Appendix A Supplementary Data. Adjustment of the season boundaries.

One effect of the Milankovich precession is a shift of the summer solistice by several days, and a consequent shift in all seasons. Since we want to calculate seasonal mean temperatures, it is important to correct for this shift.

A.1 The drift of the annual maximum of the insolation values

We choose the day with the highest surface temperature of the year as the day of the middle of the summer season. Our model shows that this maximum temperature day of the year follows the day with the highest insolation of the year with a delay of 14 days on average. As can be seen from Fig. A1, the days of maximum insolation vary between the 158th and 187th day of the year. At the same time, the Blackbody temperature equivalent of the highest insolation fluctuates with a maximum amplitude of 22°C.

If we follow the drift of the day with the highest insolation, i.e. we always choose this day with the highest insolation as midsummer day, we obtain a step function instead of a smooth/steady curve of the Blackbody temperature equivalents of the insolation. To arrive at a smooth representation, we use a cubic spline interpolation. See Fig. A2.

With this definition of the season periods, we choose the season beginning days in such a way, that both the mean insolation values, see Fig. A3 and Fig. A4 (and its Blackbody temperature equivalents, see Fig. A5) and the fluctuation amplitudes of autumn and spring (see Table at Fig. A3) are approximately equal (for this we chose the 176th day of the year as the day to which we rotated the day of the highest insolation of the year and then chose the 190th day of the year as midsummer day).

A.2 Correlation of Emissions and Temperatures

The emission values matching the temperature values of Fig. 2 and Fig. 3 are shown in Fig. A6 and Fig. A7.

References

[1] Skirbekk, K., Hald, M., Marchitto, T.M., Junttila, J., Kristensen, D.K., Sørensen, S.A.: Benthic foraminiferal growth seasons implied from mg/ca-temperature correlations for three arctic species. Geochem.Geophys. Geosyst. **17**, 4684–4704 (2016)

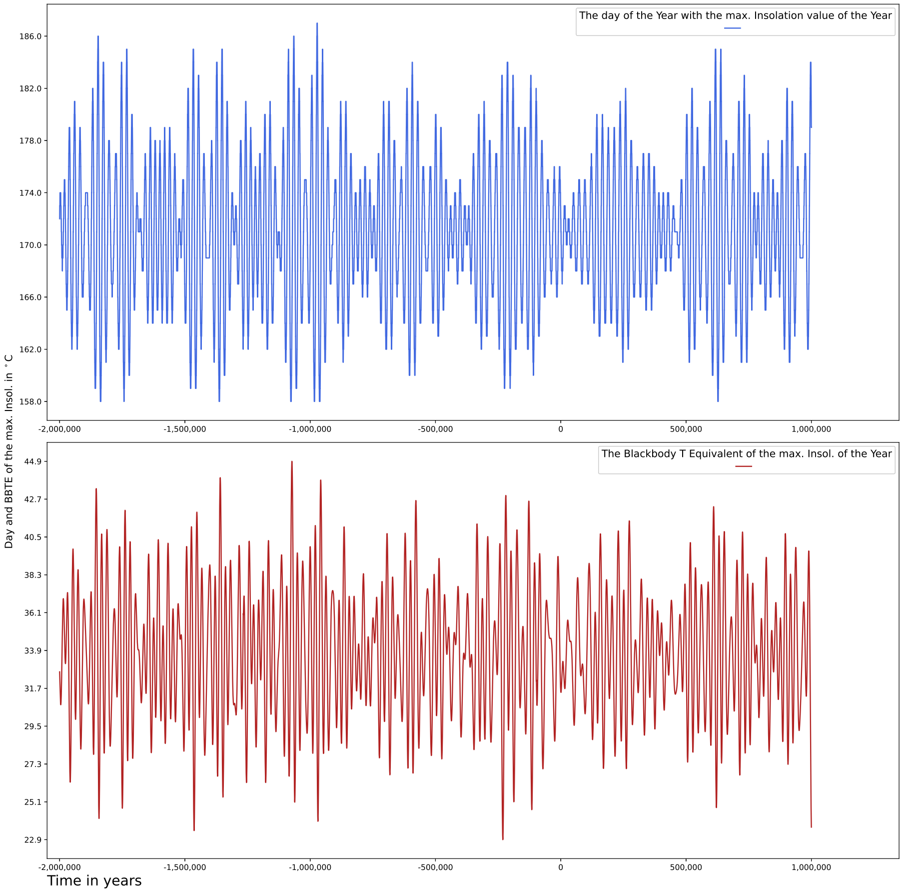

Fig. A1 Day and height of the maximum solar irradiation of the year at 68°N latitude.
We see that the day of the year with the highest insolation varies from the 158th to the 187th day of the year, thus, according to our understanding, the beginnings of the seasons are also subject to a variation of up to 29 days in the course of the 3 million years of the simulation time.
At the same time, we see that in the course of the same time, the Blackbody temperature equivalents of the annual maximum solar irradiation are subject to a variation of up to 22°C.

