REGIONAL CARBON FLUX ESTIMATION USING THE MAXIMUM LIKELIHOOD ENSEMBLE FILTER

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ABSTRACT

We have developed a carbon flux inversion method for using a mesoscale meteorological model (CSU-RAMS) within a Maximum Likelihood Ensemble Filter (MLEF, Zupanski 2005; Zupanski and Zupanski 2005). The MLEF is a variant of the Ensemble Kalman Filter, and is used to optimize model state variables and parameters based on continuous observations of CO_2 mixing ratio. The method does not require the development of a model adjoint, but rather relies on transformation of variables to efficiently obtain estimates of fluxes with uncertainties and dynamical model error from an ensemble of forward model simulations. We demonstrate this method using a mesoscale simulation of weather, transport, and the surface carbon budget over the continental USA during the summer. The estimation procedure decomposes the total surface flux into photosynthesis and respiration (which are assumed to be modeled correctly to first order), plus an unknown but time-invariant fractional error in each. These residuals are estimated for each model grid cell over a moving window in time, allowing atmospheric observations to be integrated over sufficient time to obtain constraint. Model error can also be estimated by this procedure, and the method can be extended to larger domains and longer integrations.

REGIONAL COUPLED SIMULATIONS WITH SiB-RAMS

We simulated a six-week period in the summer of 2004 using a coupled model of mesoscale meteorology and terrestrial ecophysiology (SiB-RAMS, Denning et al, 2003; Nicholls et al, 2004). For the experiments described here, we used a 20-km grid over the continental USA, extending several hundred km into the Atlantic and Pacific Ocean basins. We used lateral boundary conditions for weather from a global reanalysis produced by the NASA GEOS-DAS, and for CO_2 from the global Parameterized Chemistry and Transport Model (PCTM, Kawa et al, 2004). We defined sampling sites at the locations of real and planned continuous analysis stations within the domain, and sampled the forward simulation at these sites to obtain synthetic timeseries of continuous observations of CO_2 mixing ratio. We used an offline Lagrangian Particle Dispersion Model (LPDM) to generate quantitative influence functions for samples taken from each observing site for each hour of the simulation, and used these to estimate time-mean fluxes on a 50-km grid as a residual after subtracting modeled photosynthesis and respiration. Results show acceptable convergence with ensembles of ~200 members, with significant skill several hundreds of km upstream of each observing site.

MAXIMUM LIKELIHOOD ENSEMBLE FILTER

The MLEF seeks a maximum likelihood state solution employing an iterative minimization of a cost function. The solution for an augmented state vector $\boldsymbol{x}$ (including initial conditions, model error, and empirical parameters), of dimension N_{state}, is obtained by minimizing a cost function J defined as

$$J(\boldsymbol{x}) = \frac{1}{2}[\boldsymbol{x}-\boldsymbol{x}_b]^T \boldsymbol{P}_f^{-1}[\boldsymbol{x}-\boldsymbol{x}_b] + \frac{1}{2}[\boldsymbol{y}-H(\boldsymbol{x})]^T \boldsymbol{R}^{-1}[\boldsymbol{y}-H(\boldsymbol{x})] \ ,$$

where $\boldsymbol{y}$ is an observation vector of dimension equal to the number of observations (N_{obs}) and H is a nonlinear observation operator (e.g., Lagrangian Particle Dispersion Model, LPDM). Subscript

b denotes a background (i.e., prior) estimate of $\boldsymbol{x}$, and superscript T denotes a transpose. The $N_{obs} \times N_{obs}$ matrix $\boldsymbol{R}$ is a prescribed observation error covariance. The matrix $\boldsymbol{P}_f$ of dimension $N_{state} \times N_{ens}$ is the forecast error covariance (N_{ens} being the ensemble size).

Uncertainties of the optimal estimate of the state $\boldsymbol{x}$ are also calculated by the MLEF. The uncertainties are defined as square roots of the analysis error covariance and the forecast error covariance, both defined in terms of ensemble perturbations, and update in each data assimilation cycle.

The MLEF approach is well suited for non-linear carbon flux inversion problems, since it calculates a non-linear solution to the minimum of J, via an iterative minimization with an effective Hessian preconditioning defined in ensemble subspace. The procedure is similar to the Ensemble Kalman Filter, but is much more flexible with respect to assumptions about error distributions and the specification of forward model error. Due to the preconditioning, the MLEF is also more efficient (i.e., converges with a smaller ensemble).

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