GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 3, PAGES 455-458, FEBRUARY 1, 2001

Interaction of rising and sinking mantle plumes

Nathanaël Schaeffer

Departement des Sciences de la Matière, École Normale Supérieure, Lyon

Michael Manga

Department of Geological Sciences, University of Oregon

Abstract. The frequency of plume formation in fully-developed thermal convection is determined experimentally. Because the fluid has a temperature-dependent viscosity, the cold and hot thermal boundary layers have different thicknesses and viscosities. As a result, plumes are released from these layers with different frequencies. There also appears to be a direct temporal interaction between the cold and hot boundary layers. In particular, whereas there is a single frequency for cold plume formation, hot plumes form with multiple frequencies, one of which is similar to the frequency of cold plumes. The measurements thus suggest that cold sinking "plumes" may induce hot rising plumes.

Introduction

Mantle plumes generated from thermal boundary layers have been invoked for decades to explain the formation of hotspots and flood basalts provinces on the Earth [*Morgan*, 1971], and the origin of features such as coronae on Venus and Mars [*Watters and Janes*, 1995]. Understanding how and why plumes form, move through the mantle, and finally interact with surface can therefore be useful for interpreting the geological, geochemical and petrological features attributed to plumes [*Hill et al.*, 1992]. In addition, the properties of plumes (both in space and time) provide information and constraints on the thermal and dynamic properties of planetary interiors.

Conceptually, the formation of a thermal plume is straightforward. Heat conducted across some boundary causes a thermal boundary layer to grow. A plume will then form once thermal buoyancy forces cause the layer to be gravitationally unstable. The details of where, when and how plumes form may be more complicated, however, because thermal boundary layers interact with the entire convecting system [*Sleep et al.*, 1988]. Accordingly, we present the results of an experimental study of convection in a plane layer heated from below, and we focus on the relationship between the frequencies at which both hot and cold plumes form. The primary goal of the experiments is to determine if there is a direct temporal relationship between processes that occur in hot and cold thermal boundary layers.

Formation of plumes

Theoretical models of boundary layer dynamics typically assume that there is "no direct influence of one boundary layer upon the other" [*Zhang et al.*, 1997]. In this case, *Howard* [1966] showed that simple scaling arguments can be used to predict the frequency of thermal formation. The thermal boundary layer thickness δ increases by thermal diffusion and as a result grows as $(\kappa t)^{1/2}$, where t is time and κ is thermal diffusivity. This layer becomes unstable once the local Rayleigh number, $\mathrm{Ra}_l = \rho g \alpha \Delta T \delta^3 / \mu\kappa$, exceeds a critical value $\mathrm{Ra}_{\mathrm{cr}} > O(10^3)$. Here ρ, α, μ, g and ΔT denote density, thermal expansivity, viscosity, gravity, and the temperature difference across the layer. The time t^* needed to reach the critical thickness is thus proportional to $(\mathrm{Ra}_{\mathrm{cr}}\mu\kappa/\rho g\alpha\Delta T)^{2/3}/\kappa$. *Howard's* [1966] model should apply in large Prandtl number ($\mathrm{Pr} = \mu/\rho\kappa$) fluids (such as the mantle and the experiments studied here).

If the fluid has a temperature-dependent viscosity, the hot and cold boundary layers will have different thicknesses and viscosities, and thermals will thus form with different frequencies. If we use the subscripts δ_h and δ_c to denote the hot and cold boundary layers, respectively, then the ratio of the frequencies ($\omega^* = 1/t^*$) of thermal formation is

$$\frac{\omega^*_{\delta_h}}{\omega^*_{\delta_c}} = \left(\frac{\mu_{\delta_c} \Delta T_h}{\mu_{\delta_{\delta_h}} \Delta T_{\delta_c}} \right)^{2/3}, \qquad (1)$$

if we assume that $\mathrm{Ra}_{\mathrm{cr}}$ is the same for both layers. Following previous studies [*Booker*, 1976], μ for each layer is the value at the mean of the boundary temperatures.

In the rest of this paper we use the word "plumes" for such thermals – volumes of either hot or cold fluid released periodically from thermal boundary layers.

Experimental procedure

In order to understand the interactions between hot and cold boundary layers (and the plumes they produce) we performed a set of experiments of Rayleigh-Bénard convection. This model problem does not account for processes such as internal heating and surface plate motion; it provides, however, a system that allows us to study the interaction of plumes and to relate measurements to theoretical models.

