymbol{\tau}_{ij}}{\partial x_j} \boxed{- C_d A_f \sqrt{\widetilde{u}_j \widetilde{u}_j}\,\widetilde{u}_i}$$

BUOY

MIXING

Pressure and Viscous Drag Force Term (sink)

SGS TKE Equation

DISSIP

$$\frac{\partial e}{\partial t} + \widetilde{u}_j \frac{\partial e}{\partial x_j} = -\tau_{ij}\frac{\partial \widetilde{u}_i}{\partial x_j} - \frac{g}{\overline{\theta}}\tau_{3\theta} + \frac{\partial}{\partial x_j}\left(2\nu_t \frac{\partial e}{\partial x_j}\right) - C_\epsilon \frac{e^{3/2}}{l} \boxed{- 2C_d A_f \sqrt{\widetilde{u}_j \widetilde{u}_j}\, e}$$

SHEAR SOURCE

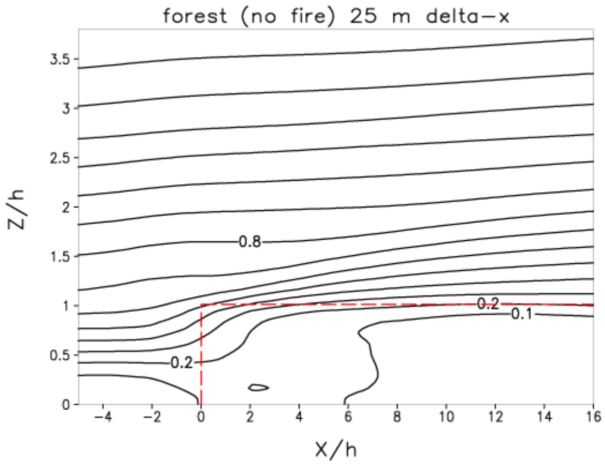
BUOY SOURCE /SINK

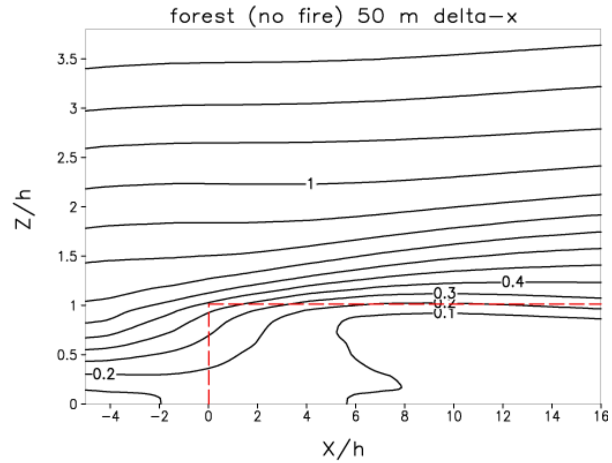
TURB TRANSPORT

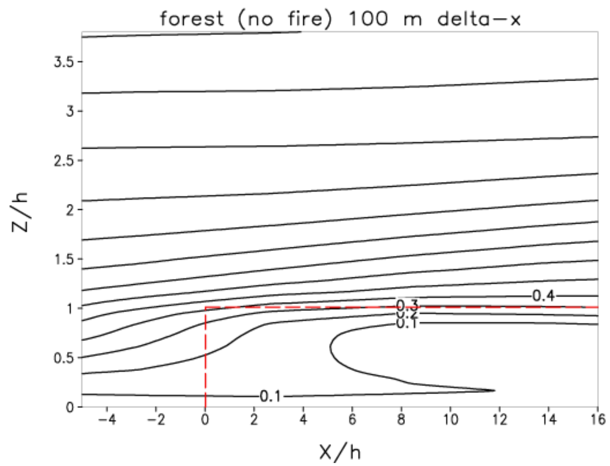
Cascade Term (sink)

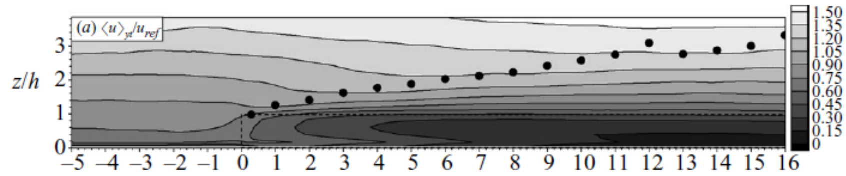
Resolution Sensitivity?

u/uref (t=40-70 min mean)





