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What can we learn from European continuous atmospheric CO₂ measurements to quantify regional fluxes – Part 2: Sensitivity of flux accuracy to inverse setup

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Abstract. An inverse model using atmospheric CO₂ observations from a European network of stations to reconstruct daily CO₂ fluxes and their uncertainties over Europe at 50 km resolution has been developed within a Bayesian framework. We use the pseudo-data approach in which we try to recover known fluxes using a range of perturbations to the input. In this study, the focus is put on the sensitivity of flux accuracy to the inverse setup, varying the prior flux errors, the pseudo-data errors and the network of stations. We show that, under a range of assumptions about prior error and data error we can recover fluxes reliably at the scale of 1000 km and 10 days. At smaller scales the performance is highly sensitive to details of the inverse set-up. The use of temporal correlations in the flux domain appears to be of the same importance as the spatial correlations. We also note that the use of simple, isotropic correlations on the prior flux errors is more reliable than the use of apparently physically-based errors. Finally, increasing the European atmospheric network density improves the area with significant error reduction in the flux retrieval.

1 Introduction

Quantitative understanding of the sources and sinks of chemically and radiatively important trace gases and aerosols is essential in order to assess the human impact on the environment. Observations of atmospheric concentration provide the basic data for inferring sources and sinks at the surface of the Earth, or in the volume of the atmosphere. For conservative tracers, which stay inert once emitted, the influences of surface fluxes are modified only by atmospheric transport, which integrates the flux heterogeneity over regional and continental scales. Starting from a set of atmospheric concentration observations, and using a model of the atmospheric transport and chemistry, it is possible to infer information about the distribution of sources and sinks at the surface. This process is known as inversion of the atmospheric transport.

In the companion paper (Carouge et al., 2010, CA08) we investigated the ability of an atmospheric network to constrain sources and sinks of CO₂ over Europe. In particular, the limits of spatial and temporal scales that could be reasonably recovered seemed closely linked to the density of the network. CA08 was only able to explore a limited subset of the choices required to construct an inverse modeling system. Here we investigate the impact of setup choices on inversion performance. As with the previous paper, we use pseudo-data experiments so that we can compare the inversion results with answers known in advance. We stress therefore that our tests are negative: we certainly cannot assume that, because a given setup works in our model world, it will



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work in a real case but we can be confident that if an inversion setup is unsuccessful with pseudo-data it is unlikely to work in realistic conditions.

There are many decisions in setting up an inversion. The choice of a particular spatial resolution to execute an inversion is tightly related to the degree of confidence we attribute to our biogeochemical knowledge on spatial heterogeneity of the fluxes and their errors. If one strongly trusts the correctness of the prior spatial structure of the sources and sinks as usually defined by models of ecosystems, or of air-sea fluxes, one needs to use only a few number of regions to solve for, whereas if not, one must increase the resolution of the solution.

Here we tackle the problem of inverting daily Net Ecosystem Exchange (NEE) from daily atmospheric concentrations over Western Europe, using pseudo-data. In this context, there is little biogeochemical knowledge about the space and time coherence of modeled NEE and its errors within a continent. Only one comparison between the results of a vegetation model and the observed daily NEE at a few tens of eddy-covariance sites was realized so far (Chevallier et al., 2006). This study suggests that the NEE errors possess strong temporal correlation (up to several weeks) but no obvious spatial correlation. In this context, a logical inversion setup would be to consider as many regions as possible (i.e. every grid point of the model) but with correlated prior uncertainties, with correlations informed by the knowledge of flux errors. Very little is known on the structure of flux errors at the scale used in this study, we thus realized different scenario.

In this paper, we perform three categories of sensitivity tests to investigate the influence on the inversion results of 1) the parametrisation of the prior flux errors structure, 2) the errors attached to the atmospheric pseudo-observations, and 3) the density of the atmospheric station network. The latter is studied by comparing the 10 stations network of the control case with a denser network of 23 stations, reflecting the evolution of European network. As in CA08 we invert pseudo-data, generated with a forward run of the transport model prescribed with an arbitrary “true” NEE flux from an ecosystem model. The prior, or first guess, NEE is given by another, independent, ecosystem model. Our main criteria for assessing the inversion accuracy are the error reduction, and the ability to retrieve the true fluxes when starting from the erroneous prior. We first describe the control inversion (S0, CA08) setup and the sensitivity tests (Sect. 2), then we analyze the inversion accuracy (Sect. 3) for each of the sensitivity tests. Conclusions are drawn in Sect. 4.

