On the North Atlantic Ocean Heat Content Change between 1955–70 and 1980–95

XIAOMING ZHAI

Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, United Kingdom

LUKE SHELDON

Department of Earth Sciences, University of Oxford, Oxford, United Kingdom

(Manuscript received 4 April 2011, in final form 2 December 2011)

ABSTRACT

The upper-ocean heat content of the North Atlantic has undergone significant changes over the last 50 years but the underlying physical mechanisms are not yet well understood. In the present study, the authors examine the North Atlantic ocean heat content change in the upper 700 m between the 1955–70 and 1980–95 periods. Consistent with previous studies, the large-scale pattern consists of warming of the tropics and subtropics and cooling of the subpolar ocean. However, this study finds that the most significant heat content change in the North Atlantic during these two time periods is the warming of the Gulf Stream region. Numerical experiments strongly suggest that this warming in the Gulf Stream region is largely driven by changes of the large-scale wind forcing. Furthermore, the increased ocean heat content in the Gulf Stream region appears to feedback on to the atmosphere, resulting in warmer surface air temperature and enhanced precipitation there.

1. Introduction

Warming of the North Atlantic over the past 50 years has not been uniform (e.g., Levitus et al. 2000, 2005a; Lozier et al. 2008). For example, using data from hydrographic stations, Lozier et al. (2008) found in the North Atlantic that the tropics and subtropics have warmed but the subpolar ocean has cooled (see also Levitus et al. 2000). These observations suggest that, instead of a diffusive process from the surface, ocean heat content change is largely a consequence of ocean dynamical adjustment to large-scale variability in wind and buoyancy forcing (e.g., Lozier et al. 2008; Zhai et al. 2011). However, the physical mechanisms behind the observed ocean heat content change are not yet well understood, partially due to the lack of subsurface data in the past.

In his seminal paper, Bjerknes (1964) conjectured that on interannual time scales the ocean reacts passively to the overlying atmosphere, whereas on decadal/interdecadal time scales changes in ocean circulation and its associated heat transport become more important—for example, in determining ocean heat content and sea surface temperature (SST) anomalies. Bjerknes’ hypothesis has been supported by both observational and modeling studies. For example, Battisti et al. (1995) showed that SST variability on interannual time scales over the Atlantic can be understood in terms of one-dimensional mixed layer processes, except in regions of the Gulf Stream and North Atlantic Current where advection by ocean currents is hypothesized to be important. Modeling studies (e.g., Halliwell 1998; Krahmann et al. 2001; Dong and Kelly 2004) later demonstrated the importance of geostrophic advection in heat content changes in the western boundary region, although the exact driving mechanism remains unclear. In a theoretical study, Marshall et al. (2001) argued that the meridional shift in the jet stream associated with the North Atlantic Oscillations (NAO) drives, through anomalous wind stress curl, an “intergyre gyre,” which alters the Gulf Stream and North Atlantic Current. The strength and position of the Gulf Stream have been reported to respond to the NAO forcing with a delay of 0–3 years (e.g., Taylor and Stephens 1998; Joyce et al. 2000; Frankignoul et al. 2001; Eden and Willebrand 2001; Visbeck et al. 2003), faster than that expected from the baroclinic response that takes 8–10 years. In the present paper, we examine the upper-ocean heat content...
change in the North Atlantic between 1955–70 and 1980–95 using both observations and an ocean general circulation model.

2. Data analysis

We analyze the ocean heat content/temperature data from the National Oceanographic Data Center World Ocean Database. This dataset updates the ocean heat content estimates made by Levitus et al. (2005a) with additional historical and modern data including Argo profiling float data that have been corrected for systematic errors and represents a 3-month average from 1955 to the present with a horizontal resolution of \(1^\circ \times 1^\circ\). Empirically determined corrections for instrumental offsets of bathythermograph measurements (both expendable bathythermographs and mechanical bathythermographs) have been applied to this dataset using data from ocean station data casts, conductivity–temperature–depth casts, and moored buoy data (Levitus et al. 2009). We caution that interpolations are used to fill data gaps, especially in the early years. The North Atlantic, on the other hand, has consistently the best observational coverage throughout the historical record. In this study, we focus on the heat content change in the upper 700 m in the North Atlantic between two time periods, 1955–70 and 1980–95, which correspond to persistent negative and positive NAO periods, respectively (Fig. 1a).

