Soil heating and evaporation under extreme conditions: Forest fires and slash pile burns

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Outline

(1) Why study this problem ?

(2) Soil moisture transport is coupled to soil heating

(3) Modeling details

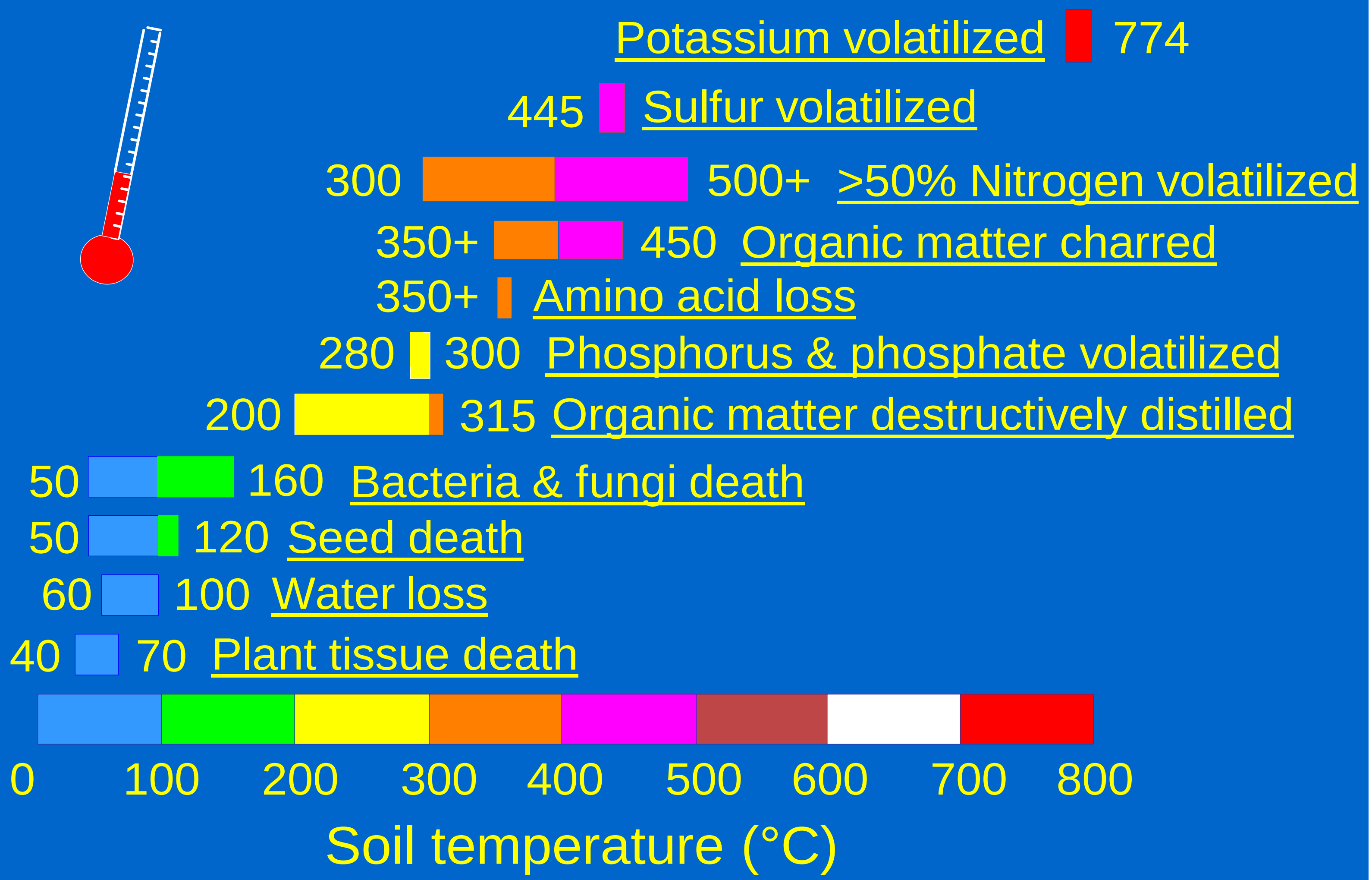
(4) Results: Model simulations vs laboratory data

(5) Why comparing model with data doesn’t tell me what I really want to know !

