Summary of the Final Report of Research Results

1) Title of the proposed research

Estimation of CO_2 and CH_4 surface fluxes

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4) Summary of the Final Report of Research Results

In order to highlight the internal logic of this research within the RA period, papers quoted here are only those that this proposal lead. Obviously, other papers contributed to the domain and many of them are quoted within the proposal papers.

Over the course of this research, we witnessed dramatic improvements brought by XCH_4 retrieval retrievals for flux inversions. We initially showed that their large-scale constraint on the inversion problem could yield flux maps that are statistically consistent with those inferred from the surface network, in contrast to SCIAMACHY at the end of its lifetime (Cressot et al. 2014). However, we found then that the coarse resolution of the transport model used in these results actually masked a poor representation of the stratosphere–troposphere methane gradient in that version of the model, that compensated a large bias in GOSAT CH_4 satellite data: improving the stratosphere–troposphere gradient with a thinner model resolution made surface and satellite inversions inconsistent again and an appropriate bias-correction is needed. At small scale, most methane signals, like those from Siberian wetlands, may be too small to be well seen by the column retrievals (Berchet et al. 2015).

For CO_2, small uncertainties in aerosols, cirrus cloud or surface albedo were known for long to heavily affect the quality of the XCO_2 satellite retrievals and to propagate into biases in the fluxes inverted from them, even when the parasite signal in XCO_2 is sub-ppm. Similarly, errors in transport modelling can also flaw the inversions (Chevallier et al. 2010). Together with the University of Edinburgh, we built an ensemble of six satellite-based global inversions for year 2010, from three atmospheric transport models, two independent Bayesian inference algorithms and two versions of bias-corrected CO_2 column GOSAT retrievals. This ensemble showed hemispheric and regional differences in posterior flux estimates that were beyond theoretical 1 sigma uncertainties and in some regions were judged unrealistic. Given we what was known about the sensitivity of XCO_2 inversion to small errors in modelling or retrievals, the spread of the results was not really surprising. What was confounding is the apparent biases of the ensemble, with, e.g., an excessive sink in continental Europe and excessive emissions in Northern Africa. In order to understand the cause of these apparent biases, we analyzed both the data flow and the model-minus-retrieval misfits in details.

From the theory, we showed that a usual two-step approach to infer the surface fluxes from the GOSAT measured radiances, with CO_2 retrievals as an intermediate product, cannot be optimal (Chevallier 2015). This suboptimality corrupts the 4D information flow from the radiance measurements to the surface flux estimates. It is amplified by the current retrieval strategy where prior errors are much larger (by an order of magnitude in terms of variances) than the performance of prior CO_2 simulations used in atmospheric inversions. Indeed, the use of averaging kernels makes atmospheric inversion insensitive to the choice of a particular retrieval prior CO_2 profile if retrievals are assimilated without any bias correction, but it does not make the retrieval prior error statistics disappear from the inverse modelling equations. The current strategy likely generates retrieval averaging kernels that are inappropriate for atmospheric inversions in their default configurations, with a wrong vertical distribution and an excessive weight towards the measured radiances. Paradoxically, empirical bias correction of the retrievals also contributes to the degradation of the 4D information flow, because it carries the imprint of the retrieval prior and of the retrieval prior error statistics. Direct assimilation of the measured radiances would solve the inconsistency, but would increase the computational burden of atmospheric inversions by several orders of magnitude. Alternatively, we could adapt the inversion systems to the current retrieval configuration by using minimal prior information about the surface fluxes, typically a flat prior flux field, but the result would still over-fit the measured radiances due to the absence of other (compensating) information.

We then compared NASA’s ACOS-GOSAT retrievals b3.4 with a transport model simulation constrained by surface air-sample measurements in order to find some evidence of retrieval sub-optimality. Flaws in this transport model and in these inverted surface fluxes necessarily flaw the simulation in many places over the globe and at various times of the year. We therefore carefully selected some of the relatively large discontinuities in the XCO_2 fields that the simulation unlikely generated. We found some evidence of retrieval systematic errors over the dark surfaces of the high-latitude lands and over African savannahs. We also found some evidence that the high-gain retrievals over land systematically over-fit the measured radiances, as a consequence of the prior uncertainty overestimation and of an underestimation of the observation uncertainty (as seen by the underlying radiative transfer model). This over-fit was partially compensated by the bias correction. An empirical test indicated that halving the retrieval increments without any posterior bias correction actually cancels the dependency of the statistics of the observation-minus-model misfits to the increment size and makes the standard deviation systematically better than for the retrieval prior.