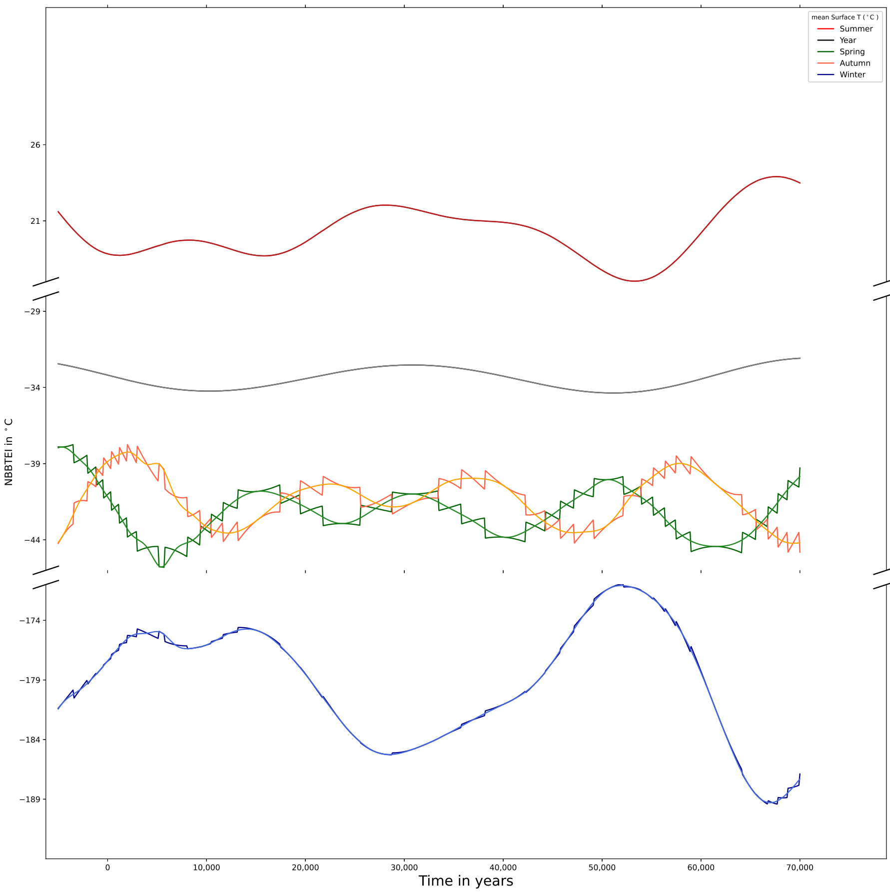

Fig. A2 "Zoom in" on the Blackbody temperature equivalent curves of the normalised insolation at 68°N latitude, calculated following the seasonal drift. When we calculate the Blackbody temperature equivalents of the insolation following the seasonal drift, we get a "stepped" temperature curve instead of the expected steady temperature curve. This is because the change in insolation values from one day of the year to the next day of the year can be as much as $5Watt/m^2$ in spring and autumn. In contrast, the change in insolation values from one year to the next year for the same day of the year is less than $0.01Watt/m^2$. To smooth this step function (which arose after we followed the drift of the day with the highest insolation), we first determine the "Subsections Centre points" of the insolation values, followed by a cubic interpolation of these "Subsections Centre points" (the "Subsections Centre points" are the middle points between two "breakpoints" of the step curve). We see both resulting Blackbody temperature equivalent curves superimposed here. If we look closely, we can see that the average winter, spring, summer and autumn temperatures vary out of phase. This also explains why, despite the high variability of the seasonal average temperatures, the variability of the annual average temperatures is so low. (Evaluated with an absorption coefficient $\gamma_A = 0.875$ and a surface emissivity of $\epsilon_G = 0.95$ (granite).)
NBBTEI is the Normalised Black Body Temperature Equivalent of the Insolation.

