Implications of high core thermal conductivity on Earth's coupled mantle and core evolution

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[1] We assess the effect of high thermal conductivity of Earth's core, which was recently determined to be 2–3 times higher than previously thought, on Earth's thermochemical-magnetic evolution using a coupled model of simulated mantle convection and parameterized core heat balance, following the best fit case of Nakagawa and Tackley (2010). The value of core thermal conductivity has no effect on mantle evolution. The core-mantle boundary heat flow starts high and decreases with time to ~13 TW, which is below the core adiabatic heat flux for the largest thermal conductivity tested (200 W/m/K), meaning that a purely thermal dynamo is not viable. However, gravitational energy release and latent heat associated with inner core growth become important in the last ~0.9 Gyr and allow continuous geodynamo generation despite high core thermal conductivity, although we estimate a subadiabatic region at the top of the core of the order of hundreds of kilometers. **Citation:** Nakagawa, T., and P. J. Tackley (2013), Implications of high core thermal conductivity on Earth's coupled mantle and core evolution, *Geophys. Res. Lett.*, *40*, 2652–2656, doi:10.1002/grl.50574.

1. Introduction

[2] Recent advances in high-pressure mineral physics have indicated that the thermal conductivity of Earth's core is likely a factor of 2 to 3 higher than previously thought. Recently calculated values of the thermal conductivity of Earth's core range from 90 to 150 W/m/K [*Pozzo et al.*, 2012; *de Koker et al.*, 2012], whereas previous estimates are typified by 46 W/m/K [*Stacey and Anderson*, 2001]. These recent high estimates indicate that the adiabatic heat flow from the core is in the range 10 to 15 TW, which is similar to current estimates of heat flow across the core-mantle boundary (CMB) [*Lay et al.*, 2008] and much higher than older estimates, and might cause a subadiabatic region of O (1000) km below the CMB [*Pozzo et al.*, 2012]. This implies that thermal convection may be unimportant in large regions of the core, with compositional convection instead being a major driver of magnetic field generation. In our previous studies on the thermal evolution of Earth's core using a coupled model of fully dynamical mantle convection simulation and parameterized core heat balance [e.g., *Nakagawa and Tackley*, 2005; *Nakagawa and Tackley*, 2010], we assumed a lower value of thermal conductivity of Earth's core based on thermodynamic theory, i.e., in the range 30 W/m/K [e.g., *Stacey and Loper*, 2007] to 46 W/m/K [*Stacey and Anderson*, 2001]. The CMB heat flow obtained in our coupled models that obtained a reasonable present-day inner core size was typically in the range 9 to 10 TW [e.g., *Nakagawa and Tackley*, 2010], which is also lower than the estimate of the adiabatic heat flow using the new core thermal conductivity calculations.

[3] Here we assess the influence of these recently determined, high core thermal conductivity values using a coupled core-mantle model. Because heat transport by mantle convection determines the CMB heat flow, the model consists of a fully dynamical mantle convection simulation combined with a global heat balance in the core, as in our previous studies [*Nakagawa and Tackley*, 2004, 2005, 2010].

2. Model Description

[4] We use a very similar physical and numerical model as in our previous study [*Nakagawa and Tackley*, 2010] with the addition of higher core thermal conductivity. Here we give a brief summary and highlight differences. The mantle convection simulations are performed in a 2-D spherical annulus geometry [*Hernlund and Tackley*, 2008], which we found to give very similar average evolution to fully 3-D spherical geometry [*Nakagawa and Tackley*, 2010] and are calculated using the code StagYY [*Tackley*, 2008].

Table 1a. Mantle Model Physical Parameters[a]

Symbol	Meaning	Non-dimensional Value	Dimensional Value
Ra_0	Rayleigh number	10^7	N/A
η_0	Reference viscosity	1	1.4×10^{22} Pa s
$\Delta\eta$	Viscosity jump at 660 km	30	N/A
σ_b	Yield stress at surface	1×10^5	117 Mpa
σ_d	Yield stress gradient	4×10^5	162.4 Pa m^{-1}
ρ_0	Reference (surface) density	1	3300 kg m^{-3}
G	Gravity	1	9.8 m s^{-2}
α_0	Reference (surface) thermal expansivity	1	5×10^{-5} K^{-1}
K_0	Reference (surface) thermal difference	1	7×10^{-7} m^2 s^{-1}
ΔT_{sa}	Temperature scale	1	2500 K
T_s	Surface temperature	0.12	300 K
L_m	Latent heat	0.2	6.25×10^5 J kg^{-1}
τ	Half life	0.00642	2.43 Gyr

[a] $Ra_0 = \rho_0 g \alpha_0 \Delta T_{sa} d^3 / K_0 \eta_0$.

