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Inverse Modeling of Atmospheric Carbon Dioxide Fluxes

Bousquet *et al.* (*1*) and Fan *et al.* (*2*) presented atmospheric transport inversions, the conclusions of which were based on the consistency of the models with observed atmospheric concentrations at a global monitoring network of 60 to 120 sites (*3*). This consistency, however, is not sufficient in itself. We show this by presenting a global surface flux field that achieves a much higher degree of consistency with the observations used by Fan *et al.*, but which is characterized by an extraordinary sink of 2 gigatonnes (10^{15} g) of carbon per year (GtC $year^{-1}$) over Europe.

The studies by Bousquet *et al.* and Fan *et al.* constructed the unknown surface flux field as a linear combination of prescribed patterns. For a few of those patterns, they adjusted the coefficients in such a way that the atmospheric concentration simulated with a numerical transport model would yield the best possible fit to their observations. From an inverse-modelling point of view, however, it is evident that the problem of inferring a surface flux field from point measurements is a highly underdetermined one: An infinite number of such fields exist that yield a perfect match to these observations. This even holds for a discretised formulation of the problem, in which the fluxes are represented at a resolution that is typical for global atmospheric transport models. Using our inverse model (*4*) we have constructed an example of such a field, which has an annual mean sink of 2 GtC over Europe (Fig. 1).

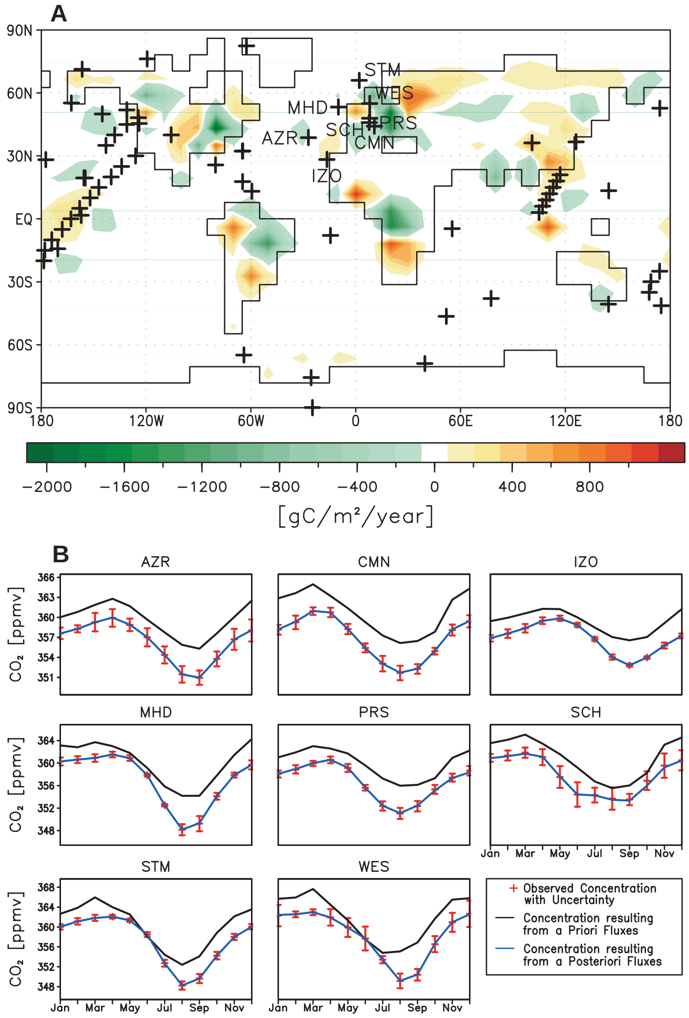

Fig. 1. (**A**) A surface flux field representing an annual mean sink of 2 GtC over Europe. The relatively well known source component due to fossil fuel burning has been subtracted. From this field, the transport model TM2 simulates an atmospheric concentration that matches the observed monthly mean concentration within less than 0.1 parts per million by volume (ppmv) in the average over all the locations indicated by crosses. The model's spatial resolution is indicated by the coastlines. (**B**) Observed concentrations with uncertainties (red), concentration simulated from a priori fluxes (black) and a posteriori fluxes (blue) at the eight sites in and closest to Europe: Azores (AZR); Mt. Cimone, Italy (CMN); Tenerife (IZO); Mace Head, Ireland (MHD); Plateau Rosa, Italy (PRS); Schauinsland, Germany (SCH); Atlantic Ocean Station M (STM); and Westerland, Germany (WES).

This example illustrates that, for this type of inversion, the degree of consistency with the observations cannot be the single criterion. A priori information regarding the unknown surface fluxes has to be added in a cautious manner. The studies by Bousquet *et al.* (*1*) and Fan *et al.* (*2*) do so by prescribing fixed flux patterns, but that ignores the large uncertainty in the small-scale structure of the fluxes, which arises from their large spatial heterogeneity (*5*).

Our field, by contrast, is constructed by leaving the fluxes in every surface grid cell of our transport model free to match the observations. Further, we require that the fluxes be as close as possible to surface flux fields computed by models of the terrestrial biosphere, land use change, and the ocean carbon cycle. In a serious inversion, any of these pieces of information must be carefully weighted in proportion to the degree of confidence one attributes to it. For this demonstration, however, we overemphasize the fit to the observations; we also prescribe the uptake over Europe. In a similar way, one could construct a sink over any region of the globe that is consistent with an arbitrarily high number of atmospheric point measurements (if necessary, by moving to a transport model with higher spatial resolution).

