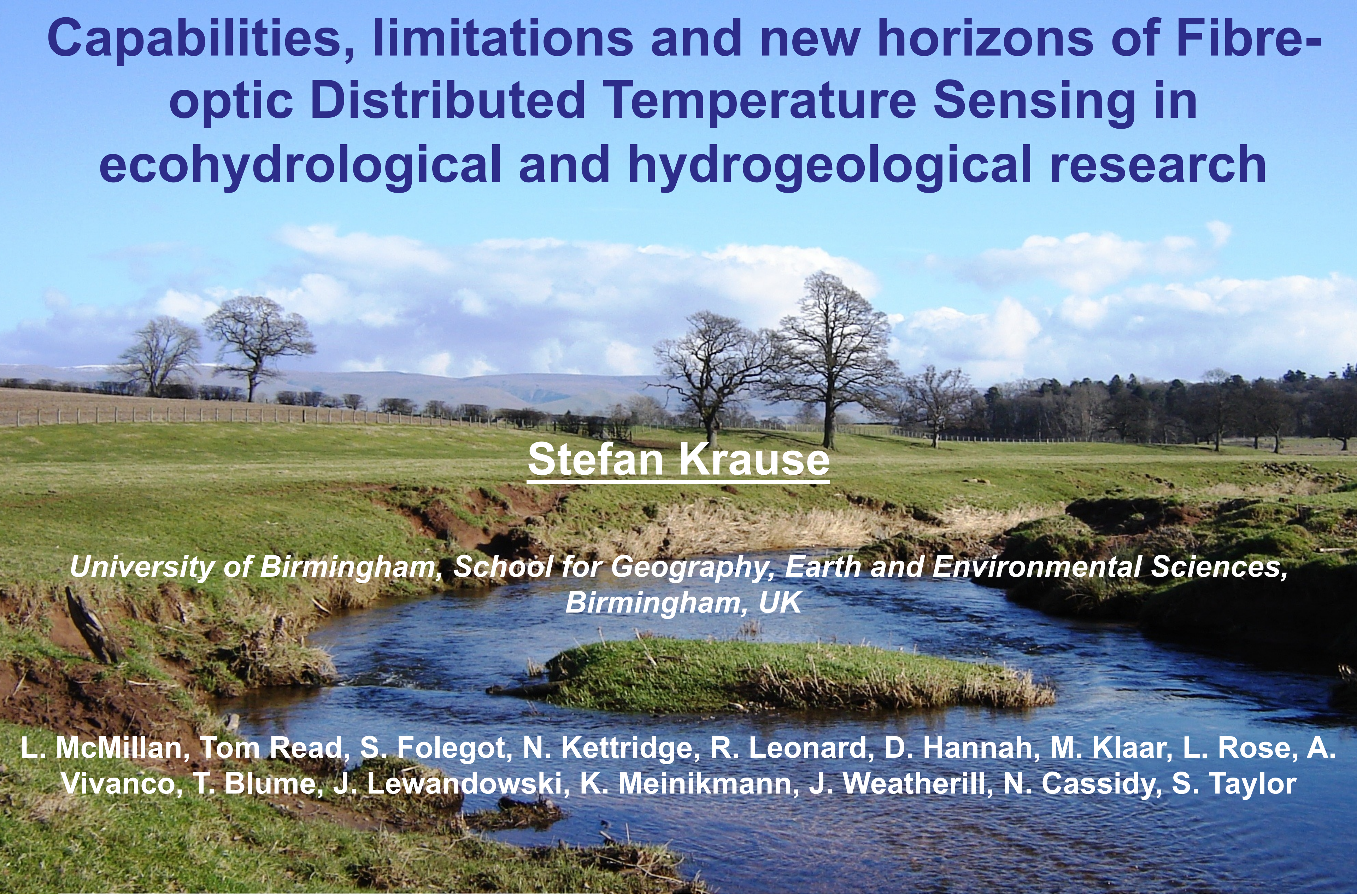
Capabilities, limitations and new horizons of Fibre-optic Distributed Temperature Sensing in ecohydrological and hydrogeological research



Stefan Krause

University of Birmingham, School for Geography, Earth and Environmental Sciences, Birmingham, UK

L. McMillan, Tom Read, S. Folegot, N. Kettridge, R. Leonard, D. Hannah, M. Klaar, L. Rose, A. Vivanco, T. Blume, J. Lewandowski, K. Meinikmann, J. Weatherill, N. Cassidy, S. Taylor

UNIVERSITY OF BIRMINGHAM

BRITISH HYDROLOGICAL SOCIETY

Fibre-optic Distributed Temperature Sensing (FO-DTS)

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L24401, doi:10.1029/2006GL02

Fiber optics opens window on stream dynamics

John Selker,[1] Nick van de Giesen,[2] Martijn Westhoff,[2] Wim Luxemburg,[2] and Marc B. Parlange[3]

WATER RESOURCES RESEARCH, VOL. 42, W12202, doi:10.1029/2006WR005326, 2006

Distributed fiber-optic temperature sensing for hydrologic systems

John S. Selker,[1,2] Luc Thévenaz,[3] Hendrik Huwald,[2] Alfred Mallet,[2] Wim Luxemburg,[4] Nick van de Giesen,[4] Martin Stejskal,[5] Josef Zeman,[5] Martijn Westhoff,[4] and Marc B. Parlange[2]

WATER RESOURCES RESEARCH, VOL. 45, W00D23, doi:10.1029/2008WR007052, 2009

Click Here for Full Article

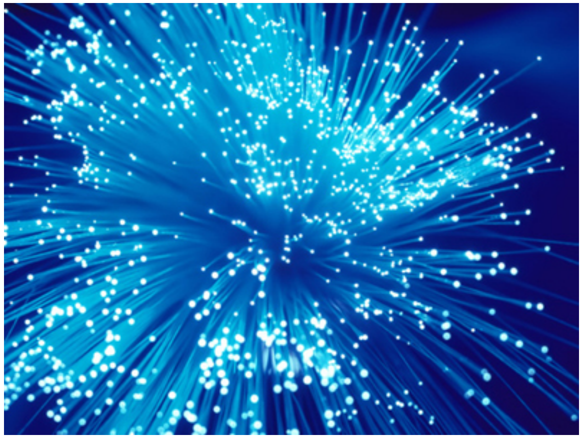
Environmental temperature sensing using Raman spectra DTS fiber-optic methods

Scott W. Tyler,[1] John S. Selker,[2] Mark B. Hausner,[3] Christine E. Hatch,[1] Thomas Torgersen,[4] Carl E. Thodal,[5] and S. Geoffrey Schladow[6]

MEETINGS

Taking the Temperature of Ecological Systems With Fiber Optics

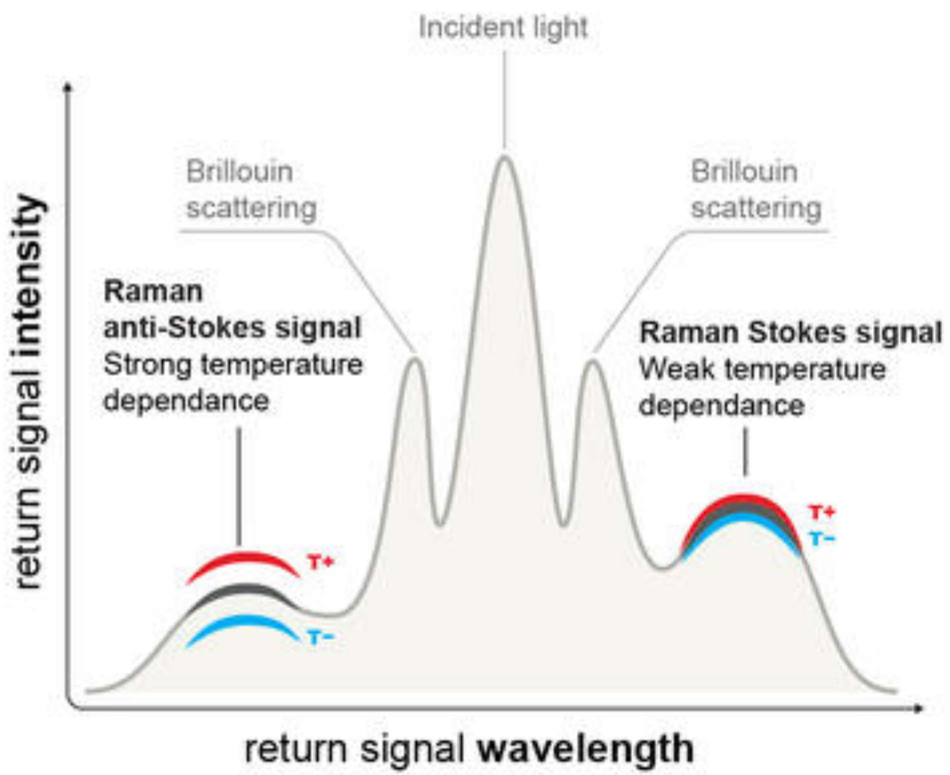
Fiber Optic Distributed Temperature Sensing for Ecological Characterization; Blue River, Oregon, 10–15 September 2007



1. Principles of FO-DTS
2. Examples of FO-DTS in Echydrological and Hydrogeological Research
3. Capabilities and Limitations of FO-DTS
4. New Developments in Fibre-optic Sensing

Fibre-optic Distributed Temperature Sensing (FO-DTS)

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science



Raman-Optical Time-Domain-Reflectometry

Back scatter of optical laser pulse

Analysis of Stokes / anti-Stokes signal

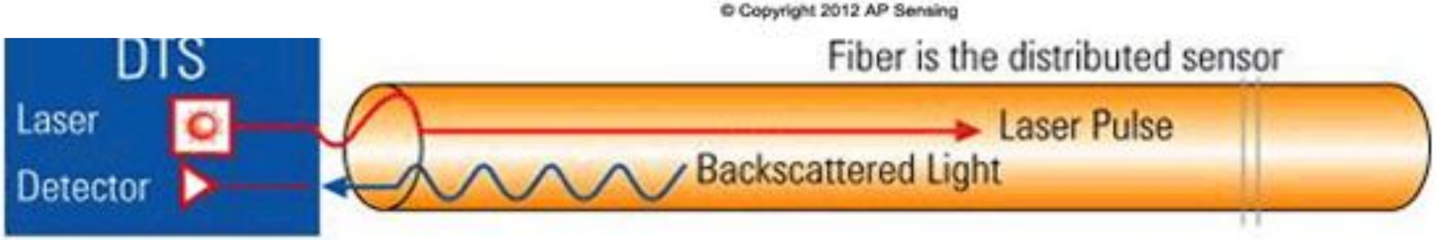


Figure courtesy of AP Sensing

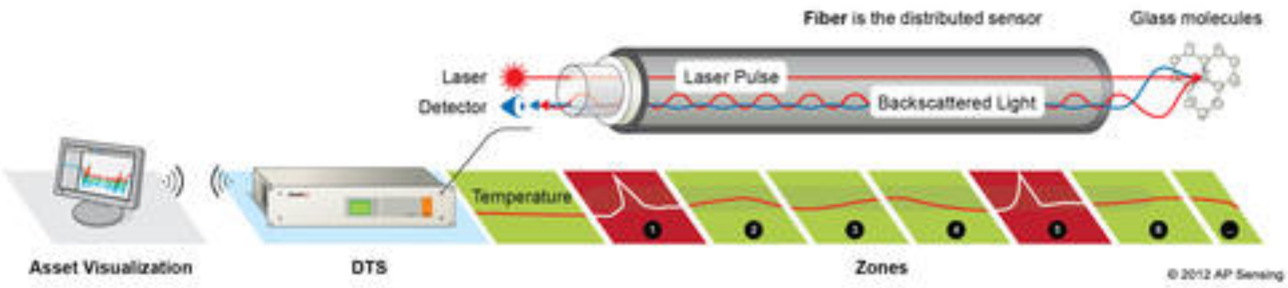
FO-DTS measurement principles

UNIVERSITY OF BIRMINGHAM

Geography, Earth and Environmental Science

FO-DTS applications:

- Hydrology
- Hydrogeology
- Glaciology
- Soil physics
- Civil engineering
- Meteorology



[*Selker et al.*, 2006 a,b; *Tyler et al.*, 2008, 2009; *Henderson et al.*, 2009; *Steele-Dunne et al.*, 2010; *Slater et al.*, 2010; *Keller et al.*, 2011; *Suárez* et al., 2011; *Krause et al.*, 2012 a, b, 2013; …]

- Main applications in hydrology for detecting spatial patterns and temporal dynamics of exchange fluxes between groundwater and surface water (rivers and lakes), dam leakage, groundwater fluxes

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

FO – Cable Design

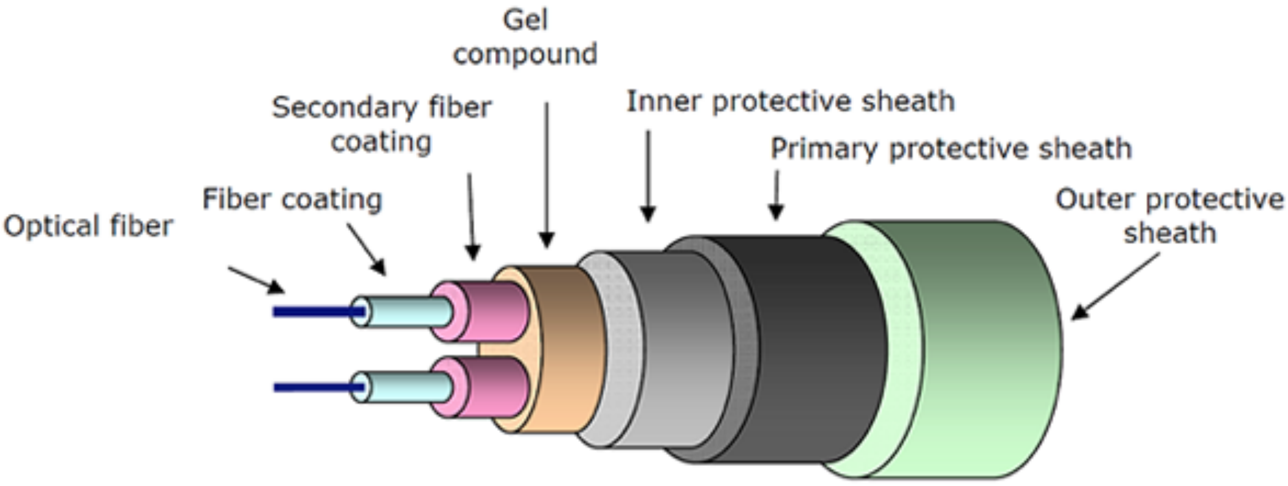


Figure courtesy of SENSORTRAN

Fibre-optic DTS cable solutions

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Fibre-modes:

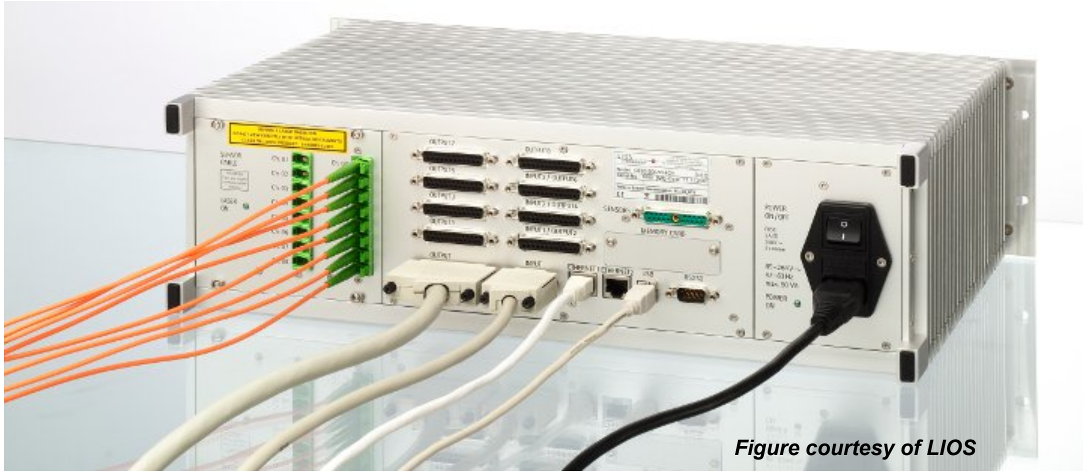
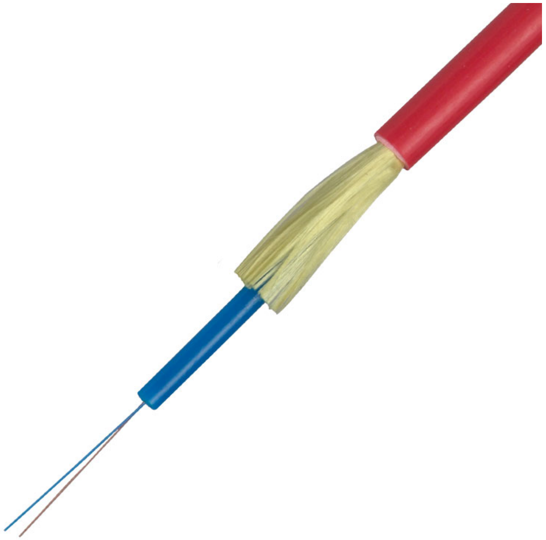


Figure courtesy of LIOS

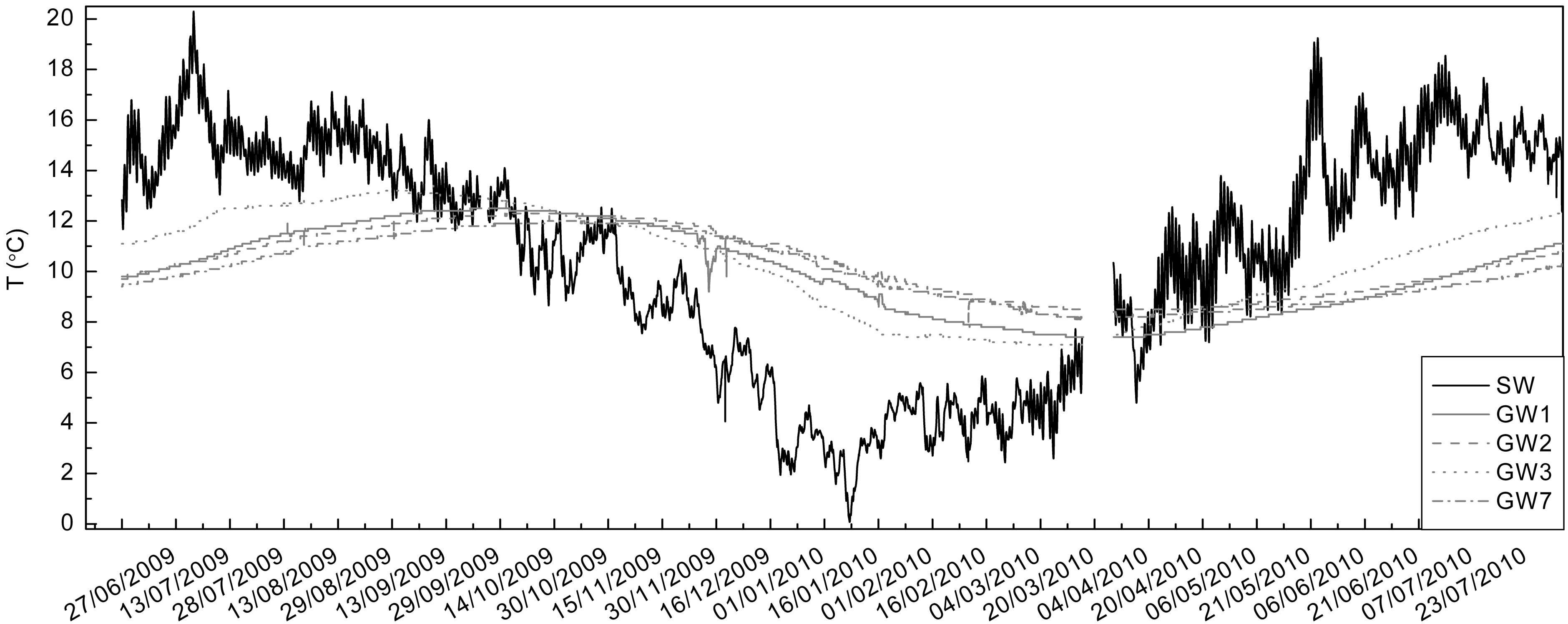


Fibre-optic DTS – measurement principles

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Tracing signal:

Difference in Groundwater-Surface Water Temperatures

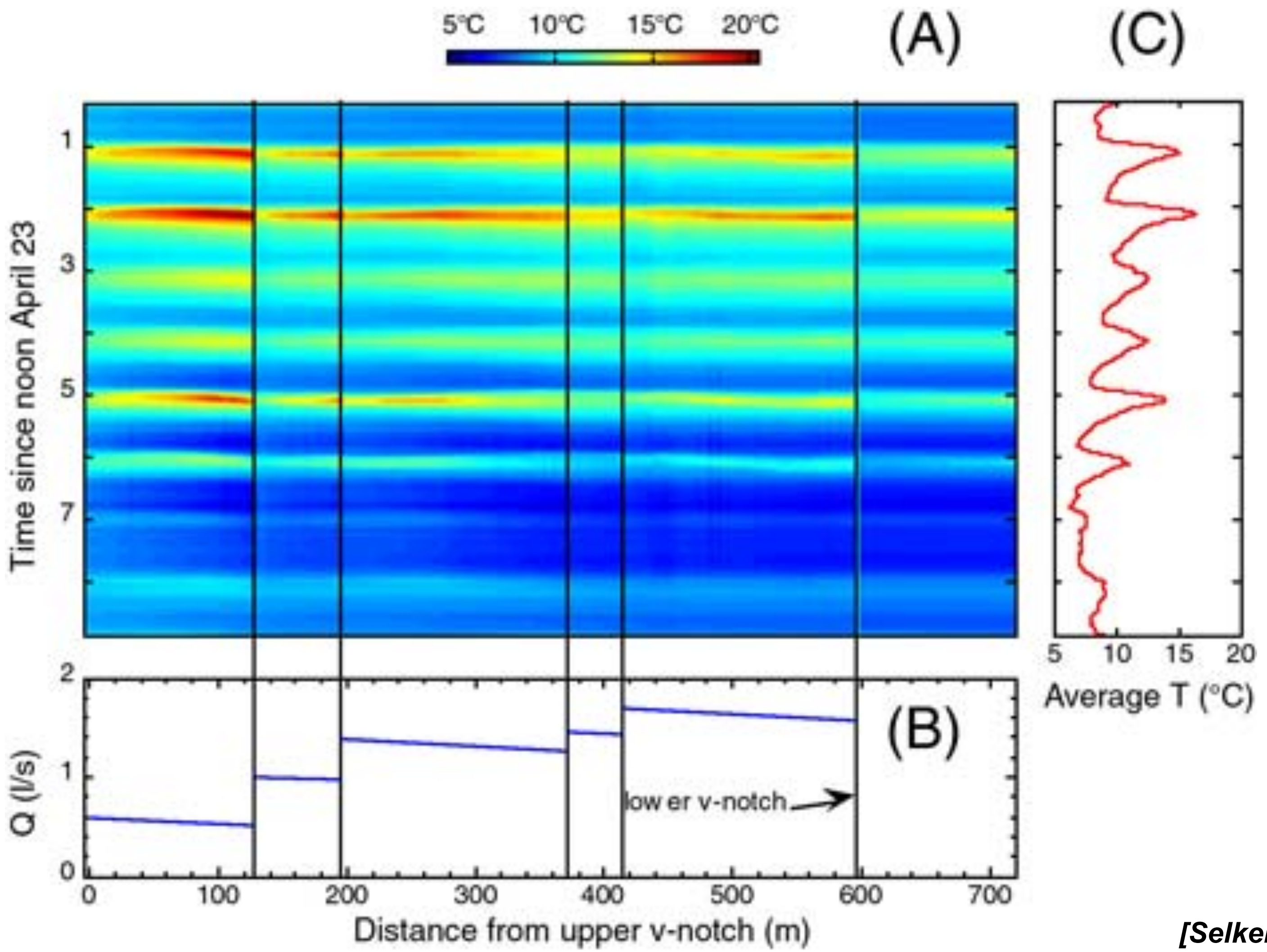


Reasonable tracer for GW/SW interface fluxes

[Krause et al., 2011, Ecohydrology; Krause et al., 2012, HESS]

Fibre-optic DTS – measurement principles

Tracing step-changes in temperature

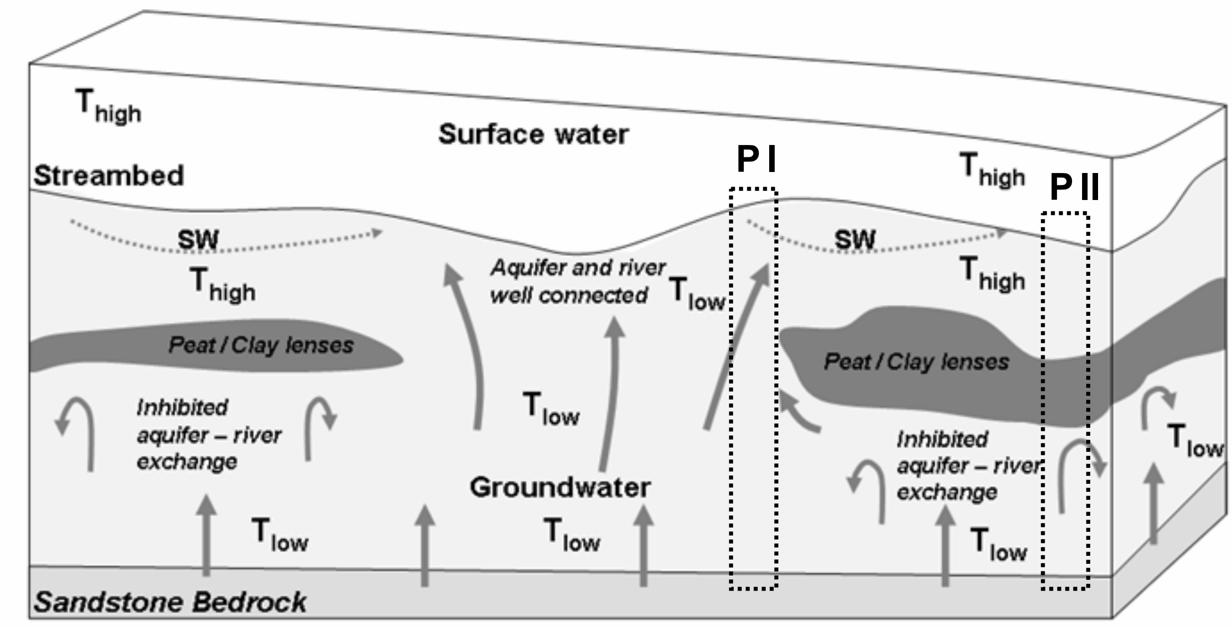


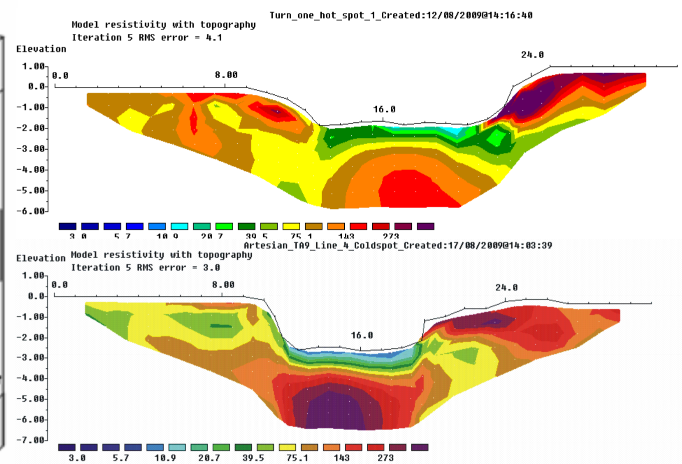
[Selker et al., 2006]

UNIVERSITY OF BIRMINGHAM

Geography, Earth and Environmental Science

Detecting complex flow patterns that do not affect surface water temperatures





Electric Resistivity Tomography -ERT

Ground Penetrating Radar - GPR

AIM:

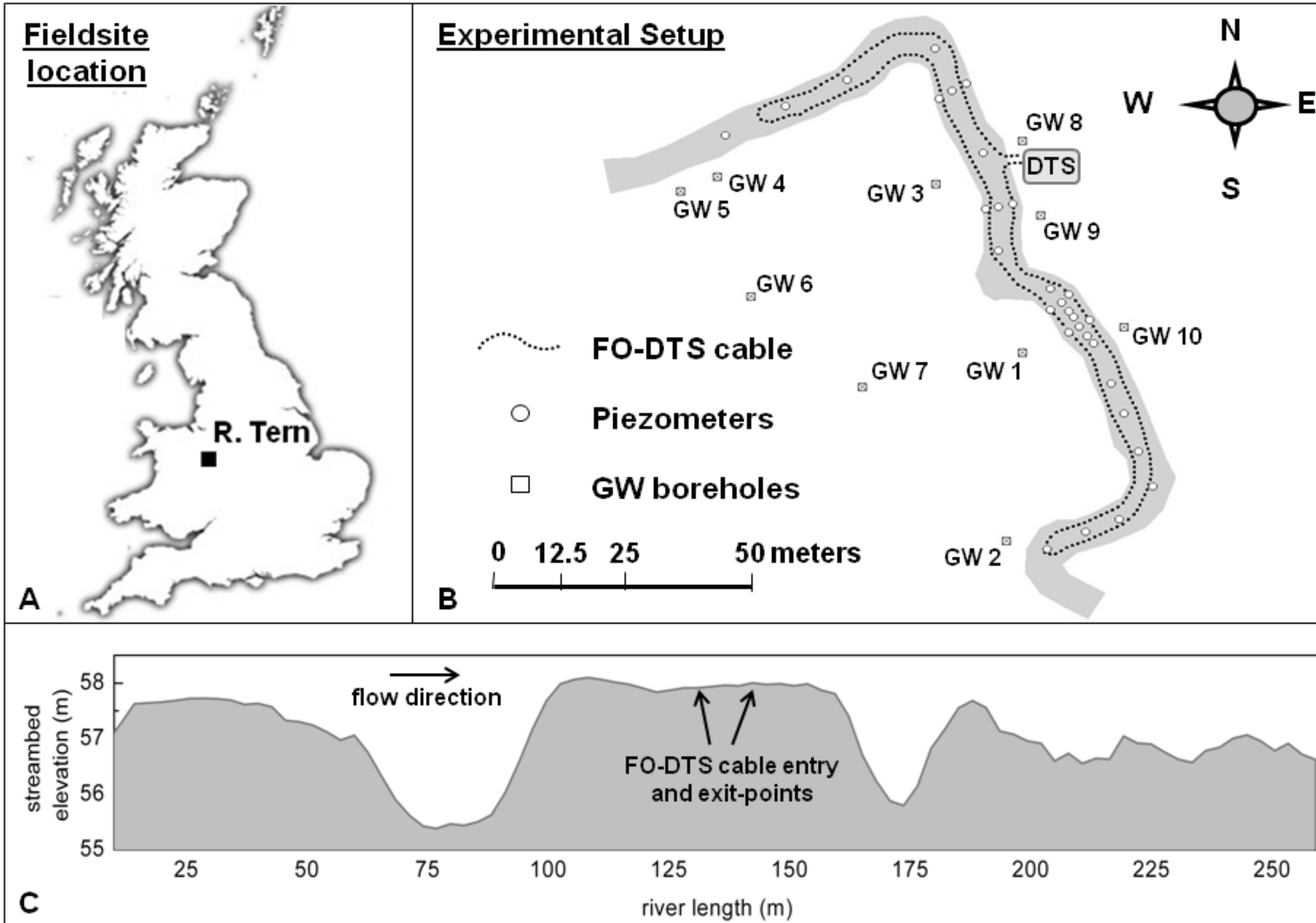
Detection of low conductivity hotspots + their dynamic impact on streambed temperature

[Krause & Blume, WRR, 2013; Rose et al., WRR, 2013; Krause et al., WRR, 2014]

FO-DTS for detecting spatial patterns & temporal dynamics of GW-SW exchange

UNIVERSITY OF BIRMINGHAM

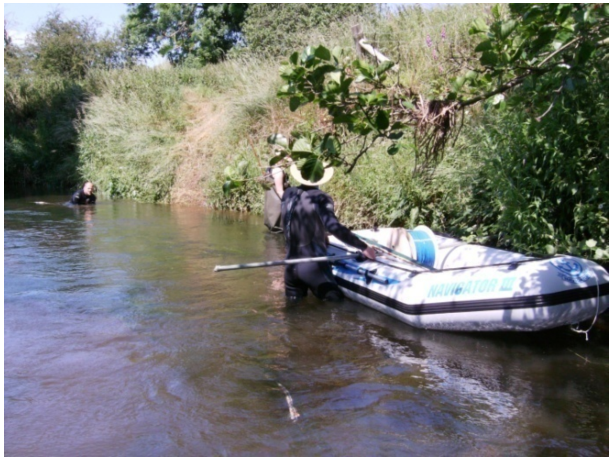
Geography, Earth and Environmental Science



(Krause et al., 2012, HESS)

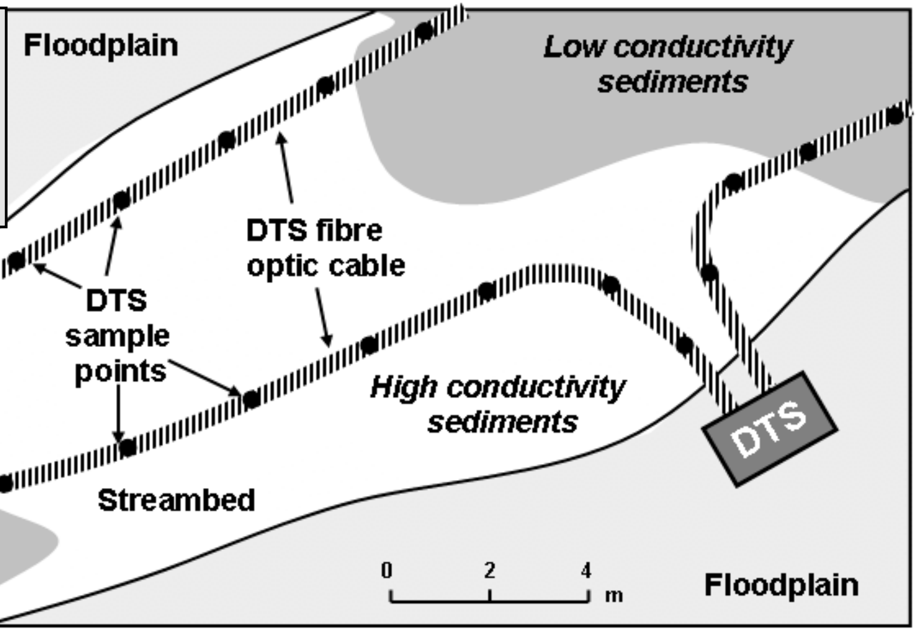
Fibre-optic Distributed Temperature Sensing (River Tern)

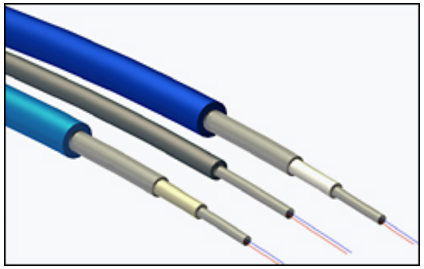
UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science



FO-DTS

Streambed temperature survey





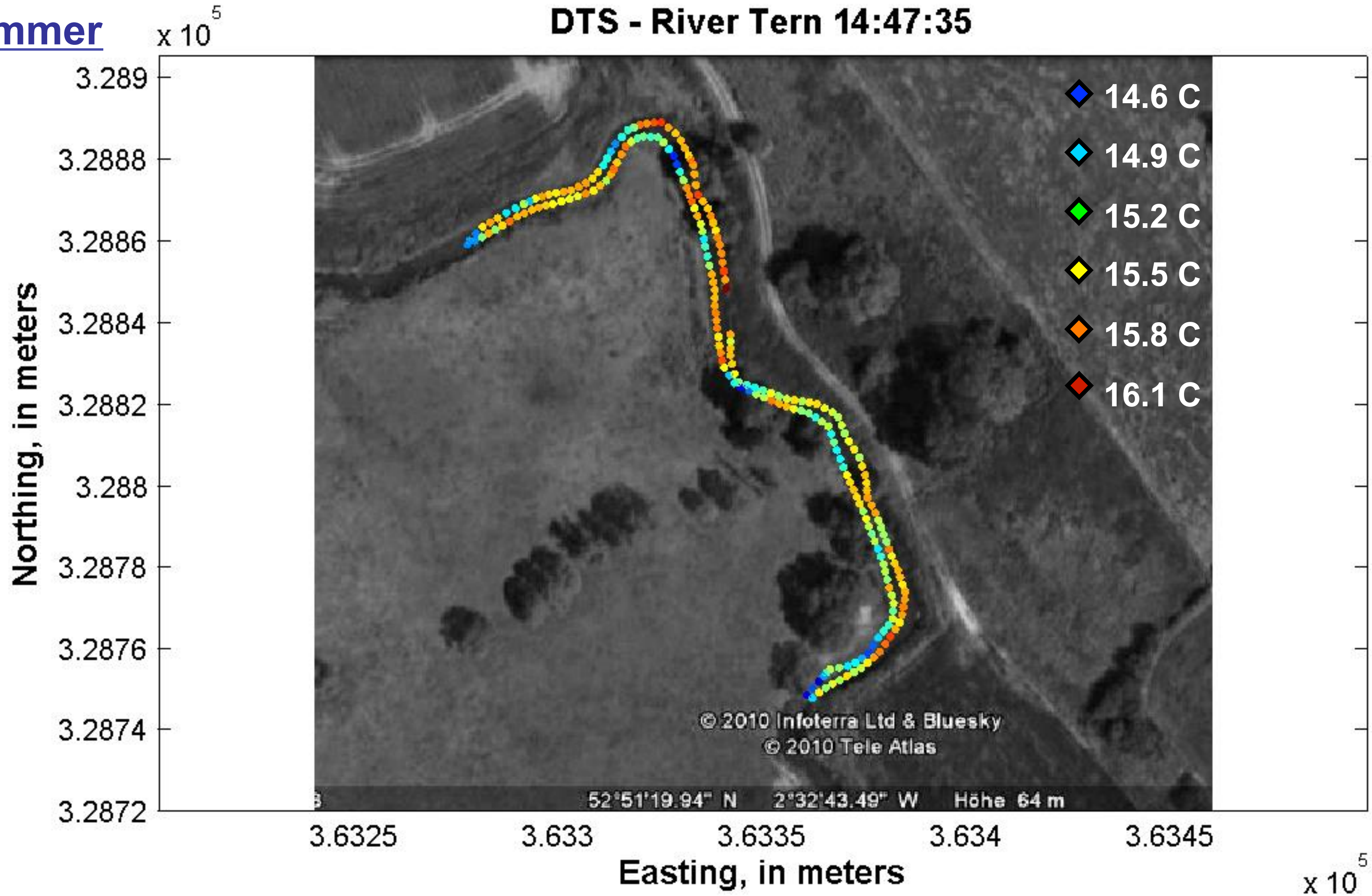
!! Buried cable !!

2 channels – both ends connected

Fibre-optic Distributed Temperature Sensing (River Tern)

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Summer

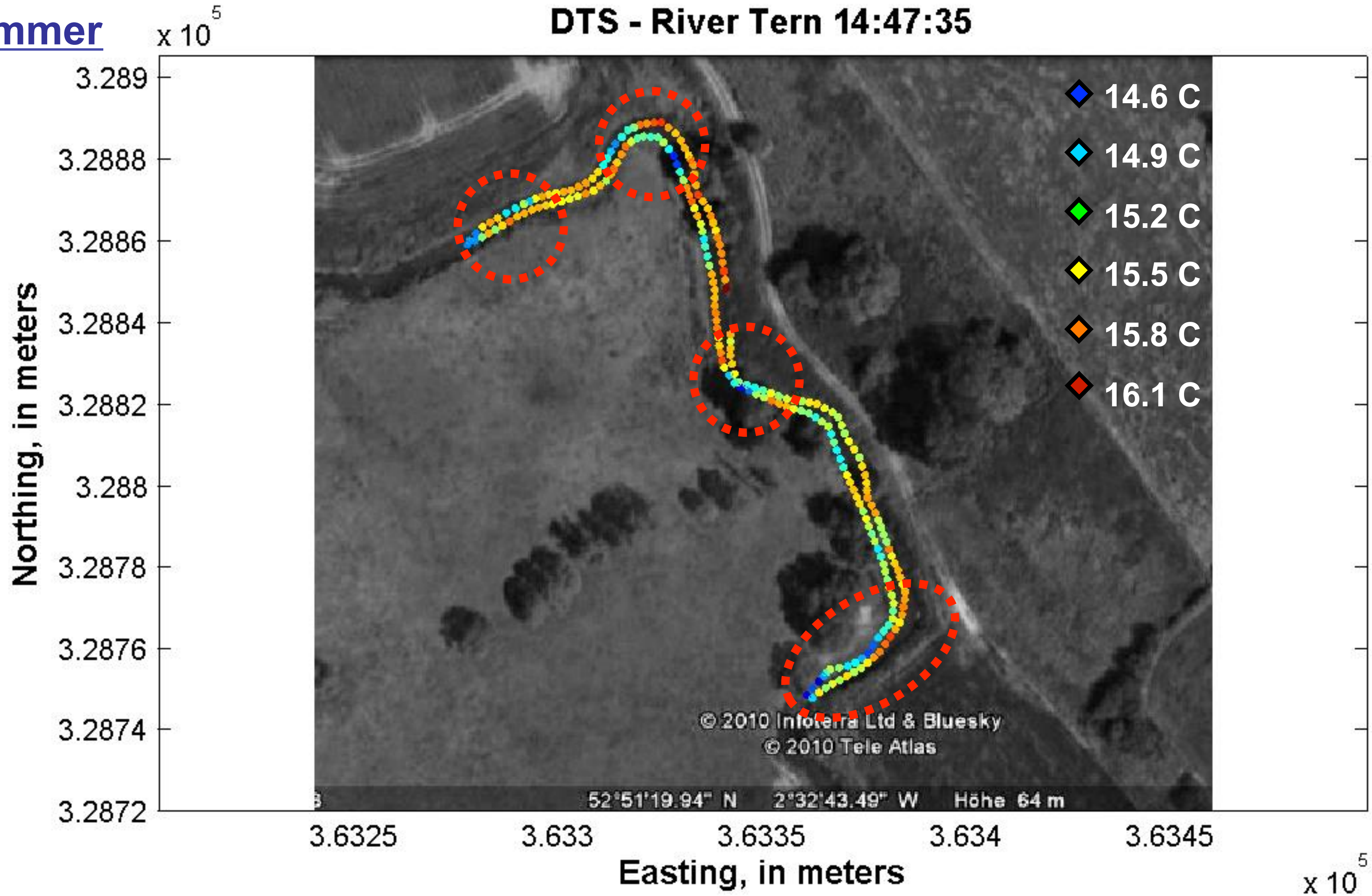


(Krause et al., 2012, HESS)

Fibre-optic Distributed Temperature Sensing (River Tern)

