Thermal structure of the subsurface of the Netherlands – a review and outlook on temperature data and predictive models

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Keywords: Temperature, the Netherlands, geothermal potential, thermal structure

ABSTRACT

During the last decades, the subsurface temperature distribution in the Netherlands is extensively studied, both on local and regional scale and at 10's of meter to kilometres depth range. In this paper, we concisely describe and bring together the main outcomes of all the temperature data analysis and temperature models described in the past. Temperature measurements from depths larger than approximately 500 meters are available from oil and gas wells, which show an thermal gradient of ~31 °C/km. At depths less than 500 meters, 400 temperature profiles (from surface to the depth of well) are available from groundwater wells showing a lower thermal gradient of ~20 °C/km. This temperature dataset is used as a basis of investigating the thermal distribution throughout the Netherlands using e.g. 1D/3D conductive local/regional models or local e.g. 3D heat transfer models, trying to explain regional and local thermal anomalies at all depths. It turns out that pure conductive models are not fully able to explain the thermal structure of the subsurface of the Netherlands and observed thermal anomalies must be explained by non-conductive processes. Transient effects like hydrothermal processes could account for the deep thermal anomaly in the Dinantian carbonates found in the Luttelgeest well. The effect of climate history (paleo-surface temperatures) is shown to have a major impact on the thermal distribution, which could clarify the observed regional lower thermal gradient at shallower depths. Remaining local thermal anomalies are possibly due groundwater or vertical fluid flow and the thermal effect related to magmatic intrusions affecting the thermal distribution. Last, the effect of extreme thermal conductivities on the thermal distribution is worth mentioning, where relatively high and low thermal conductivities of salt and shales, respectively, result in local and regional temperature effects.

1. INTRODUCTION

Temperature is one of the most important parameters defining the geothermal potential of the subsurface. Last years, geothermal energy gained popularity in the Netherlands because of the decrease of gas production and consumption and increasing necessity of sustainable heat. In the Netherlands, geothermal energy is nowadays mainly used for heating greenhouses, which requires warm water of 65 - 80 °C coming from a depth of 2 - 3 km. Those temperatures are to low for the traditional central heating systems in existing buildings, which need temperatures > 80 °C. However, newly built houses are more energy efficient and uses low temperature heating systems with supply temperatures of 25 - 55 °C. On the other hand, higher supply temperatures (>100 °C) are required for industrial processes, which are still using fossil fuels but considering sustainable alternatives like geothermal energy. Sustainable energy (wind, solar, geothermal energy) is marked by limitations in matching demand and supply year-round. To overcome this for geothermal energy, heat storage in the subsurface at a depth of 0-500 meters (low, mid, high temperature) could help to balance this mismatch. So, for minimizing the risks for shallow (0.3 – 1.5 km), deep (1.5 – 4 km) and ultradeep (> 4km) geothermal systems, and also heat storage (0 – 0.5 km), it is important to know the temperatures at all depths.

Last decade, several studies investigated the 3D temperature regime of the onshore Netherlands on regional scale (Bonté et al., 2012; Békési et al., in prep.; Gies et al., in prep.). Other studies investigated the effect of hydrothermal convection in the deep subsurface (> 4 km; Lipsey et al., 2016), on the thermal state of the Roer Valley Graben (Luijendijk et al., 2011; Verweij, 2003) and the effect of climate history on the shallow subsurface (Ter Voorde et al., 2014; Beglinger et al., 2012). This paper presents an overview by reviewing the research done regarding subsurface temperatures analysis and modelling in the Netherlands.

2. GEOLOGICAL MODELS AND SETTING

2.1 Geological models

The last decades, the subsurface of the Netherlands from surface down to a depth of 6-7 km is investigated in detail. The rationale for geological mapping over the last decades have been diverse and have resulted in various studies for different depth ranges. The Geological survey started in 1985 to compile a regional-scale 2.5D geological framework (Digital

Geological Model: DGM-deep) focussing on the deep subsurface to the base of the Permian mainly supporting the hydrocarbon E&P industry (Fig. 1) (Kombrink et al., 2012). However, the last decades more interest has been arising for targeting the subsurface for geothermal energy and storage and new and ongoing research will give us still new geological insights. For example, in the scope of the SCAN project (Seismic Campaign Geothermal Netherlands), the Dinantian reservoir is being studied in more detail and new insights will be incorporated in next versions of the geological model.