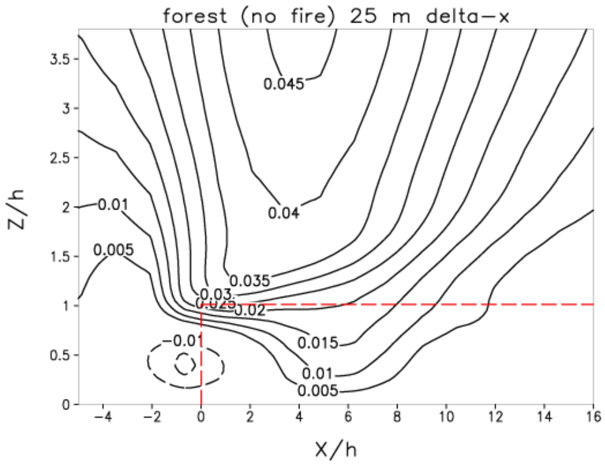


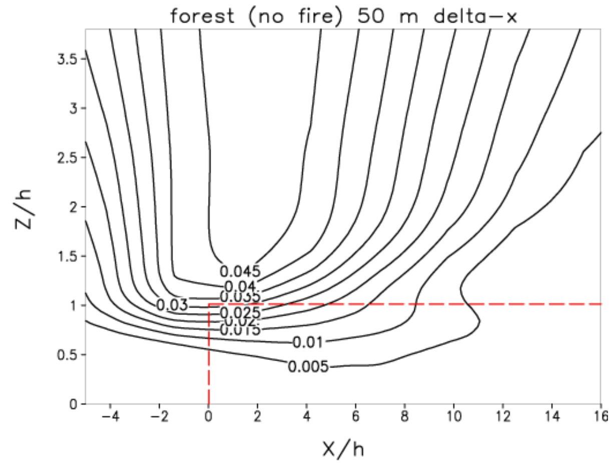


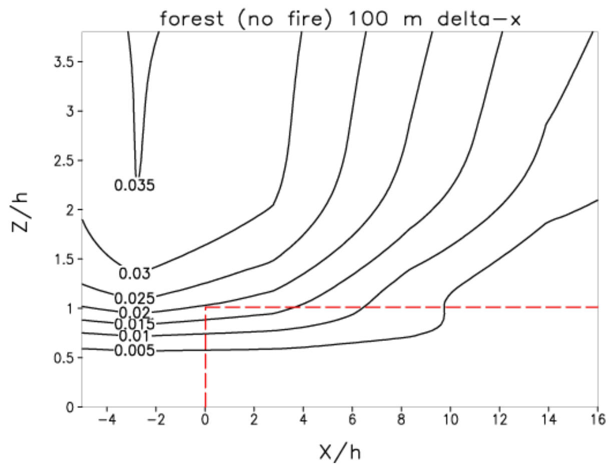
From Dupont and Brunet (2009, JFM)

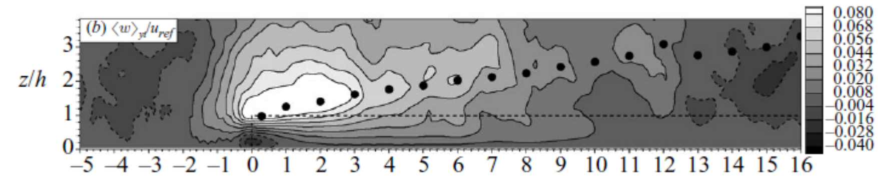
Resolution Sensitivity?

w/uref (t=40-70 min mean)