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Summer

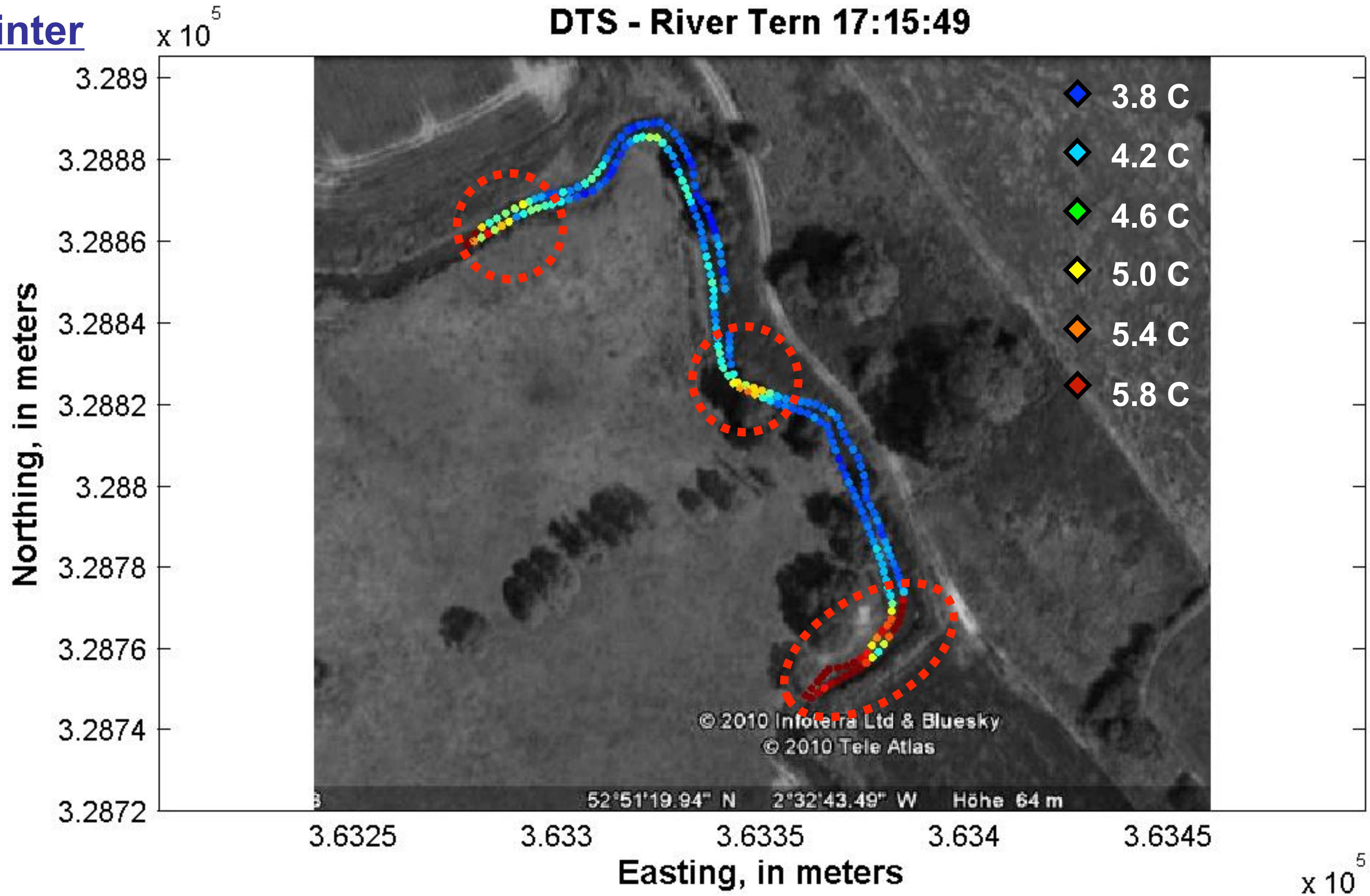


(Krause et al., 2012, HESS)

Fibre-optic Distributed Temperature Sensing (River Tern)

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Winter



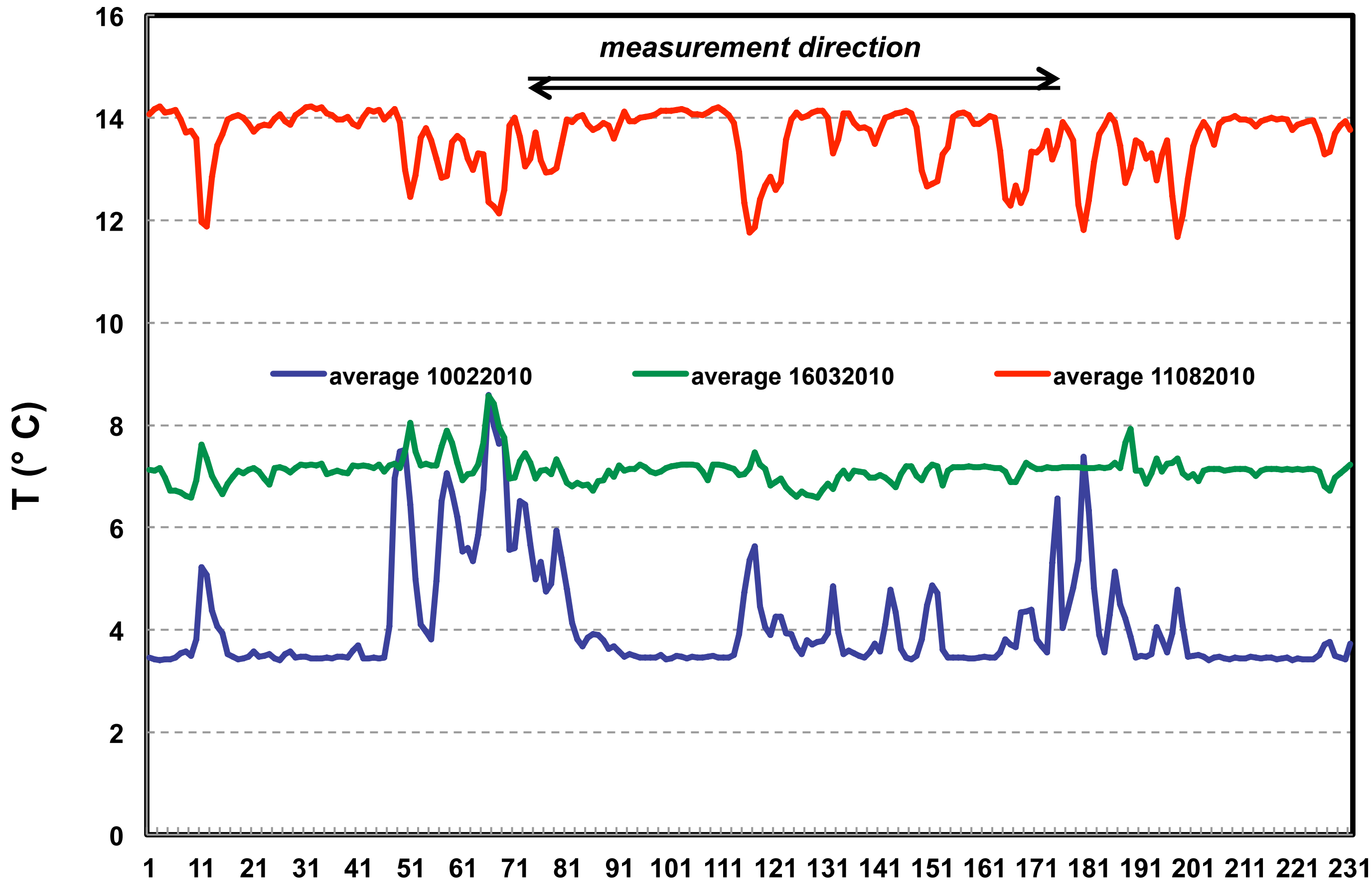
(Krause et al., 2012, HESS)

UNIVERSITY OF BIRMINGHAM

Geography, Earth and Environmental Science

FO-DTS - Impact of seasonal signal variation

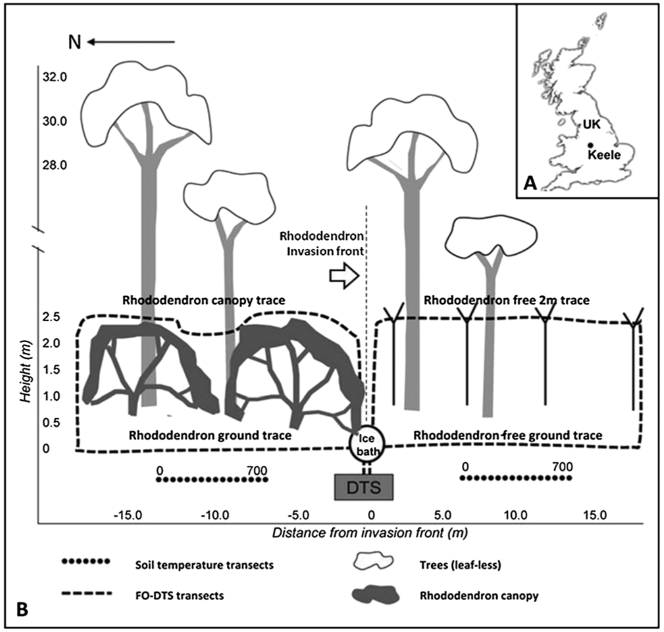
Two-way single-ended averaging mode

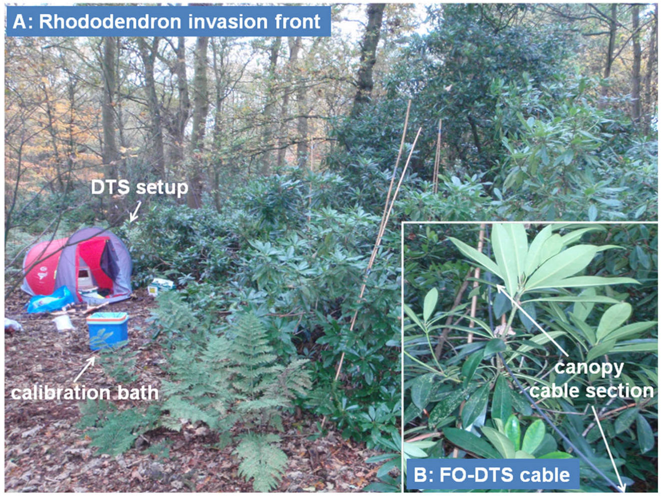


[Krause & Blume, WRR, 2013; Rose et al., WRR, 2013; Krause et al., WRR, 2014]

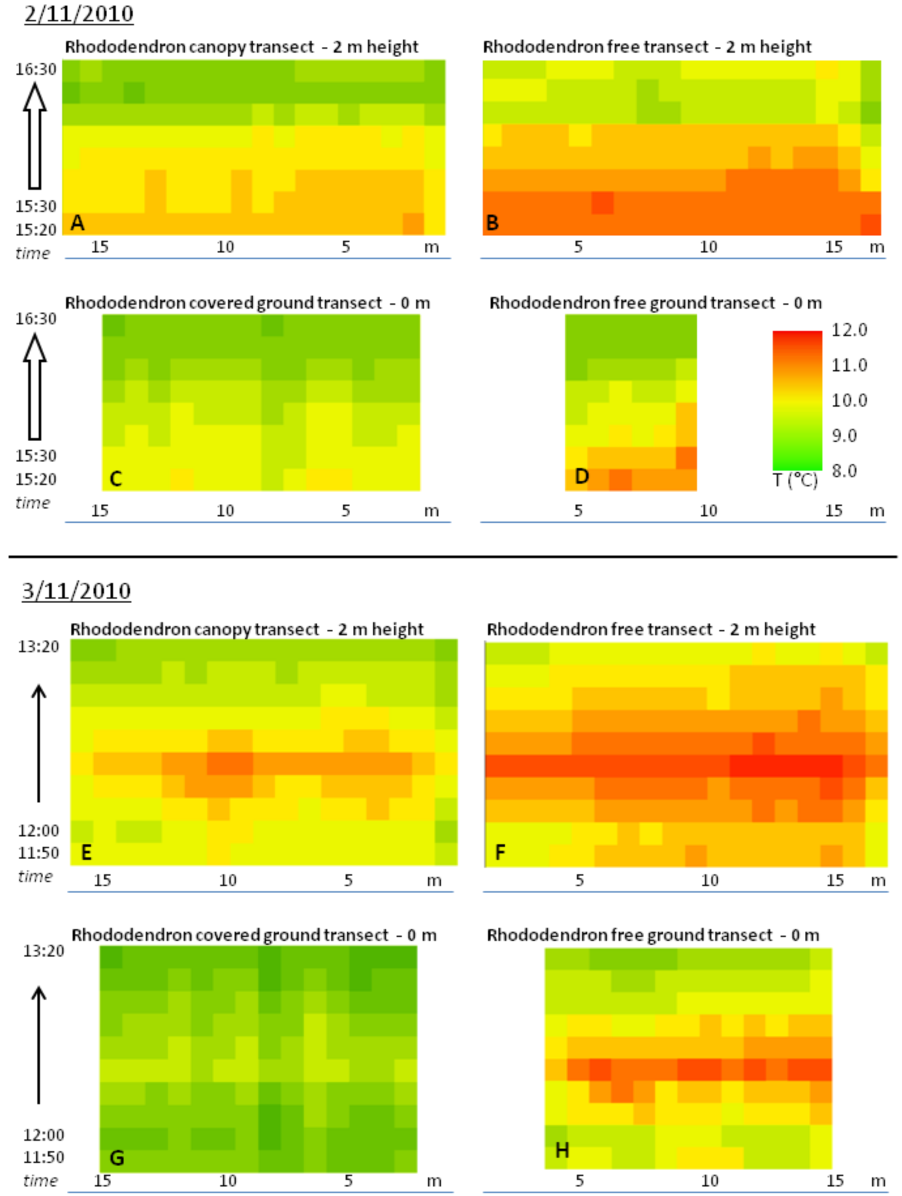
FO-DTS – In Terrestrial Ecology/Biogeochemistry

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science



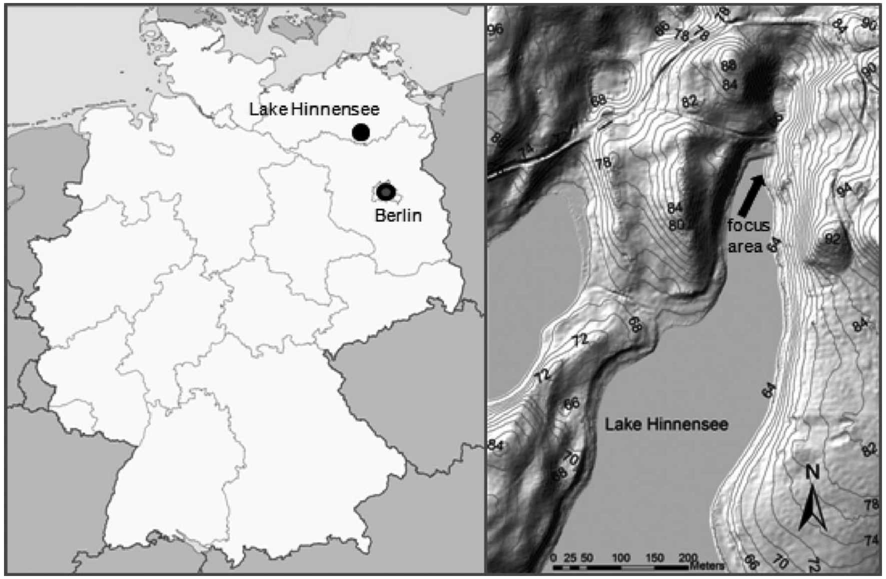


[Krause et al., Ecohydrology, 2012a]



