

GLIMMER Antarctic Ice Sheet Model, an experimental research of moving boundary condition

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Abstract A 3-D coupled ice sheet model, GLIMMER model is introduced, and an idealized ice sheet experiment under the EISMINT-1 criterion of moving boundary condition is presented. The results of the experiment reveal that for a steady-state ice sheet profile the characteristic curves describe the process of evolution which are accordant with theoretical estimates. By solving the coupled thermodynamics equations of ice sheet, one may find the characteristic curves which derived from the conservation of the mass, energy and momentum to the ice flow profile. At the same time, an agreement, approximate to the GLIMMER case and the confirmed theoretical results, is found. Present study is exploring work to introduce and discuss the handicaps of EISMINT criterion and GLIMMER, and prospect a few directions of the GLIMMER model.

Key words Antarctic ice sheet, GLIMMER model, EISMINT, Numerical simulation.

1 Introduction

Antarctic ice sheet, as a significant part of the earth system, commands profound and important influence on atmosphere, ocean circulation, sea level change, and earth topography. Therefore, the evolution of Antarctic ice sheet has been one of the important aspects of South Pole research. And under the background of global warming, it has been even a focus to conduct research on how to predict the evolution tendency of ice sheet. Numerical model brings in an approach to indicate physical processes of ice sheet and has become a key method^[1-2] to probe the evolution history as well as the future changes of ice sheet.

Since the large-scale mathematic model of simulating Antarctic ice sheet was established in 1977 by Budd and others^[3], the three-dimensional dynamics model of ice sheet with coupled temperature field has been the significant researching domain in ice sheet numerical simulation. Since then, researchers have figured out several numerical models to probe how to establish a more reasonable three-dimensional coupling model of ice sheet^[4-13]. And the specific researching process was summarized as following: increasing level space dimension, hypothesizing that ice sheet maintains the ideal isothermal property,

then transiting to taking coupled temperature field into consideration.

The principle of ice sheet numerical simulation mainly originated from the shallow-ice approximation^[14] theory developed by Nye, which primarily considered the fact that the ice thickness of ice sheet is of extremely small-scale comparing with the horizontal scale of Antarctic ice sheet. Jessen put forward the first dynamics model of coupled temperature field successfully in 1977 on basis of the theory, and a vertical coordinate with scale is utilized in the model to solve the derived nonlinear system^[12]. Mahaffy gave consideration to the ice body deformation caused by dislocated displacement, thus obtained a physical quantity^[13] for grid points of square domain of any ice sheet; Budd, Jessen, Radok, Oerlemans, Smith and others have worked for the large-scale simulation of Antarctic ice sheet in early stages, when ice flow lines could be identified through their models to conclude the two dimensional space distribution of temperature and speed along the cross-section of ice flow. Budd also took account of some additional characteristics of ice flow in calculating the shear rate and gravitational stress of vertical and tangential direction of ice. In 1982 Oerlemans^[7], Budd and Smith^[9] has respectively and independently brought forward the dynamics model of ice sheet which was dependent on temporal evolution, this model coupled isostasy and ice shelf structure and was achieved through integrating the vertical direction, the model can also simulate the current distribution of ice thickness, and the prominent sensitivity of west Antarctic ice sheet when combining with sea level and atmospheric temperature. Hertenrich^[15], Huybrechts and Oerlemans^[5] firstly undertook the work of coupling temperature field in ice flow; they took the fast ice flow, grounding-line of ice sheet and ice shelf into consideration at the same time to simulate the Antarctic ice sheet without too much restrictive hypothesis. After Huybrechts' model^[16-17], the establishment of three-dimensional criterion finite difference coupling model of GLIMMER model became an important field in numerical simulation of Antarctic ice sheet.

Numerical simulation of ice sheet in China is still in its initial stage; however, through nearly 20 years of field investigation in Antarctica, a large number of datasets has been collected by Chinese researchers that will provide powerful support for the development of numerical simulation. Given the facts, first of all, it is necessary to conduct a systematic simulated performance examination to an Antarctic ice sheet model as a preparation for the following adaptation to the numerical simulation work of the parts, areas and the entire ice sheet of the Antarctica. Therefore, in this paper, the internationally developing three-dimensional criterion finite difference coupling model of ice sheet, -namely GLIMMER model, is chosen and carried out.

2 GLIMMER ICE SHEET Model

GLIMMER model is a three-dimensional finite difference model of ice sheet which stemmed from the simulation work^[18] of the Antarctic land ice in Tony Payne's research on GENIE Earth system model, the GENIE here is a simulation plan for the expectation of developing a unified Earth System Model (ESM). The object of GLIMMER model is to set a criterion model for the calling of other Earth system simulation plans. GLIMMER model can be achieved through a Fortran95 program library and invoked by other models with boundary condition, and it also encompasses complicated driving term from simple type of

EISMINT to the coupled GENIE ESM. The input and output is authored in netCDF format. The model has passed strict test^[19-22] pursuant to criterions of EISMINT-1 and EISMINT-2 by M. Hagdorn, I. C. Rutt and A. T. Payne up to 2006.

