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Relations between basal condition, subglacial hydrological networks and geothermal flux in Antarctica

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Abstract

When modelling the Antarctic ice sheet, the velocity of the ice flow is linked to its temperature. Depending on the thermal rate, the flow rate may vary between deformation and sliding. In this study, we focus on the geothermal flux because it is the least well-known component of the heat equation, and because it constrains the temperature at the bottom of the ice sheet. We used available geological data to build a map of the geothermal flux, which was found to increase from 51 mW/m^2 in East Antarctica to 68 mW/m^2 in West Antarctica. These values were integrated in the computation of a basal temperature map. The available map of hydrological networks clearly shows more melted areas in West Antarctica than in the earlier results. So we suggest that the model should be forced with higher geothermal flux values, over 85 mW/m^2 in this sector. This increase is in good agreement with published results which found a geothermal flux three times higher in West Antarctica. Finally, we computed the bottom melt rate over the ice sheet area which has a mean value of 3.5 mm/yr resulting in a lost of melted ice equal to 1% of the total mass balance.

Keywords: Antarctica; Geothermal flux; Subglacial hydrological networks

1. Introduction

Basal conditions of ice sheets, such as basal temperature or presence of water, are crucial for ice sheet modelling. This is because the basal temperature controls ice flow and hence horizontal flow velocity. The type of flow, by internal deformation or by sliding over the bedrock, depends on whether the temperature is close or not to the pressure melting point. Furthermore, extensive networks of hydrological drainage channels have been identified deep beneath the thick ice sheet of Antarctica. These hydrological networks can transport mass in the form of subglacial meltwater produced at the base of the ice cover to other regions of the ice sheet [1]. Such subglacial networks have important consequences for ice flow, mass balance studies and subglacial lake formation. Consequently, ice sheet dynamics cannot be properly modelled without knowledge of the location of subglacial hydrological networks and of the basal temperature.

However, it is very difficult to acquire these data. Radio echo sounding (RES) measures the ice sheet thickness, from which bedrock topography and basal boundary conditions can be inferred, yet the existing data coverage for Antarctica is still sparse [2]. Surface

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elevation data from the ERS-1 radar altimeter (RA) can provide indirect information on the location of some subglacial lakes and thus on basal conditions, but it is usually limited to the detection of large lakes (greater than 4 km at their widest part). Finally, basal temperature derived by modelling is limited by the poor knowledge of several parameters; the large uncertainty of the geothermal flux is the greatest limitation [3].

Recently, a methodology for mapping subglacial hydrological networks has been developed by [4,5]. They have shown that subtle surface features observed in precise topography derived from the ERS-1 geodetic mission [6] can be enhanced by generating maps of a parameter that describes the curvature of the surface topography [7], which permits a more reliable mapping of subglacial channels than direct observation of surface topography. This method was favourably tested at Dome C ([5], see Fig. 1 for location) and extended to the whole Antarctica ice sheet. Rémy and Legrésy [4] observed that the distribution of the high surface curvature values linked with the existing hydrological networks is not homogeneous, but rather skewed toward the western part of Antarctica (Fig. 2). Since neither the ice thickness nor the ice sheet flow characteristics were sufficient to explain such an East–West gradient, they claimed it was due to the distribution of the geothermal flux.

They also noted an abrupt transition between an area characterised by a wide distribution of the hydrological network and an area with no detected hydrological network along the meridian 135°E between 82°S and 75°S (corresponding to the Adventure trench, see Fig. 1 for location). They argued that the transition corresponds to the western edge of the Precambrian East Antarctic Craton on the eastern flank of the Wilkes Subglacial Basin and that it was produced by changes in the geothermal flux in the basement.

