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Diurnal Habitability of Frozen Worlds

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Abstract In this work we discuss effects allowing local habitability of some extraterrestrial planets of low average surface temperatures. We analyze the problem of diurnal and seasonal changes of temperature and biological productivity at different locations on a hypothetical Earth-like planet. We have found, that under some circumstances the temperature may locally rise well above the average value, allowing periods of enhanced biological activity. In this way, bioproductivity can become periodically possible on a planet that has an average temperature clearly below 0°C. Such thermal conditions are encountered on Mars (Smith et al. in Science 306:1750–1753, 2004) generally considered as inhabitable. In reality, an appropriate temperature is not sufficient for habitability. The presence of liquid water at the considered location is also necessary. We discuss how temperature oscillations affect habitability in the framework of a conceptual model. We find that the considered effect of diurnal and seasonal temperature oscillations can extend the outer boundary of the habitable zone up to 2 AU, while global average temperatures are below 0°C for heliocentric distances $R_{\mathrm{h}} > 1.12$ AU (dry atmosphere, low CO_2 pressure), or $R_{\mathrm{h}} > 1.66$ AU (humid atmosphere, high CO_2 pressure).

Keywords Extrasolar planets · Geodynamics · Habitable zone · Obliquity · Biological productivity

1 Introduction

Since 1995, more than 300 exoplanets orbiting main-sequence stars have been discovered. The large number of extrasolar planets demonstrates that planetary systems are common and show a large variety of properties. The distribution of planetary masses derived from

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observations rises rapidly toward lower masses, $dN/dM \propto M^{-1.0}$ (Marcy et al. 2005) favoring low-mass (Earth-like) planets. Furthermore, planetary formation models predict the existence of terrestrial planets (Wetherill 1996; Raymond et al. 2004). In less than 10 years, the lowest known detected planetary mass has decreased by about two orders of magnitude. The discovery of so called super-Earths (e.g., Rivera et al. 2005; Beaulieu et al. 2006; Udry et al. 2007), i.e. massive terrestrial planets with one to ten Earth masses (Valencia et al. 2006), have stimulated research in this area. The recently discovered super-Earth Gliese 581d might be at the outer edge of the habitable zone (von Bloh et al. 2007; Selsis et al. 2007). Therefore, in the near future we can expect the discovery of many super-Earths and Earth-like planets within or at the outer edge of the habitable zone (HZ).

Usually the HZ of an Earth-like planet is defined as the region within which liquid water is present at the surface. According to this definition the inner boundary is determined by the loss of water via photolysis and hydrogen escape. The outer boundary is determined by the distance where the greenhouse effect is just strong enough to keep the surface temperature above 0°C. Kasting et al. (1993) calculated the present HZ boundaries for the solar system as $R_{inner} = 0.95$ AU and $R_{outer} = 1.37$ AU. The outer limit is the distance were CO_2 first condensed in the model prohibiting further warming by an increase of CO_2. Forget and Pierrehumbert (1997), however, have shown that CO_2 cloud might additionally warm the climate extending the out limit of the HZ up to 2 AU.

We present a modified version of a somewhat different definition of the HZ already introduced by Franck et al. (1999, 2000a, b). In their notion, habitability (i.e., presence of liquid water at all times) does not just depend on the parameters of the central star, but also on the properties of the planet itself, especially on its geodynamic evolutionary state. In particular, habitability is linked to photosynthetic bioproductivity, which in turn depends on the planetary surface temperature and the atmospheric CO_2 concentration. The appropriate values of temperature and CO_2 concentration are necessary conditions, but they are not sufficient. Presence of water in some form, at the appropriate time, is also necessary. Unfortunately, accurate simulation of water circulation at different scales, from the global down to the microscale is currently impossible. Thus, we do not intend to develop a complete, self consistent model of a planet. Our scope is to emphasize the importance of one effect, namely short- and long-term temperature oscillations. For this purpose we developed a relatively simple model that includes smooth changes of soil temperature versus time and depth. Using this model we examine an Earth-like planet at a snapshot of its evolution state with 2/3 of its surface covered by ocean and 1/3 covered by continents located at different latitudes. Such an Earth-like planet possesses a large ocean-covered surface area and therefore may be a good representative for a water world (Franck et al. 2003).

