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Key Points:
- The continental drift convection cell is new, robust, and realistic
- The cell strongly alters heat flux and lateral temperature
- Realistic numerical models and geophysical data might find this drift cell

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2

Correspondence to:
J. A. Whitehead,
jwhitehead@whoi.edu

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The continental drift convection cell

J. A. Whitehead[1] and Mark D. Behn[2]

[1]Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA,
[2]Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

Abstract Continents on Earth periodically assemble to form supercontinents and then break up again into smaller continental blocks (the Wilson cycle). Previous highly developed numerical models incorporate fixed continents while others indicate that continent movement modulates flow. Our simplified numerical model suggests that continental drift is fundamental. A thermally insulating continent is anchored at its center to mantle flow on an otherwise stress-free surface for infinite Prandtl number cellular convection with constant material properties. Rayleigh numbers exceed 10^7, while continent widths and chamber lengths approach Earth's values. The Wilson cycle is reproduced by a unique, rugged monopolar "continental drift convection cell." Subduction occurs at the cell's upstream end with cold slabs dipping at an angle beneath the moving continent (as found in many continent/subduction regions on Earth). Drift enhances vertical heat transport up to 30%, especially at the core-mantle boundary, and greatly decreases lateral mantle temperature differences.

1. Introduction

Plate tectonics describes our Earth as covered with large rigid plates that move with constant speed driven primarily by slab subduction with smaller contributions from buoyancy forces at spreading centers and near hot spots. The continents are swept along within the plates although their presence/absence might modulate this flow through a combination of thermal insulation and enhanced viscous drag. In this study we follow the suggestion that continents exert a fundamental influence on convection and specifically that they self-propel themselves in the presence of mantle convection [*Elder*, 1967]. This suggestion is reinforced by a number of studies; in the fluid mechanics literature, including the observation that floating heaters drift at the top of a laboratory convection chamber [*Knopoff*, 1969; *Howard et al.*, 1970] and that thermally insulated floats drift above cellular convection heated from below [*Zhang and Libchaber*, 2000; *Zhong and Zhang*, 2005; *Liu and Zhang*, 2008; *Whitehead et al.*, 2011, 2014]. Even an adiabatically stratified viscous fluid with an internally heated surface layer adopts cellular convection with traveling waves that can break up into continent-like traveling parcels of surface fluid [*Busse*, 1978; *Rasenat et al.*, 2006]. These studies all suggest that continents might exert a first-order effect that helps to drive convection.

Numerical models of mantle convection with continents also generally point toward a viewpoint in which continents help drive convection [*Gurnis*, 1988; *Zhong and Gurnis*, 1993; *Lowman and Jarvis*, 1995, 1996]. Continents are found to contribute to episodic rearrangement of convection cells [*King et al.*, 2002; *Koglin et al.*, 2005], including the Wilson cycle [*Trubitsyn and Rykov*, 1995; *Rolf et al.*, 2012], and influence many aspects of convection below them, including heat flux, temperature enhancement under continents, aggregation into supercontinents, subsequent dispersal of continents, and plume generation [*Guillou and Jaupart*, 1995; *Honda et al.*, 2000; *Coltice et al.*, 2007; *Grigné et al.*, 2007a; *Li and Zhong*, 2009; *O'Neill et al.*, 2009; *Phillips and Coltice*, 2010; *Lenardic et al.*, 2011; *Rolf et al.*, 2012; *Cooper et al.*, 2013; *Heron and Lowman*, 2014]. Therefore, as models have become more realistic through great advancements, it remains clear that continents exert some influence but precisely how this happens has become increasingly difficult to quantify.

This study focuses on whether the continents trigger a fundamental new mode of convection or simply rearrange cells. We use a highly simplified numerical configuration to both qualitatively and quantitatively examine the role of mobile, thermally insulating continents on cellular convection. Such a simple study is advantageous in this context because it helps to isolate effects that are obscured when Earth-like complexities are added to the analysis. Therefore, we stress that we do not attempt to model Earth but instead ask the following: Is the basic and fundamental form of the convection cells altered by a simplified continent and in particular by its mobility over a wide range of governing parameters? Further, does the continent and its mobility generate large changes in parameters such as the magnitude of the heat flow or the strength of convection near the continent? And finally, is the internal distribution of temperature altered by mobility compared to a fixed supercontinent? We find that the answer to all these questions is yes, even though some other properties such as vertical mean temperature distribution appear to remain unchanged.