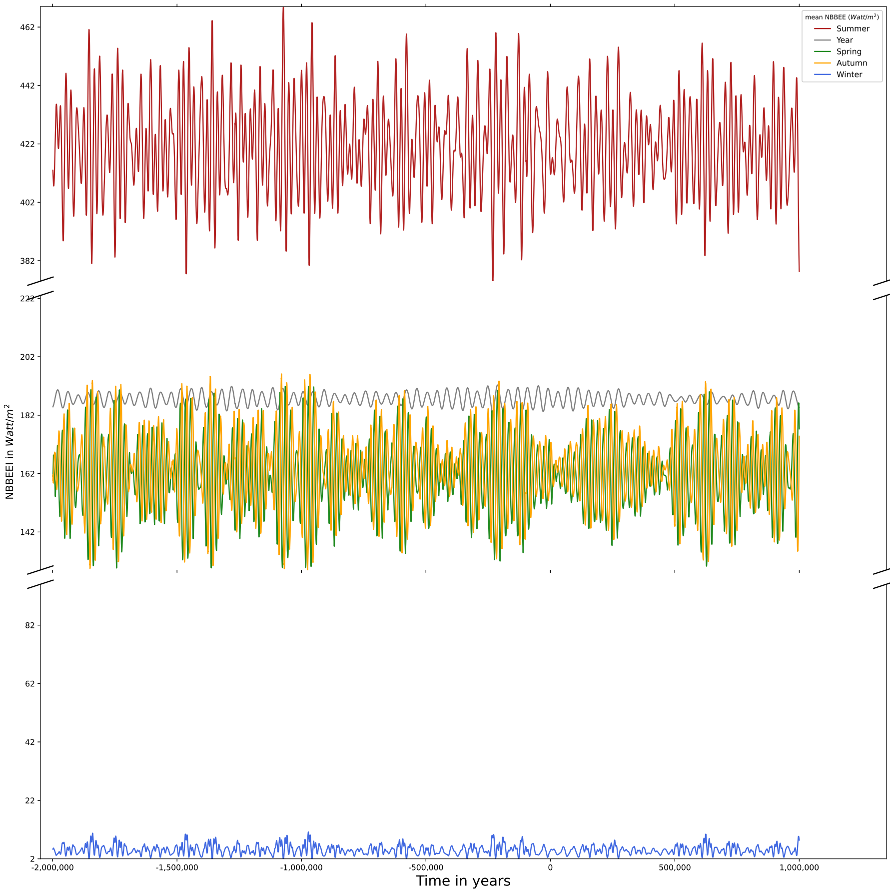

Fig. A3 Curves of the normalised insolation at 68°N latitude, calculated following the seasonal drift. We have corrected ("normalised") the insolation values for γ_A and ϵ_G to ensure comparability with the calculated surface emission of Fig. A6. (Evaluated with an absorption coefficient $\gamma_A = 0.875$ and a surface emissivity of $\epsilon_G = 0.95$ (granite).)
NBBEEI is the Normalised Black Body Emissions Equivalent of the Insolation.
We see the corresponding amplitudes in the table

Amplitude		mean		season	Beginn	End
in °C	in $Watt/m^2$	in °C	in $Watt/m^2$		day	
3.0	9.4	-33.3	187.6	Year	1	360
43.9	9.4	-175.7	5.1	Winter	325	54
16.5	94.4	20.4	421.2	Summer	145	234
22.5	62.2	-42.3	161.0	Spring	55	144
24.3	67.5	-41.6	163.1	Autumn	235	324

