Assessing Climate Sensitivity and Mechanisms in a One-Dimensional Climate Energy Balance Model

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Abstract. Addressing the pressing concerns surrounding climate sensitivity, particularly within the context of Earth's changing climate, remains a pivotal endeavor. In this paper, the earth global temperature variation modeled by a one-dimensional climate energy balance model (EBM) is studied using a variance-based sensitivity analysis. The outcomes of this study offer a comprehensive analysis on each parameter that govern Earth's climate dynamics. Specifically, the analyses highlight that land albedo possesses the most substantial First-Order Sobol indices; the solar multiplier and the constant coefficient in the linearized Stefan-Boltzmann Law emerge as the second and third-largest contributor to Sobol indices, while the sensitivity of albedo of ice, temperature dependent coefficient of linearized Stefan-Boltzmann Law, and Transfer Coefficient remain insignificance. The analysis also suggests the non-negligible role of ice-albedo feedback and supports the hypothesis of the "Snowball Earth". This research holds significance as it uniquely addresses Earth's climate sensitivity using a one-dimensional Energy Balance Model, offering fundamental yet essential insights into the dynamics of earth's climate system, particularly its temperature variations.

Keywords: Global temperature variation; one dimensional EBM; variance-based sensitivity analysis.

1. Introduction

In recent years, there has been a heightened focus on exploring Earth's climate and its inherent sensitivity, owing to its pivotal role in comprehending the potential consequences of ongoing climate shifts. The intricacies of Earth's climate system have undergone rigorous examination, especially in the contemporary era, revealing the undeniable impact of human activities on climate change since the industrial revolution [1]. For instance, intensified fossil fuel combustion, coupled with unequal and unsustainable energy practices and land use, has unequivocally triggered the greenhouse effect, resulting in global warming manifested as a 1.1°C increase in global temperature compared to pre-industrial benchmarks [2]. Consequently, this escalation has further contributed to an increase in the frequency and intensity of extreme weather phenomena, leading to increasingly hazardous implications for ecosystems and societies worldwide [2]. The undeniable fact is that Earth's climate system is currently undergoing a profound transformation. To gain a comprehensive understanding of these changes and accurately forecast the deteriorating outcomes, the development of a digital twin of Earth is imperative.

This study explores climate sensitivity and underlying mechanisms modelled by a One-Dimensional Energy Balance Model (EBM). A One-Dimensional Energy Balance Model (EBM) is a simplified yet robust mathematical framework utilized to investigate and replicate temperature fluctuations along a single spatial dimension, typically representative of the Earth's surface [3]. This model adeptly captures the core principles governing energy interchange within the Earth's system. By encompassing pivotal components such as incident solar radiation, outgoing long-wave (infrared) radiation, and thermal conduction through the surface layer, the EBM unveils profound insights into how diverse processes, including alterations in greenhouse gas concentrations, shifts in surface reflectivity (albedo), and variations in the solar constant, exert influence on temperature trends [3, 4]. The one-dimensional EBM emerges as a potent instrument for comprehending the underlying mechanisms steering temperature alterations, thus facilitating simulations of a simplified Earth model and enabling multifaceted and exhaustive sensitivity analyses. Its utility extends to both basic explorations and intricate examinations, establishing itself as a versatile instrument for unravelling

the intricate interactions between energy fluxes and temperature dynamics across a constrained spatial dimension. The significance of Earth's climate sensitivity and its dynamic interplay has prompted insightful research. Pioneering this exploration, Sellers introduced a global climatic model rooted in energy balance principles [5]. Budyko further illuminated the link between solar radiation fluctuations and climatic trends, offering key insights into external drivers [6]. Building on this foundation, North and Cahalan delved into energy balance climate models, unveiling the roles of albedo, radiation, and conduction [3]. The Biosphere-Atmosphere Transfer Scheme (BATS) developed by Dickinson et al. demonstrated the impacts of land cover changes [7]. Betts and Ball highlighted albedo's variation in boreal forests and temperature [8], while Bonan underscored the role of land use [9].

