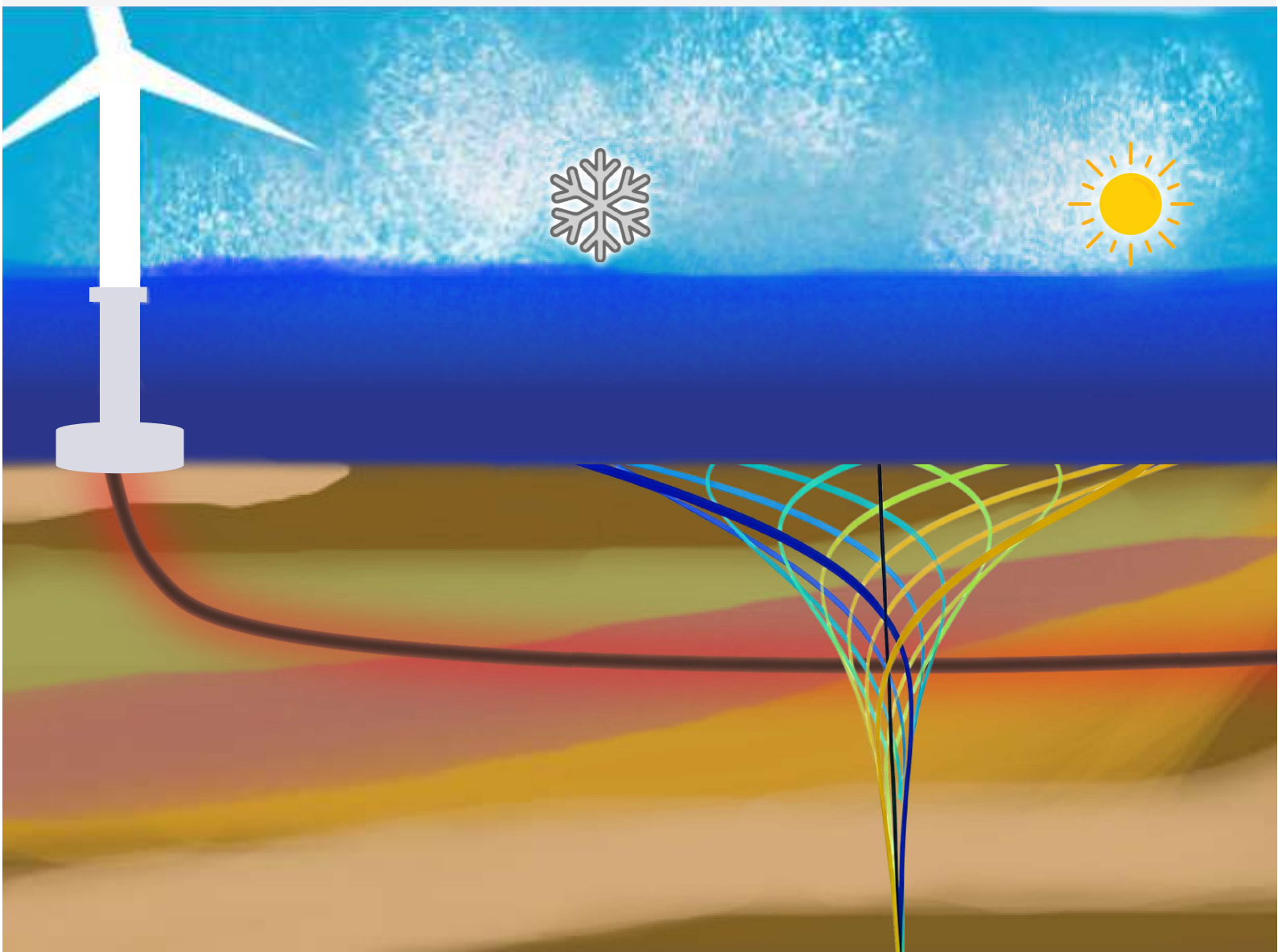


FIELDAX

Sediment Temperatures



$$\partial_t T(\vec{x}, t) - \nabla \cdot (\kappa(\vec{x}) \nabla T(\vec{x}, t)) = \frac{H(\vec{x}, t)}{\rho c_v}$$



