# A Brief Introduction to BNU-HESM1.0 and Its Earth Surface Temperature Simulations

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ABSTRACT

Integrated assessment models and coupled earth system models both have their limitations in understanding the interactions between human activity and the physical earth system. In this paper, a new human–earth system model, BNU-HESM1.0, constructed by combining the economic and climate damage components of the Dynamic Integrated Model of Climate Change and Economy to the BNU-ESM model, is introduced. The ability of BNU-HESM1.0 in simulating the global $CO_2$ concentration and surface temperature is also evaluated. We find that, compared to observation, BNU-HESM1.0 underestimates the global $CO_2$ concentration and its rising trend during 1965–2005, due to the uncertainty in the economic components. However, the surface temperature simulated by BNU-HESM1.0 is much closer to observation, resulting from the overestimates of surface temperature by the original BNU-ESM model. The uncertainty of BNU-ESM falls within the range of present earth system uncertainty, so it is the economic and climate damage component of BNU-HESM1.0 that needs to be improved through further study. However, the main purpose of this paper is to introduce a new approach to investigate the complex relationship between human activity and the earth system. It is hoped that it will inspire further ideas that prove valuable in guiding human activities appropriate for a sustainable future climate.

**Key words**: economic model component, earth system model, human activity, global change

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## 1. Introduction

Integrated assessment models (IAMs) and coupled atmosphere–land–sea-ice earth system models are two major tools used to investigate issues relates to climate change. However, both IAMs and coupled earth system models have their advantages and limitations in simulating and projecting emissions scenarios and climate changes.

IAMs are widely used to provide information on global and national emissions and the costs of different climate polices. They can depict the cause–effect chain between emissions and rising temperature, but with relatively simple equations (Matsuoka et al., 1995; Brenkert et al., 2003; Sokolov et al., 2005; Bouwman et al., 2006; Moss et al., 2010). For example, the Dynamic Integrated Model of Climate Change and Economy (DICE) uses just one or two simple equations to calculate the global $CO_2$ concentration and temperature change, and most IAMs use a linearized representation of ocean carbon uptake (van Vuuren et al., 2011; Hof et al., 2012). This is an obvious oversimplification of the complex physical and biochemical processes of the earth system. Indeed, recent studies have shown that the lack of complexity in the representation of physical processes in IAMs is likely to have significant impacts on the outputs of policy cost, carbon tax, and so on (Schneider and Thompson, 1981; Schultz and Kasting, 1997; Smith and Edmonds, 2006). For example, Smith and Edmonds (2006) demonstrated that the uncertainty in the carbon cycle results in a broader range of the cost of achieving certain $CO_2$ concentrations, and is equivalent to a change in the concentration target of up to 100 ppmv.

Coupled earth systems models, which include ocean and terrestrial carbon cycle feedbacks, are designed to capture the biophysical processes of the real climate system (Taylor et al., 2012). They possess unique advantages in simulating, projecting and attributing climate change under given natural

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and anthropogenic forces (Wei et al., 2012; Gillett and Fyfe, 2013; Weller and Cai, 2013; Bellenger et al., 2014; Wei et al., 2014) and can be used to compensate for the deficiencies of IAMs. For example, Wei et al. (2012) investigated the responsibilities of developed and developing countries in terms of historical climate change and $CO_2$ mitigation using two earth system models, and the results showed contributions to historical climate change of 2/3 and 1/3, respectively, while their contribution to future climate mitigation was predicted to be 1/3 and 2/3. Additionally, coupled earth system models provide larger datasets for the Intergovernmental Panel on Climate Change (IPCC) reports, which deepen our understanding of climate change. However, these models still do not include economic and climate-damage modules; they can only use the carbon emissions provided by separate economic models as external forces, and are thus unable to reflect the interactions between human activity and the physical earth system. So, to achieve more realistic simulations, it is essential and necessary to combine the economic and climate-damage components of IAMs with coupled earth system models, which should be possible in this era of increasing supercomputing power. A successful precedent is the integrated global system model framework (IGSM) of the Massachusetts Institute of Technology. The IGSM includes an emissions prediction and policy analysis model (EPPA) and uses an earth system model with intermediate complexity as its earth system component. It has been widely used in addressing scientific goals of earth system modeling and helping to inform the policy-making process (Prinn, 2012; Reilly et al., 2013). However, in China, very little progress has been made in this area of study.