2 Grid-based regional inversion and sensitivity tests

2.1 Control inversion (S0)

2.1.1 Overall setup

The Bayesian synthesis inversion formalism is used (Enting, 2002). We invert CO₂ fluxes each day over a European grid, which has the same spatial resolution as the transport model (50 km). The input information is a time-series of simulated, daily CO₂ concentration from a network of European stations. The pseudo-data framework allows us to test the impact of different inversion setups on the accuracy of the solution. This will be done by comparing the retrieved fluxes with the “true fluxes” used to generate the pseudo-data. The goal is to optimize daily land-ecosystem CO₂ fluxes (NEE) over Europe, and daily air-sea fluxes over the Northeastern Atlantic. It is assumed that, outside these two regions, all the fluxes are perfectly known and are not optimized. We construct separately the true and the a priori NEE fluxes using two independent terrestrial ecosystem models (see below). The time series of pseudo-data are generated for year 2001 by the LMDZ transport model, prescribed with true fluxes from the ORCHIDEE ecosystem model (Krinner et al., 2005). These pseudo-data are further perturbed with Gaussian noise, in order to account for data errors and, in an idealized way, for model representation errors. Technically, we divide the inversion during one year into a series of consecutive 3-monthly inversions, (see CA08 for details). The performance of the inversion will be analyzed by comparing: 1) the optimized fluxes with the true fluxes (error diagnostic), and 2) the optimized flux uncertainties with the a priori uncertainties (error reduction diagnostic).

2.1.2 Calculation of the sensitivity of concentrations to surface fluxes

We use the LMDZ global transport model with 19 sigma-pressure layers (Sadourny and Laval, 1984, Hourdin and Armengaud, 1999). The grid of the model is zoomed over Western Europe, with a maximum resolution of 50 km by 50 km. The modeled winds are nudged to the analyzed fields of the European Center for Medium Range Weather Forecasting (ECMWF) for the year 2001. The sensitivity of daily CO₂ concentration at a given station and time step to all the surface fluxes is called the influence function (also the Green’s function). The influence function of each datum is calculated with the LMDZ retro-transport (Hourdin and Talagrand, 2006), where a pulse of “retro-tracer” is emitted each day and transported backwards in time. In this formulation, the sign of the advection term is reversed, and the sign of the unresolved diffusion terms is unchanged. Computing the sensitivity of one daily CO₂ observation to all the fluxes is computationally efficient because it requires only one backward simulation per datum.

2.1.3 Construction of pseudo-data

We rely on a European network of 10 stations, as it existed in 2001 in the CARBOEUROPE cluster of projects (see Fig. 1). The pseudo-data are generated with LMDZ for that year, prescribed with “true” daily NEE from the ORCHIDEE model. For inverting the fluxes, the modeled CO₂ pseudo-data are selected for daytime only, between 11:00 and 16:00 local time, and their influence functions calculated accordingly. This daytime selection strategy is currently applied by modelers simulating continuous CO₂ data (Geels et al., 2007; Peters et al., 2007; Law et al., 2008), and by experimentalists taking flask samples. This selection recognizes the difficulties of large-scale models simulating nocturnal CO₂ trapping near the ground during the growing season. In the control inversion S0, only a small noise with a standard deviation 0.3 ppm, representative of instrumental noise, is added to the pseudo-data (CA08).

2.1.4 A priori fluxes and errors

These errors are as in CA08. The CO₂ fluxes over all the regions outside Europe and the Northeast Atlantic (see Fig. 1) are not optimized. For each grid-point of the Northeastern Atlantic region, the prior air-sea flux is set to zero, with a small total regional error of ± 0.05 GtC/year. The prior air-sea flux errors are spatially correlated between ocean grid-points, with an exponential decrease with distance (e-folding length of 1500 km). Some temporal correlations are considered with an exponential decrease with time (e-folding time of 10 days) but no cross-correlations are applied. For each grid point of Europe, the prior daily NEE is taken from the TURC model (Lafont et al., 2002). TURC is a diagnostic NEE model driven by climate data and satellite observations of NDVI for the period April 1998–April 1999. The differences between fluxes produced by biospheric models are principally driven by differences in the meteorological constraints and the differences in the internal structure of the models. The fact that TURC has a very different structure from ORCHIDEE, used to produce the true fluxes, and that it is integrated with climate forcing of a different year, maximizes the difference between prior and true NEE. From these differences, we assess an average prior daily flux standard deviation error of $3 \text{ gC m}^{-2} \text{ day}^{-1}$ for each grid-point. The structure of terrestrial flux correlations varies between sensitivity tests and is presented in the next section for each test.