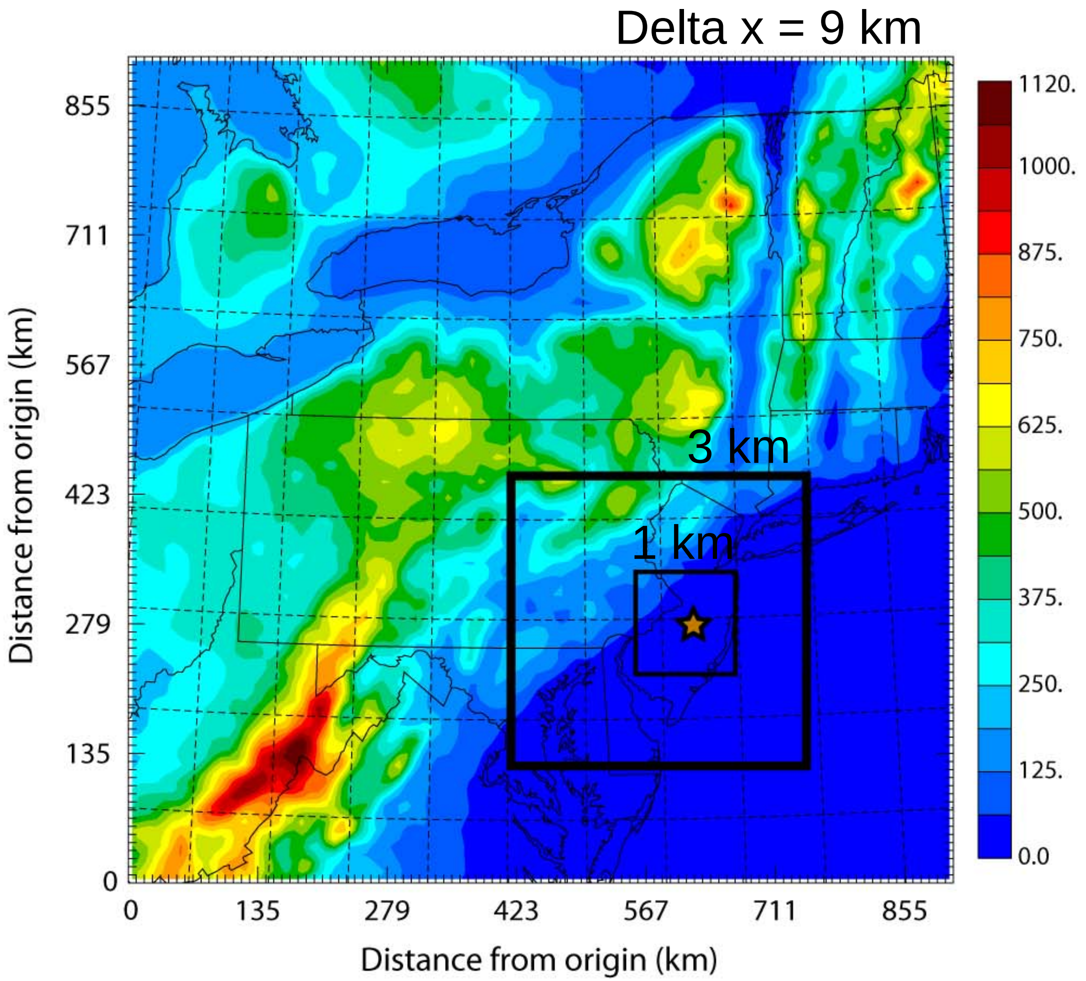


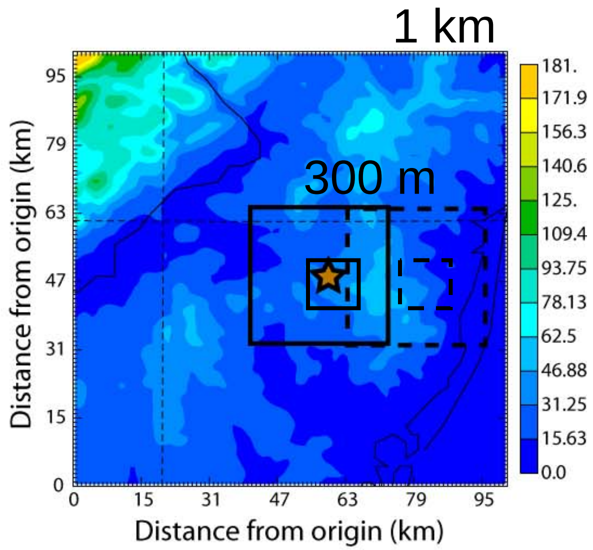




From Dupont and Brunet (2009, JFM)