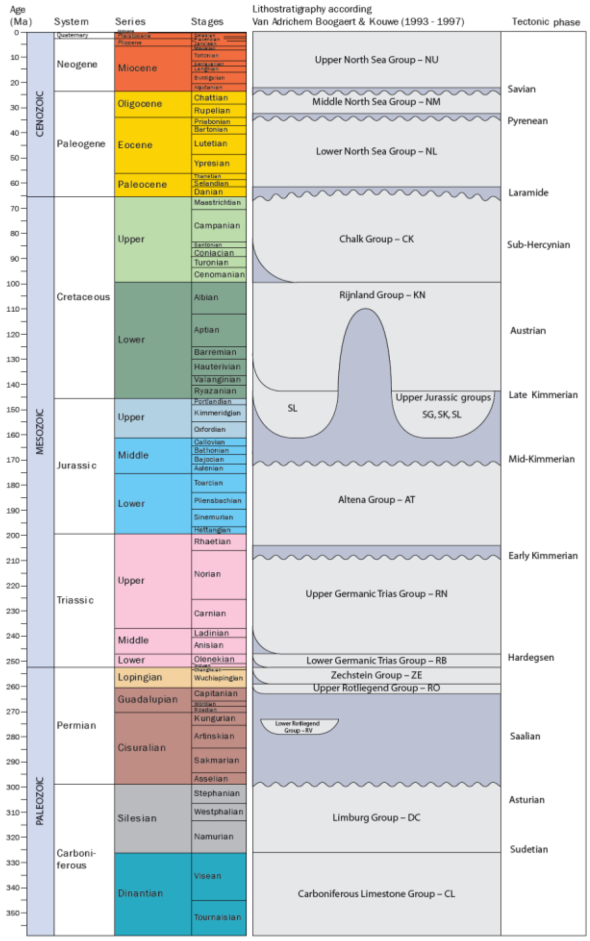

Figure 1: Table with lithostratigraphy of the subsurface of the Netherlands included in DGM-deep v4.0 (https://www.nlog.nl/en/details-dgm-deep-v4-onshore) (Kombrink et al., 2012).

2.1 Main geological structures

In the Carboniferous, the Netherlands were located in the northern foreland of a mountain range caused by the Variscan Orogeny. In the early Carboniferous, carbonate platforms developed in the north and south of the Netherlands where on top of these Dinantian carbonates late Carboniferous Silesian sandstones, shales and coals were deposited coming from the southern Variscan thrusts. The orogenic collapse of the Variscan orogeny started in Late Carboniferous - Early Perm associated with tensional tectonics and locally observed magmatic intrusives which extension remain uncertain. Afterwards, Rotliegend and Zechstein sediments developed in the formation of the post-Variscan basin (Sissingh, 20014; Kombrink, 2010). Marine evaporites of the Zechstein Group are deposited in the north which are gradually replaced by more siliciclastic and carbonate-like rocks towards the southern part of the Netherlands. After the break-up of Pangea, the Triassic clastic sediments alternated with some shales are deposited. During Jurassic time, marine deposition took over the shallow marine deltaic sedimentation in the Triassic (Altena Group) and rift basins, as a result of Late Kimmerian rifting phase, were filled with Late Jurassic and Early Cretaceous shallow marine siliciclastic sediments (Schieland en Rijnland Group). This was followed by calcareous infilling by the end of the Cretaceous (Chalk). Late Cretaceous time, the first inversional phase occurred in the Netherlands due to compressional stresses resulting in siliciclastic deposition in the Early Paleogene. Different new inversion phases in the Cenozoic (Laramide, Pyrenean and Savian) that followed are associated with alternation of sand-clay deposition (Paleogene). In Neogene time, a huge delta system developed filling up the remaining accommodation space (Kombrink et al., 2012).