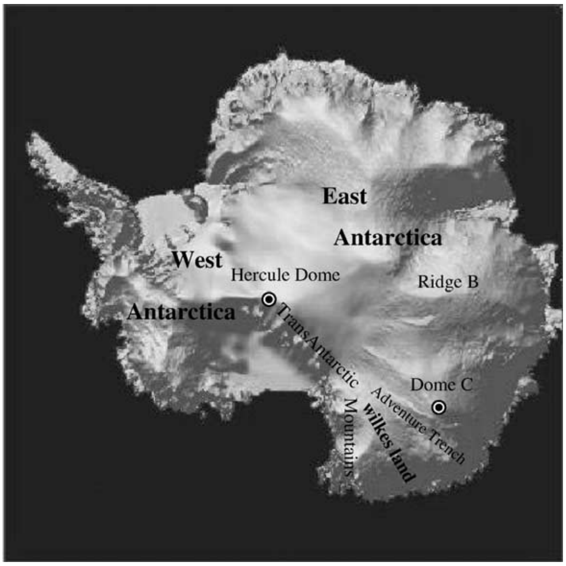

Fig. 1. Antarctica ice sheet topography derived from the geodetic orbit of the ERS-1 satellite. The principal locations are shown.

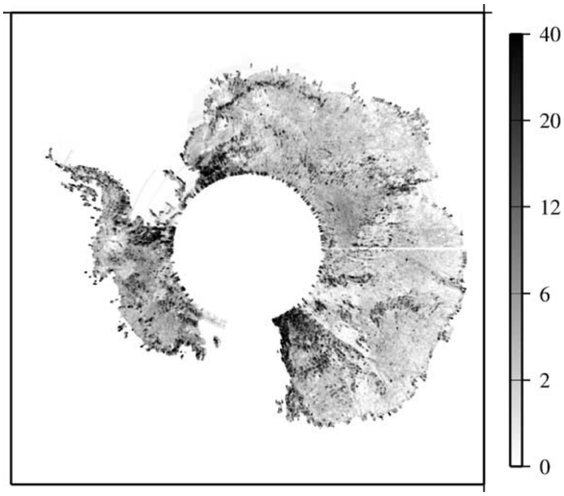

Fig. 2. Map of the rms of the surface curvature assumed to be linked with the presence of subglacial hydrological networks. Large values indicate high subglacial network density. Note the East–West gradient and the abrupt change along the Adventure trench (see Fig. 1 for location).

The conclusions of these previous studies indicate the important role of geothermal flux in modifying the basal temperature and therefore with a direct impact on ice sheet modelling. In Antarctica, few geothermal flux data have been collected and all of these data are located on the edge of the continent or on the ocean margins (see world database of IHFC, http://www.geo.lsa.umich.edu/IHFC/index.html). Several studies have tried to evaluate the geothermal flux globally using a method based on the age of the crust [8] or on the identification of geological units [9]. However regionally, the geothermal flux can vary by up to 60% of the mean value due to varying geological features. With such large variations, it is necessary to test the sensitivity of the basal temperature to the geothermal flux, in order to determine the most realistic values. The same process described for the global studies can be applied to Antarctica, using geological information to select the values of the geothermal flux. Recent work focusing on this continent [10] proposes a geothermal flux distribution showing a strong East–West gradient, with very high values in West Antarctica where the crust is youngest.

The aim of this paper is to confirm this East–West Antarctic gradient in the geothermal flux and to estimate the global geographical pattern of basal melting of the ice sheet. The first section describes the relation between geothermal flux and basal temperature, and the second discusses a map of the geothermal flux prepared from comparisons of geological similarities. This map was used to compute basal temperatures for the entire Antarctic ice sheet and to estimate the melt rate at the bottom.

2. Link between basal temperature and flux

The bottom temperature can be estimated from the thermodynamic equation in [3,11–13] which, assuming a steady state, is:

$$\kappa \partial T^2/\partial z^2 - u\partial T/\partial x - w\partial T/\partial z + \tau(1 - z/H)/C\partial u/\partial z = 0 \qquad (1)$$

where x is the flow direction, z the depth, T the temperature, κ the thermal diffusivity and C the specific heat capacity. H is the ice thickness and τ the basal shear stress induced by the surface slope and the ice thickness. The horizontal velocity in the x direction is u, provided by the balance velocity from Testut et al. [14], and w is the vertical velocity in the z direction, as given by Lliboutry [15].

