Modelling Soil Heat and Water Flow as a Coupled Process

GROMIT project: **GRO**und coupled heat pumps **MIT**igation potential

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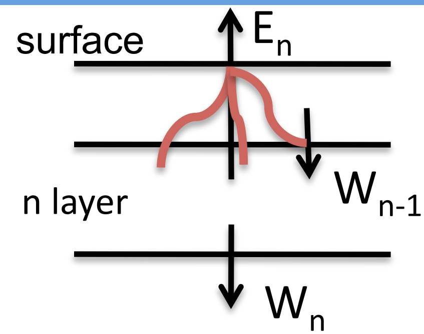
Outline of presentation

- Theory of soil water+thermal transfer in a nutshell
- Model inter-comparison
  - SiSPAT – Water vapour flux + Vertical soil resolution
  - JULES – Water vapour flux + Vertical soil resolution
- Conclusions
- GROMIT project outline
- Questions/ideas

How do LSMs usually simulate soil hydrology and heat transfer ?



A quite simple soil hydrology, i.e. JULES:

4 layers (standard !!): 0.1 , 0.25 , 0.65 , 2.0

$$\frac{dM_n}{dt} = W_{n-1} - W_n - E_n$$

(as in JULES documentation)

Capillary capacity

$$C_{h,n}\frac{\partial \psi_n}{\partial t} = \frac{\partial}{\partial z}\left(K_n \frac{\partial \psi_n}{\partial z} - K_n\right) - \frac{E_n}{\rho_w \Delta z_n}$$

(standard Richard's equation)

Some models consider coupled heat and water movement in the soil

$$C_A \Delta z_n \frac{dT_n}{dt} = G_{n-1} - G_n - J_n \Delta z_n$$

$$G = \lambda \frac{\partial T}{\partial z}$$ Diffusive flux

$$J = c_w W \frac{\partial T}{\partial z}$$ Advective flux

Apparent volumetric heat capacity

But what about … vapour transport ?

Due to soil water potential (isothermal) and thermal gradients…

$$C_{h,n}\frac{\partial \psi_n}{\partial t} = \frac{\partial}{\partial z}\left(\left(K_n + D_{\psi,v,n}\right)\frac{\partial \psi_n}{\partial z} + D_{T,v,n}\frac{\partial T_n}{\partial z} - K_n\right) - \frac{E_n}{\rho_w \Delta z_n}$$

Isothermal vapour conductivity

Thermal vapour diffusivity

$$C_A\frac{\partial T_n}{\partial t} = \frac{\partial}{\partial z}\left[\lambda_n \frac{\partial T_n}{\partial z} + \rho_w L D_{\psi,v,n}\frac{\partial \psi_n}{\partial z}\right] - c_w W \frac{\partial T_n}{\partial z}$$

These gradients will induce soil moisture transport and affect soil moisture distribution, which in turn will affect heat flow

Milly, et. 1982, 1984

Background/Questions

Thermal and isothermal water vapour flux become increasingly important in the top-soil layers (Grifoll et al. 2005, Milly, 1982), in particular when:

- Soil becomes drier, and
- Near the soil surface (from about 20 cm or so, but this depends on the soil texture and soil moisture content)

To what extent will the near-surface vapour fluxes affect:

- Water and heat fluxes in the deeper layers
- Evapo-transpiration
- Heterotrophic respiration
- The performance of a horizontal GSHP
- Climate and weather prediction (NWP)

Model inter-comparison JULES / SiSPAT

Why ? To quantify the changes we expect to find when we introduce thermal vapour conductivity and diffusivity in JULES and compare JULES to a more complete and complex numerical model

- JULES (Joint UK Land Environment Simulator, Cox et al., 1998)
- SiSPAT (Simple Soil Plant Atmosphere Transfer Model, Braud et al., 1995)

Model inter-comparison

SiSPAT

Coupled moisture & Heat flow

Isothermal vapour conductivity

Thermal vapour diffusivity

Boundary conditions

≠ Thermal parameterization

- de Vries (1963)
- constant thermal conductivity
- Laurent &Guerre-Chaley (1995)
- Van de Griend & O'Neill (1986)

Soil vertical resolution:
"As desired"

JULES

Coupled moisture & Heat flow

Boundary conditions

Thermal parameterization

-Farouki (1981)
- Dharssi (2008)
-Verhoef & Vidale (2008)

Soil vertical resolution:
Normally coarser
(standard is 4 layers)

→ We performed sensitivity analyses with SiSPAT
Water vapour flux is now implemented into JULES