In this paper, a new coupled human–earth system model (BNU-HESM1.0) is introduced. Designed to simulate the interaction between human activity and the earth system, the model was developed by integrating a simplified version of DICE and the coupled earth system model from Beijing Normal University (BNU-ESM). The construction of BNU-HESM1.0 is described in section 2. In section 3, the model's capability in simulating the global $CO_2$ concentration and surface temperature is evaluated. A summary and further discussion are provided in section 4.

## 2. Methods

### 2.1. *DICE*

DICE, which was first developed by Nordhause (1992), an economist from Yale University, formed the basis of IAMs in climate change. DICE was based on the Ramey model of optimal economic growth and was designed to maximize the discounted "utility" under a number of economic and climate constraints. The model consists of three parts: (1) an economic–emissions relationship; (2) an objective function; and (3) an emissions–climate relationship. In the following, we provide the main equations for the first and second parts, but for a more detailed description of DICE readers are referred to Nordhaus (1992).

In the first part, the output is given by the Cobb–Douglas function, Eq. (1), where $Q(t)$ represents the net outputs and $\gamma$ is the elasticity of output with respect to the capital. The terms $K(t)$ and $L(t)$ represent the capital and technology, respectively. The term $\Omega(t)$ represents the net output ratio, which is the fraction of the rest of the output that the impact of climate damage and policy interference on the total output is removed—see Eq. (2). In Eq. (2), the term $\mu(t)$ represents the fraction of the reduction of the emission relative to uncontrolled emission, and $T(t)$ is the global averaged temperature. The empirical coefficients $b_1, \theta_1$ and $\theta_2$ in Eq. (2) are 0.0686, 2.887, 0.00144 and 2.0, respectively.

$$Q(t) = \Omega(t) \times A(t) \times K(t)^{\gamma} \times L(t)^{(1-\gamma)} , \quad (1)$$

$$\Omega(t) = \frac{1.0 - b_1 \times \mu(t)^{b_2}}{1.0 + \theta_1 \times T(t)^{\theta_2}} . \quad (2)$$

DICE also includes two equations that describe the distribution of net output and the process of capital accumulation. The net output is divided into investment $(I)$ and consumption $(C)$, Eq. (3), and the term $\delta t$ in Eq. (4) is the depreciation rate.

$$Q(t) = I(t) + C(t) , \quad (3)$$

$$K(t+1) = (1.0 - \delta t)K(t) + I(t) . \quad (4)$$

Equation (5) describes the relationship between the net outputs and emissions, where $\sigma(t)$ is the exogenous technology parameter, which describes the trend of the output and emissions ratio.

$$E(t) = [(1.0 - \mu(t))] \times \sigma(t) \times Q(t) . \quad (5)$$

DICE maximizes a social welfare function that is the discounted sum of the utility of per capital consumption. The mathematical expression is given as follows,

$$\max_{c(t)} \sum U[c(t), L(t)](1.0 + \rho)^{-t} ,$$

where $c(t)$ represents the per capital consumption and $\rho$ is the pure rate of social time preference. The utility function is given in Eq. (6), in which $\alpha$ represents the rate of inequality aversion.

$$U[c(t), L(t)] = L(t)\{[c(t)^{1-\alpha}]\}/(1-\alpha) . \quad (6)$$

In this paper, we assume the $\mu(t) = 0$ and use Eqs. (1–5) to calculate the global emissions amount by prescribing the exogenous variables $A(t)$, $K(t)$, $L(t)$ and $\sigma(t)$. This simplified approach is designed to match the integration algorithm of BNU-ESM, and is inconsistent with the original algorithms that calculate the optimal emissions path by maximizing the discounted utility.