ARPS Nesting Strategy

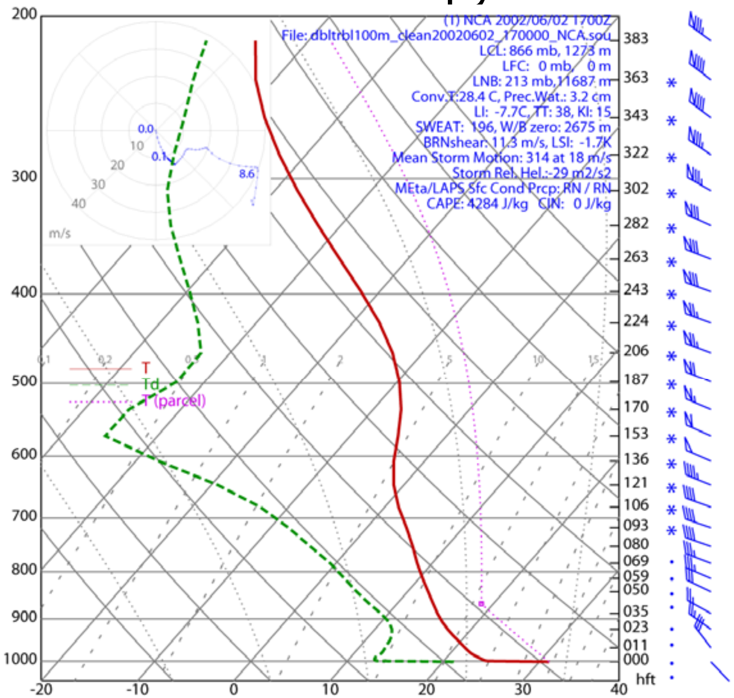




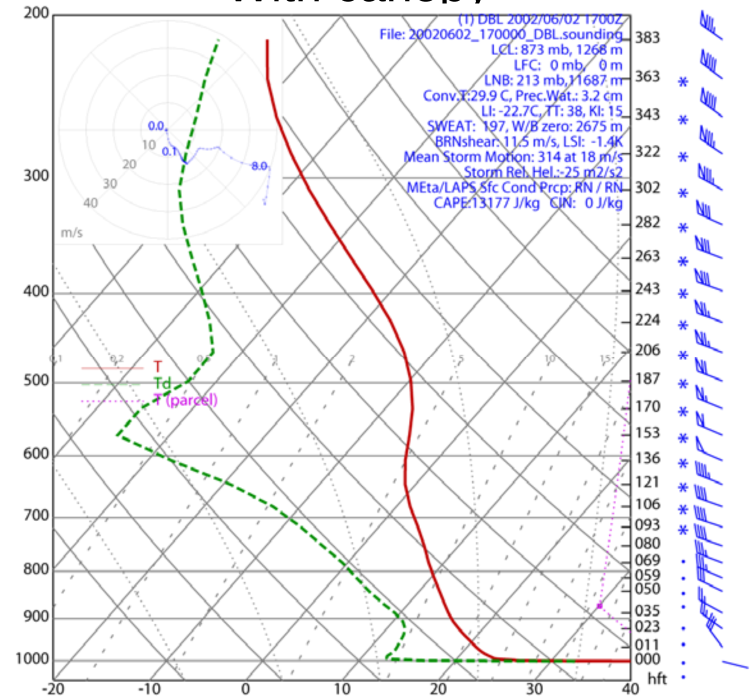
Innermost nest: horizontal grid spacing is 100 m, and vertical grid spacing is 2 m

