Low Pacific Secular Variation

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Abstract. The historical record shows that secular variation at Hawaii is limited to a few degrees in the last 400 years, whereas in the Atlantic hemisphere it often exceeds 30°. Paleomagnetic measurements from Hawaii show virtually no change in declination during the last 5 kyr and only a slow, millenium-scale inclination change of less than 20°. The usual directional scatter analysis of paleomagnetic data cannot discriminate between the two time scales. The disparity of time scales and difference in activity suggest different physical mechanisms for secular variation in the two hemispheres. This could arise from thermal core-mantle interaction. Seismic models of the lower mantle give a pattern of lateral variations that is nearly symmetric about the Pacific rim: two slow regions centred beneath the Pacific and Atlantic separated by a fast ring below the Pacific rim. These seismic anomalies are thought to be caused mostly by temperature variations in the bottom 200 km of the mantle. It is difficult to see how such a symmetric pattern could lead to long-term hemispheric differences. We show here a convection solution in a rapidly rotating sphere with heat flux on the outer boundary determined from a seismic model. The convection is suppressed beneath the Pacific but the usual drifting convection (Busse) rolls remain beneath the Atlantic. This mode of periodic convection arises because the Pacific hot region extends east-west and is much larger than a single convection roll, whereas the Atlantic hot region is elongated north-south and is about the same east-west size as a convection roll. This could explain the absence of normal, century-long secular variation in the Pacific: hot mantle suppresses short wavelength phenomena at the century time scale but not the longer wavelengths at the millenium time scale.

Introduction

There is growing evidence for influence of temperature anomalies in the overlying mantle on the Earth's magnetic field [*Bloxham*, 2000; *Bloxham and Gubbins*, 1987; *Olson and Glatzmaier*, 1996]. Magnetic flux on the core-mantle boundary (CMB) tends to concentrate near regions of fast lower mantle seismic velocity, leading to departures from axial symmetry in both the present field [*Bloxham and Gubbins*, 1987] and the long-term time average [*Gubbins and Kelly*, 1993; *Johnson and Constable*, 1995; *Kelly and Gubbins*, 1997]; virtual geomagnetic poles tend to concentrate on a great circle enclosing the Pacific during reversals [*Laj et al.*, 1991]; and the Pacific region appears to have low secular variation (SV) [*Merrill, McElhinny and McFadden*, 1998; *Walker and Backus*, 1996]. While all this evidence is the subject of current debate, the first two can be explained by a single theory in which cold mantle induces downwelling in the core and concentrates surface magnetic field. This, together with the repeated occurence of the same pair of longitudes around the Pacific where the seismic velocity is fast, is compelling evidence that the lower mantle does influence the geomagnetic field.

Rapid convection in the core maintains the temperature very close to the adiabat. The CMB may be considered isothermal for the purposes of mantle convection, which is much slower and allows departures from the adiabat of several hundred degrees. The appropriate boundary condition for core convection is fixed heat flux, including the lateral variations imposed by the convecting mantle. We may estimate the pattern, and to some extent the amplitude, of CMB heat flux from seismic tomography. If S-wave speed in the lowermost mantle is assumed to be caused entirely by temperature variations in a thermal boundary layer, the heat flow across the CMB is simply proportional to the variations in S-wave velocity. The constant of proportionality is difficult to estimate: it depends on the thermal conductivity of the lower mantle and the thickness of the boundary layer. A recent tomographic model [*Masters et al.*, 1996] of lower mantle S-wave velocity is shown in Figure 1. This is used as the pattern of Figure 1 boundary heat flux in the calculations of this paper. Other studies have used similar patterns. The dominant features are the ring of high velocity around the Pacific, taken to be cold mantle and high heat flow from the core, and low velocity in the central Pacific and Atlantic, taken to be low heat flow. The dominant spherical harmonic in the expansion of the S-wave velocity has degree and order 2. Given such a pattern it is difficult to see how the Pacific hemisphere could behave any differently from the Atlantic hemisphere for a significant length of time. It is possible that the cold regions could produce a blocking effect, perhaps inhibiting SV in the Pacific for a few overturn times of core convection (1000 years), but it is very unlikely to do so for longer periods.