### 2.2. *BNU-ESM*

The earth system model of Beijing Normal University (BNU-ESM) is an atmosphere–land–sea-ice fully coupled model, and was one of the models that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5). Recently, various aspects of the simulation ability of BNU-ESM have been evaluated, and it is has also been widely used in climate attribution and projection studies (Wuebbles et al., 2013; Bellenger et al., 2014; Mehran et al., 2014). Briefly, the atmosphere component is CAM3.5 (Community Atmosphere Model Version 3.5) from the NCAR (National Center for Atmospheric Research), the land component is CoLM (Common Land Model), which includes the LPJ (Lund–Postdam–Jena) DGVM (dynamic global vegetation model), and its ocean component is the idealized biogeochemical cycling (iBGC) module. Wu et al. (2013) provides a detailed description of BNU-ESM. Comparison between BNU-ESM results, observation, and other Chinese coupled climate model outputs indicates reasonable performance (Zhou et al., 2014).

### 2.3. *BNU-HESM1.0 model construction*

BNU-HESM1.0 was built by coupling the economic parts of DICE with BNU-ESM. The coupled model includes the following two steps: First, the economic model calculates global emissions using exogenous variables (e.g., capital, population, technology etc.), and then BNU-ESM uses these emissions as external forcing to calculate the possible climate changes. The second step connects the climate change results and the economic components through the damage function, describing the climate impact on the economic process (e.g., the GDP or outputs). These two processes are similar to the integrated approach of general climate–economic models.

In the first step, BNU-ESM usually uses the monthly gridded $CO_2$ fossil fuel flux (units: kg m$^{-2}$ s$^{-1}$) as the external forcing, but DICE only outputs the annual global emission (units: Gt C). So, we have to convert the annual global $CO_2$ emissions amount to $CO_2$ flux, which has a certain spatial and temporal resolution, and we realize this goal by defining the $M$ index as follows:

$$M = \frac{E_{\rm m}}{E_{\rm ann}} = \frac{E'_{\rm m}}{E'_{\rm ann}} \, , \tag{7}$$

where $E_{\rm m}$ and $E_{\rm ann}$ represent the observed monthly gridded $CO_2$ flux and annual emissions amount, respectively. The terms $E'_{\rm m}$ and $E'_{\rm ann}$ represent the monthly gridded $CO_2$ flux and annual emissions amount calculated by DICE, and we can thus obtain $E'_{\rm m}$ as follows:

$$E'_{\rm m} = E'_{\rm ann}\frac{E_{\rm m}}{E_{\rm ann}} = E'_{\rm ann}M \, . \tag{8}$$

In the second step, the global annual averaged temperature $T(t)$ is calculated using parallel computing methods, and is called by the damage function, Eq. (2), in the economic components. Besides, it should be noted that we modified the original time step of DICE (10 yr) to 1 yr, to coordinate it with BNU-ESM. As the exogenous variable of DICE is expressed in exponential form, this modification is reasonable and has no effect on the outputs (Figs. 1 and 2). The economic components calculate the emissions each year, and the climate damage also feeds back to the economic components each year. Therefore, BNU-HESM1.0 can describe the complete cycle of the socioeconomic–earth system.

