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Simulation of Weather Conditions on Mars

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Abstract: In times of active research of the possibilities of colonization of other planets, it is important to acquire the skills of forecasting weather conditions on the planets, which are the prospects for human settlement. In this research, the theoretical model is developed that describes the physical processes that occur in the atmosphere of Mars in order to calculate the surface temperature of the planet for any point of the planet's area, time of day, and day of the year. The following theoretical model is implemented in computer software realized by Python programming language to calculate the necessary data.

Key words: Surface temperature, sublimation, desublimation, theoretical model, horizontal layers, vertical layers.

1. Introduction

Consideration of the problem of weather conditions on the planets, which look promising for human colonization, is highly important. Nowadays, there are almost no opportunities on Mars to directly measure atmospheric parameters to predict weather conditions on the planet.

Therefore, it is significant to be able to calculate the climatic conditions on the planet by determining the key processes that influence the weather and obtaining the required parameters of the planet's atmosphere.

2. Research Tasks

Create the theoretical model that can calculate the surface temperature of Mars for any point on the surface at any time of day

Consider the processes of sublimation and desublimation of carbon dioxide in the atmosphere of Mars, which significantly affect the surface albedo and the size of polar caps on the planet's surface

Develop programming code in the Python programming language that calculates the value of the surface temperature of Mars and the mass of sublimated ice on the surface of Mars

Compare the obtained temperature values with real data measured by a rover directly on Mars to determine the accuracy of our model

3. Development of Theoretical Model

The theoretical model is based on the division of the Martian atmosphere into layers in two ways, considering the transmission of energy fluxes through the Martian atmosphere.

3.1 Model of Vertical Layers

The core point of the theoretical model of vertical layers is to consider the energy balance that occurs in the vertically divided layers of Martian atmosphere. Each layer of the atmosphere emits with the appropriate temperature and emissivity, and absorbs the energy obtained from solar radiation. In this work, the transfer of energy among the layers of the atmosphere caused by thermal conduction is also considered.

The model of vertical layers consists of 10 vertical layers. In order to estimate the number of layers, the method, suggested by International Standard Atmosphere (ISA) [1], is deployed, recognizing that each layer has a constant temperature, and the edge of atmosphere is located at the point where pressure is significantly lower than the surface pressure.

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The model of vertical layers consists of five main types of energy flows:

1) Energy from the radiation of the atmosphere and the surface of the planet: energy flux of radiation is determined by the law of Stefan-Boltzmann, assuming from spectrum analysis of Martian emission that the planet's radiation is similar to the blackbody one:

$$F_{rad} = \varepsilon\sigma T^4$$

where $\sigma -$ Stefan-Boltzmann constant, $\varepsilon -$ emissivity

2) Energy of thermal conductivity: through each layer of the atmosphere there is a transfer of the flux of energy produced by thermal conductivity [2]:

$$F_{conduct} = -k \cdot \frac{\partial T}{\partial H}$$

where $k -$ coefficient of thermal conductivity, $H -$ height of the atmosphere

3) Energy from solar radiation [2]:

$$F_{sun} = \frac{L_{sun}}{4\pi r^2} \cdot \sin(\omega_{axis} t) \cdot \sin(h_{sun}) \cdot (1 - A)$$

where $h_{sun} -$ height of Sun over horizon, $L_{sun} -$ luminosity of Sun, $r -$ current distance from Sun to Mars, $\omega_{axis} -$ rotational speed of Mars, $t -$ time of day, $A -$ albedo

The $\sin(\omega_{axis} t)$ term represents the changing insolation angle of the Sun over a day. As this value depends on local time of day, it is possible to establish the dependence of solar emission on the value of geographical longitude.

The variation of distance from Sun to Mars, caused by an ellipticity of Martian orbit, is calculated by deploying the spherical trigonometry [3].

It is necessary to consider that the value of the absorbed solar radiation is based on the value of the albedo of Martian atmosphere and surface.

4) Energy of heat accumulation by the atmosphere and the surface of Mars: heat is stored during the evolving seasonal cycle by the thermal inertia of the atmosphere and land:

$$F_{storage} = C \cdot \frac{\partial T}{\partial t}$$

where $C -$ heat capacity of atmosphere or surface, $\frac{\partial T}{\partial t} -$ change of temperature over time

5) Energy of re-emission of energy: each layer re-radiates energy of previous layer with the value of emissivity of $1 - \varepsilon$:

$$F_{re-rad} = (1 - \varepsilon)\sigma T^4$$

Consequently, the system of equation that describes the energy balance of Martian surface and each layer of atmosphere of the planet is:

$$F_{sun} = F_{re-rad} + F_{rad} + F_{conduct} + F_{storage}$$

Applying the aforementioned reasoning about the atmospheric processes of the planet provides with the system of equations for each layer of the atmosphere.

The value of the emissivity is defined as a function of wavelength. In the calculations, the estimated value for atmosphere is considered to be equal to $\varepsilon_{air} = 0.75$ [4] and for ground $\varepsilon_{ground} = 1$ (without involving the alteration of this value due to ice accumulation on the surface)

3.2 Model of Horizontal Layers

This model is derived by including reasonably similar energy balance to the one of the model of vertical layers, and the effect of horizontal atmospheric transport and sublimation or desublimation energy of carbon dioxide on this balance.

