A High Temperature Heat Injection Test – Numerical Modelling and Sensitivity Analysis

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Motivation

- The parameter sensitivities for High-Temperature-ATES have to be understood for:

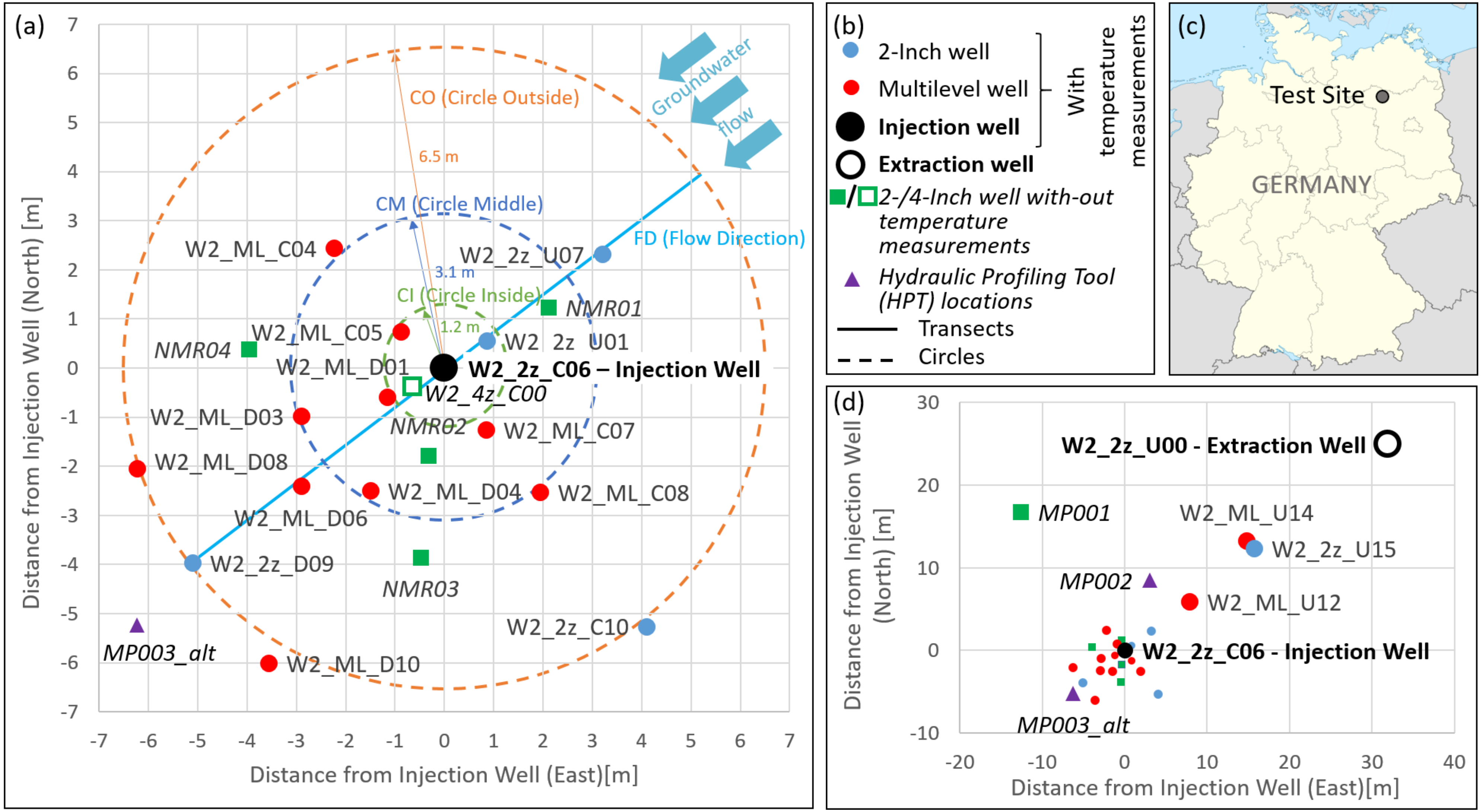
➢ Focusing parameter investigation efforts in the field

➢ Reliable numerical modeling

➢ Dimensioning and regulatory approval

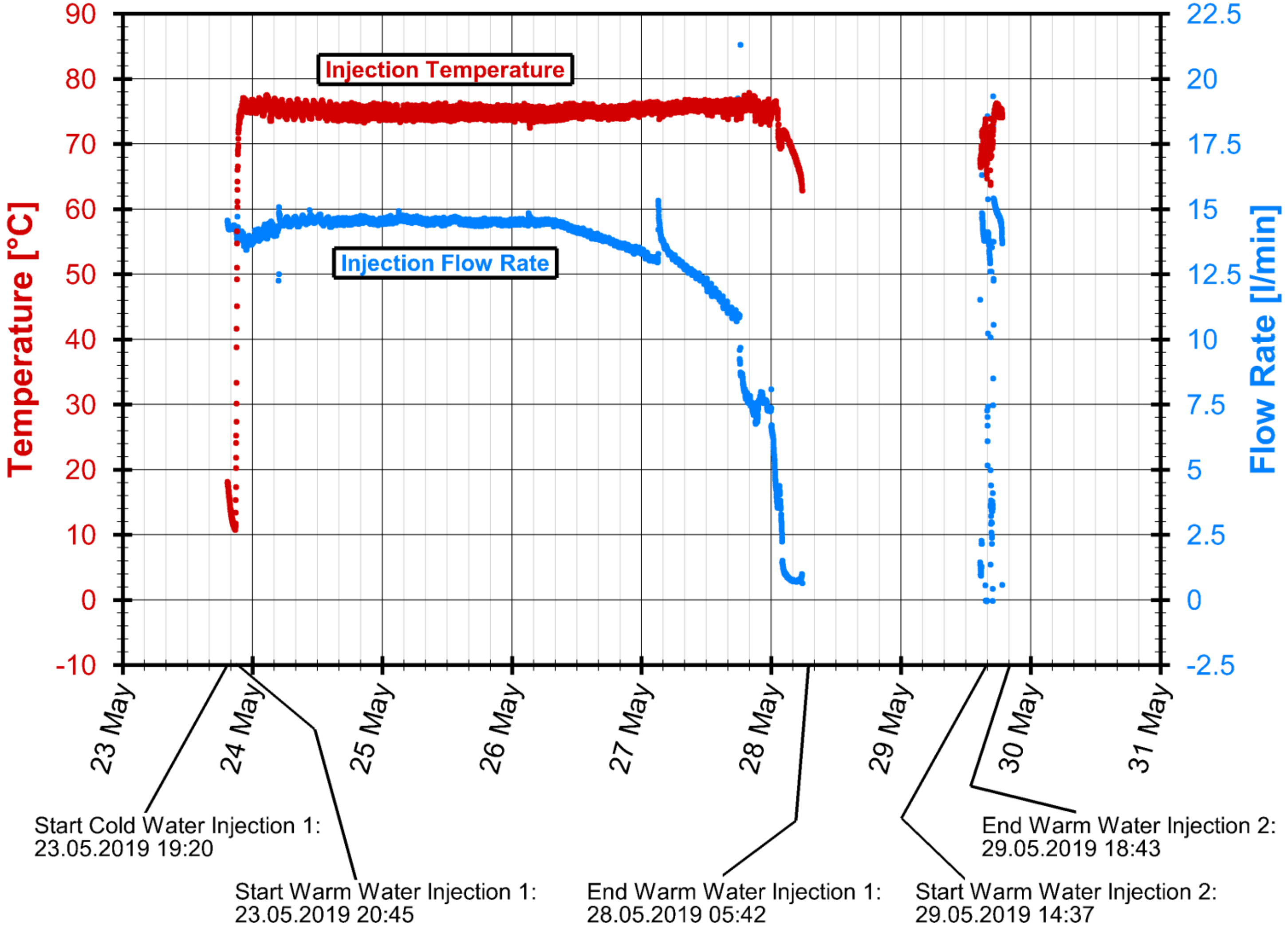
- To this end, we conducted a sensitivity study for a High-Temperature Heat Injection Test (HIT) by numerical modelling
- The focus was to examine, whether the parameter ranges derived from the field site investigation could be further constrained
- The numerical model of the induced coupled thermo-hydraulic processes is thus used for the inversion of parameter ranges through comparison of simulated and measured temperatures induced by the HIT