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Table 1b. Physical Parameters for the Core Heat Balance[a]

Symbol	Meaning	Value
r_{CMB}	Radius of the core	3486 km
ρ_c	Initial density of core	12,300 kg m^{-3}
ρ_{iron}	Density of pure iron	12,700 kg m^{-3}
ρ_{li}	Density of light elements	4950 kg m^{-3}
$\Delta\rho_{IC}$	Density difference	400 kg m^{-3}
ΔS	Entropy change	118 J kg^{-1} K^{-1}
$C_l(t=0)$	Initial concentration of light elements	0.035
C_p	Heat capacity of the core	800 J kg^{-1} K^{-1}
α_c	Thermal expansivity of the core	10^{-5} K^{-1}
C_K	Radioactive potassium in the core	400 ppm
$T_L(r=0, C_l(t=0))$	Melting temperature at the center	5400 K

[a]The value of entropy change is taken from *Labrosse* [2003]. The melting temperature at the Earth's center is taken from *Lister* [2003]. All other values are taken from *Buffett et al.* [1996].

[5] The viscosity of the mantle is described as in our recent study [*Nakagawa and Tackley*, 2012], given as

$$\eta_d = A_0\left(\prod_{ij}\Delta\eta_{ij}^{\Gamma_{ij}f_j}\right)\exp[9.1535(0.5-z)]\exp\left[\frac{32.716}{T+0.88}\right]$$
$$\eta_Y = \frac{\sigma_0+\sigma_1(1-z)}{2\dot{\varepsilon}}$$
$$\eta = \left(\frac{1}{\eta_d}+\frac{1}{\eta_Y}\right)^{-1}, \quad (1)$$

where T and d are the nondimensional temperature and depth, respectively; A_0 is a prefactor determined such that the nondimensional viscosity is 1 at $T = 2500$ K and $d = 1445$ km; σ_0 and σ_1 are yield stress at the surface and its gradient; and $\dot{e}$ is the second invariant of the strain-rate tensor. All dimensional physical properties of mantle and core are listed in Table 1a. Compositionally, the mantle is assumed to be a mechanical mixture of harzburgite and mid-oceanic-ridge-basalt (MORB), with C being the fraction of MORB. The density difference between two endmembers at the CMB is 1.8%. Oceanic crust is generated by partial melting of the MORB end-member and may then be subducted and gravitationally segregate above the CMB. Melting may also occur in the deep mantle, but its only effect is on temperature via latent heat; it does not move relative to the solid or affect physical properties. As an initial condition, the mantle is assumed to have a uniform composition C = 0.2 [*Xu et al.* 2008] and to be thermally adiabatic with a potential temperature of 2000 K, except in thermal boundary layers at the top and bottom. The initial CMB temperature is assumed to be 6000 K, which is a best fitting value found in *Nakagawa and Tackley* [2010]. A numerical resolution of 1024 azimuthal cells by 128 radial cells, with 4 million tracers to track composition, as found to be sufficient in resolution tests [*Nakagawa et al.*, 2012], is used.

[6] For the core heat balance, we use the formulation described in *Nakagawa and Tackley* [2005], which is based on *Buffett et al.* [1996] and *Lister* [2003]. Parameter values are given in Table 1b. The main difference to our previous studies is the higher thermal conductivity. Adiabatic heat flow at the CMB is related to this by the following:

$$Q_{ad} = k_c\left(\frac{\partial T}{\partial r}\right)_{ad} S_{CMB} = k_c\frac{\alpha_c g_0}{C_p}T_{CMB}S_{CMB}, \quad (2)$$