2.2 Sensitivity tests

2.2.1 Prior flux errors (SP tests)

In addition to S0, we ran four sensitivity tests with a distinct a priori NEE error covariance. A summary of the error characteristics and of the total European NEE prior error for each test is given in Table 1:

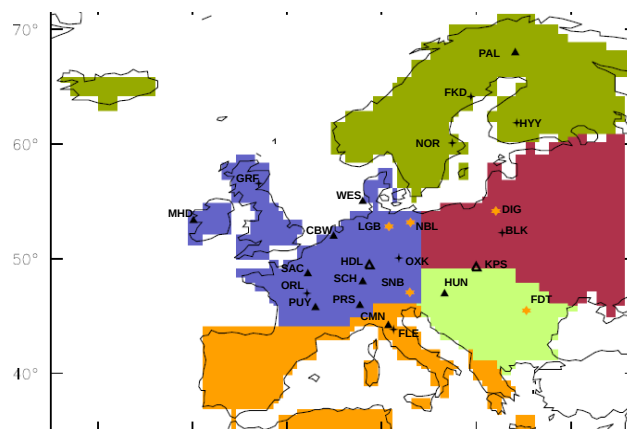


Fig. 1. Map of European continuous stations. The 2001 AERO-CARB stations are represented by black filled triangles, CarboEurope stations by black empty triangles, CHIOTTO tower by black crosses and WDCGG stations by orange stars. After inversion, fluxes were aggregated over five different regions: “Western Europe” in blue, “Mediterranean Europe” in orange, “Balkans” in light green, “Central Europe” in red and “Scandinavia” in green.

S0. Control inversion setup, with both spatial and temporal correlation being defined by an exponential attenuation, with an e-folding time of 10 days and an e-folding distance of 1000/1500 km over land/ocean. This setup, detailed in CA08 is also called “isotropic flux correlation”. Note that the e-folding time length was chosen from the autocorrelation in time of the NEE differences between TURC and ORCHIDEE that shows for each grid-point an exponential decrease, with $R \approx 0.3$ after 10 days. We choose to neglect cross-correlations in time and space. Then each of the spatial and temporal covariance matrices need to be divided by 2 before to add them together (CA08). In this way, we ensure the mathematical properties of the total covariance matrix.

SP1. Test with no spatial and no temporal correlations between grid points, also called “No-correlation”.

SP2. Test with temporal but no spatial correlations, called “time-only correlation”. There are no cross-correlations, so the factor 0.5 is not applied and the resulting temporal correlations are higher than the correlations used in S0 case.

SP3. Test with spatial but no temporal correlations, called “distance-only correlation”. Here again, there are naturally no cross-correlations, so the spatial correlations are higher than the correlations used in S0 case.

SP4. Test with both spatial and temporal correlation patterns, based upon the difference between prior and true NEE. In time, we use the exponentially decreasing temporal correlation (as in S0 and SP2). In space, we constructed a daily error covariance matrix of NEE, from the spatial correlations of the TURC minus ORCHIDEE difference taken over a 5 day running window. This NEE error structure combines both structural differences between the two models, as well as differences in their meteorological forcing. Such a spatial

Table 1. Name of the different inversions and flux error correlations used in each case.