Test site



Overview over the test site with a) the wells near the injection well, b) a legend, c) the location of the test site in northern Germany and d) the wells of the whole test site (Heldt et al., 2021).

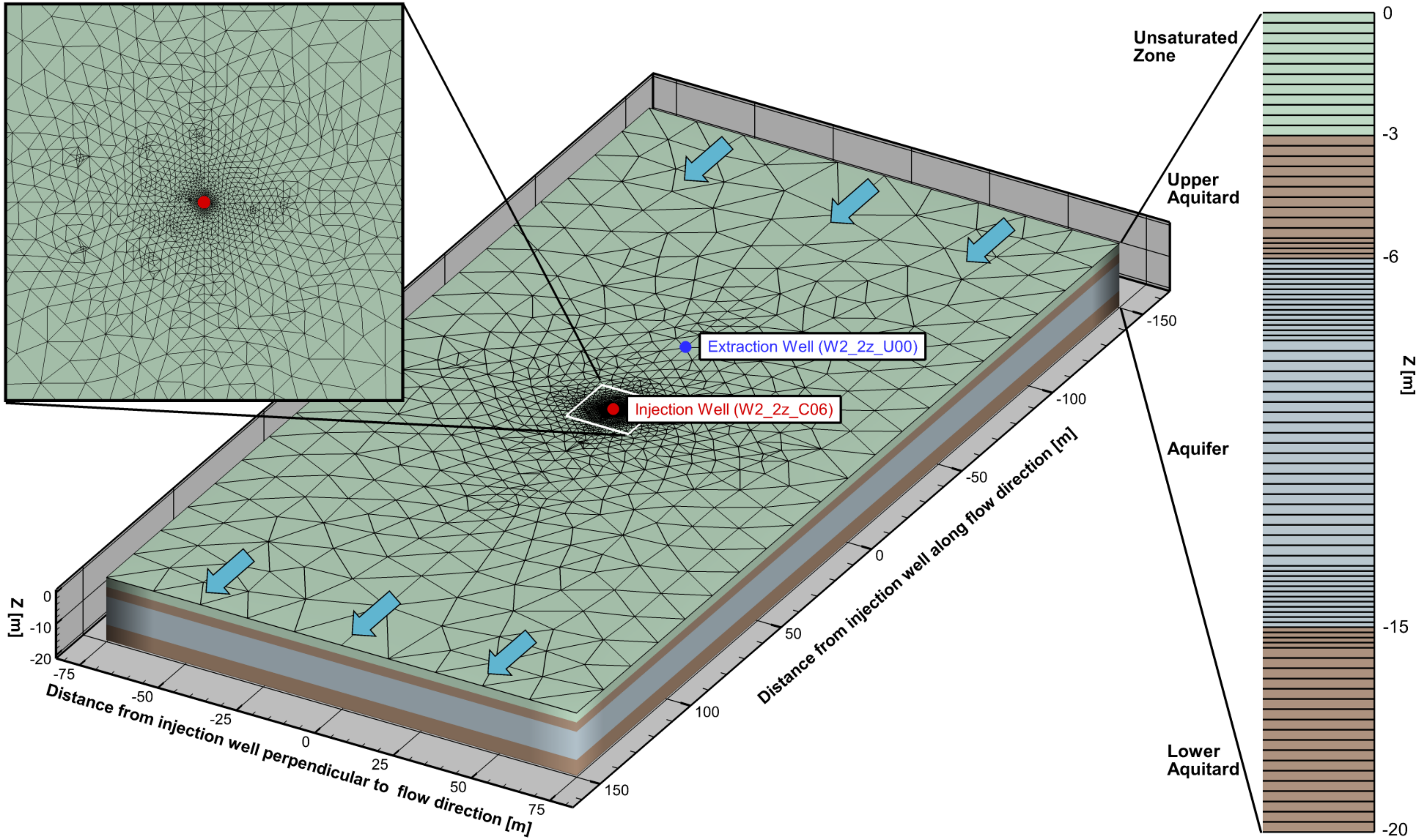
Injection scheme



Injection flow rate and injection temperature during the heat injection experiment.