According to Raymond et al. (2004) the formation of wet planets is in all probable. We are interested in planets that are close to the outer edge of the HZ, so we take into account high atmospheric CO_2 concentrations to keep the planet's surface temperature as high as possible. For studying the influence of atmospheric CO_2 concentration on habitability we also consider low concentrations of atmospheric CO_2. In our model the outer boundary of the HZ is defined as the edge of the spatial domain where planetary surface temperature of at least a part of the continents stays at least some days of the year at least some time per day above 0°C. Our approach is important for Earth-like planets with mean global surface temperatures always below 0°C, but local continental surface temperatures that are at least partly above 0°C. The permafrost region on Earth could be an analog on a local scale (Gilichinski 2002). In this region there are sediments with seasonally thawed active layers (Wagner et al. 2002), which harbor a variety of cryophilic life forms. It is also interesting, whether some life forms could exist on the surface itself. The largest temperature fluctuations are encountered just on the surface. In such a location, water availability can be a problem. However, periodic deposition of water from fog may be sufficient for some life forms. Despite of a large amount of water on the planet, at large heliocentric distances the ocean is frozen at least at the surface and the actual amount of water in the atmosphere should be low, as observed in the polar regions on the Earth. Low humidity does not imply that the atmosphere becomes cloudless, but allow us to ignore rainfall and snowfall. In addition, the contribution of humidity to the greenhouse effect becomes small. Nevertheless, our model accounts for the influence of the surface temperature on the atmospheric humidity.

Our target objects are Earth-like planets orbiting Sun-like stars to be discovered in the future. Therefore, we introduce a simple Earth-mass planet at the current evolutionary state but with a much higher concentration of CO_2 in the atmosphere. This is similar to an Archaean atmosphere (Franck et al. 2002). We apply a rather simple latitude-dependence with only four latitude belts and perform numerical experiments with three different obliquities (0°, 23°, 90°). The influence of the obliquity on the habitability of an Earth-like planet has been already studied by Williams (1998). Furthermore, Williams and Pollard (2002) investigated the habitability of Earth-like planets on eccentric orbits with excursions beyond the HZ. None of the above papers discussed the effects of a time-scale shorter than seasonal. We are going a step further by including diurnal changes of temperature and biosphere productivity.

2 Model Description

2.1 Basic Properties

In this work we calculate changes of the surface temperature and the productivity of the continental biosphere on diurnal and seasonal time scales, including the evolution of the subsurface temperature versus depth. Most of the surface of our hypothetical planet is covered by ocean. We assume that the whole ocean has a uniform temperature. It is determined be the heliocentric distance of the planet and the state of the ocean: liquid, or surface frozen. This is simplification, but it is not critical due to high efficiency of the heat distribution by ocean currents. For the continents we consider the influence of both time and latitude on temperature and hence bioproductivity. They are assumed to be constant across latitudinal belts. We consider four belts of equal surfaces, two in each hemisphere. In such a case, the latitudes corresponding to the centers of the belt areas are 48.59°S, 14.24°S, 14.24°N, and 48.59°N (see Fig. 1). We assume that the continents are located in one hemisphere and their surface is equally distributed between two belts. Eccentricity of the considered planet is very small (0.01), like for the Earth. For nearly circular orbits the results of our approach do not change qualitatively if the continents are concentrated on the northern or southern hemisphere. For each of the belts, where the considered continents are located, we calculate the insolation, the time-dependent values of the surface temperature, and the bioproductivity at the latitude corresponding to the center of the area.

The temperature of the continents is calculated with the help of a modified Lindau–Warsaw–Mars–Regolith-Model (LWMRM) (Kossacki and Markiewicz 2002; Kossacki et al. 2003, 2006). The LWMRM calculates the diurnal and seasonal cycle of heat and vapor transport within the porous regolith, including sublimation and condensation of both

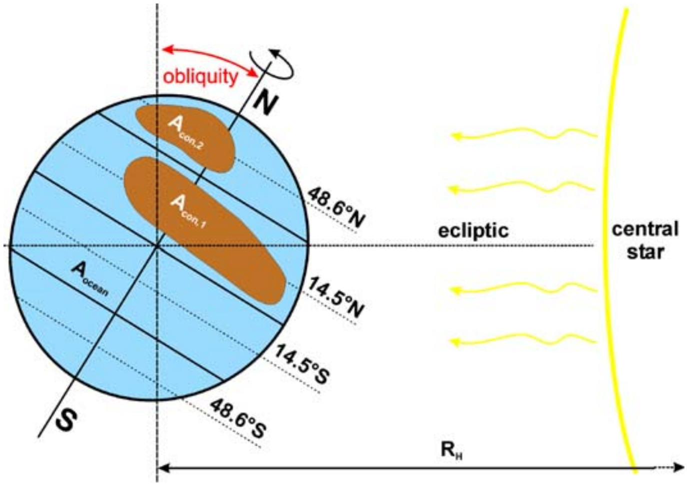

Fig. 1 Latitudinal distribution of the continental area for the hypothetical planet