(6) Results: From the solution space perspective

(7) Conclusions

Fire effects on soils & soil biota



Conservation of Energy

$$C_s(T,\theta)\frac{\partial T}{\partial t}-L_v(T,\psi)\rho_w\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}[\lambda_s(T,\theta)\frac{\partial T}{\partial z}]-(\eta-\theta)\rho_a c_{pa}U\frac{\partial T}{\partial z}$$

Conservation of Mass

(liquid + vapor)

$$\rho_w\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}[D_{ve}(T,\theta)\frac{\partial \rho_v}{\partial z}-(\eta-\theta)U\rho_v]$$

Advection due to rapid volitalization

$$\frac{\partial U}{\partial z}=-\frac{\rho_w}{(\eta-\theta)\rho_v}\frac{\partial \theta}{\partial t}$$

But there are 3 moisture variables: θ, ψ, ρ_v
so we need 2 more equations:

The water retention curve

$$\theta(T,\psi) = -\frac{\theta_l}{\alpha_l}\ln\left(\frac{\psi}{\psi_{od}}\psi_T\right) + \theta_h\left[1+\left(\alpha_h\frac{\psi}{\psi_{od}}\psi_T\right)^4\right]^{-\frac{1}{m}}$$

The Kelvin Equation

$$\rho_v(T,\psi) = h_s\rho_{sat}(T) = \exp\left(\frac{M_w\psi}{RT}\right)\rho_{sat}(T)$$

Final Modeling Details

(1) Surface Energy Boundary Condition (*Campbell et al. 1995*)

(2) Numerical Lower Boundary Condition (*Thomas 1995*)

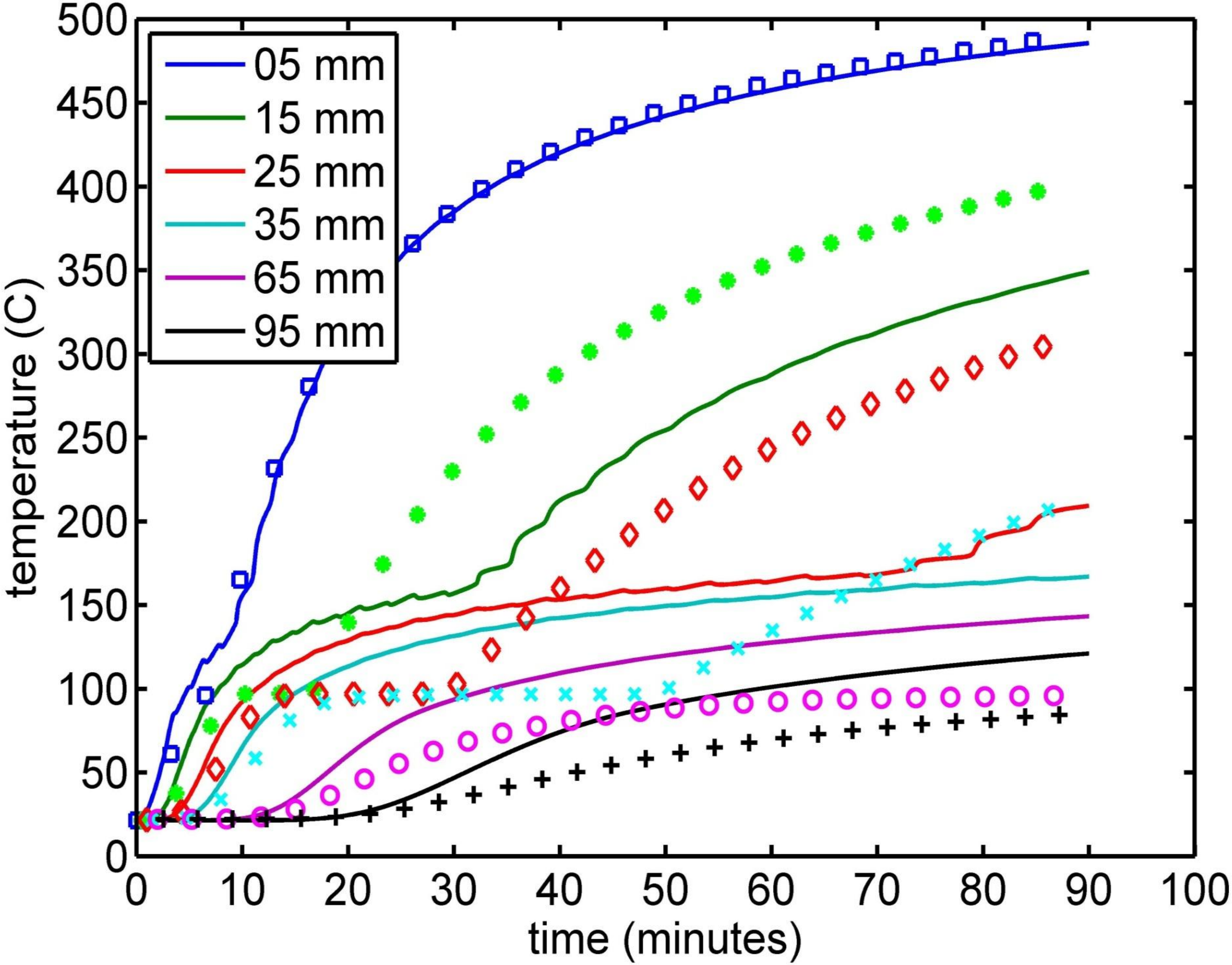
(3) Newton-Raphson method of solving PDE’s (*Campbell 1985; Lynch 2005*)