2. Methods

Focusing on continent mobility, we abandon a more Earth-like model and do not include temperature- and stress-dependent rheology within the mantle. We use the simplest possible prototype dynamics and geometry for convection in the mantle: convection with constant viscosity. Effects of compression are also ignored, as are phase changes and other Earth-like realistic constraints. The fluid occupies a two-dimensional chamber of depth D' and length L' (the prime denotes a dimensional quantity; unprimed is dimensionless, so $L = L'/D'$). Initially, the temperature everywhere is set to $T_0' + \Delta T'$, and this is suddenly changed to T_0' along the top boundary. Equations are made dimensionless using the velocity scale κ'/D', temperature scale $\Delta T'$, time scale $D^{2\prime}/\kappa'$, and length scale D', where thermal diffusivity is $\kappa' = k'/\rho_0' C_p'$, k' is thermal conductivity, average density is ρ_0', and specific heat at constant pressure is C_p'. The dimensionless equations in the limit $Pr = \nu'/\kappa' \gg 1$ (Stokes flow with kinematic viscosity ν') are

$$\frac{\partial T}{\partial t} + \tilde{u} \cdot \nabla T = \nabla^2 T + h, \tag{1}$$

$$\nabla^2 \zeta = -Ra \frac{\partial T}{\partial x}, \quad \text{and} \tag{2}$$

$$\nabla^2 \psi = \zeta, \tag{3}$$

where velocity vector is $\tilde{u}$, the dimensionless temperature greater than $T_0'/\Delta T'$ is T, vorticity is $\zeta = \partial w/\partial x - \partial u/\partial z$, stream function is ψ, and internal heat generation is $h = H'D'^2/\rho_0' C_p' \Delta T'$ with H' the heat production rate per unit volume. In addition, $u = -\partial\psi/\partial z$ and $w = \partial\psi/\partial x$, where velocity direction and Cartesian coordinates x and z are positive toward the right and upward, respectively, with origin in the lower left corner. It has only two dynamical variables; the Rayleigh number $Ra = g'\alpha'\Delta T' D'^3/\kappa'\nu'$ (acceleration of gravity is g', and the linear thermal coefficient of expansion is α') and internal heating Rayleigh number $Rai = hRa$. Two geometric dimensionless numbers express the rectangular chamber length $L = L'/D'$ and continent width $W = W'/D'$.

Initial conditions are $\psi = \zeta = 0$ and $T = 1$ in the interior. For most runs the continent starts on the far right, but trial runs with other initial locations produce no change in properties reported here. The procedure has equation (1) advanced numerically in time [*Whitehead et al*., 2013] using a leapfrog-trapezoidal scheme. Then equation (2) is solved by inverting the Poisson equation, and equation (3) is solved the same way. Boundary conditions $\psi = \zeta = 0$ on all boundaries impose zero tangential stress and zero normal flow along lateral sides, top, and bottom of the chamber. For temperature, the top boundary is set to $T = 0$ except for locations where the continent is present, in which case the temperature gradient in an external set of grid points is set to zero ($\partial T/\partial z = 0$). The importance of limited heat flux at the base of the continents has been demonstrated by *Lenardic et al*. [2005, 2011]. The chamber sides have zero lateral heat flux such that $\partial T/\partial x = 0$ resulting in reflective side boundary conditions. The boundary condition for temperature along the chamber bottom is one of two types. The first is a constant bottom temperature $T = Tb = 1$, so the heat flux q up through the bottom is determined by the convection. In the special case $h = 0$, Nusselt number is used ($Nu = q$). The second type of bottom boundary condition is zero heat flux $\partial T/\partial z = 0$ at $z = 0$ with $h = 4$, specified. Here bottom temperature is a free parameter determined by the convection.

We impose zero heat flux along the bottom of the continent. Our numerical algorithm utilizes an external layer of grid points outside all four boundaries to control heat flow at the chamber surfaces with the truncation error of $O(10^{-15})$ rather than at the boundary layer resolution accuracy of $O(10^{-6})$ or less.