where α_c is the thermal expansivity of the core, g_0 is the gravity at the CMB, C_p is the heat capacity of the core, T_{CMB} is the temperature at the CMB, S_{CMB} is the surface area of the CMB, and k_c is the thermal conductivity of Earth's core. Here we assume three values of core thermal conductivity, which are 46 W/m/K, 100 W/m/K, and 200 W/m/K. The first two values are based on theoretical and experimental constraints (*Stacey and Anderson* [2001] for the smaller value; *de Koker et al.* [2012] and *Pozzo et al.* [2012] for the intermediate value), while the last one is set to an extreme value for the purposes of testing. These give adiabatic CMB heat flows in the range 5 to 21 TW. The adiabatic heat flow affects only the magnetic dissipation caused by dynamo action [*Lister*, 2003], given as

$$\Phi_m = \varepsilon_s(Q_{CMB}-Q_{ad}) + (\varepsilon_L+\varepsilon_C)(Q_{CMB}-Q_R), \quad (3)$$

where ε_s, ε_L, and ε_C are the energy efficiency associated with secular cooling, latent heat release due to the inner core growth, and gravitational energy due to the inner core growth, respectively, and Q_{CMB} and Q_R are the CMB heat flow calculated from the mantle convection simulation and the radioactive heating in Earth's core, respectively. For radioactive heating in the core, we assume 400 ppm of potassium at the present time, corresponding to a best fit case in *Nakagawa and Tackley* [2010], while energy efficiencies from thermal to magnetic are taken from *Lister* [2003].

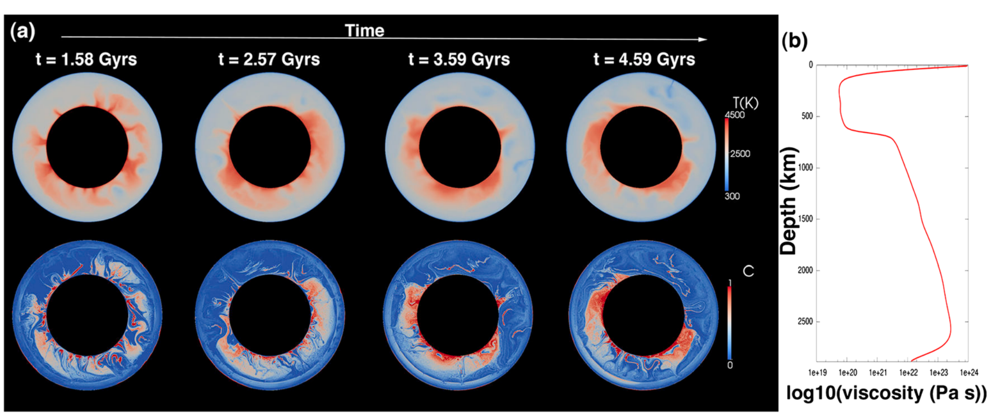

Figure 1. (a) Time variation of thermochemical structures in the mantle. Top: Temperature. Bottom: Compositional field. (b) Viscosity structure at t = 4.59 Gyr.

