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# [Geophysics Research Letters]

Supporting Information for

# The Continental Drift Convection Cell

J. A. Whitehead<sup>1</sup>

Mark D. Behn<sup>2</sup>

<sup>1</sup> Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole MA 02543 <sup>2</sup> Department of Geology and Geophysics, Woods Hole Oceanographic

Institution, Woods Hole MA 02543

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#### 1. Additional Results of computations

One of the most convincing views of the continental drift convection drift cell shows it as an isolated convection cell under the moving continent amongst numerous normal convection cells in a simulation with a large aspect ratio (32:1) box (Figure S1.1).

It is useful to define a quantitative measure of the drift cell temperature change across the region under the continent. The difference between the depth-averaged temperature of the mantle under each of the two edges is one good measure. We define

the depth-averaged temperature under the right edge as TR(t) and the depth averaged temperature under the left edge as TL(t). The difference is DelT(t)=TR-TL and this is plotted with time in Figure S1.1. The governing parameters are the same as the example in Figure 1a,b. The same parameters are used in a smaller chamber for Figure S1.2. Results are almost identical for  $Rai=2x10^7$ . When the continent moves toward the right (greater x), the right temperature is colder than the left (DelT < 0) and the inverse is true for the continent moving to the left. Therefore, *DelT* correlates negatively to the sign of the travel direction. This means that the cold mantle leads the moving continent and hot mantle trails behind it. This of course drives the drift cell with the proper sense to propel the continent. Over time, there are almost no exceptions to this correlation, so drift is relatively steady and a Wilson cycle exists. Note also that the reversal of the continent direction at the end, which is a model of supercontinent formation and breakup, is accompanied by a large spike in *DelT*. Mechanically, this spike would correspond to a very large compression into the wall before the torque and the direction of flow reverse. Perhaps this may be correlated with intense mountain building forces during collision, as is the case with the Himalayas.



Figure S1.1. (a) Section showing stream function (color contours) and isotherms (every 0.1 temperature unit in black). The continent is grey and moving toward the left as indicated by the arrow.  $Rai=1.6\times10^6$ , h=8, W=2.5, L=32, Tb=1. (b) TL, the temperature vertically averaged along the grid points exactly below the left edge of the continent (red, top) and TR, averaged along the grid points exactly below the right edge of the continent (blue, top). Also the difference (DelT(t), black, bottom). (c) Location of the center of the continent over time.



Figure S1.2. Closer view of the difference in depth-averaged temperature DelT(t) (solid) under the two edges of the continent versus time in a smaller chamber. Above this curve is the location of the center of the continent (dashed).  $Ra=1.6\times10^6$ , h=8, W=2.5, L=8.

The fixed continent creates much larger lateral temperature variations in the mantle than does the moving continent. This is shown in runs with a variety of internal heating values and also runs with internal heating and a zero heat flux bottom boundary condition (Figures S1.2 and S1.3).



Figure S1.3. Horizontal temperature distribution at constant elevations above the bottom for both fixed continents (top row, panels a,b) and moving continents (bottom row, panels c,d). The numbers indicate elevation above the bottom.  $Ra=2x10^5$ , L=8, W=2.5, and (a,c)  $Rai=8x10^5$ , h=4,  $\partial T/\partial z = 0$  at z=0. (b,d) h=0, Tb=1.



Figure S1.4. As in Figure S1.3b,d with Tb=1 and progressively greater internal heating (a,d) h=4. (b,e) h=8, (c,f) h=16.

The heat flux is slightly time dependent, so the actual mean over time varies with the averaging interval. For the case in Figure 3 in which  $Ra=2x10^5$ , with Tb=1 and h=0, the variations are less than 2% for intervals with different starting times with a duration of 0.2 time units. This variation is much less than the difference in heat flux of approximately tens of percent from a drifting continent compared to a fixed continent and thus it is safe to conclude that drift increases heat flow by factors of tens of percent.

