Carleton UNIVERSITY
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IP3
Improved Processes & Parameterisation for Prediction in Cold Regions

Evaluation of the heat-pulse probe method for measuring frozen soil moisture content

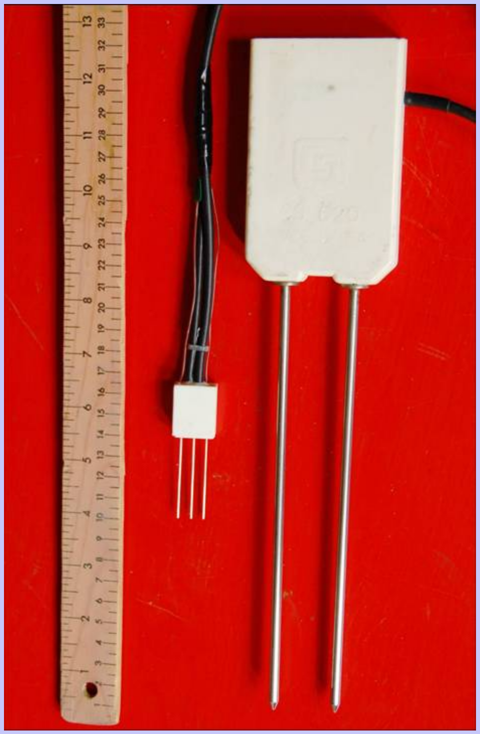
Yinsuo Zhang Mike Treberg
Sean Carey and Elyn R. Humphreys

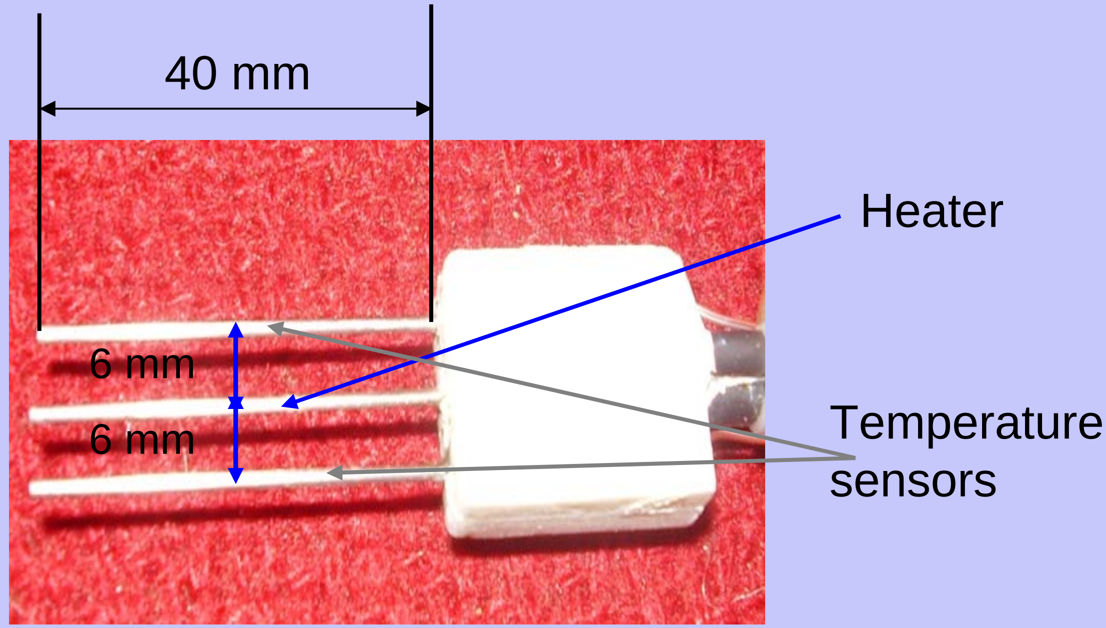
Carleton University, Ontario, Canada

NSERC
CRSNG

Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
Fondation canadienne pour les sciences du climat et de l'atmosphère (FCSCA)

What is Heat Pulse Probe (HPP)