Zhang and Gubbins [1992] studied the effects of laterally varying heat flow on rotating convection in a sphere by calculating the steady thermal wind in the absence of heating from within and for stable stratification. *Zhang and Gubbins* [1993] explored the effects of simple patterns of boundary temperature on non-magnetic, rapidly rotating, infinite Prandtl number convection at low and moderate Rayleigh numbers. They found three effects: spatial resonance, where convection is dominated by the same azimuthal wavenumber m as the boundary condition; locking, where the drifting convection rolls become stationary; and secondary resonance, where convection was preferred with m a simple multiple of that of the applied boundary condition. Locking and resonance could, therefore, lead to a pattern of core convection that reflects the pattern of lower mantle heat flux.

Sun, Schubert and Glatzmaier [1994] studied some solutions at high Rayleigh number and found less evidence of locking or boundary influence. *Zhang and Gubbins* [1996] found locking to be less prevalent at finite Prantl number because of inertia. *Olson and Glatzmaier* [1996] were first to study magnetoconvection with boundary variations, finite Prandtl number, a highly supercritical Rayleigh number, and very strong lateral variations. Like *Sun, Schubert and Glatzmaier* [1994], they found no locking in either of the two combinations of parameters they examined. *Sarson, Jones* *and Longbottom* [1997] were first to include inhomogeneous boundary conditions in a dynamo calculation. They found flux concentrated by downwellings but downwellings did not always coincide with high heat flux.

Inhomogeneous thermal boundary conditions have also been applied to dynamo models. *Glatzmaier et al.* [1999] examined a number of different boundary conditions and their effect on reversal behaviour, and found the most "realistic" reversal with homogeneous boundary conditions. *Bloxham* [2000] (see also *Bloxham* [2002]) studied the time-averaged field for a dynamo model with a spherical harmonic degree and order 2 pattern of heat flow and found strong similarity between the time average of his dynamo and the paleomagnetic time average of *Kelly and Gubbins* [1997]. He also speculated that low SV in the Pacific could arise from eastward convective flow, associated with displacement of the main convection rolls into that hemisphere, cancelling the general westward drift of the core as a whole. His model rarely generated a field like the present-day geomagnetic field and he concluded that the resemblance between the present-day field and the paleomagnetic time average is largely fortuitous. The most complete study to date of SV with a dynamo model is by *Christensen and Olson* [2003] [see also *Olson and Christensen* [2002]], who use a boundary heating based on the seismic tomography truncated back to spherical harmonic degree 4, 27% of the vertical heat flux, and three vertical heating strengths. Their model has rather weak SV for their main choice of heating and a highly variable dipole moment for stronger heating. They find strongest SV where the boundary heat flux is highest and variations in VGP scatter in both latitude and longitude. Westward drift is low in the east Pacific but not the west.

While some of these models hint at low SV in the hot Pacific region, none of them reproduce as clear a hemispheric division as we see in the historical record of *Jackson, Jonkers and Walker* [2000]. The main question remains: is the present situation merely an occasional pattern that contributes to the time-average, as Bloxham suggests, or is it a semi-permanent feature of the geomagnetic field? If it is a long-term feature, how could it arise from a lower mantle heat flow pattern that is predominantly symmetric about the two hemispheres?