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Response: Bousquet *et al.* (*1*) estimated the year-to-year variations of the regional surface carbon fluxes using inversion of atmospheric transport. These estimates, like most other recent inversions of the mean surface fluxes [e.g., Fan *et al.* (*2*)], not only are based on the consistency between modeled and observed

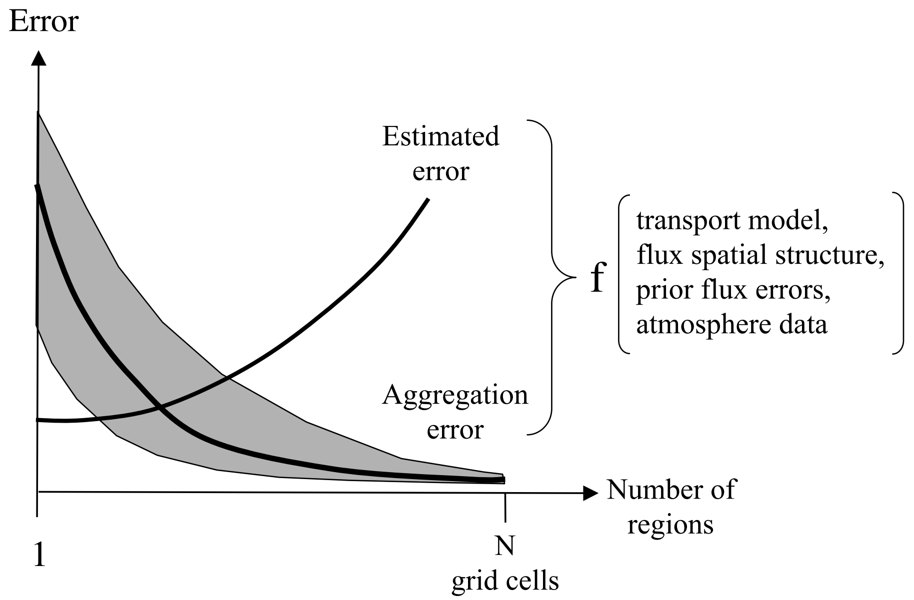

Fig. 1. Schematic view of the estimated error from the inverse procedure and the potential error that results from the aggregation of many grid cells into large regions with prescribed spatial patterns as function of the number of regions solved for (from a single big region to *N* grid cells). The large uncertainty in the aggregation error is indicated in gray, and the key parameters that control both errors are listed.

concentrations at 60 to 90 monitoring sites, but also rely on different prior assumptions regarding the unknown surface fluxes. Prescribed fixed flux patterns for large regions are used in most studies [except in (*3*)], as well as a priori values for the unknown fluxes. There is currently a debate about whether one should solve for a large number of regions (the limit being every grid cell of the transport model), or only for few continental and oceanic regions with fixed a priori spatial structure for the fluxes.

Given the sparseness of the present atmospheric network, using only few large regions avoids underdetermination of sources. By doing so, one assumes that all grid cells of a large region are perfectly correlated: Fluxes of all grid cells within a region are adjusted proportionally to the prior flux structure in that region. In this case, the "estimated error" (the random uncertainty calculated by the inversion) decreases as the number of regions decreases (Fig. 1). The large uncertainty that exists on the small-scale structure of CO_2 surface fluxes, however, may add up systematic bias on the estimated fluxes when solving for large regions. This leads to an "aggregation error" [formally described in (*4*)] that decreases as the number of regions increases (Fig. 1). Increasing the number of independent regions allows the model to recover more information from the atmospheric data and to be less sensitive to the a priori spatial structure of the fluxes. However, each small region is adjusted independently from the others. That approach thus ignores independent knowledge on biogeochemical processes and climate factors that control the carbon sources and sinks: Large ecosystems (e.g., boreal or tropical forest, pasture) under coherent climate forcing may behave similarly. The existence of seasonal and interannual variations in atmospheric concentration demonstrates by itself that, even if the surface fluxes may be highly heterogeneous in space and time, they must exhibit an organized response over sufficiently large areas to be felt by the atmosphere.

The choice of a particular spatial resolution is tightly related to the degree of confidence we attribute to our geochemist's knowledge on spatial heterogeneity of the fluxes and to the transport model that is used. If one strongly trusts the correctness of the spatial structure of the sources and sinks as usually defined by global models of the terrestrial biosphere, land use change, and the ocean carbon cycle, one should solve for a small number of regions [e.g., seven, as in (*2*)]; if not, one should solve for a larger number of regions. There is probably an optimal number of regions to consider in inverse modeling of CO_2 sources that minimizes both the potential aggregation error and the estimated error.

Given the present understanding of the small-scale flux variability and the atmospheric network, we believe that only a few regions (on the order of 10) is likely to be too small, while solving for all grid cells of the transport model largely disregards important known biogeochemical coherency among ecosystems. A possible improvement would be to consider as many regions as possible, but with correlated prior uncertainties; the degree of correlation would be proportional to our current knowledge on the spatial flux structure. In this approach, perfect correlations would not be imposed between small regions, and one could afterward verify how these constraints are violated.

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