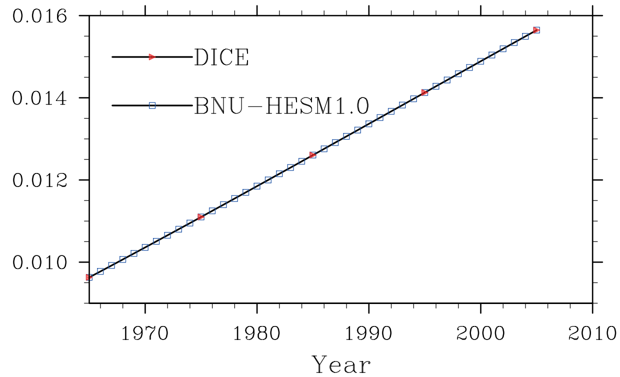


**Fig. 1.** The annual (BNU-HESM1.0) and decadal (DICE) level of technology.

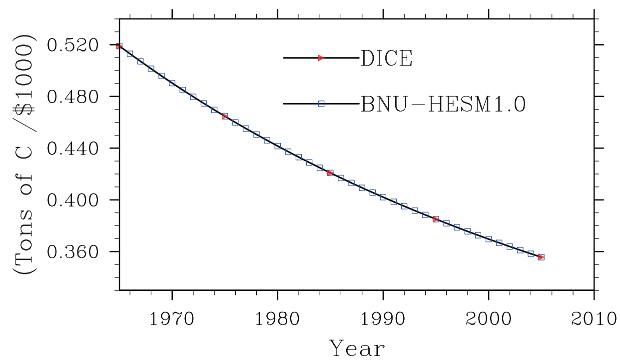


**Fig. 2.** The annual (BNU-HESM1.0) and decadal (DICE) $CO_2$ equivalent emissions to net output ratio.

## 3. Experimental design

We conducted two simulations to evaluate the simulation ability of BNU-HESM1.0. One was the historical simulation carried out by the original model (BNU-ESM), referred to as ESM-Hist, which followed the CMIP5 historical simulation requirements (Taylor et al., 2012) and whose simulation period ran from 1850 to 2005. The other simulation, referred to as HESM-Hist, was carried out by BNU-HESM1.0. In terms of the input data of the economic components, which began in 1965, HESM-Hist was simulated from 1965 to 2005 and used the simulation results of ESM-Hist in 1965 as the initial condition. In the HESM-Hist simulation, BNU-HESM1.0 calculated the $CO_2$ flux with its economic component, so there was no need to provide the observed $CO_2$ flux as external forcing. Apart from the $CO_2$ flux, the other forcing conditions were the same as those used in ESM-Hist during the period 1965–2005. Further details regarding the natural and anthropogenic forcing conditions are provided in Table 1.

## 4. Results

### 4.1. *$CO_2$ emissions and concentration*

Figure 3 shows the observed and simulated global $CO_2$ concentrations from BNU-ESM and BNU-HESM1.0. It is

**Table 1.** Forcing data for the experiments.

| | Experiment | |
|---|---|---|
| | ESM-Hist | HESM-Hist |
| Model | BNU-ESM | BNU-HESM1.0 |
| $CO_2$ forcing | Observed $CO_2$ flux | Provided by the economic component |
| Other forcings | Solar radiation, volcanos, ozone, other greenhouse gases ($CH_4$, $N_2O$, CFCs), aerosol concentration and aerosol flux (black carbon, organic carbon, dust, sulfate) | |

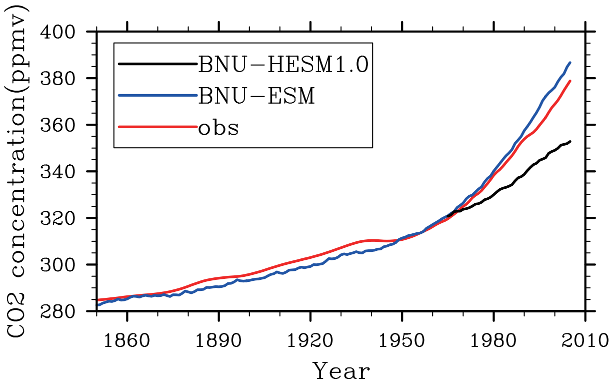


**Fig. 3.** The observed (red) and simulated $CO_2$ concentration by BNU-ESM (blue) and BNU-HESM1.0 (black).

clear that BNU-ESM overestimates the $CO_2$ concentration and its rising trend after the 1970s, while BNU-HESM1.0 produces a much lower $CO_2$ concentration during 1965–2005, resulting from its underestimations of global annual emissions (Fig. 4). Figure 4 also indicates that BNU-HESM1.0 can reproduce the increasing trend of global emissions, but it does not have the ability to capture the interannual variability of global emissions. We consider this inability mainly result from the uncertainty of the economic exogenous variables, such as the population, capital, and so on. For 2005, the $CO_2$ concentration simulated by BNU-HESM1.0 model is about 25 ppm less than that observed, which is much greater than the BNU-ESM uncertainty.