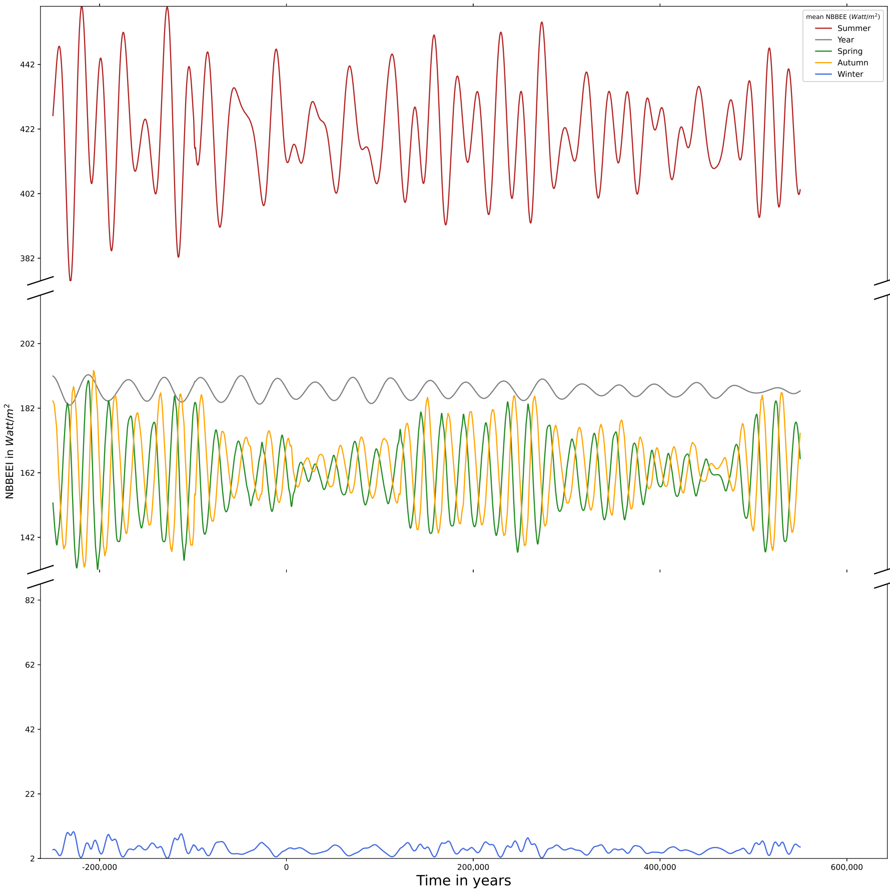

Fig. A4 "Zoom in" on curves of the normalised insolation at 68°N latitude, calculated following the seasonal drift. We have corrected ("normalised") the insolation values for γ_A and ϵ_G to ensure comparability with the calculated surface emission of Fig. A6. If we look closely, we can see that the average winter, spring, summer and autumn insolations vary out of phase. This also explains why, despite the high variability of the seasonal average insolations, the variability of the annual average insolations is so low. (Evaluated with an absorption coefficient $\gamma_A = 0.875$ and a surface emissivity of $\epsilon_G = 0.95$ (granite).)
NBBEEI is the Normalised Black Body Emissions Equivalent of the Insolation.