(Heldt et al., 2021)

Geometry and mesh of the numerical model



Three-dimensional, horizontal and vertical view of the model domain with the numerical mesh, injection and extraction wells and direction of ambient groundwater flow indicated. The horizontal view of the numerical mesh around the injection well has a dimension of 20 m x 20 m. (Heldt et al., 2021)

Parameters of the basis scenario and the sensitivity scenarios

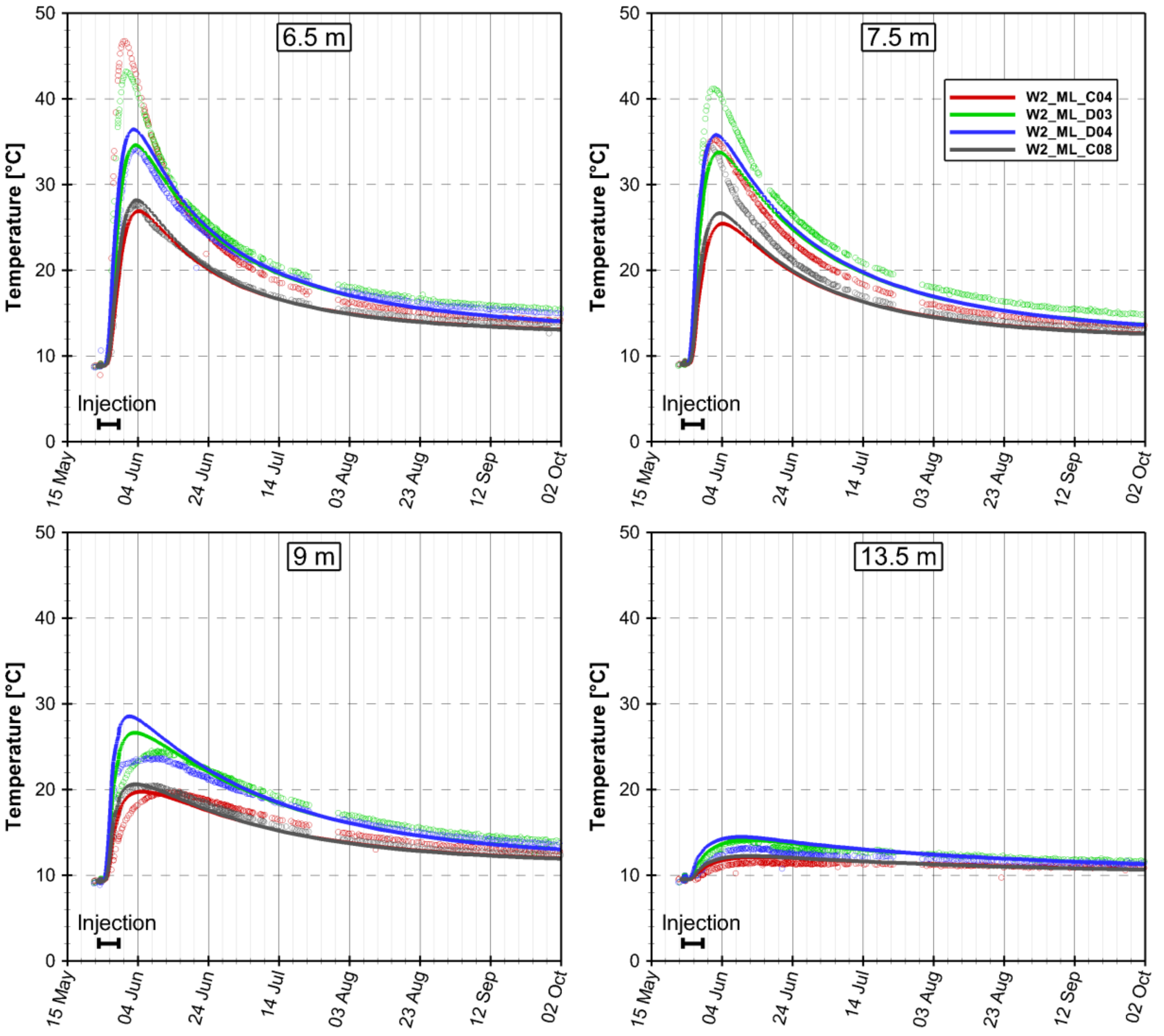
- Parameter were varied within the ranges of field measurements and additional scenarios were considered

Parameter	k_f^h	k_f^v	S_0	λ	$c \cdot \rho$	v_a	n	β_l	β_t
Unit	m/s	m/s	1/m	W/(m·K)	MJ/(m³·K)	m/d	-	m	m
Basis	**$3.19 \cdot 10^{-4}$**	**$1.33 \cdot 10^{-4}$**	**$3.39 \cdot 10^{-5}$**	**3.00**	**2.70**	**0.070**	**0.34**	0.001	0.001
Sensitivity analysis scenarios	$9.20 \cdot 10^{-6}$	$3.71 \cdot 10^{-5}$	$4.68 \cdot 10^{-6}$	1.57	2.25	0.036			
	$3.00 \cdot 10^{-5}$	**$7.04 \cdot 10^{-5}$**	**$1.26 \cdot 10^{-5}$**	1.84	2.47	**0.050**			
	$6.60 \cdot 10^{-5}$	**$9.69 \cdot 10^{-5}$**	**$8.62 \cdot 10^{-5}$**	2.17	**2.58**	**0.059**			
	$1.45 \cdot 10^{-4}$	**$2.24 \cdot 10^{-4}$**	$2.19 \cdot 10^{-4}$	**2.55**	**2.97**	**0.079**			
	$4.78 \cdot 10^{-4}$	**$4.19 \cdot 10^{-4}$**		**2.77**	**3.26**	**0.090**			
	$7.15 \cdot 10^{-4}$	$7.44 \cdot 10^{-4}$		**3.19**	3.94	0.116			
	$1.60 \cdot 10^{-3}$	$1.32 \cdot 10^{-3}$		**3.40**					
	$8.05 \cdot 10^{-3}$			3.85					

Bold values are within the field measurement range.

k_f^h: horizontal hydraulic conductivity; k_f^v: vertical hydraulic conductivity; S_0: specific storage; λ: thermal conductivity; $c \cdot \rho$: heat capacity; v_a: effective groundwater flow velocity; n: porosity; β_l: longitudinal thermal dispersivity; β_t: transversal thermal dispersivity.