To make the continent drift freely, its lateral speed is set equal to the speed of the flow at its center. This criterion is a simplification of a more correct principle, which is to set the integral of the viscous stress on a block-like continent to zero [*Gurnis*, 1988]. When the continent drifts onto the end of the chamber the continent speed is set to zero until the speed under the continent reverses. Therefore, the fixed continent does not exert stress on the fluid and does not directly affect the velocity fields. If the continent is rigidly attached to the fluid, differences are minor (section 4 in Text S1 in the supporting information).

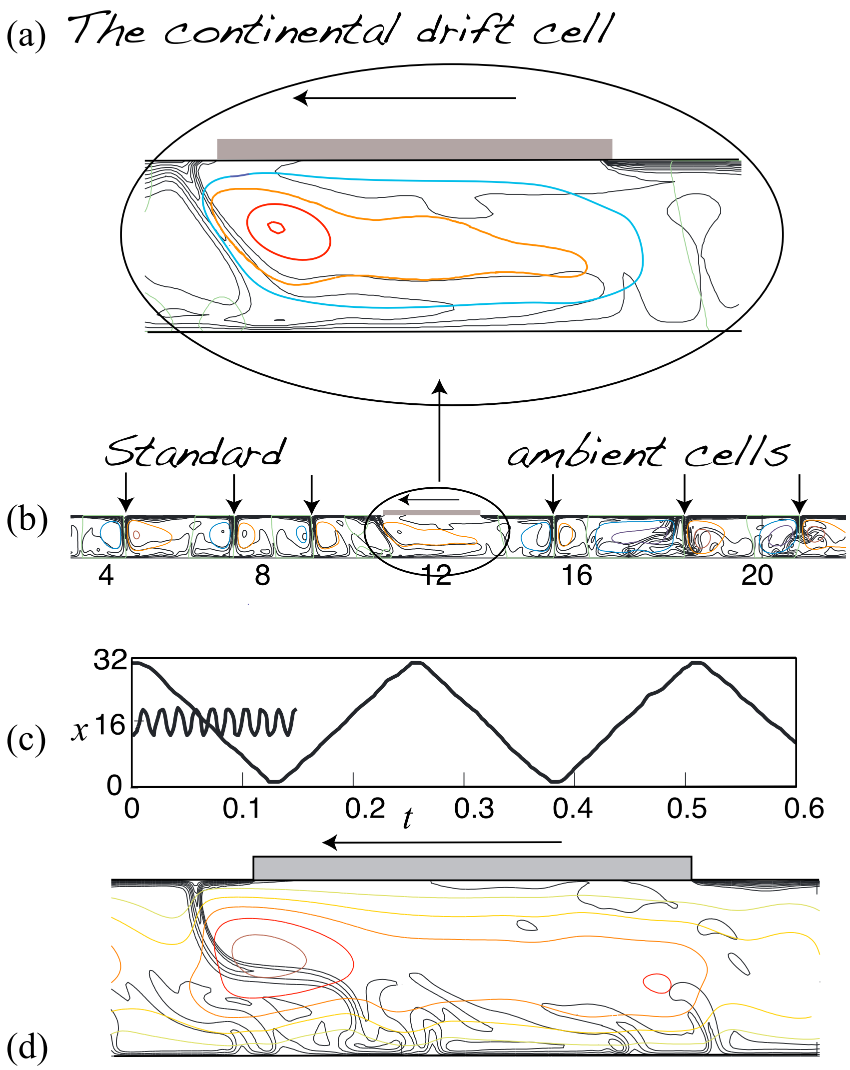

Figure 1. The continental drift convection cell. (Figures 1a and 1b) $Rai = 1.6 \times 10^6$, $h = 8$, $W = 2.5$, and $L = 32$ (more details in section 1 in Text S1). (a) Side view showing the tilted cold slab dipping under the leading edge of the moving continent (grey) and the recirculation under the continent. Behind the continent, a small plume from the bottom hot boundary rises. The stream function is shown by color contours, and every 0.1 temperature isotherm is in black. (b) A more distant view of the same drift cell. The convection cells on either side of the moving continent are undisturbed. (c) Continent locations with time. The long record is for the run shown in Figures 1a and 1b, and the short record is for the run shown in Figure 1d. (d) The drift cell with $Rai = 1.6 \times 10^7$, $h = 8$, $W = 2.5$, and $L = 8$.