(4) Block Tri-diagonal Matrix solved with Generalized Thomas Algorithm (*Karlqvist 1952; Mendes et al 2002*)

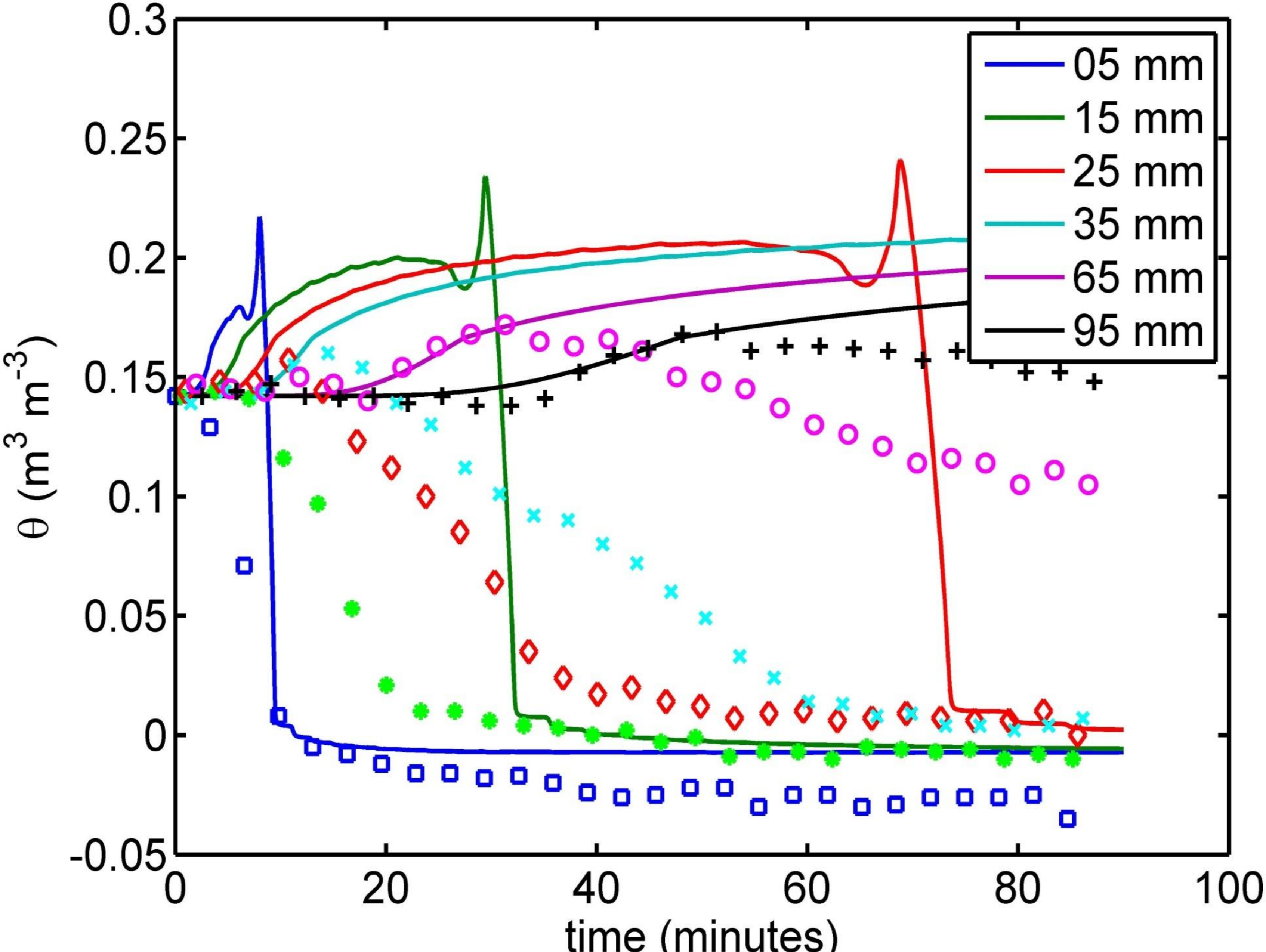
Model Simulations vs Observations

Laboratory data from *Campbell et al (1995).*

Specifically, Quincy Sand with an initial soil moisture of 0.14 m^3/m^3.