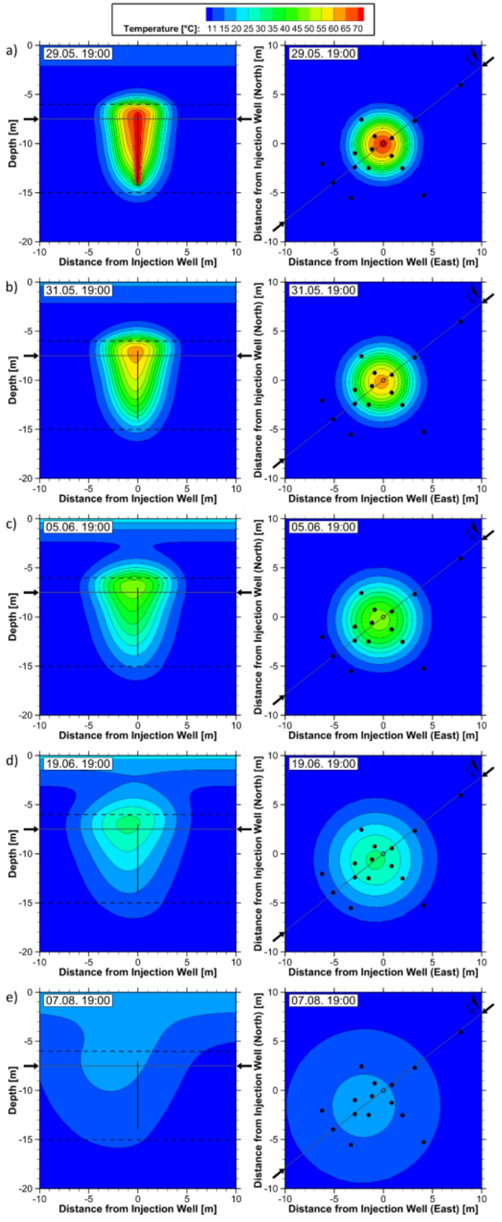
Basis scenario



(Heldt et al., 2021)

Simulated (lines) and measured (circles) temperatures in different depths at the wells of the "Circle Middle", with a distance to the injection well of ~2.9 m. No temperatures were measured at well W2_ML_D04 at 7.5 m depth and at well W2_ML_C08 at 13.5 m depth due to defective thermocouples.

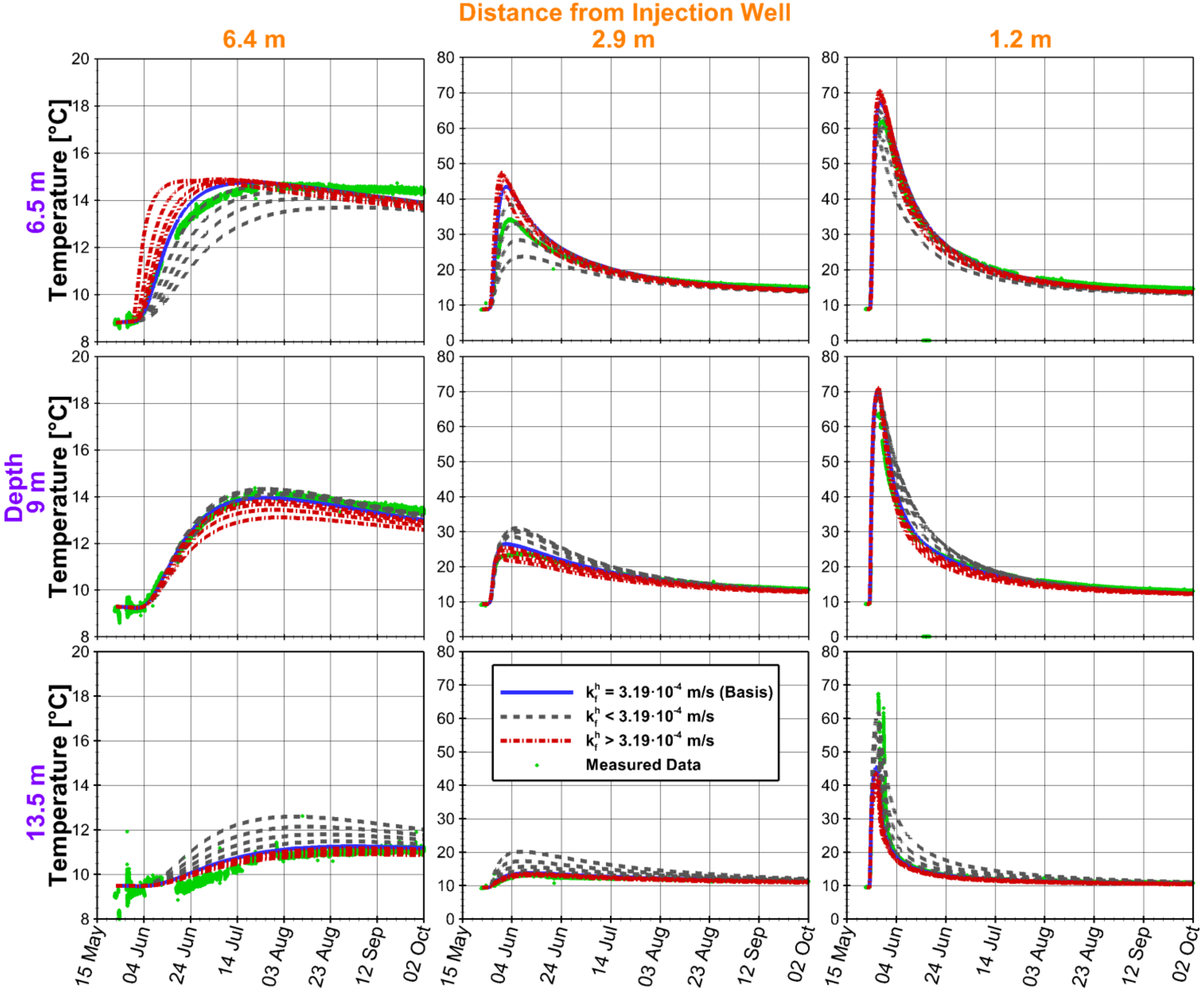
Simulated temperatures depicted on a vertical cross-section (left) and horizontal (right) plane through the model area. a) at the end of the injection, and b) two days; c) one week; d) three weeks and e) ten weeks after the end of injection. The horizontal section is shown for a depth of 7.5 m below ground level, i.e., near the top of the aquifer. The vertical section is taken along the profile "FD (Flow Direction)", with groundwater flow from the top right to the lower left along the indicated profile. The black line in the vertical cross-section and the open circle in the horizontal plane mark the open screen section and the location of the injection well, while the filled circles in the horizontal plane mark the temperature measuring locations and the grey horizontal line in the vertical cross-section marked by the arrows indicates the position of the horizontal plane.