Sensitivity test: Anduo site

(Lat. 32.241N, Lon.91.635E, elev. 4700m, Tibet)
Yang, 2005

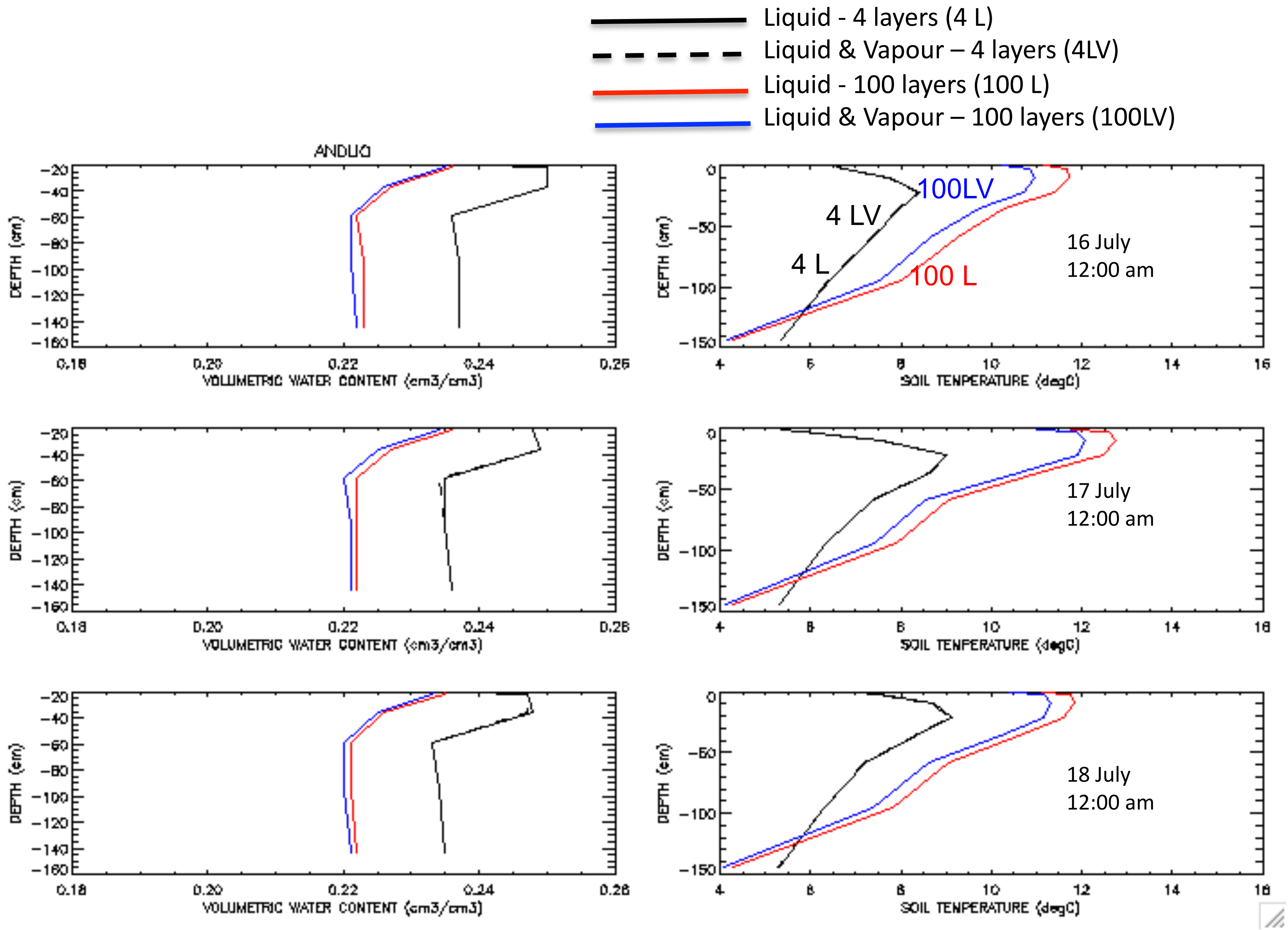
3rd July – 23rd July 1998
(during May surface wetting occurred every two days, followed by predominantly dry months)

Flat grassland, sparse short grasses

Soil parameters derived from soil texture data at 5 cm, 20 cm and 60 cm (Cosby et al., 1984)

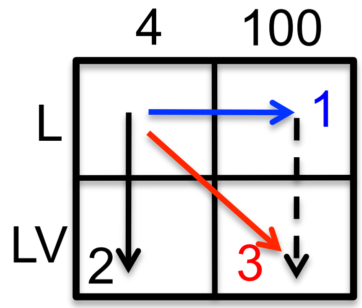
Sensitivity test - SiSPAT

Water Vapour Flux & Vertical Soil Resolution



Increasing soil vertical resolution reduce soil moisture content in the profile

Sensitivity test - SiSPAT
Water Vapour Flux & Vertical Soil Resolution

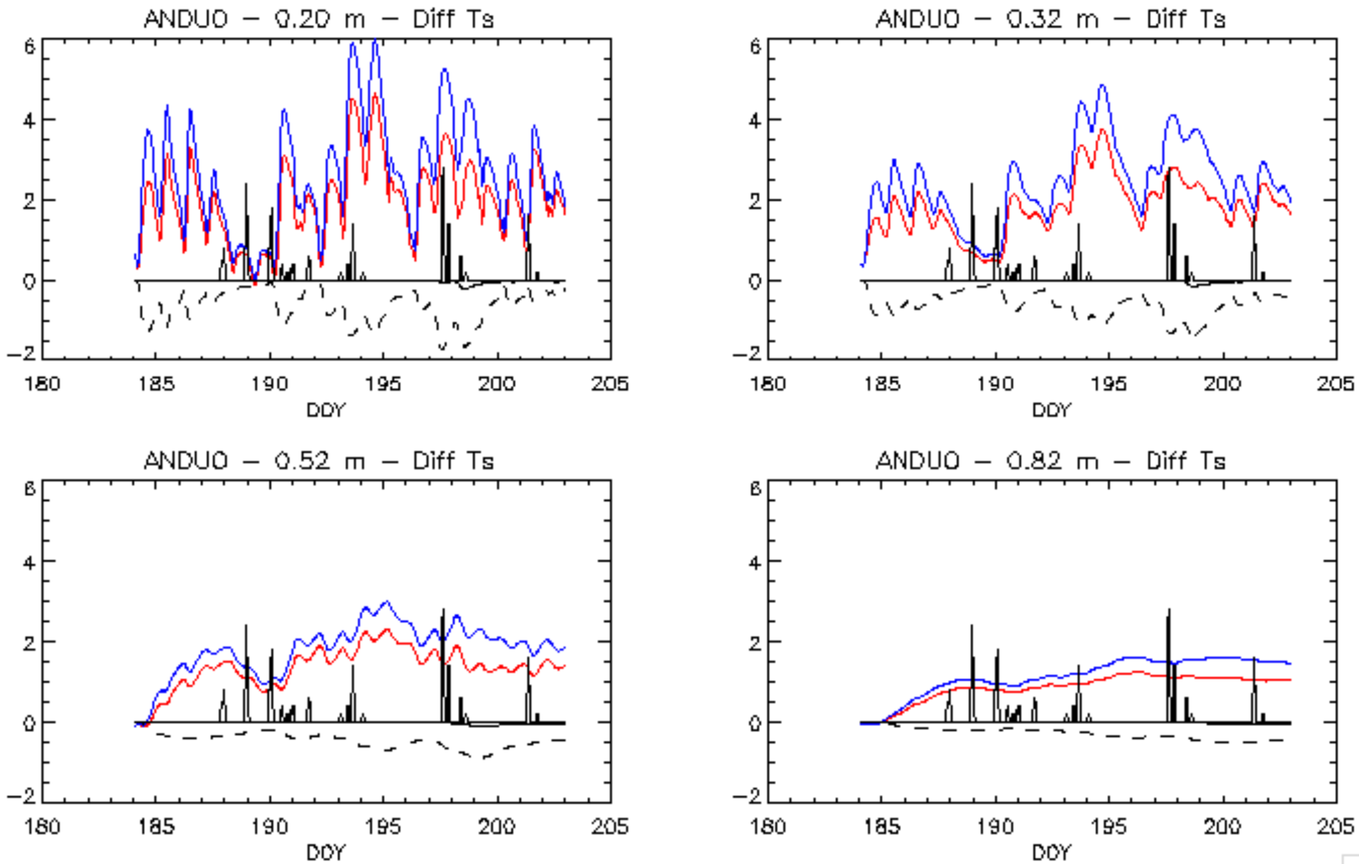


Effect of Soil Vertical Resolution — (100 – 4) L

Effect of Water vapour FLux — 4 (LV – L) / 100 (LV – L)