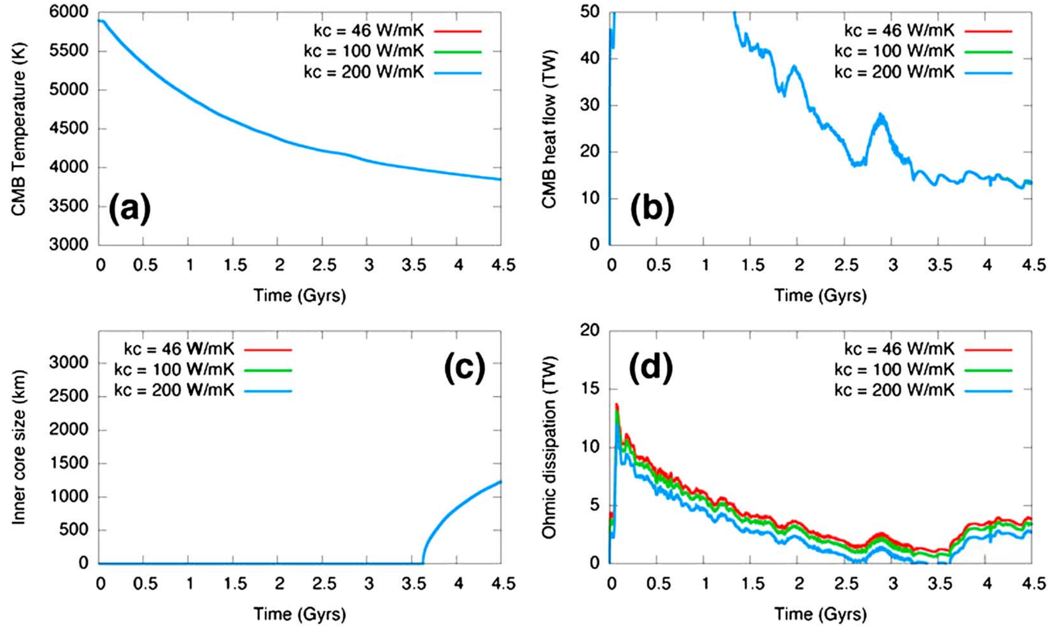

Figure 2. Time evolution of (a) CMB temperature, (b) CMB heat flow, (c) the size of the inner core, and (d) magnetic dissipation (ohmic dissipation).

3. Results

[7] Figure 1 shows the time variation of thermochemical structures in a case with a core thermal conductivity of 100 W/m/K. Early on (left of Figure 1), small-scale thermochemical structures in the deep mantle are observed. With time, these small-scale structures merge to form one to two large-scale dense basaltic piles (t = 3.59 Gyr to t = 4.59 Gyr). The viscosity profile is consistent with observationally derived profiles as well as the results of *Nakagawa and Tackley* [2012]. Thermochemical structures for cases with higher core thermal conductivity (not shown) are identical to those in Figure 1, because the thermal conductivity of Earth's core is not expected to have any impact on thermochemical structures in the deep mantle.

[8] Figure 2 shows globally averaged diagnostics of core evolution. The time evolution of CMB temperature, CMB heat flow, and inner core size are the same regardless of the value of core thermal conductivity. The present-day size of the inner core (at t = 4.5 Gyr) is around 1250 km, only slightly

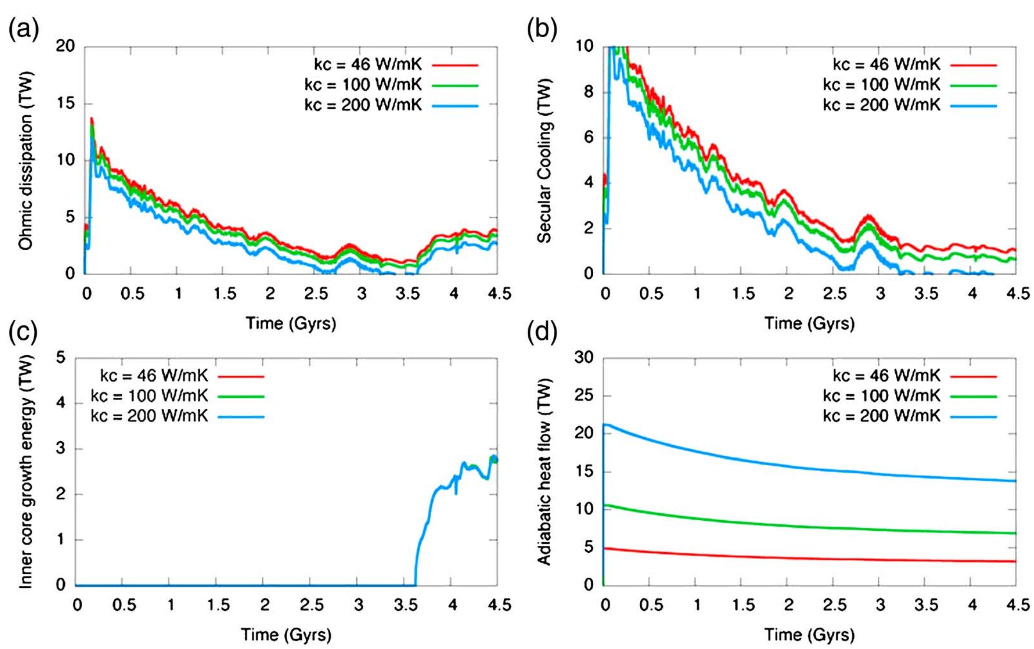

Figure 3. Time evolution of (a) total magnetic dissipation calculated using equation (3). (b) Contribution of secular cooling to magnetic dissipation (first term of equation (3)). (c) Contribution of inner core growth to magnetic dissipation (second term of equation (3)). (d) Adiabatic heat flow from the core (equation (2)).