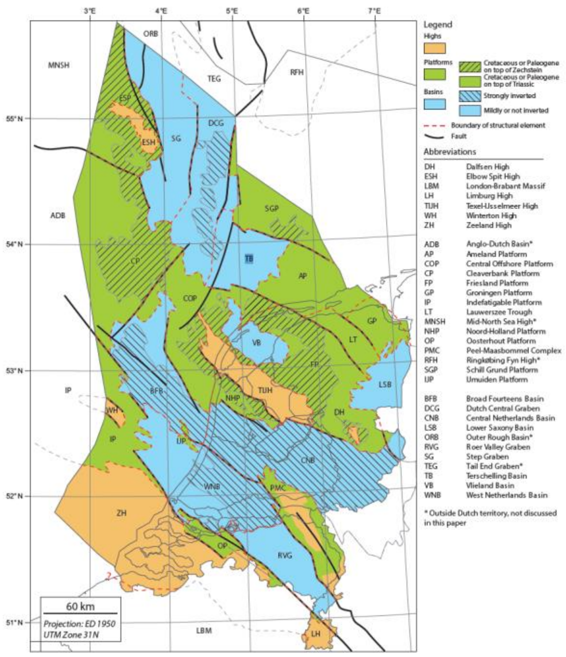

Figure 2: Structural elements of the Netherlands during Late Jurassic – Early Cretaceous (Kombrink et al., 2012).

3. TEMPERATURE DATA AND ANALYSIS

The subsurface temperature data within the Netherlands, at depths > ~500 meter, are available from oil, gas and geothermal wells, where the temperatures are based on Bottom Hole Temperature (BHT) data, Drill-Stem Tests (DST), Repeat Formation Tests (RFT) and Well Tests. In particular, BHTs are not very accurate, so correction is needed. This is done using a statistical and analytical method (Bonté et al., 2012). The total amount of the "deep" temperature measurements is about ~1500. They are publicly available at https://www.nlog.nl/en/temperature-data. For the shallower subsurface (0-400 meter), half of the available temperature profiles are measured in groundwater observation wells commissioned by Dalfsen et al., 1980 & 1981 to investigate the shallow geothermal potential of the country. In total, ~420 temperature profiles are available from which ~400 going down to a depth of 400 metres and ~15 even down to 600 meter. The maximum uncertainty defined for the shallow temperatures is estimated to be minor (~0.1°C). Therefore no correction is required (Dalfsen, W., 1981).

Analysis of the "deep" temperature dataset showed an average thermal gradient of 31°C/km (Bonté et al., 2012, Békési et al., in prep). For the "shallow" temperatures various studies (Van Dalfsen 1980, Ter Voorde et al., 2014) observed an average gradient of ~20°C/km in the first ~500 meters.

Table 3.1: Overview of all available temperatures measurements.

Type of measurements	origin	Depth range	Amount	Uncertainty
"deep" temperature dataset				
Bottom Hole Temperatures	Oil and Gas wells	>500 meter	~1400	± 10-15°C
Drill Stem Tests / Repeat Formation Tests	Oil and Gas wells	>500 meter	65	± 8°C
Well Tests	Geothermal wells	>500 meter	16	± 5°C
"shallow" temperature dataset				
Shallow temperatures	Groundwater observation wells	< 500 meter	~400 wells	0.1 -2 °C