Double Trouble Soundings – innermost nest

Without canopy



With canopy

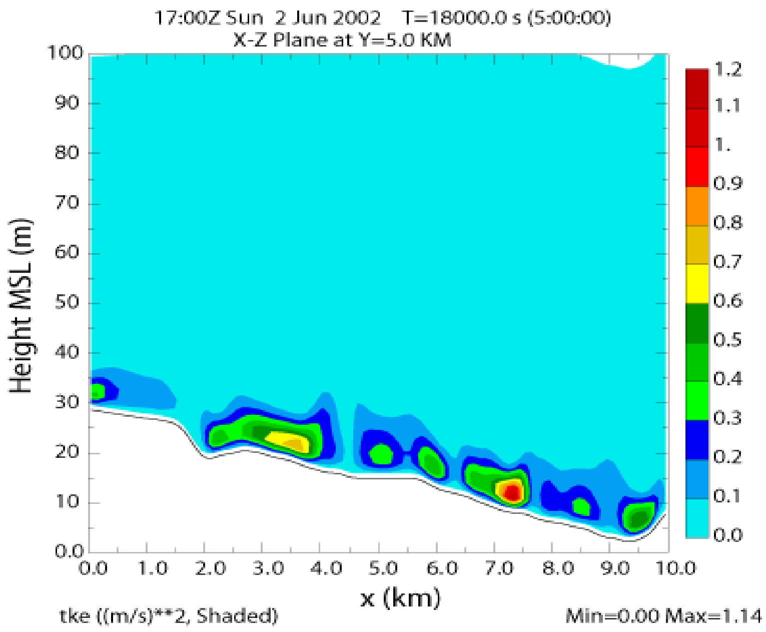


1700 UTC 2 June 2002

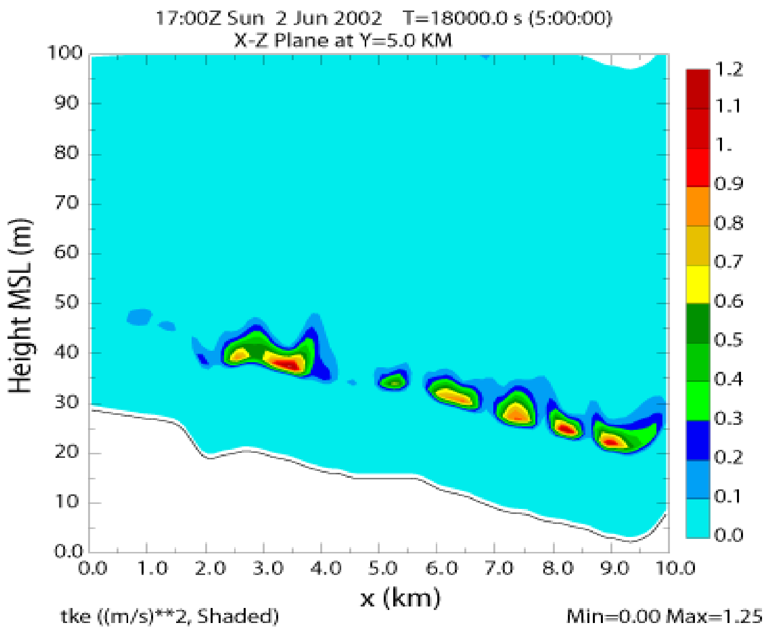
Issues Addressed

- Regardless of canopy presence or absence, surface temperatures too high
  - Easy fix – use option in ARPS to distribute fluxes quadratically (i.e., smooth the scalar flux profiles)
- Inclusion of canopy exacerbates problem
  - TKE term
  - Shading effect

TKE

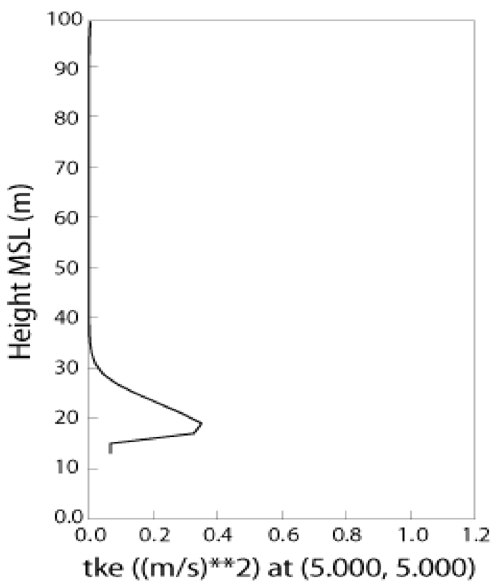


17:00Z Sun 2 Jun 2002 T=18000.0 s (5:00:00)
X-Z Plane at Y=5.0 KM
Height MSL (m)
x (km)
tke ((m/s)**2, Shaded)
Min=0.00 Max=1.14

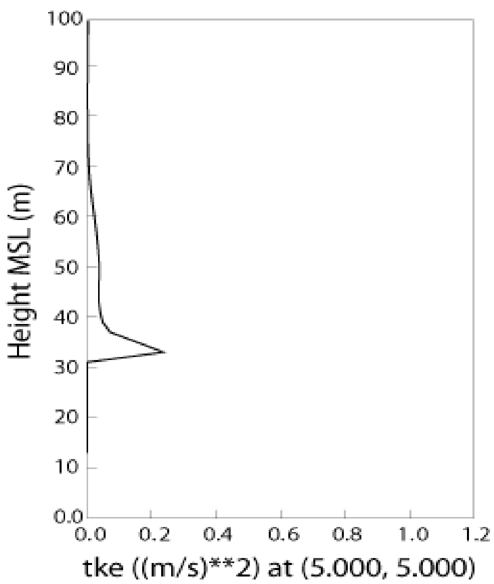


17:00Z Sun 2 Jun 2002 T=18000.0 s (5:00:00)
X-Z Plane at Y=5.0 KM
Height MSL (m)
x (km)
tke ((m/s)**2, Shaded)
Min=0.00 Max=1.25