FO-DTS: Identification of lacustrine GW discharge

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

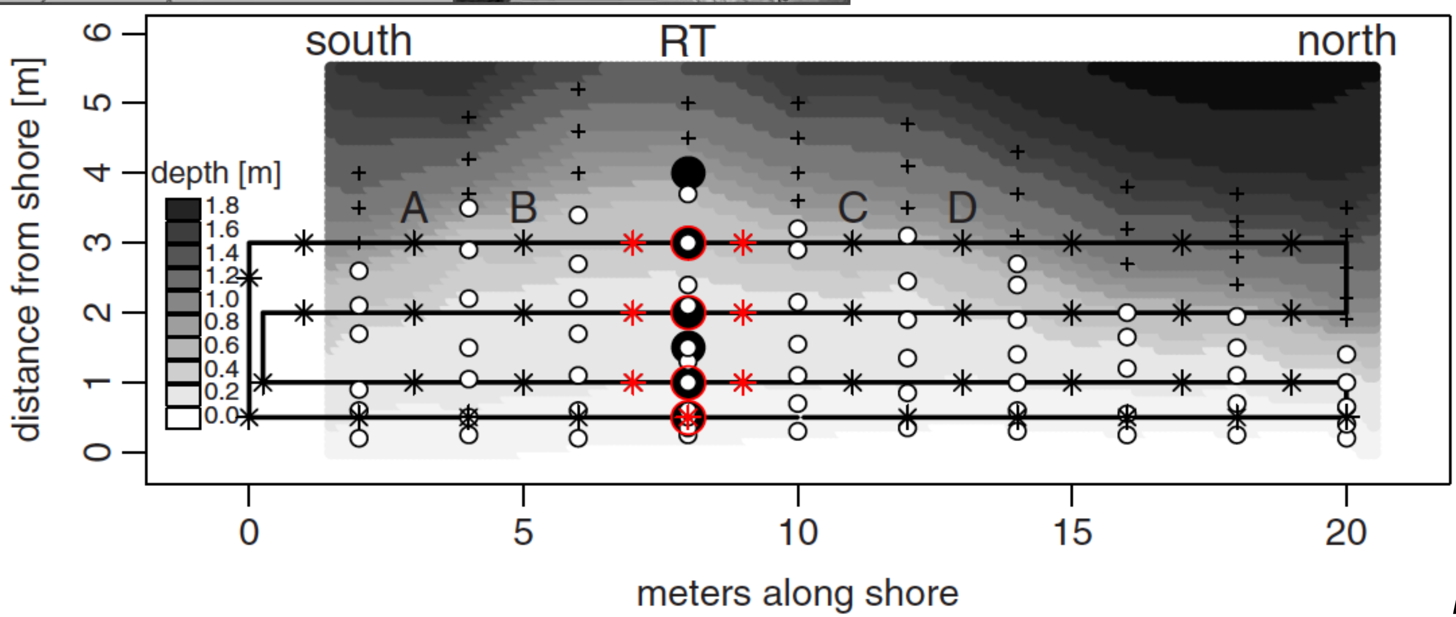


WATER RESOURCES RESEARCH, VOL. 49, 7929–7944, doi:10.1002/2012WR013215, 2013

Upscaling lacustrine groundwater discharge rates by fiber-optic distributed temperature sensing

Theresa Blume,[1] Stefan Krause,[2] Karin Meinikmann,[3] and Jörg Lewandowski[3]

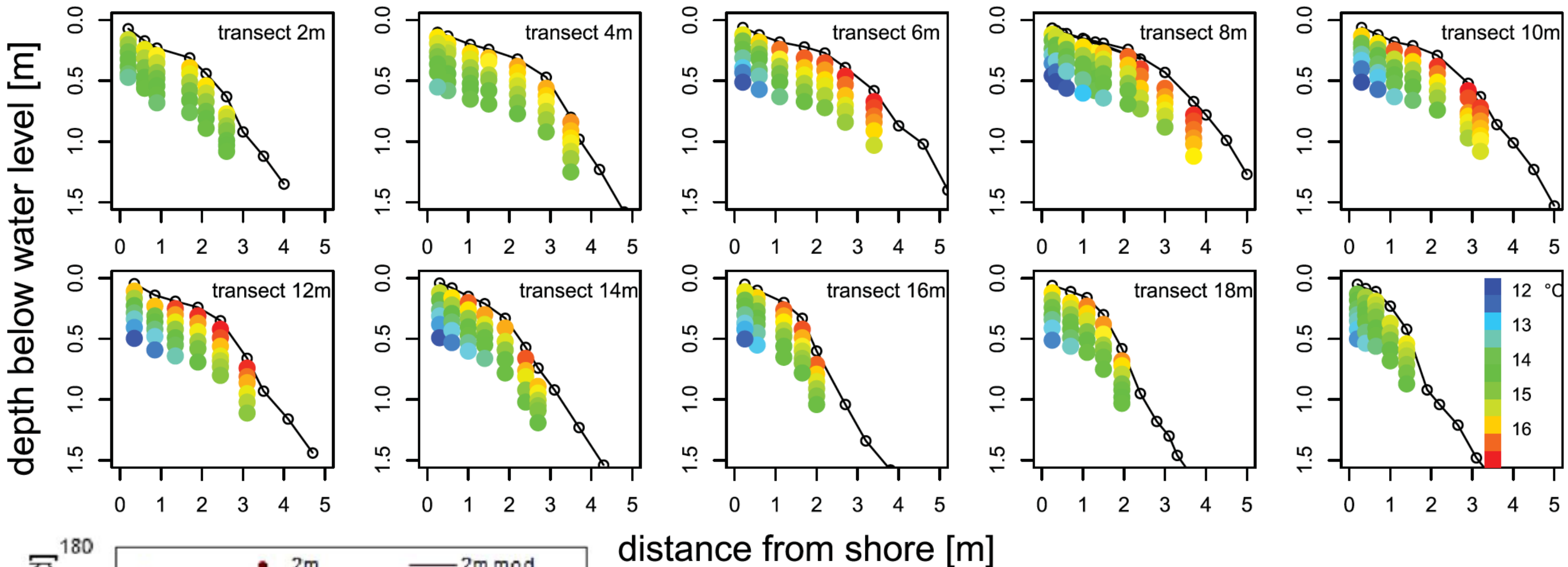
Received 31 October 2012; revised 28 October 2013; accepted 30 October 2013; published 4 December 2013.

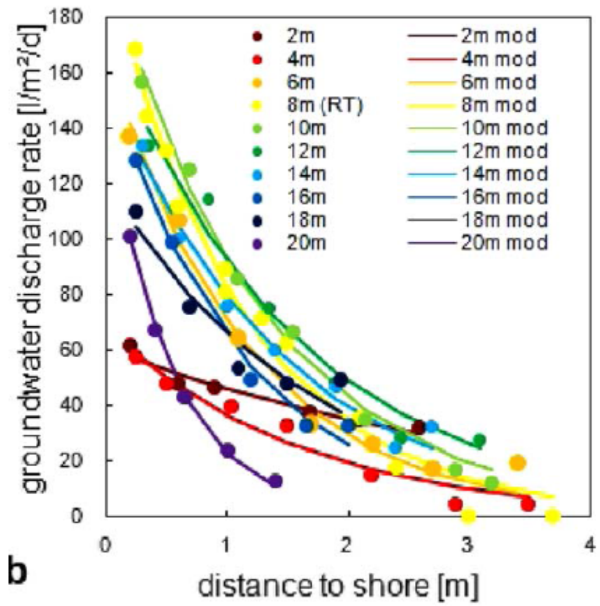


[Blume, et al., WRR, 2013]

FO-DTS: Identification of lacustrine GW discharge

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science





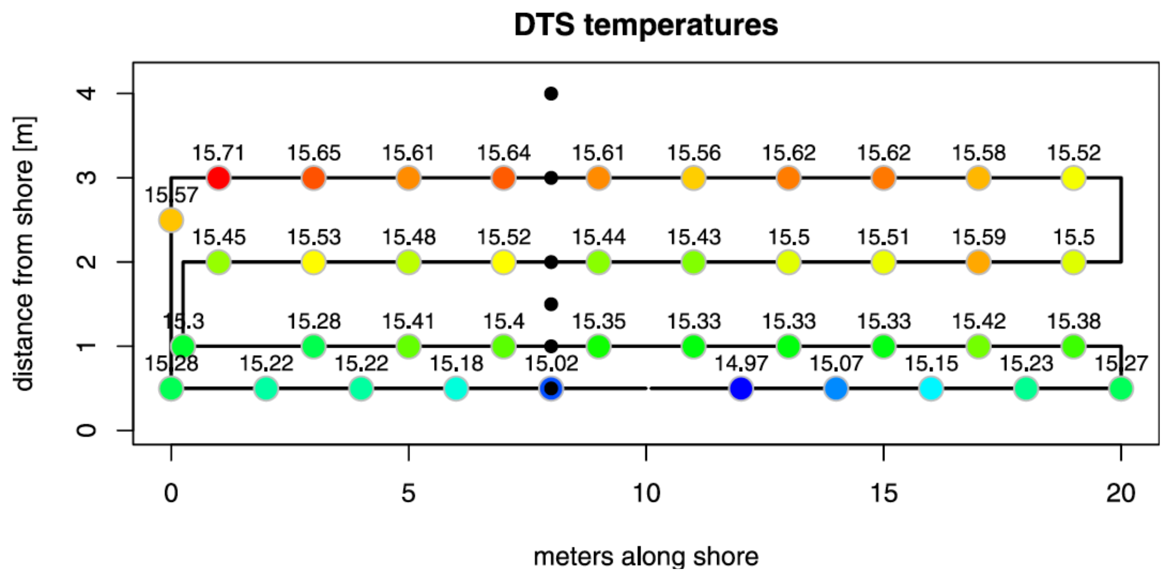
1-D Heat Flow:

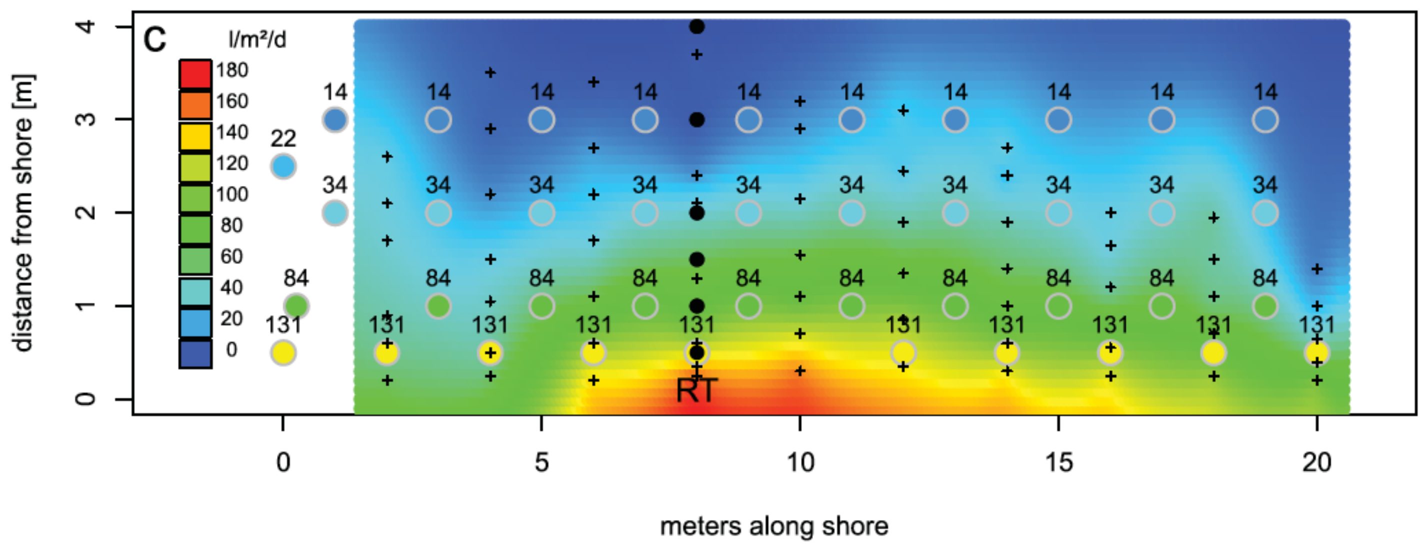
$$T(z) = \frac{\exp\left(\frac{q_z \rho_f c_f}{K_{fs}} z\right) - 1}{\exp\left(\frac{q_z \rho_f c_f}{K_{fs}} L\right) - 1} (T_L - T_0) + T_0$$

[Blume, et al., WRR, 2013]

FO-DTS: Identification of lacustrine GW discharge

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science





[Blume, et al., WRR, 2013]

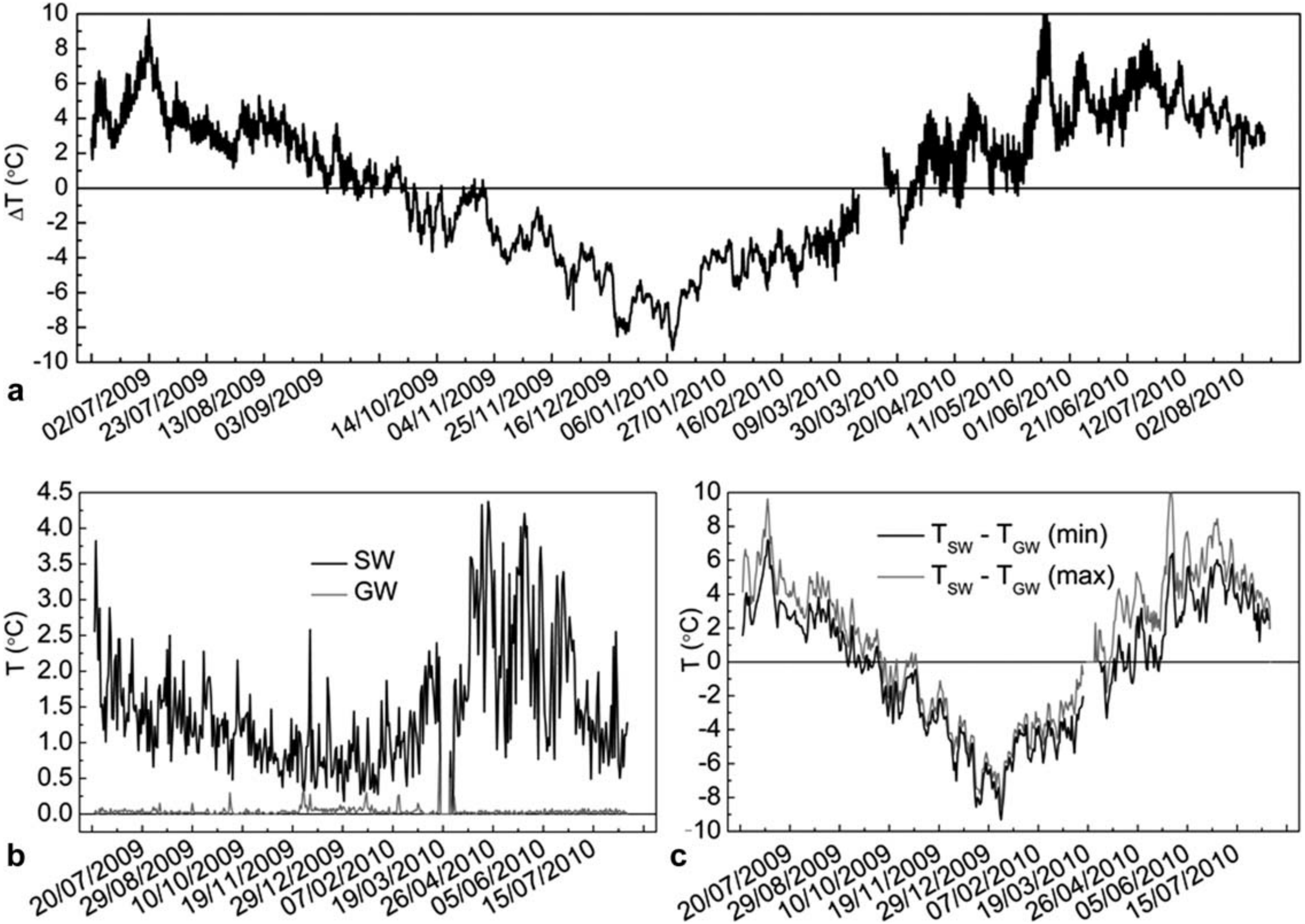
Limitations and Challenges

- Variability (space and time) in signal strength
- Experimental design and monitoring mode
- Sampling resolution and ambiguity of data interpretation (correlation between signal size and signal strength)