The constituent parts of the GLIMMER model are as follows:

1) GLIDE: land ice dynamic model, this is the actual ice sheet model for calculation of ice velocities, ice temperature distribution and isostasy adjustment as well as melt water.

2) SIMPLE: climate driving term of EISMINT, this is an ice sheet comparison plan sponsored by European Science Foundation with two level-criterions of EISMINT-1 and EISMINT-2 that includes constraints of temperature, mass balance and time period and so on, the difference of between the two criterions consists in is whether the temperature field is coupled.

3) GLINT: the interface to the Earth coupled system model of GENIE.

4) EIS: the climate driving term of Edinburgh ice sheet; it is based on the parameterization treatment process of the equilibrium line altitude, surface temperature of sea level and sea level changes.

The latter three parts described above are climate driving term; in addition, there is also a multi-functional module GLUM that can be invoked by other parts and some general visualized programs included in GLIMMER.

2.1 Physical principle and continuity equation of GLIMMER model

The fundamental physical principle of GLIMMER model is the shallow - ice approximation^[23] that considered the fact of the extremely small-scale ice thickness of ice sheet compared with the horizontal scale of the Antarctic ice sheet, as well as the rather small surface slope in global effect, as a result, the normal stress ignored, and the horizontal shearing stress (τ_{xz} , τ_{yz}) considered mainly which equals to approximately: $\tau_{xz} = -\rho g(s - z) \frac{\partial s}{\partial x}$; $\tau_{yz} = -\rho g(s - z) \frac{\partial s}{\partial y}$. The deformation and shearing stress are formulated through the

nonlinear flow law of ice: $\dot{\epsilon}_{iz} = \frac{1}{2} \left(\frac{\partial u_i}{\partial z} + \frac{\partial u_z}{\partial i} \right) = A(T) |\tau|^{n-1} \tau_{iz}$, ($i = x, y$), $\dot{\epsilon}_{iz}$, here refers to the deformation rate, τ is the invariant of second order of the shear stress tensor, n represents constant of ice flow law with normal value of 3. The prognostic equation of ice sheet model can be derived, and this type of equation mostly refers to the ice thickness evolution equation of ice flow and ice temperature evolution equation; also, the supporting diagnostic equation can be deduce for the calculation of vertical velocities, accumulation rate and ablation factor and other properties. The ice thickness evolution equation can be formulated as follows in the rectangular coordinate system:

$$\frac{\partial H}{\partial t} = M - \nabla \cdot (\bar{U}H) \quad (1)$$

Here \bar{U} represents the horizontal average velocity field, $H = H(x, y, t)$ means surface elevation, M is the mass balance term of surface, and ∇ refers to divergence operator of horizontal plane. Then ice temperature evolution equation may be:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \frac{\partial^2 T}{\partial z^2} - U \cdot \nabla T - w \frac{\partial T}{\partial z} - \frac{g(s - z)}{C_p} \nabla s \cdot \frac{\partial U}{\partial z} \quad (2)$$

In this equation, T refers to absolute temperature, U represents horizontal velocity field, w represents vertical velocity field, ρ refers to ice density, C_p refers to the heat capacity of ice.

The major factors forming the ice flow includes basal sliding and inner deformation which is hypothesized as generating from horizontal shearing stress. The expression of horizontal velocity field can be worked out as follows on basis of Glen's Law and the hypothesis:

$$U(z) - U(h) = -2(\rho g)^n |\nabla s|^{n-1} \nabla s \int_h^z A(T) (s - z)^n dz \quad (3)$$

In the above expression, $A(T) = fA_0 \exp(\frac{-Q}{RT})$ refers to Arrhenius Relationship, $h = h(x, y, t)$ is the vertical coordinate of bottom of ice sheet. And the ice sheet is considered incompressible, which means the condition of $\nabla \cdot (U, w) = 0$ is met and thus the distribution of vertical velocity is obtained:

$$w(z) - w(h) = - \int_h^z \nabla \cdot U(z) dz \quad (4)$$

2.2 The numerical scheme of the GLIMMER model

The GLIMMER model uses (x, y, σ) coordinate system, $\sigma = 1$ as at the bottom of ice sheet, $\sigma = 0$ as at the surface of ice sheet, the above equations should be solved through finite difference method. This model is conducted using two sets of staggered grids in horizontal direction, the ice temperature, ice thickness and vertical velocity are calculated on integer grids, and the horizontal ice velocity and the gradient of various physical quantities are calculated on the half integer grids; σ coordinate system is adopted for vertical direction; the number of grid in horizontal and vertical direction can be freely determined according to the practical needs. (Refer to [22] for the details)

3 The experimental model set up

As some tricky physical processes are often ignored, instability is occurred for most ice sheet models, thus the thermodynamics instability identified by the model may not be practical. Especially for some instability, the mechanism normally can only show in the millennial scale, the ice sheet evolution is just the result of the past climatic changes and has little connection with the climate warming caused by human activities. The hypothesis of unstable grounding line is an artificially introduced concept, and obviously can not be the latent reason that caused the calving of Antarctic ice sheet. Looking on the hundreds-years timescale, the ocean warming is another crucial factor to the land ice sheet for its directly weakening the ice shelf to speed ice melting in the bottom. Based on the present result of the model, researchers predicted that there would be no major ice loss occurred in Antarctica in the following several hundred years, but little is known about its physical process.