This equation describes the vertical diffusion (first term), horizontal advection (second term), vertical advection (third term) and dissipation (last term). The horizontal temperature gradient is negligible compared to the vertical one. More details can be found in [3,16,17]. The Antarctic continent is divided into a regular 5 by 5 km grid, and at each point we solve Eq. (1) using a classical matrix solver. The numerical schema is a finite difference method with a 100-m grid step in the z direction, from the surface to the bottom of the ice cap.

This process needs two boundary conditions. The upper boundary condition is to specify the surface temperature. For this, we used the linear dependence on altitude and latitude given by King and Turner [18]. The lower boundary condition is to specify the basal gradient temperature, derived from the geothermal flux Φ following the relation:

$$\frac{\partial T_b}{\partial z} = \frac{\Phi}{K} \qquad (2)$$

where K is the thermal conductivity.

The different terms in Eq. (1) are not accurately known everywhere on the continent. In most cases (for instance for the ice thickness or the accumulation rate), in situ measurements are mapped onto a regular grid by spatial interpolation; these data are noisy but not too biased. In contrast, the geothermal heat flux is poorly constrained due to the lack of in situ data over the continent and may have a distinct geographical pattern. The values found in the literature for this parameter vary greatly from 35 to 130 mW/m^2 (e.g. [10,8]). On stable old continents, the geothermal flux is generally much lower than in younger regions and varies due to changes of either heat flux at the base of the lithosphere or crustal heat production [19].

In order to show the high sensitivity of Eq. (1) to the geothermal heat flux, the equation was computed for the whole Antarctica ice sheet with two different values of geothermal flux (Φ=40 mW/m^2 and Φ=60 mW/m^2), values centred around the global mean value of 50 mW/m^2 for old cratons. The ice thickness was provided by the BEDMAP compilation [2], the vertical velocity was deduced from the accumulation rate [20], the surface slope and basal stress were derived from precise topography [6] and the horizontal velocity from Testut et al. [14].

Fig. 3 shows the maps of the basal temperatures computed from Eq. (1) for grounded ice, with respect to fusion temperature. In Fig. 3a,b, the geothermal flux is, respectively, 40 mW/m^2 and 60 mW/m^2. When the ice thickness is less than 500 m, or the horizontal velocity greater than 55 m/yr, or the surface slope stronger than 0.015 m/km, the computation stops and the area is mapped in grey.

In the first map, only 16% of the data shows a basal temperature greater than the melting point. When the basal ice is frozen, the mean temperature with respect to melting point is −13 °C. On the other hand, when taking a larger geothermal flux value (Fig. 3b), more than 50% of the basal temperature is greater than the melting point and the mean temperature is −7 °C.

There is a large difference between the two estimates, from a few degrees near the coast to up to 15 °C in the central part of East Antarctica (Fig. 3c). In the central part, horizontal advection and above all dissipation are negligible, which means that there is a greater sensitivity to the boundary conditions. On the other hand, the sensitivity of the basal temperature computation to the geothermal flux appears to be not very significant in Western Antarctica and near the coasts. We shall see later that above a certain threshold value, the sensitivity is greatly enhanced in the western part. The mean difference of 6 °C between the two maps greatly affects the ice flow estimate. The ice flow can include sliding or internal deformation, and the induced velocity estimate can have large discrepancies.

The ice flow law is temperature dependant, meaning that, to the first order, the temperature dependence of the velocity is $\exp\left(\left(\frac{Q}{RT_b^2}\right)\cdot(T_b - T_f)\right)$ where Q is the