In the dynamic realm of climate research, understanding Earth's climate sensitivity remains paramount, with one-dimensional energy balance models (1D EBMs) representing a foundational yet under-explored field. The scarcity of systematic sensitivity analyses, particularly within the context of one-dimensional EBMs, highlights a crucial research gap that this study aims to address. Through rigorous parameter variation within the EBM framework, the aim is to decipher the nuanced mechanisms driving climate sensitivity. The elegance of the one-dimensional EBM's simplicity amplifies its significance, rendering it a foundational reference that underpins more complex models, serving as a cornerstone for climate understanding. The framework of this paper is structured into four key sections, each contributing distinct insights to the study. In Sec. 2, this study expounds upon the establishment of the model and its governing equation. Moreover, the methods for sensitivity analysis and sampling are also mentioned. Sec. 3 centers on the execution of a variance-based sensitivity analyses that encompasses the Greenhouse effect, Albedo-driven Land cover changes, solar multiplier, and Transportation Coefficient-driven Atmospheric Circulation and Ocean Current variations. This study will thoroughly analyze the results of these simulations, shedding light on their implications for Earth's climate sensitivity and responses. Sec. 4 transparently delineates the inherent limitations of the model, such as simplifications and uncertainties, while outlining potential avenues for future enhancements. Finally, Sec. 5 succinctly encapsulates the paper's essence and summarizes the significant findings.

2. Method

2.1. Model Construction

The central concept of Energy Balance Models (EBMs) revolves around equating the incoming solar radiation from the sun with the outgoing long-wave radiation emitted by the Earth's surface, and the model's governing equation is constructed based on the study by McGuffie etc. [4]. In a one-dimensional framework, the Earth's climate system is divided into discrete latitudinal zones. Therefore, it allows different solution in different latitude zones. The energy balance equation for a specific latitudinal zone, labeled "i," is given by:

$$C\frac{dT_i}{dt} = R_{in} - R_{out} \tag{1}$$

Where C is the effective heat capacity of earth's fluid layer. $\frac{dT_i}{dt}$ represents the rate of change of surface temperature in latitudinal band "i". R_{in} represents the the incoming shortwave solar radiation received by latitudinal band "i". R_{out} represents the outgoing long-wave radiation emanating from latitudinal band "i" The incoming shortwave radiation (R_{in}) of a cross-sectional area of earth is represented by:

$$R_{in} = (1 - \alpha_i) \cdot S_i \cdot S_m \tag{2}$$

Where α_i is the albedo of latitudinal band "i". S_i is the solar insolation with respect to latitudinal band "i". S_m refers to a solar multiplier.

In the computation of Earth's solar insolation for different latitudinal zones (S_i), several key factors come into play. These factors include Earth's axial tilt, the duration of days in a year, the length of

hours in a day, and the solar constant (S_c). Utilizing these parameters, the cumulative insolation received within a year across varying latitude zones denoted as "i" can be derived. By subsequently calculating the average of these values, the daily mean insolation for different latitudinal zones can be determined. To account for the varying intensity of the sun's influence, a coefficient, denoted as Solar Multiplier (S_m), is introduced. This coefficient effectively scales the solar insolation, simulating the effects of a stronger or weaker sun. Notably, the default value for this coefficient is set at 1.

The concept of a Critical Temperature (T_c) is also taken into account and plays a crucial role in the simulation. When the temperature of a specific latitudinal band (T_i) falls below freezing, a deliberate adjustment in albedo (α_{ice}) occurs to account for increased ice and snow cover. Conversely, as temperature rises above the critical temperature, the albedo returns to the global average (α_{land}). The counterpart to incoming solar radiation, outgoing long-wave radiation (R_{out}), is governed by the Stefan-Boltzmann Law $F_{bb} = \epsilon \cdot \sigma \cdot T_s^4$. Notably, Earth's surface temperature exhibits a relatively narrow range of change (less than 30 degrees Celsius), affording a fitting opportunity for a linear approximation, which in turn lends a simpler version of this equation. This approach also enables the model to simulate the effect of Greenhouse gases by adjusting the coefficient of the linear equation. The linearized long wave radiation (R_{out}) is shown as below:

$$R_{out} = A + B \cdot T_i \tag{3}$$

Here, A is the constant coefficient and B is the temperature dependent coefficients for the linearized Stefan-Boltzmann Law. T_i is the surface temperature in latitudinal zone "i"