Figure 1b shows the ocean heat content change in the North Atlantic between these two time periods, where the color red means the ocean is warmer during the 1980–95 time period than the 1955–70 time period and the color blue means cooler. The large-scale pattern, that is, warming in the tropics and subtropics and cooling in the subpolar ocean, is similar to that found by Lozier et al. (2008). Note that Lozier et al. (2008) used only the hydrographic station data, and their ocean heat content is integrated over the whole water column and also over two slightly longer time periods. However, the most significant heat content change in the North Atlantic we find is the warming of the Gulf Stream region, where, in contrast, Lozier et al. (2008) found cooling in their Hydrobase data. This discrepancy appears to be due mostly to the difference between integrating to 700 m versus full depth since a similar warming pattern in the Gulf Stream region is found when the temperature anomaly is averaged over only the top 750 m using the same HydroBase data (see Fig. 2a in Lozier et al. 2010). We have also tried different instrument types in the World Ocean Atlas and got consistent warming in the Gulf Stream region. We therefore believe the warming in the Gulf Stream region shown in Fig. 1b is robust, based on analysis using different instrument types and also datasets compiled by averaging on both depth surfaces (Levitus et al. 2009) and potential density surfaces (Lozier et al. 2010). Note that warming in the Gulf Stream region is also a prominent feature in EOF analysis (Levitus et al. 2005b). The cooling that occurs over the Gulf Stream region when integrating the temperature anomaly over the whole water depth found in Lozier et al. (2008) has to be caused by a very strong negative temperature anomaly in the deep ocean. Although interesting, due to the sparseness of data in the deep ocean, especially before the Argo era, we focus our study only on the top 700 m.

To understand the mechanisms behind the observed heat content change, we plot in Fig. 1c the difference of the net surface heat fluxes between these two time periods using monthly National Centers for Environmental Prediction (NCEP) reanalysis product (Kalnay et al. 1996), where the color red indicates the ocean gaining more heat through air–sea heat fluxes, and the color blue indicates the ocean losing more heat during the 1980–95 time period than the 1955–70 time period. The basinwide anomalous heating in the tropics and subtropics is consistent with the warming there and vice versa for the subpolar region. However, there is significant cooling over the Gulf Stream region where the ocean has warmed the most. Comparison between Figs. 1b and 1c demonstrates that warming in the Gulf Stream region during the 1980–95 time period cannot be a result of enhanced surface heat flux into the ocean but driven instead by changes in ocean circulation.

At periods longer than a month, one hypothesis (e.g., Willebrand et al. 1980) on the oceanic response predicted by linear theory to large-scale atmospheric disturbances is a time-dependent Sverdrup balance. Now we estimate ocean circulation changes in response to changes of the large-scale wind stress curl using linear flat-bottomed Sverdrup dynamics. The depth-integrated streamfunction \(\Psi\) is given, at equilibrium, by

\[
\Psi(\lambda, \phi) = \frac{1}{\beta \rho} \int_{\lambda_E}^{\lambda} (\mathbf{k} \cdot \mathbf{V} \times \tau) \, d\lambda',
\]

where \(\phi\) is latitude, \(\rho\) is seawater density, \(\lambda\) is longitude, \(\lambda_E\) is the longitude of the eastern boundary, \(\beta\) is the change of Coriolis parameter with latitude, \(\mathbf{k}\) is a unit vector pointing in the vertically upward direction, and \(\tau\) is the wind stress vector. The integral is evaluated from the eastern boundary to the outside of the western boundary. Changes of the interior Sverdrup transport predicted by (1) are expected to be balanced by changes of the western boundary current transport, forming anomalous horizontal gyre circulations.

Figure 1d shows the difference in the interior Sverdrup transport between these two time periods (1980–95 minus
1955–70), where the color red indicates anomalous northward interior Sverdrup flow, and the color blue indicates anomalous southward interior Sverdrup flow. The most prominent feature in Fig. 1d is the anomalous southward interior Sverdrup transport between 33° and 57°N, with a maximum strength of about 6–7 Sv (1 Sv = 10^6 m^3 s^{-1}) at 45°N. This anomalous southward interior transport forced by the large-scale wind stress curl anomaly is, in turn, balanced by an enhanced northward Gulf Stream transport, and they together form an anomalous anticyclonic circulation straddling the climatological subtropical and subpolar gyres. This anomalous anticyclonic circulation located between the two main gyres is dubbed the “intergyre gyre” by Marshall et al. (2001) (also see Czaja and Marshall 2001; Visbeck et al. 2003). We will show later that the enhanced western boundary current transport associated with the “intergyre gyre” is largely responsible for the observed warming in the Gulf Stream region. To the south of this “intergyre gyre”, there are also a few anomalous recirculations with reduced magnitude and meridional extent.