Combine effect → (100 LV – 4 L)

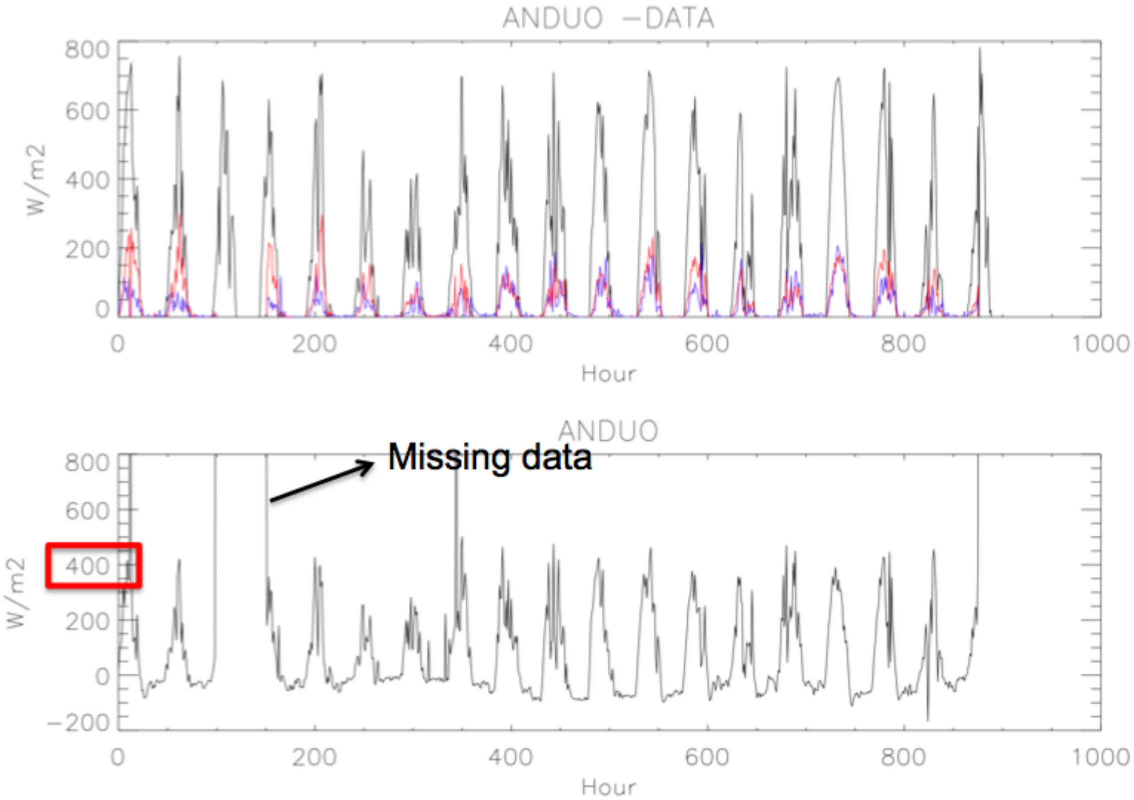
Average temperature at 20 cm is ~ 10 degC



Anduo data

Is there a large soil heat flux to explain such strong sensitivity ?