Similarly to the model of vertical layers, one of horizontal layers includes five types of energy fluxes [5]:

1) Heat accumulation
2) Energy from the radiation of the surface of the planet
3) Energy from solar radiation
4) Flow of energy formed by the absorption or release of heat during sublimation and desublimation of carbon dioxide over a period of time:

$$F_{subl} = \pm L_{ice} \cdot \frac{dm}{dt}$$

where $L-$ specific heat of sublimation CO_2, $\frac{dm}{dt}-$ sublimated or desublimated mass of CO_2.

5) Horizontal convective heat transfer occurs through the meridional transport of air masses. Atmospheric circulation creates an energy flow per unit time across a latitude circle of:

$$F_{diff}=\frac{\partial}{\partial x}(D(1-x^2)\cdot\frac{\partial T}{\partial x})$$

where $D-$ horizontal diffusivity coefficient for meridional energy flux, $x=\sin(\varphi)$, $\varphi-$latitude.

For calculation of number of layers, the atmosphere is divided along the meridian on 36 layers, basing on the conclusion that the step of $\Delta\varphi=5°$ in the obtained system of equations provides highly accurate results of the surface temperature.

Finally, system of equation that describes energy balance in Martian atmosphere for horizontal layers:

$$F_{sun}+F_{diff}=F_{rad}+F_{subl}+F_{storage}$$

This approach is deployed to conclude the equations for each layer with the step of $\Delta\varphi=5°$ in the model of horizontal layers.

3.3 Processes of Sublimation and Desublimation

The processes of sublimation and desublimation of carbon dioxide in the atmosphere of Mars significantly affect the surface albedo and the size of polar caps on the planet's surface.

The released energy of sublimation or desublimation process is assumed to depend on the radiation of the surface of Mars and the radiation of the Sun [5]:

$$L\cdot\frac{dm}{dt}=F_{sun}\cdot(1-A_{ice})-\varepsilon_{ice}\cdot\sigma\cdot T_{surf}{}^4$$

The mass of dry ice sublimated or desublimated in the northern or southern hemisphere is calculated by integrating the weight gain per unit area from the pole to a point with a certain latitude [5]:

The sublimated or desublimated mass on the north is:

$$\frac{dM}{dt}=2\pi R^2\cdot\int_x^{+1}\frac{dm}{dt}\cdot dx$$

where $R-$ planet's radius

The sublimated or desublimated mass on the south is:

$$\frac{dM}{dt}=2\pi R^2\cdot\int_{-1}^{x}\frac{dm}{dt}\cdot dx$$

The process of sublimation is associated with not only energy release but also with alterations of values surface albedo and surface emissivity. For ground covered with dry ice and ground without ice values of these physical variables are completely different [1]:

$$\varepsilon_{ground}=\begin{Bmatrix}1.0 \\ \varepsilon_{ice}=0.58\end{Bmatrix}\begin{vmatrix}T_{surf}>T_{subl} \\ T_{surf}<T_{subl}\end{vmatrix}$$

$$A_{ground}=\begin{Bmatrix}0.3 \\ A_{ice}=0.8\end{Bmatrix}\begin{vmatrix}T_{surf}>T_{subl} \\ T_{surf}<T_{subl}\end{vmatrix}$$

where $T_{subl}-$ temperature of sublimation or desublimation of CO_2.

4. Implementation in Computer Programming

Developed theoretical model is implemented into our computer software which is based on Python programming language that solves the derived system of equations numerically and calculates the value of the surface temperature of Mars depending on the value parameters that are entered by user.

5. Results

After developing the model, it is necessary to examine an accuracy of the obtained data by comparing it with real measurements.

There is an example of comparison of Mars Curiosity Rover (which is located on the Gale Crater on Mars) measurement data of the maximum surface temperature on each day in the end of February, 2020 with the results, received from the software's calculations [6]:

Table 1 Comparison of our results with results measured by Curiosity Rover.

Date	Surface Temperature (Curiosity Measurement)	Surface Temperature (Results of Model)	Absolute Error
Feb. 24	-13℃	-5.4℃	7.6℃
Feb. 23	-22℃	-11.5℃	10.5℃
Feb. 22	-20℃	-9.4℃	10.6℃
Feb. 21	-10℃	-3.5℃	6.5℃
Feb. 20	-9℃	+2.8℃	11.8℃
Feb.19	-15℃	-3.6℃	11.4℃
Feb.18	-8℃	+3℃	11℃

The real measurements of Mars Curiosity Rover confirm that the developed theoretical model is correct because it demonstrates qualitatively similar to the real results.

Moreover, the developed software, established by this theoretical model, allows observing the alterations of the value of temperature depending on different parameters of Mars (geographical latitude and longitude, day of the year, etc.).

6. Conclusion

The main modernization, suggested by the research, is to combine the energy balance of the fluxes of the vertical and horizontal layers in order to obtain more accurate results.

In summary, the theoretical model that calculates the surface temperature of Mars and the mass of sublimated or desublimated ice depending on geographical coordinates, time of day and day of the year is developed. The calculated data are qualitatively similar to the data obtained by the spacecraft on the surface of Mars.

In the future, we are planning to apply a similar theoretical model to other planets of the terrestrial group of the solar system.

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