Observations

Hawaii offers an ideal dataset to examine SV. It lies close to the centre of the Pacific Basin, so that magnetic measurements made there are predominantly influenced by the CMB within the ring of high seismic velocity. It has a magnetic observatory and has been well sampled in both declination D and inclination I since James Cook's arrival in 1778. Earlier measurements of D were made nearby by navigators crossing the Pacific, the most notable voyage being that of Jacques L'Hermite [*Hutcheson*, 1990]. The global historical record dates from AD1550; I measurements are rare anywhere before AD 1700 and non-existent in the Pacific; and intensity measurements are nonexistent before 1839. The time-dependent global field model of *Jackson, Jonkers and Walker* [2000] gives reliable D in the Pacific back to at least 1600, and I can be relied upon back to 1700. Claims of a D anomaly in the Pacific in the 17th century [*Yukutake* [1993], discussed in *Merrill, McElhinny and McFadden* [1998]] are based on uncorrected catalogue data; using original sources [*Hutcheson and Gubbins*, 1990] and a vastly enlarged database [*Jackson, Jonkers and Walker*, 2000] shows no strong SV in the Pacific in the last 400 years.

Determining SV from paleomagnetism in the Pacific has a long history, starting with *Doell and Cox* [1963]. A controversy centres on whether the lava flows sampled a sufficiently long time interval to provide a representative record. The time average in question is one that removes normal SV, namely fluctuations in the field that do not encompass transitions of polarity during excursions and reversals. Excursions occur every 20–50 kyr, so a shorter time is needed for the average to have its intended meaning. Bloxham found 5 kyr adequate for his dynamo, and 10–20 kyr should be plenty for the Earth. The time interval 1–50 kyr lies within the range of C^{14} dating and many Hawaiian lava flows have been dated. These dates, plus Hawaii's unique position in the central north Pacific, make the recent lava flows ideal for extending the historical record.

We first compare SV on Hawaii with that in the Atlantic hemisphere by plotting variations in D and I from model `gufm` [*Jackson, Jonkers and Walker*, 2000] for a location on Kilauea volcano and a point on the same latitude on the Greenwich Meridian Figure 2. Choosing the same latitude makes D and I directly comparable. Both D and I change by 30° in 150 years in the Atlantic, whereas the variation in Hawaii is less than 5°. This illustrates quite dramatically the lack of SV in Hawaii in historical times. The point on the Greenwich Meridian does not have particularly strong SV: the largest variations are in southern Africa. 400 years is sufficiently long to show the kind of variation seen in the Atlantic but it is too short a time to establish the Hawaiian low as a permanent feature: for that we need paleomagnetism. Figure 2

The historical record also provides an opportunity to check the accuracy of published paleomagnetic data using lava flows that have erupted in historical times[1]. These are also plotted in Figure 2. They are consistent with model `gufm`. The systematic low paleomagnetic I has not been noted before: it could be caused by magnetisation of the seamount. Even with this systematic error paleomagnetism can detect Altantic-type SV: 30° is a huge variation and 150 years a short time. The problem is not accuracy of measurement but resolution in time.

Many recent lava flows have been dated by C^{14} [*Lockwood*, 1995]. While there are known problems with C^{14} dating in volcanic environments, this is still the best dating series available for SV studies anywhere. Paleomagnetism has been carried out on most

[1]Historical flows include all those recorded since Cook's arrival in the Islands, including the AD1750 and 1775 flows that were within living memory on Cook's arrival.

of the younger lavas [*Hagstrum and Champion*, 1995]. Their compilation of D and I are plotted in Figure 3 for the last 5 kyr. If we drew a smooth curve through each of these sets of points, allowing 10° scatter to account for the paleomagnetic errors as suggested by the historical flows and for errors in the dating, we would conclude that D is effectively constant and I has suffered a dip of about 20° at age 1–2 ka. We could draw a much rougher line, with the 150-year time variation of Atlantic SV, and fit the points more accurately. Such a curve would be physically plausible because we see similar rapid SV in the Atlantic region today, but it would require over-fitting of both the paleomagnetic and the age data. The only reasonable interpretation of Figure 3 is a slow change in I with a possible century-timescale SV limited in amplitude to about $\pm 10^\circ$ in both D and I. The larger change in I (20°) takes place over a much longer time scale of about 5 kyr and is significantly smaller in amplitude than than is observed in the Atlantic hemisphere in a mere 150 years ($> 30^\circ$). Figure 3

If we were to abandon the time series and examine VGP scatter statistics we would lose the difference in time scales between Atlantic and Pacific SV. Instead, we would find Hawaii registering a VGP scatter somewhat smaller than the global mean, which is the case for most of the Brunhes [*Love and Constable*, 2003]. This is not a very strong result, but the difference in timescales demands a different physical mechanism for the short term SV in the Atlantic, which defines normal "geomagnetic" SV, and the long term variations in the Pacific, which can only be detected by paleomagnetism and is usually called "paleomagnetic" SV.