3. Results

We report a unique form of convection—the "continental drift convection cell," which is subsequently called the "drift cell" for short. The distinct structure, not described previously (Figure 1a), is monopolar with closed streamlines with the sense of rotation correlated with the continent drift direction instead of bipolar with both clockwise and counterclockwise circulation. At the propagating front of the drift cell, a cold sinking (subducting) thermal "slab" plunges under the moving continent near the leading edge with a downdipping angle. The cold slab provides torque-generating circulation of the proper sense to propel the continent (see Movies S1 and S2 in the supporting information). The subducting slab and the upper half of the fluid under the continent move with the continent. Like a solitary wave, the drift cell and continent move without significantly changing shape. The drift cell overrides ambient cold slabs associated with conventional convection cells, which join the existing subducting slab and become stretched and distorted with time. Near the bottom of the chamber, fluid flows from in front of the

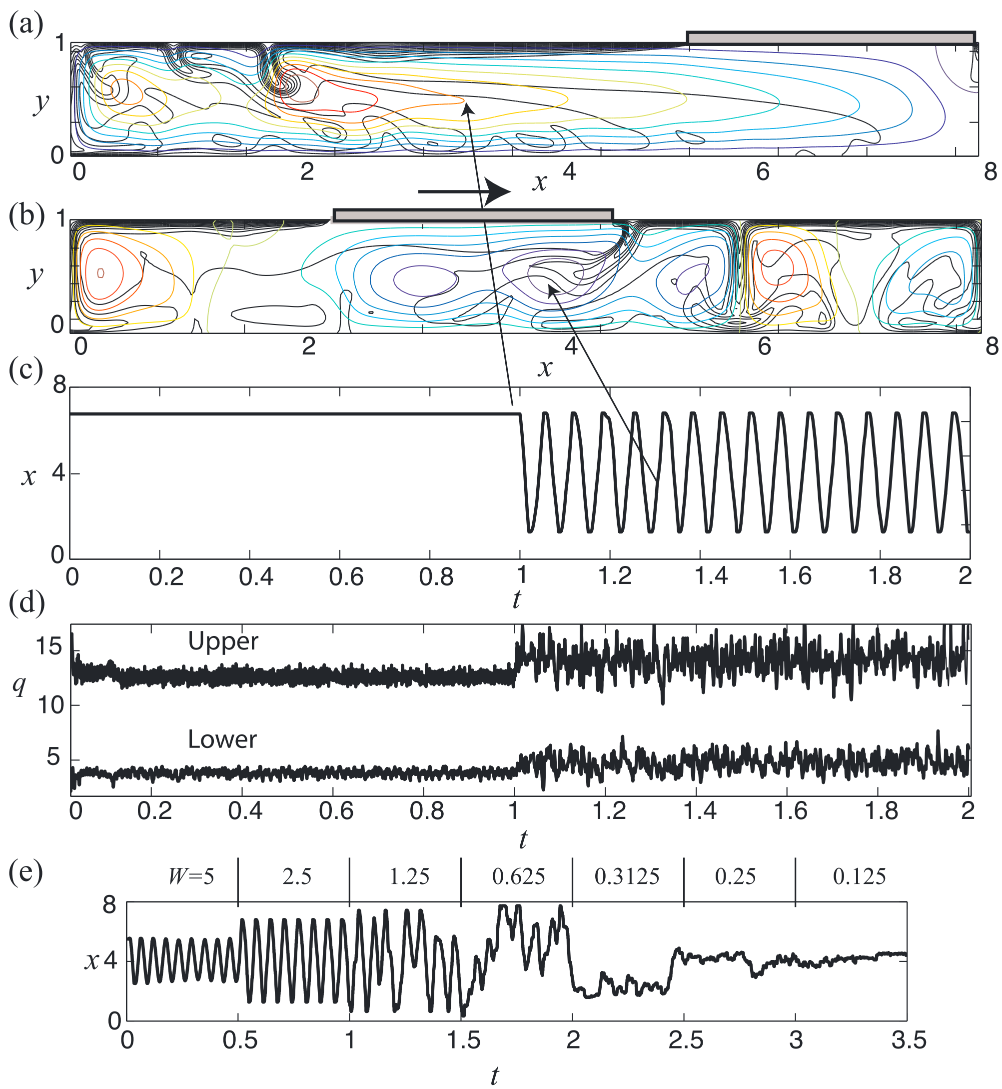

Figure 2. Results for convection with $Rai = 1.6 \times 10^6$, $h = 8$, $L = 8$, and (Figures 2a–2d) $W = 2.5$. (a) The flow with a fixed continent at $t = 1$ (continent shaded) is one long convection cell. Isotherms are black, and colored contours are streamlines. Surface fluid moves toward the left and returns along the bottom toward the right. Thermals only penetrate to the bottom and top at the extreme ends. (b) Convection with a moving continent at $t = 1.3$. Both the drift cell and the