The disparity of solar radiation amongst latitudinal zones impels heat transport, predominantly orchestrated by atmospheric circulation and ocean currents in the real-world panorama. The mechanism of meridional heat advection can simply take the form of $F(T_i - T_{avg})$, where F refers to the coefficient of heat transportation. T_{avg} represents the global average temperature. Through the integration of these fundamental facets, the governing equation of the one-dimensional EBM is written as:

$$C\frac{dT_i}{dt} + F(T_i - T_{avg}) = (1 - \alpha_i)S_i \cdot S_m - A - BT_i \tag{4}$$

In this precise formulation, the variable T_i, α_i, and S_i are interlinked as function of latitude. Although this ordinary differential equation cannot be solved analytically, it is able to be solved numerically by establishing an initial value for a uniform distribution across latitudinal zones and iterate through it. By having the program cycle through several times, it should converge to a steady-state temperature solution.

2.2. Methodology for Sensitivity Analysis

Sensitivity analysis is a fundamental tool employed to investigate climate sensitivity and its underlying mechanisms within a one-dimensional Energy Balance Model (EBM), which allows to quantify the influence of individual input parameters on the model's output variability, facilitating a rigorous understanding of the key drivers shaping climate behavior within this simplified representation of Earth's climate system. In this study, the chosen approach is variance-based sensitivity analysis, centers on Sobol indices [10]. These indices offer a structured framework to dissect the total output variance, enabling precise quantification of the effect of each input parameter. This study opts for Latin Hypercube Sampling (LHS) to select input parameter [11]. This method strategically divides each parameter's range into equally probable intervals, ensuring a consistent sampling and convergent approach. Mathematically, this process is expressed as:

$$X_i^{(j)} = a_i + \frac{(b_i - a_i)}{N} \cdot (j - 1) \tag{5}$$

Where $X_i^{(j)}$ is the jth sample value of input parameter X_i, a_i and b_i are the lower and upper bounds of X_i, and N is the number of intervals.

The first-order Sobol indices can then be calculated based on the selected input hypercube, which measures the unique influence of each parameter on output variability. Mathematically, the first-order Sobol index S_i for parameter X_i is defined as the ratio of the variance V_i, the variance of model output generated by inputting different parameter X_i, attributable solely to to the overall output variance $Var(Y)$:

$$S_i = \frac{V_i}{Var(Y)} \tag{6}$$

The range of Sobol indices if from 0-1. A Sobol index value of 1 denotes a scenario where the output's entire variance is attributed solely to the variations in a specific parameter, which could indicate its critical role in driving model responses. Conversely, a Sobol index value of 0 signifies that the parameter's variations have negligible impact on the output's variance, indicating a lack of sensitivity to that particular parameter.

3. Result and Discussion

3.1. Variance-Based Sensitivity Analysis

In this section, the outcomes of the sensitivity analysis conducted on the one-dimensional Energy Balance Model (EBM) are presented. The ranges and default values of the input parameters considered for the analysis are given in Table. 1. The default value of each parameter is set as the average within its defined range. The albedo of ice and land is selected based on the study by Stephens et al. [10], while the values of A and B are derived from the works of Budyko [6] and Cess [11].

Table 1. Input parameter.

Input Parameter	Range	Default Value
Solar Multiplier (SM)	0.9 - 1.1	1.0
Transport Coefficient (F)	1.5 - 5.5	3
A	180 - 220	200
B	1 - 2	1.5
Ice Albedo (Alb_Ice)	0.5 - 0.7	0.6
Land Albedo (Alb_Land)	0.2 - 0.4	0.3

To initiate the simulation and solve the ordinary differential equations (governing equation) of the one-dimensional Energy Balance Model (EBM), a uniform latitude distribution requires an initial value.

An initial uniform temperature distribution of 15 degrees Celsius is selected based on AR 6 [2], which aligns with current global temperature and anomaly trends, ensuring realism in the model's simulation. A fixed value of 1370 W/m² is also selected for Solar Constant, the mean solar irradiance at Earth's outer atmosphere. The Critical temperature is set at $-10^{\circ}C$ to distinguish land and ice.

In the course of the sensitivity analysis, a uniform interval of 20 is chosen for each input parameter to conduct a Latin Hypercube Sampling (LHS). Applying LHS, a total of 21 trials were conducted, each corresponding to a unique set of input parameter values. The resulting model outputs for each trial were recorded and compiled into the Table. 2.