water and carbon dioxide. The equations of energy and mass transport can be solved in one or two dimensions. The boundary conditions can be up to three dimensional, taking into account multiple reflections of radiation from the walls of depressions or trenches. In this way the LWMRM is a 2.5-D model. In the present work we use a simplified 1-D version. This is sufficient since the horizontal scale (size of continental area) of the model is much larger than the vertical one characterizing the depth of heat wave penetration in the regolith. The modeling of sublimation and condensation of ices either on the surface or in the regolith requires knowledge of the atmospheric composition and circulation. Usually this information can be obtained from observations or calculated with the help of a general circulation model (GCM). Nevertheless, in the current work dealing with hypothetical planets we start with a dry, non-condensing atmosphere, a zero concentration of the subsurface ice, and a simple parameterization of large-scale meridional atmospheric heat transport. The previous version of LWMRM contains a parameterization of single scattering of solar radiation in the atmosphere, as well as a simple parameterization of the IR emission in the atmosphere accounting for changes of the atmospheric opacity. In the current work we use alternative approach: we multiply solar constant by a term depending on the atmospheric content of greenhouse gases.

Here we want to examine a cold planet with continents covered by a porous material, i.e. regolith. It is assumed to be homogeneous at least up to a depth of a few meters. The granular structure of the regolith, accounting for the contact area of the grains, can be very fine. Typically, regolith is characterized by a certain distribution of grain sizes. We assume that all grains are of the same size and shape; they are spheres flattened at the contact points. This flattening depends on the porosity. When the porosity is small, the grains are of nearly cubical shape. The porosity of the regolith in fact depends on the local content of ice or water, which in the present work is zero. Under cold conditions heat transport in the regolith occurs only by conduction within the solid matrix of grains and not by thermal radiation. Molecular conduction by the gas phase can be neglected, because we assume small pores and small porosity. The thermal conductivity of the regolith stays constant during the simulations because the matrix of grains does not change and its thermal properties do not depend on the temperature.

2.2 Mathematical Formulation

The equation for the heat transport in the regolith is

$$\varrho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right), \tag{1}$$

where T denotes the temperature, z the soil depth and t the time. The other symbols denote material parameters: the effective thermal conductivity, λ, the density, ϱ, and the specific heat, c. These variables determine the thermal inertia, $I = (\lambda \varrho c)^{0.5}$, commonly used to characterize the thermal properties (heat storage) of the soil. The effective thermal conductivity itself may depend on the porosity of the medium, the temperature, the thermal conductivity of the individual grains, the heat transfer by vapor, and the grain-to-grain contact area. In the current work all parameters characterizing the regolith are constant.

The surface temperature, T_s, is calculated with the help of the following energy balance equation:

$$\frac{S}{R_h^2}(1+0.75\tau)(1-a)\max(\cos\alpha, 0) - \sigma\epsilon {T_s}^4 - \lambda \frac{\partial T}{\partial z}\bigg|_{z=0} - K(T_s - T_{ocean}) = 0, \tag{2}$$

where a denotes the surface albedo, α is the time-dependent zenith angle of the Sun, S is the solar constant, σ is the Stefan–Boltzmann constant, ε is the emissivity, and R_h is the actual heliocentric distance in AU. The term τ describes the greenhouse effect and depends on the actual atmospheric CO_2 partial pressure. We calculate it using a gray atmosphere approximation by Chamberlain (1980), with an additional term depending on the actual relative humidity h_r

$$\tau = 1.73\left((P_{atm}[\mathrm{bar}])^{0.263} + \left(h_r c_1 \exp\left(-\frac{c_2}{R_g T_s}\right)\right)^{0.5}\right), \tag{3}$$