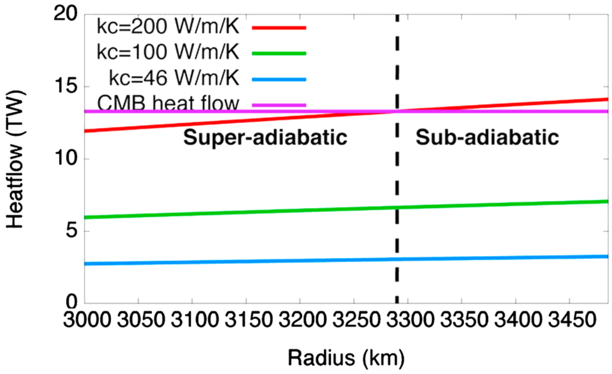

Figure 4. Relationship between the CMB heat flow calculated from the numerical mantle convection simulation and core adiabatic heat flow as a function of radius (the uppermost 150 km below the CMB) at time of final snapshots of Figure 1 for three cases of thermal conductivity of the core (46, 100, and 200 W/m/K). Only for 200 W/m/K, the subadiabatic region is found in about 200 km thickness below the CMB.

larger than the seismically observed value [e.g., *Dziewonski and Anderson*, 1981]. The CMB heat flow starts very high and decreases with time, with a present-day value (at 4.5 Gyr) of around 13 TW, consistent with the observational constraints [e.g., *Lay et al.*, 2008]. Ohmic dissipation calculated using equation (3), however, depends on the core thermal conductivity because the adiabatic heat flow is different.

[9] Figure 3 shows both components of the magnetic dissipation (i.e., the two terms of equation (3)) and the adiabatic heat flow from the core. There is a large difference in CMB adiabatic heat flow (Figure 3d), which decreases with time in all cases due to cooling of the core to a present-day value in the range 3 to 14 TW. This, when multiplied by the efficiency factor, results in differences in the contribution of secular cooling to ohmic dissipation. With the highest core thermal conductivity of 200 W/m/K, the CMB heat flow drops below the adiabatic heat flow during much of the last ~1.2 Gyr, which would result in a subadiabatic region at the top of the core. In the last ~0.9 Gyr, this is more than compensated by the energy release from inner core growth (Figure 3c), making a dynamo still possible. Hence, compositional convection in the core is likely important for understanding its evolution if the thermal conductivity of Earth's core has a very high value such as 200 W/m/K.

[10] Following *Pozzo et al.* [2012], the condition for obtaining a subadiabatic region can be written as $k_c(r)\mathrm{d}T_a/\mathrm{d}rS(r) > F_{\mathrm{CMB}}$, where T_a is the adiabatic temperature given as $T_a = T_{\mathrm{CMB}}\exp\left[\left(\alpha_c g_0/2C_p r_{\mathrm{CMB}}\right)\left(r_{\mathrm{CMB}}^2 - r^2\right)\right]$, F_{CMB} is the heat flow across the CMB imposed by mantle convection, $S(r)$ is the surface area at a certain radius of the Earth's core, $\mathrm{d}T_a/\mathrm{d}r$ is the adiabatic temperature gradient given as $\alpha_c g_0(r/r_{CMB})T_a/C_p$, and $k_c(r)$ is the thermal conductivity of Earth's core, which can be approximated as $k_c(r) = k_c(r_{\mathrm{CMB}})(1 + (r_{\mathrm{CMB}} - r)/r_{\mathrm{CMB}})$, where $k_c(r_{\mathrm{CMB}})$ is the thermal conductivity of core alloy at the CMB pressure. We assume that the Earth's outer core is compositionally well mixed. Using this relationship, the thickness of the subadiabatic region can be estimated. Figure 4 shows the adiabatic heat flow as a function of radius for all thermal conductivity used here (46, 100, and 200 W/m/K) compared to the present-day value of CMB heat flux from the mantle convection simulation. The crossover point indicates the bottom of the subadiabatic region for the most extremely large thermal conductivity (200 W/m/K), from which a subadiabatic region thickness of 100 km can be estimated, which is one order of magnitude thinner than that estimated from *Pozzo et al.* [2012], and other two values of thermal conductivity (46 and 100 W/m/K) could not have such a region, mainly because of our different assumed physical parameter values.