The Overall Variance is calculated as follows:

$$Var(Y) = \frac{\sum_{i=1}^{21}(Y_i - \overline{Y})}{21} = 715.3506 \tag{7}$$

Where Y_i is the value of each output (average temperature), and $\overline{Y}$ refers to the mean of all value in output.

The Sobol indices is then calculated, which involves isolating a single parameter's influence while keeping all other variables constant at their default value mentioned in 3.1.1. By sequentially varying the value of one input parameter at a time, from its minimum to maximum value, and employing a uniform interval of 20 subdivisions, the sensitivity of the model to that specific parameter can be quantitatively measured.

Table 2. Input and output for different trials.

	Input Parameters						Output
	SM (X_1)	F (X_2)	A (X_3)	B (X_4)	Alb_Ice (X_5)	Alb_Land (X_6)	Avg_Temp in $°C$ (Y_i)
Trial 1	1.050	2.300	218.0	1.200	0.6700	0.2700	7.8363
Trial 2	0.950	4.300	190.0	1.800	0.6100	0.3600	-2.5188
Trial 3	0.930	2.900	184.0	1.850	0.6200	0.3400	-0.5376
Trial 4	1.040	2.700	194.0	1.500	0.5200	0.3700	3.6134
Trial 5	0.900	3.300	200.0	1.350	0.6300	0.3900	-70.9329
Trial 6	1.020	4.700	206.0	1.400	0.6400	0.2900	15.2618
Trial 7	0.910	1.900	202.0	1.100	0.6800	0.2400	0.3067
Trial 8	1.080	3.700	214.0	1.300	0.7000	0.2500	31.1421
Trial 9	0.970	3.100	182.0	1.900	0.5900	0.3300	8.0472
Trial 10	1.070	5.500	196.0	1.450	0.5800	0.2800	33.2303
Trial 11	1.100	4.900	186.0	1.250	0.5400	0.3200	41.0785
Trial 12	0.960	2.100	188.0	1.600	0.6900	0.3800	-13.6104
Trial 13	0.920	3.500	198.0	1.950	0.5600	0.2300	9.1067
Trial 14	1.030	5.100	216.0	1.150	0.5300	0.2000	40.3338
Trial 15	0.990	1.700	192.0	1.550	0.5100	0.3500	-1.9019
Trial 16	0.940	1.500	204.0	1.750	0.5700	0.3100	-13.7595
Trial 17	1.060	4.500	180.0	2.000	0.6600	0.2200	38.7326
Trial 18	0.980	4.100	212.0	1.650	0.5000	0.4000	-35.4731
Trial 19	1.010	5.300	208.0	1.700	0.6000	0.2100	25.4976
Trial 20	1.000	3.900	220.0	1.050	0.6500	0.2600	9.7927
Trial 21	1.090	2.500	210.0	1.000	0.5500	0.3000	24.7905

Table 3. First-Order Sobol Indices

Input parameter (X_i)	First-Order Sobol Indices
SM (X_1)	0.1559
F (X_2)	0.0243
A (X_3)	0.1415
B (X_4)	0.0183
Alb_Ice (X_5)	0.0002
Alb_Land (X_6)	0.3329

A total of 126 trials are conducted, and the first-order Sobol index is calculated independently for the following input parameters: solar multiplier, A, B, transport coefficient, albedo of ice, and albedo of land. The output (average global surface temperature) of each trial is compelled. The First-Order is the calculated and visualized as Table 3. Among the six input parameters analyzed, the sensitivity is sequenced as follows: Albedo of land exhibits the highest sensitivity, followed by parameters A, Solar Multiplier (SM), Albedo of ice, parameter B, and finally, the Transport Coefficient, which demonstrates the lowest sensitivity.