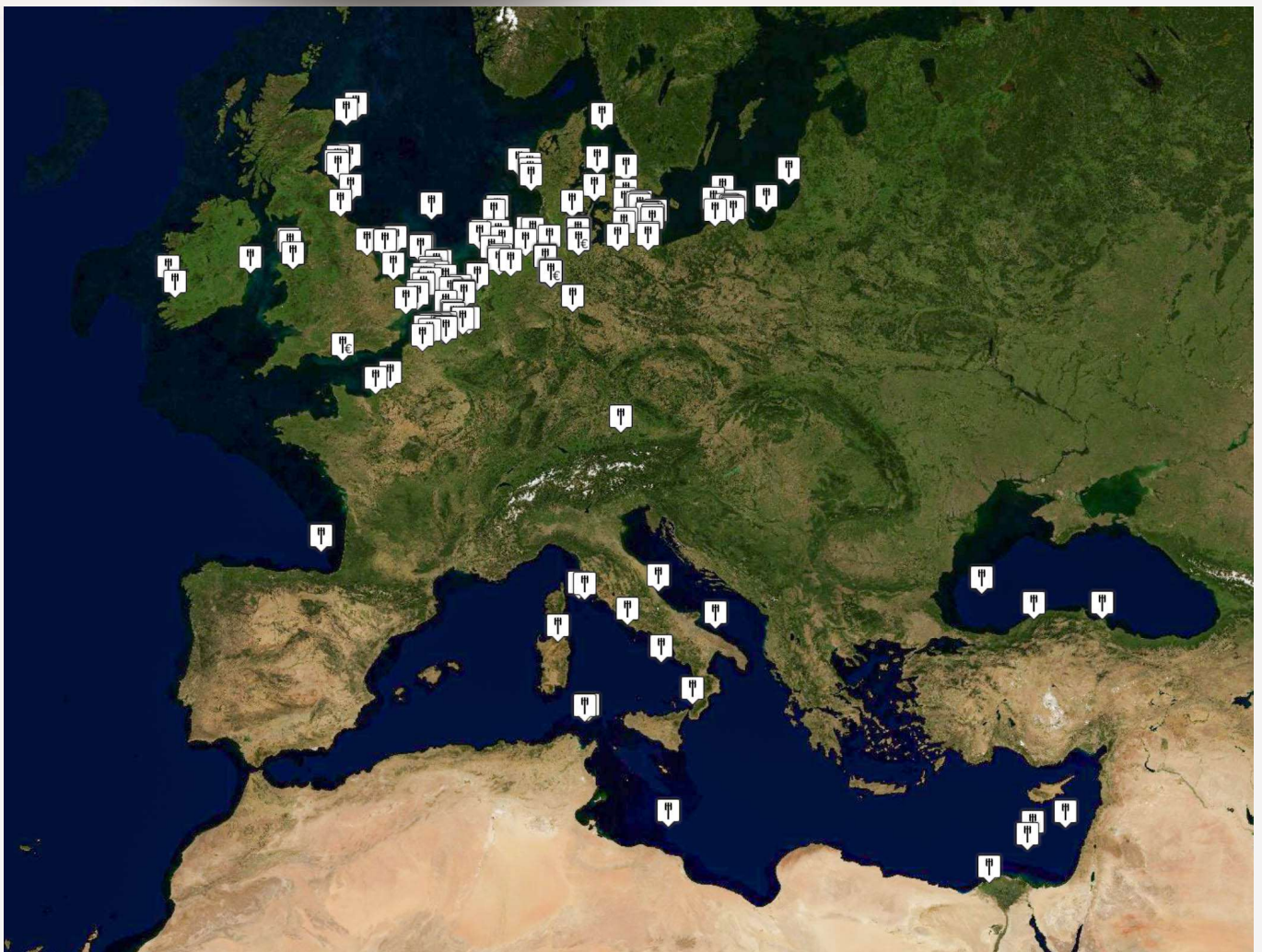
Worldwide experience

Temperature

Thermal conductivity

Thermal resistivity

Geothermal heatflow





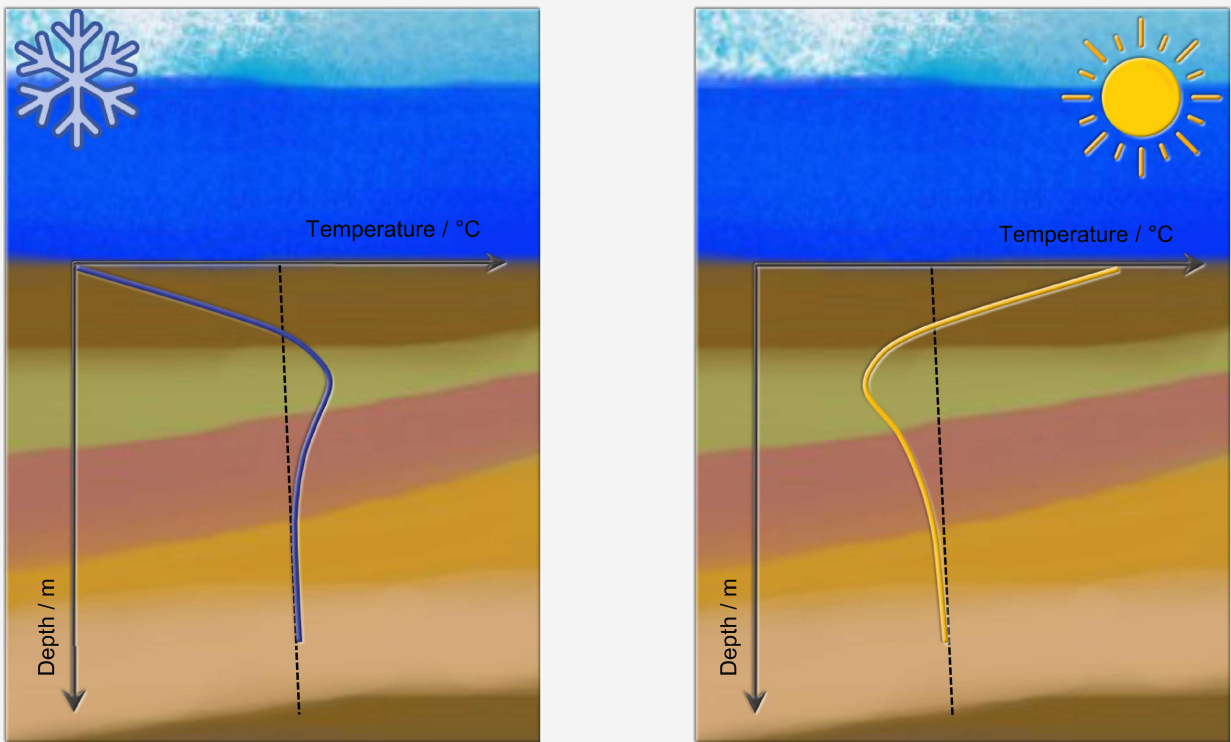
In-situ measurements of temperature and thermal properties

For more than 20 years FIELAX has been working on the determination of in-situ thermal parameters in marine sediments. Starting from classical measurements of the geothermal heat flow in soft deep-sea sediments, FIELAX has continuously developed its instrumentation to enable measurements in shallow waters, thus expanding the knowledge base and understanding of transport processes of heat (natural or man-made) in marine sediments. Our worldwide experience with thermal measurements in different marine environments makes FIELAX a pioneer in performing thermal measurements in the field and sets standards for data processing and interpretation.

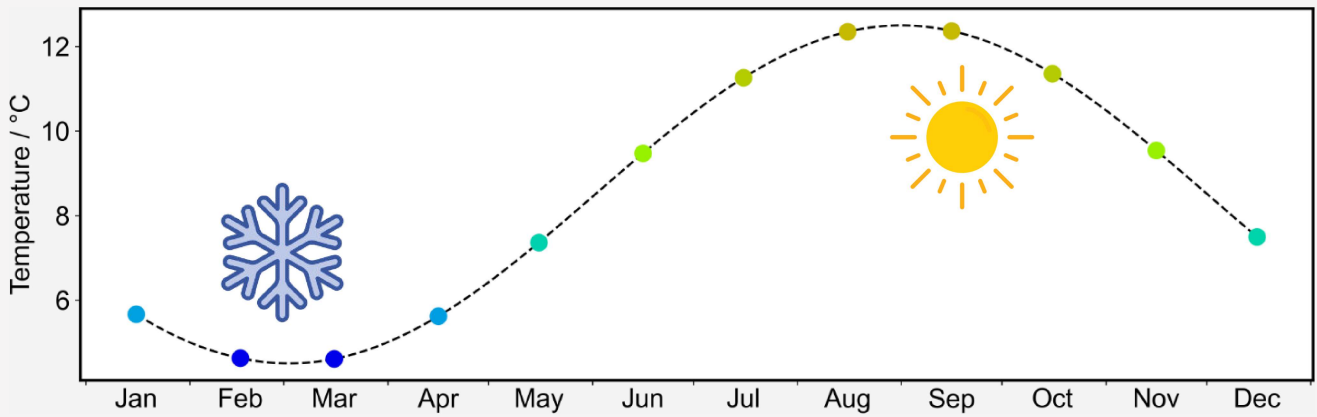
Knowledge of the thermal properties of coastal sediments has become increasingly important due to the expanding offshore energy industry. While thermal conductivity has steadily gained importance over the years, sediment temperatures have received little to no attention. However, both parameters directly influence, for example, the heat loss (cooling) of buried power cables and thus their temperature.