where R_g is the gas constant and $c_1 = 1.4 \times 10^{11}$ bar and $c_2 = 155.91$ J mol^{-1} are numerical coefficients. The zenith angle α depends explicitly on the obliquity γ. The term $\frac{\partial T}{\partial z}\big|_{z=0}$ is the time-dependent temperature gradient in the surface regolith layer. The parameter K describes the meridional heat transport and T_{ocean} is the ocean temperature. In the current work T_{ocean} is assumed to be equal to the temperature of a uniformly illuminated, fast-rotating planet. We assume that the considered planet has an almost circular orbit thus T_{ocean} remains constant with a value of

$$T_{ocean} = \sqrt[4]{\frac{(1-a_o)\cdot S(1+0.75\tau)}{4R_h^2 \cdot \epsilon \cdot \sigma}}, \tag{4}$$

where a_o is the ocean albedo.

In our model the productivity of the biosphere, Π, depends on the temperature and the atmospheric CO_2 content. The continental surface temperatures for the two continental areas $T_s = T_{cont,i}$, $i = 1, 2$ depend on the time and the latitude and, therefore the biological productivity:

$$\frac{\Pi}{\Pi_{max}} = \max\left(\left(1 - \left(\frac{T_{cont,i} - 323\mathrm{K}}{50\mathrm{K}}\right)^2\right)\left(\frac{P_{atm} - P_{min}}{P_{1/2} + (P_{atm} - P_{min}})\right), 0\right), \tag{5}$$

where Π_{max} is the maximum biosphere productivity, P_{atm} is the atmospheric CO_2 partial pressure of the hypothetical planet, and P_{min} denotes the minimum CO_2 partial pressure allowing photosynthesis. $P_{1/2} + P_{min}$ is the pressure corresponding to the productivity of the biosphere when it is two times smaller than its maximum value.

The globally averaged surface temperature is

$$\langle T \rangle = A_{cont,1}\langle T_{cont,1}\rangle + A_{cont,2}\langle T_{cont,2}\rangle + (1 - A_{cont,1} - A_{cont,2})T_{ocean}. \quad (6)$$

The terms $A_{cont,1}$ and $A_{cont,2}$ are the dimensionless continental areas in two considered latitudinal belts. $\langle T_{cont,1} \rangle$ and $\langle T_{cont,2}\rangle$ are the continental temperatures averaged over diurnal and seasonal time scales.

2.3 Parameters

The model parameters characterizing the regolith and used in this paper are only example values, which could characterize a hypothetical planet. They are summarized in Table 1. In reality, the albedo should change when ice appears on the surface, when it melts away, or becomes covered by dust. However, these effects cannot be considered without a simulation of the atmospheric circulation. Thus, in the first approximation we assume that the albedo changes when the temperature drops below 0°C implicitly including an ice-albedo

Table 1 Variables and the values applied in this study

Variable	Symbol	Applied value
Effective thermal conductivity of regolith	λ	2 W $m^{-1}K^{-1}$
Density of regolith	ρ	3,200 kg m^{-3}
Density of regolith (compact)	ρ_{bulk}	3,600 kg m^{-3}
Specific heat of regolith	c	1,500 J kg^{-1}
Thermal inertia	I	3,100 J m^{-2} K^{-1} $s^{-1/2}$
Albedo of the continental surface for $\langle T\rangle \leq 273$ K	a	0.7
Albedo of the continental surface for $\langle T\rangle > 273$ K	a	0.2
Albedo of the ocean for $\langle T\rangle \leq 273$ K	a_o	0.7
Albedo of the ocean for $\langle T\rangle > 273$ K	a_o	0.2
Insolation at 1 AU	S	1,360 W m^{-2}
Obliquity	γ	0°, 23°, 90°
Emissivity	ε	0.8
Minimum CO_2 pressure for photosynthesis	P_{min}	10×10^{-6} bar
Atmospheric CO_2 pressure	P_{atm}	280×10^{-6} bar, 1 bar
Michaelis Menten parameter	$P_{1/2}$	210.8×10^{-6} bar
Maximum biosphere productivity	Π_{max}	180×10^{12} kg $year^{-1}$
Dimensionless continental area (1)	$A_{cont,1}$	1/6
Dimensionless continental area (2)	$A_{cont,2}$	1/6
Meridional heat transport	K	4.87 W m^{-2} K^{-1}

The values for the regolith are based of some artificial material with a porosity of 10%

feedback. Two more values of the albedo, a_o, for temperatures below and above 0°C are needed to calculate the ocean temperature, T_{ocean}, and finally the globally averaged temperature, $\langle T \rangle$. For this purpose $a_o = 0.2$ as long as for the given value of S the obtained value of T_{ocean} is above 0°C. When it falls below, a_o switches to 0.7 and T_{ocean} is calculated again.