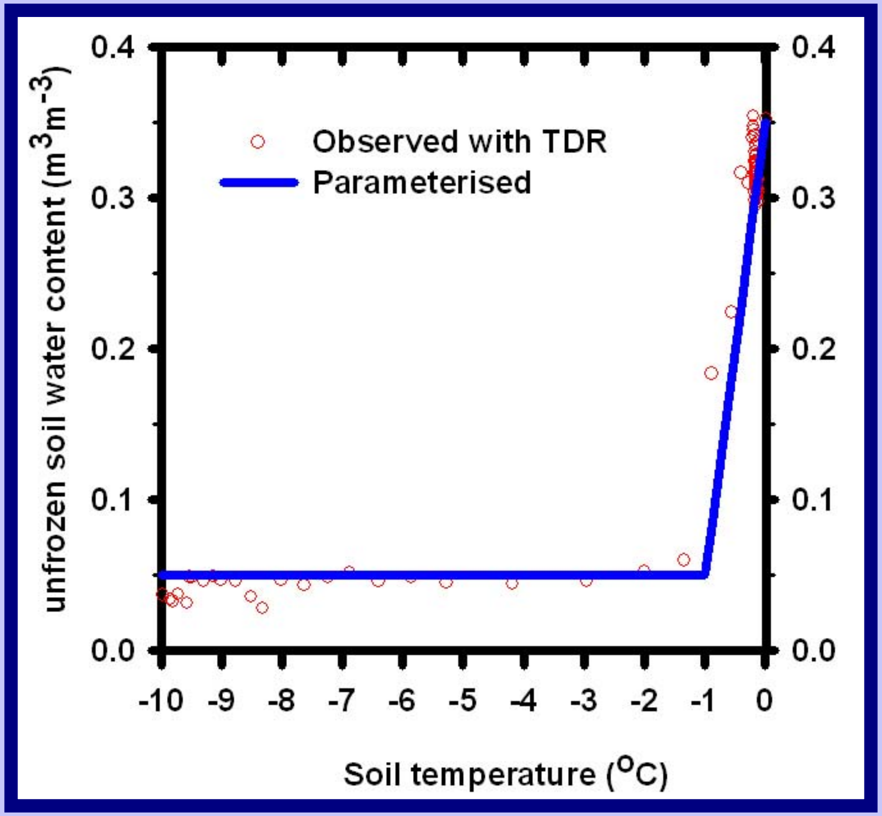


$\Delta T = f\,(C, q, t_0, t, r)$ → Determines C

$C = \Sigma\,(C_m\theta_m + C_o\theta_o + C_l\theta_l + C_i\theta_i)$ → Determines θ_l, θ_i

Why HPP for soil ice ?

- No other options for θ_i other than radioactive methods.
- Successfully tested in unfrozen soil.
- θ_i could be determined by TDR or θ_l-T curves.



- HPP has the potential for soil ice measurements with:
  - ✓Relatively low cost
  - ✓Continuous measurements
  - ✓Minimum disturbance to natural conditions

How to make HPP work for frozen soil?

Problems for frozen soils:

Possible ice melting will null the assumptions of current mathematical solutions for HPP:

- ✓ All energy is used to raise soil temperature by conduction
- ✓ soil thermal properties (C, λ, κ) are constant and homogenous

Possible solutions:

- ✓ Control q, t_0 to limit melting
- ✓ Revise the mathematical solution to include soil thawing

Lab experiments

Material:

fine sand with porosity of 0.35

Tests conducted

Controls	Ranges
q	100 – 2000 J m^{-1}
t_0	8s, 15s, 30s, 60s
T	20 °C, -2 °C, -4°C, -10°C
s	100%, 50%, 25%, 1%

Mathematical solutions

1. Instantaneous Infinite Line Source (IILS)

$$\Delta T(r,t) = \frac{q}{4\pi\lambda t} \exp\left(\frac{-r^2}{4\kappa t}\right)$$

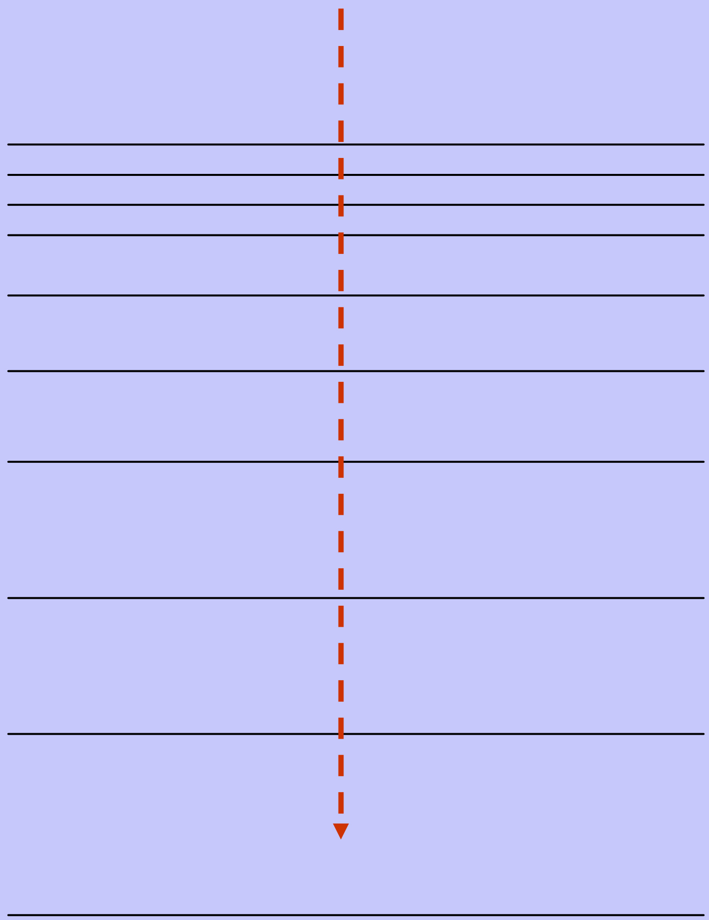
2. Pulsed Infinite Line Source (PILS)