The upper-ocean heat content integrated down to a fixed depth of h is balanced by surface heating/cooling, the divergence of heat transport and diffusion, and can be written as

\[
\frac{\partial}{\partial t} \int_{-h}^{0} \theta \, dz = \frac{Q_{\text{net}}}{c_p} - \int_{-h}^{0} \nabla \cdot (\mathbf{u} \theta) \, dz + \int_{-h}^{0} \kappa \nabla^2 \theta \, dz, \tag{2}
\]

where \( \theta \) is potential temperature, \( c_p \) is specific heat at constant pressure, \( Q_{\text{net}} \) is the net surface heat flux (positive when the ocean gains heat), \( \kappa \) is the thermal diffusion coefficient, and \( \mathbf{u} \) is the three-dimensional velocity vector. When applying (2) to the Gulf Stream region over the time periods of interest, some terms turn out to be small and we can simplify the heat budget.

First, consistent with other studies (e.g., Qiu 2000; Dong and Kelly 2004), contributions of anomalous Ekman transport/pumping and diffusion to the heat content budget...
in the western boundary region are found to be small in comparison with that of the geostrophic current and are hence not considered further. Furthermore, the anomalous heat transport in the western boundary region is found due mostly to advection of the mean state by anomalous ocean circulation, rather than the transport of temperature anomalies by the mean flow, supported by previous studies (e.g., Iou 2000; Eden and Jung 2001; Jayne and Marotzke 2001). Eddies have been known to be important in shaping the large-scale ocean circulation and transporting heat, especially in the western boundary regions (e.g., Jayne and Marotzke 2001; Zhai et al. 2004; Greatbatch et al. 2010). However, it is difficult to use data to estimate ocean heat content changes associated with changes of eddy fluxes in the Gulf Stream region, especially in the early years. Previous model–data comparison studies (e.g., Penduff et al. 2004) suggest only a very weak link between the NAO-related atmospheric forcing and eddy kinetic energy variability in the Gulf Stream region. We therefore assume changes in the Gulf Stream eddy field between the 1980–95 and 1955–70 periods play only a secondary role in our heat budget.

Now integrating (2) over the Gulf Stream region, we get

$$\frac{\partial}{\partial t} \int \rho c_p \theta dV \approx \int Q_{\text{net}} dS + \alpha \rho c_p \Psi \Delta T,$$

where $S$ is the surface area of the Gulf Stream region, $V = S \times h$ is the control volume, and $\Delta T$ is the time-mean horizontal temperature difference between regions where the Gulf Stream enters the control volume and where it exits. Note that $\theta$, $Q_{\text{net}}$, and $\Psi$ are anomalies from the time-mean quantities. The nondimensional coefficient $\alpha$ in (3) measures the fractional change of the western boundary current transport that takes place in the upper 700 m. Depending on whether the baroclinic Rossby wave adjustment processes are complete, changes of the western boundary current transport can extend to the whole water depth ($\alpha \sim 0.2$) or be confined to the upper ocean ($\alpha \sim 1$). On interdecadal time scales, we expect $\alpha$ to be much larger than 0.2. It is worth noting that the ocean heat content change due to horizontal gyre circulation changes depends both on the mean temperature gradient and velocity anomaly, both of which are functions of space. The heat content change is concentrated in the Gulf Stream region (Fig. 1b) because of the sharp thermal front and large velocity anomalies there.