### 4.2. *Global temperature*

Figure 5 shows the observed and simulated global temperature anomalies relative to 1965–99. It indicates that BNU-ESM underestimates the global temperature during 1850–1970, but overestimates it after the 1970s. In 2005, the temperature simulated by BNU-ESM is 0.4°C above the observation. This deviation is within the range of CMIP5 model uncertainty (−0.1°C to 0.7°C). Relatively, the temperature simulated by BNU-HESM1.0 during 1965–2005 is much closer to that observed. The linear trend of the temperature over 1965–2005 is 0.16°C $(10\ \mathrm{yr})^{-1}$, 0.3°C $(10\ \mathrm{yr})^{-1}$ and 0.14°C $(10\ \mathrm{yr})^{-1}$ for the observation, BNU-ESM and BNU-HESM1.0, respectively. However, this result does not mean that BNU-HESM1.0 is better than BNU-ESM at simulating

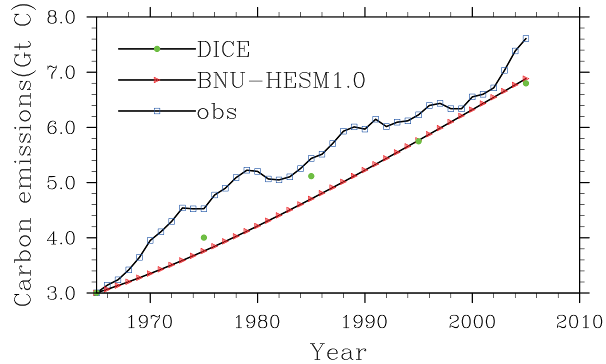


**Fig. 4.** The observed (blue) and simulated global carbon emissions by DICE and BNU-HESM1.0 (red).

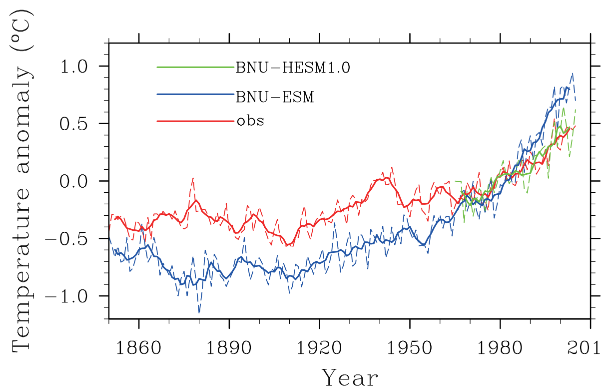


**Fig. 5.** The global averaged annual surface temperature anomalies (relative to 1965–94) from observation (red) and the simulations of BNU-ESM (blue) and BNU-HESM1.0 (green). The thick lines denote variability with period exceeding 5 yr.

the temperature, because BNU-HESM1.0 underestimates the global emissions amount. Both BNU-ESM and BNU-HESM1.0 can reproduce the global temperature gradient with latitude, with little difference between the two models (Fig. 6). This means that BNU-HESM1.0 can maintain BNU-EMS' ability in simulating the spatial distribution of climate variables.

### 4.3. *Conclusion and discussion*

This paper describes the first attempt to construct a human–earth system model (BNU-HESM1.0) by coupling an economic model to an earth system model, and provides a new approach to investigating the complex interactions between human activity and the earth system. BNU-HESM1.0 is more advanced compared to DICE or BNU-ESM. Specifically, compared to DICE, BNU-HESM1.0 includes a fully coupled earth system model, which is superior in simulating various aspects of climate change. Meanwhile, compared to BNU-ESM, it not only retains the simulation ability of BNU-ESM, but is also able to quantify emissions levels and climate damage by itself, which represents an advancement over BNU-ESM. Thus, we could use BNU-HESM1.0