05 mm
15 mm
25 mm
35 mm
65 mm
95 mm
temperature (C)
time (minutes)
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100



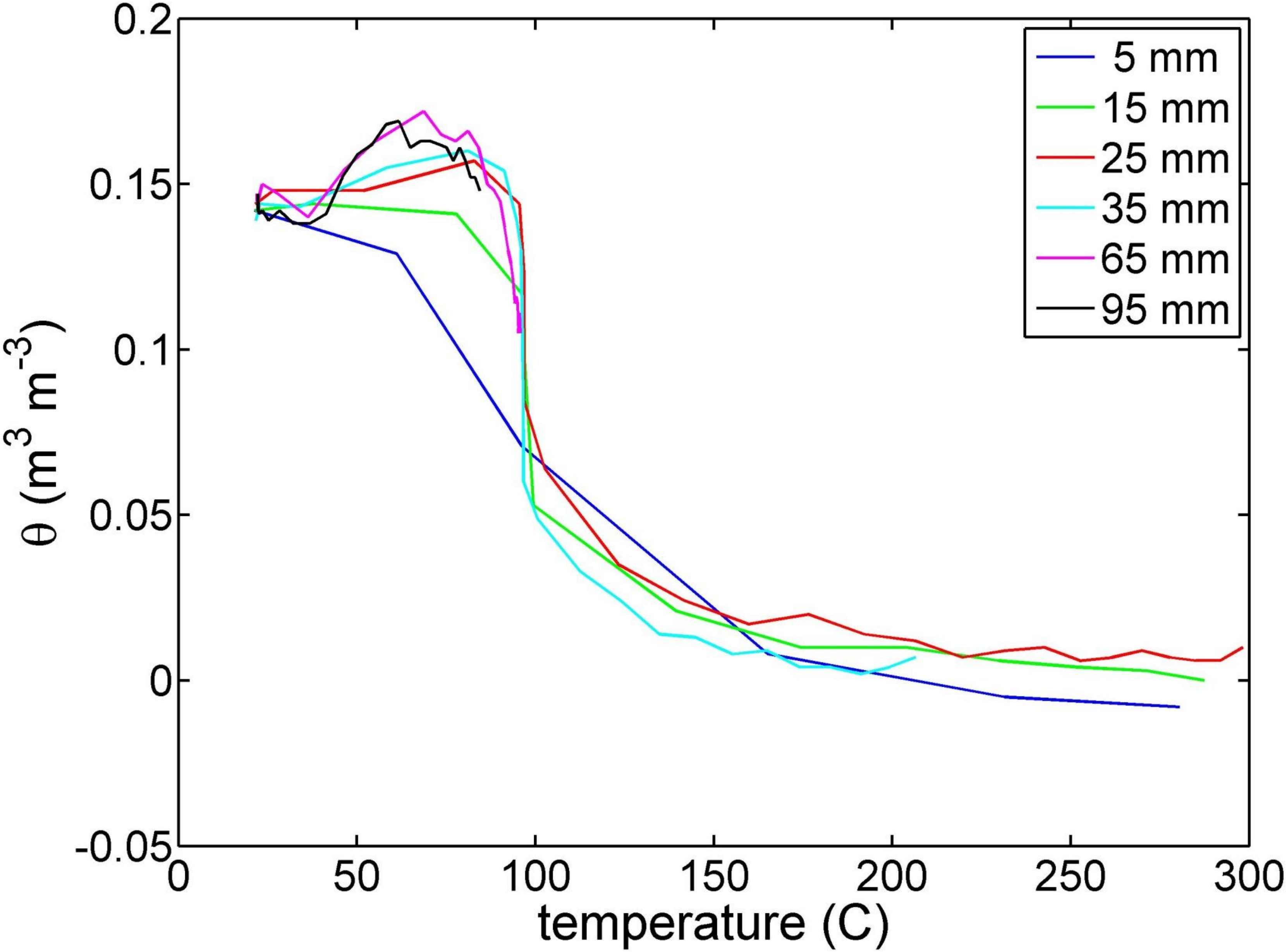
05 mm
15 mm
25 mm
35 mm
65 mm
95 mm
θ (m^3 m^-3)
time (minutes)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
20
40
60
80
100