EISMINT-1 climate drive, a test comparison criterion level sets of ice sheet model established by EISMINT (European Ice Sheet Modeling INitiative), was adopted for the experiment and installation in this paper. The ice sheet models passed the criterion test must fully describe the boundary condition and parameters of fixed model to examine whether the model can compare and confirm the accuracy and efficiency between different programs

while solving the continuity equation of ice sheet, in addition, this level collection conduces to discovering the deficiency of the programs in the model, and can conduct comparison^[19] with the accurate solution of the simplified equations. The level collection also includes two testing collections of fix boundary condition and moving boundary condition. Huybrechts *et al.*^[19] provided a new criterion for the evolution of ice sheet model on this basis. Later, Payne *et al.*^[21] compared various experimental results under the radial symmetric zone boundary condition after coupling temperature, and discovered a kind of radial symmetric deletion in relative low temperature. Similar situation was also brought about in the research by Payne and Dongelmans^[24]. Payne and Baldwin^[25] discussed the present-called "self-organization" phenomenon. After that, Fuyuki Saito *et al.*^[26] further disserted that EISMINT has made some possible explanations for the strange phenomena emerged in the model from the angle of numerical algorithm and ice sheet dynamics under the condition of using shallow - ice approximation theory^[27], and adopting the numerical discretization scheme^[19], basal temperature condition of ice sheet and surface accumulation that different from the previous ones, as well as ice sheet evolution without coupling temperature field.

Meanwhile, the test of the models is very important, the ice sheet models have been confirmed through a series of experiments, and the plane model^[19-21] applied to Antarctica and Greenland has been derived in the frame of EISMINT, so the researchers who conduct the simulation can modified the models or find the errors in their models. Of course, a model must pass the field data test which, however, restricted by the lack of data on specific spatial -temporal scale. The most crucial one is: there is no rational test for the models in addition to several rough confirmations from drilling and geophysical conclusions on data of radar and earthquake, in aspects such as bottom geothermal stream, bottom hydrology, deformation of subglacial sediments. And the existing models also lack the ability to express the spillover glacier and fast flow of ice stream in details, this is mainly because of the resolving capability and little understanding of the physical process at the bottom of ice sheet. Research on simulation of ice models confronts particular difficulties, including how to reasonably deal with the sliding and stress effect at the bottom of ice sheet and what approach should be chosen for evaluation of integrals. These problems mostly relate to the west Antarctic ice sheet, the ice sheet model established on basis of shallow-ice approximation theory for the east Antarctic ice sheet has reached reliable results. These problems must be integrally considered for the further progress of the models.

EISMINT-1 moving boundary condition was used for this paper; the sensitivity test was conducted under the moving boundary condition of the GLIMMER model with basic hypothesis that the ice sheet has isothermal properties, the constants was extracted for Arrhenius relationship^[28] in flow law. The test, which in fact has been still in the stage of detection and sensitivity, mainly focused on the developing reality of the GLIMMER model. According to the results (EISMINT-2) from Magnus Hagdorn's Group which engaged in the programming work for the model, the coupling temperature field should be a very attractive direction of exploration, but at present there are some difficulties during the investigation of this area emerged, as it is very hard to managing the sliding status at the bottom and the over-low bottom temperature of the ice sheet leading to the dissipation^[22] of solution stability while solving the equations, thus it is necessary to reinvestigate the influence of basal boundary condition on the evolution of ice sheet under the condition of non-coupling temper-

ature field.

EISMINT-1 moving boundary condition:

Surface temperature forcing: $T_{\text{sur}} = t_1 - t_2 H$, where H is ice thickness. $t_1 = -3.15^\circ\text{C}$ or 270 K is the initial temperature as the ice thickness equals to 0; $t_2 = 10^{-2}\text{ Km}^{-1}$, represents gradient^[11,19] of surface temperature along with elevation.

1) Annual accumulation rate of surface mass balance: $M = \min\{m_1, m_2(m_3 - d)\}$, $d = \max\{|x - x_{\text{summit}}|, |y - y_{\text{summit}}|\}$, is the maximum horizontal distance from surface to the center of ice sheet; $m_1 = 0.5\text{ ma}^{-1}$, expresses the surface accumulation rate of ice sheet center; $m_2 = 10^{-2}\text{ ma}^{-1}\text{ km}^{-1}$, refers to the change rate of mass balance function; $m_3 = 450\text{ km}$, represents the horizontal distance of the ice sheet center as the root of the mass balance.