Regarding the energy balance at Anduo site

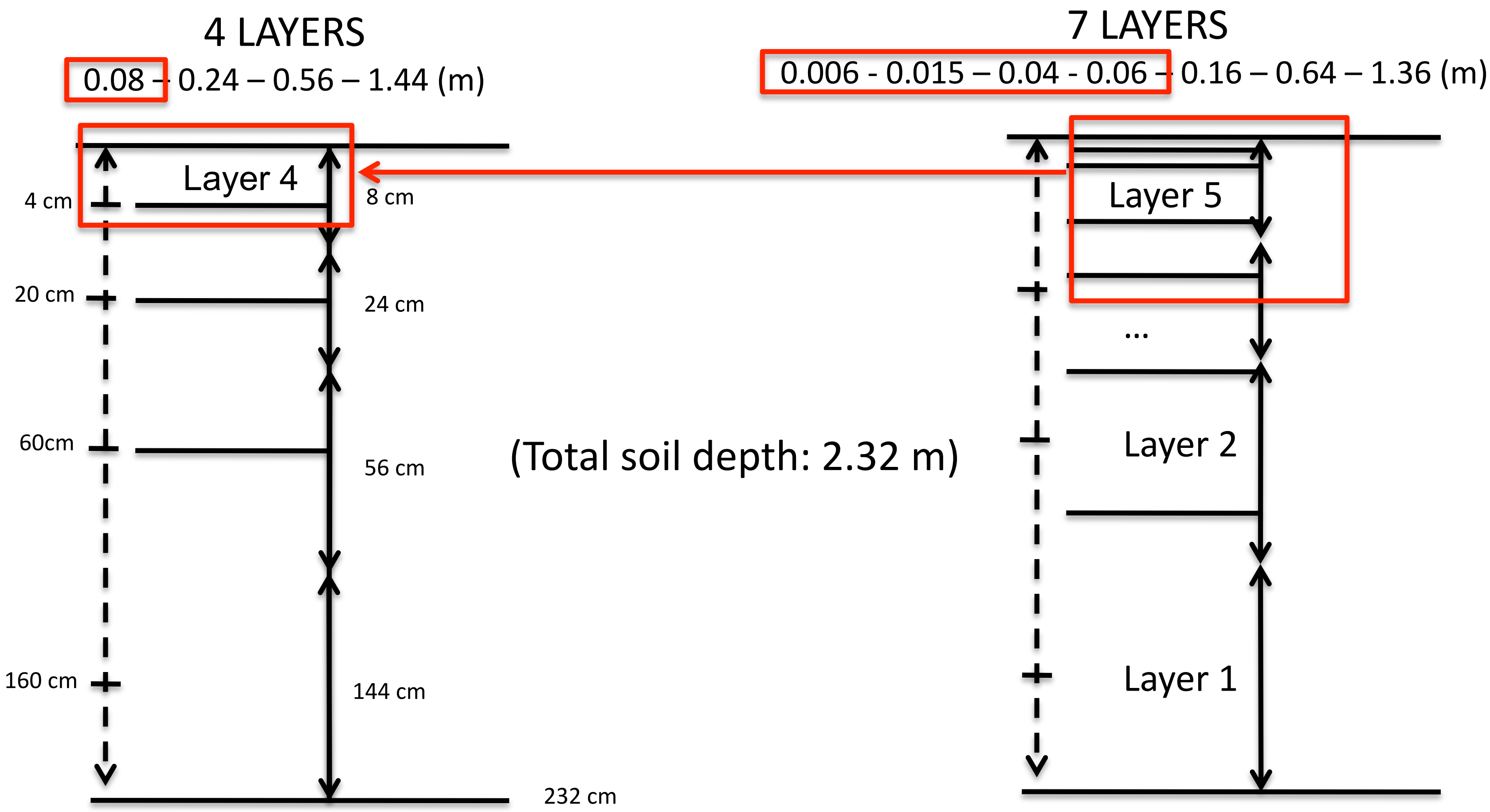


Energy balance (W/m2) at Anduo site (DATA). (Top figure: black line: net radiation; blue line: latent heat; red line: sensible heat) (Below: soil heat flux as the result of the difference between the other terms of the energy balance equation) 18

Conclusions I - SiSPAT

- ✓ Not considering water vapour fluxes increases soil moisture content over the profile
- ✓ Almost no differences in the vertical profiles were found when comparing the four-layer liquid flux simulation (4L) and liquid/vapour simulation (4LV)
- ✓ Overall, water vapour fluxes change temperature gradients in the entire vertical soil profile and introduce an overall surface cooling effect.
- ✓ Increasing the vertical soil resolution introduces an absolute temperature increase over the vertical soil profile
- ✓ The incorporation of water vapour flux in our simulations reduce such temperatures differences for all soil depths

JULES
Vertical Soil Resolution



Layer 4 (~ 8 cm) is now divided in 4 sub-layers

Currently experimenting with a 20-layer vertical grid

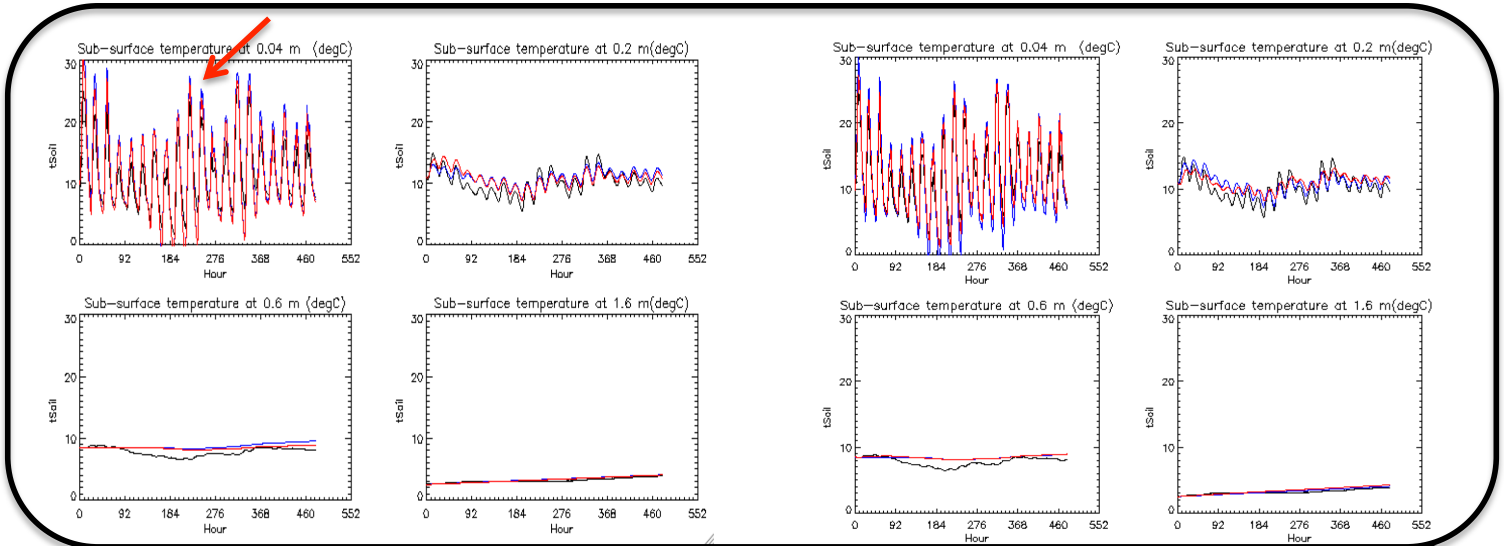
JULES
Water Vapour Flux & Vertical Soil Resolution