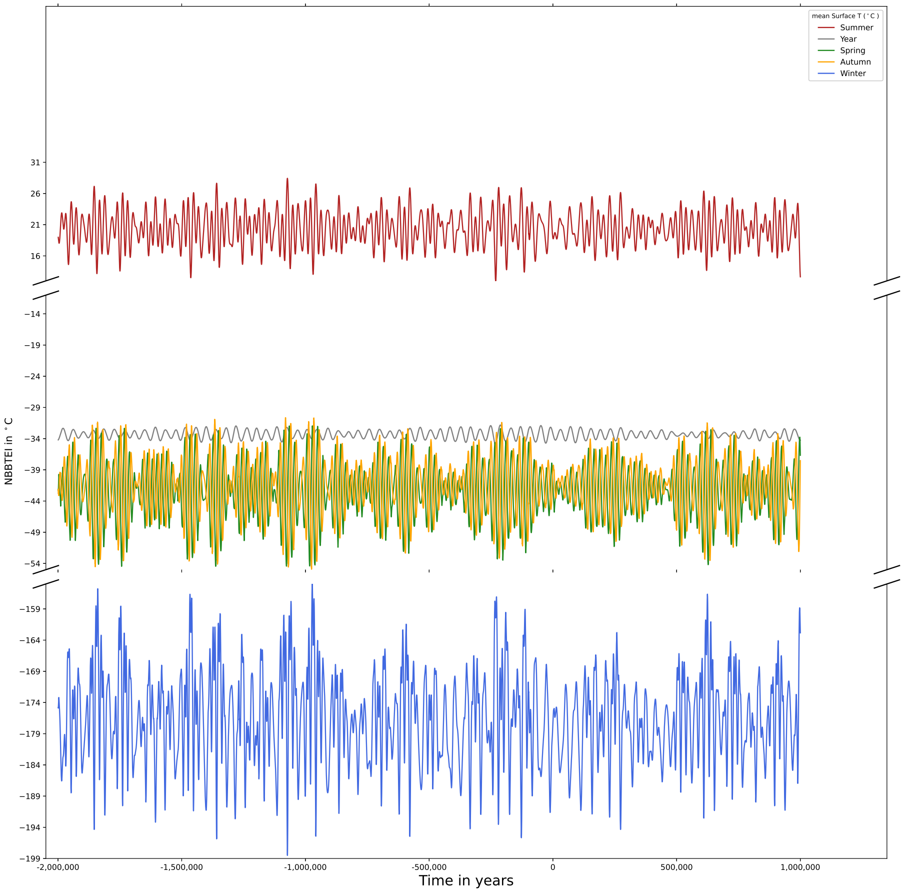

Fig. A5 Following the seasonal drift, calculated Blackbody temperature equivalent curves of the normalised insolation at 68°N latitude. We corrected ("normalised") the insolation values for γ_A and ϵ_G to ensure comparability with the calculated surface temperature of Fig. 2. We see some differences between Fig. 2 and Fig. A5. The annual average values have an almost identical course. The seasonal amplitudes at the lithosphere surface in Fig. 2 are damped. The summer average values of the lithosphere surface temperature are lower than the summer Blackbody temperature equivalent because part of the irradiation energy is transferred to the deeper lithospheric layer. At the same time, the winter average values of the lithosphere surface temperature are much higher than the Blackbody temperature equivalent because the heat stored in the deeper lithospheric layers in summer is transferred to the higher lithospheric layers and thus ensures a higher surface temperature. (Evaluated with an absorption coefficient $\gamma_A = 0.875$ and a surface emissivity of $\epsilon_G = 0.95$ (granite).)

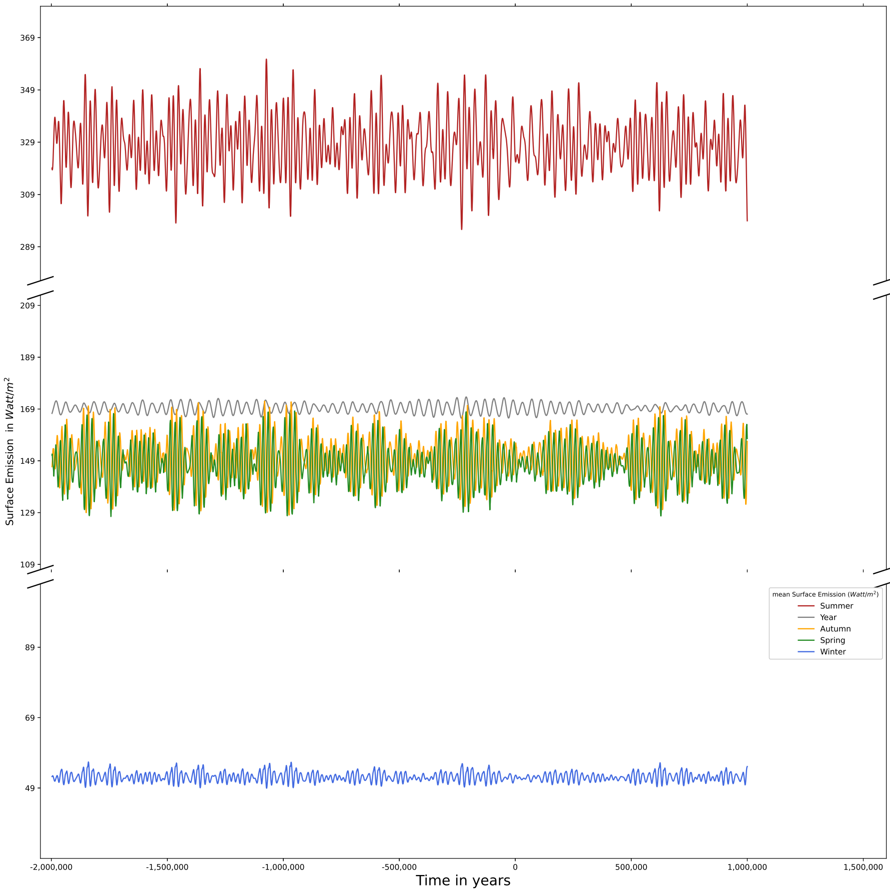

Fig. A6 Annual and seasonal mean surface emissions at 68°N latitude. (Evaluated with an absorption coefficient $\gamma_A = 0.875$ and a surface emissivity of $\epsilon_G = 0.95$ (granite).)