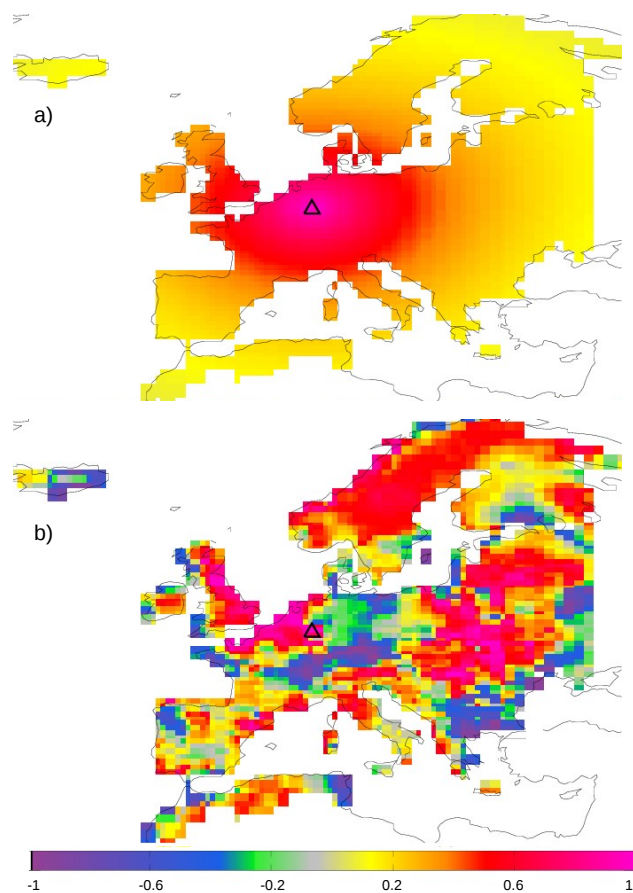
Cases	Temporal Correlations	Spatial Correlations	Total European error (GtC/yr)	Data uncertainty (ppm)
Control (S0)	Exponential($\tau=10$ d)	Exponential ($\lambda=1000$ km)	0.150	0.3
“No-corr” (SP1)	None	None	0.008	0.3
“Time-only-corr” (SP2)	Exponential($\tau=10$ d)	None	0.030	0.3
“Dist-only-corr” (SP3)	None	Exponential ($\lambda=1000$ km)	0.080	0.3
“Diff-corr” (SP4)	Exponential($\tau=10$ d)	Based on ORCHIDEE minus TURC differences	0.062	0.3
SD1	Exponential($\tau=10$ d)	Exponential ($\lambda=1000$ km)	0.150	variable
SN1	Exponential($\tau=10$ d)	Exponential ($\lambda=1000$ km)	0.150	variable

Table 2. List of European continuous stations with their location and additional stations for SN1.

Station name	Station symbol	Latitude	Longitude	Altitude (m a.s.l.)
Cabauw	CBW	51.97° N	4.92° E	200
Monte Cimone	CMN	44.18° N	10.70° E	2165
Hegyhatsal	HUN	46.95° N	16.65° E	363
Mace Head	MHD	53.32° N	9.88° W	25
Pallas	PAL	67.97° N	24.12° E	560
Plateau Rosa	PRS	45.93° N	7.70° E	3480
Puy de Dôme	PUY	45.75° N	3.00° E	1465
Saclay	SAC	48.75° N	2.17° E	120
Schauinsland	SCH	47.92° N	7.92° E	1205
Westerland	WES	54.93° N	8.32° E	8
Diabla Gora	DIG	54.15° N	22.07° E	157
Fundata	FDT	45.47° N	25.30° E	1383
Neuglobsow	NBL	53.17° N	13.03° E	65
Sonnblick	SNB	47.05° N	12.98° E	3106
Waldhof	LGB	52.80° N	10.77° E	74
Heidelberg	HDL	49.40° N	8.70° E	116
Kasprowy	KPS	49.22° N	19.99° E	1987
Bialystok	BLK	52.25° N	22.75° E	300
Florence	FLE	43.82° N	11.26° E	245
Griffin	GRF	56.55° N	2.99° W	232
Orléans	ORL	46.97° N	2.12° E	203
Norunda	NOR	60.08° N	17.47° E	102
Hyytiälä	HYY	61.84° N	24.28° E	73
Flakaliden	FKD	64.12° N	19.45° E	57
Ochsenkopf	OXK	50.03° N	11.80° E	1185

error structure is more complex than in the S0 case (Fig. 2). The cross-correlations are also discarded in this case, in the same way than in S0 case.

For all experiments, prior fluxes over land are assigned standard deviations of $3 \text{ gC m}^{-2} \text{ day}^{-1}$. Because we neglect cross-correlations in case S0 and SP4, correlations are smaller (factor 2) compared to the initial “space-only” and “time-only” correlation matrices (SP2 and SP3). Note that

**Fig. 2.** Example of correlations for a point in Germany (symbolised with a black triangle) for correlations in distance (a) and correlations based on TURC and ORCHIDEE fluxes difference for 1 January 2001 (b).

this is similar for oceanic grid points. In the following, we thus mainly compare the cases with both spatial and temporal correlations together (S0 and SP4) on one hand and the cases with only spatial or temporal correlations (SP2 and SP3) on the other hand.

2.2.2 Data errors (SD test)

We consider in addition to S0, a sensitivity test with larger random errors on the daily pseudo-data, which intend to represent the random part of transport model errors. In all cases, the daily data errors are not correlated spatially and temporally in the data error covariance matrix. Note also that flux error reduction does not depend on the value of the concentration data, but only on its prior uncertainties (Sect. 3.2).