FO-DTS: Capabilities and Limitations

1. Impact of seasonal signal variation

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

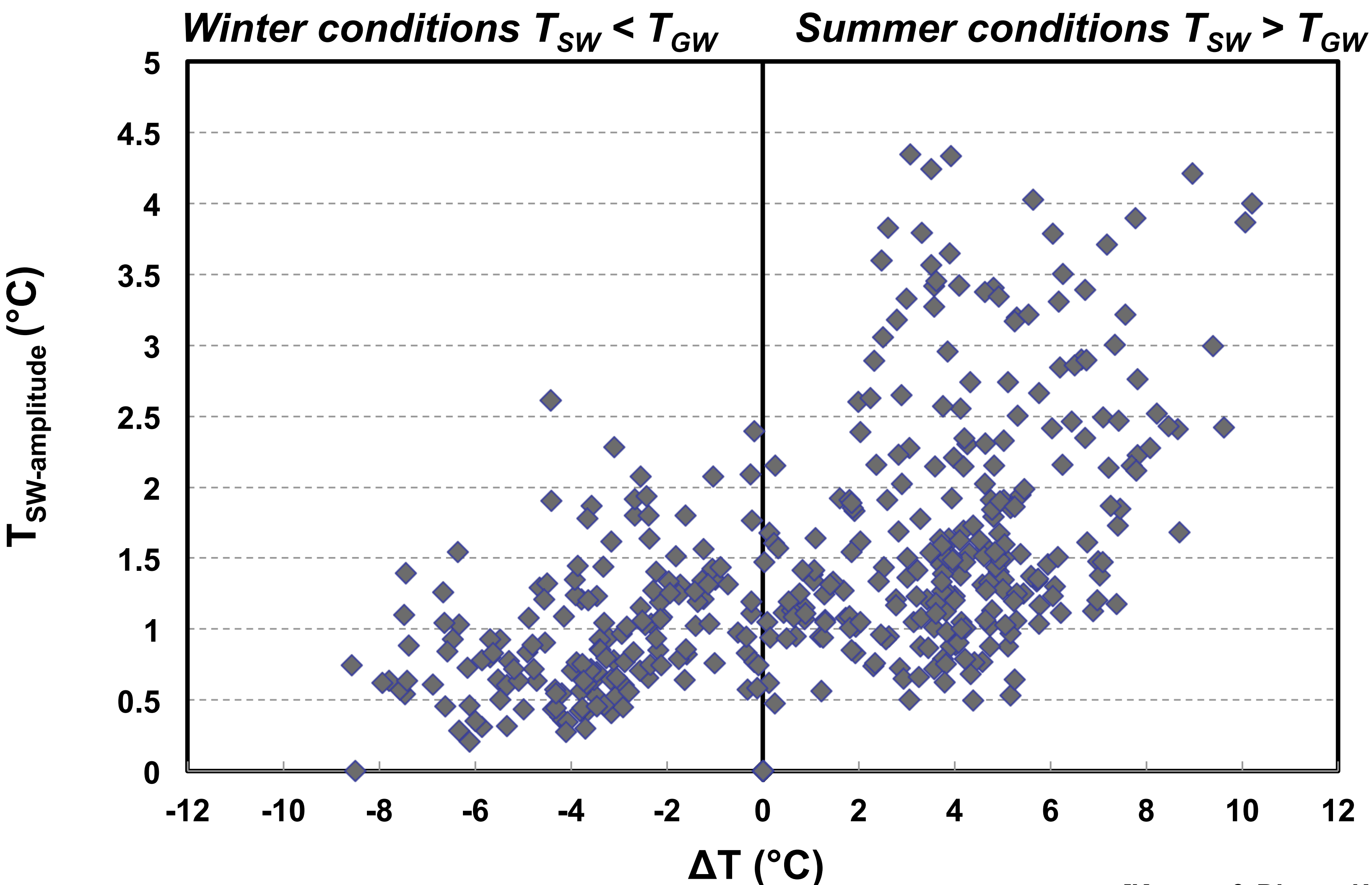


[Krause & Blume, WRR, 2013]

1. Impact of seasonal signal variation

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Seasonal variability of signal strength

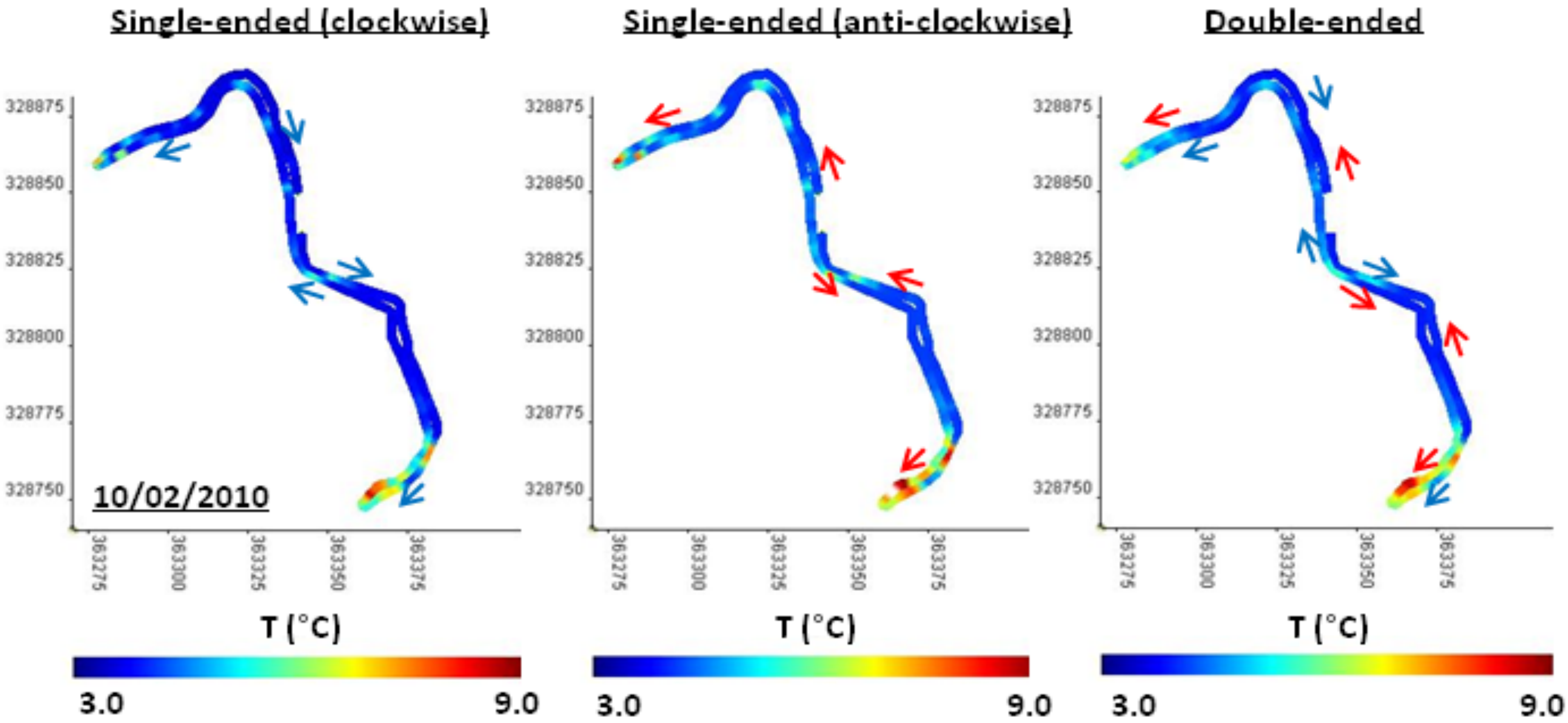


[Krause & Blume, WRR, 2013]

1. Impact of seasonal signal variation

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Winter:

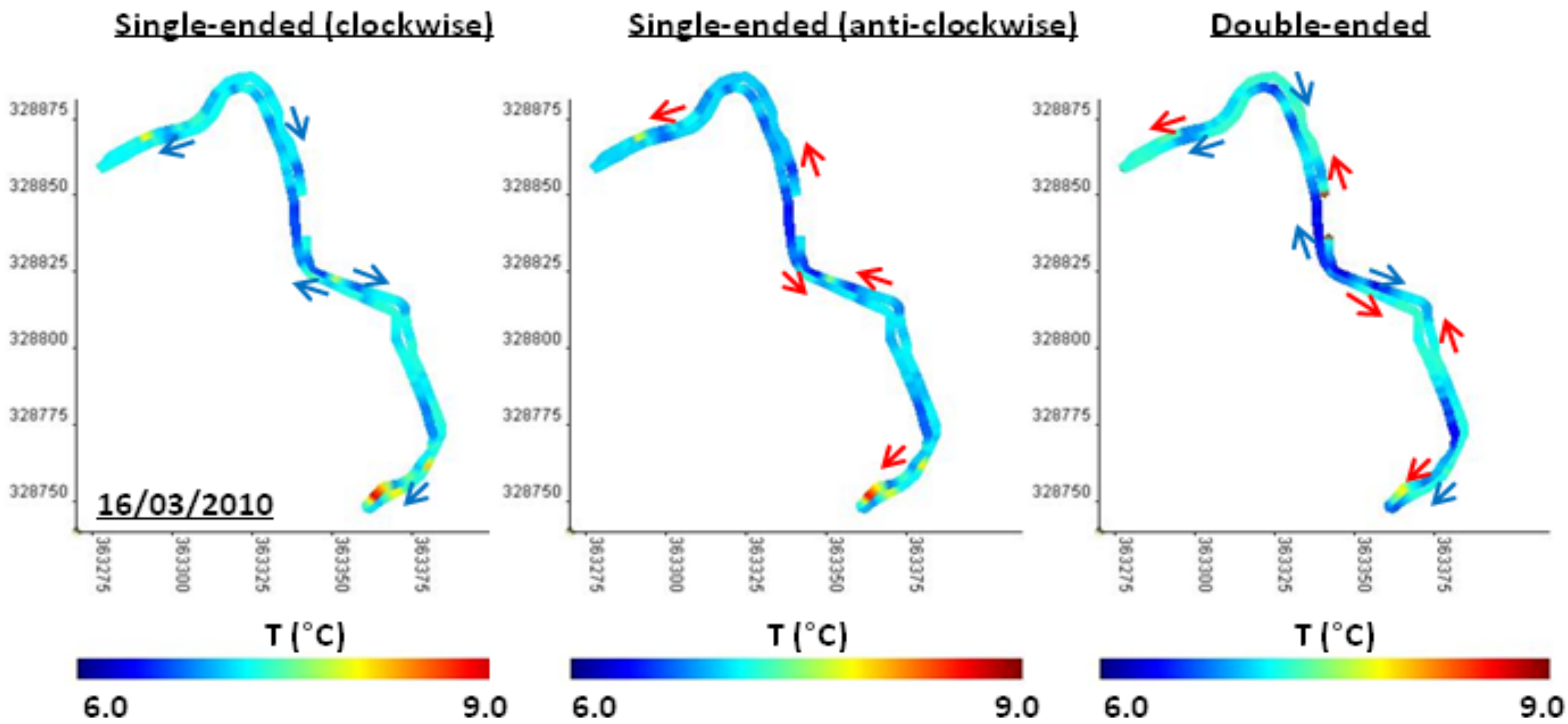


Krause & Blume, WRR, 2013

1. Impact of seasonal signal variation

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Spring:

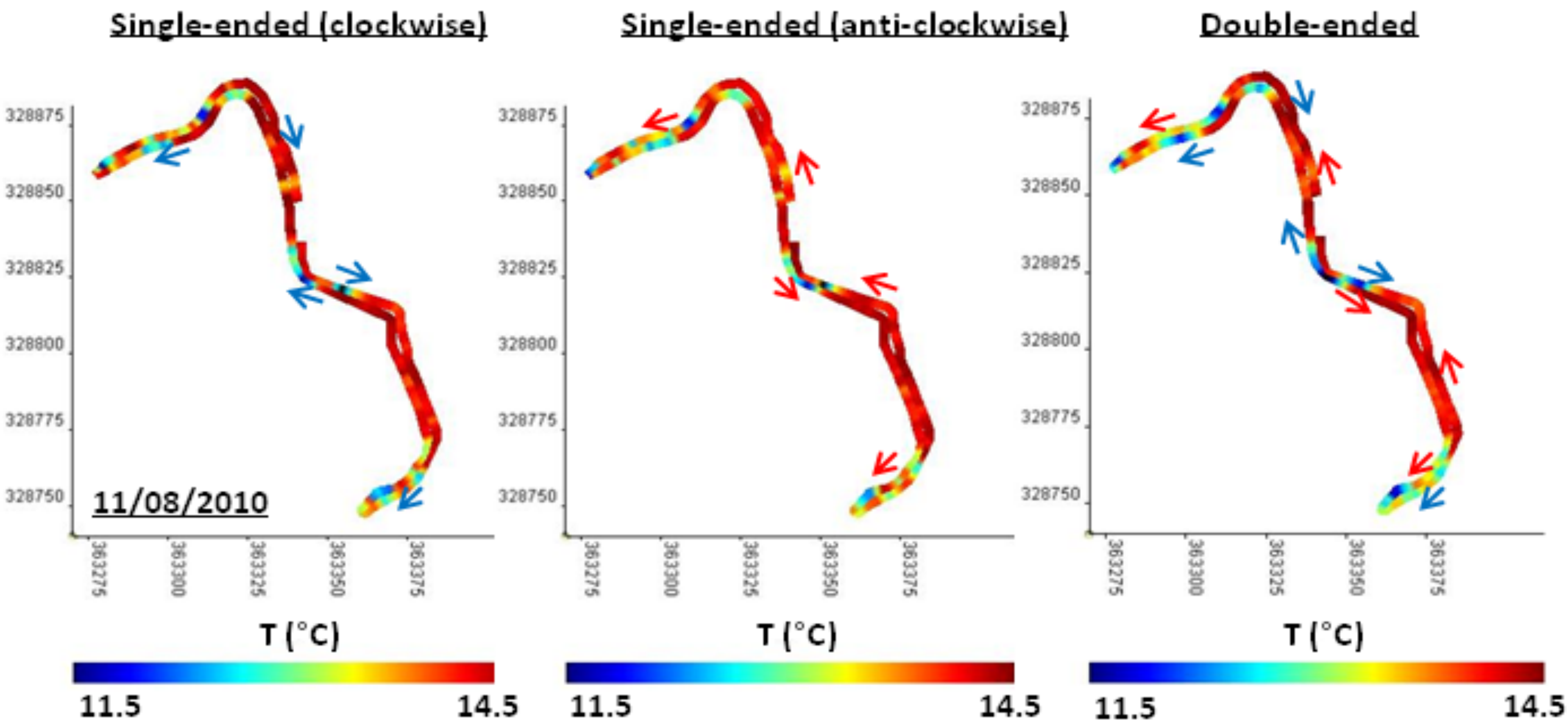


Krause & Blume, WRR, 2013

1. Impact of seasonal signal variation

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

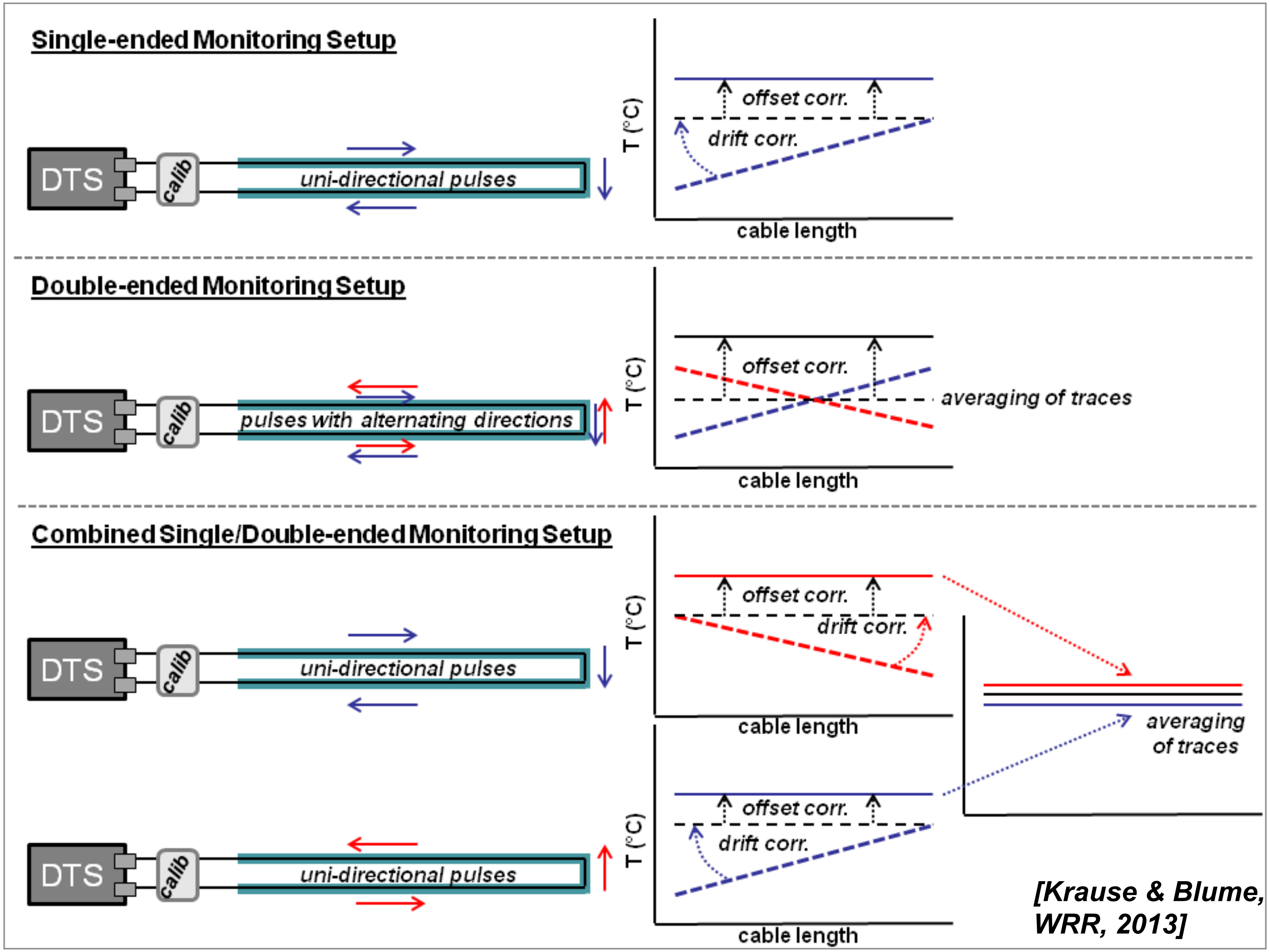
Summer:



Krause & Blume, WRR, 2013

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

2. Impact of monitoring modes

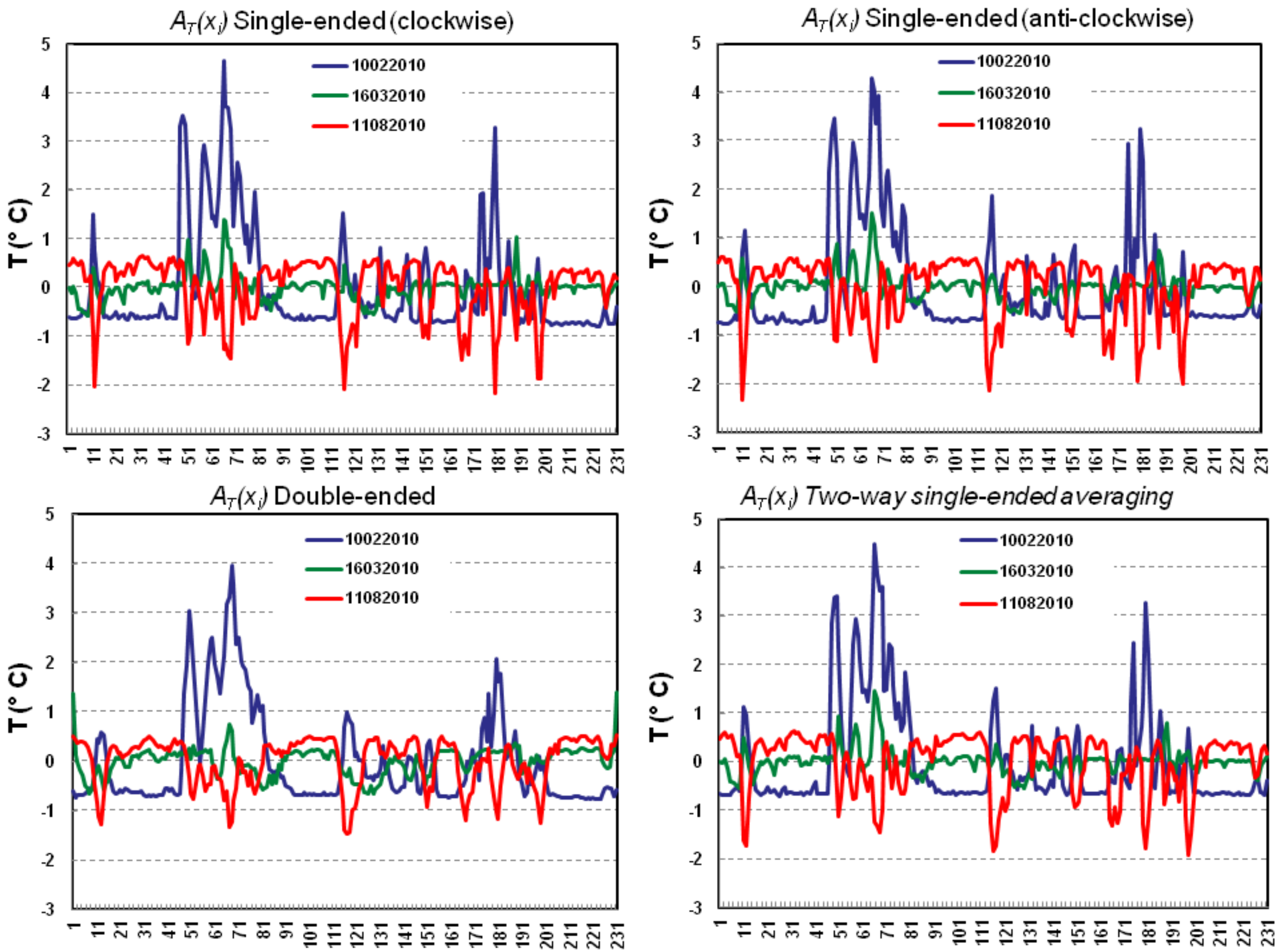


[Krause & Blume, WRR, 2013]

FO-DTS: Capabilities and Limitations

UNIVERSITY OF BIRMINGHAM

Geography, Earth and Environmental Science

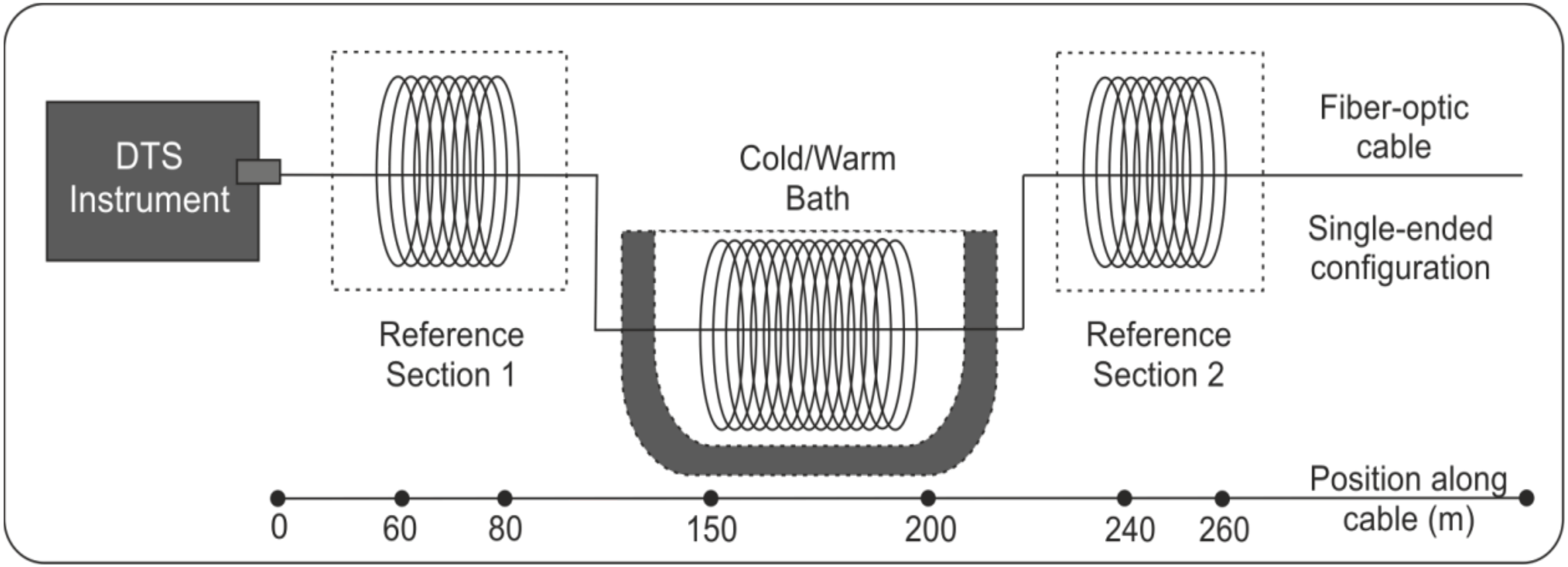


[Krause & Blume, WRR, 2013]

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

3. Impact of signal strength and signal size

Setup of controlled lab-experiment:



Variation of:

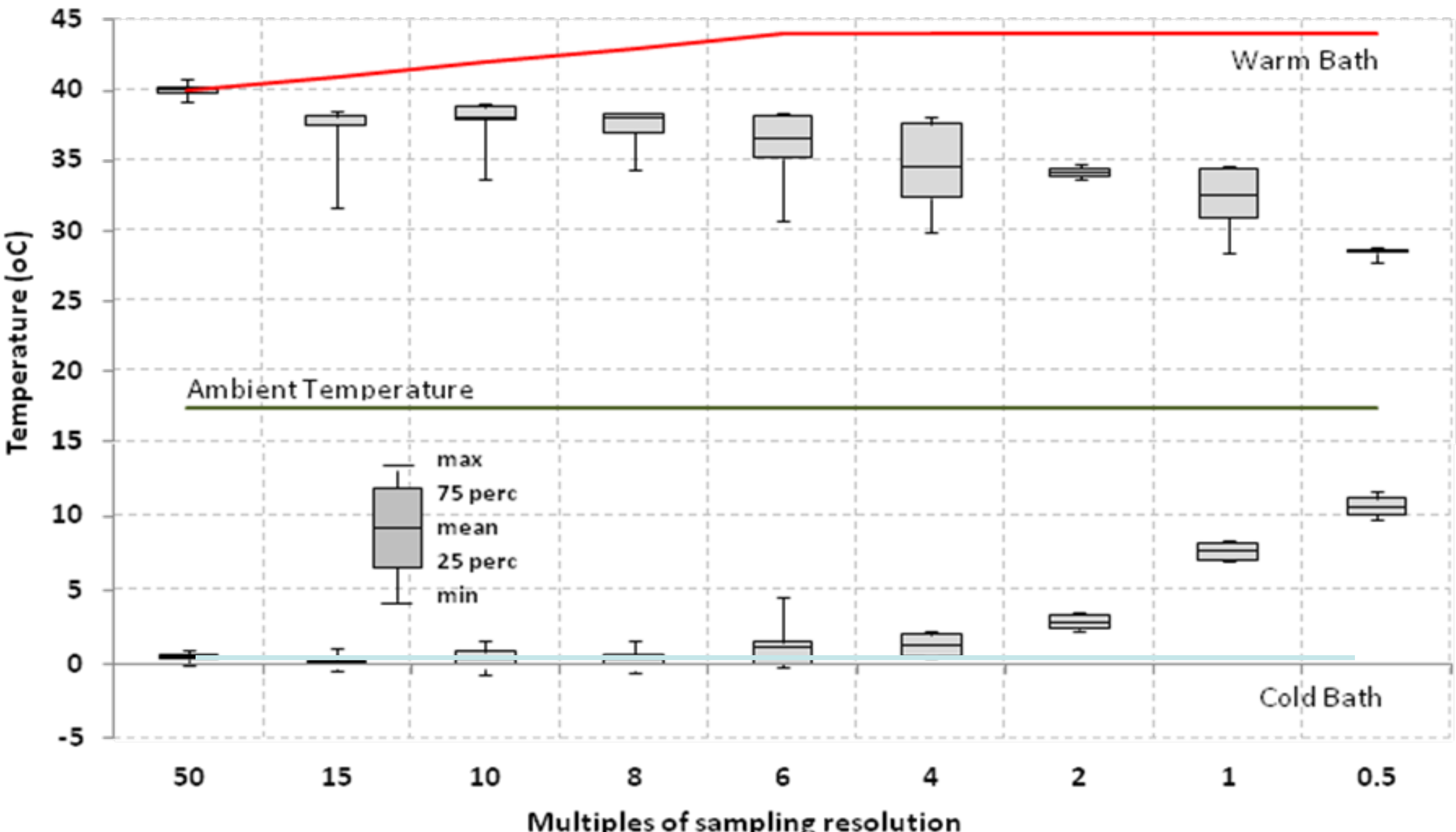
- **Signal strength (0.25 – 0.5 x sampling resolution)**
- **Signal size / direction (positive / negative T-anomaly)**