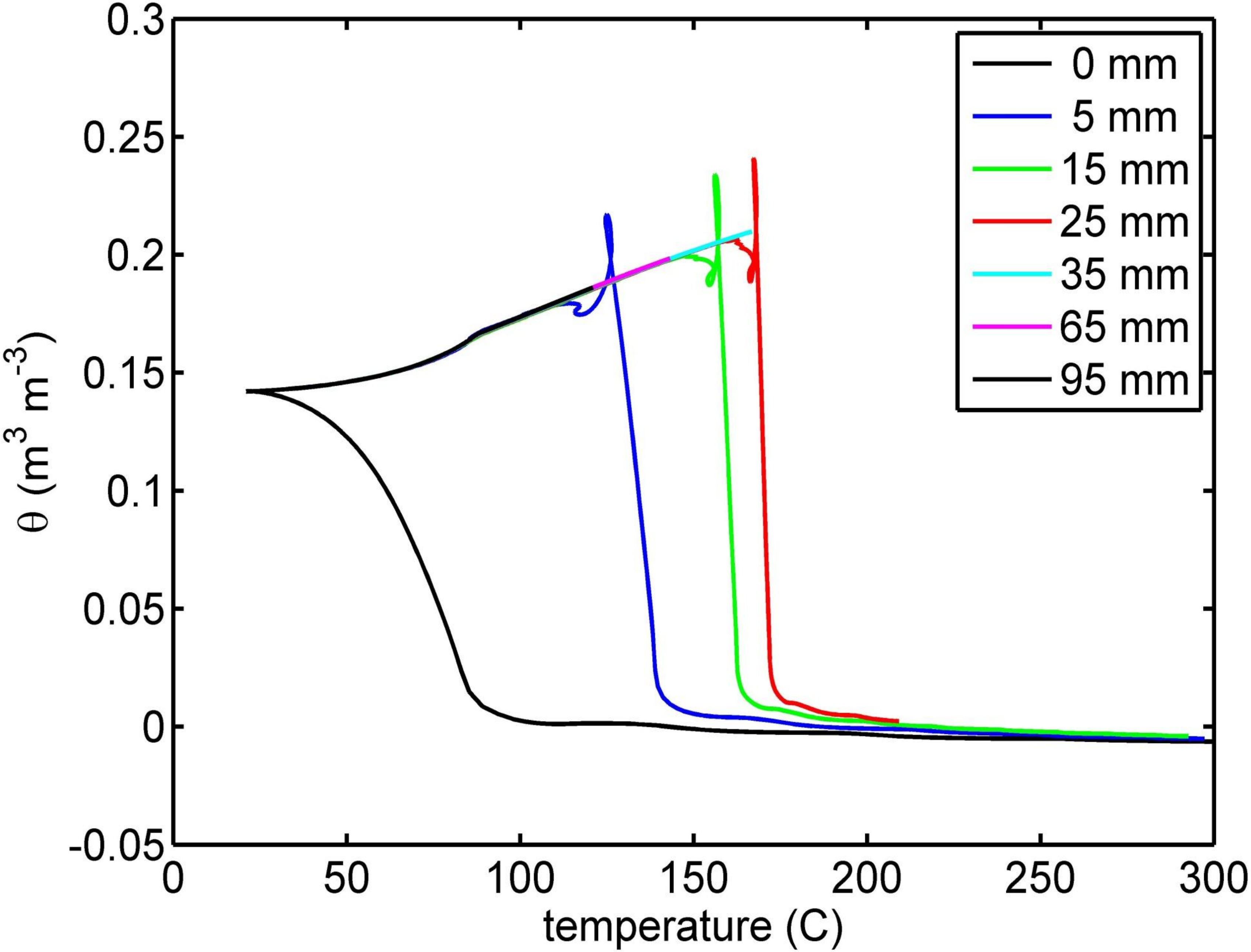
Comparisons suggest that present model provides a reasonable qualitative picture of soil moisture evaporation and heat flow during fires. <u>But for quantitative purposes the new model may not be as accurate as the original *Campbell et al.'s (1995)* model !!</u>

So let's look at the data and simulations in a different way: the solution space approach.