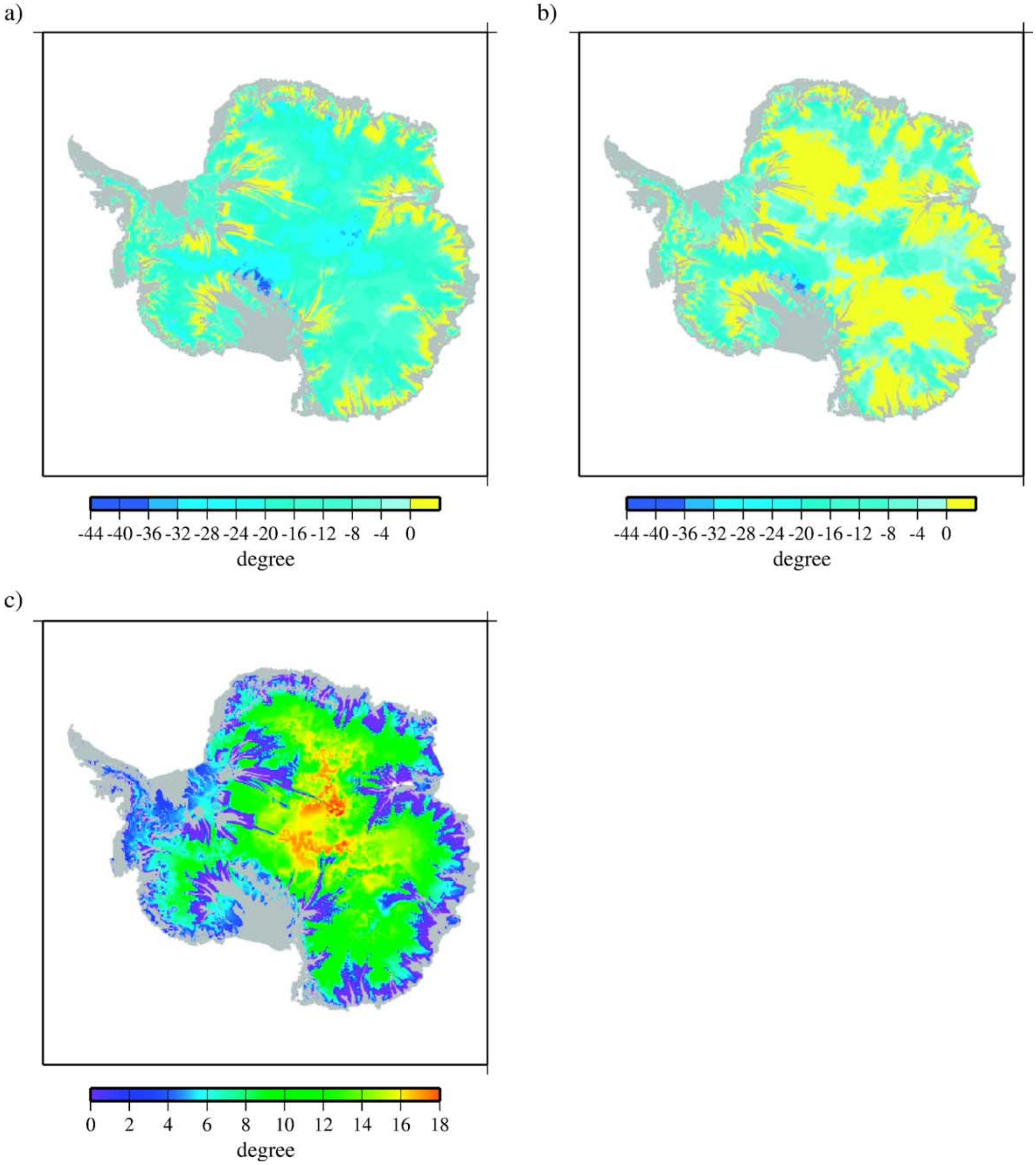

Fig. 3. Basal temperature with respect to fusion temperature, calculated from Eq. (1) (see text) with a constant geothermal flux of 40 mW/m^2 (a) and of 60 mW/m^2 (b). Differences in degrees between these two maps are shown below (c).

activation energy, R is the perfect gas constant, T_b and T_f are, respectively, the basal and the fusion temperatures. If we assume an activation energy of $Q = 70$ kJ/mol, then a temperature difference of 6 °C would induce a velocity change by a factor of 1.8. In addition, the glen parameter (i.e., the power at which the basal shear stress intervenes in the strain rate) is also suspected to be temperature dependant, varying from 1 for cold temperature to 3, or greater for high temperatures [16].