This brochure illustrates the importance of the ambient temperature of the sediments for the cooling of underground power cables, both in water-saturated sediments offshore and onshore, where additional factors need to be considered.

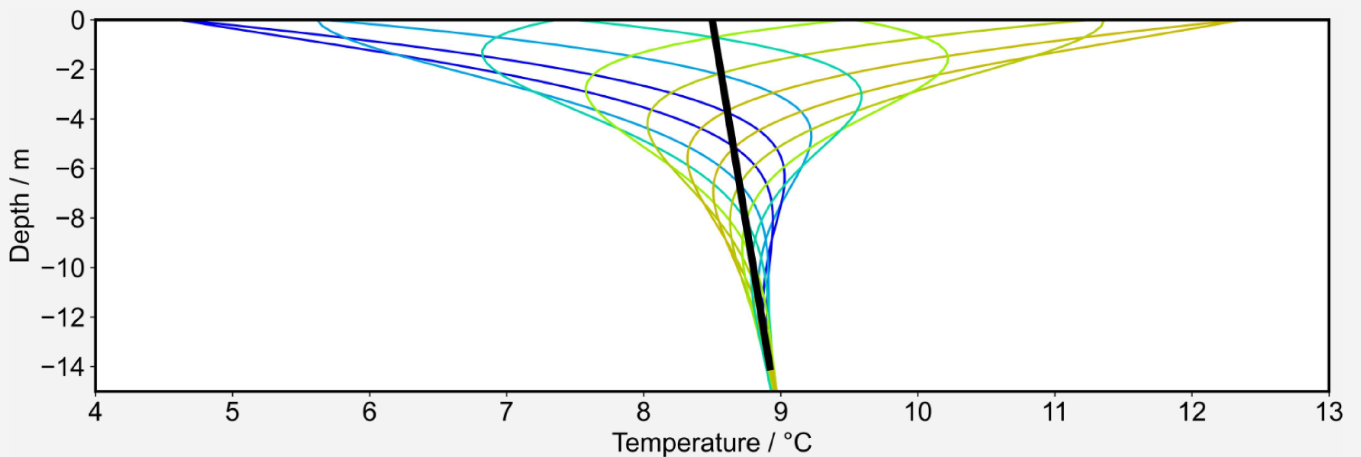
Sediment temperatures in shallow coastal regions



Annual bottom water temperature variations



Analytical solution of the one-dimensional heat equation



Natural temperature variability

In general, the temperatures of marine sediments obey the universal laws of thermodynamics and are determined by internal heat sources and sinks, heat exchange with the overlying water and the Earth's interior, and their thermal properties.

The greatest natural influence on sediment temperatures is the average temperature of the Earth's surface (or bottom water) and its seasonal fluctuations. In the deep sea and at low latitudes, seasonal variability can be considered insignificant, but at high latitudes and/or shallow water depths, this effect can be quite large. In the well-mixed North Sea, the seasonal temperature change of the bottom water may well exceed 10°C.