<u>From 3 July – 23 July 1998</u>

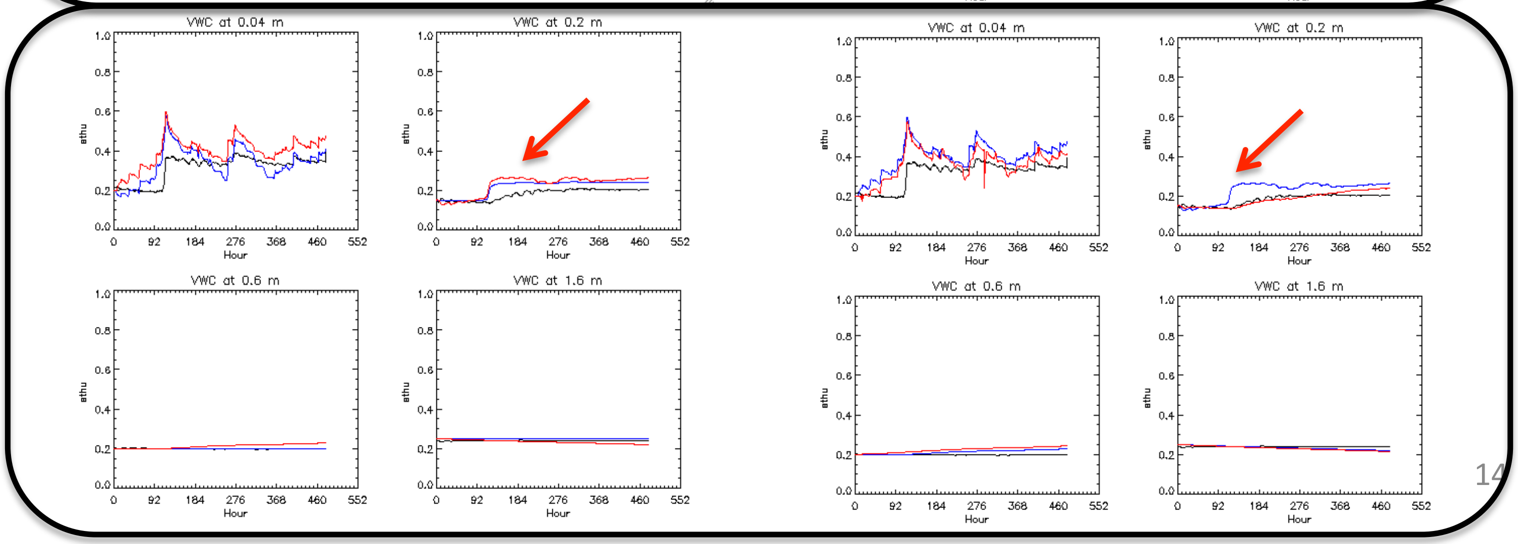
Bare soil: 0.95; C3 grass: 0.05

4L / 4LV   4LV / 7LV

Soil temperature

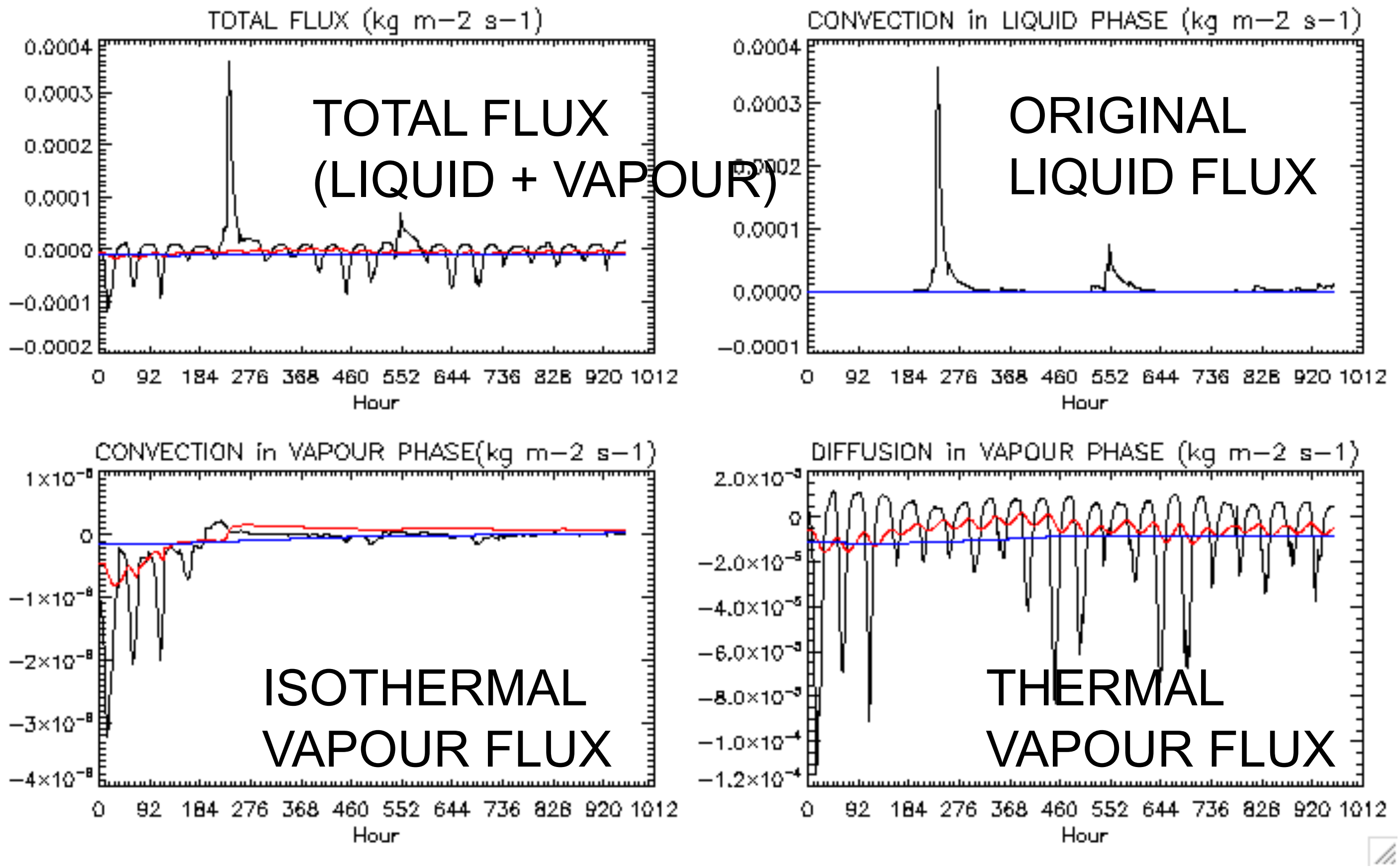


Soil moisture content



JULES
Water Vapour Flux

Simulated water flux for each transport mechanism (JULES-4 layers)