The experimental apparatus, similar to those used in previous studies [*Richter et al.*, 1983; *Giannandrea and Christensen*, 1993], is illustrated in Fig. 1. Briefly, the working fluid, corn syrup diluted with water, is contained horizontally by glass panels and vertically by square aluminum plates. Temperature at the top of the fluid is controlled with circulating water. Heat is added through the square bottom with a resistance heater. The entire apparatus is insulated with 5-cm-thick sheets of polystyrene foam. Temperatures within the fluid and on the boundaries, along with the room temperature, are recorded digitally at 5 second in-

Paper number 2000GL012215.
0094-8276/01/2000GL012215$05.00

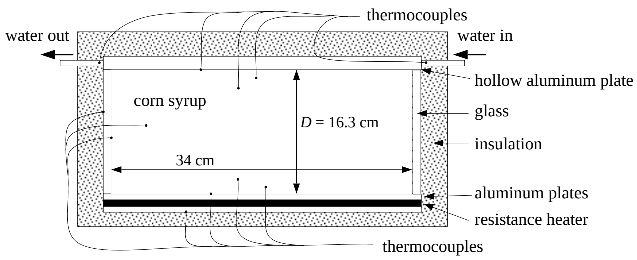

Figure 1. Experimental apparatus.

tervals by an array of 18 calibrated thermocouples. There are two thermocouples in each thermal boundary layer. Pr is always sufficiently large that the Reynolds is less than 0.5 for all experiments. Hence, inertia plays no dynamic role.

All the data presented here are based on equilibrium conditions. This is identified by requiring that the time-averaged interior and boundary temperatures are constant. Each experiment typically runs for several days, and long enough to record at least 50 plumes.

Results

Below we summarize experimental results, first the time-averaged properties of the thermal boundary layers, and second the time-varying behavior of these layers. Time is normalized by the diffusive time scale D^2/κ, and dimensionless temperatures are defined as $\theta = (T - T_c)/(T_h - T_c)$, where the subscripts h and c refer to the lower and upper boundaries, respectively. Here, Ra is the "global" value for variable-viscosity convection (based on the viscosity at the mean of the boundary temperatures and the layer thickness D).

Time-averaged properties

Fig. 2a shows the measured Nusselt number (Nu, the ratio of total heat transport compared to the conductive transport in the absence of convection) as a function of Ra. We used Eq. (6) in *Richter et al.* [1983] to account for the effect of conductive heat losses on Nu. A best fit to our data, $\mathrm{Nu} = 0.150\mathrm{Ra}^{0.294}$, is similar to that at smaller Ra [*Giannandrea and Christensen*, 1993].

Fig. 2b shows the relationship between the mean interior temperature θ_i and the viscosity ratio λ (defined in the caption). *Solomatov* [1995] presents a boundary layer analysis that relates θ_i and λ for the case that viscosity varies exponentially with temperature. His results can be modified to account for the different scaling relationships with no-slip boundaries [*Manga and Weeraratne*, 1999], yielding

$$\theta_i = \frac{1}{1 + \lambda^{-1/6}}. \tag{2}$$

Eq. (2) agrees well with the measurements.

Overall, Fig. 2 shows that measurements related to the time-averaged boundary layer thicknesses, both the absolute values (which determine Nu) and relative thicknesses (which govern θ_i), are compatible with previous data and simple boundary layer models.

Time-dependent behavior of plumes

At sufficiently high Ra, typically $> O(10^6)$, discrete thermals or plumes will form for convection between no-slip boundaries [*Weeraratne and Manga*, 1998]. Here we examine the frequency at which these plumes form. Of the experiments shown in Fig. 2, only a subset could be studied – Ra must be high enough to form discrete plumes. These plumes appear to form with well-defined frequencies. However, at very large Ra, $> O(10^7)$, plumes form with a wider range of frequencies [*Lithgow-Bertelloni et al.*, 2001] and it becomes more difficult to identify individual frequencies and thus reliably establish the correlations we seek.

Fig. 3a shows partial time series of temperature measurements in the hot and cold boundary layers. Fig. 3b shows the power spectrum of these temperatures. Whereas only one obvious frequency exists for plumes formed in the cold boundary layer, multiple frequencies for hot plumes are apparent in the hot boundary layer. One of these frequencies, we call the "cold frequency", is identical to that of the cold plumes. Two closely spaced higher frequencies are also apparent.