The continents are uniformly distributed between two latitudinal belts in the northern hemisphere. The total continental area is 1/3 of the planet surface. Thus, $A_{\mathrm{cont,1}} = A_{\mathrm{cont,2}} =$ 1/6 of the planetary surface.

We consider a 2 m thick layer of regolith, thicker than the seasonal skin depth. The values of λ, ϱ, and c are chosen to result in a high value of the thermal inertia (Table 1). Therefore, temperature oscillations, either diurnal or seasonal, are relatively small. This makes our approach conservative. The spatial resolution must be comparable to the diurnal skin depth, resulting in a resolution of 5 cm. A time step has to be much smaller than the diurnal period, because we include both annual and diurnal fluctuations. In most cases the time step is 3 min.

3 Results

We performed simulations for two values of the CO_2 partial pressure (280×10^{-6} bar and 1 bar) and for two values of the relative humidity (0 and 0.9). The low atmospheric CO_2 partial pressure of 280×10^{-6} bar corresponds to the preindustrial state on Earth. The simulations cover two orbital revolutions. The biological productivity and the average temperatures are calculated for the second orbit only; the first is included to eliminate the influence of the initial conditions.

The simulations were repeated for different heliocentric distances in the interval between 1 and 2 AU. They were carried out for a dry ($h_r = 0$) and humid ($h_r = 0.9$) atmosphere. The results for these calculations are presented in Fig. 2a, c, e for the three obliquities (0°, 23°, 90°) and a dry atmosphere. The global averaged temperature $\langle T \rangle$ is additionally plotted. The temperature drops below 0°C and the ocean begin to freeze at a critical distance of 1.12 AU independent of the planetary obliquity. As expected, in all cases we find a monotonously decreasing bioproductivity when shifting the virtual planet outward. The dark-gray-shaded areas in Fig. 2 denote the range of orbital distances, where only diurnal habitability can be achieved, i.e. biological productivity is non-vanishing only for a certain period of time. In the case of 90° obliquity we have higher bioproductivity at higher latitudes (48.6°N), allowing habitable conditions when shifting the virtual planet up to 1.36 AU. In the case of a humid atmosphere (Fig. 2b, d, f) the outer boundaries for habitability at all times and diurnal habitability are extended for all three obliquities.

An Earth-like planet more distant to the Sun is expected to have a higher atmospheric concentration of CO_2. This is caused by lowering silicate rock weathering as the main sink of carbon in the atmosphere. Therefore we repeated our simulations for an atmospheric partial pressure of CO_2 of 1 bar. Fig. 3a, c, e plot biological productivity as a function of heliocentric distance under the condition of a dry atmosphere. The critical distance for freezing of the oceans is shifted to 1.58 AU. In the case of 90° obliquity there is still a chance for a biosphere to exist for distances less than 1.93 AU. In general the productivity is higher than in the case of $P_{\mathrm{atm}} = 280 \times 10^{-6}$ bar because of the fertilization effect of CO_2. For obliquities of 0° and 23° the results are qualitatively the same. For an obliquity of 90°, however, the result is significantly different. The planet remains habitable for a globally averaged temperature 20°C lower than for small obliquities. Another difference in