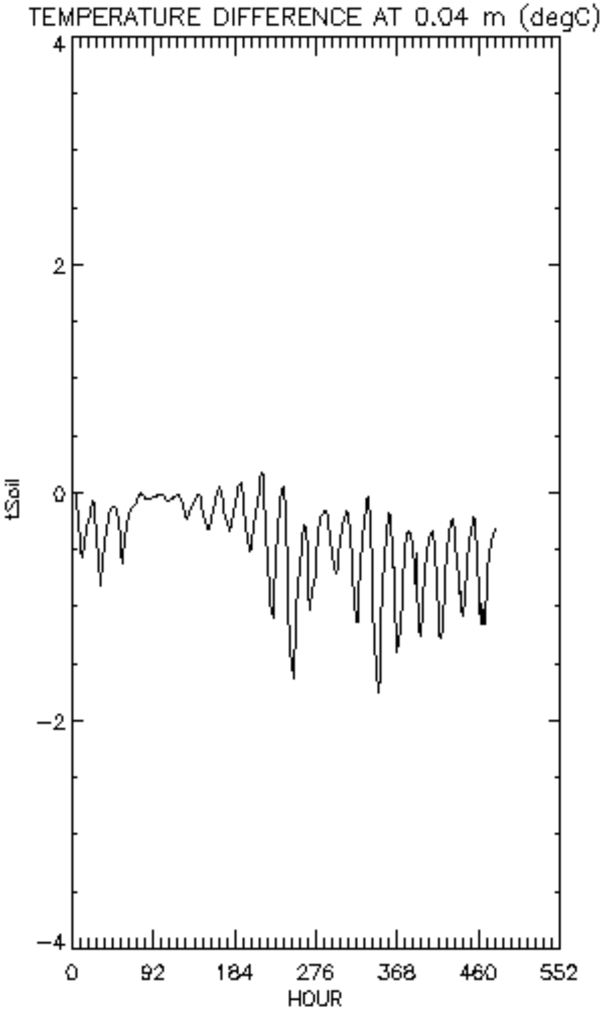
Surface soil layer (0.08m)

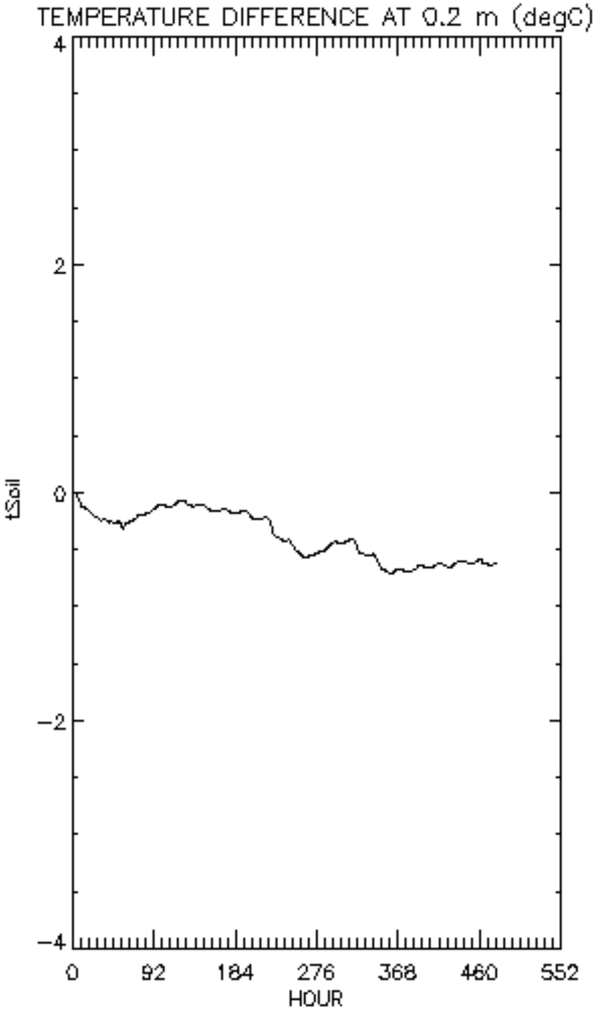
Intermediate soil layer (0.24m)

Deeper soil layer (0.56m)

JULES
Water Vapour Flux

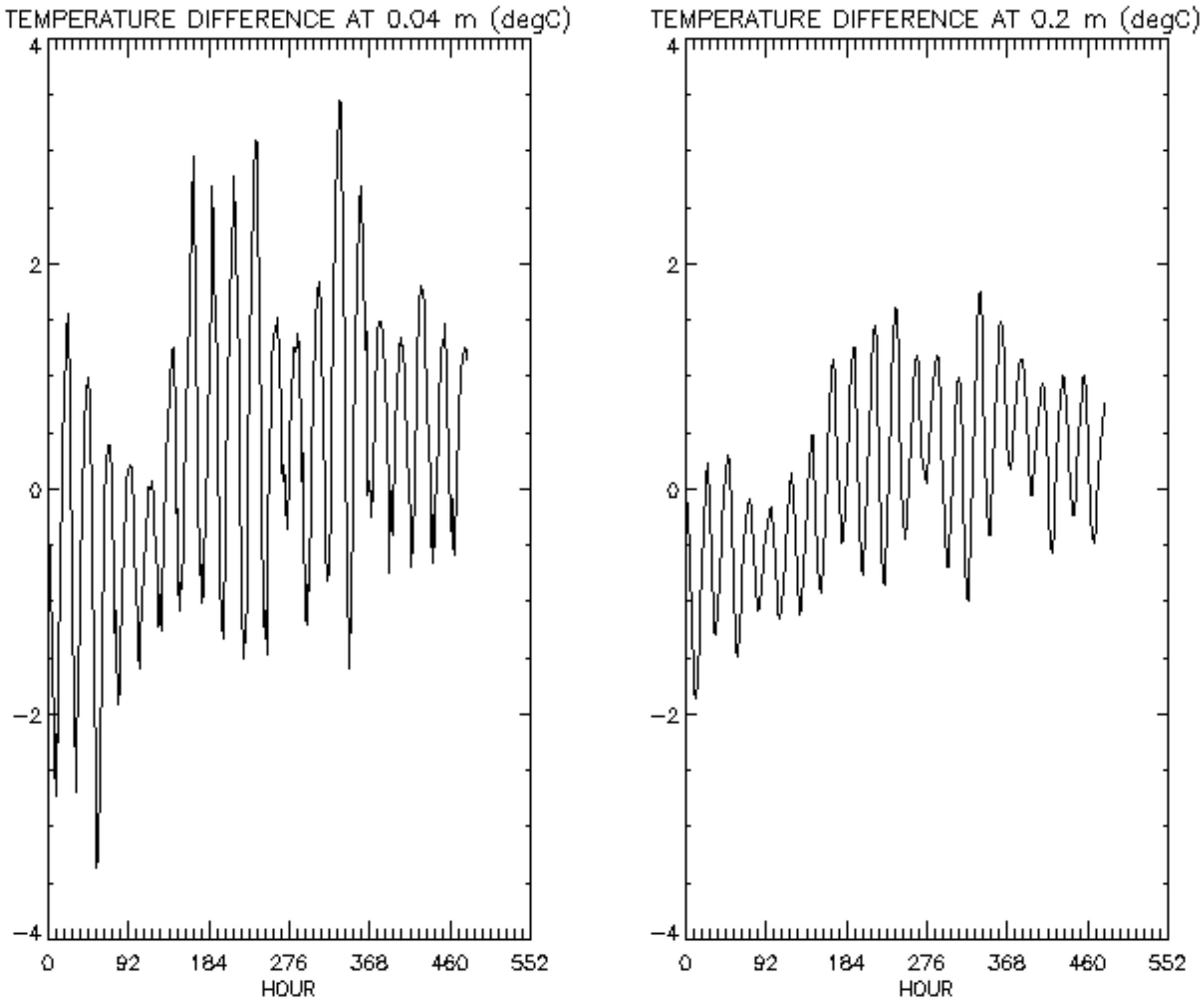
Temperature differences at 4 cm and 20 cm, as a result of the **incorporation of water vapour flux only** at the Anduo site using the JULES model (4LV-4L)