Core Convection

We have explored the influence of lateral variations in boundary heat flux on non-magnetic, rotating, convection in a spherical shell with the same dimensions as the Earth's outer core. A fixed heat flux is imposed on the outer boundary; fixed temperature on the inner boundary. We studied the thermal winds driven by the outer boundary condition in an earlier paper [*Gibbons and Gubbins*, 2000], which gives further details of the model formulation; in this paper we also drive convection from below. The solutions are time-dependent; they are obtained using the *GJZ* code from the convection and dynamo benchmark study [*Christensen et al.*, 2001]. The only modification necessary was the implementation of laterally heterogeneous heating at the boundary, which was tested by reproducing the time-dependent results of *Zhang and Gubbins* [1996].

The solution depends on four parameters: the Ekman number E, which measures the importance of rotation; the Prandtl number P_r, the ratio of diffusivities; the vertical Rayleigh number Ra^{V}, which measures the strength of vertical heating; and the horizontal Rayleigh number Ra^{H}, which measures the strength of the boundary variations:

$$E = \frac{\nu}{2\Omega d^2}, \quad P_r = \frac{\nu}{\kappa}, \quad Ra^{\mathrm{V}} = \frac{\alpha\beta\gamma d^6}{\nu\kappa},$$

where ν is the kinematic viscosity, κ the thermal diffusivity, Ω the rotation rate, d the shell (outer core) thickness, α the coefficient of thermal expansion, β the mean temperature gradient on the boundary, and γ gravitational acceleration divided by radius. Ra^{H} is defined in the same wave as Ra^{V} with β replaced by the variation in temperature gradient around the boundary.

We illustrate the result relevant to this paper with three simple calculations. All have $E = 2 \times 10^{-4}$, $P_r = 1$, and $Ra^{\mathrm{V}} = 1.15 \times 10^5$; they differ by $Ra^{\mathrm{H}} = 0.1Ra^{\mathrm{V}}, 0.3Ra^{\mathrm{V}}, 0.7Ra^{\mathrm{V}}$. The solution with homogeneous boundary conditions ($Ra^{\mathrm{H}} = 0$) has critical Rayleigh number $Ra^{\mathrm{V}}_{\mathrm{C}} = 1.04 \times 10^5$, so our choice of Rayleigh number (Ra^{V}) is $1.1Ra^{\mathrm{V}}_{\mathrm{C}}$. The solution at onset takes the usual form of prograde-(eastward)-drifting convection ("Busse") rolls aligned with the spin axis and stationary in a co-rotating frame of reference. The critical number of convection rolls is $m = 7$.

The three solutions with inhomogeneous boundary conditions are shown in Figure 4. Figure 4
All solutions are periodic in time, but they do not drift steadily. They cannot be

stationary in a co-rotating frame because the boundary conditions are time-dependent in such a frame. The solution with weakest boundary variation, $Ra^{\mathrm{H}} = 0.1Ra^{\mathrm{V}}$, is very similar to the homogeneous case. The convection rolls are only slightly distorted by the boundary condition and the drift rate is nearly uniform. The second solution is dramatically different and exhibits convection rolls only in one half of the sphere, away from the Pacific region. The third solution is dominated by $m = 2$ convection and is almost stationary.