We now estimate each term in (3) for the control volume of the upper 700 m between 35° and 49°N and between 75.5° and 34.5°W. The ocean heat content change between these two time periods, 1980–95 minus 1955–70, is estimated to be (6.6 ± 1.0) × 10^{21} J, and the time-integrated NCEP surface heat flux anomaly is (−1.8 ± 0.5) × 10^{22} J. There is a large uncertainty associated with the heat transport divergence due to changes in ocean circulation. For our control volume, we estimate $\Delta T = 5° \pm 1°C$ from the World Ocean Database and $\Psi = 4 \pm 1$ Sv from Fig. 1d. Assuming $\alpha = 0.6$, we estimate the anomalous heat transport into the Gulf Stream region between the two time periods to be $(2.7 \pm 1.0) \times 10^{22} J$, which is broadly consistent with previous studies (e.g., Marshall et al. 2001; Visbeck et al. 2003). For example, Marshall et al. (2001) estimated the heat transport associated with the ““intergyre gyre” to be $\sim 0.07$ PW using $\Psi = 3$ Sv and $\Delta T = 6°C$, that is, $\sim 3.4 \times 10^{22} J$ when integrated for 16 years in our case. Visbeck et al. (2003) estimated this term to be $\sim 0.05$ PW using $\Psi = 6$ Sv and $\Delta T = 2°C$, or $\sim 2.5 \times 10^{22} J$ for 16 years. We have, within error bars, a closed heat budget for the Gulf Stream region; again we emphasize the large uncertainties in these estimates. The picture that emerges from the heat budget analysis is as follows. On decadal/interdecadal time scales, the meridional shift of the jet stream associated with the positive NAO drives, through an anomalous negative wind stress curl, anomalous southward Sverdrup transport in the ocean interior at midlatitudes (between about 30° and 55°N; Fig. 1d), which is balanced by an enhanced western boundary current transport. This, in turn, transports an anomalous amount of heat into the Gulf Stream/North Atlantic Current region, the majority of which is lost to the atmosphere (Fig. 1c). The residual results in the observed warming in the Gulf Stream region (Fig. 1b).

There is no good way to estimate from data the change in ocean circulation due to changes in the buoyancy forcing and whether it contributes to the observed warming in the Gulf Stream region. On the other hand, given that the heat budget for the Gulf Stream region is closed within error bars without invoking the buoyancy forcing, it suggests that changes in buoyancy forcing between the two time periods need play only a secondary role in determining the observed warming pattern in the Gulf Stream region. In the next section, we will explore the mechanisms further using an ocean general circulation model.

3. Numerical experiments

The model used in this section is the Massachusetts Institute of Technology (MIT) general circulation model in a global configuration from 78°S to 74°N. The horizontal resolution is 1° × 1°, with 33 geopotential levels ranging in thickness from 10 m at the surface to 250 m at the bottom. Exchange with the Nordic Seas, which lies outside of the model domain, is crudely taken into
account by restoring the model temperature and salinity fields near the northern boundary toward the observed, climatological values. In addition, sea surface temperature and salinity are restored to climatological values on a time scale of 30 days to prevent model drift. Readers are referred to Czeschel et al. (2010) and Zhai et al. (2011) for more detailed model description.

The model is spun up for 900 years, forced by NCEP climatological monthly mean forcing. After that, it is forced by monthly mean NCEP wind stress and heat fluxes from 1948 to 2000 (the control experiment; hereafter EXCONTROL).

Figures 2a shows the modeled ocean heat content change in the upper 700 m in the North Atlantic (1980–95 minus 1955–70) in EXCONTROL. Even though there are some regional differences, the model reproduces remarkably well the observed pattern of heat content change in the North Atlantic. In particular, the largest heat content change in the model between these two time periods occurs in the Gulf Stream region, just as observed.
There is widespread cooling in the subpolar gyre, with the maximum cooling being displaced slightly farther to the east than observed. A cold tongue, southeast of the Gulf Stream region, extends southwestward to the outside of the western boundary. There is indication of such a cold tongue in the data, but it appears less pronounced and also discontinuous (Fig. 1b). Farther to the south, the model captures the basinwide warming centered to the east of the Caribbean Sea.

Figure 2c shows the change in barotropic streamfunction (1980–95 minus 1955–70) in EXCONTROL. Both the subpolar gyre and the Gulf Stream spin up during the 1980–95 time period, with a maximum increase of 8 Sv in the Labrador Sea and 7 Sv to the south of the Grand Banks, respectively. Eden and Jung (2001) also found that the oceanic response north of 30°N to a persistent positive phase of the NAO is an amplification of the mean state. Farther to the south, there are three anomalous recirculation gyres of alternating signs. The strength of Atlantic meridional overturning circulation (AMOC) also increases during the 1980–95 time period, but it is mostly confined to north of 40°N with a maximum increase of 2 Sv at 45°N (Fig. 2e).