continent move toward the right (arrow). (c) Continent center location, fixed until $t = 1$ and then drifting. The drift cell forms almost immediately. (d) Heat flux versus time through the upper and lower boundaries. (e) Continent location for various values of W.

moving continent toward its rear. Some of these features are visible in previous studies [e.g., *Elder*, 1967, Figure 6; *Gurnis*, 1988, Figure 5].

The drift cell is robust and universal. Its existence does not depend on the initial location of the continent, and even if a drifting continent is held fixed for a period of time, the drift cell reappears. A continent located at the exact center of the numerical chamber grid starts with no initial drift, but $O(10^{-15})$ numerical truncation noise grows exponentially and initiates drift and the formation of the drift cell (at approximately 0.2 time units for $Rai = 1.6 \times 10^7$, $h = 8$, $W = 2.5$, and $L = 8$). A small off-center additional numerical perturbation initiates the drift cell even earlier. Therefore, the stationary continent is linearly unstable to drift.

The continental drift cell exists for almost all parameters studied producing long-term cyclic behavior; our ranges for approximately 80 runs are the following: $1000 < Ra < 2 \times 10^6$, $h = 0$, 1, 2, 4, and 8 (up to $Rai = 1.6 \times 10^7$), $W \leq 5$, and $L = 1$, 8, and 32. Figures 1 and 2 show examples with $h = 8$, Figure 3 with $h = 0$, and Figure 4 with $h = 4$ and a thermally insulated bottom. This includes $Ra = 1000$, and a continent with fixed temperature, and rigid continent. Calculations (not described here) also show drift for fluids with $Pr = 1$, 10, and 100.