3.2. Interpretation

The Solar Multiplier is a parameter used to emulate shifts in solar intensity, and its Sobol Index ranks second highest among the six input parameters under scrutiny, which demonstrates the non-negligible influence of solar energy on Earth's climate, especially the global temperature. In the real world, the Sun's radiative output exhibits temporal fluctuations, exemplified by an 11-year cycle marked by alternating phases of heightened and diminished solar activity, attributed to shifts in solar magnetic polarity [12]. During solar maxima, characterized by heightened solar activity, the Sun's overall luminosity experiences a minute augmentation of approximately 0.1% relative to solar minima [12]. The sensitivity analysis reveals a pivotal observation: a 1 per cent escalation in solar irradiance will yield an approximate temperature variance of 1.4 to 1.5 degrees Celsius in the simulation of one-dimensional EBM. Correspondingly, the model suggests that a 0.1% normal variation of solar strength would yield an influence on global temperature, approximating 0.14 to 0.15 degrees Celsius or even less. This demonstrates the fact that, in the real world, the fluctuation of the sun's radiation output only serves as a secondary contributor to the scenario of global warming in contrast to more potent drivers. Furthermore, the model imparts insights into the "young sun paradox" and the hypothesis of a "snowball Earth" [13]. Prevailing studies postulate that the historical solar intensity was roughly 70-85 % of the contemporary magnitude, which would make the earth entirely frozen [13]. Within the model's framework, a scenario suggests that as solar radiance recedes to 93 % of present levels, global temperatures exhibit a distinctive descent below the zero thresholds. This observation imparts tangible support to the proposition of a "snowball Earth" from the energy balance perspective.

The Transfer Coefficient possesses the second lowest Sobol index value among the six parameters in the sensitivity analysis. This outcome aligns harmoniously with the theoretical underpinnings of the parameter, which posits that the Transfer Coefficient serves to facilitate the even distribution of heat across Earth's surface, not to influence the global mean temperature. Absent this mechanism, the observation could be a drastic imbalance: the polar regions would undergo intensified cooling while the equatorial belt would experience intensified heating.

The Greenhouse Effect, represented by parameters A and B, is another dynamic facet wielding non-negligible influence over Earth's global temperature. Within the analysis, it's notable that parameter A is at the third place, while parameter B is in the last place. This distinction underscores

that while both parameters contribute significantly, the sensitivity of A surpasses that of B. The Greenhouse Effect pertains to the interaction of parameters A and B within the linearization of the Stefan-Boltzmann equation. Through the sensitivity analysis, one observes that parameter A exerts considerable influence. A minor 1% escalation in the greenhouse effect, as encapsulated by A, yields a substantial 1.5-degree Celsius increase in global temperature. Parameter B, while ranking slightly lower in sensitivity, also wields notable influence. A 3% increase in the effect governed by B translates to a discernible 0.7-degree Celsius elevation from the default state.

Within the analysis, the Albedo parameters emerge as a important influencers in Earth's energy equilibrium. When Earth's initial condition assumes a uniform distribution at 15 degrees Celsius, the sensitivity study suggests that Surface Albedo holds the most substantial Sobol index, signifying its paramount influence over the planet's climate dynamics. Besides, the Sobol index for the Albedo of Ice parameter assumes insignificance in this scenario, where substantial portions of the planet remain devoid of ice cover due to temperatures exceeding the critical threshold of -10 degrees Celsius, and this observation follows the governing equation. Real-world insights underscore the significance of albedo in shaping Earth's climate. Earth's average albedo is around 0.3. Intriguingly, the model's estimations underscore that minor albedo adjustments yield substantial temperature shifts. A mere 3% increase in land albedo—from 0.3 to 0.31—engenders a significant 2-degree Celsius temperature reduction. Moreover, the model introduces a scenario where land albedo escalates to 0.34 or higher, inciting a transformative sequence of events. The subsequent interplay among variables triggers a remarkable transformation: after the new equilibrium is established, extensive land regions experience temperature reductions below 10 degrees Celsius, inducing their transition into ice-covered terrains. This transition from land albedo to ice albedo, with a value of 0.6, further amplifies the cooling effect. It is also essential to state its real-world connection that the potential increase in albedo can be triggered by various scenarios, with deforestation being a significant contributor. Notably, deserts exhibit an albedo of around 0.4, while forests typically range from 0.2 to 0.35 [10]. When forest or grassland transforms into desert, the global temperature will increase in a notable and sensitive manner. This accentuates the importance of preserving Earth's diverse environments to sustain its delicate energy equilibrium.

Central to this discussion is the compelling phenomenon of the ice-albedo feedback mechanism. The dynamic interplay of albedo shifts initiates a cascade—a domino effect. Elevated land albedo prompts diminished solar energy absorption, leading certain regions to breach the critical temperature threshold and transition into ice-covered domains. The albedo of these newly formed ice surfaces intensifies, reflecting a greater share of solar energy and thereby augmenting the cooling process. The intricate interplay between albedo shifts and temperature dynamics, modeled by the One-Dimensional Energy Balance Model, underscores the potency of the ice-albedo feedback effect.