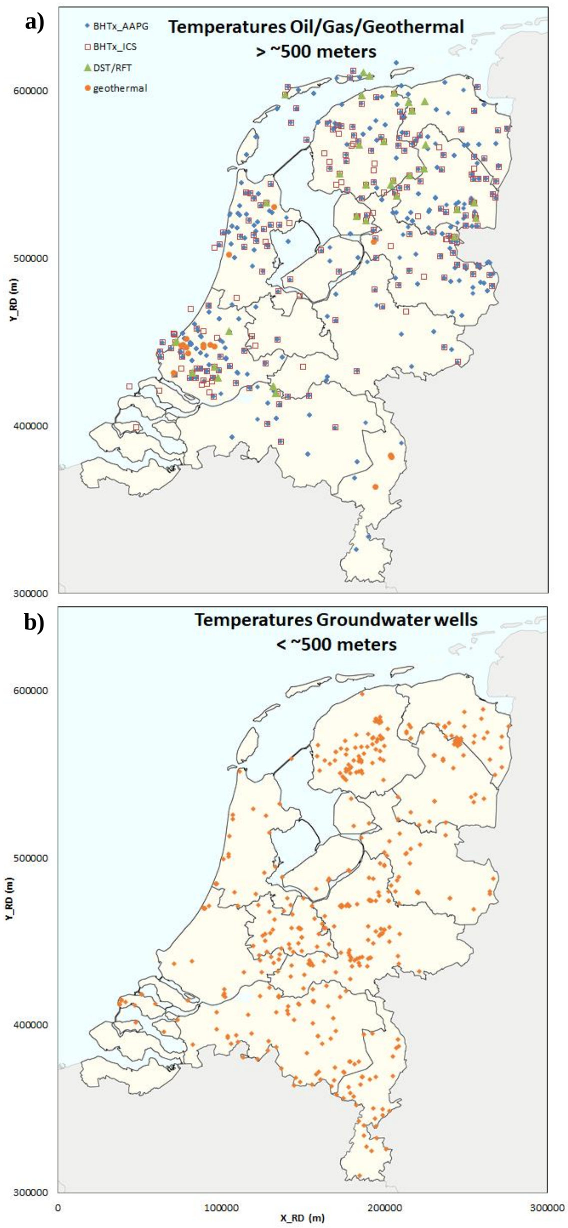

Figure 3: Overview of all locations of available temperature measurements or profiles for a) "deep" temperatures and b) "shallow" temperatures.

4. TEMPERATURE MODELLING AND IMPLICATIONS FOR THE NETHERLANDS

4.1 3D regional temperature modelling

From 2012 until now, the 3D regional temperature model of the onshore Netherlands is continuously updated and improved in terms of temperature data, modelling workflow and new geological insights. The onshore geological model, DGM-deep, forms the framework for these 3D temperature models. The first 3D temperature model has been constructed by Bonté et al., 2012. This model calibrated the 3D temperature distribution using a purely conductive methodology (thermal conductivity and radiogenic heat production) with temperature data, including transient effects for the basin evolution of the last 20 Ma in terms of crustal deformation (stretching of the lithosphere) and sedimentation (accumulation or erosion). The effects of incorporating these transient effects showed to have no significant impact on the present-day temperatures. The model from Bonté et al. (2012) model could not reproduce the higher than expected temperatures in the Luttelgeest well (LTG-01) within the Dinantian carbonates at 4000 meters depth where the influence of hydrothermal convection is suggested as explanation (Lipsey et al., 2016; Békési et al., in prep) (4.2). An alternative explanation is an higher expected radiogenic heat generation as a consequence of possible magmatic material present beneath the Dinantian carbonates increasing the radiogenic heat production (Bonté et al., 2012) (4.3). The process of hydrothermal convection is taken into account for the updated 3D temperature model including most recent temperature data, new insights into the geological model and incorporating an improved inverse modelling technique (Békési et al., in prep) (4.2). At larger depth, this updated model shows an improved match with temperature data. However, the most remarkable misfit of Békési et al. (in prep) is found at shallower depth (0-2000m), where observed temperatures are consistently overestimated by the model. Various studies explained this by the impact of variable paleo-surface temperatures in climate history on the subsurface temperatures, which lowers the geothermal gradient from 31°C/km to ~20°C/km (e.g. Ter Voorde et al., 2014; Gies et al. (in prep.) (4.4). The local misfits still existing are likely to be caused by local convectional processes (4.2) and uncertainties in assumed thermal properties. Last, although those are conductive processes, it is worthwhile to mention the effect of extreme thermal conductivities associated with specific rock types causing insulating thermal (4.5) and salt chimney effects (4.6).

4.2 Hydrothermal processes

Previous research has shown that hydrothermal convection or groundwater flow could affect the subsurface temperatures at shallower depths (1000-1500) (e.g. Luijendijk et al., 2011; Beglinger et al., 2012) but also at larger depths (>4000 m) (Lipsey et al., 2016). Initiating convectional processes is strongly dependent on the permeability and thickness of the aquifer. Bjorlukke et al. (1988) disputes that subsurface temperatures are affected by thermal convection, since even a thin impermeable layer could impede the chance of convection to occur. At larger depth, convectional processes occurring along faults planes (secondary permeability) are suggested to be more likely than within formations (primary permeability) (Simmons et al., 2008).