We conducted an exercise to find out how well average heat flow values are resolved. The precision of the heat flux calculations is indicated by the average q and its standard deviation (Table 1) for the case with zero heat flow into the bottom and h=4. The value of ideal q is calculated by using the elevation of a point between grid points and multiplying by h. For example, the lowest internal grid point is at x=1/32 and the elevation of the point between this grid point and the one above is 3/64. Using h=4, the value of ideal q is 3/16=0.1875, which is rounded off to the value in Table 1. The values for q and standard deviation for the fixed continent are averaged over the interval 0.8 < t < 1.0 and for the drifting continent 1.8 < t < 2.0. The greatest difference between the measured amount and the ideal value is 0.104, a value less than the standard deviation. Some of the difference is due to the scatter visible in Figure S1.5 and this depends on

depth and the interval of the averaging. Other differences are due to errors in the computation from the finite grid size, especially near the top where the thermal boundary layer is not perfectly resolved.

	Ideal	Fixed continent		Moving continent	
x	q	q	SD	q	SD
0.9687	3.925	3.995	0.407	3.982	0.283
0.9374	3.812	3.916	0.148	3.899	0.364
0.5	2.063	2.081	0.58	2.07	0.969
0.0626	0.313	0.317	0.084	0.321	0.186
0.0313	0.188	0.189	0.084	0.188	0.102

Table 1. Heat flux q for convection with an insulating bottom to the chamber and h=4 at different elevations and their standard deviation from time series like those in Figure S1.5. The values in the column labeled "ideal" are the upward integral of the heat flow for constant q taking account of the different grid point locations.

For convection with zero heat flow into the bottom  $(\partial T/\partial z = 0)$  and with internal heating, since heat flow out of the top is fixed an alternate indicator of heat flow efficiency is the average of temperature along the bottom Tb(t). For the time interval 0.8 < t < 1 with the continent held fixed, the average value of Tb is  $0.339 \pm 0.002$  and for the interval 1.8 < t < 2.0 with drifting continent, the average value of bottom temperature is  $0.359 \pm 0.008$  (Figure S1.5). The fact that the drifting continent has a warmer bottom temperature than the stationary continent is surprising as it seems to disagree with the notion that drifting continents provide enhanced heat flux. The reason for the colder bottom temperatures with fixed continent appears to be associated with the mass of colder fluid (of order 0.2) that descends at the left end of the chamber and flows along the bottom (see Figure 2). This mass is also shown in Figure S1.3a.



Figure S1.5. Laterally averaged bottom temperature in convection with zero heat flux set at the bottom and h=4. Rai=8x10<sup>5</sup>, W=2.5, and L=8. (a) T averaged over x at y=0. (b) The location of the continent center. The continent is fixed in one spot until t=1 when the Wilson cycle starts.

Figures S1.6 and S1.7 show horizontally averaged temperature versus elevation over the bottom for both fixed and drifting continents in runs with different internal heating and bottom boundary conditions. Figure S1.6 shows results for two cases with particularly extreme conditions: one case has only internal heating along with zero bottom heat flow, and the other case has zero internal heating with a fixed bottom temperature. As discussed in the preceding paragraph, the convection with internal heating and zero bottom heat flux does not have a cooler bottom temperature with a drifting continent (Figure 1.6a). The overall shapes of the vertical temperature distributions are generally insensitive to drift, although exact values do change. Figure S1.7 has fixed bottom temperature and three values of internal heating. Again, all the curves have similar shapes. There is a boundary layer at the top, a temperature maximum at about 0.1 to 0.2 depth, and relatively constant decrease in temperature below that. The cases with heat flow coming from below have bottom boundary layers but for h=16 the heat flow through the bottom is close to zero. Therefore, to a first approximation the vertical temperature distribution is relatively unaffected to either fixed or drifting continents.



Figure S1.6. Vertical distribution of horizontally averaged temperature moving continents (dashed), fixed continents (solid) and without a continent (heavy solid), with  $Ra=2x10^5$ , W=2.5, and L=8. (a) Pure internal heating,  $Rai=8x10^5$ , h=4,  $\partial T/\partial z = 0$  at z=0. (b) Purely heated from below, h=0, Tb=1.



