

As mentioned above, the EnKF ensemble randomly samples the probability distribution function defined by the model, data and prior assumptions. Therefore, the ensemble members do not themselves converge to the optimum but instead sample the region around it, with the ensemble mean being a good estimate of the optimum. Where all uncertainties are well defined, the spread of the ensemble members indicates the uncertainty surrounding this optimum. However, this is not the case here, since many model parameterizations are poorly understood and may be inadequate in various ways. A good example is the uncertainty surrounding the role of dust and the marine iron cycle (Jickells et al., 2005). The formulation of the biogeochemical model is thus inherently more uncertain than that of a physical model, and, at this stage, there is no clear way to estimate the true uncertainty of the calibrated model. We therefore use the EnKF to produce a single calibrated model version, taking the mean of this ensemble as an estimate of the best parameters.

The marine carbon cycle is calibrated against long-term average observations of  $\text{PO}_4$  (Conkright et al., 2002) and ALK (Key et al., 2004) distributions in the ocean. We chose these data targets on the basis that  $\text{PO}_4$  will help constrain the cycling of organic matter within the ocean, while ALK will (primarily) help constrain the cycling of  $\text{CaCO}_3$  in the ocean. We assume that their observed distributions are relatively unaffected by anthropogenic change (Orr et al., 2005) (although see Feely et al., 2004). To create the  $\text{PO}_4$  and ALK assimilation targets, we transformed the 3-D data-sets of Conkright et al. (2002) and Key et al. (2004), respectively, to the GENIE-1 model grid, and salinity-normalized the data. For the surface data target, although the model surface layer is 175 m thick, the observed data is integrated only over the uppermost 75 m for calculating surface boundary conditions – the depth assumed in the OCMIP-2 protocol as the nominal consumption depth separating the production zone (above) from the consumption zone (below) (Najjar and Orr, 1999).

The calibration of the biogeochemistry used an ensemble size of 54, which was chosen primarily for computational convenience. Ocean chemistry was initialized with uniform concentrations of:  $2244 \mu\text{mol kg}^{-1}$  DIC (estimated pre-Industrial) (Key et al., 2000),  $2363 \mu\text{mol kg}^{-1}$  ALK (Key et al., 2000),  $2.159 \mu\text{mol kg}^{-1} \text{PO}_4^{3-}$  (Conkright et al., 2001), and  $169.6 \mu\text{mol kg}^{-1} \text{O}_2$  (Conkright et al., 2002). Initial concentrations of dissolved organic matter are zero, as are  $\delta^{13}\text{C}$  and  $\delta^{14}\text{C}$ . Atmospheric  $p\text{O}_2$  was initially set at 0.2095 atm and allowed to evolve freely in response to net air-sea gas exchange thereafter. Atmospheric  $\text{CO}_2$  was continually restored to a value of 278 ppm throughout the assimilation. The parameters we considered in the EnKF assimilation as well as our prior assumptions regarding their likely values are listed in Table 1.

**Table 2.** EnKF calibrated climate parameters in the GENIE-1 model.

Parameter <sup>a</sup>	Original posterior mean <sup>b</sup>	Revised posterior mean <sup>c</sup>
<i>Ocean</i>		
Wind-scale	1.67	1.93
Isopycnal diffusion ( $\text{m}^2 \text{s}^{-1}$ )	4,126	4,489
Diapycnal diffusion ( $\text{m}^2 \text{s}^{-1}$ )	$1.81 \times 10^{-5}$	$2.72 \times 10^{-5}$
1/friction (days)	3.43	2.94
<i>Atmosphere</i>		
T diffusion amplitude ( $\text{m}^2 \text{s}^{-1}$ )	$3.75 \times 10^6$	$4.67 \times 10^6$
T diffusion width (radians)	1.31	1.08
T diffusion slope	0.07	0.06
T advection coefficient	0.06	0.11
$q$ diffusion ( $\text{m}^2 \text{s}^{-1}$ )	$1.75 \times 10^6$	$1.10 \times 10^6$
$q$ advection coefficient	0.14	0.23
FWF adj (Sv)	0.28	0.23
<i>Sea-ice</i>		
Sea ice diffusion ( $\text{m}^2 \text{s}^{-1}$ )	6,249	6,200

<sup>a</sup> see Edwards and Marsh (2005) and Lenton et al. (2006)

<sup>b</sup> Hargreaves et al. (2004)

<sup>c</sup> parameter values employed here (re-calibrated as per Hargreaves et al., 2004, but using a corrected equation of state – see Sect. 3.1)

### 3.2 Results of the EnKF assimilation

The mean and standard deviation of the ensemble values of the controlling biogeochemistry parameters are listed in Table 1. Most of the parameters showed only weak correlations in the posterior ensemble, with the striking exception of  $r_0^{\text{CaCO}_3:\text{POC}}$  and  $\eta$ , as shown in Fig. 4. We can trace this relationship back to Eqs. (8) and (9), where it implies that  $r_0^{\text{CaCO}_3:\text{POC}} \cdot (\Omega - 1)^\eta$  is close to being constant. We interpret this to mean that although total global production of carbonate is relatively tightly constrained by the data, the spatial variation, which is a function of local saturation state ( $\Omega$ ) in the model, is not as well constrained.

We explored the sensitivity of the model calibration to the assimilated data by using the ALK data of Goyet et al. (2000) as an alternative to Key et al. (2004), although we omitted assimilating surface model layer ALK in this case because the Goyet et al. (2000) data-set is valid only below the mixed layer depth in the ocean. We found that the marine carbon cycle model and GLODAP  $\text{PO}_4$  data set (Key et al., 2004) were less consistent with the Goyet et al. (2000) ALK distributions compared to the GLODAP ALK data (Key et al., 2004). Assimilation of the latter data rather than the former reduced the root mean square difference between model ALK and  $\text{PO}_4$  fields taken together by about 10%. Most of the improvement occurred in the fit of the model to the ALK data set but there was also a slight improvement (1%) in the fit of the  $\text{PO}_4$