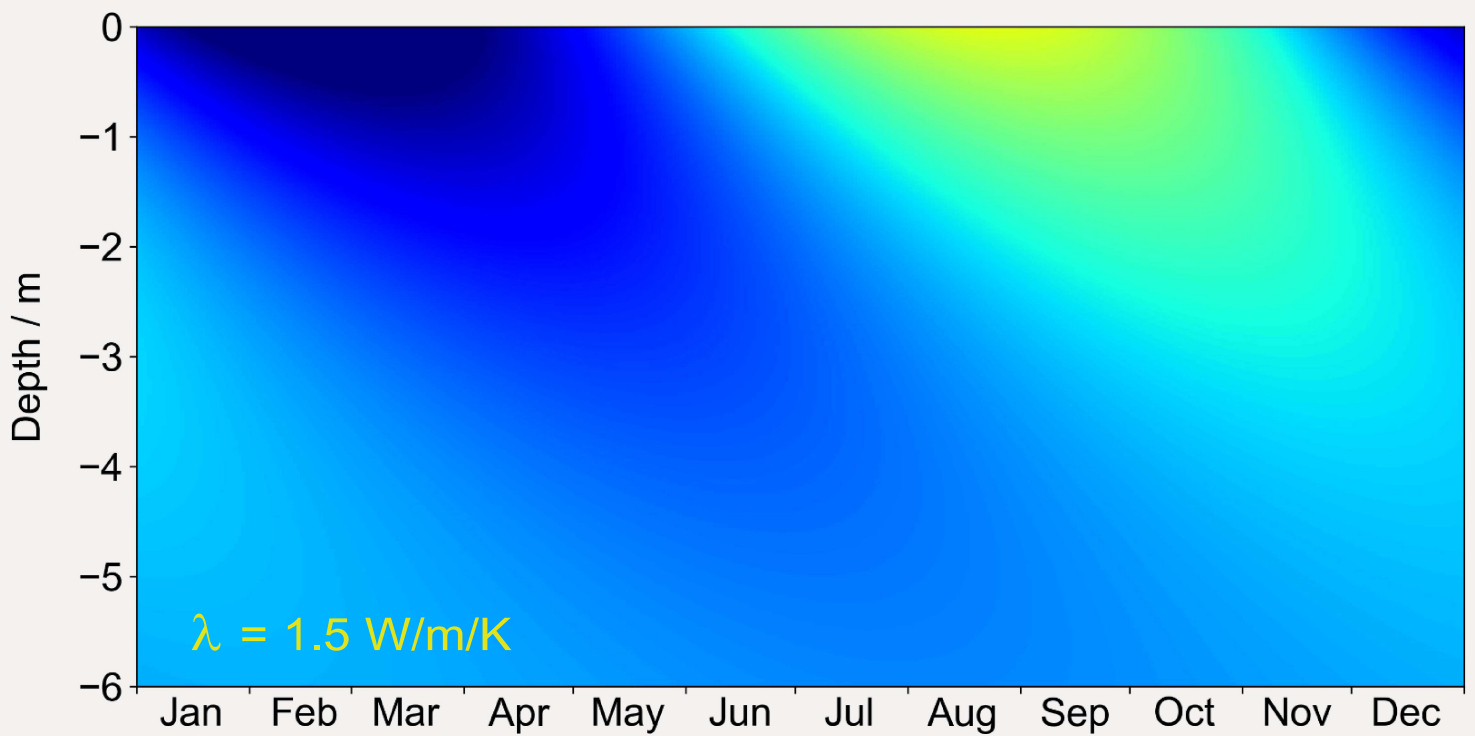
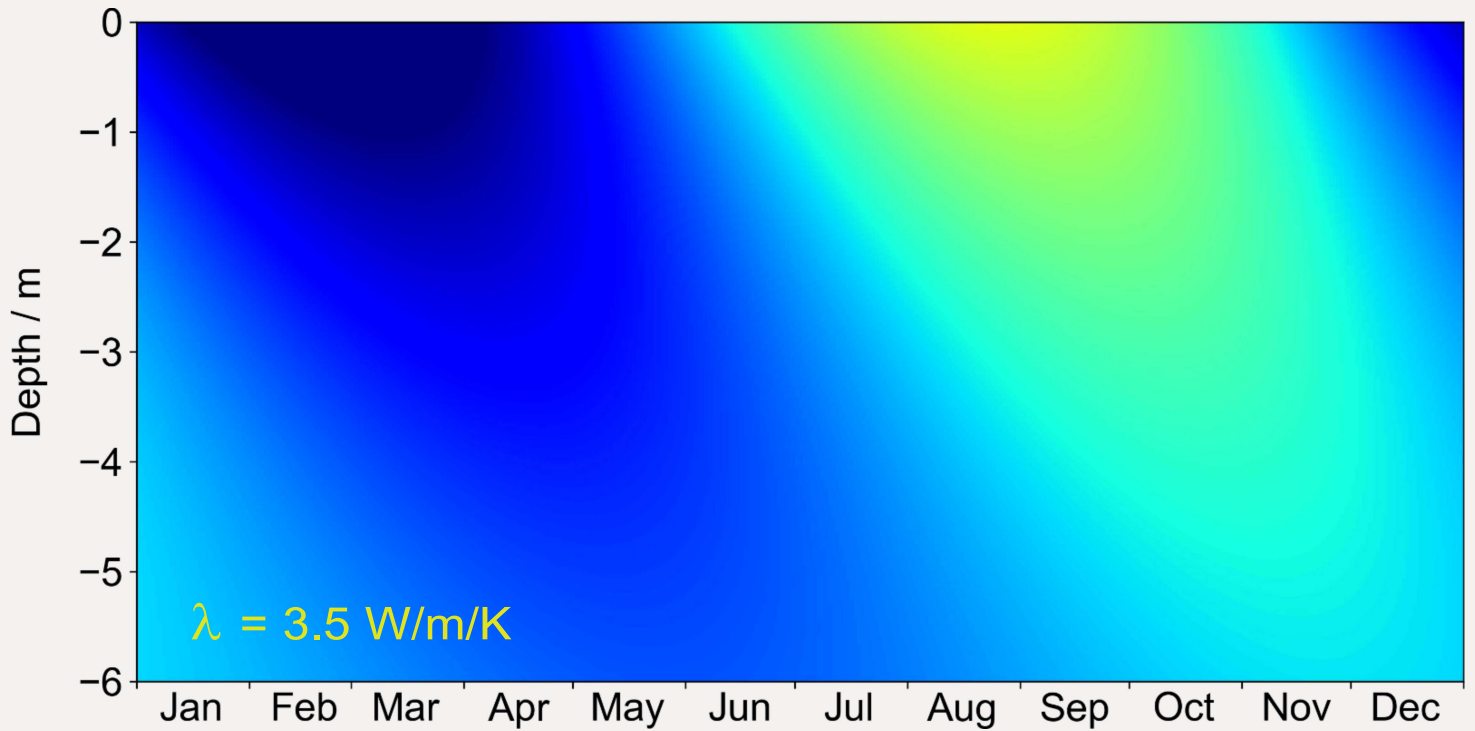
The influence of seasonal warming/cooling on the temperature distribution in marine sediments can be calculated by solving the one-dimensional heat transfer equation, using the bottom water temperature fluctuations as boundary condition at the surface. The figures on the left illustrate the processes:

- The middle figure shows an example of bottom water temperatures approximated by a sine wave.
- The bottom figure shows the resulting temperature-depth curves (color-coded) as a solution of the one-dimensional heat conduction equation, the solid black line represents the constant background geothermal gradient (global average 0.03 K/m).

It should be noted that there is usually a considerable time lag before the natural seasonal fluctuations spread from the water to the seabed.

Another - more recent - aspect is the general (slow) increase in sediment temperatures that can be expected due to the continuous increase in average air temperature as a result of climate change.

*Annual sediment temperature variations for
high and low thermal conductivity*





Influence of thermal conductivity

The thermal conductivity of the sediments determines the time scale on which temperature changes are transferred. This is not only important for the dissipation of artificial heat, such as that emitted by offshore power cables, but already has a major impact on the temperatures of the upper approximately 10-15 m of the seabed during the year when the temperature of the atmosphere or bottom water varies.

The figures on the left show the analytical solution of the heat conduction equation over the entire year for the upper 6 m of the seabed for two types of sediments.

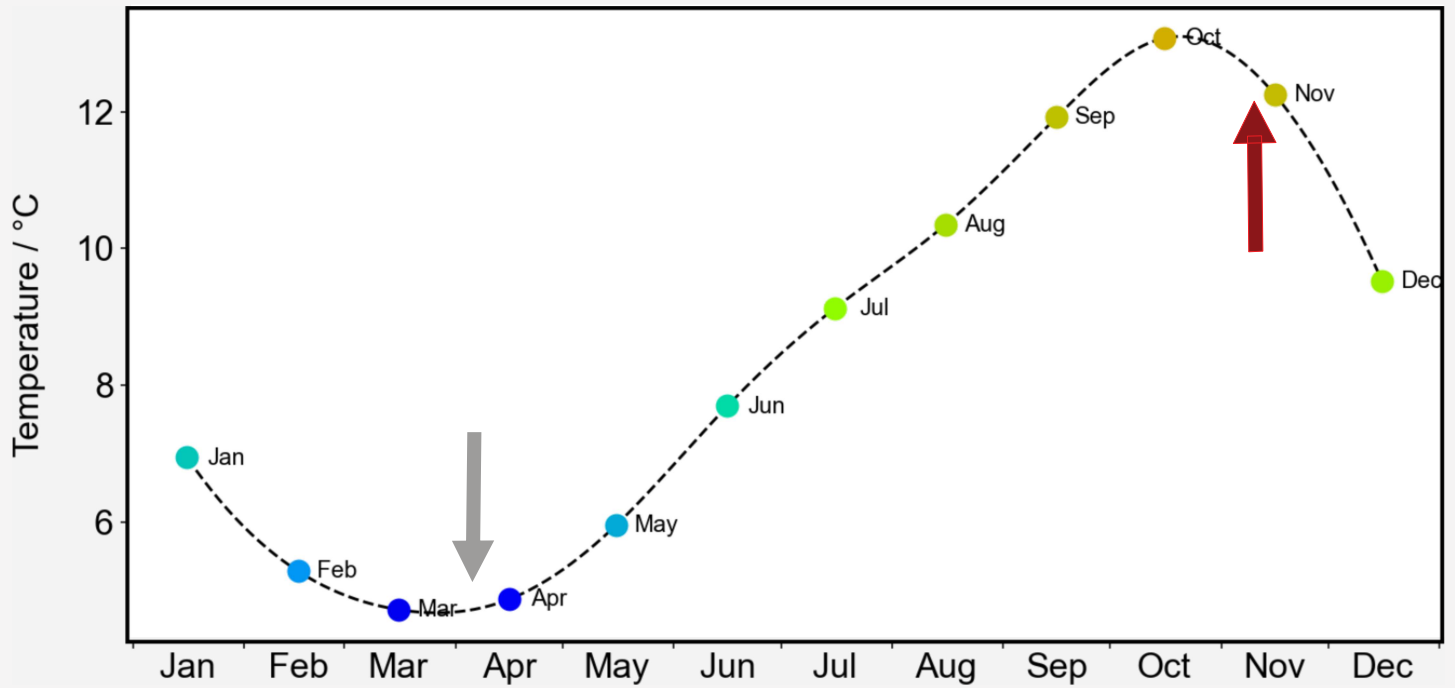
In both scenarios, a simple cosine variation of bottom water temperature was assumed with the coldest day at the end of February, an average temperature of 10.4°C and an amplitude of 7.1°C to resemble a typical variability found in the North Sea.