The larger than expected temperatures within the Dinantian carbonates in the LTG-01 well has been extensively studied by Lipsey et al., 2016, using 3D numerical models including thermal convection. Rayleigh number calculation shows that convective flow could explain the higher temperatures. Incorporating this non-conductive effect in the regional 3D temperature model, which is based on a purely conductive method, is not possible. However, this effect could be mimicked by increasing the thermal conductivity in layers where convection occurs (Fig. 4) (e.g. Luijendijk et al., 2011; Beglinger et al., 2012). For the Netherlands, Békési et al. (in prep) assumed that convection is only possible in the deeper Dinantian carbonate platforms in the North.

At shallower depths (1000-1500 meters), local positive thermal anomalies are found in the Roer Valley Graben which could not be explained by a purely conductive approach, so the influence of groundwater flow and upward flow of fluids along faults are suggested to be a possible explanation (Luijendijk et al., 2011).

4.3 Magmatic intrusions

Intrusion of igneous material (magma) into a sedimentary basin in the past could still have an effect on the current thermal subsurface structure. This is mainly depending on the extent of the magmatic body, the duration of the process of heating and melting (Sissingh, 2004), and the time passed for equilibration of the thermal regime. In the Netherlands, different periods of magmatic activities are identified by Sissingh (2004). Apart from the hypothesis of hydrothermal convection explaining the higher than expected temperature in the LTG-01 well, Bonté et al. (2012) suggested magmatic intrusions formed during the collapse of the Variscan orogen (Ziegler, 1990) may have increased the heat flow. In the surrounding of the LTG-01 well, Permian-Carboniferous magmatic rocks are found in well logs (Sissingh, 2004) However, Dinantian carbonates are deposited before this period, during the Early Carboniferous, making it unlikely that younger intrusion have caused the high thermal anomaly within the Dinantian. In northern England and Ireland, locations of Late Caledonian intrusions (490-390 Ma) are related to the Carboniferous basement highs (Smits et al., 2018; Milton et al., 2010). If similar tectonic activities in the Netherlands took place and locations of Dinantian platforms are related to igneous intrusion, intrusions could have elevated the heat flow at the base of the Dinantian (Early Carboniferous). It is impossible, from a physics based perspective, that the long time lapse since the intrusions are still resulting in a thermal anomaly from cooling. However, increased radiogenic heat production related to granitic rocks

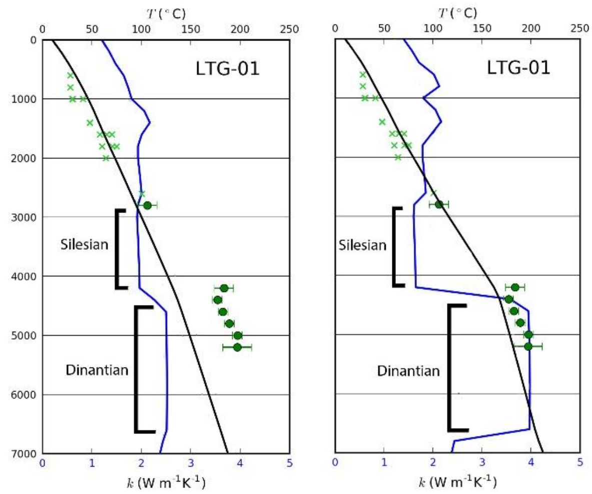

Figure 4: Modelled temperature (black) and thermal conductivity before calibration (dashed blue) and after calibration (solid blue) profiles for the Luttelgeest well (LTG-01). Green dots and green squares are temperature measurements in the well and in nearby wells (<10 km), respectively.

could still affect the thermal gradient (Bonté et al., 2012; Jolivet et al., 1989).

Magmatic intrusions in the crust and mantle are found in the upper Rhine and Limagne Graben (Clauser et al., 2005b, Lucazeau et al., 2002), which are part of the European Cenozoic Rift System (ECRS) that formed during the Late Eocene, which resulted in elevated heat flows with values over 100 mWm^{-2}. In the southern part of the Netherlands, the Roer Valley Graben (Fig. 2) is also part of the ECRS (northwestern). It is suggested that local positive thermal anomalies are a result of magmatic intrusions (Verweij, 2003). However, Luijendijk et al., 2011 state that a limited amount of magma bodies are present in the Roer Valey Graben. Besides, this rift basin shows no elevated heat flow in comparison with the neighboring structural highs suggested, which is suggested to be related to low stretching factors (β=1.06-1.15) (Luijendijk et al., 2011).