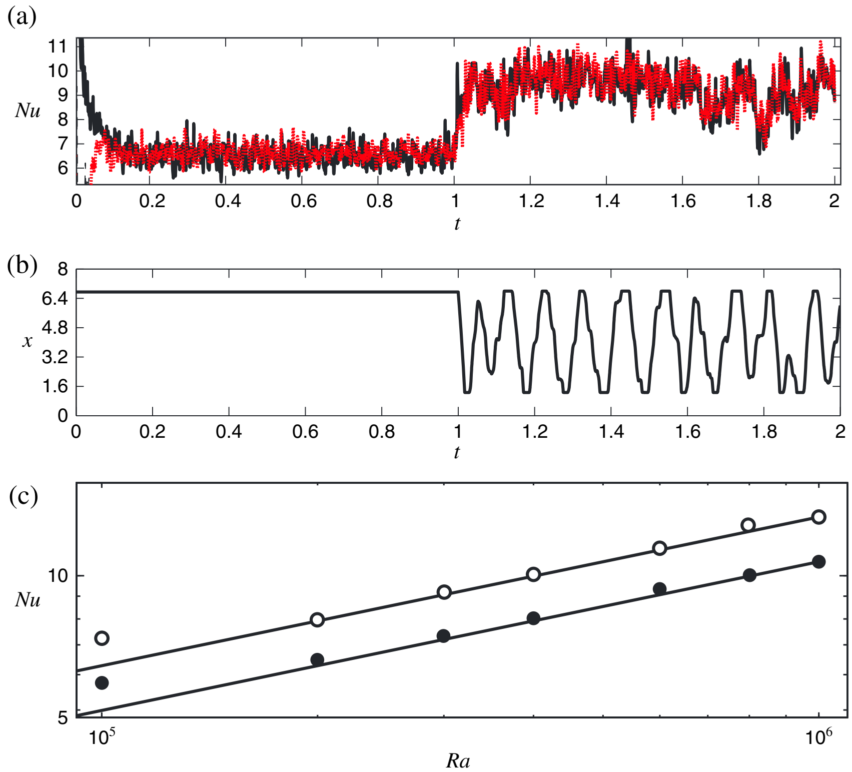

Figure 3. (a) Nusselt number from upward heat flux averaged over the bottom (dashed red curve) and over the top boundary (solid black curve) $Ra = 2 \times 10^5$, $h = 0$, $W = 2.5$, and $L = 8$. (b) Location of the continent center. Continent center location, fixed until $t = 1$ and then drifting. Note a less regular trajectory than in Figure 2. (c) Log-log time-averaged Nu versus Ra for fixed (solid circles) and moving (open circles) continents. Straight lines are fit to the value at $Ra = 10^6$ for each case and are $Nu = 0.1354\, Ra^{1/3}$ for the moving continent and $Nu = 0.1075\, Ra^{1/3}$ for the fixed continent.

Movies S1 and S2 (supporting information) show that the drift cell is easy to identify in the long convection chamber containing many conventional convection cells (Figure 1b). The continent and the drift cell underneath it move through conventional convection cells, which are reestablished after the continent passes. Occasionally the drift cell incorporates additional cells in passing (Figures 1d and 2b). The drift speed is almost constant for each "Wilson cycle" transit except for small changes as ambient convection cells are engulfed (Figure 1c). The relatively constant speed in the midst of undisturbed ambient cells shows that the drift cell is not driven by heating near either sidewall or long wavelength convection cells.

The reflective sidewall boundary conditions produce an array of chambers and continents of alternating sign extending infinitely in both horizontal directions. Thus, the immovable continent at a boundary represents a supercontinent remaining in place [*Grigné et al.*, 2007b], and the continent drifting from the sidewall represents a supercontinent splitting apart into two continents. Later, when the drifting continent arrives at the opposite boundary, a second supercontinent forms. The continent drifting periodically back and forth behaves like the Wilson cycle with cyclic formation and splitting of supercontinents.

The continental drift cell and continent mobility have important consequences. Some are illustrated by comparing two conditions: (1) a continent held fixed at the upper right-hand corner of the domain, as in *Lenardic et al.* [2005, 2011], and (2) a continent free to drift. The fixed continent (Figure 2a) produces a large overturning cell with upwelling under the continent and sinking at the opposite end of the chamber. Most of the sinking plumes move toward the left and reach the bottom at the left end of the tank far away from the continent. Upwelling occurs in much of the interior of the mantle, especially under the continent due to the "thermal blanketing" effect observed in previous studies [*Gurnis*, 1988; *Zhong and Gurnis*, 1993; *Lowman and Jarvis*, 1995, 1996; *Lenardic et al.*, 2005, 2011].

In contrast, the drifting continent and drift cell move back and forth absorbing ambient convection cells as they travel (Figures 2b and 2c). Movies S1 and S2 in the supporting information show this behavior clearly for