Solution Space or Model Trajectory

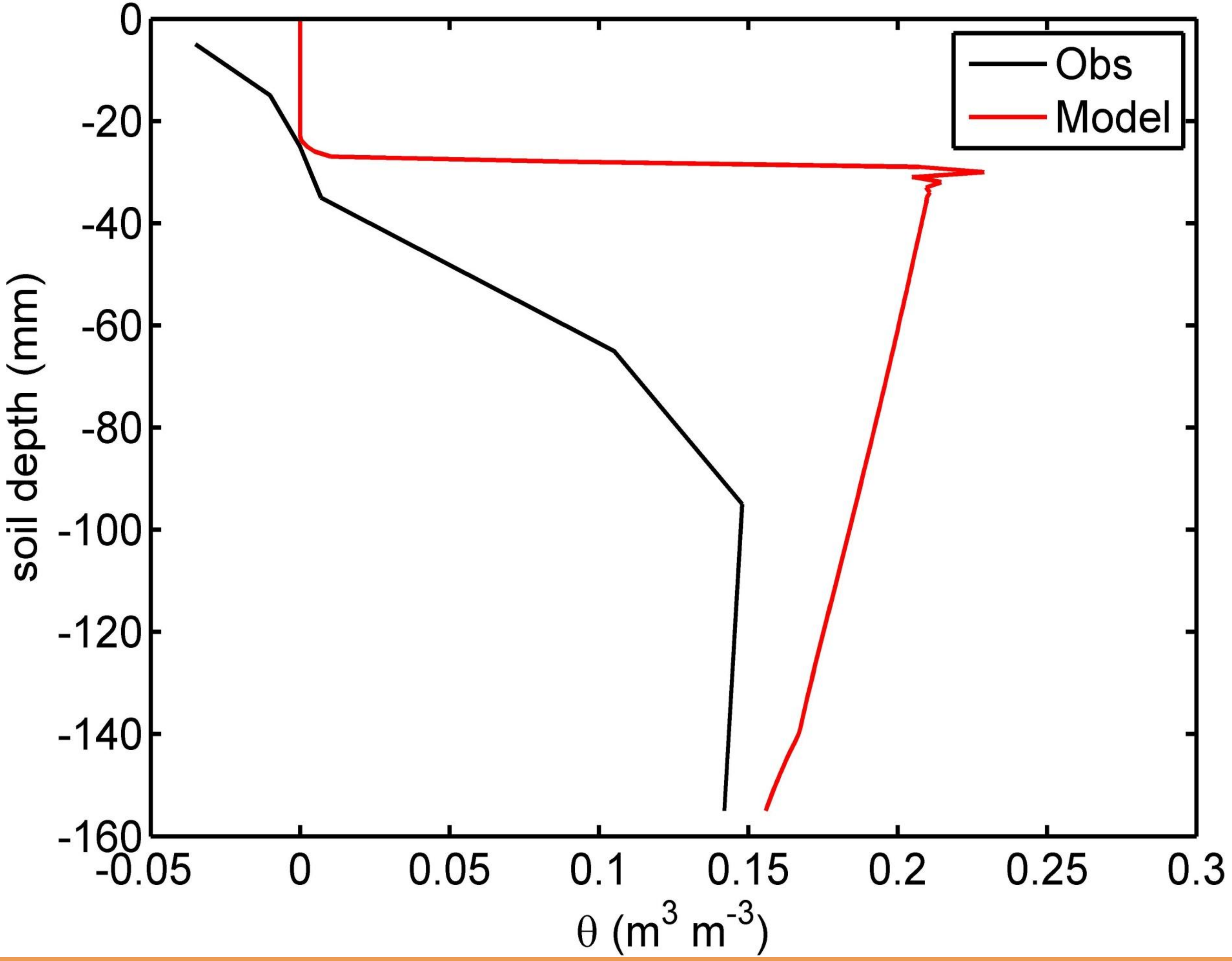
θ vs T


0.2
0.15
0.1
0.05
0
-0.05
θ (m³ m⁻³)
0
50
100
150
200
250
300
temperature (C)
5 mm
15 mm
25 mm
35 mm
65 mm
95 mm