2) Time-dependent periodic forcing:

$$\Delta T = 10 \sin \frac{2\pi t}{T}, M = \min\{m_1, m_2(m_3 + 100 \sin \frac{2\pi t}{T} - d)\}, \text{ where } T = 40000 \text{ years is}$$

served as a Milankovitch period which mainly selected through the exploration of evolution status of ideal ice sheet in the Pleistocene of the Quaternary period.

3) Initial conditions, division of grids and integral time: Refer to^[11, 19, 24] for simplification, zero thickness is selected as the initial thickness of ice sheet, domain of integration is set as a square ice bed with zero height and size of $1500\text{ km} \times 1500\text{ km}$, and central point $(x_{\text{summit}}, y_{\text{summit}}) = (750\text{ km}, 750\text{ km})$; 31×31 is selected as number of grid points on horizontal plane grids, 50 km as step length, and 11 layers for vertical; the integral time is 200000 years, and 10 years is selected as the time step.

4) Boundary condition: The ice temperature of upper boundary is set as surface temperature; the lower boundary ice is heated through friction between geothermal flux and sliding, which meets: $\frac{\partial T}{\partial \sigma} \Big|_{\sigma=1} = -\frac{Gh}{k} - \frac{H\tau_b u(1)}{k}$, $\tau_b = -\rho gh \nabla s$ means the basal shear stress, $u(1)$ is the basal ice velocity, if the melting point of ice T_0 (that is $T \geq T_0$) is reached in the bottom, the constant $T^* = T_0$ is extracted as ice temperature; the heat of the surpassing part transforms into melting rate of $S = \frac{k}{\rho L}(\frac{\partial T^*}{\partial z} - \frac{\partial T}{\partial z})$, L here refers to specific latent heat of fusion. The boundary condition of vertical velocity field is moving boundary condition at the bottom of ice sheet, which meets $\omega(h) = \frac{\partial h}{\partial t} + U(h) \cdot \nabla h + S$; the upper boundary condition meets the expression $\omega(s) = \frac{\partial s}{\partial t} + U(s) \cdot \nabla s + M$.

4 Results and analysis

The moving boundary simulation experiment on the square ice sheet area was conducted utilizing EISMINT-1 ice sheet comparison test criterion, after analytical study, the researchers found that: when the ice sheet area (square) evolved into stable state, the distribution of ice thickness is still maintain axis symmetrical and central-symmetrical, and gradually increasing from the boundary to the center, the horizontal gradient of ice thickness is

correspondingly decreased, which conforms^[19] to the requirement on the moving boundary

Table 1. The physical parameters in the experiments

Physical Value	Physical quantity
$\rho = 910 \text{ kg/m}^3$	Ice density
$g = 9.81 \text{ m/s}^2$	Gravity acceleration
$R = 8.321 \text{ J/molK}$	Gas constant
$A_0 = 2.948 \times 10^{-9} / \text{Pa}^3 \text{ s}$	Glen law constant
$T_r = 273.39 \text{ K}$	Tristate critical value of water
$C_p = 2009 \text{ J/kgK}$	Water heat capacity
$Q = 7.88 \times 10^4 \text{ J/mol}$	Creep activation
$\beta = 8.7 \times 10^{-4} \text{ K/m}$	variable rate of melting point with depth
$G = 0.042 \text{ J/m}^2 \text{ s}$	Geothermal flux
$\kappa = 1.17$	Constant in Arrhenius relation
$k = 2.10 \text{ J/mKs}$	Thermal conductivity of ice
$c = 0.16612 \text{ K}^\kappa$	Arrhenius constant

The data are from Refs. [19] and [28].

condition of the first level collection in the EISMINT test collection criterion (Figure 1(a)), and thus indicates that the GLIMMER model can clearly mark the gradient term of ice thickness evolution equation of continuity equation for ice sheet on symmetrical area of ice sheet. In order to reveal the spatially two-dimensional distribution of ice thickness, certain characteristic sections must be intercepted from ice sheet for investigation, the distribution of the ice thickness in stable state can actually be reflected by the horizontal section in ice sheet center for its symmetry characteristic; and in view of the directional distribution of ice sheet physical variables (horizontal velocities, vertical velocities, ice temperature, etc.) can meet the requirement of radial and axial symmetry at any moment, the directional distribution of ice thickness could also be shown as a whole if this kind of horizontal section is selected, therefore, it was chosen to connect three reference points on the section from grid(1,16) to grid(16,16): grid(4,16), grid(8,16), grid(16,16) (Figure 1(b)), the result of simulation indicated the maximum value of ice thickness stayed around 3093 m in stable status, and there is no distribution area (Figure 1(a) and (b)) of ice sheet within a 150Km radius from the boundary of the original domain of integration (square region) (Figure 1(a) and (b)), therefore the temporal spatial distribution characteristics of ice thickness distribution in different climate boundary conditions (here mainly refers to the changes of annual net accumulation rate of surface in one Milankovitch period) can be shown and the boundary position of the ice sheet evolution in different time can be found (Figure 2(d)).