(Heldt et al., 2021)

Temperature changes – horizontal hydraulic conductivity

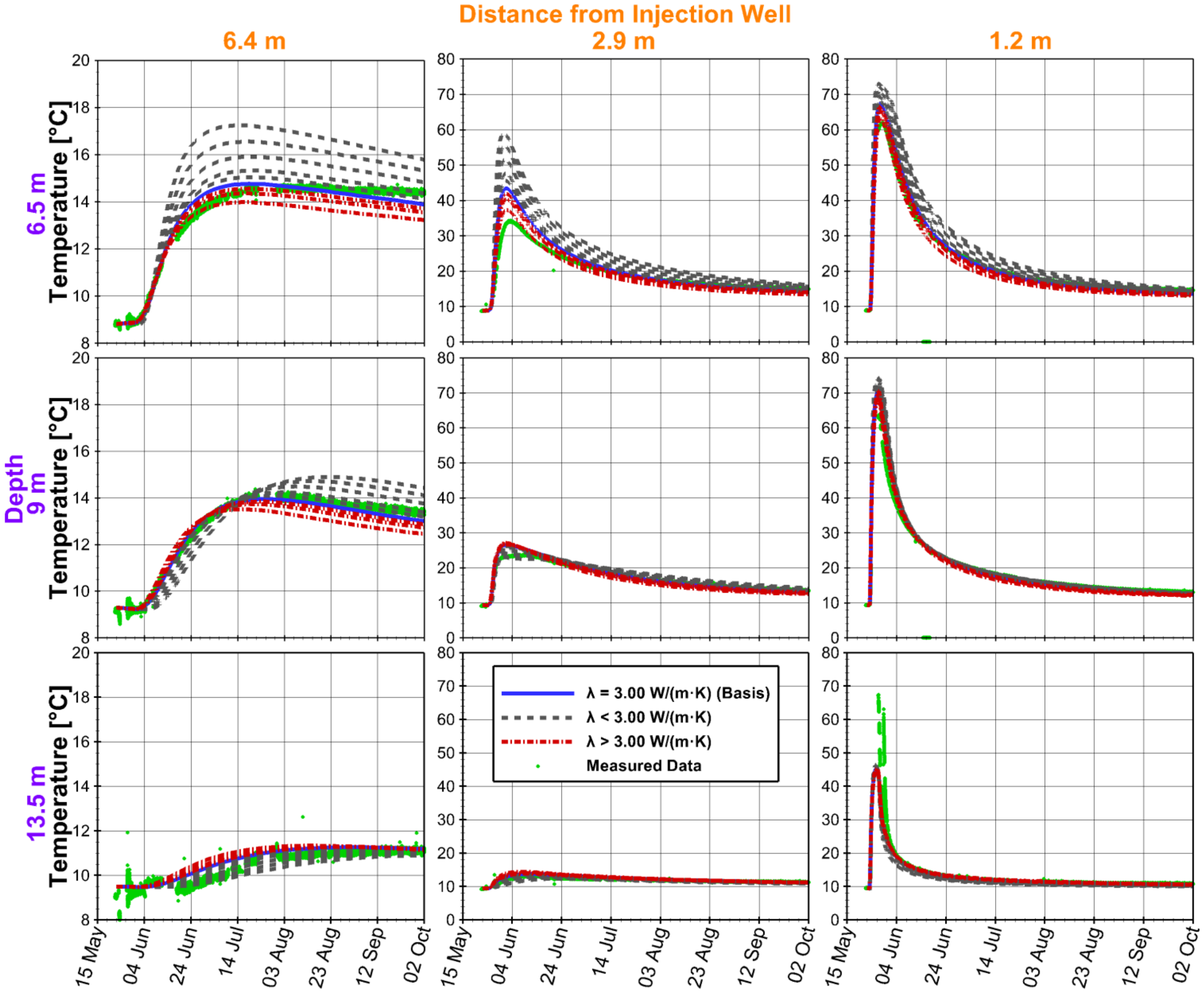
- The basis scenario shows a relatively good overall fit to the measured data
- The fit cannot be significantly improved by varying k_f^h
- A higher k_f^h makes the heat accumulate more at the upper part of the aquifer
- A higher k_f^h intensifies buoyancy driven flow



- All parameter scenarios displayed in the table above are considered
- The data in 6.4 m and in 2.9 m distance from the injection well is from wells W2_2z_D09 and W2_ML_D04, respectively
- The data in 1.2 m distance is from W2_ML_C05 in 6.5 m and 9 m depth and from W2_2z_U01 in 13.5 m depth

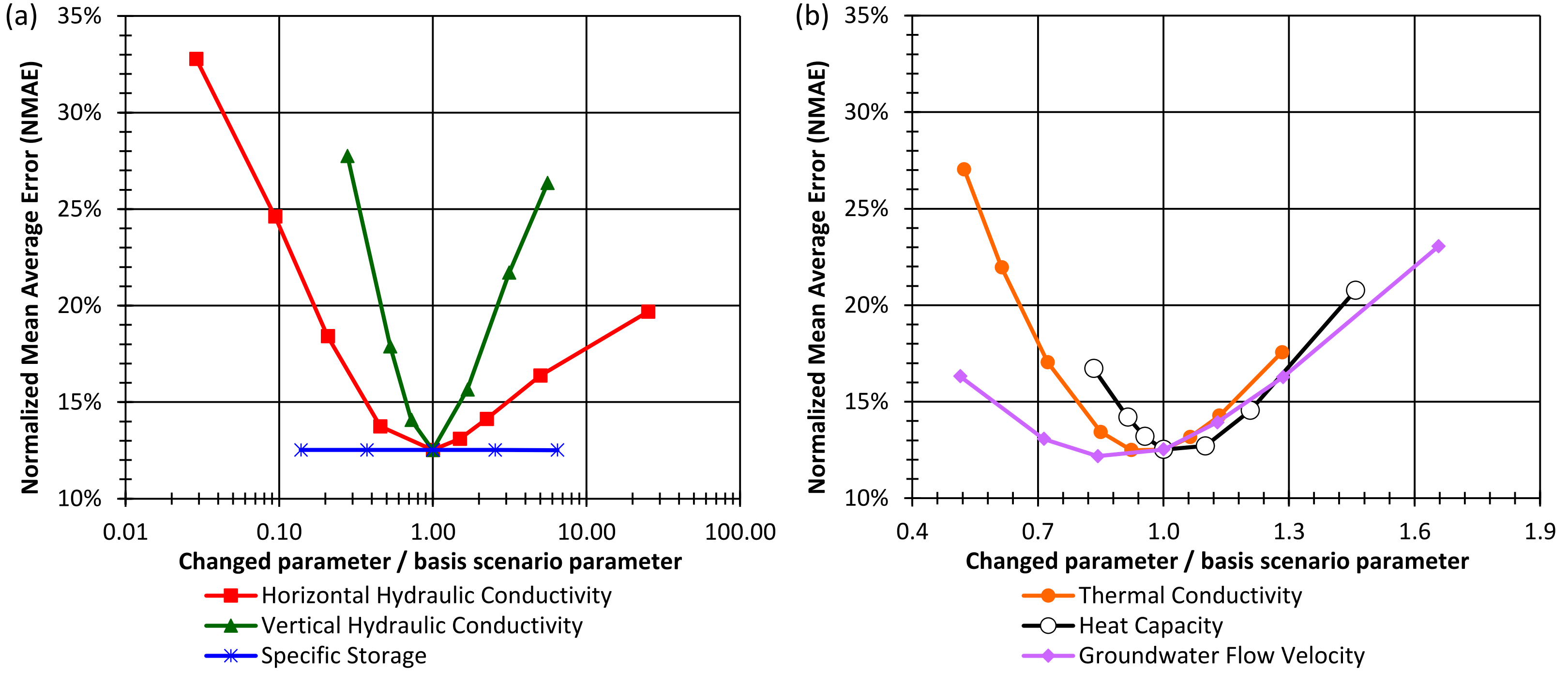
Temperature changes – thermal conductivity

