INFERRING TERRESTRIAL BIOSPHERE CARBON FLUXES FROM COMBINED INVERSIONS OF ATMOSPHERIC TRANSPORT AND PROCESS-BASED TERRESTRIAL ECOSYSTEM MODELS

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ABSTRACT

This paper describes the construction and application of a terrestrial carbon cycle assimilation/prediction scheme. In the assimilation step, we constrain the parameters in a terrestrial biosphere model subject to observations. We demonstrate the technique using atmospheric CO_2 concentration observations and satellite estimates of greenness. The method returns not only the values of the parameters but an estimate of their uncertainties. In the prediction step we can use these parameters and their uncertainties to either predict the future behaviour of the terrestrial biosphere or to test the model against data not used in the assimilation. The method relies heavily on the automatic generation of tangent linear and adjoint models for the optimization and uncertainty propagation steps.

1. INTRODUCTION

The estimation of surface sources from atmospheric concentration observations has been a mainstay of carbon cycle research in the last two decades. Such so-called inverse methods, however, have several important shortcomings. Firstly, since the source function is continuous, they are in principle always under-determined. We attempt to deal with this by imposing structure on the source functions. Errors in the specification of this structure seriously bias our estimates. Secondly the methods have difficulty incorporating all the other observations which may bear on source estimates. These can be included as a prior estimate in Bayesian methods but it is difficult to assign proper weight to this prior compared with the observations. Thirdly and most importantly the flux inversions have no predictive power. These three shortcomings can be partially addressed if we replace the estimate of fluxes with the assimilation of observations into process-based models.

This approach is not especially new. Tuning model parameters to optimize a fit to atmospheric concentration observations was used by Fung et al. (1987) and Knorr and Heimann (1995) to constrain diagnostic models of the terrestrial biosphere and by Randerson et al. (2001) who additionally tuned isotopic discrimination. These three studies used ad hoc parameter tuning and did not attempt a formal estimate of uncertainty. Kaminski et al. (2001), using the same model as Knorr and Heimann (1995) and more formal data assimilation techniques produced a set of optimized parameters and uncertainties for 12 biomes. That model, however, was purely diagnostic so that one could not make a meaningful prediction with it. Here we build on that study with a more mechanistic model which allows a forecast of at least some of the behaviour of the terrestrial biosphere. In this abstract we describe only the methods and models we use.

2. METHODS AND MODELS

We largely follow the methodology of Kaminski et al. (2001) and that paper should be consulted for details. Here we concentrate on the differences from that work. In summary we form a quadratic cost function based on the mismatch between quantities derived from the biosphere model and comparable observations. We minimize this cost function with respect to the controlling parameters in the model. Since these controlling parameters also define the initial state of the model (the model is spun up to equilibrium) they are sufficient to completely define the model. Like Kaminski et al. (2001) we calculate the uncertainty of these parameters at the cost function minimum. Subject to the Gaussian assumptions in this work, that uncertainty is embodied in the inverse of the Hessian matrix. Kaminski et al. (2001) neglected second derivatives in this expression but here we calculate the Hessian explicitly. Note that all derivative code, i.e. the gradient of the cost function, the Hessian and the Jacobian, was generated by the automatic differentiation tool TAF (Transformation of Algorithms in Fortran) from the code of Bethy.

2.1. Biosphere Model

The biosphere model we use is based on the BETHY model as described by Knorr (2000). It simulates photosynthesis based on a Farquhar/Collatz scheme (Farquhar et al., 1980; Collatz et al., 1992) and plant and soil respiration embedded within the full energy and water balance. Hence, it is structured into four compartments: (1) energy and water balance, (2) photosynthesis, (3) phenology and (4) carbon balance. The model is used in two forms. In its full form it is used to assimilate AVHRR data for 1989–90 following the method of Knorr and Schulz (2001). Essentially, this assimilation technique relies on an estimate of model simulated and satellite derived FPAR, the fraction of photosynthetically active radiation absorbed by the vegetation. Within this scheme model parameters controlling soil moisture and phenology are optimized.

Most importantly this first assimilation step provides monthly time series of leaf area index (LAI) and plant available soil moisture for later use. We next use a simplified form of the model (known as IMBETHY) to assimilate atmospheric concentration observations. The model is slightly reduced by leaving out the water balance from compartment one and the phenology compartment (3) completely. Therefore it can be run “off-line” with prescribed LAI and soil moisture from the full model. Parameters control the photosynthesis scheme, and both the autotrophic and heterotrophic respiration schemes.

One important part of the formulation of the model is the calculation of the long-term mean net flux to the atmosphere that is defined as NET = SR-NPP, where NPP is the net primary productivity and SR denotes the heterotrophic soil respiration. Here this flux is prescribed through the ratio between respiration from the various detrital pools (SR) and NPP. This ratio is embodied in the model parameter β. If $\beta = 1$ then NPP and soil respiration are in balance and there is no net flux. The determination of β is an important part of the assimilation. This formulation avoids the need to spin up the slow carbon pools but it also means that net fluxes in the future are a fixed proportion of NPP. We are exploring other formulations for the long-term net flux.

2.2 Atmospheric Transport and Concentrations

The critical output from IMBETHY is the space-time history of land-atmosphere CO_2 fluxes. As with Kaminski et al. (2001), we subject these fluxes to atmospheric transport and compare the resulting concentrations with atmospheric observations. Atmospheric transport is provided by the adjoint version of TM2 (Heimann, 1995) generated by Kaminski et al. (1999). The transport is invariant through the study period. Dargaville et al. (2000) suggest this is unlikely to be a serious deficiency for mean fluxes although the case for the amplitude of the seasonal cycle is less clear.

For observed concentrations we use the internal release of the GLOBALVIEW CO_2 compilation spanning 1979–1999. For simplicity we use the extended records in our control case although we also test the impact of using data only from months with actual observations. We use the same 41 stations as Kaminski et al. (2001).

2.3 Ancillary Fluxes

The natural land-atmosphere flux is only one component of the atmospheric carbon budget. In order to compare with atmospheric concentrations, we need to include all other components as well. In the best case these would be included in the assimilation but here we included them as so-called presubtracted fluxes. Uncertainties in these fluxes must be accounted for in uncertainties in the data. We use the climatological cycle of ocean fluxes provided by Takahashi et al. (1999) plus anomalies from Le Quéré et al. (2000) in the version used by Bousquet et al. (2000). The detail of these ocean anomalies is not critical to this study since interannual variations in ocean fluxes appear to contribute only slightly to variations in atmospheric growth rate.

For the fossil fuel input we use the spatial pattern of Andres et al. (1996) and magnitudes from Marland et al. (2001). We do not account for the change in spatial distribution noted through the 1990s.

The last and most problematic of the extra fluxes we include is that due to land-use change. Here we use the distribution of Houghton et al. (1990). We apply no seasonal or spatial variation to this pattern. Hence its major role will be in helping determine the net flux (and hence β) for the tropics. Future work should attempt to parameterize this flux in terms of fire likelihood based, for example, on soil moisture.

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