$$\Delta T(r,t) = \begin{cases} \dfrac{-q'}{4\pi\lambda} Ei\left(\dfrac{-r^2}{4\kappa t}\right) & 0 < t \le t_0 \\ \dfrac{q'}{4\pi\lambda}\left\{Ei\left[\dfrac{-r^2}{4\kappa(t-t_0)}\right] - Ei\left(\dfrac{-r^2}{4\kappa t}\right)\right\} & t > t_0 \end{cases}$$

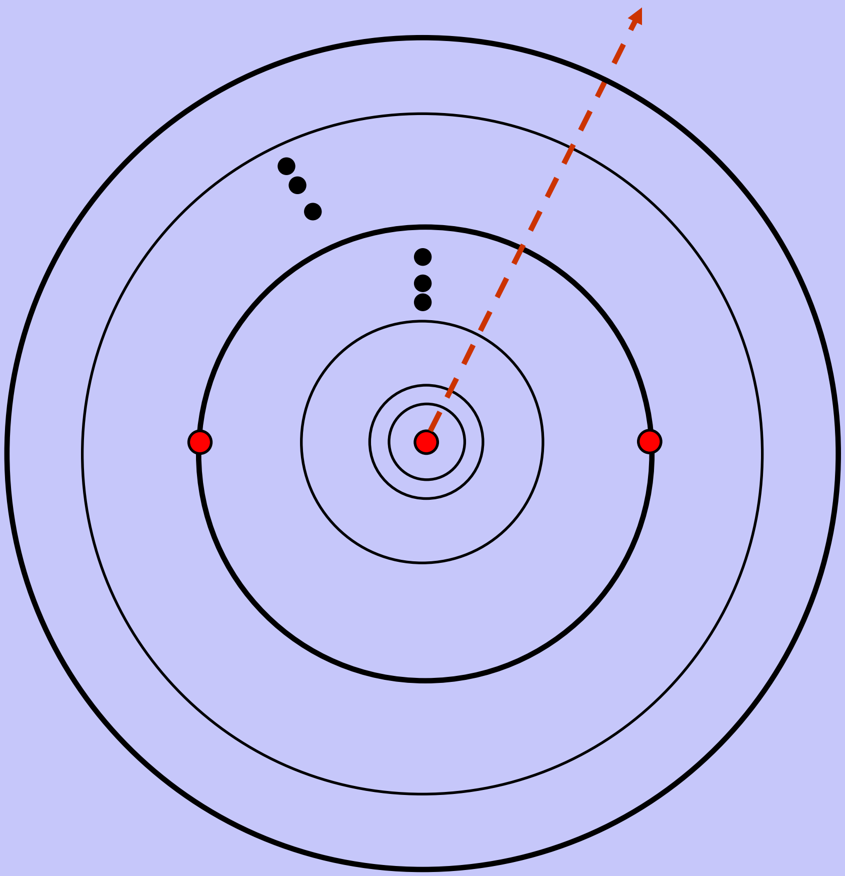
3. Finite Difference Numerical Model (FDNM)

$$C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial T}{\partial r}\right) + q' \qquad C_p = C_v + \rho_i L \frac{d\theta_u}{dT}$$