The upper figure shows the expected temperature development at a high thermal conductivity of 3.5 W/m/K, characteristic for consolidated sand. The lower figure shows the temperature development to be expected at a low thermal conductivity of 1.5 W/m/K, a typical value for mixed sediments with a higher content of organic mud or peat.

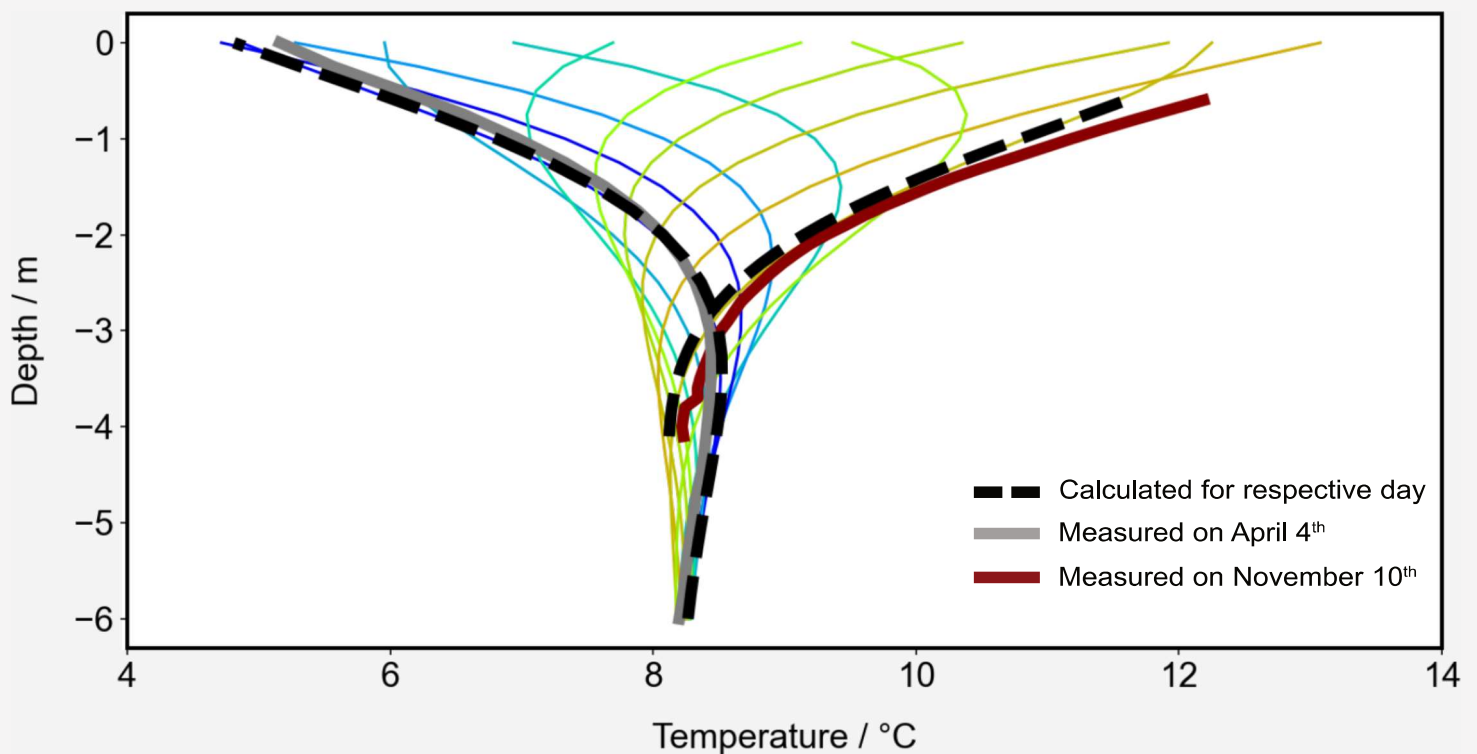
The significantly “faster” and “deeper” transmission of the seasonal signal at higher thermal conductivity is obvious.

Fourier approximation of bottom water temperature variations derived from the Boknis Eck Time Series Station

(data available under <https://doi.pangaea.de/10.1594/PANGAEA.973020>)



Calculated sediment temperature compared with actually measured sediment temperatures on April 4th (grey) and November 10th (red)



Case study from the Eckernförde Bay, Baltic Sea

The theoretical assumptions were tested in a case study in Eckernförde Bay in the Baltic Sea, where bottom water temperatures are available from long-term buoy measurements (www.bokniseck.de). The upper figure on the left shows a fourier approximation of the average annual cycle of the last decade. The colored dots mark day 15 of each month.