3. Link between geothermal flux and crust

The challenge was to find a more realistic heat flux to use in our models. Few data is available for this parameter, due to the difficulty of measuring it.

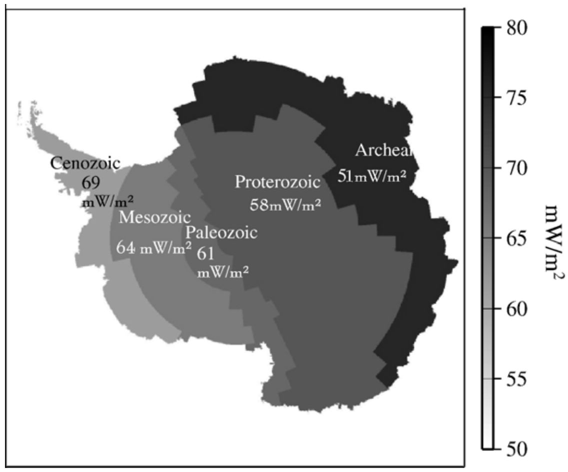

Fig. 4. Map of geothermal flux based on a geologic cutting inspired from [23] and assuming that the same geologic units will have the same geothermal flux. Values are computed as the mean of similar terrains found in Pollack's Table [8].

Here we attempt a similar approach to [8] to produce a geothermal flux map of Antarctica. Geological studies show that the Antarctic continent is divided into two parts, separated by the highly elevated barrier of the Transantarctic Mountains. East Antarctica is a thick old craton, which evolved slowly over the years. West Antarctica is a puzzle of micro-plates, younger and thinner than the other sector, with a more complicated younger geological history ([21,22]).

Hence, considering the empirical law defined by Sclater et al. [9] which shows a heat flow decreasing with the age of the crust, we suggest low values in East Antarctica and higher values on the other side of the Transantarctic Mountains. Old cratons have typical values between 40 and 60 mW/m^2, but heat flux can reach more than 90 mW/m^2 in younger regions.

The geological map of Antarctica proposed by Borg et al. [23] was thus used to make a new map of geothermal flux. A value was assigned to each geological province by computing the mean of all corresponding terrains found in Pollack's Table [8]. Following these values, the continent was divided into five zones. The geothermal flux increased from 51 mW/m^2 in the coastal zone of East Antarctica, to 68 mW/m^2 at the northern limit of West Antarctica (Fig. 4).

This is in good agreement with Siegert and Dowdeswell [24] who used the presence of lakes to estimate the geothermal flux. They found a gradient from East to West Antarctica for which the geothermal flux in the Hercules Dome region (WAIS) was 10–15 mW/m^2 greater than in the Dome C region, and 20–25 mW/m^2 greater than in the Ridge B region (see Fig. 1 for the location).

This is also in good agreement with the recent work by Shapiro and Ritzwoller [10] who found geothermal flux values using seismic models. They focussed on Antarctica, where the geothermal flux has been found to be three times higher in the western part than in the eastern one.

4. Discussion

4.1. Basal temperature estimate

Based on the heat flux map (Fig. 4), we have calculated the basal temperature of the Antarctic ice sheet (Fig. 5). Compared to the results obtained using a constant value of 40 or 60 mW/m^2, there are many more areas of melting ice in East Antarctica. This result agrees better with the map of the subglacial hydrological network (Fig. 2) and with the numerous subglacial lakes counted in this part of the continent, especially near Dome C and in the Aurora basin [25].

The mean basal temperature above the melting point was found to be -7.4 °C, which is close to the values found for a fixed geothermal flux of 60 mW/m^2. The percentage of areas where the basal temperature is higher than the fusion temperature is around 50%.