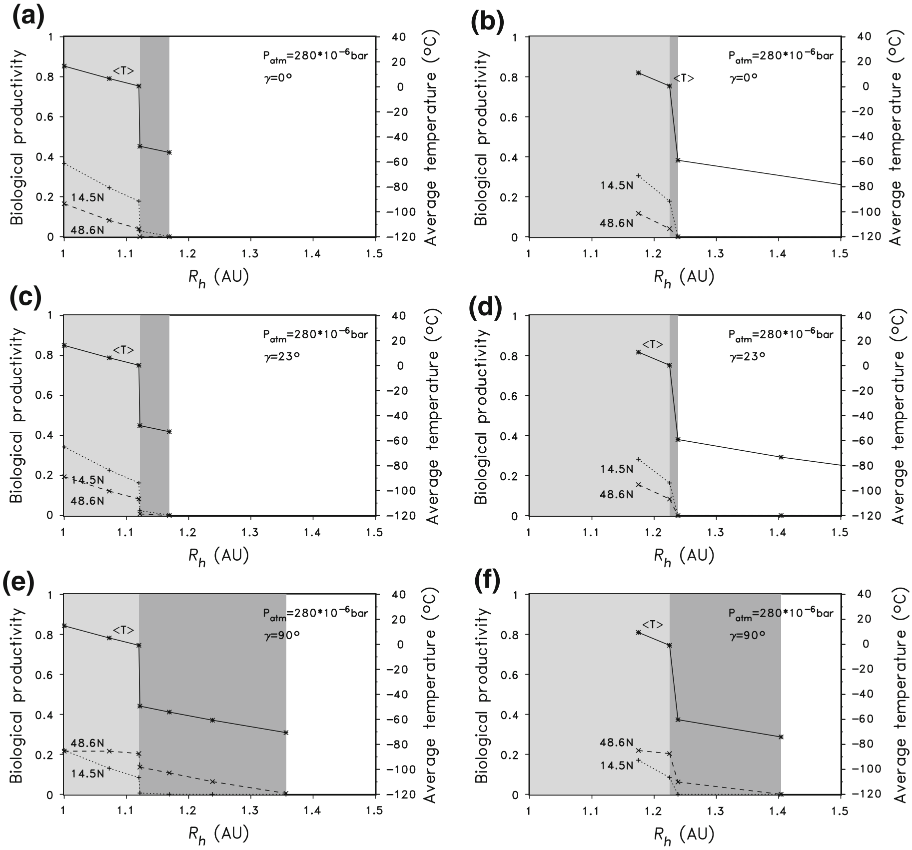

Fig. 2 Dependence of biological productivity on distance from the Sun, R_h, for $P_{atm} = 280 \times 10^{-6}$ bar and obliquity $\gamma = 0°, 23°, 90°$ for a dry atmosphere (**a**, **c**, **e**) and a humid atmosphere (**b**, **d**, **f**). The *solid line* denotes the corresponding average temperature $\langle T \rangle$. The *light gray shaded* area denotes the range for habitability at all times, while the *dark gray shaded* area denotes the range for diurnal habitability

the results for small obliquities is the dominating habitability of the continents located at high latitudes when $\langle T \rangle$ is lower than about 15°C. At higher $\langle T \rangle$ habitability is greater for the low latitude continental area than for the high latitude one. Relatively low productivity of the continental biosphere at high latitude increasing with distance from the Sun can be explained by warm values of the diurnal temperature exceeding the temperature for maximum bioproductivity. Figure 3 b, d, f plot the results for a humid atmosphere. Analogous to the case of low CO_2 atmospheric pressure the habitable zone is extended to a value of $R_h =$ 1.99 AU. For obliquities of 0° and 23° the range of orbital distances for diurnal habitability disappears almost completely, while for 90° obliquity the range is even extended. The inner and outer boundaries of the diurnal habitable zone are summarized in Table 2. It should be kept in mind, that the inner edge of the diurnal habitability zone is only the freezing point of the ocean. It is not the inner edge of the classically defined habitability zone.

The results depend on the thermal parameters of the regolith. In order to demonstrate the role of the thermal parameters we performed comparative calculations. For the regolith