As ignoring the basal sliding of ice sheet and considering the influence of geothermal flow, the changes of characteristic physical quantities of ice sheet on flow section of ice accord with the basic character of ice sheet evolution, which means in a comparable scope, the temperature is gradually decreasing from margin to the core of ice sheet at the same height, the difference is quite small between different location, and only when the depth reaches a certain critical value, the ice temperature will be drop first and then rise with the increasing depth (Figure 3(a)). The changes in velocity of ice flow in vertical direction increase along with growing height, but from margin to the central section, the average veloci-

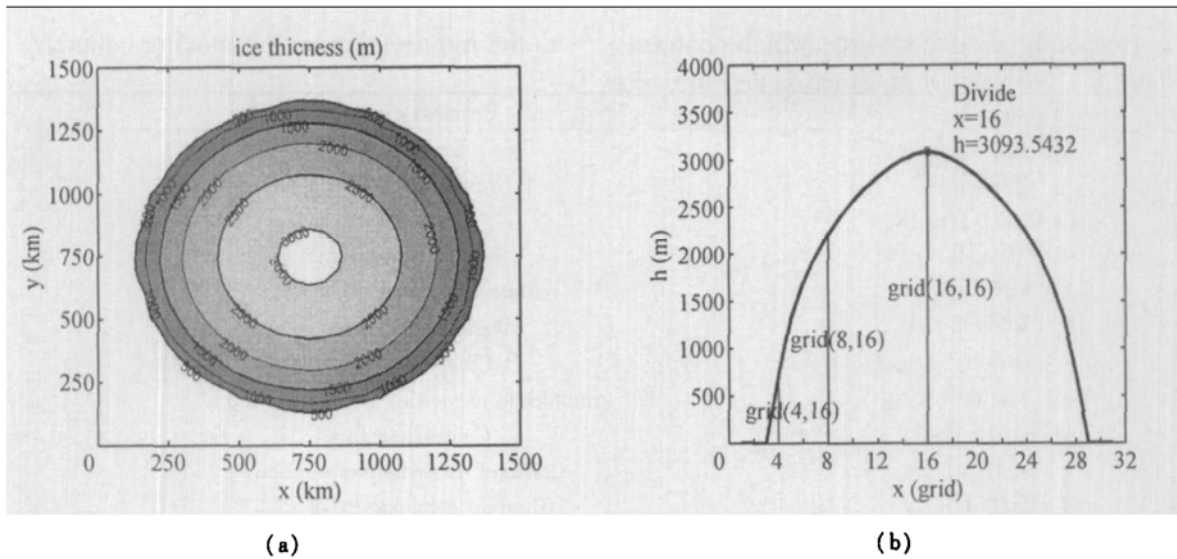


Fig. 1 Ice thickness distribution for the EISMINT-1 moving boundary condition test (50 km per grid) (a) Distribution of ice thickness in steady state ice sheet; (b) distribution of ice thickness of ice flow profile parallel to x-axis through center of ice sheet.

ty of vertical ice flow decreases gradually at the same height, so does the velocity gradient (Figure 4(b)); The changes of physical characteristics in different areas of ice sheet in time dimension can be studied through the one-dimensional distribution character of the middle area and ice dome (grid(8,16) and grid(16,16)) in domain of integration. For example, when ice sheet meets the term 5 from the characteristic description of EISMINT-1 moving boundary condition test, its bottom temperature will be strictly limited within the scope of the pressure melting point, which results in the periodical changes of the distribution of temperature and thickness at different position of ice sheet, and the distribution of ice thickness and temperature meet the characteristics showed in Figure 1(b) at any time.

For the sake of bringing to light the influential process of climate change on ice sheet as well as the feedback of the variability of ice sheet to climate system, a key method is to understand the changes of ice sheet scale on large scale through long term series, this can be realized by the estimation of the volume changes of ice sheet on the premise of detailed knowledge of ice sheet thickness distribution and margin position, for the ice sheet volume is actually the integral to the ice thickness distribution functions defined in ice sheet area. In EISMINT-1 moving boundary condition, the initial experiment conducted to GLIMMER model can reach the overall and every-section ice thickness distribution (Figure 1(a), (b)) and at specific moments, at the same time, in the scope of long term series, it can describe the periodical variations of ice thickness and margin position (Figure 2(a), (d)). The experiment indicates that, the ice thickness at the position of grid(8,16) and grid(16,16) (Figure 2(a)) and the section (equaling to extract $y \equiv 16$, $1 \leq x \leq 8$ on the grid plane (x, y)) (Figure 2(d)) surpassing the center of ice sheet and parallel to axis x , as time variable data, all recorded the Milankovitch period as the feedback effects to climate changes, for instance, there are 5 periods during the evolution of margin for ice sheet within the time scale of 200000 years, and the margin of the section is variable contiguously from grid to grid (6,16) in a period (Figure 2(d)). Therefore, the size (volume) of ice sheet at different moments can be estimated through physical theory of glaciers. In fact, for the ice