- Also a change of λ cannot significantly improve the model fit
- A lower λ induces higher temperatures at the aquifer top and lower temperatures at the aquifer bottom
- The reason is an impact on the intensity of buoyancy flow
- A small λ increases the temperature gradients and consequently the density gradients by reducing conduction, which leads to more intense buoyancy flow



Sensitivity of NMAE to the parameters

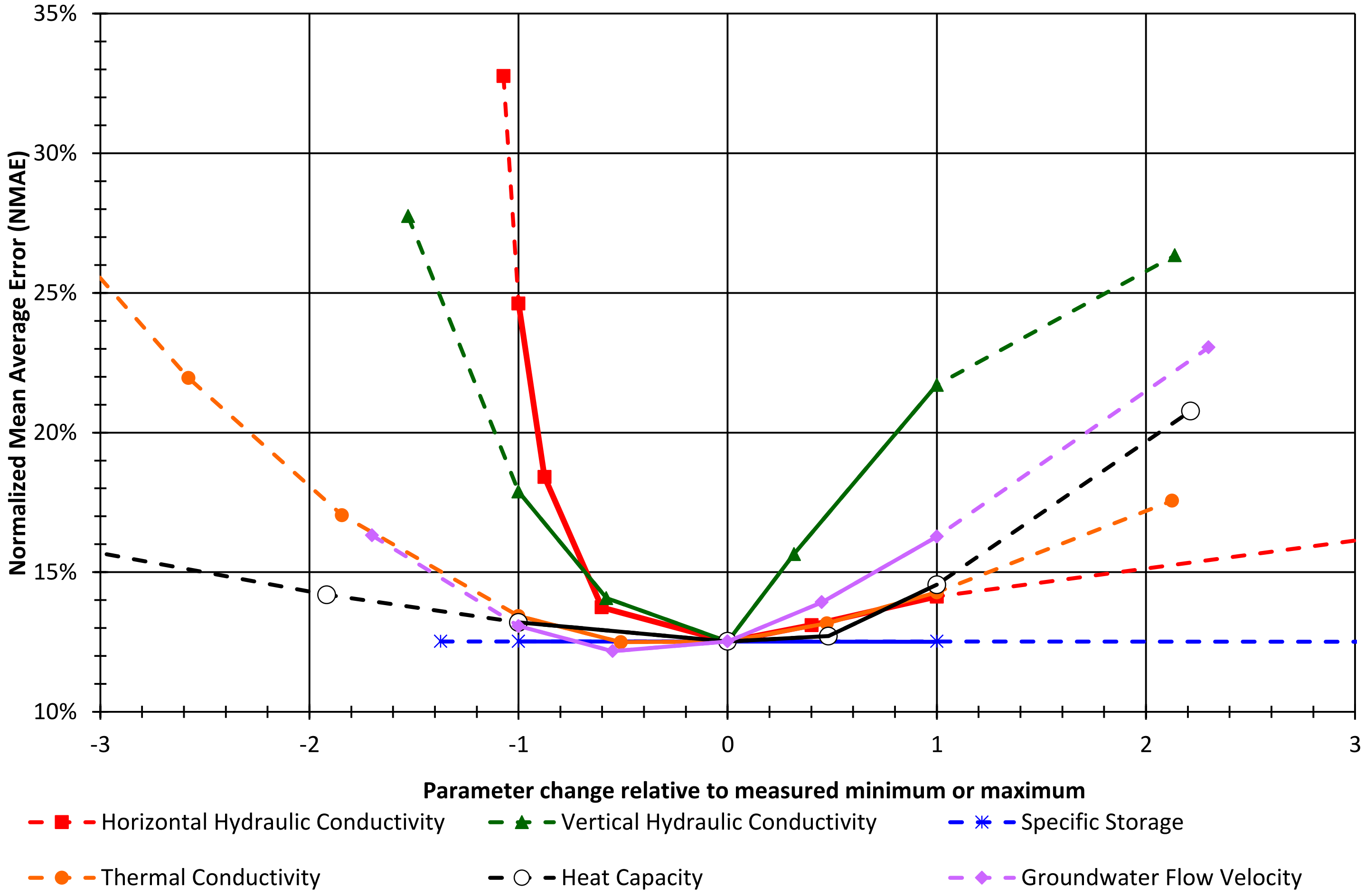
- All parameter scenarios displayed in the table above are considered
- The mean absolute gradient (MAG) was calculated as a measure of sensitivity
- In relation to the parameter change relative to the basis scenario, λ, c·ρ and v_a have a stronger impact than k_f^h and k_f^v, while S_0 has no impact
- However, k_f^h and k_f^v have a higher overall variability



Parameter	k_f^h	k_f^v	S_0	λ	c·ρ	v_a
Mean absolute gradient (MAG)	0.091	0.223	0.000	0.490	0.516	0.306

Sensitivity of NMAE to the parameters

- Consequently, this figure shows the sensitivity in relation to the measured ranges
- Based on the figure and the MAG, NMAE is more sensitive to k_f^v and k_f^h than to v_a, $c \cdot \rho$ and λ



Parameter	k_f^h	k_f^v	S_0	λ	$c \cdot \rho$	v_a
Mean absolute gradient (MAG)	0.068	0.073	0.000	0.013	0.014	0.021