Given that the model reproduces faithfully the observed heat content change in the North Atlantic, an additional model run (hereafter EXWIND) is conducted to help to understand the driving mechanism responsible for the observed pattern (see also Eden and Willebrand 2001; Lozier et al. 2008). EXWIND is identical to EXCONTROL, except that in EXWIND the climatological monthly mean surface heat flux forcing is used. Since both the heat content and horizontal transport changes in EXWIND are similar to those in EXCONTROL, we take the difference between them (EXCONTROL − EXWIND) to reveal the role played by the surface heat flux anomalies. The most significant heat content change in the North Atlantic driven by the surface heat flux anomalies is the cooling to the east of Newfoundland (Fig. 2b), which offsets the wind-induced warming there, such that the net heat content change driven by both the wind stress and heat fluxes (Fig. 2a) resembles the observations. Variability of the surface heat flux forcing makes a relatively small contribution to the modeled warming in the Gulf Stream region, although it clearly strengthens the subpolar gyre (Fig. 2d) and the AMOC (Fig. 2f) during the 1980–95 time period (also see Eden and Jung 2001; Lozier et al. 2010). Our model results confirm the picture that emerges from data analysis in the previous section, that is, changes of the large-scale wind forcing are the main cause of the observed warming in the Gulf Stream region between the two time periods (1980–95 minus 1955–70).

Figure 3a shows the change in barotropic streamfunction (1980–95 minus 1955–70) in EXWIND, which captures most of the horizontal gyre circulation change in EXCONTROL (Fig. 2c), and accounts for, within observational errors, almost all the observed ocean heat content change in the Gulf Stream region and south of it. For easy comparison, we plot in Fig. 3b the interior Sverdrup transport averaged over the 1955–70 time period minus that over the 1980–95 time period estimated from NCEP reanalysis data, that is, the negative of Fig. 1d. Simple Sverdrup theory explains, to leading order, changes of the depth-integrated ocean circulation in an ocean general circulation model. For example, Fig. 3b reproduces the three anomalous recirculation gyres to the south of the latitude of Cape Hatteras, the anticyclonic intergyre gyre, and the cyclonic circulation farther to the north. However, (1) underestimates the strength of the
intergyre gyre by ~30% to the east of the Grand Bank and also significantly overestimates the subpolar gyre circulation, possibly because of nonlinearity and the presence of bottom topography (e.g., Willebrand et al. 1980; Greatbatch et al. 1991; Zhang and Vallis 2007). A detailed analysis of the dynamical adjustment processes involved and their contributions to the observed heat content change are beyond the scope of this paper and left for a future study.

4. Influence on the atmosphere

There is a weak, and often inconsistent, response in atmospheric models to midlatitude SST anomalies (e.g., Palmer and Sun 1985; Kushnir and Held 1996). Recent studies (e.g., Nakamura et al. 2004; Minobe et al. 2008; Joyce et al. 2009) show that the most likely regions where the atmosphere responds to the underlying ocean are the western boundaries, for example, the Gulf Stream. Since the observed warming in the Gulf Stream region leads to an enhanced surface heat flux into the atmosphere (Fig. 1c), we now explore the response of the atmosphere to this oceanic heating using NCEP reanalysis data. Figure 4a shows the surface air temperature difference between the two time periods (1980–95 minus 1955–70), where there is a band of pronounced warming of the surface atmosphere over the Gulf Stream region, with the center of the atmospheric warming slightly downstream (eastward) of the warming of the Gulf Stream. The amplitude of the surface air temperature change is similar to that of the SST anomaly (not shown), consistent with the notion that the atmospheric temperatures and SST covary at low frequencies. Our study thus supports the following picture: on decadal/interdecadal time scales, the large-scale atmospheric variability drives changes of the upper-ocean heat content in the Gulf Stream region, which lead to anomalous surface heat fluxes (Fig. 1c).

These anomalous surface heat fluxes act to damp the SST variability and drive the surface air temperature variability (Fig. 4a), such that the atmospheric temperatures and SST covary at low frequencies. The upper-ocean heat content anomaly in the Gulf Stream region continues to imprint itself on SST through the so-called “re-emergence mechanism” (Alexander and Deser 1995). Note that unlike the SST anomalies which decorrelate seasonally, the upper-ocean heat content anomaly persists throughout the year, representing an integral measure of the anomalous heat flux that can potentially influence the overlying atmosphere (e.g., Alexander and Deser 1995; Deser et al. 2003).