4.4 Paleo-surface effect

The influence of the climate signal, in terms of the surface temperature history, on the current thermal structure of the subsurface is extensively studied (e.g. Kukkonen en Joeleht, 2003; Luijendijk et al., 2011; Ter Voorde et al., 2014). For the Netherlands, the surface temperature of the last 130.000 years is determined based on climate proxy data (Fig. 5). It is shown that the observed lower thermal gradient of ~20°C/km for the shallow subsurface (~0-500 m) could be explained by this paleo-surface effect (Luijendijk et al., 2011; Ter Voorde et al., 2014). The colder period ($T_{surface}<0$) during the Weichselian (~10-100 kyr) with the subsequent warmer period during the Holocene caused this steeper geothermal gradient. Gies et al. (in prep.) incorporated the correction for the paleo-surface temperature within the 3D temperature modelling workflow of Békési et al. (in prep), which resulted in major improvements in terms of matching the shallow part of the model with temperatures at shallow depths.

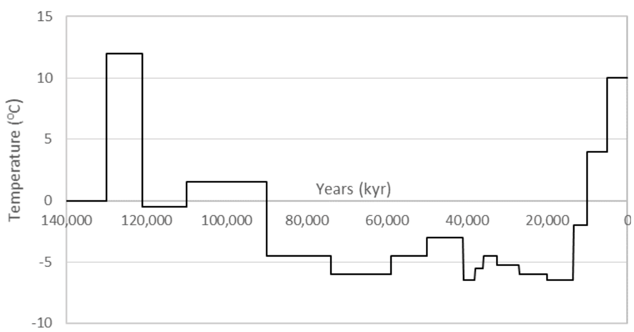

Figure 5 Paleo-surface temperatures of the last 140,000 kyrs (Luijendijk et al., 2011) based on climate proxy data (Caspers and Freund, 2001; Van Gijsel, 1995; Huizer & Vandenberghe (1998) and Zagwijn (1996).

4.5 Insulating thermal effect

Sediments such as shale, mudstone and coal are characterized by low thermal conductivities relative to other sedimentary rocks. These sediments have an insulating thermal effect and retain heat which is transported to the surface. This in turn results in a higher thermal gradient within these sedimentary units. In the Netherlands, it has been suggested that the thick shaly Silesian sediments on top of the Dinantian exhibit this effect, where you expect lower temperatures at the top and higher temperatures at the base of the Silesian unit (Fig. 4) (Bonté et al., 2012; Békési et al., in prep).

4.6 Salt chimney effect

Rock salt has thermal conductivities two to three times higher than other sedimentary units. Therefore, heat is transported faster through salt (chimney effect) resulting in a lower thermal gradient within and higher temperatures at the top of the salt layer (Verweij, 2003). In the northern Netherlands, the Zechstein group mainly comprises salt. Several wells show the influence of the salt on the heat flow and temperature. Higher values for the calculated heat flow are found within the Zechstein salt (>100 mW/m^2), where the rapid heat transfer results in higher temperatures in the overlying sedimentary units in comparison with the surroundings (Verweij, 2003).

5. CONCLUSIONS

Investigating the thermal structure of the subsurface at all depths is important for exploring the geothermal potential and minimizing the risks for shallow, deep and ultradeep geothermal and heat storage systems. In the Netherlands, the available temperature data is extensively analysed and temperature models are executed attempting to explain the thermal structure and thermal anomalies on regional and local scale.

It has been shown that purely conductive models are not able to reproduce the whole thermal structure of the subsurface of the Netherlands. Although, extreme thermal conductivities (insulating thermal effect of shales and chimney effect of rock salt) already explain some of the interesting regional thermal structures, but not all. Higher than expected temperatures in the Dinantian carbonates are suggested to be an effect of hydrothermal processes, however the thermal effect associated with possible magmatic intrusions is also proposed as driving mechanism. The observed lower gradient at regional scale of the shallow subsurface (~20°C/km) is most likely an effect of paleo-surface temperatures. Remaining local thermal anomalies at shallower depth are probably the effect of groundwater flow and upward flow of fluids along faults.

Ongoing and new research will provide better insights in the temperature distribution and associated processes of the subsurface. For example, in the scope of the SCAN project (Seismic Campaign Geothermal

Netherlands), the Dinantian reservoir is studied in more detail. New insights in the scope of temperature will be gained in the near future.

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