TKE



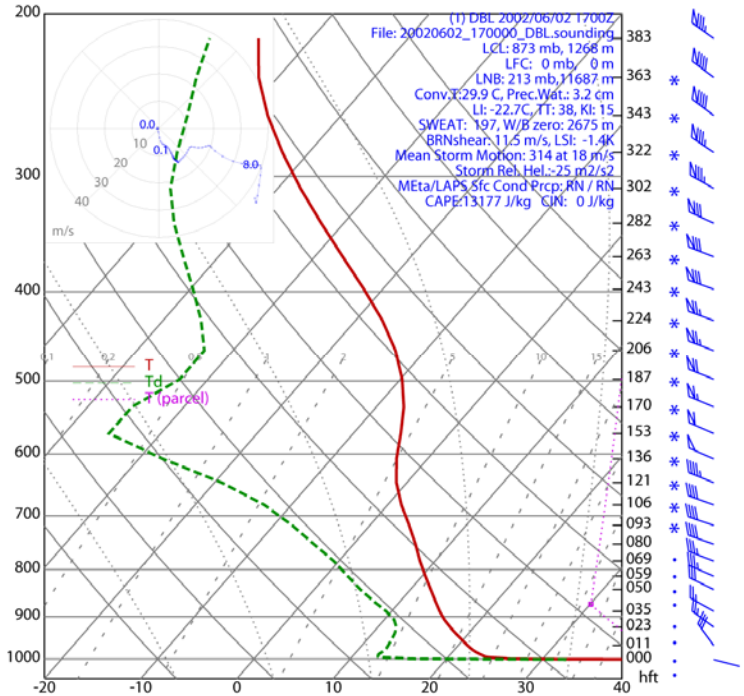
Height MSL (m)
100
90
80
70
60
50
40
30
20
10
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2
tke ((m/s)**2) at (5.000, 5.000)



Height MSL (m)
100
90
80
70
60
50
40
30
20
10
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2
tke ((m/s)**2) at (5.000, 5.000)

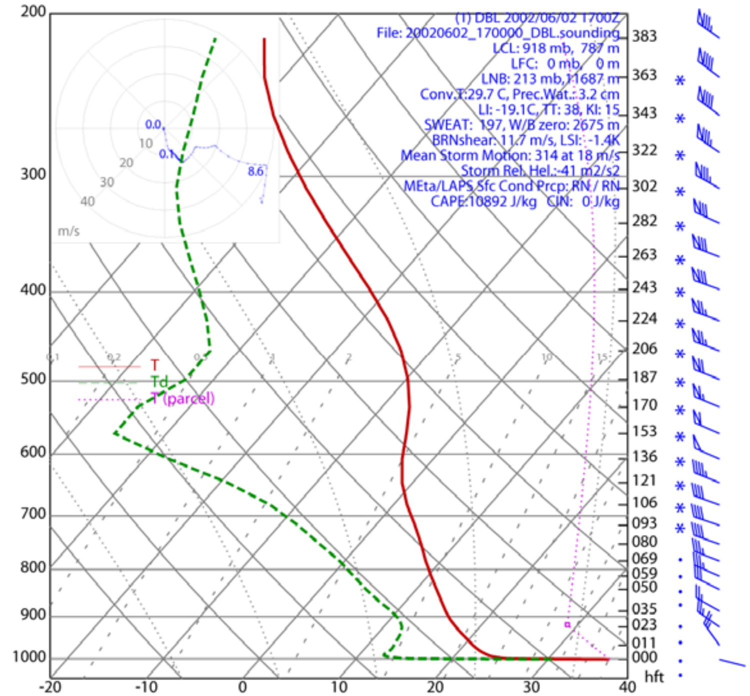
Double Trouble Soundings – innermost nest

With canopy – Bad TKE code



Max T: 39.98 C

With canopy – Good TKE code



Max T: 36.38 C

Include effect of canopy shading

With canopy – Good TKE code

Quadratic Vertical Flux Distrib., and prescribed heat flux profile

Shaw and Schumann (1992), Brown and Covey (1966)