These results can be interpreted in terms of the resonance between the applied boundary heat flux pattern and the natural length scale of convection with homogeneous boundary conditions, as established in the study by *Zhang and Gubbins* [1993]. Weak boundary heating simply alters the uniform drift of the convection rolls so that it slows when convection brings heat up beneath regions of high boundary heat flux, and speeds up when convection brings heat up beneath regions of low boundary heat flux. There is no locking because the predominant azimuthal wavenumber ($m = 8$, Figure 4a) is so different from that of the boundary heating ($m = 2$). Strong boundary heating causes the resonance with $m = 2$ convection, and almost locks it (Figure 4c).

The intermediate case, $Ra^{\mathrm{H}} = 0.3Ra^{\mathrm{V}}$, is the most interesting. The drifting roll structure is maintained for about half the sphere. Rolls initiate to the east of the Pacific hot region and drift east, then dissipate at the western end of the hot region. An animation shows that, in between, they drift fairly uniformly, even beneath the Atlantic hot region. The Pacific hot region covers a far wider range of longitude than the Atlantic hot region and the resulting stable stratification penetrates far deeper into the core beneath the Pacific than beneaththe Atlantic. The length scale of the underlying convection, which has $m = 8$, is comparable to the longitudinal extent of the Atlantic hot region but is considerably smaller than that of the Pacific hot region, with the result that rolls on this scale are completely suppressed beneath the Pacific, as could be expected with 30% lateral variation in heating and only 10% supercritical heating.

The appearance of rolls at one side of the Pacific and their dissipation at the other is, apart from the sense of drift, reminiscent of the way in which features in the geomagnetic field at the CMB drift westwards from the longitude of Australia and Indonesia towards that of the west coast of the Americas but no further. This very simple convection result can explain why there is a difference between the Atlantic and Pacific hemispheres despite a predominantly symmetric lower mantle structure: the Pacific anomaly is sufficiently extensive in longitude to suppress convection whereas the Atlantic anomaly is not.

Eastward rather than westward drift is an obvious limitation of this model. It is well known that, under the majority of conditions, convection rolls drift prograde (eastward) in the absence of a magnetic field (see, for example, *Zhang and Busse* [1987]). The presence of a magnetic field complicates things greatly; *Zhang and Gubbins* [2002] demonstrate how convection propagates either prograde or retrograde depending upon the exact form of the magnetic field applied. Most of the current numerical dynamo simulations (see, for example, *Christensen, Olson and Glatzmaier* [1999]) display retrograde or westward drifiting rolls. A companion study to this one, including magnetic fields, is underway and will be reported on elsewhere.

Discussion

The historical record shows that ordinary geomagnetic ("Atlantic") SV is almost entirely absent from Hawaii. Paleomagnetism cannot contradict this result because it lacks the necessary time resolution to detect rapid SV. Paleomagnetism has recorded changes in direction in Hawaii, but they are smaller and ten times slower than those in the Atlantic region. A different physical mechanism is needed for the two hemispheres; the simple convection model described here suggests that the effects of convection, at least in the upper reaches of the core, is suppressed beneath the Pacific. Hawaiian paleomagnetism could then register only deep and distant convective effects that involve global changes in the entire geomagnetic field.

Suppression of convection beneath the Pacific but not the Atlantic regions in our model arises because of the subtle difference in shape of theise two main hot regions at the bottom of the mantle. The Pacific region is elongated east-west whereas the Atlantic region is elongated north-south. The Atlantic region is about as wide as a single convection roll in the calculation, which has $m = 8$. The Pacific region is much wider, occupying nearly half the core's circumference, and completely suppresses the smaller rolls.

None of the geodynamo simulations to date reproduce a hemispheric difference with anything like the clarity of either the Earth or the simple convection solution presented here. It may be that we have not yet found the appropriate dynamo regime. The Rayleigh number may be too high in all the dynamo simulations. We know that high Ra^{V} ultimately removes the Taylor constraint and destroys the usual roll structure. This probably explains the lack of boundary effects in the high Rayleigh number studies of *Sun, Schubert and Glatzmaier* [1994] and *Olson and Glatzmaier* [1996]. When *Christensen and Olson* [2003] apply a sufficiently high Ra^{V} to obtain the correct time scale for SV the main dipole becomes weak and highly variable. Lowering Ra^{V} at these values of E results in dynamo failure, probably because the flow lacks sufficient chaotic time dependence to prevent flux concentration [*Gubbins et al.*, 2000].