In summation, the sensitivity analysis demonstrates the pivotal role of the Albedo parameters in modulating Earth's climate dynamics. The profound influence of Albedo, coupled with ice-albedo feedback and temperature fluctuations, underscores their significance in governing Earth's energy balance and temperature regulation.

4. Limitation and Future Outlook

Inherent to the analysis, certain limitations stem from the simplified nature of the model. The challenge lies in attaining precise values for the linearized coefficients A and B to simulate the exact effect of Greenhouse Effect. Likewise, the representation of atmospheric circulation, while foundational, assumes a simplified rendition devoid of precise quantification.

For Future works, several ways for refinement are present. A primary focus could be dedicated to incorporate more realistic surface and atmospheric characteristics. This might involve introducing additional layers to account for vertical temperature profiles and atmospheric properties. By integrating real-world data and incorporating more nuanced insights into atmospheric circulation patterns, the model's fidelity could be elevated. Furthermore, a promising direction involves

segmenting the analysis to consider the Southern and Northern Hemispheres independently. Given the unique climatic features, circulation patterns, advection dynamics, and land cover characteristics in these regions, this bifurcation could provide deeper insights into the distinct influences and interactions within Earth's intricate climate system.

5. Conclusion

To sum up, a one-dimensional energy balance model is employed to systematically analyze global temperature variations through a variance-based sensitivity analysis. As result, the First-Order Sobol Indices for each parameter are calculated, which reveals the remarkable sensitivity of land albedo and the astonishing impact of the ice-albedo feedback and alternation of land type, such as deforestation. Additionally, the sensitivity analysis of the solar multiplier parameter, ranking second in Sobol indices, not only unveils its influence on Earth's energy balance but also lends support to the Faint Young Sun Paradox and the Snowball Earth hypothesis. The constant coefficient in the linearized Stefan-Boltzmann Law (A) also emerge as significant contributors to Earth's simulated conditions. The albedo of ice, temperature dependent coefficient in Stefan-Boltzmann Law (B) and transport coefficient remains relatively insignificant in temperature sensitivity.

However, it's essential to acknowledge the inherent simplicity of the model, which excludes factors like realistic data and complex circulation patterns. To enhance accuracy, future research endeavors could focus on integrating these complexities. The study's significance lies in its capacity to provide valuable insights into Earth's climate dynamics using a straightforward yet systematic methodology. Through the dissection of various factors' contributions to the average global temperature, this research elaborates the fundamental mechanisms steering climate variability.

References

[1] Schneider S H. The changing climate. Scientific American, 1989, 261(3): 70-79.

[2] IPCC. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022, 3056.

[3] North G R, Cahalan R F, Coakley Jr J A. Energy balance climate models. Reviews of Geophysics, 1981, 19(1): 91-121.

[4] McGuffie K, Henderson-Sellers A. The climate modelling primer. John Wiley & Sons, 2014.

[5] Sellers W D. A global climatic model based on the energy balance of the earth-atmosphere system. Journal of Applied Meteorology and Climatology, 1969, 8(3): 392-400.

[6] Budyko M I. The effect of solar radiation variations on the climate of the Earth. tellus, 1969, 21(5): 611-619.

[7] Dickinson R E. Biosphere/atmosphere transfer scheme (BATS) for the NCAR community climate model. Technical report, National Center for Research, 1986.

[8] Betts A K, Ball J H. Albedo over the boreal forest. Journal of Geophysical Research: Atmospheres, 1997, 102(D24): 28901-28909.

[9] Bonan G B. Observational evidence for reduction of daily maximum temperature by croplands in the Midwest United States. Journal of Climate, 2001, 14(11): 2430-2442.

[10] Stephens G L, O'Brien D, Webster P J, et al. The albedo of Earth. Reviews of geophysics, 2015, 53(1): 141-163.

[11] Cess R D. Climate change: An appraisal of atmospheric feedback mechanisms employing zonal climatology. Journal of Atmospheric Sciences, 1976, 33(10): 1831-1843.

[12] Benestad R E. Solar Activity and Earth’s Climate. Springer Science & Business Media, 2006.

[13] Hoffman P F, Kaufman A J, Halverson G P, et al. A Neoproterozoic snowball earth. Science, 1998, 281(5381): 1342-1346.