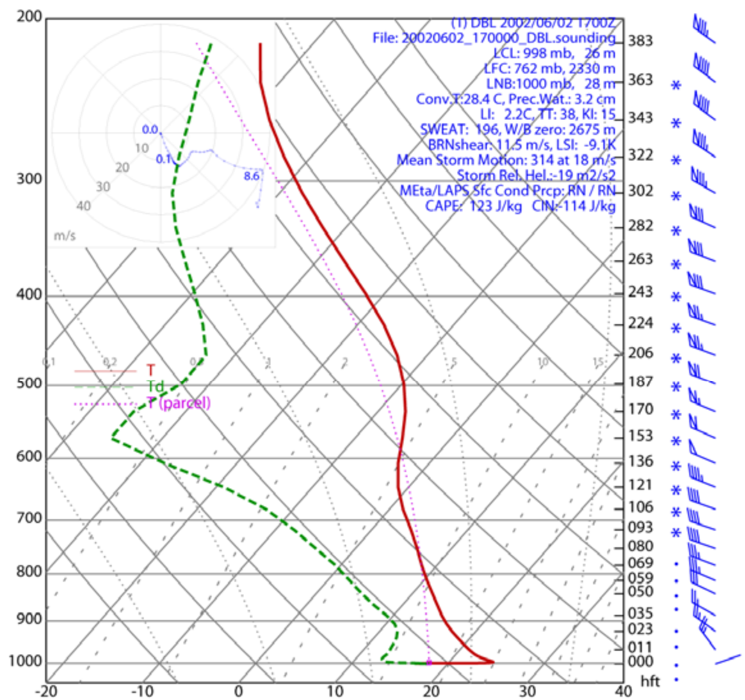
$$Q(z) = Q(h)\exp(-\alpha F), \quad F = \int_z^h a\,\mathrm{d}z$$