Conclusions

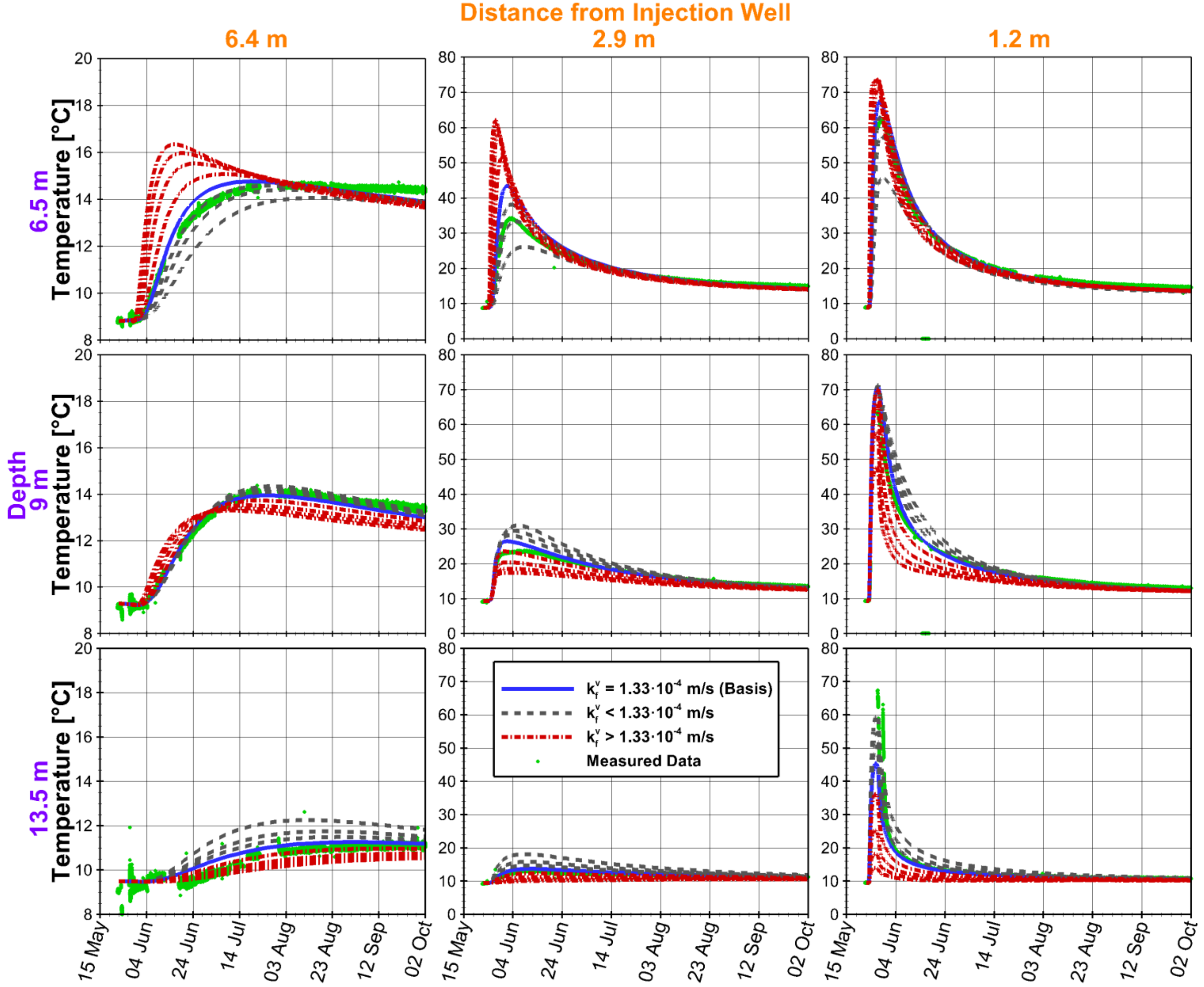
- When comparing the sensitivity in relation to the relative parameter changes, the thermal behavior is most sensitive to c·ρ, λ and v_a, followed by k_f^v and k_f^h, while it is insensitive to S_0.
- When considering the natural variability of the parameters, which is larger for the hydraulic parameters than for the thermal parameters and v_a, the thermal behavior is most sensitive to k_f^v and k_f^h, while it is less sensitive to v_a, c·ρ and λ and insensitive to S_0.
- The pronounced sensitivity to the k_f^v and k_f^h even in a conduction dominated experiment is caused by the buoyancy flow, which is a relevant process due to the high injection temperature.
- The derived parameter ranges from field measurements for k_f^v and k_f^h could be constrained significantly by means of inverse thermo-hydraulic modeling of the HIT, while this was not possible to that extent for λ, c·ρ, v_a and S_0. Thus, the uncertainty in the simulation of the thermal impacts could be reduced.
- The site investigation yielded an almost optimal parameter set.