The Numerical Scheme



Vertical system



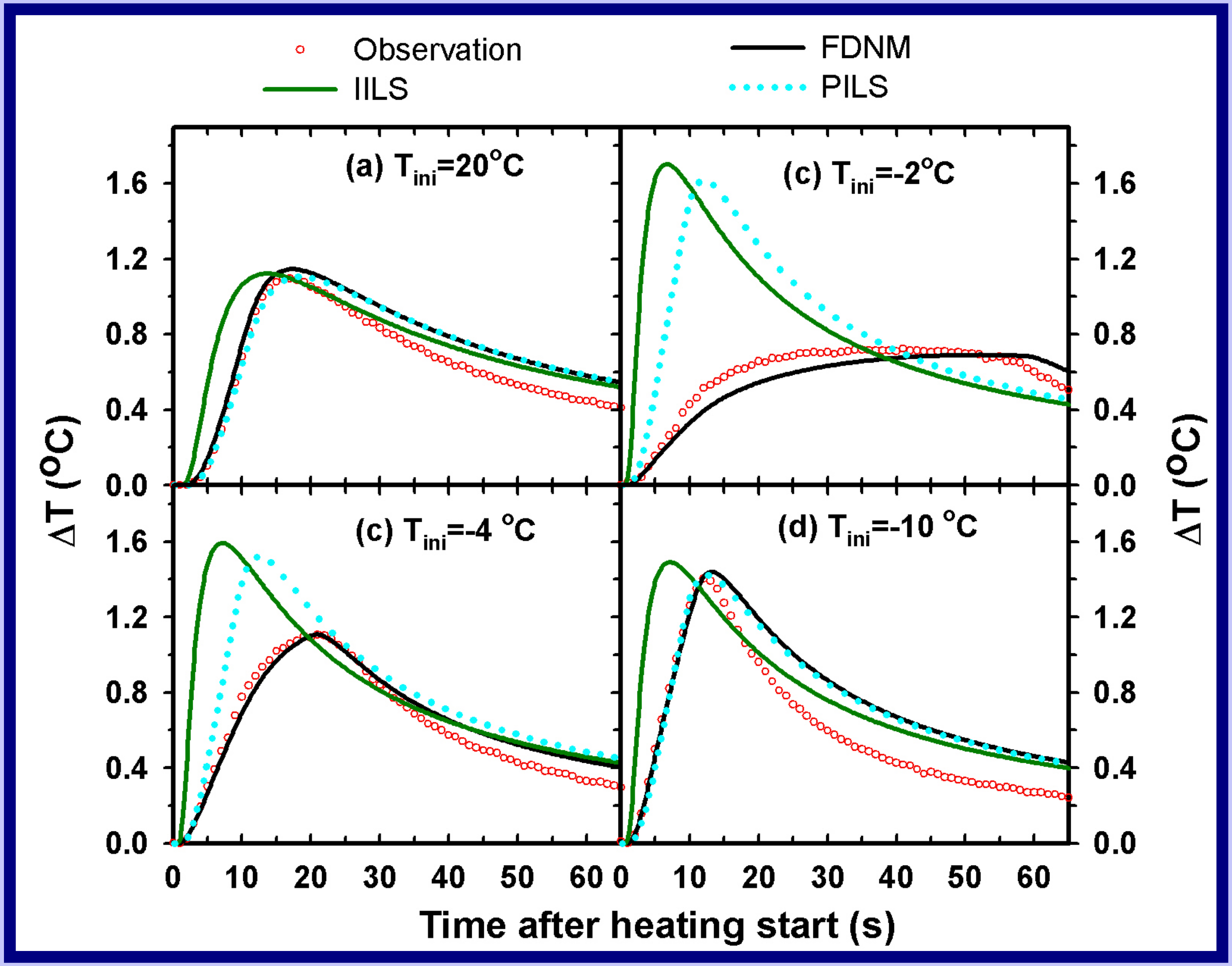
Radial system

Performance of three methods in different initial temperature

$q \approx 900\ \mathrm{J\ m^{-1}}$

$t_0 = 8$ seconds

$s = 1.0$ (Saturated)