4. Discussion and Conclusions

[11] Here we have quickly assessed the influence of the high core thermal conductivity indicated by recent high pressure physics on core thermal evolution, focusing on the preferred evolution scenario from our previous paper [*Nakagawa and Tackley*, 2010]. Mantle evolution is independent of the core thermal conductivity. The main influence is that higher thermal conductivity results in higher adiabatic heat flow, reducing the contribution of secular cooling to magnetic dissipation. In our preferred case, this only becomes problematic for the most extreme thermal conductivity (200 W/m/K), for which the CMB heat flow imposed by mantle convection becomes lower than the adiabatic heat flow during much of the last 1.2 Gyr, meaning that dynamo action cannot be maintained by thermal convection in the core and must instead be maintained by compositional convection associated with inner core growth, as it does in our simulations. The recently obtained values of core thermal conductivity are in the range 90 to 150 W/m/K [e.g., *Pozzo et al.*, 2012; *de Koker et al.*, 2012], which are lower than the most extreme value in our models, implying that thermal convection may be sufficient to drive the dynamo although the magnetic dissipation caused by thermal effects alone is only 1 to 2 TW. Inner core growth helps enormously, increasing the present-day magnetic dissipation to around 4 TW, which is not much different from that obtained using the old estimate of core thermal conductivity [*Stacey and Anderson*, 2001] and higher than a theoretical estimate of magnetic dissipation (0.5 to 1 TW) required to explain the current strength of the geomagnetic field [*Buffett*, 2002].

[12] Regarding the radial structure of Earth's core, while [*Pozzo et al.* 2012] prefer a thick subadiabatic stratified region below the CMB, our models here indicate a 100 km thick subadiabatic region below the CMB, which is 1 order of magnitude thinner than in *Pozzo et al.* [2012]. However, this comparison is not perfect because our heat balance model is not designed for calculating the radial structure of the Earth's core. In our next study, our core heat balance model should include the depth-dependent density structure [e.g., *Labrosse*, 2003] as well as the depth dependence of core thermal conductivity, which may be 50% larger at the inner core boundary than at the CMB [*Pozzo et al.*, 2012; *de Koker et al.*, 2012]. Even though our present estimate of subadiabatic region thickness is only approximate, the thickness of the subadiabatic region obtained here is consistent with seismological observations [e.g., *Helfrich and Kaneshima*, 2010], i.e., O(100) km thickness, as well as by first-principle calculations [*de Koker et al.*, 2012], which may be explained by the effect of compositional stratification below the CMB. Possible compositional stratification below the CMB is another effect that should be considered in future studies.

[13] As in previous models, we assume a two-component (harzburgite and MORB) compositional model. Recent hypotheses for the origin of deep mantle thermochemical structure, such as the basal magma ocean [*Labrosse et al*., 2007] and upside-down differentiation [*Lee et al*., 2010], resulting in a Basal Mélange (BAM) [*Tackley*, 2012], require a more sophisticated model of composition and melting, which will be considered in the future.

[14] In this initial study, we use parameters for the best fit model obtained from our previous studies [*Nakagawa and Tackley*, 2010; *Nakagawa and Tackley*, 2012] in which the present-day size of the inner core was a key criterion used to judge fitting scenarios as various parameters are varied (convective vigor, viscosity formulation, and melting temperature at the center of the Earth). In *Nakagawa and Tackley* [2010], the present-day size of the inner core was affected by thermochemical structure in the mantle, amount of radioactive elements in the core, initial CMB temperature, and the initial temperature in the mantle. In the next study, we should establish for what range of these various unknowns a successful thermal and magnetic evolution of Earth's core can be obtained, which will be a more limited parameter range than previously obtained with lower core thermal conductivity.

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