S0. Control inversion setup. A small white noise of standard deviation 0.3 ppm is assumed (CA08). This small noise is representative of instrumental noise.

SD1. Test with a larger noise added to the pseudo-data. We add to the pseudo-data a noise with a realistic value based on temporal variability of real observations, and corresponding to the typical error that could be used in an inversion with real observations. Following Peylin et al., 2005, daily errors are calculated as the standard deviation of actual hourly (or half-hourly) CO₂ measurements, each day between 11:00 and 16:00. The underlying assumption to link this error calculation to the random part of error in transport modeling is that atmospheric transport models tend to be less reliable for sites and days with larger hourly variability (Geels et al., 2007). The resulting annual mean daily error varies between 0.56 ppm at Pallas, up to 2.84 ppm at Cabauw. In summer, the seasonal mean daily error varies between 0.84 ppm at Plateau Rosa, up to 3.51 ppm at Schauinsland. In winter, the data error ranges between 0.29 ppm at Pallas up to 2.63 ppm at Cabauw. In winter, plain stations, like Cabauw, are more likely to present large variability in their measurements. Indeed, the planetary boundary layer (PBL) is low in winter. Thus, plain stations are likely to measure blobs of concentrated air from time to time. At the opposite, mountain sites measure almost exclusively the free troposphere in winter. Thus the measurements at these sites are likely to show little variability. At the opposite in summer, the PBL is more developed. The plain sites measure then a more uniformly mixed air than in winter. At the opposite, the mountain sites are more likely to measure air from free troposphere and the PBL. The variability in their hourly measurements is then enhanced compared to winter. In the SD1 setup, the flux error reduction reflects more realistically the error reduction structure of actual data. Yet, this data error setup might not account completely for the lack of ability (and the systematic biases) of a transport model with a resolution of 50 km to reproduce faithfully a point-scale measurement.

2.2.3 Network of stations (SN test)

All previously described inversion tests have been conducted with 10 European continuous stations, as operational in 2001 (Fig. 1). However, the European atmospheric CO₂ network is still growing, both in spatial (more stations) and temporal (more continuous stations) density.

SN1. Test with 13 new stations added to the 2001 European network. To do so, the influence functions are calculated for additional pseudo-stations with LMDZ. We restrict the SN sensitivity test to three months in summer in order to avoid a too large computation time. We use the error reduction as a measure of the “power” of a denser network. The calculation of this term only requires the influence function and the data error for each new observation. For data errors, we adopted the case of a large noise, as described in the SD1 test above and thus compared the SN1 inversion to the SD1 inversion. Three groups of new stations are added to the network in the SN1 test. The first group contains five stations which are measuring CO₂ continuously and reporting data to the World Data Center for Greenhouse Gases (WDCGG, <http://gaw.kishou.go.jp/wdcgg/>), but which are not inter-calibrated with the high-precision CARBOEUROPE network (Fig. 1). Their data errors are taken as the daily standard deviations of available hourly observations, as for other sites. The second group contains two continuous sites, Heidelberg and Kasprowy, which became part of the CARBOEUROPE-IP project after 2001 (see Fig. 1; <http://ce-atmosphere.lsce.ipsl.fr/>). The errors at both sites are set to the average error of the 2001 network, excluding Hegyhatsal and Cabauw stations. The third group contains six tall towers, which progressively became operational as part of the CHIOTTO project (<http://www.chiotto.org/>). These tall towers (Fig. 1) were assigned a summer mean error identical to the one of the Hegyhatsall tower in Hungary (2.24 ppm).

3 Results

We analyze in this section the sensitivity of the accuracy of the inversion to the different setups described in Sect. 2. To focus on synoptic changes, we only compare deseasonalized fluxes (see CA08). The results from the control inversion S0 of CA08, briefly summarized below, are then systematically compared with those of each sensitivity test.

3.1 Control inversion results

With daily data at 10 stations, a small data noise of 0.3 ppm, and a prior NEE significantly different than the truth (TURC versus ORCHIDEE), the S0 inversion cannot reconstruct European daily fluxes at the transport model grid resolution of 50 km. However, the accuracy of the flux retrieval improves markedly with spatial and temporal aggregation of the results. CA08 computed the correlation (R) and the normalized standard deviation (NSD) between optimized and true fluxes, as a function of space and time aggregation for the regions defined in Fig. 1. CA08 analyzed the retrieval of deseasonalized daily fluxes, i.e. the ability of the S0 inversion to capture weather induced synoptic NEE changes. The results are illustrated in Fig. 3a. At scales larger than ~ 1000 km and ~ 10 days, in the western European region covered with