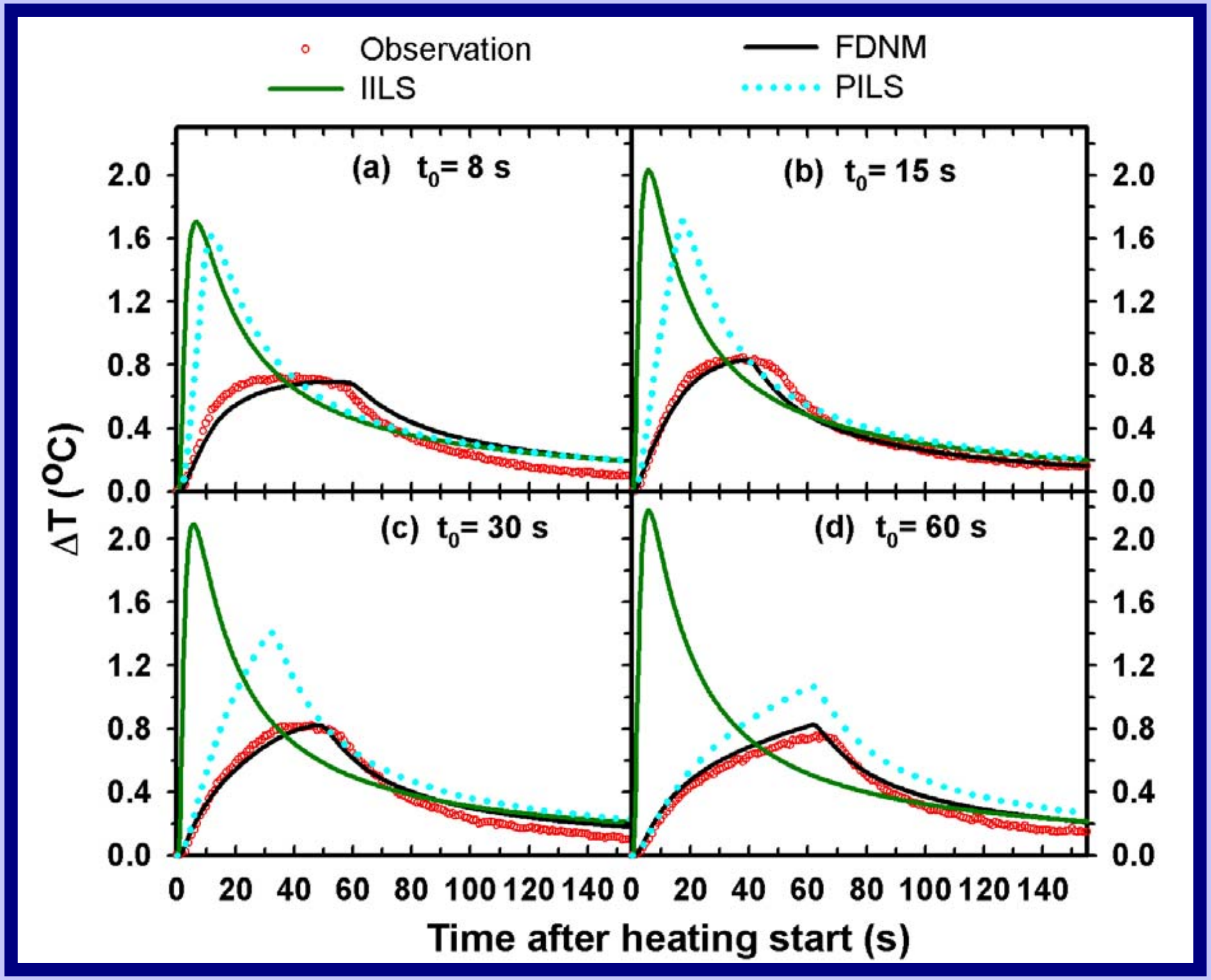


Performance of three methods under different heating time

q ≈ 1000 J m^{-1}

T_{ini} ≈ -2.0 °C

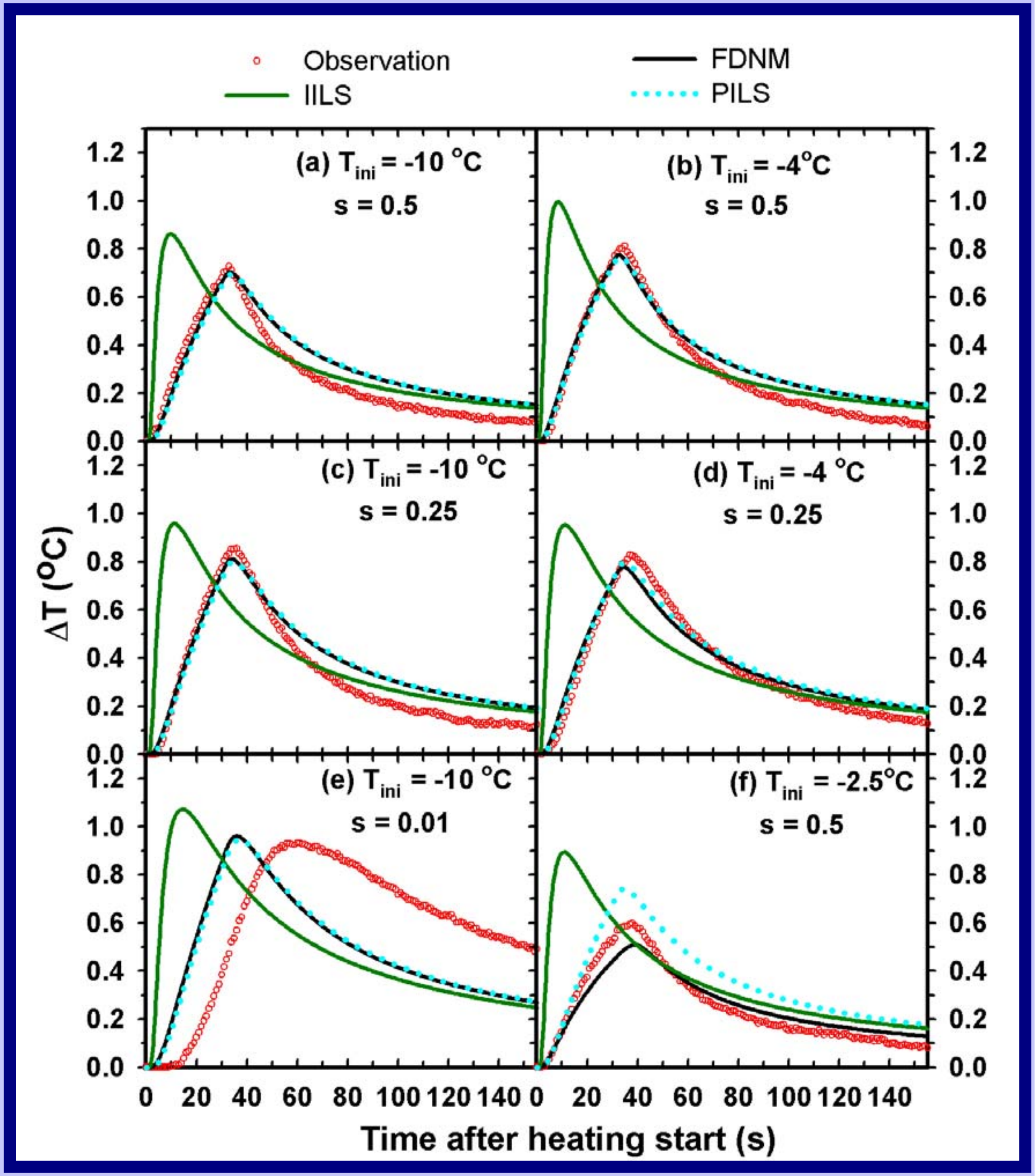
s =1.0 (saturated)