Fig. 4 summarizes measured frequencies. These are determined by examining both power spectra (Fig. 3b) and autocorrelation functions [*Manga and Weeraratne*, 1999]. We also verify that the frequencies we identify do indeed correspond to recognizable frequencies of hot rising plumes in the original time series (see Fig. 3a). The absolute value of "hot frequencies" follows the $\mathrm{Ra}^{2/3}$ scaling found in previous studies of such plumes [*Sparrow et al.*, 1970]. Similar to Fig. 3, we see two sets of frequencies in the hot boundary layer, one that is nearly the same as that in the cold boundary layer, and a second that is similar to the prediction of Eq.

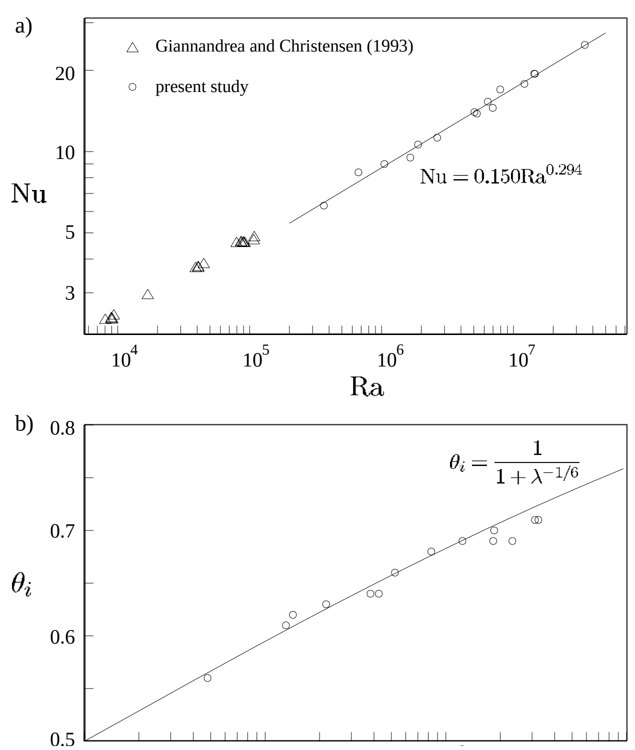

Figure 2. a) Nusselt number, Nu, as a function of the Rayleigh number, Ra. Ra is based on the viscosity at the mean of the boundary temperatures (T_c and T_h at the top and bottom, respectively). The line is the best-fit to our data. b) Dimensionless interior temperature, $\theta_i = (T - T_c)/(T_h - T_c)$, as a function of the viscosity ratio, $\lambda = \mu(T_c)/\mu(T_h)$. Curve is prediction of Eq. (2).

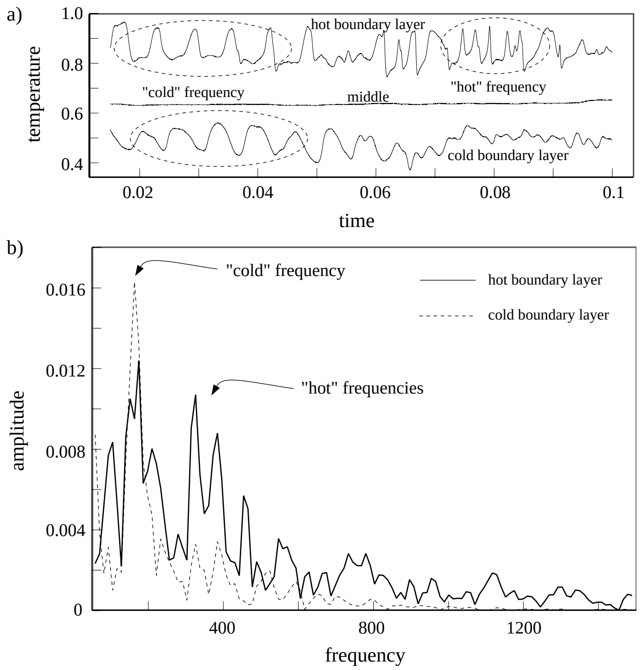

Figure 3. a) Partial time series of temperature measurements in the hot and cold boundary layers, and the mean interior temperature; Ra $= 1.8 \times 10^6$ and $\lambda = 38$. b) Power spectra for the time series shown in a.

(1). The time series in Fig. 3a indicates that the location of plume formation changes in time, but also changes slowly enough that we can see repeated plume formation at a given location [*Davaille and Jaupart*, 1993].