The Earth's core has a much smaller E than the simulations. Heat flux constraints limit Ra^{V} to reasonable values. *Jones* [2000] and *Gubbins* [2001], using independent methods, estimate Ra^{V} to be less than 1,000 times the critical value for magnetoconvection, or about equal to the critical value for non-magnetic convection assuming turbulent values for the diffusivities. The numerical simulations are necessarily run at $Ra^{\mathrm{V}}/Ra_c^{\mathrm{V}} \approx 20$ or greater in order to get dynamo action, but such high supercritical values may not be needed at lower E. Keeping $Ra^{\mathrm{V}}/Ra_c^{\mathrm{V}}$ constant and small while reducing E might ultimately yield dynamo action in the right regime, but such low Ekman numbers have yet to be achieved.

Conclusions

The historical record from Hawaii lacks any significant century-scale, SV. The paleomagnetic record does show millenium-scale variations that are rather smaller than typical century-scale SV. The disparity in time scale demands different physical processes. Lateral variations in shear wave velocity have been taken as representative of temperature in the lower mantle boundary layer and hence heat flux through the CMB. The pattern is dominated by the spherical harmonic Y_2^2 and would not, at first sight, be expected to produce a long-term difference in core dynamics between the Pacific hemisphere and the Atlantic side. Recent geodynamo simulations using the seismic velocity for a thermal boundary condition do exhibit some hemispheric differences in the time average but differences in snapshots of the magnetic field at instants of time are difficult to discern. We have found a simple, periodic, example of non-magnetic convection showing permanent hemispheric differences arising from subtle departures of the boundary conditions from the Y_2^2 harmonic. The conditions for this solution to hold are that the underlying convection contain significant energy in azimuthal wavenumbers around 8, which allows convection rolls that can drift past the narrow Atlantic low velocity anomaly but not the broader Pacific anomaly. We suggest no similar dynamo example has yet been found because the Rayleigh number required for dynamo action at these high Ekman numbers is too large to produce energy in the right wavenumber band for resonance with the boundary conditions.

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Figure Captions

Figure 1. S-wave velocity anomalies for the lowermost 250 km of the mantle [*Masters et al.*, 1996], with spherical harmonic degree and order up to 10. Dark (light) regions represent higher (lower) velocities within a range of approximately $\pm 2.5\%$, corresponding to possible temperature variations of several hundred degrees in the lower mantle thermal boundary layer.

Figure 2. Comparison of magnetic field components on Hawaii (solid line) and representative point on same latitude in the Atlantic hemisphere (dashed). (a) D (b) I. Points give paleomagnetic measurements on historical lava flows.

Figure 3. D and I from Hawaiian lavas with C^{14} ages less than 5 ka. Note the scale on the y-axis: D varies by only $\pm 5°$ over 5 kyr compared with over 30° change in Figure 3(b). I dips by just 15° from 0–1000AD, compared with a 30° change in 300 years in Figure 3(c).

Figure 4. Snapshots of convective solutions subject to lateral heat-flux variations at the outer surface. Plots (a), (b), and (c) show contours of temperature perturbations and arrows of flow in an equatorial section for $Ra^{\mathrm{H}} = 0.1 Ra^{\mathrm{V}}$, $Ra^{\mathrm{H}} = 0.3 Ra^{\mathrm{V}}$, and $Ra^{\mathrm{H}} = 0.7 Ra^{\mathrm{V}}$ respectively. Darker shades represent higher temperatures. The large arrows indicate the direction of propagation of the convection rolls and the thick arc indicates the approximate extent of the Pacific Ocean. Plot (d) shows temperature and flow at the outer surface corresponding to the solution in (b).