Performance of three methods under different moisture and temperature combinations

$q \approx 450$ J m^{-1}

$t_0 = 30$ seconds

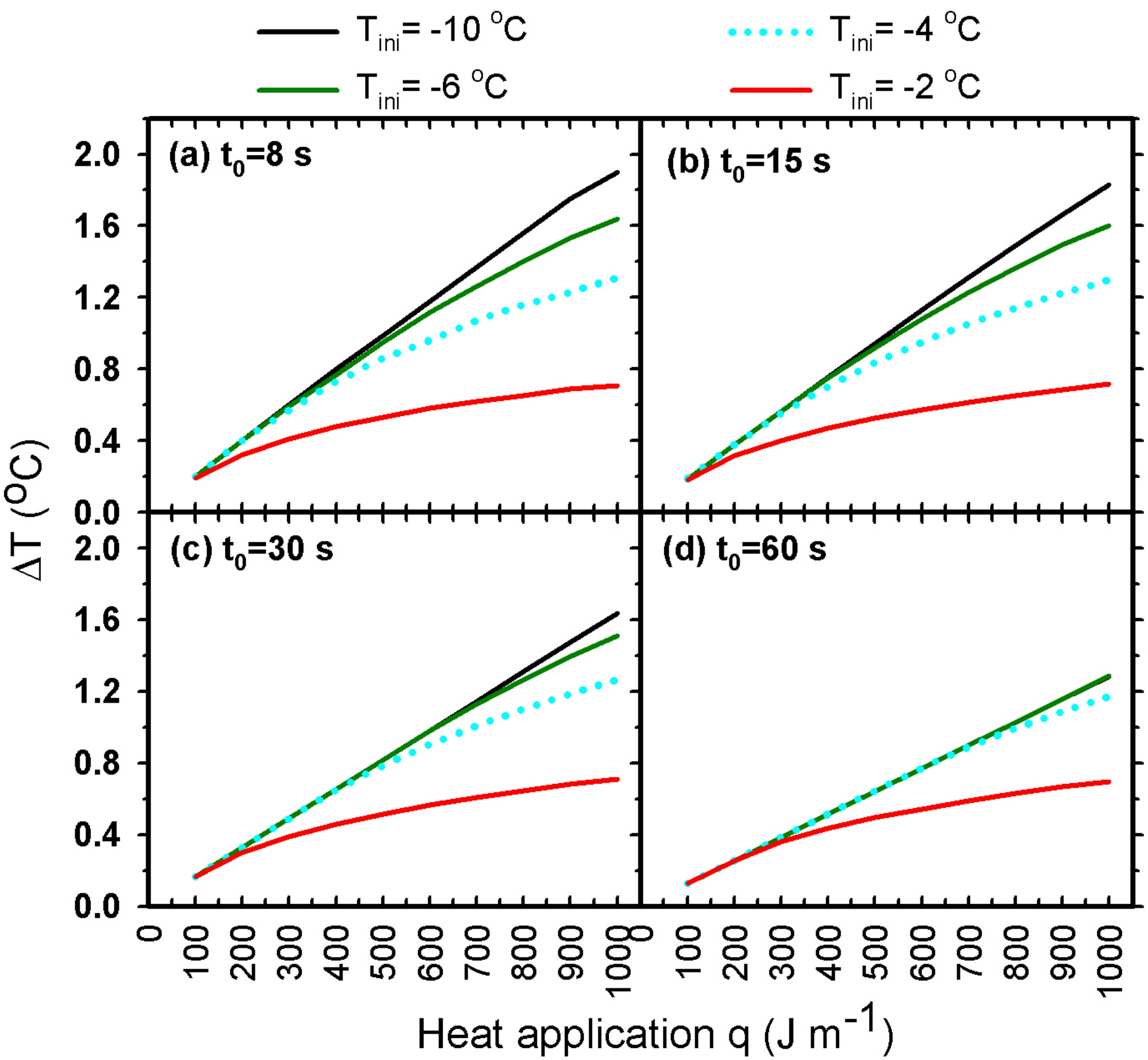


Sensitivity of ΔT to heat application

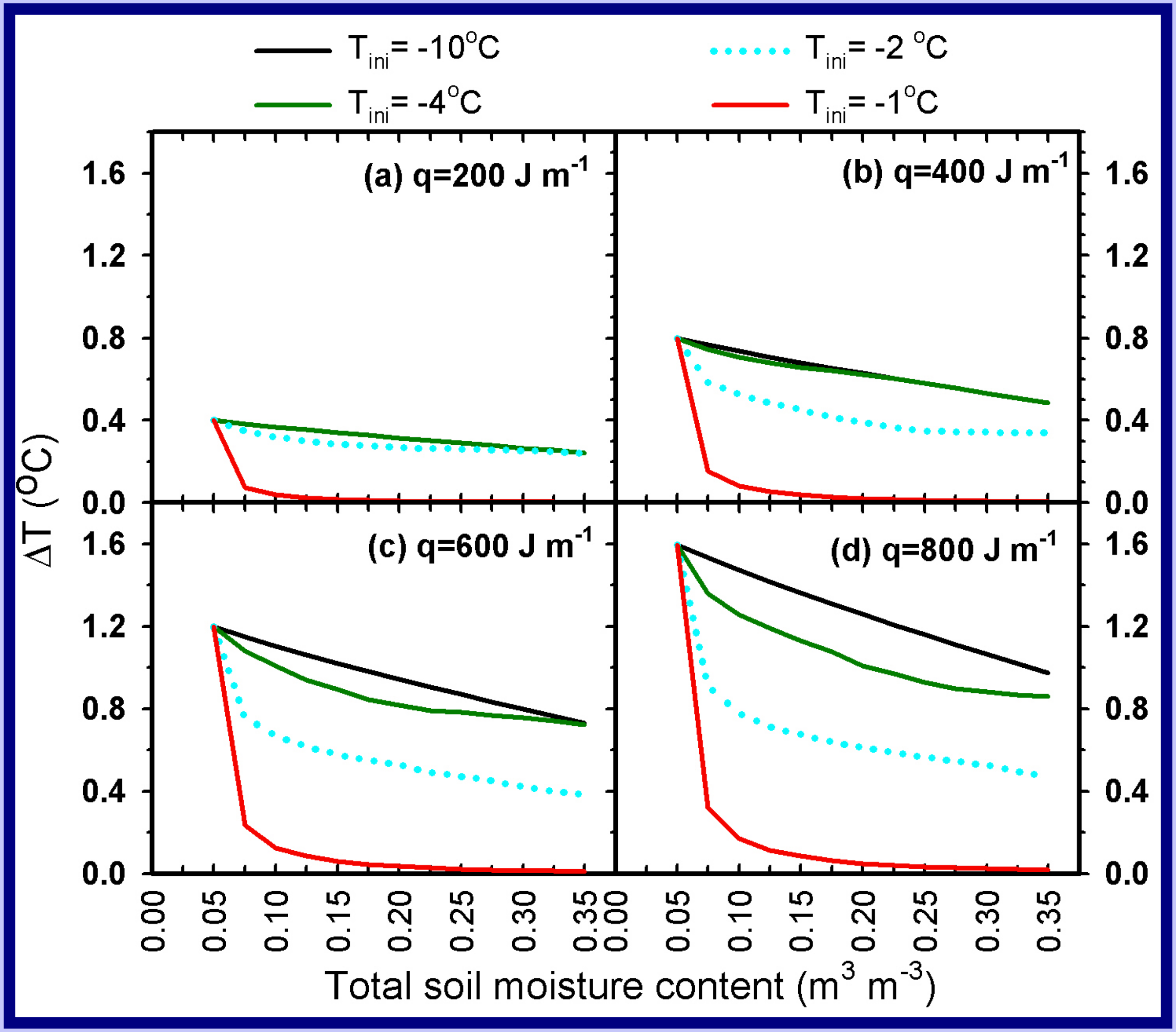
q = 100 ~ 1000 J m^{-1}

T_{ini} = -2 ~ -10 °C

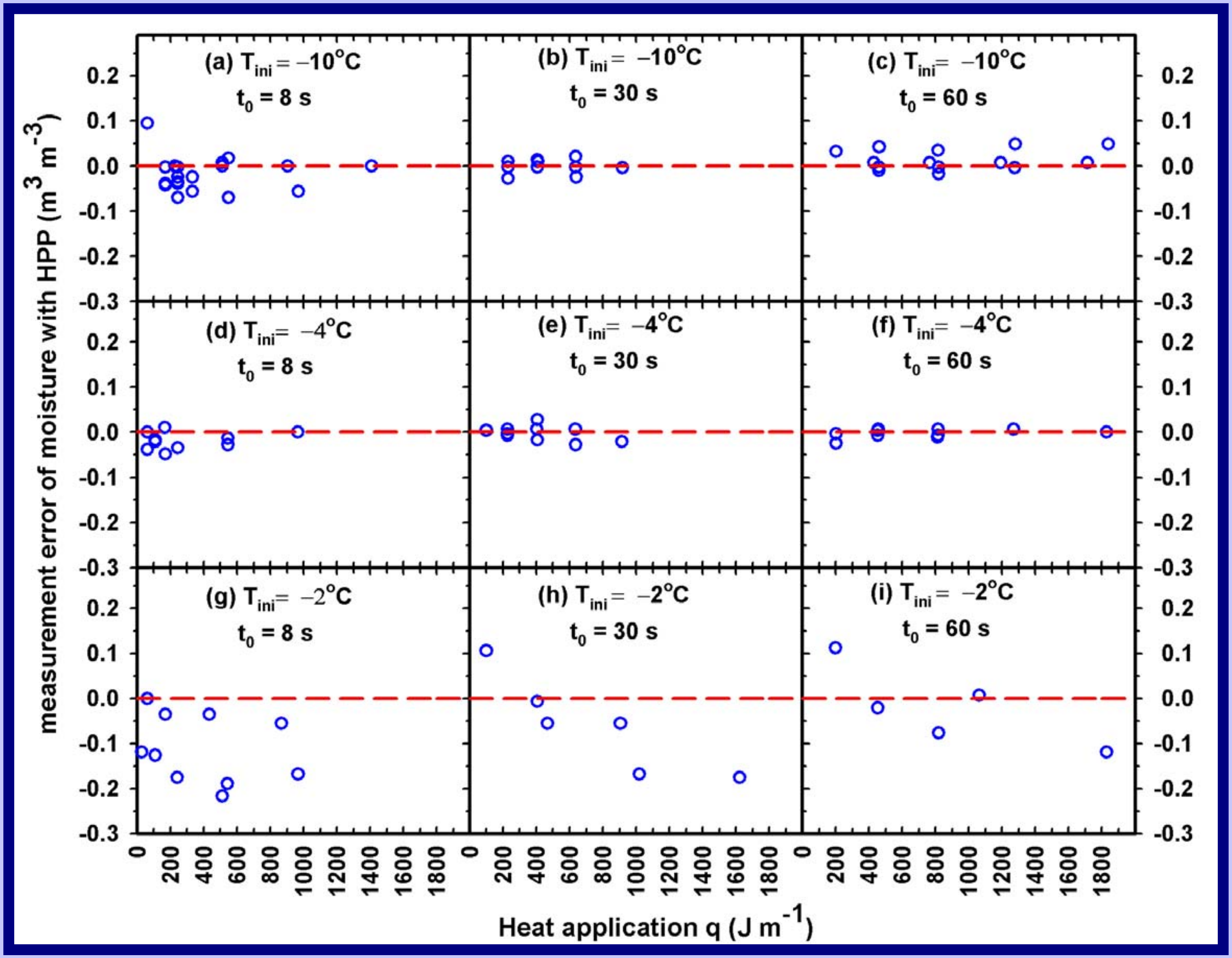
s =0.5



Sensitivity of ΔT to total moisture content (θ) under different heat applications (HPP applicability)



Error distribution of frozen moisture measurement of HPP with calibrated probe spacing (5.0-6.2mm)



Conclusions

- Only the numerical model could represent the measured ΔT curves once ice melting occurs during HPP measurements.
- Below -4°C, ice melting could be controlled to a limited level such that it has little effects to HPP measurements .
- The measurement errors of θ were well within ±0.05 $m^3\ m^{-3}$ under -4°C, but become unpredictable between -2°C and 0°C .
- The failure of HPP between -2°C and 0°C are mainly due to the retarded response of ΔT to changing θ and q.
- The probe spacing is a very sensitive parameter and needs recalibration each time the probe inserted into soil or the soil goes through a thawing/freezing processes.