JULES
Water Vapour Flux & Vertical Soil Resolution

Soil temperature differences at 4 cm and 20 cm, as a result of **increasing the vertical resolution only, with vapour flux implemented,** at the Anduo site for the JULES model (7LV-4LV)



Conclusions I - JULES

- ✓ Water vapour flux varied with soil texture, depth and soil moisture content
- ✓ Overall our results suggest that incorporating water vapour fluxes change temperature gradients in the entire soil profile, and introduces an overall surface cooling effect
- ✓ Increasing the vertical soil resolution increases the temperature over the entire soil profile. Now testing the use of 20 layers in JULES
- ✓ Thermally driven vapour fluxes rather than vapour flow as a result of soil water potential gradients seem to cause temporal and spatial (vertical) soil temperature variability

Conclusions II

A multi-layer scheme configuration may improve:

- Soil water dynamics, heat transfer and coupling of these processes
- Evapo(trans)piration
- Soil-Vegetation-Atmosphere coupling

It must be a compromise between:

- Numerical aspects (JULES seems to have problems when dealing with layer thickness between 1-6 mm)
- Assimilation data (SMOS): upper soil layers should be at most 3 cm thick

Conclusions II

- To what extent is the variability found in the propagation of soil temperature into deeper soil layers, and the variability of surface temperature due to:

  - Neglecting important processes not considered previously in most LSMs

  - Incorrect parameterization of the soil thermal properties and/or

  - Soil vertical resolution

- Further sensitivity tests will be necessary to reach further conclusions

Aims of GROMIT project

- Modelling soil heat and water flow as a coupled system:
    - Better understanding of the processes involved and their interactions
    - Identify which processes are missing
- Application for Impacts work :
    - Renewable Energy Sector

      What are the best locations in the UK where to deploy ground source heat pumps ? What is the optimal depth ?

      What is the CO_2 emission mitigation potential of ground source heat pumps on a 1-km resolution over the UK ?

GROMIT
Ground Source Heat Pumps – Outline

- What is a Ground Source Heat Pump?

  Renewable energy source

- How can we estimate the mitigation potential of a GSHP

  – Tools >> JULES model

  We need >> Correct predictions of soil moisture content and soil temperature

  – Measurements >> Field campaigns (UK)

  We need >> Understand which processes we need to take into account

Which issues may be important?

- Water vapour flux
- Soil vertical resolution
- Infiltration Rates / Evaporation
- Upper and Lower Boundary Condition

  (energy balance/ground water level, which vary in time and space)
- Thermal soil properties
- Cooling/melting could also be important

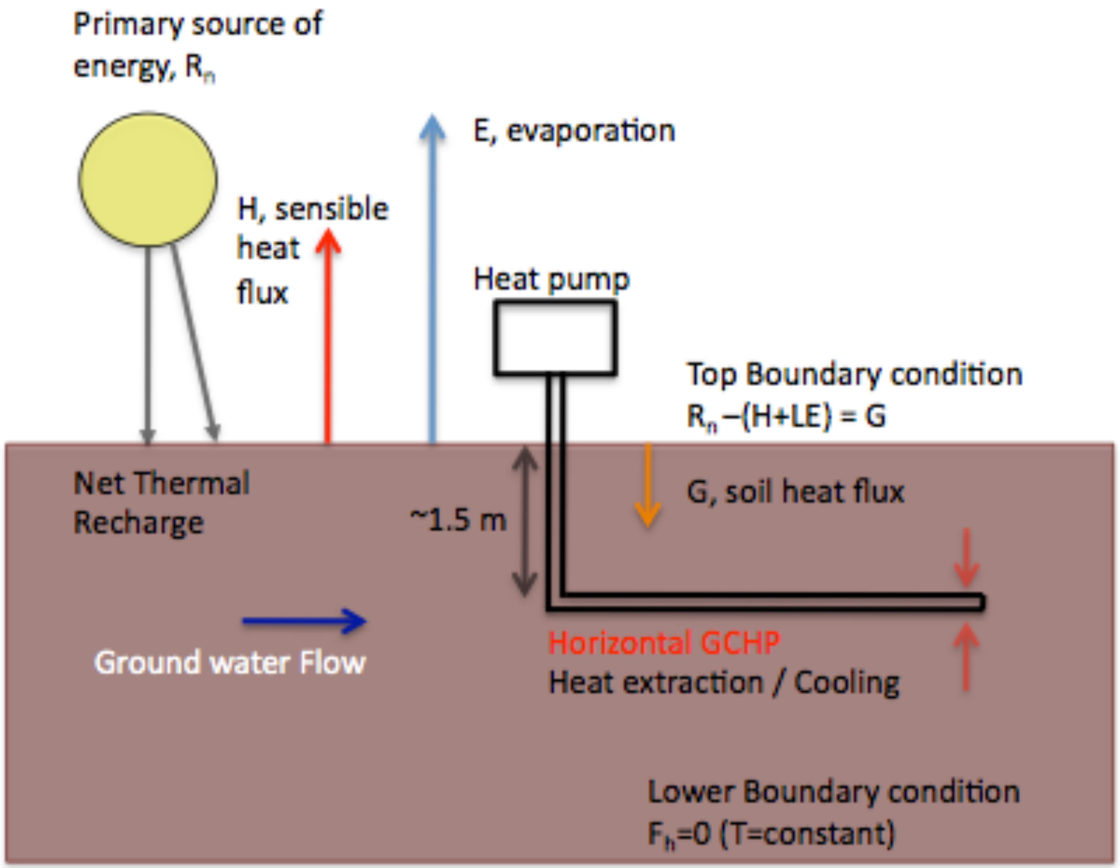


Diagram: Heat and water exchange processes near GCHP

THE REAL WORLD !!