References

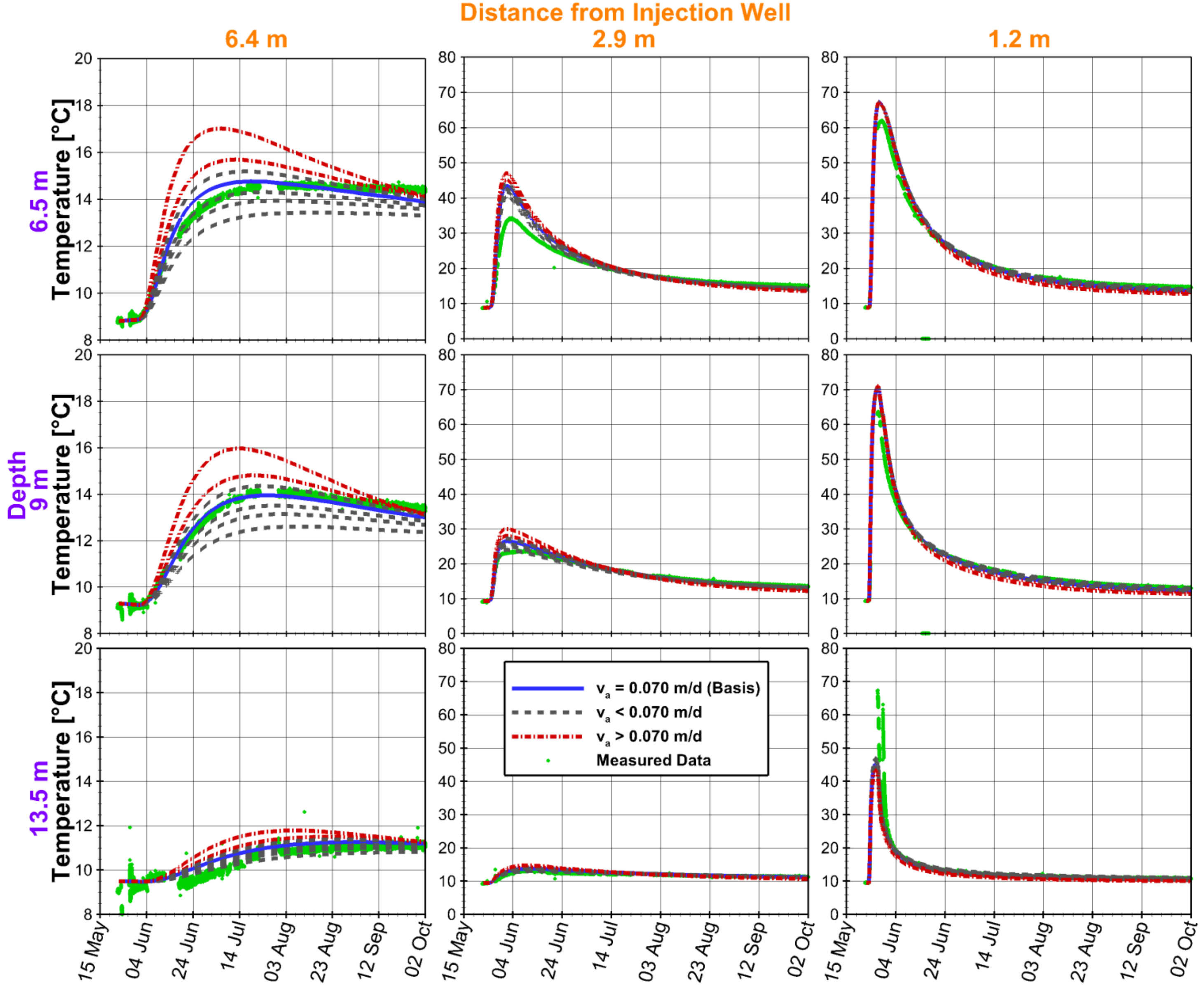
- Heldt, S., Wang, B., Hu, L., Hornbruch, G., Lüders, K., Werban, U., Bauer, S., 2021. Numerical Investigation of a High Temperature Heat Injection Test. J. Hydrol. 597. https://doi.org/10.1016/j.jhydrol.2021.126229

Supplementary Material

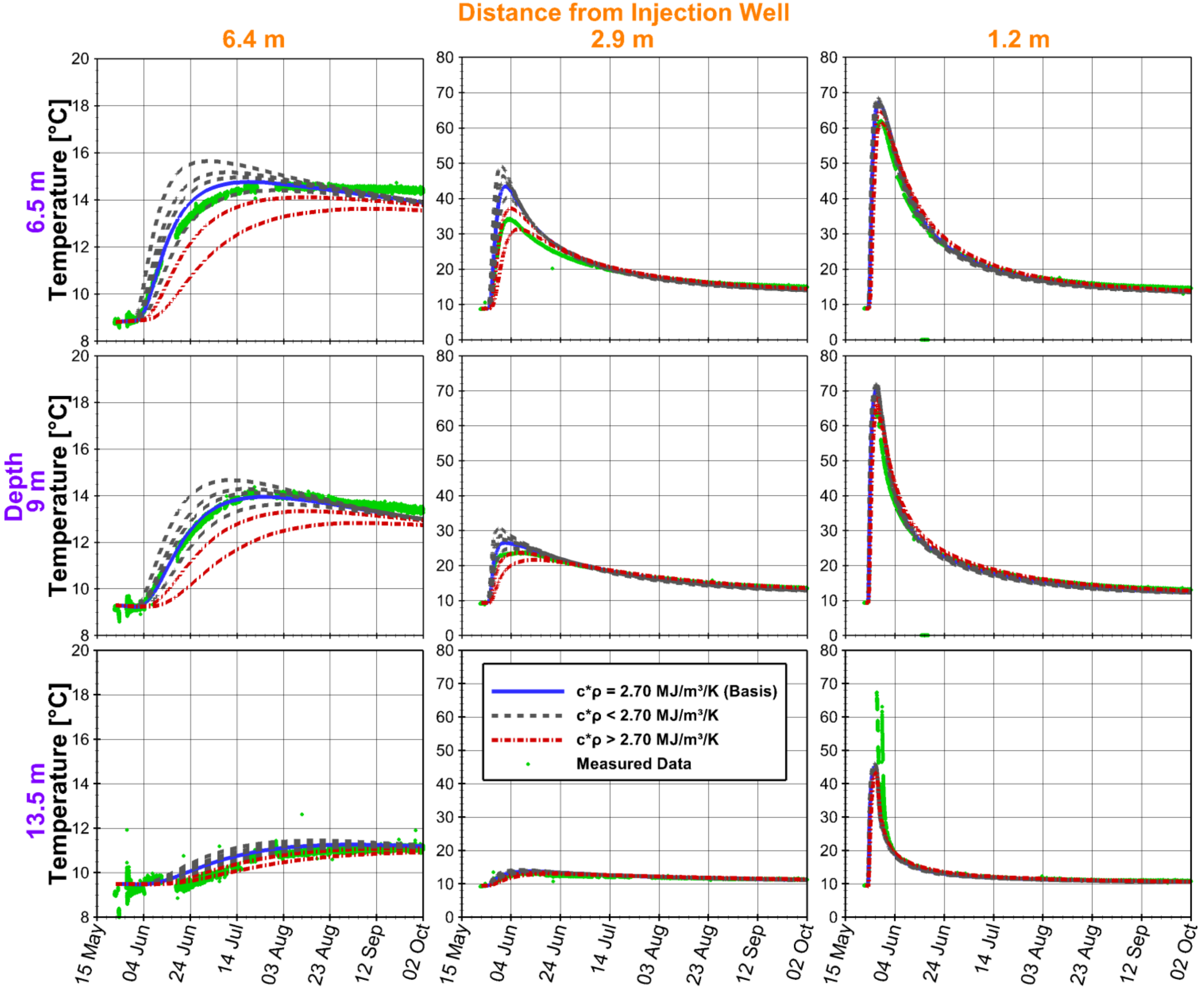
Temperature changes – vertical hydraulic conductivity



Temperature changes – groundwater flow velocity



Temperature changes – heat capacity



Temperature changes – specific storage