sheets with circular bottom zone, the volume can be given as the function of bottom radius L and the maximum ice thickness $H \propto L^{1/2}$; $\log V = 1.23(\log S - 1)$, V refers to the volume of ice sheet in the expression, $S = \pi L^2$ represents the basal area of ice sheet, \log is the logarithm operator^[28] with natural logarithm as base. Obviously, V is also a function with 40000 years as a period, which means the changes of ice sheets will feedback to the climate changes the same way as others such as changes of ice thickness and temperature does. Given the facts that the experimental region is an ideal ice sheet area (a circular-bottom ice sheet of cyclical change with no topographical difference in stable state), so it has no practical significance to calculate the specific numerical value of V . Since the periodic characters (Figure 2(d)) of the margin position objectively reflects the relation between V and S , it is not necessary to elaborate the simple $\log V = 1.23(\log S - 1)$.

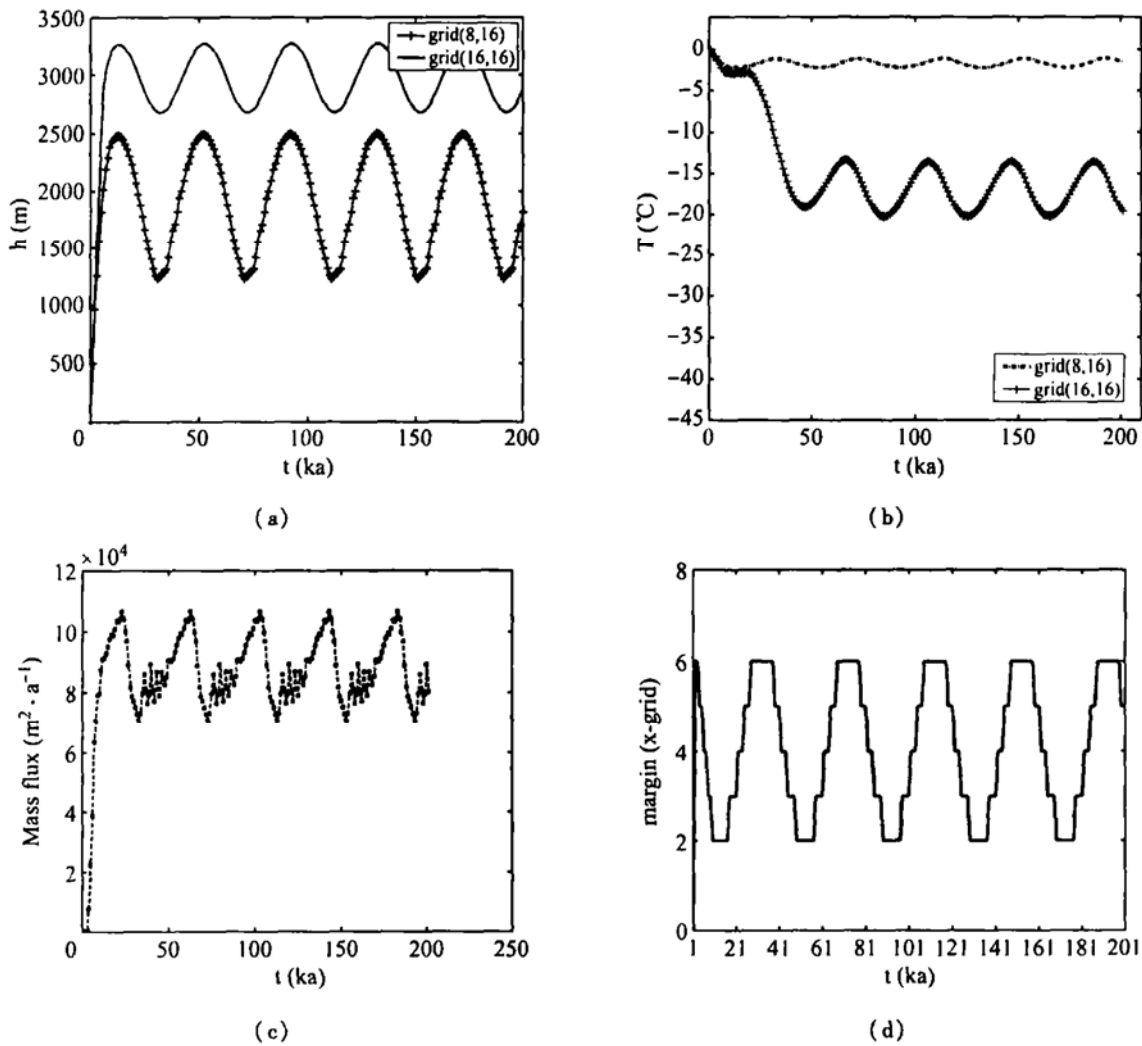


Fig. 2 Forcing and predicted evolution of key glaciological variables (ice thickness, basal temperature, mass flux and margin position) for EISMINT-1 moving boundary condition. (a) Distribution of ice thickness with time under steady state; (b) basal temperature with time; (c) mass flux of ice sheet with time (at $\text{grid}(8,16)$); (d) the change of margin position of ice sheet with time at the interval $y \equiv 16$, $1 \leq x \leq 8$.