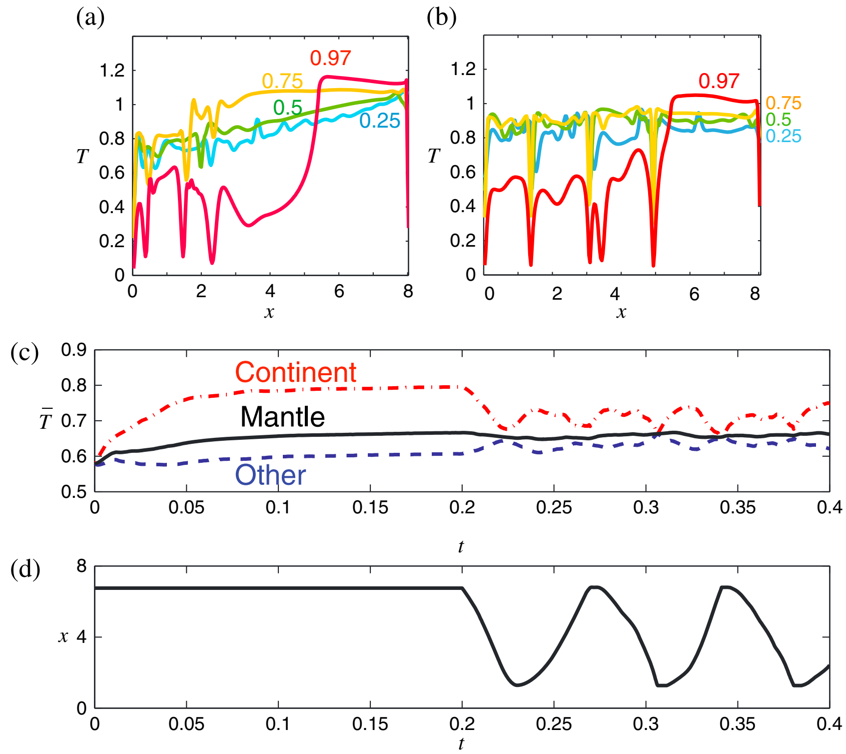

Figure 4. Results with $Rai = 8 \times 10^5$, $L = 8$, and zero chamber bottom heat flux. Horizontal temperature distribution at depths indicated by the numbers for convection for (a) a fixed continent and (b) a moving continent. The continent is at the right-hand side of the chamber in both cases. The temperature distribution curves nearest the surface are almost identical for fixed and moving continents; however, deeper layers have more uniform temperature for the moving continent. (c) Average mantle temperature variation with time in three regions: first below the continent (red dash dotted), second in the mantle not covered by the continent (blue dashed), and third for the entire mantle (black solid). (d) Continent center location with t.

chambers with different aspect ratios. Heat flux q (Figure 2d) with a fixed continent shows little variation with time, but as soon as drift starts, q increases and temporal variation increases. Drift increases q for all runs with $T = 1$ at $z = 0$.

The continental drift cell is sensitive to continent width W (Figure 2e). Drift is relatively steady for $W = 5$ and 2.5, more random for $W = 1.25$ and 0.625, and not present for 0.375. This result is in agreement with laboratory observations of drift for moderate raft sizes, but not small ones [*Zhang and Libchaber*, 2000; *Zhong and Zhang*, 2005; *Liu and Zhang*, 2008]. This implies that small continents might not be associated with steady drift but instead be passively moved by the great tectonic plates.

The increase in heat flux is most dramatic for $h = 0$ (in which $q = Nu$) There is more irregular drift and a substantial change in Nu after drift commences (Figures 3a and 3b). Time-averaged values are $Nu = 6.5$ for $0.8 < t < 1.0$ and $Nu = 8.4$ (29% greater) for $1.8 < t < 2.0$. The increased heat flux with continent mobility holds over a wide range of Ra (Figure 3c). The log-log values have slopes close to one third for $Ra > 10^5$, with a prefactor that is 26% greater for continental drift compared to the fixed continent. The factors that are responsible for q increase with drift seem to be that rising and sinking thermals leave the boundaries more frequently and at more locations with continent movement. They are also less tilted and less impeded by shear of the large cell generated by a stationary continent. Both factors result in more thermals striking the opposite boundary more vigorously and thereby increasing heat flux.

Drift strongly influences other properties of the mantle thermal structure in addition to those shown in Figure 3. For example, the amplitudes of lateral temperature differences changes with drift (Figures 4a and 4b). The average mantle temperature under a fixed continent is approximately 0.2 above the average mantle temperature within the sinking region at the chamber's opposite end (Figure 4c). In contrast, with a moving continent (Wilson cycle) the average lateral temperature differences are < 0.1 with peaks during continent assembly (see section 2 in Text S1). Results shown in Figure 4 have zero bottom heat flow, but similar results occur with the bottom at $T = 1$ and $h = 0$, 1, 2, 4, and 8.