From the table of the amplitudes of the temperature and emission fluctuations it can be seen that autumn has the highest amplitude of temperature fluctuation with about 17°C, while summer has the highest emission fluctuation with about $65 Watt/m^2$.

amplitude		mean		season	Beginn	End
in °C	in $Watt/m^2$	in °C	in $Watt/m^2$		day	
2.9	8.2	-36.3	169.4	Year	1	360
6.3	7.5	-96.8	52.2	Winter	325	54
13.9	65.2	6.2	328.0	Summer	145	234
15.9	40.8	-44.4	147.5	Spring	55	144
16.9	44.0	-43.5	149.9	Autumn	235	324

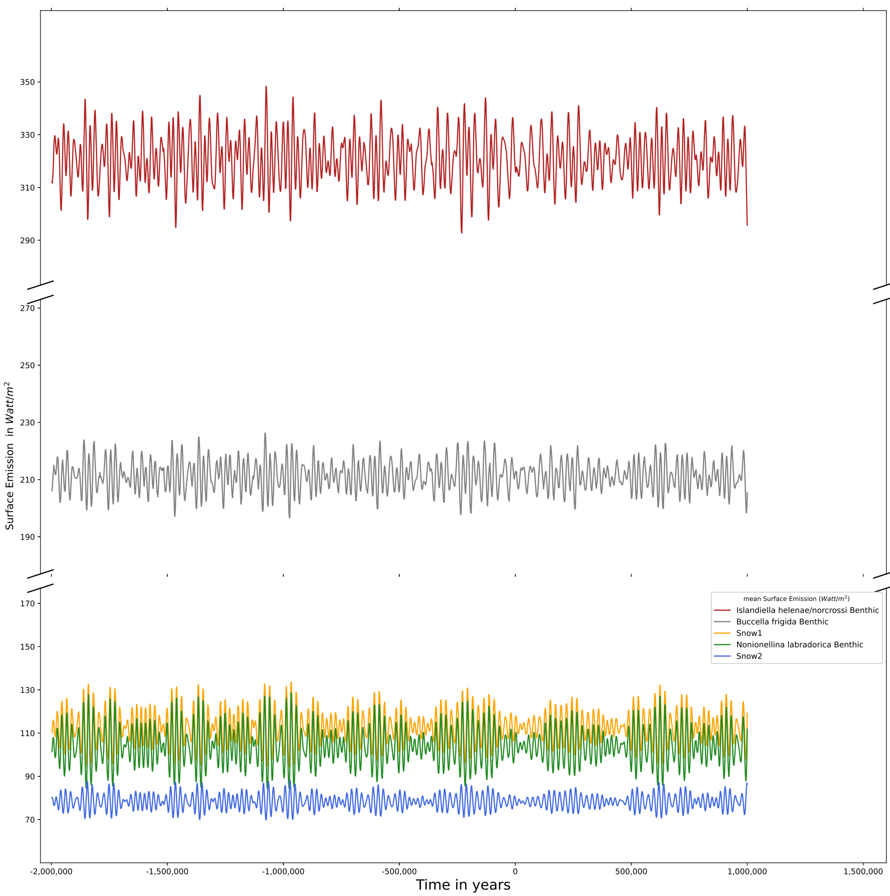

Fig. A7 Mean surface emission during the assumed growing seasons of bentics [1] and snow at 68°N latitude. (Evaluated with an absorption coefficient $\gamma_A = 0.875$ and a surface emissivity of $\epsilon_G = 0.95$ (granite).)

The table shows that Nonionellina labradorica has the highest amplitude of the temperature fluctuation with about 22°C, while Islandiella helenae/norcrossi, with its rather summery growth period, shows the highest variation in emission with approx. $55 Watt/m^2$.

amplitude		mean		growth	Begin	End
in °C	in W/m^2	in °C	in W/m^2	Benthic/Snow	day	
8.8	29.7	-22.9	211.3	Buccella frigida	180	330
11.4	18.3	-77.8	78.4	Snow2	300	120
12.1	55.6	4.6	320.7	I. helenae/n.	180	240
18.5	39.2	-59.3	112.6	Snow1	250	350
22.2	44.3	-63.5	104.1	N. labradorica	270	330