Q(h) = prescribed heat flux at top of canopy

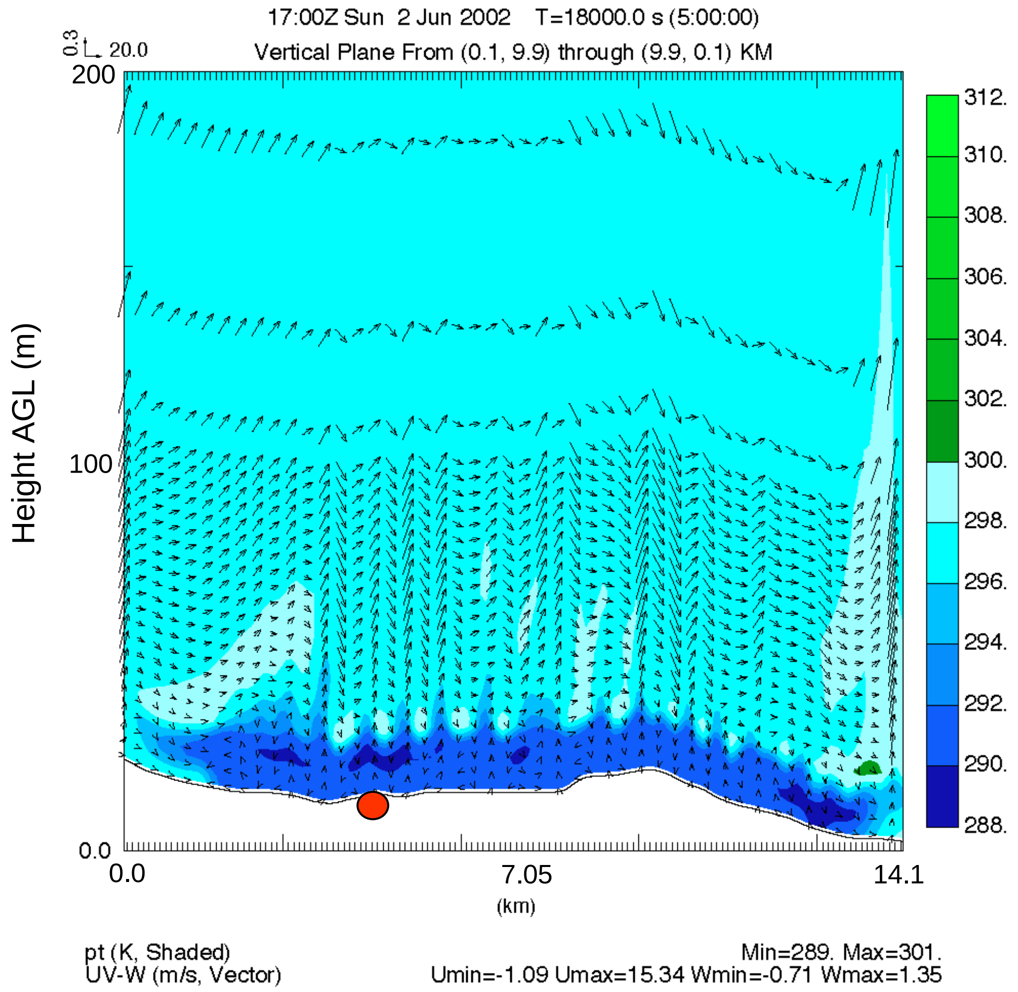
F = downward cumulative LAI

a = frontal area density of vegetation

α = extinction coeff. = 0.6



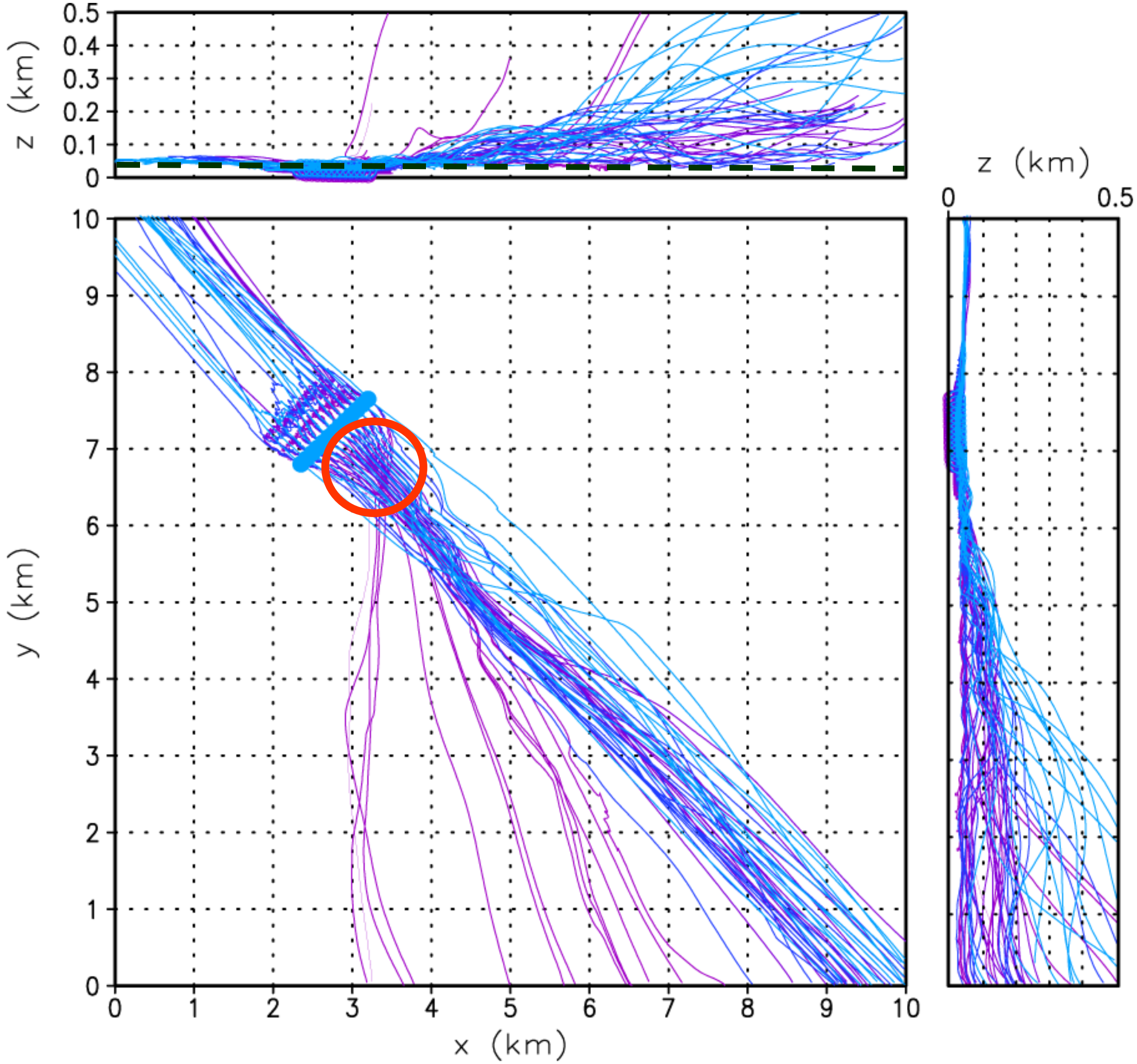
Idealized fire (800 W/m^2) imposed



prescribed heat flux as in Sun et al. (2006) (Can. J. For. Res., V 36, 2894-2908)

Released at 18 UTC 2 June 2002

Parcel Trajectories



Ongoing Efforts

- Double Trouble simulation analysis
  - Plume height vs. fire intensity
  - Air parcel trajectories
  - How does fire impact exchange of air through canopy interface?
- Idealized simulations
  - Improve understanding of sensitivity of vertical exchange to various parameters
    - Fire intensity, canopy height, background wind & stability, etc.

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