Recently, Minobe et al. (2008) showed that the warm SST in the Gulf Stream region affects the entire troposphere through surface wind convergence, anchoring a

![Fig. 4. Changes of (a) the surface air temperature and (c) precipitation from NCEP reanalysis data (1980–95 minus 1955–70) are shown. Red indicates warmer surface air temperature and more precipitation, whereas blue indicates cooler surface air temperature and less precipitation. (b) The annual-mean precipitation is shown. Here, (a) is in units of °C, and (b), (c) are in kg m⁻² s⁻¹.](image-url)
narrow band of precipitation along the Gulf Stream with potentially far-reaching impacts. However, it is not clear whether decadal SST variability in the Gulf Stream region can also cause a decadal signal in precipitation there. The annual-mean precipitation field from NCEP reanalysis data (Fig. 4b) is very similar to satellite observations and high-resolution model simulations (e.g., Minobe et al. 2008; Kuwano-Yoshida et al. 2010), where we observe a narrow rainfall band confined sharply on the warmer flank of the SST front associated with the Gulf Stream. Figure 4c shows the precipitation averaged over the 1980–95 time period minus that over the 1955–70 time period. There is a remarkable narrow band of enhanced precipitation along the Gulf Stream, suggesting the influence of ocean heat content change on local precipitation over the Gulf Stream region on decadal/interdecadal time scales, although it is not clear what the exact mechanisms are. It is possible that the decadal upper-ocean heat content anomaly in the Gulf Stream region imprints itself on SST through the “re-emergence mechanism” (Alexander and Deser 1995), and the resultant SST anomaly influences the troposphere through anomalous surface wind convergence (e.g., Minobe et al. 2008), causing a decadal rainfall signal there. The enhanced band of precipitation may also be associated with northward migration of the SST front and its resultant convective precipitation since there appears to be a band of reduced rainfall immediately to its south. Figure 5 shows the time series of the low-frequency upper-ocean heat content from the World Ocean Database and precipitation from NCEP reanalysis data in the Gulf Stream region from year 1955 to year 2009. Both time series are 5-yr running means and linearly detrended.

5. Summary and conclusions

The upper-ocean heat content change in the North Atlantic between two time periods, 1980–95 minus 1955–70, has been investigated using both observations and an ocean general circulation model. Our main results are as follows.

- The large-scale heat content change consists of warming in the tropics and subtropics and cooling in the
subpolar ocean. However, the most significant heat content change in the North Atlantic is the warming of the Gulf Stream region.

- Warming in the Gulf Stream region is not a result of enhanced surface heat flux into the ocean but driven instead by changes in ocean circulation.
- Changes in the large-scale wind forcing and associated changes in the horizontal gyre circulation are found to be the main cause of the observed warming in the Gulf Stream region.
- The increased ocean heat content in the Gulf Stream region appears to feedback on to the atmosphere, resulting in warmer surface air temperature and enhanced precipitation there.

Simple Sverdrup theory captures the leading-order large-scale changes in the horizontal gyre transport, which account for most of the observed heat content change, especially in the tropics and sub tropics; however, nonlinearities and the presence of bottom topography are clearly important in the Gulf Stream region and the subpolar gyre (e.g., Greatbatch et al. 1991; Zhang and Vallis 2007). Future research is clearly needed to improve the theory. Our study also suggests that the low-frequency ocean heat content changes in the Gulf Stream region may feedback on to the atmosphere and cause a low-frequency rainfall signal along the Gulf Stream. If confirmed, this may have important implications for decadal/interdecadal midlatitude air–sea interactions. Further studies are required to show whether this oceanic influence is confined locally near the western boundary or if it has far-reaching effects on, for example, the climate of western Europe.

Acknowledgments. We thank David Marshall for constant encouragement, Helen Johnson, Richard Greatbatch, Ralf Hand, and Noel Keenlyside for helpful discussions, and three anonymous reviewers for their insightful and constructive comments that led to a significant improvement in the manuscript. We gratefully acknowledge the financial support provided by the Department of Earth Sciences, University of Oxford.

REFERENCES