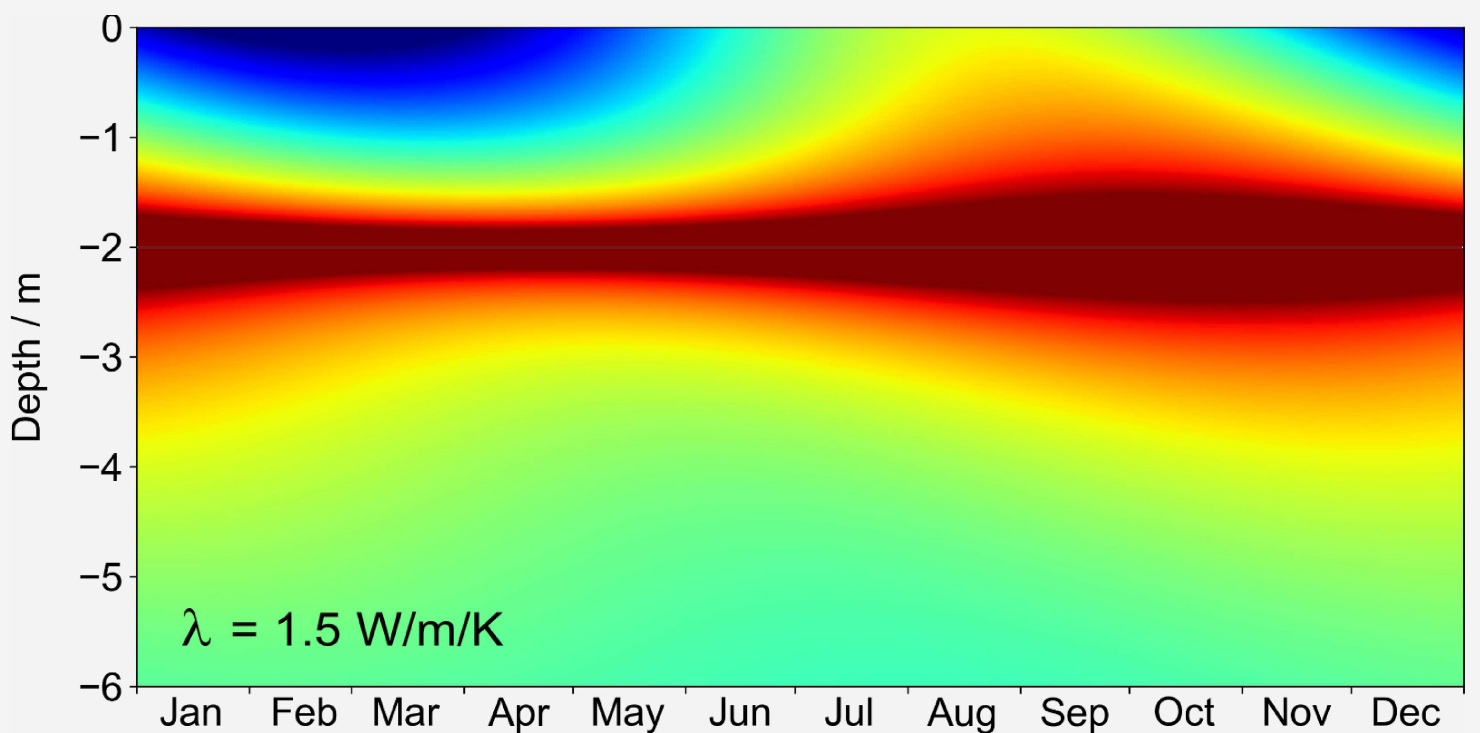
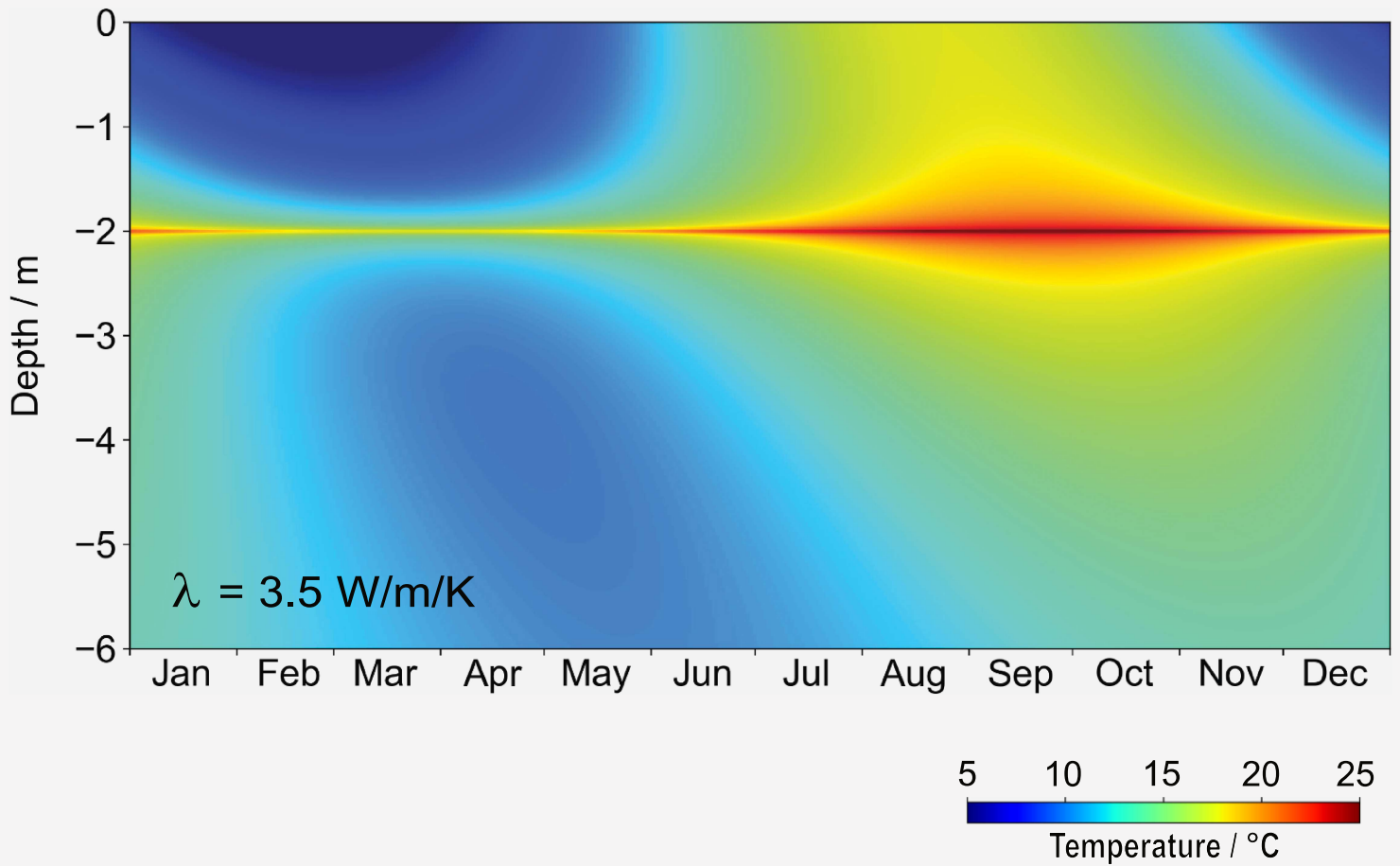
FIELAX investigated the sediment temperatures and thermal conductivities in this area in November 2022 and April 2023. The thermal conductivity was rather constant with depth at approximately 0.73 W/m/K . The sediment temperatures showed a strong seasonal difference that could be traced down to at least 6 m below the seafloor.