Orgin of the temporal relationship

The cartoon in Fig. 5 illustrates one way in which plumes may interact. Locally, a high-viscosity cold plume will produce an advective disturbance in the hot boundary layer as it approaches the hot layer (illustrated schemtically with streamlines in Fig. 5). The resulting advective thickening

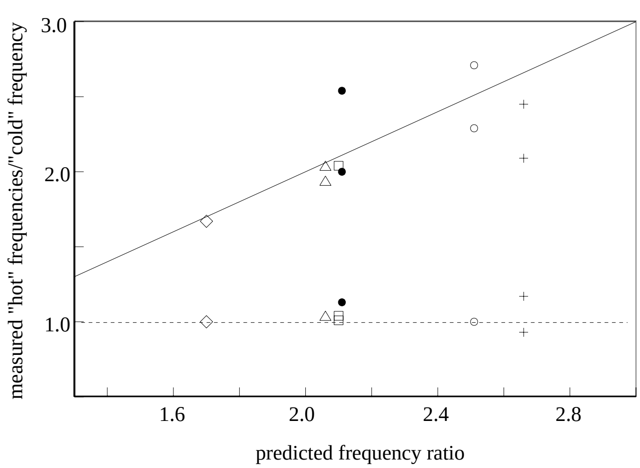

Figure 4. Measured frequencies of hot plumes divided by the frequency of plumes produced from the cold boundary layer, as a function of the ratio predicted by Eq. (1). Different symbols are used for each experiment. Filled circles correspond to the experiment shown in Fig. 3. Solid line has a slope of 1.

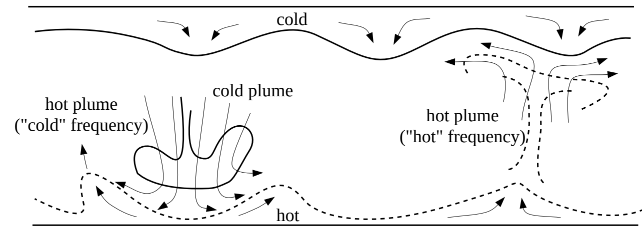

Figure 5. Cartoon illustrating the origin of two distinct plume frequencies in the hot boundary layer.

of the hot boundary layer may cause the layer to become unstable, leading to the release of a new hot plume. In contrast, a low-viscosity hot plume spreading below the more viscous cold boundary layer will induce a smaller distortion in the cold layer. We attempted to establish spatial and causal relationships between rising and sinking plumes by removing the insulation and studying shadowgraphs. Some observations are suggestive of the processes illustrated in Fig. 5, but are not definitive due to the spatial averaging of shadowgraphs.

Discussion

The model problem considered here is specifically designed to allow us to focus on the temporal interaction of plumes formed from thermal boundary layers. Several potentially important aspects of planetary interiors are thus not accounted for in the experimental model, including internal heating, the motion of surface plates, and the possible influence of chemical heterogeneity. Nevertheless, the fundamental physical processes that result in the formation and interaction of plumes should still apply in more complicated systems.

Figs. 3 and 4 show that hot plumes can form with more than one frequency and size, and thus hot plumes presumably form by different processes. Specifically, our measurements suggest that hot plumes might form either naturally as boundary layer instabilities once the local Rayleigh number exceeds a critical value or indirectly through the arrival of a cold plume in the lower thermal boundary layer. There is observational evidence from both Venus and the Earth that mantle plumes with different sizes and properties can coexist in the same system [*Herrick*, 1999]. For example, on Venus where convection may be dominated by hot and cold plumes [*Bindschadler et al.*, 1992] coronae and other plume-related features show “multiple spatial and temporal scales” [*Stofan et al.*, 1992]. The interaction between descending plumes and the hot boundary layer is one way to produce hot plumes with different sizes and frequencies.

On the Earth, a spatial correlation between the locations of hotspots and subduction is well-established [*Weinstein and Olson*, 1989]. It is also argued that the accumulation of slabs at the base of the mantle may induce hotspot-forming plumes [*Namiki and Kurita*, 1999]. *Gaffin and O’Neill* [1994] suggest that the dramatic increase in mantle plume activity about 120 Ma [Fig. 1 in *Larson and Olson*, 1991] may have been a response to increasing spreading rates around 200 Ma. A time lag of about 80 m.y. is consistent with slabs sinking, and the induced plumes rising, at a reasonable mean rate of 8 cm/year. Unfortunately, establishing a correlation between the initiation of individual plumes and the arrival of a slab at the base of the mantle is hampered by the long time lag between subduction and plume eruption relative to the time period over which plate motion histories can be reconstructed.

The correlations in Figs. 3 and 4, do not prove causality. Nevertheless, the measurements shown in Figs. 3 and 4 provide further evidence that cold sinking "plumes" in the mantle (e.g., slabs) may have the ability to induce hot rising plumes.