However, this model is still too cold in West Antarctica for explaining Fig. 2. Indeed, less ice than expected reaches the melting point. Fig. 2 shows more extensive areas of basal ice melt. The geothermal flux seems to be higher in this part of the continent than

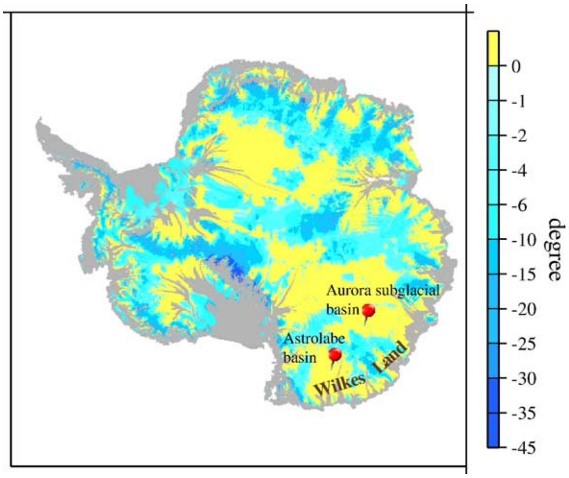

Fig. 5. Geothermal flux values given in Fig. 4 are used to solve Eq. (1) and to compute a map of basal temperatures with respect to fusion temperature. We plotted in yellow areas with melted ice at the base of the ice sheet.

the value we used. The two westernmost geological units are dated, respectively, Mesozoic and Cenozoic, with heat flux of 63.9 and 68.5 mW/m^2 found by computing the mean of Pollack's values [8]. It is well known that the computation in the younger regions have many discarded values. For instance, according to Pollack's Table the heat fluxes range from 64 to 97 mW/m^2 for continental Cenozoic formations, but even higher values have been measured. Indeed, the authors [10] find that mean heat flow in West Antarctica may be three times higher than in the East and more variable. It can reach 110 mW/m^2 or more, with minimum values of 70–75 mW/m^2.

Hence, we may realistically increase our geothermal flux estimate for West Antarctica. As mentioned in the discussion for Fig. 3a and b, the west Antarctic temperature model appears to be less sensitive to small changes in the geothermal flux than the East Antarctic model. However, there is a threshold associated with the geothermal flux value. Above 85 mW/m^2, the basal temperature reaches melting point over extensive areas of West Antarctica, which agrees with the features observed in Fig. 2. The ice thickness is also weaker than in East Antarctica, so the model will be more sensible to surface parameters, such as the accumulation rate or the surface temperature.

These numerical observations of basal temperature are obtained by solving Eq. (1), which depends on several parameters. With an accuracy of 100 m over 100 km, the topography is now very well known and topographic errors do not influence our results. But the mean accumulation rate has an accuracy of only about 20%. That could lead to an error of a few degrees on the estimate of basal temperature. Variations in surface temperature can have a similar impact on the basal temperature. Compared to these relatively small uncertainties, the geothermal flux can sometimes be three times higher than the mean used value in certain regions. We have seen that these errors can have a strong impact on the basal temperature (variations of 15 °C or more).

When interpreting the results, we must remember that the geothermal flux can also vary over short spatial scales, which can cause melting or non-melting areas which are distinct from the mean value. The Adventure Trench is a good region to test the sensibility of temperature to local heat flux variations. Indeed, the Wilkes basin (Fig. 1) is located to the west and is associated with a thinning of the Earth's crust [26]. Precambrian formations on the eastern edge of the trench are supposed to have lower heat flux values. Thus, a difference of 15 mW/m^2 appears to be enough to cause ice sheet base melt in the western sector while leaving the eastern part frozen.

4.2. Basal melting estimate

The computation of the melting rate at the bottom of the ice sheet yields information on the quantity of ice that reaches the melting point. It can be determined with the following equation:

$$v = \frac{\Phi + \Phi_{\mathrm{d}} - K \cdot \dfrac{\partial T}{\partial z}}{\rho L} \tag{3}$$

in which Φ is the geothermal flux, Φ_{d} the dissipation flow generated by the ice dynamics, ρ the ice density (in kg/m^3) and L the ice latent heat of fusion = 321 kJ/kg. We used the temperature gradient computed in the 'cold' ice, lying just above the 'temperate' ice at the base of the ice sheet (see [3] for the definition). Fig. 6 maps the melting rate v. Dark blue areas represent frozen ice zones. Locations where the computation failed due to reduced ice thickness, or excessive horizontal velocity or a too steep surface slope are shaded in grey.