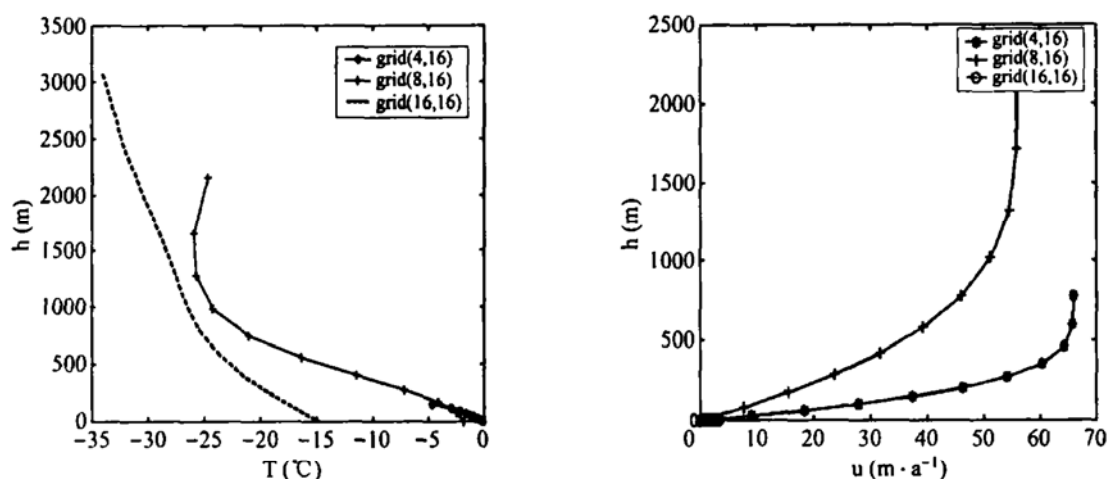


Fig. 3 The vertical distribution of the temperature and the horizontal velocities for EISMINT-1 moving boundary condition. (a) Vertical distribution of the temperature in the ice sheet; (b) the change of horizontal velocity with height.

The feedback mechanism of ice sheet changes to the ocean circulation relates to the investigation of the water fluxes flowing into the ocean from ice sheet. An effective approach is provided to solve the problem through the calculation of mass fluxes on ice-flow section. In the EISMINT-1 moving boundary condition, GLIMMER model can simulate mass flux on any grid, which mainly because it can work out the velocity field of any grid point by solving the coupling system constituted by evolution equations of ice thickness and temperature through step-by-step iterative method. Figure 2(c) depicts the mass flux on the grid(8, 16), it can be seen that, in any Milankovitch period, a maximum and a minimum value of mass flux can be occurred, and within the most time in a period, the change of mass flux approximates the linear variation, certain oscillating phenomena can only emerge in the beginning stage of the period, according to the facts, Philippe Huybrechtst suggested that it might be caused by the over-thick grid scale as the time-dependent margin position changed from one point to another, essentially, it was not against the characteristics^[19] reflected by the feedback mechanism of ice sheet to climate variation, actually, it implied in all probability that the evolution of ice sheet could not maintain its axisymmetry^[26-27] under the EISMINT-1 moving boundary condition.

The investigation of velocity field is also very crucial in respect of mass balance of ice sheet, in addition to calculating the changes of ice sheet size. In view of the axisymmetric and centrosymmetric integral region of the experiment, the simulation results of GLIMMER can also meet the distribution requirement of central and axial symmetry, the ice flow should flow towards margin along radial started from the core of ice sheet (grid (16, 16)) under EISMINT-1 criterion. The spatial distribution of velocity field can be inspected through researching the vertical distribution of the horizontal and vertical component generated from decomposition of velocity field, it can be seen from the experimental result (Figure 3(b)) that, at the same depth, the horizontal component of velocity field increased successively from the core of ice sheet to the margin with the value close to 0 reaching the maximum value, and the gradient along the vertical direction is also in accordance with this discipline; the horizontal distribution of vertical velocity gradually increased along the horizon-

tal direction to the core of ice sheet, and reached the maximum value right at the center, which is at the same time a singular point (means not the smoothing solution of ice sheet equations) (Figure (a)); the vertical distribution of vertical velocity component can be seen from Figure 4(b), the component is close to 0 at the center(grid(16,16)) of ice sheet, and taking the horizontal component(Figure 3(b)) of the velocity field into account, it can be obtained that the velocity at the core is close to 0. The changing characteristics of vertical distribution of vertical velocity is as same as that of horizontal velocity (Figure 3(b), Figure 4(b)); the above said variation characteristics of velocity field coincide with^[4,19] the basic theory of glacier and ice sheet, this indicates the GLIMMER model can greatly describe the changes of velocity fields.