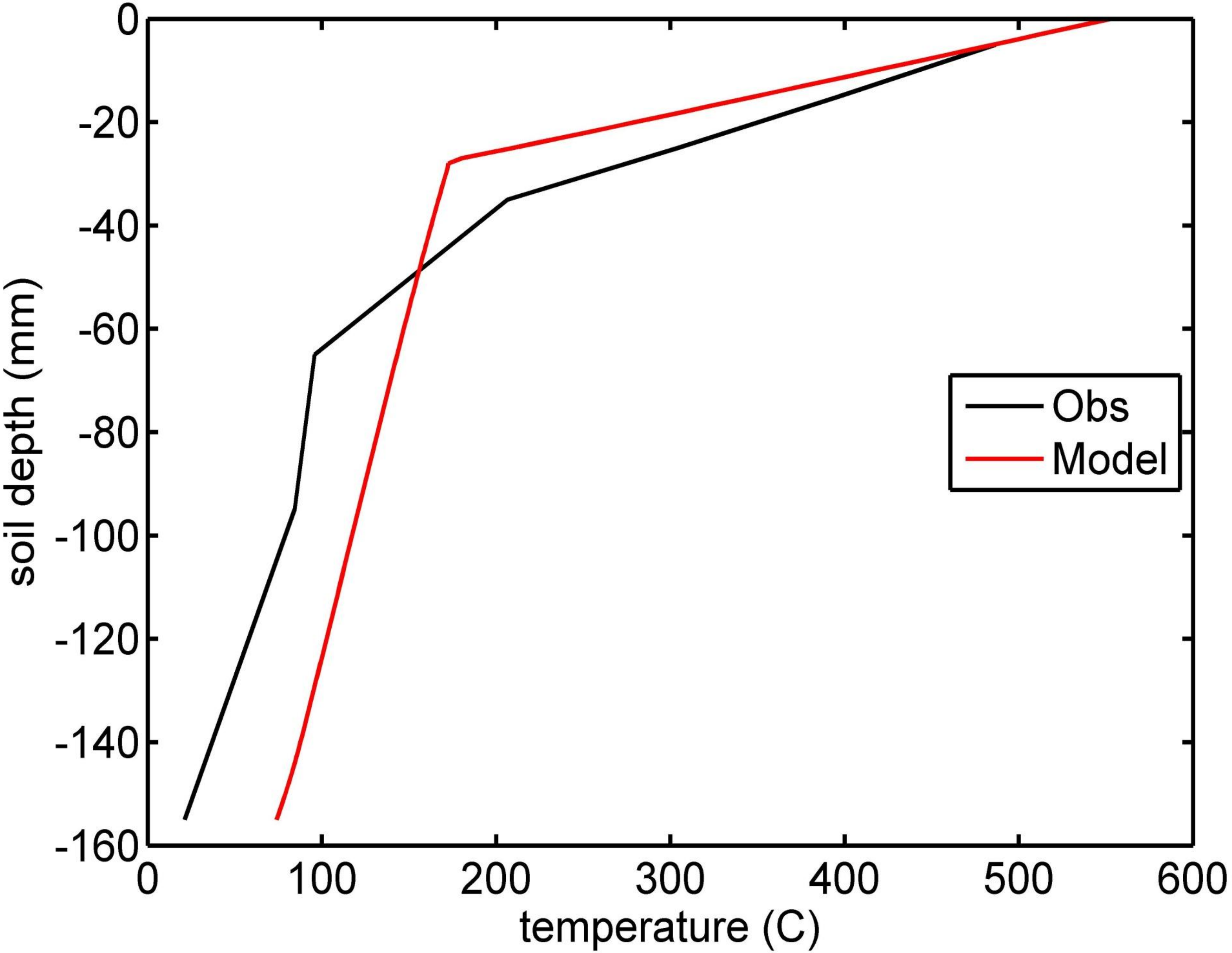


0 mm
5 mm
15 mm
25 mm
35 mm
65 mm
95 mm
θ (m3 m-3)
temperature (C)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
50
100
150
200
250
300

Final vertical profiles of observed and simulated temperature and moisture.