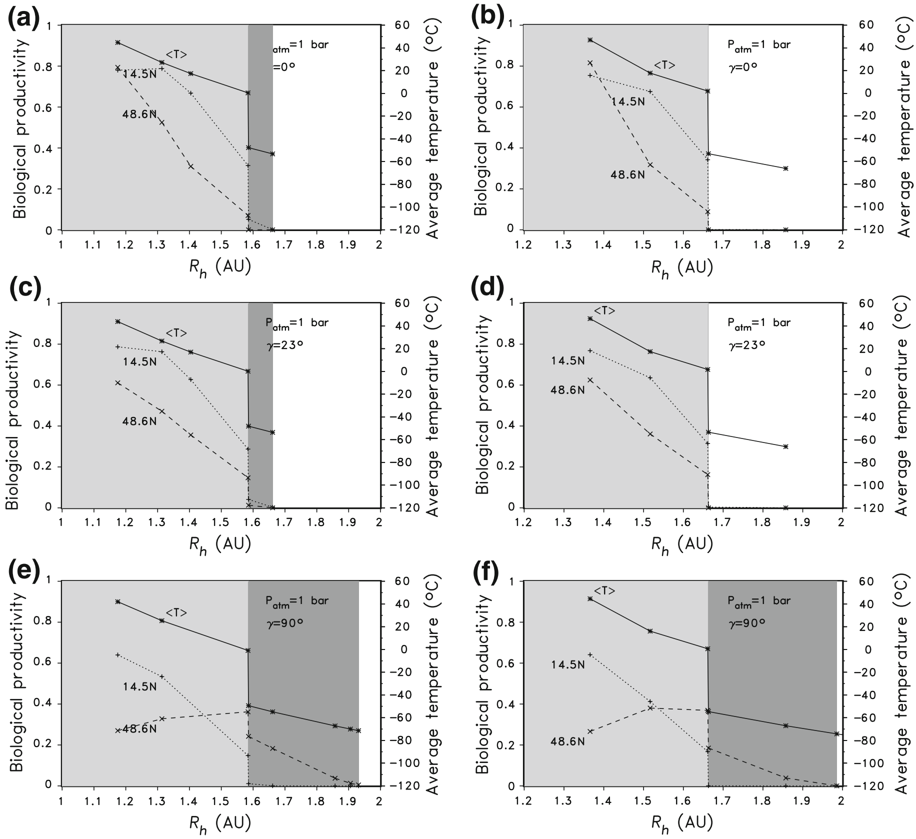

Fig. 3 Biological productivity in dependence on distance from the Sun, R_h, for $P_{atm} = 1$ bar and obliquity $\gamma = 0°, 23°, 90°$ for a dry atmosphere (**a**, **c**, **e**) and a humid atmosphere (**b**, **d**, **f**). The *solid line* denotes the corresponding average temperature $\langle T \rangle$. The *light gray shaded* area denotes the range for habitability at all times, while the *dark gray shaded* area denotes the range for diurnal habitability

Table 2 Dependence of inner and outer limits of diurnal habitability (R_{inner}, R_{outer}) on obliquity γ, atmospheric CO_2 pressure P_{atm}, and relative humidity h_r

γ (°)	P_{atm} (bar)	$h_r = 0$		$h_r = 0.9$	
		R_{inner} (AU)	R_{outer} (AU)	R_{inner} (AU)	R_{outer} (AU)
0	280×10^{-6}	1.12	1.17	1.22	1.24
23	280×10^{-6}	1.12	1.17	1.22	1.24
90	280×10^{-6}	1.12	1.36	1.22	1.40
0	1	1.58	1.66	1.66	1.66
23	1	1.58	1.66	1.66	1.66
90	1	1.58	1.93	1.66	1.99

density rho = 1,300 kg m^{-3}, a specific heat $c = 820$ J kg^{-1} and the thermal conductivity $\lambda = 10$ mW m^{-1} K^{-1} reflecting Martian conditions we get a continental temperature at 14.5°N latitude of 239.89 K, while for the values depicted in Table 1 a value of 250.72 K is obtained. Despite lower average temperature the bioproductivity is much higher, 0.29 instead 0.001. This emphasizes conservative character of our results. We applied material parameters corresponding to the regolith of very high thermal inertia and small diurnal oscillations of the temperature, but our simulations still predict strong effect of the diurnal habitability.

The temperature evolution at latitude 48.6°N as a function of the solar longitude L_s is depicted in Fig. 4 for 23° and 90° obliquities at different distances from the Sun, corresponding to different luminosities. The figures show distinct characteristics for 23° and 90° obliquities. The distances from the Sun have been chosen to be just at the point before and after freezing of the ocean. While the curves are sinusoidal in the low obliquity case, the high obliquity curves show a stronger deviation between the first and second half of the solar longitude.