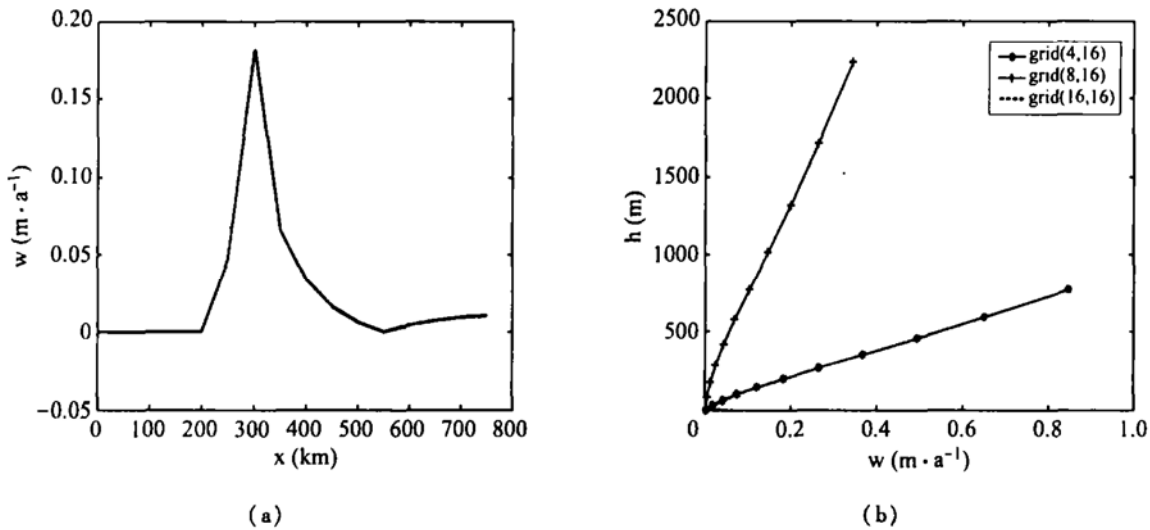


Fig. 4 The vertical and horizontal distribution of the vertical velocities for EISMINT-1 moving boundary condition. (a) The horizontal distribution of vertical velocity under steady state(at the sixth layers); (b) vertical distribution of vertical velocity under steady state.

5 Conclusion and Discussion

Under the moving boundary condition of EISMINT-1 criterion, and through 3-D coupled GLIMMER ice sheet model, a comparative experiment was conducted to analyze the producing background, progresses, theoretical basis and conclusions of the GLIMMER model of ice sheet, and probe into its present developing status and obstacles. The result of experiment shows that, under the EISMINT-1 moving boundary condition, GLIMMER model can simulate the response of ice sheets to the climate change, and obtain various evolution characteristic curves of time-depend momentum, mass and energy balance described in stable state, and distinguish the temperature field and velocity field as well as the scope of ice sheets in any moment. By the comparison with the results of other 3D ice sheet models, the GLIMMER model has been found having the ability to identify the response process of mass balance of ice sheet under the changeable background temperature. In addition, all kinds of dynamic processes described by this model have been initially proved to be up to present understanding of the Antarctic ice sheets.

The experiment specifically described an ideal ice sheet area, such an experimental

project was chosen for the consideration of the developing status of and the needs to elaborate the principle of the GLIMMER model as well as the requirements of EISMINT comparison plan, apparently, the emphasis of the experiment is to explain whether the specific characteristics of ice sheet evolution can be simulated rather than the specific data being output, which conduces to a better analysis on the physical process in ice-sheet evolution.

It can also be learnt from the above experimental study that the description of basal boundary condition concluded by the model and the parameterization procedures of surface accumulation rate are all desirable, as we don't know much about the large-scale basal dynamic situation of the Antarctic ice sheets and mass balance under paleoclimate condition. Actually, there are still some questions need to be investigated in research of numerical simulation of the Antarctic ice sheets. First one is the boundary condition and adding of more reasonable physical process. Because the climate and mass balance related to boundary condition are important factors for the simulation of the Antarctic ice-sheet evolution, and it is the measurement index for the accuracy of ice sheet model, but for various reasons, the climate changes will distort in exploration of the past or future changing trend of ice sheets. And the bottom melting rate of ice shelf, which directly influences on the grounding line, is more intractable for researchers' very little understanding. Otherwise, the geothermal flow at the bottom of ice sheet is a major difficult issue as well, because the geothermal flow can heat the basal ice sheet and thus rise its melting rate, it is a pity that there is no concerning data at present; and little has been known about the collapse process of iceberg and ice shelf, which brought much affects on the numerical simulation of ice sheet. Therefore, the following aspects should be included in future research of GLIMMER model of ice sheet: fully coupled temperature field and specifically investigating the corresponding mechanism of ice flow; wholly understanding how the ice sheet to respond to the various climate (for example, changes in surface temperature and net accumulation rate of ice sheet); the influence of subice topography on the evolution of ice sheets, etc.

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