The lower figure shows the theoretical temperature-depth curves, which are color-coded according to the different colored dots of the upper figure. The dashed lines mark the analytical solution for the heat conduction equation for the respective days of measurement.

The actually measured temperatures are shown in gray for the winter situation and in red for the summer situation. The data is in excellent agreement with the theoretical values.

This example illustrates the possibility of predicting the annual development of the ambient temperature of the sediment based solely on the thermal conductivity and an approximation to the temperature of the bottom water, as well as the great potential associated with this.

Temporal evolution of sediment temperatures including an idealized power cable with a constant power loss of 50 W/m buried in 2 m depth





Effects on buried power cables

The laying and operation of offshore power cables creates an artificial heat source in the seabed. The resulting physical heat flow and the actual ambient temperatures result from the thermal conductivities of the sediment and temperatures of the heat sources:

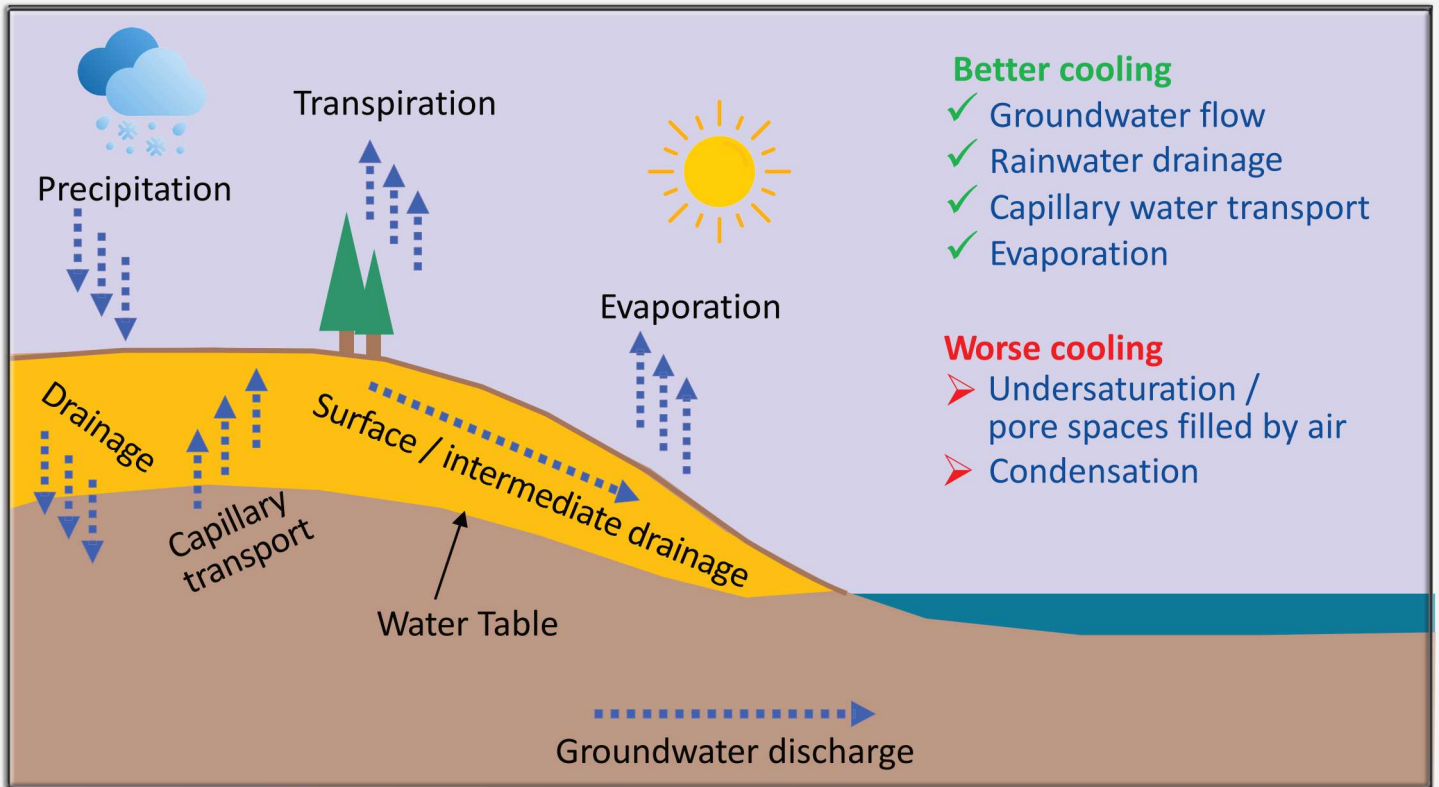
- The peak-to-peak amplitudes of the natural seasonal bottom water temperature (and thus the sediment temperature near the mudline) can be more than 10°C.
- Depending on the electrical load, power cables can heat up by several tens of degrees.

We reiterate that there is a considerable time lag before the natural fluctuations propagate across the seabed and eventually reach a typical cable laying depth of 1-2 meters. The highest (summer) temperatures would reach this depth about 3-5 months later. It takes just as long for the maximum cooling from the winter months to reach this depth. Conversely, it takes a correspondingly long time for the additional excess heat introduced by offshore power cables to eventually be absorbed by the seawater.

The figures on the left illustrate the evolution of seabed temperatures (upper 6m) over the year for high (upper figure) and low (lower figure) thermal conductivities as before, but including an idealized cable with a constant power loss of 50 W/m. This comparison shows impressively that the cable temperature varies considerably depending on the season, even at constant power loss, but also that a lower thermal conductivity greatly hinders the effective cooling of the cable, which leads to overall higher sediment temperatures.

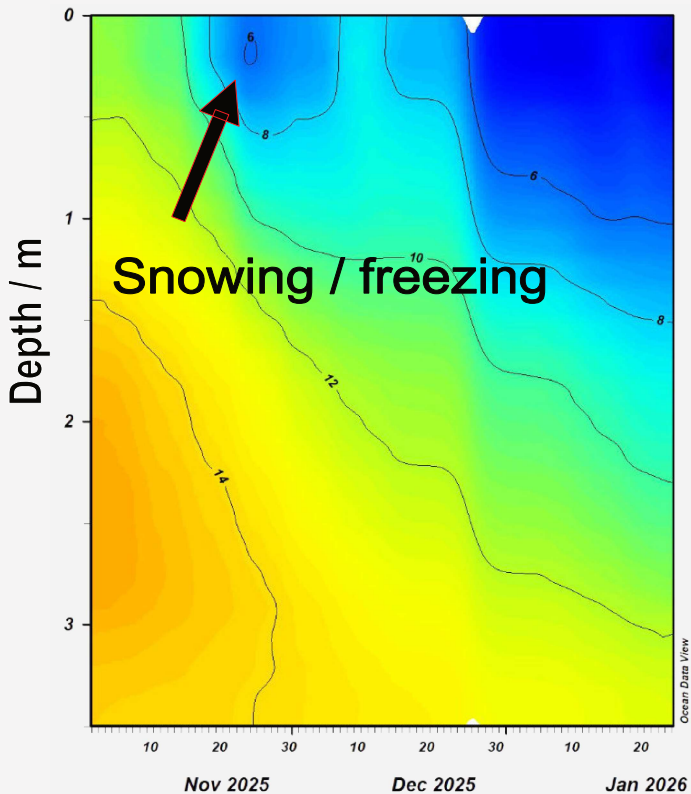
In summary, both thermal conductivity and sediment temperatures are important for offshore power cables and compose the sediment's potential to compensate for the additional heat.