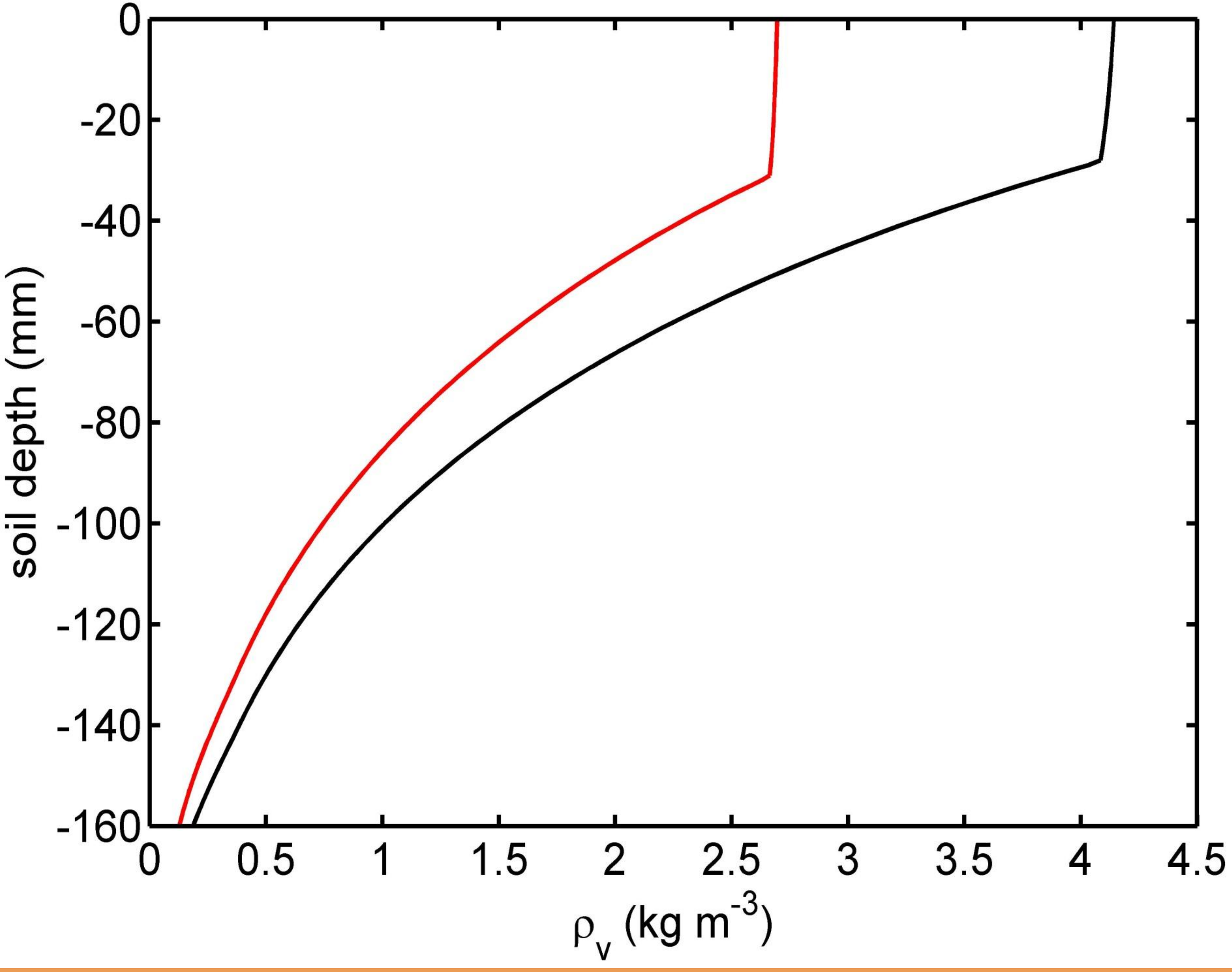
Obs
Model
soil depth (mm)
0
-20
-40
-60
-80
-100
-120
-140
-160
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
θ (m3 m-3)



0
-20
-40
-60
-80
-100
-120
-140
-160
soil depth (mm)
0
100
200
300
400
500
600
temperature (C)
Obs
Model

<u>Why is the model behaving this way?</u>

The answer can be found in the vertical profile of moisture vapor density.



0
-20
-40
-60
-80
-100
-120
-140
-160
soil depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
ρv (kg m-3)

Reconsidering the Kelvin Equation

A simple calculation will suffice

$$h_s = \exp\left(\frac{M_w \psi}{RT}\right)$$

M_w=0.018 kg/mol; R=8.314 J/kg/K; Dry soil: $\psi \approx$ -1.25 MJ/kg

For T = 350 K h_s = 0.044%

For T = 650 K h_s = 1.6%

For T = 850 K h_s = 4.1%

In other words, near the end of the soil drying phase when the temperature begins its steep rise, the relative humidity increases!! The opposite of expectations.

Not only that, but the saturation density increases with temperature as well.

So that the vapor density increases to the point that it is being driven only by the temperature and so the gradient in vapor density follows the temperature gradient, driving the evaporated moisture deeper into the soil.

Conclusions

The issues with the present model result from the interaction of the Kelvin Equation and the water retention curve by producing the autonomous "creation" and transport of water vapor that is largely independent of soil moisture !! (Not serious when T < 70 C.)

Laboratory observations and modeling results indicate that current modeling concepts may not capture evaporation dynamics and soil moisture transport at very low soil moistures.

So at this point I invite questions and ask the audience to consider the implications of my modeling results to modeling soil evaporation for very dry soils (and at high temperatures).

I would be happy to discuss possible solutions to this modeling conundrum.

Thank You !