

# **An Ensemble Kalman Smoother for the Coupled Greenhouse Gas and Flux estimation problem: Design of the Environment Canada Carbon Assimilation System**

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Climate change is one of the pressing issues of our time. In an effort to understand and quantify the biospheric and anthropogenic contributions to the atmospheric rise of CO<sub>2</sub>, climate scientists are building comprehensive carbon monitoring systems of the global carbon cycle. The core of such systems is an atmospheric transport model constrained by atmospheric measurements. Eventually, this will be coupled to terrestrial biospheric models and ocean carbon cycle models each constrained by observations. The primary goal of the system is to estimate the atmospheric exchange of carbon with the Earth's surface.

There are many challenges particular to the carbon flux estimation problem. Unlike the weather forecasting case, the background state derives not from a geophysical model, but rather, from a combination of industry and government reported anthropogenic emissions along with ecosystem model outputs of biospheric fluxes and an ocean model of carbon fluxes. The propagation of the background state does not follow a dynamical model yet has clear biases, and temporal (diurnal to annual) scales of variability. This renders covariance estimation of the prior flux a daunting prospect. Yet, the prior flux is critical to the estimation problem, because the surface measurement network is sparse and satellite measurements are very new—the first dedicated greenhouse gas instrument (GOSAT) was launched in 2009 and OCO-2 will be launched in 2014. The promise of the new satellite measurements is improved spatial scales of retrieved fluxes. The promise of advanced assimilation methods such as ensemble Kalman smoothers is improved uncertainty estimates since conventional methods of flux estimation typically assume that transport is perfect (i.e. no initial CO<sub>2</sub> concentration, model or analysed wind errors).

In this work, the formulation of the data assimilation problem through the design of the Environment Canada Carbon Assimilation System is presented. The core of the system is the operational weather and environmental prediction model. Key model adaptations needed for greenhouse gas simulation included mass conservation, improvement of boundary layer mixing, and the addition of convective transport of tracers. The assimilation system is an extension of the operational Ensemble Kalman filter (to be adapted for constituents and for the smoothing problem). In addition to covariance estimation of prior fluxes, the assimilation challenge is one of multiple time scales. The large diurnal cycle of the terrestrial biosphere in summer provides gradients which, if detected by measurements, can be used to infer upstream fluxes. However, the sparse measurement network dictates update cycles of days to weeks, and the signal of an instantaneous pulse disperses on the order of months. At surface measurement sites, synoptic to inter-hemispheric transport operating on daily to inter-annual time scales determines concentrations. The issues in designing the assimilation system (i.e. choosing the update frequency, prior covariance modeling for additive inflation, ensemble generation and localization, etc.) will be presented along with preliminary results from the system development.