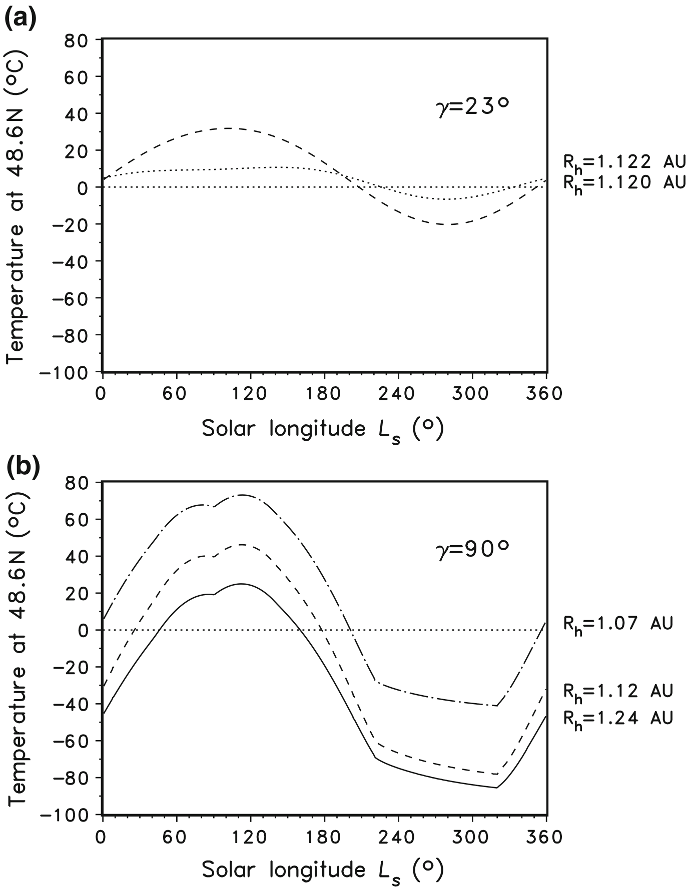

Fig. 4 Seasonal variation of temperatures at 48.6°N at noon for 23° obliquity (panel a) and 90° obliquity (panel b). The distances R_h to the Sun correspond to different situations: In the *upper panel* profiles are plotted just before and just after ocean freezing ($R_h =$ 1.20 AU and $R_h =$ 1.22 AU). The plots in the *lower panel* correspond to the situations well before ocean freezing at $R_h =$ 1.07 AU, just after ocean freezing at R_h = 1.12 AU, and close to the outer limit of planetary habitability at $R_h =$ 1.24 AU. The *horizontal dotted line* indicates the critical threshold for non-vanishing biological productivity

4 Discussion

The proposed model for calculating the habitability of Earth-like planets at diurnal and seasonal time scales shows the limits of a habitability definition based only on mean global surface temperatures averaged over one orbital revolution. We have shown that despite a low mean global temperature of about −50°C there may exist certain local continental regions where the temperature rises at least temporarily above 0°C, yielding a non-vanishing biological productivity. The reason for this effect is the finite value of the thermal inertia of the continental land mass. In contrast to models with a uniform planetary temperature, only a fraction of energy received from the central star during mid-day can be stored beneath the surface. Hence, the local surface temperature can follow diurnal changes in illumination. The local time shift of temperature changes relative to the changes in surface illumination depends on the particular value of the thermal inertia. This shift is smallest on the surface and increases with depth. The discussed effect is real and was observed from the Mars Exploration Rovers Miniature Thermal Emission Spectrometer (Smith et al. 2004): Soil temperatures closely follow the solar input with maximum temperatures well above 0°C. Therefore, from this point of view Mars could be diurnal habitable concluding from the surface temperatures in some regions. But the present Martian surface is inhabitable because of the absence of liquid water under the condition of extremely low atmospheric pressure.

Our results of higher mean annual temperatures at the poles than at the equator for 90° obliquity are a well-known effect that was already described by Williams (1975) and is valid for all obliquities greater than 54°. This phenomenon was also discussed as an alternative hypothesis for explaining low-latitude glaciations within the framework of the snowball Earth hypothesis (Hoffman and Schrag 2002).

Our results may be important for Earth-like planets situated near the outer edge of the HZ. In this case our previously applied definition of habitability (Franck et al. 2000a) should be generalized: An Earth-like planet may be diurnally habitable if at least some special regions of the planetary surface have non-zero biological productivity during certain time intervals of the year. This effect depends strongly on the obliquity. It should be noted that the effect of diurnal habitability discussed in our paper only allows for the existence of primitive organisms as observed in terrestrial polar cold deserts.

There exist other limitations and restrictions of our model: the distribution of water, warming of the surface due to the presence of clouds, greenhouse gases other than CO_2, and topographic effects are neglected. On the other hand data needed to model such effects are almost impossible to obtain for extrasolar planets. The model used in this study must be seen as a first approach. The physical parameters of an extrasolar planet are not known, too, but they are likely to be very distinct from Mars and Earth. However, the qualitative effect of diurnal habitability should remain valid.

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