Field campaign 2th October 2009
Drayton St Leonard (UK)

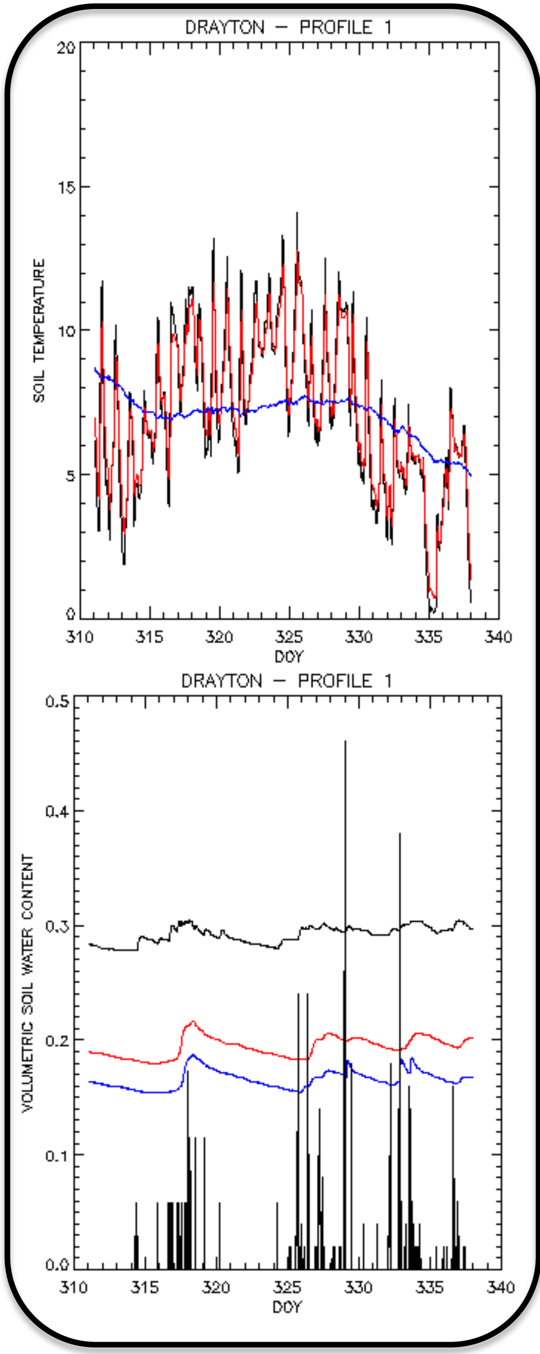
GSHP Profile over ~ 1m:
- 8 Thermistors
- 6 Thetaprobes

Cooling near the slinky due to heat extraction… how will this affect the water and heat transfer and hence the performance of GSHP…

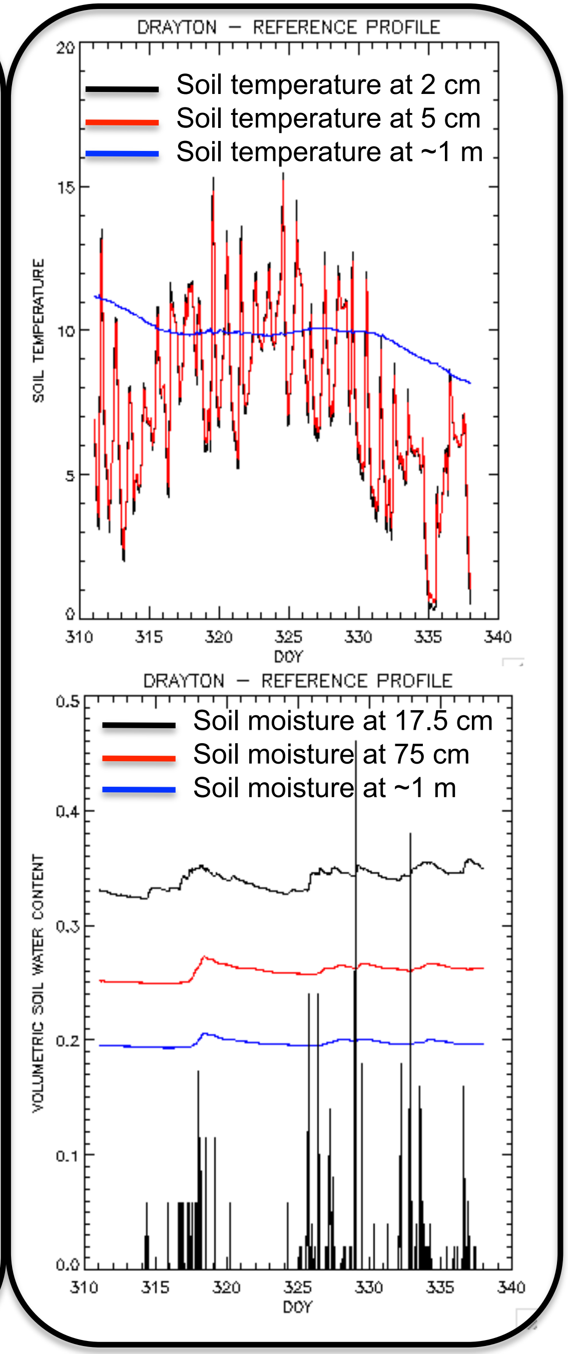
4 trenches every 5 m

2 Profiles:
-GSHP profile
-Reference profile

GSHP PROFILE



REFERENCE PROFILE



Any questions / Ideas ??

GROMIT is an excellent opportunity
to address all these issues !!

Thanks !!