Given the diversity of existing satellite retrieval algorithms, our conclusions cannot be easily extrapolated to other GOSAT retrieval products and even less to XCO_2 retrievals from other instruments, but we note that such mistuning like the one highlighted here is common practice, both because the errors of the retrieval forward model are difficult to characterize and because satellite retrievals are usually explicitly designed to maximize the observation contribution, at the risk of over-fitting radiance and forward model noise. A primary consequence of this mistuning is the usual underestimation of retrieval errors. More importantly, our results show that the mistuning generates excessive (unphysical) space-time variations of the retrievals up to ~1%. This noise level would not matter for short-lived species, but for CO_2 it is enough to significantly degrade the assimilation of the retrievals for flux inversion and may explain some of the inconsistency seen between GOSAT-based top-down results and bottom-up results for CO_2 (Chevallier et al. 2014). Therefore, with the current mistuning, we reiterate previous recommendations to take GOSAT-based CO_2 inversion results particularly cautiously. But we also suggest that this situation may dramatically improve by simply retuning the retrieval schemes.

5) List of publications relating to the proposed research

Berchet, A., I. Pison, F. Chevallier, J.-D. Paris, P. Bousquet, J.-L. Bonne1, M. Yu. Arshinov, B. D. Belan, C. Cressot, D. K. Davydov, E. J. Dlugokencky, A. V. Fofonov, A. Galanin, J. Lavrič, T. Machida, R. Parker, M. Sasakawa, R. Spahni, B. D. Stocker, and J. Winderlich, 2015: Natural and anthropogenic methane fluxes in Eurasia: a meso-scale quantification by generalized atmospheric inversion. Biogeosciences, accepted.

Chevallier, F., L. Feng, H. Boesch, P. Palmer, and P. Rayner, 2010: On the impact of transport model errors for the estimation of CO_2 surface fluxes from GOSAT observations. Geophys. Res. Lett., 37, L21803, doi:10.1029/2010GL044652

Chevallier, F., and C. W. O'Dell, 2013: Error statistics of Bayesian CO_2 flux inversion schemes as seen from GOSAT. Geophys. Res. Lett., 40, 1252–1256, doi:10.1002/grl.50228.

Chevallier, F., P. I. Palmer, L. Feng, H. Boesch, C. W. O'Dell and P. Bousquet, 2014: Toward robust and consistent regional CO_2 flux estimates from in situ and space-borne measurements of atmospheric CO_2. Geophys. Res. Lett., 41,1065–1070, doi:10.1002/2013GL058772

Chevallier, F., 2015: On the statistical optimality of CO_2 atmospheric inversions assimilating CO2 column retrievals. Atmos. Chem. Phys. Discuss., 11889-11923, doi:10.5194/acpd-15-11889-2015

Cressot, C., F. Chevallier, B. Bousquet, C. Crevoisier, E. J. Dlugokencky, A. Fortems-Cheiney, C.

Frankenberg, R. Parker, I. Pison, R. A. Scheepmaker, S. A. Montzka, P. B. Krummel, L. P. Steele, and R. L. Langenfelds, 2014: On the consistency between global and regional methane emissions inferred from SCIAMACHY, TANSO-FTS, IASI and surface measurements, Atmos. Chem. Phys., 14, 577-592, doi:10.5194/acp-14-577-2014

Locatelli, R., P. Bousquet, M. Saunois, F. Chevallier, and C. Cressot, 2015: Sensitivity of the recent methane budget to LMDz sub-grid scale physical parameterizations. Atmos. Chem. Phys., 15, 9765-9780, doi:10.5194/acp-15-9765-2015