From this estimate, the average rate of basal melting is 3.5 mm/yr. Integrating this value over the whole ice sheet gives a total ice loss by basal melting of 16 km^3/yr, which is around 1% of the annual ice sheet balance. The calculation is based on the difference between the mass input minus output. Note that the ice lost by this mechanism would be only 6.7 km^3/yr assuming a mean geothermal flux of 40 mW/m^2, and would reach 18 km^3/yr for an average geothermal flux of 60 mW/m^2.

There is a clear difference between the two parts of the continent. In East Antarctica, the melting rate remains low all over the central regions—around 3

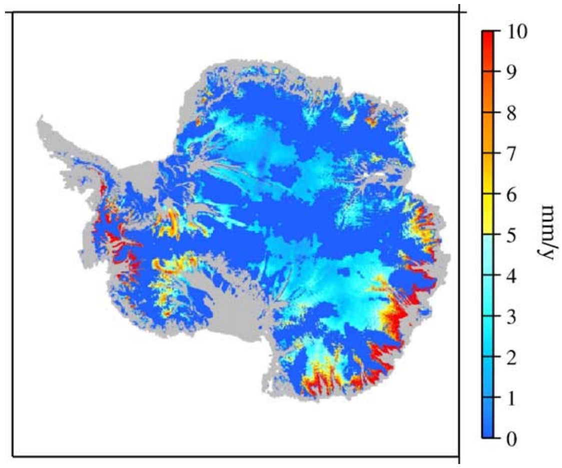

Fig. 6. Ice melting rate estimate for the Antarctic ice sheet. In the computation, we use the geothermal flux proposed in Fig. 4.

mm/yr. It can reach 10 mm/yr in the coastal area, especially near the Wilkes Land coast (Fig. 1). Moreover, the melting is around 4–5 mm/yr in large areas in the central part, especially near Dome C and the Aurora subglacial basin (Fig. 5) where many lakes and hydrological networks were discovered. In West Antarctica, the thermal rate is very different. As soon as the ice starts to melt, it does so in great quantities. The mean melting rate is above 5 mm/yr and can reach 12 mm/yr.

5. Conclusion

Siegert and Dowdeswell [24] determined the minimum geothermal flux necessary to produce basal melting of the ice sheet, using the presence of subglacial lakes that are directly linked to basal thermal conditions. They found a large spatial variability, depending on the geographic position of the lakes. More recently, Rémy et al. [5] proposed a surface curvature-based coefficient for detecting all melted zones at the bottom of the ice sheet. Their spatial distribution varies locally, especially around the Adventure trench. They also found that the quantity of melted areas tends to increase toward West Antarctica [4]. In a recent work, Shapiro and Ritzwoller [10] used seismic models to define similarities between geological structures around the Earth in order to construct a new global heat flux model.

This paper describes another tool to investigate the heat flow pattern: dividing the continent according to the different geological crustal regions. A geothermal flux value was assigned to each formation. When tied to this geological assumption, the heat flux was found to be distributed and ranged from 51 mW/m^2 to 85 mW/m^2 from East to West Antarctica.

Such a high value in West Antarctica is needed to obtain the melting point over large areas. We have estimated the effect of the geothermal heat flux on the basal temperature (Fig. 3). This is not the only factor responsible for the discrepancies between our calculations and the field observations, for instance the errors in the ice velocity is another factor. However, the geothermal flux is the only one that can provide an East/West gradient and allows the calculations to be in better agreement with the observations.

This work confirms [10] that high heat flow rates are needed to explain the large melt area in West Antarctica. This western continental region has a more recent and complicated geological history that may provide a heterogeneous distribution of geothermal flux. We have assumed that this parameter varies geographically according to geological patterns, but more data are needed. For example, seismological studies can be helpful for constraining the changes in the structure of the crust and lithosphere. Further studies are needed in order to carefully map the geothermal flux and the basal temperature in West Antarctica, which is crucial for studying the ice sheet mass balance and its effect on mean sea level.

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