Acknowledgments. Supported by NSF grant EAR-9701768. We thank D. Senkovich, D. Weeraratne, and H. Gonnermann for technical assistance, and M. Jellinek and C. Lithgow-Bertelloni for comments.

References

Bindschadler, D.L., G. Schubert and W.M. Kaula, Coldspots and hotspots – Global tectonics and mantle dynamics of Venus, *J. Geophys. Res., 97*, 13, 495-13, 432, 1992.

Booker, J.R., Thermal convection with strongly temperature dependent viscosity, *J. Fluid Mech., 76*, 741-754, 1976.

Davaille, A. and C. Jaupart, Transient high-Rayleigh-number thermal convection with large viscosity variations, *J. Fluid Mech., 253*, 141-166, 1993.

Gaffin, S.R. and B.C. O'Neill, Pulsation in seafloor spreading rates and transit time dynamics, *Geophys. Res. Lett., 21*, 1947-1950, 1994.

Giannandrea, E. and U. Christensen, Variable viscosity convection experiments with a stress-free upper boundary and implications for the heat transport in the Earth's mantle, *Phys. Earth Planet. Int., 78*, 139-152, 1993.

Herrick, R.R., Small mantle upwellings are pervasive on Venus and Earth, *Geophys. Res. Lett., 26*, 803-806, 1999.

Hill, R.I., I.H. Campbell, G.F. Davies and R.W. Griffiths, Mantle plumes and continental tectonics, *Science, 256*, 186-193, 1992.

Howard, L.N., Convection at high Rayleigh number, in *Proc. 11th Intl. Congr. Applied Mech.*, edited by H. Görtler, Springer, Berlin, 1109-1115, 1966.

Larson, R.L., and P. Olson, Mantle plumes control reversal frequency, *Earth Planet. Sci. Lett., 107*, 437-447, 1991.

Lithgow-Bertelloni, C., M.A. Richards, C.P. Conrad, and R.W. Griffiths, Plume generation in natural thermal convection at high Ra and Pr numbers, *J. Fluid Mech.*, in press, 2001.

Manga, M. and D. Weeraratne, Experimental study of non-Boussinesq Rayleigh-Benard convection at high Rayleigh and Prandtl numbers, *Phys. Fluids., 11*, 2969-2976, 1999.

Morgan, W.J., Plate motions and deep mantle convection, *Nature, 230*, 42-43, 1971.

Namiki, A., and K. Kurita, The influence of boundary heterogeneity in experimental models of mantle convection, *Geophys. Res. Lett., 26*, 1929-1932, 1999.

Richter, F.M., H. Nataf, and S.F. Daly, Heat transfer and horizontally averaged temperature of convection with large viscosity variations, *J. Fluid Mech., 129*, 173-192, 1983.

Sleep, N.H., M.A. Richards and B.H. Hager, Onset of mantle plumes in the presence of preexisting convection, *J. Geophys. Res., 93*, 7672-7689, 1988.

Solomatov, V.S., Scaling of temperature- and stress-dependent viscosity convection, *Phys. Fluids, 7*, 266-274, 1995.

Sparrow, E.M., R.B. Husar and R.J. Goldstein, Observations and other characteristics of thermals, *J. Fluid Mech., 41*, 793-800, 1970.

Stofan, E.R. and 6 others, Global distribution and characteristics of coronae and related features on Venus: Implications for origin and relation to mantle processes, *J. Geophys. Res., 97*, 13, 347-13, 378, 1992.

Watters, T.R. and D.M. Janes, Coronae on Venus and Mars – Implications for similar structures on Earth, *Geology, 23*, 200-204, 1995.

Weeraratne, D. and M. Manga, Transitions in the style of mantle convection at high Rayleigh numbers, *Earth Planet. Sci. Lett., 160*, 563-568, 1998.

Weinstein, S.A. and P. Olson, The proximity of hotspots to convergent and divergent plate boundaries, *Geophys. Res. Lett., 16*, 433-436, 1989.

Zhang, J., S. Childress and A. Libchaber, Non-Boussinesq effect: Thermal convection with broken symmetry, *Phys. Fluids, 9*, 1034-1042, 1997.

Nathanaël Schaeffer, Departement des Sciences de la Matière, École Normale Supérieure, Lyon, France.

Michael Manga, Department of Geological Sciences, University of Oregon, Eugene, OR 97403.
(email: manga@seismo.berkeley.edu)

(Received August 15, 2000; revised November 7, 2000; accepted November 16, 2000.)