Figure S1.7. The same as S1.6 for internal heating and fixed bottom temperature. Vertical distribution of horizontally averaged temperature for both moving (dashed) and fixed continents (solid) with  $Ra=2x10^5$ , W=2.5, L=8, and Tb=1 with internal heating. (a) h=4, (b) h=8, (c) h=16.

#### 2. The continental drift convection cell at *Ra=1000*.

The continental drift convection cell exists at all values of *Ra* studied. For example, the convection at Ra=1000 has an unmistakable drift cell (Figure S2). This run was started with the continent located at the far right and mantle T=1. Convection starts as a Rayleigh – Taylor instability of the cold top boundary layer (growing very much like an error function) with cold sinking plumes starting first near the continent and then propagating toward the left. The continent then moves to the left accompanied by a periodic strengthening and weakening of the drift cell as revealed by the red isopleths that move with the continent. Other starting locations similarly produce the drift cell. The cold subduction zone is not tilted as at larger Ra. Instead, downwelling is closer to the leading edge of the moving continent than the downwelling behind the trailing edge. Notably, the maximum value of streamfunction is much larger for the drift cell than for the ambient cells, in fact the amplitude of the continental drift convection cell is almost two times greater than the amplitude of the ordinary convection cells. This is quantitative evidence that supports the idea that the continental drift convection cell is a different mode of flow from normal Rayleigh-Benard cells. Further studies in this range of Ra can be expected to clarify the nature of the drift convection cell.



Figure S2. (a) A continent moving toward the left (arrow) in a wide chamber for  $Ra=10^3$ , h=8, W=2.5, L=32. (b) The maximum value of stream function under each point along the top of the chamber.

#### 3. Drift with a continent held at fixed temperature.

A continent that is held at a fixed temperature *Tcn* develops the same type of selfpropelled drift as an insulated continent. The example shown in Figure S3 has clearly developed Wilson cycles for continents with the temperature of the continent set to the two values *Tcn*=1 and *Tcn*=0.5. In contrast, there is a less developed periodicity with *Tcn*=0.25. There is moderate sinking under the continent (panel a) and the drift cell is absent. Studies at low *Ra* in a chamber with *L*=1 also find similar drift back and forth for either insulating and for fixed-temperature continents [Whitehead et al 2011, 2014]. Thus drift under a warm continent seems to be similar to those with an insulating continent



Figure S3. (a) Section showing isotherms and streamfunction at t=2.8. (b) Continent trajectory with the continent temperature held at Tcn=1 for t<t<1, then held at Tcn=0.5 until t=1.9, and finally held at Tcn=0.25 until t=2.8.  $Ra=2x10^5$ ,  $Rai=1.6x10^6$ , h=8, W=2.5, L=8.

#### 4 Rigid coupling of continents with flow

We mechanically couple the continent to the fluid by adding additional flows to the interior to match the continent velocity at the surface. Since the flow equations are linear, superposition applies to the equations of motion, and the sum of all the flows is used to advect temperature. Velocity profiles (Figure S4.1) show how the two successive approximations improve the profile to a rigid lid flow. The continent trajectories (Figure S4.2) show that there is a small change in drift velocity but the trajectory shape is approximately the same. Further results are currently being prepared.



Figure S4.1. The lateral velocity *u* along the top showing a first approximation (red dashed) and a second approximation (solid blue) to a stress-matching condition under the continent in comparison with the free-slip profile (green dashed) used in the present calculations.



Figure S4.2. Continent trajectories for the cases shown in Figure S4.1: the original freeslip under the continent (green dashed), first approximation (red dashed), and second approximation (solid blue).

## **5** List of Movies

The videos Movie S1 and Movie S2 show the evolution of steamfunction, temperature, and continent position with two different values of L. The brown rectangle shows the continent.

Movie S1, WhiteheadBehn-ms01.mp4 has  $Rai=1.6 \times 10^6$ , h=8, W=2.5, and L=8.

Movie S2, WhiteheadBehn-ms02.mp4 has  $Rai=1.6 \times 10^6$ , h=8, W=2.5, and L=16.