Factors influencing sediment temperatures on land

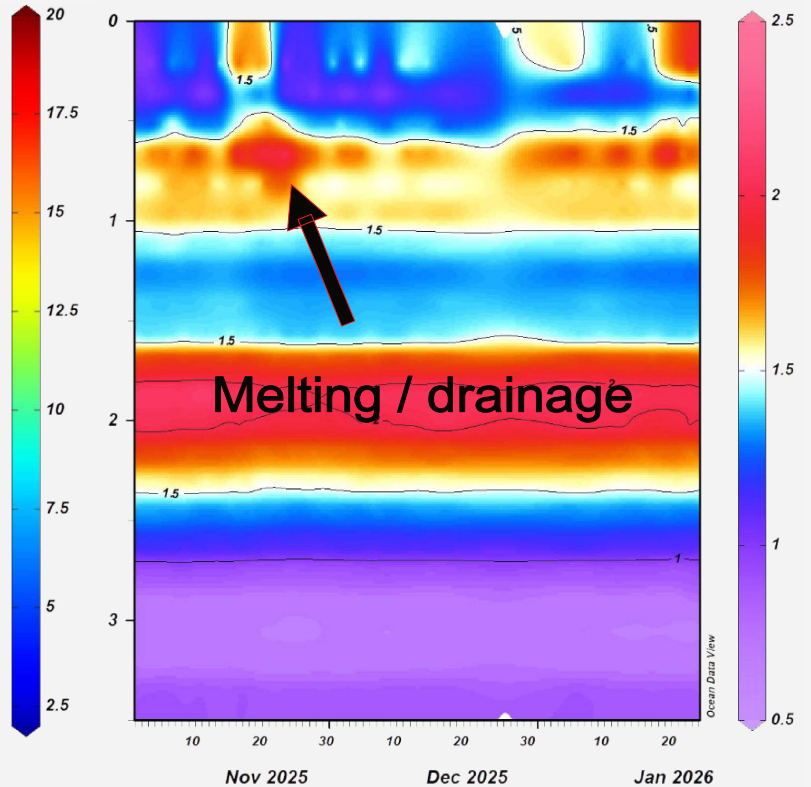


Onshore monitoring of soil temperature and thermal conductivity

Temperature / °C



Thermal Conductivity / W/m/K





Onshore & Monitoring

In contrast to offshore sediments, the potential for absorbing thermal energy in terrestrial soils cannot be considered constant. Other processes can dominate heat transfer in porous media. Most important for heat transfer is usually advection, i.e. the active transport of warmer or colder air or water. The figure above (left) summarizes processes that regularly occur in places where the exchange of water and air in porous soils takes place as a direct response to weather and climate:

- Groundwater flow, precipitation and evaporation remove or add heat many times more efficiently than conduction.
- Drying out of the soil can reduce thermal conductivity by more than an order of magnitude.

The figures below show a snapshot of the complex interplay. We have installed temporal monitoring at a location where the soil consists of a porous medium on top and a layered soil below with thermal conductivities between less than 1 W/m/K and more than 2 W/m/K, as is typical for this area. The left figure shows the temperature evolution at this location from beginning of November to end of January. The temperature drops by more than 10°C, and the very low temperatures at the surface coincide with snowfall. The right figure shows the “apparent thermal conductivity” for the same period. The replacement of air by water in the pore spaces increases the thermal conductivity of the soil. It can be seen that the precipitation, including snowfall and snowmelt, has led to surface water drainage to at least 1 m below the soil surface.

This means that at critical points, such as the land connections of submarine cables, both weather and climate change can lead to a dramatic change of the cooling potential of the soil and critical long-term thermal conditions that can have a negative impact on the cable.

Further readings

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- Evenset, L., Thillart, R., Daniela, D., de Vries, G.T. & Dillon, M. (2016), Thermal characterization of seabed along the NordLink cable route –results and comparison of measurement methods, CIGRE Session 2016, B1-583
- Miesner, F., Lechleiter, A. & Müller, C. (2015), Reconstructing bottom water temperatures from measurements of temperature and thermal diffusivity in marine sediments, Ocean Science
- Müller, C., Miesner, F., Usbeck, R. & Schmitz, T. (2013), 2K-criterion: measuring and modelling temperatures and thermal conductivities/diffusivities in shallow marine sediments, Proc. Conference on Maritime Energy 2013, TUHH
- Dillon, M., Müller, C. & Usbeck, R. (2012), Acquiring thermal conductivity data from shear resistant sediments, Sea Technology



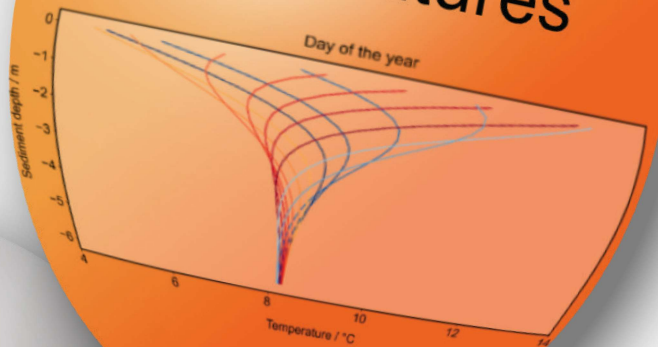
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We offer

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measurements
of temperature
&
thermal properties

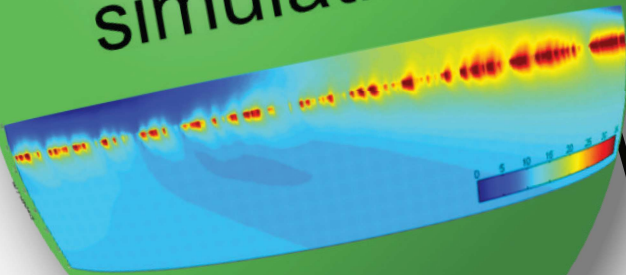
Prediction
of sediment
temperatures



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