Rose et al., WRR, 2013

FO-DTS: Capabilities and Limitations

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

3. Impact of signal strength and signal size



Rose et al., WRR, 2013

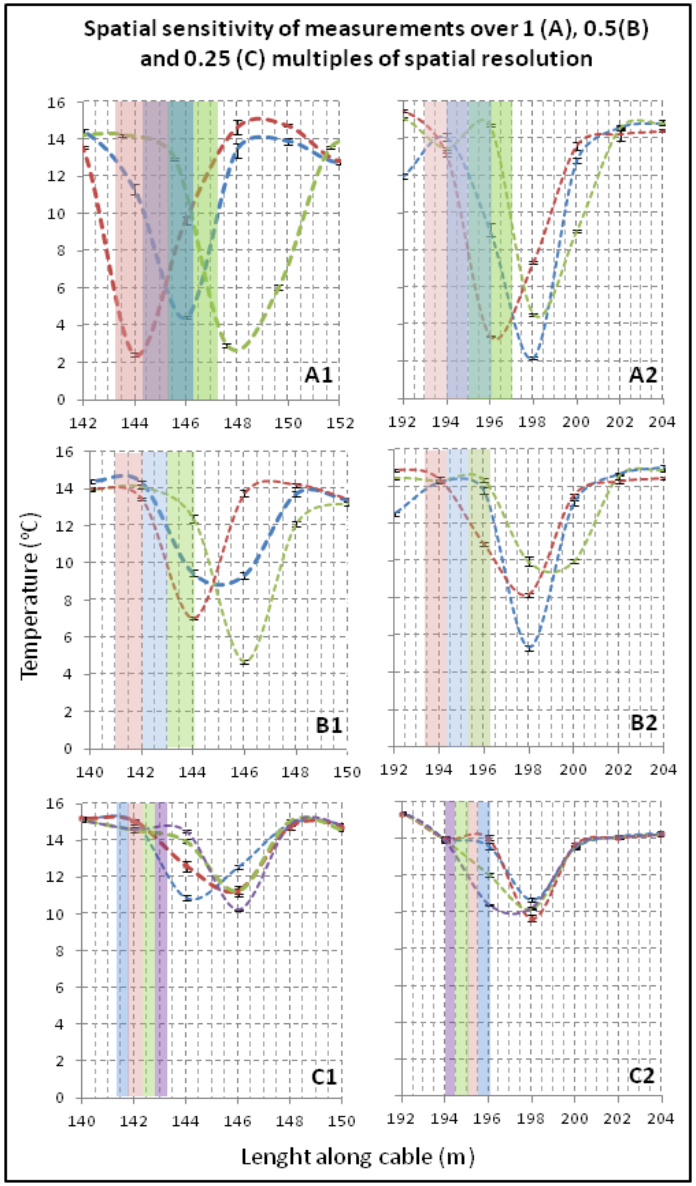
FO-DTS: Capabilities and Limitations

Signal detection close to / below sampling resolution

In reality signal-size usually unknown

Small signal size:

- **errors in detection of spatial signal extend (size)**
- **error in signal strength increases with reduction in signal size**
- **signal dislocation**



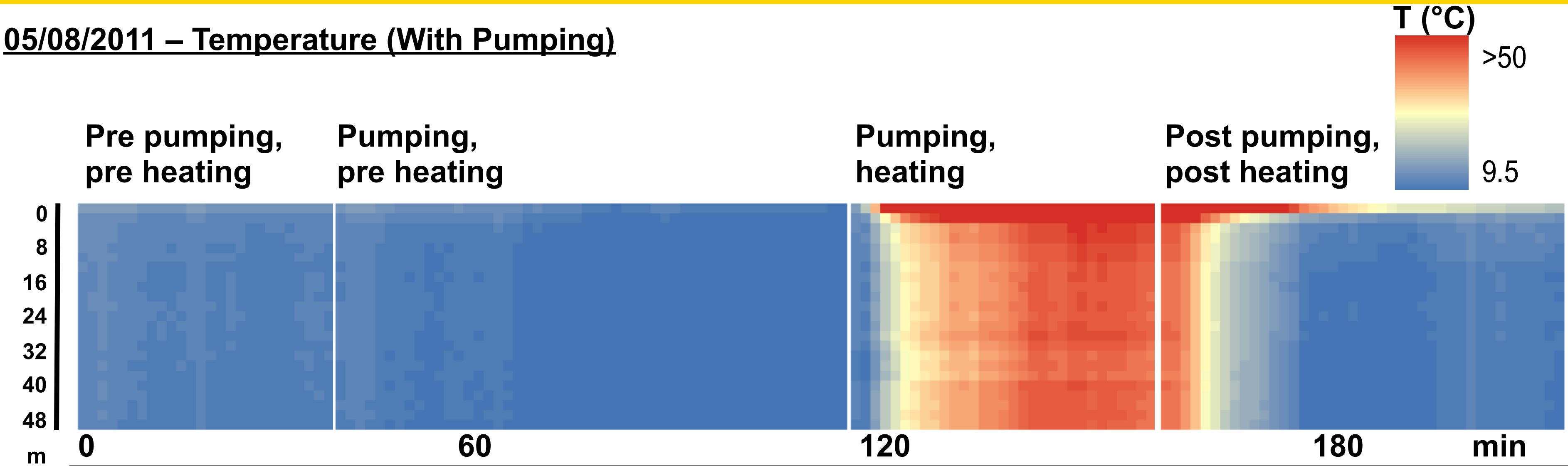
Rose et al., WRR, 2013

New perspectives: Active FO-DTS

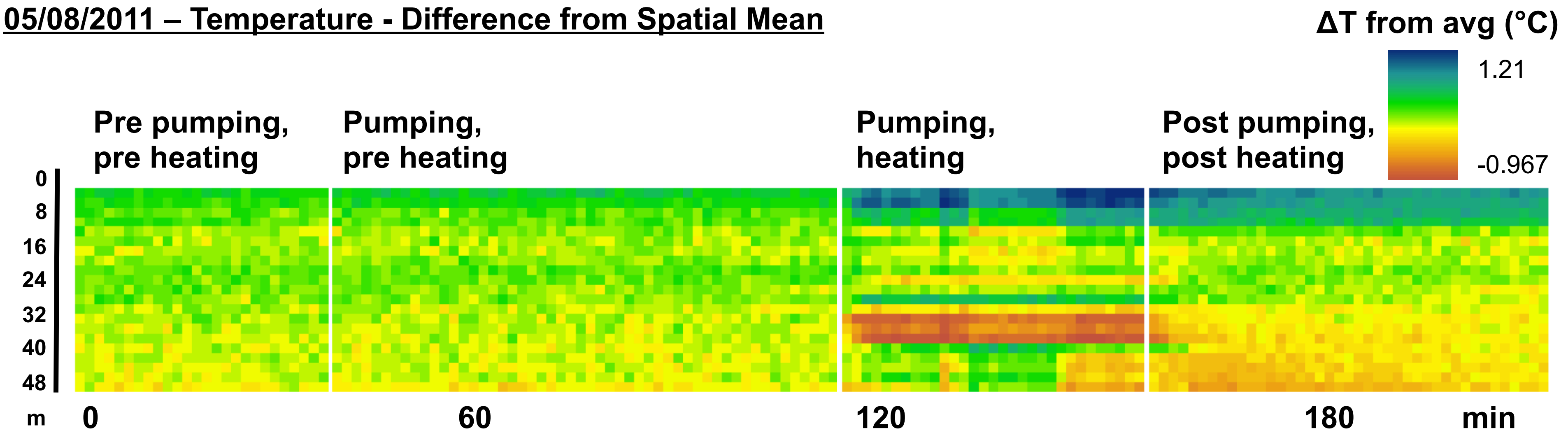
UNIVERSITY OF BIRMINGHAM

Geography, Earth and Environmental Science

05/08/2011 – Temperature (With Pumping)



05/08/2011 – Temperature - Difference from Spatial Mean



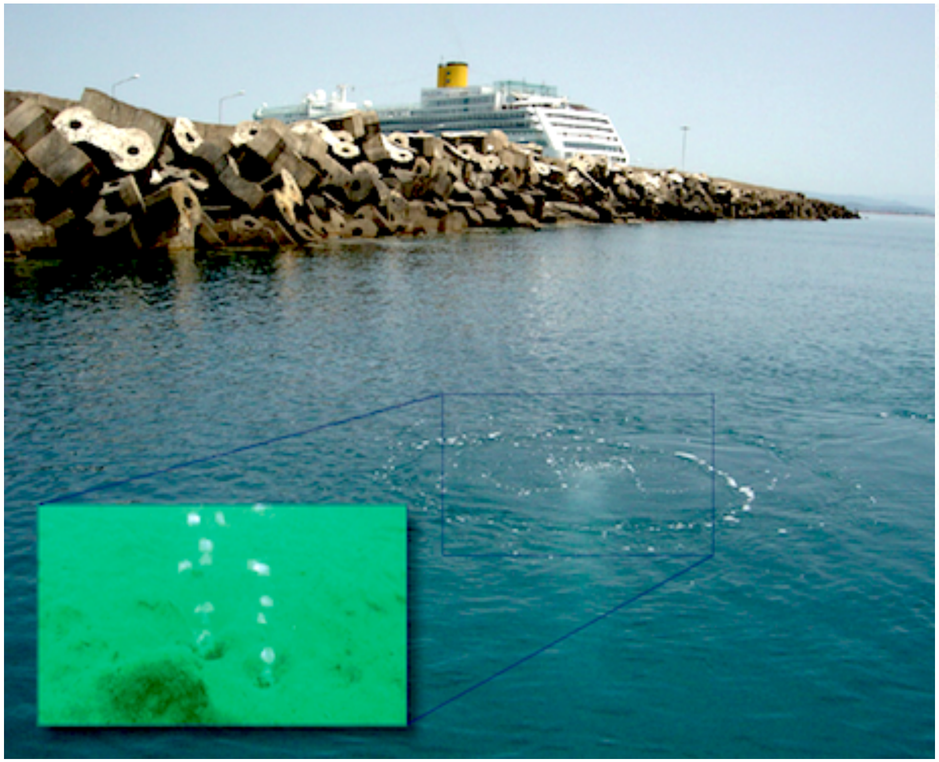
[McMillan et al., WRR, submitted]

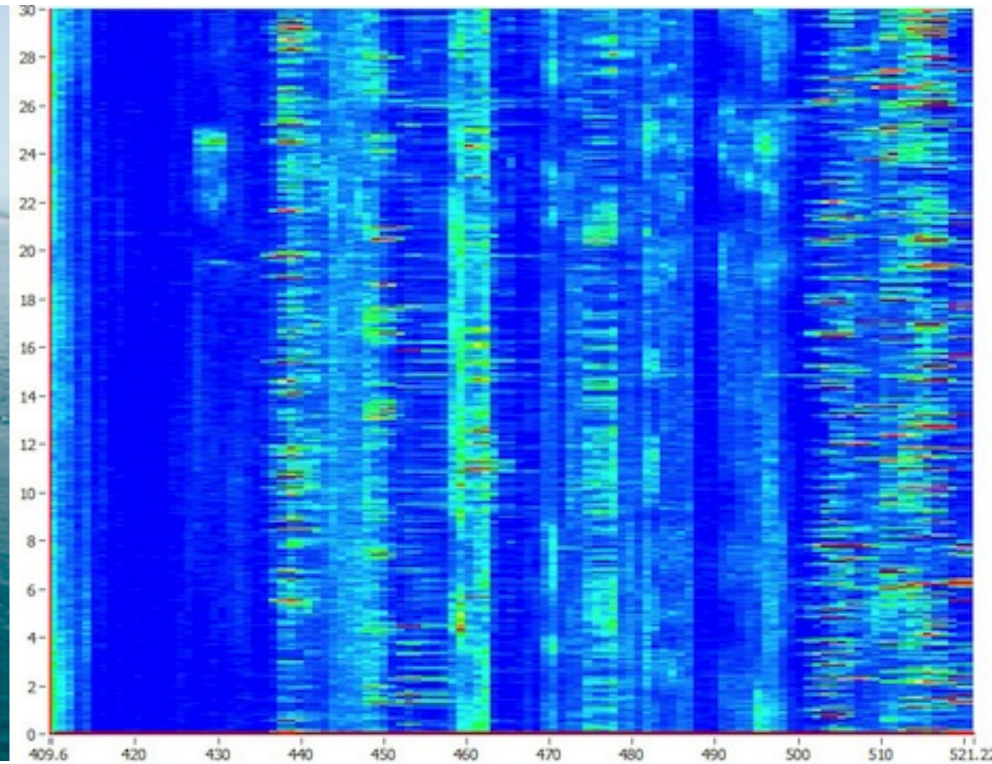
New perspectives:
IDAS – Intelligent Distributed Acoustic Sensing

UNIVERSITY OF BIRMINGHAM

Geography, Earth and Environmental Science

IDAS-based quantification of gas ebullition





SILIXA

Stefan Krause University of Birmingham, UK s.krause@bham.ac.uk

UNIVERSITY OF BIRMINGHAM
Geography, Earth and Environmental Science

Opportunistic and ~~vs~~. hypothesis driven research

Be aware of the limitations and uncertainties!

Thank You

Special thanks to:

- D.M. Hannah, L. Rose, L. McMillan, S. Folegot, S. Milner (University of Birmingham)
- J. Lewandowski, K. Meinikmann (IGB-Berlin)
- A. Binley, L. A. Heathwaite, P. Keenan (Lancaster University)
- V. Bense, T. Read (University of East Anglia)
- T. Blume, L. Angermann, C. Tecklenburg (GFZ-Potsdam)
- J. P. Zarnetske (University of Michigan)
- J.H. Fleckenstein, C. Schmidt (UFZ-Leipzig)
- F. Day-Lewis, J. Gomez, (USGS)
- J. Weatherill, S. Ullah, N.J. Cassidy, (University of Keele)
- M. Munz (University of Potsdam)
- D. Kaeser (Uni Neuchatel)
- A. Chalari, M. Mondanos (SILIXA)

MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

INTERFACES - Ecohydrological interfaces as critical hotspots for transformations of ecosystem exchange fluxes and biogeochemical cycling. FP7-PEOPLE-2013-ITN, 2013-2017

NERC SCIENCE OF THE ENVIRONMENT

Large woody debris -A river restoration panacea for stream-bed nitrate attenuation? NERC-NE/L004437/1, 2014-1017

Groundwater flooding: GW-community recovery following an extreme recharge event. NERC-NE/M005151/1, 2014-2015

Active Distributed Temperature Sensing for high-resolution fluid-flow monitoring in boreholes. NE/L012715/1, 2014-2015

Smart tracers and distributed sensor networks for quantifying the metabolic activity in streambed reactivity hotspots NERC-NE/I016120/1, 2011-2013

The Leverhulme Trust

Where rivers, groundwater and disciplines meet: a hyporheic research network. 2014-2017

Environment Agency

Risk assessment and potential for attenuation of TCE in hyporheic sediments, 2010-2014

C-KIC: Prediction of drought impacts on thermal and water quality extremes, 2014-2017

FO-DTS for identifying GW-SW exchange flow in Icelandic lakes 2012-2013

eit Knowledge & Innovation Community Climate-KIC

IGB Leibniz-Institute of Freshwater Ecology and Inland Fisheries

Research for the future of our freshwaters