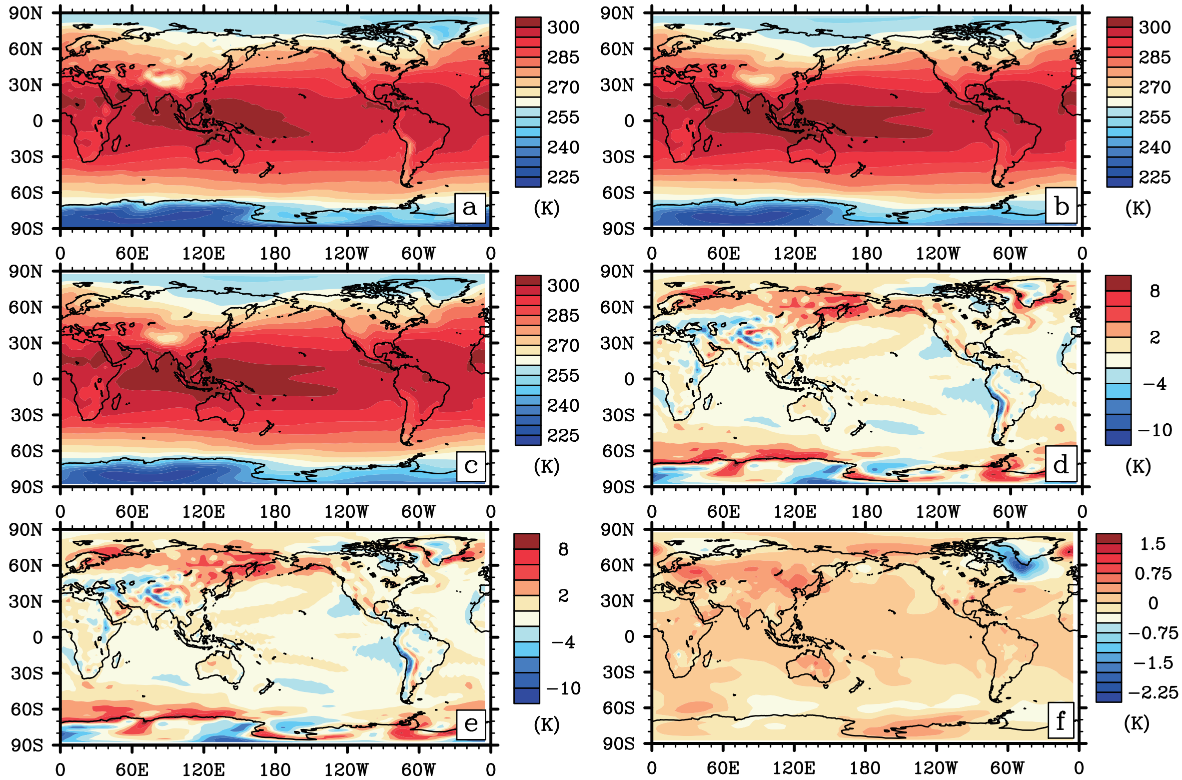


**Fig. 6.** The observed and simulated spatial pattern of temperature averaged over 1965–2005: (a) observation; (b) BNU-ESM; (c) BNU-HESM1.0; (d) observation minus BNU-ESM; (e) observation minus BNU-HESM1.0; (f) BNU-ESM minus BNU-HESM1.0.

to project future emissions levels and climate change under given macroeconomic conditions (e.g., population, capital etc.). However, there are still many unresolved problems and uncertainties with BNU-HESM1.0. For example, the results of the present reported experiments showed it underestimates global $CO_2$ emissions and cannot reproduce its interannual variability, due to the uncertainty of the empirical parameters and exogenous variables. As we know, economics comprises complex issues affected by numerous social activities (e.g., policy, employment etc.). These complex processes are highly parameterized or even ignored in DICE, resulting in its limitations in capturing a complete socioeconomic picture. Besides, economic processes also possess large regional disparities, and these features are not well expressed in DICE. Therefore, in future work, we should try to use, instead of DICE, much more complex economic models, such as RICE (Nordhaus, 2010) or EPPA (Paltsev et al., 2005), which feature more detailed economic processes and can reflect the regional disparity of the economy. Alternatively, we could seek to add new parameters to make the economic model much more reflective of reality. In terms of the climate damage component, this is excessively simple, possessing many deficiencies. For example, as well as economic output, climate change also has significant impacts on agriculture, ecology, health, and so on, which is not well expressed in this study. So, other methods to develop BNU-HESM1.0 must include attempts to improve the climate-damage function. A final but very important point is that the ability of BNU-HESM1.0 in simulating various aspects of the natural system is largely dependent on that of BNU-ESM. So, we also need to improve BNU-ESM using traditional development methods, such as enhancing the resolution, adding physical processes with smaller scales, and so on.

Despite the limitations acknowledged in the above discussion, this paper represents a pioneering attempt to build a human–earth system model, and several ways to improve or complete BNU-HESM1.0 have been identified. We hope that the development of BNU-HESM1.0 in the future produces a comprehensive tool that not only provide guidance for appropriate human activity (Fu and Ye, 1995; Ye et al., 2001, 2003, 2009) and global and regional sustainable development, but also strengthens the communications and exchanges of the IPCC's three working groups.

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