Other aspects of the temperature distribution within the chamber are less affected by drift. With zero heat flux boundary condition imposed at the bottom, the horizontally averaged basal temperature at $y = 0$ is altered from fixed to drift by only 5%. In addition, the vertical temperature distribution is not sensitive to drift (supporting information).

4. Discussion

Calculations in the range $10^4 > Rai > 2 \times 10^7$ universally reveal the existence of a distinct continental drift convection cell. Instead of a fixed supercontinent producing a large convection cell as in Figure 2a, the drift cell is localized under the drifting continent as in Figure 1a. The drift cell is rugged and emerges as a linear instability as found for small chambers [*Whitehead et al*., 2011, 2014]. Important parameters such as vertical heat transfer and lateral temperature changes are greatly affected by the drift cell and its associated continent motion. Heat transfer increases with drift because the drift makes more plentiful thermals that more efficiently penetrate vertically in the mantle. Lateral temperature changes are smaller because heat does not have time to build up under a moving continent compared to a stationary one.

Attributing a specific value of *Ra* to the Earth is not precise because Earth properties vary greatly with pressure, temperature, and deformation rate. Thus, although $Ra = 1.6 \times 10^7$ only approaches the value generally attributed to Earth ($Ra \sim 10^7$–10^9), we hope this letter will stimulate further calculation at larger values of *Ra*.

Although our model is sufficiently simple that one might not expect details resembling mantle convection on Earth, remarkably, the drift cell, produces some distinctive features of plate tectonics. For example, the "Ring of Fire" surrounding the Pacific Ocean is circumscribed by continents and outward dipping subduction zones, consistent with our result that subduction zones are preferentially located at the leading edge of moving continents with a dip direction toward the continent (Figure 1). Moreover, the drift cell has subduction zones moving with the adjacent continent. This is generally true for the Pacific as the ocean basin is currently closing and the continents (and subduction zones) are migrating together [*DeMets et al*., 1990]. Also, mantle flow at shallow levels under a continent is directed in the same direction as the continent motion. Finally, there is a return flow at deep levels beneath the moving continents. These are observed to some extent within the Earth in global models of instantaneous mantle flow driven by plate motions and mantle density heterogeneity [*Becker et al*., 2003; *Conrad and Behn*, 2010]. However, mantle flow direction under continents is difficult to verify unambiguously given the three dimensionality of mantle convection and because of uncertainties in what constitutes the most appropriate absolute reference frame for plate motions [*Becker and Faccenna*, 2009]. Not surprisingly, other results in our simple model are not as easily compared with Earth. For example, our predicted heat flow under the continent varies with the Wilson cycle (Figures 2d and 3a), but such a correlation is unclear for Earth, although similar results are suggested by *Rolf et al*. [2012].

Some results here agree with other studies and some do not. The decrease in lateral mantle temperatures with drift that is found here is also observed in simulations with moving continents [*Lenardic et al*., 2011], and with assembling and dispersing continents [*Rolf et al*., 2012]. Fixed continents with insulating boundary conditions rather than stress conditions are also known to generate warmer mantle beneath them, but the effect is alleviated by temperature-dependent viscosity and with greater *Ra* [*Lenardic et al*., 2011]. In contrast, our results show an increase in heat flow with a continent, while some realistic mantle convection models do not [*Lenardic et al*., 2005, 2011]. Moreover, we note that there is no mention of the presence of subduction under the leading edge of continents in the numerical models cited in section 1 and in the laboratory [*Zhang and Libchaber*, 2000; *Zhong and Zhang*, 2005; *Liu and Zhang*, 2008]. Also, very little is known about the effects of continents on heat flow out of the core (Figure 4).

Since the present study is too simplified to apply to Earth, the primary purpose of this letter is to motivate additional studies. More observations are of course, most welcome. Additional laboratory and numerical studies are needed with mobile continents, realistic Earth properties, and spherical geometries to answer the following outstanding questions: Does flow under the continents with Earth-like viscosity structures resemble the monopolar continental drift convection cell with subduction under the leading edge? Does the Wilson cycle affect lateral variations in mantle structure? Does the Wilson cycle increase the rate of heat transfer from both the core and mantle as found here?

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