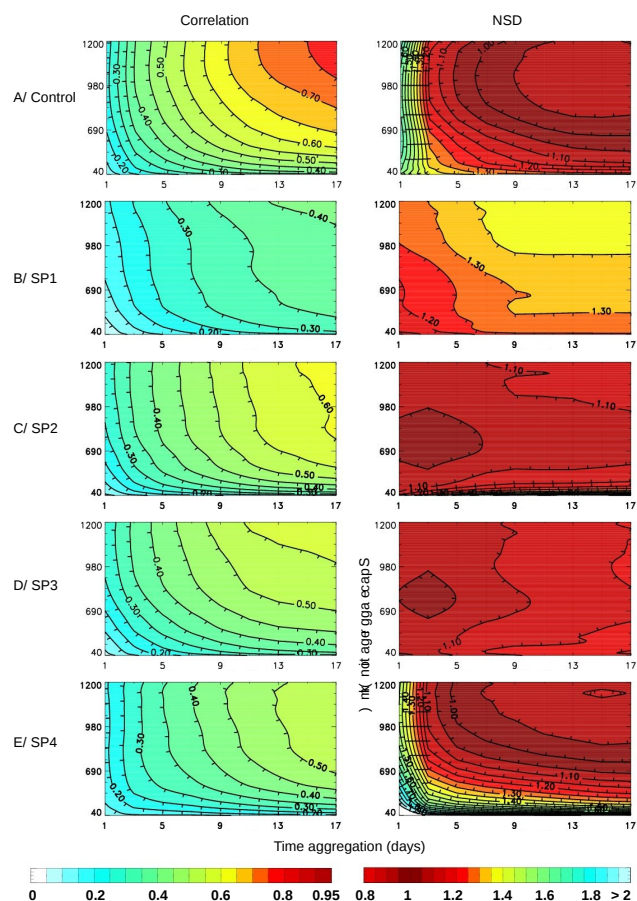


Fig. 3. Evolution of correlation and NSD with spatial and temporal aggregation for the posterior flux residuals of the control (a), SP1 (b), SP2 (c), SP3 (d) and SP4 (e) inversions.

the densest network, the NEE can be reasonably well reconstructed, with $R > 0.63$ and $NSD \approx 1$. The maximum values of R reached 0.75 at the scale of the entire western European region, for a 15-days aggregation scale. For other European regions, the true fluxes could not be accurately reconstructed, due to the sparse atmospheric observing network (CA08).

3.2 Sensitivity to prior flux error correlations (SP tests)

Figure 3b–e display for the four SP sensitivity tests the R and NSD statistics between inverted and true fluxes (deseasonalized) as a function of space (y-axis) and time (x-axis) aggregation. We also discuss the statistical significance of the correlations and variance differences as in CA08, using confidence interval for a Gaussian law and F-variance tests, respectively (Saporta, 1990). At the 95% level, we obtain, for 365 daily values, a confidence interval of ± 0.1 for the correlations.

In all cases, we found $NSD > 1$ (Fig. 3), which reflects the fact that the inversion cannot entirely correct for the much larger variability of the prior NEE in TURC as compared to ORCHIDEE. This result confirms the dependence of the results on the prior in Bayesian inversions but also suggests the overall procedure may work better with an improved prior.

SP1. With no correlations of prior NEE errors, the inversion accuracy is degraded, as shown by comparing SP1 to the control inversion S0 results (Fig. 3b vs. Figs. 3a, 6a). A maximum value of $R=0.4$ is reached, while NSD always lies above 1.15. The evolution of R and NSD as a function of space and time aggregation is similar for SP1 as for S0 (Fig. 3 of CA08), showing that aggregation does not improve the inversion accuracy, except for NSD corresponding to spatial aggregation > 1000 km. The statistical significance analysis shows no statistical differences between SP1 and the prior for correlations and variances (not shown). These limited improvements in the estimated fluxes from the prior fluxes illustrate the fact that prior flux error covariances are critical to spread the information content of concentration measurements to a large domain (Kaminski et al., 1999).

SP2. As mentioned in Sect. 2.2, including only temporal error correlations in the inversion does not directly compare to S0 because of the construction of the prior flux error matrix. We thus mainly compare SP2 to SP1 and SP3 cases. SP2 case clearly improves R and NSD statistics compared to SP1 case but with still intermediate results between S0 and SP1. We obtain $R=0.6$ when aggregating the optimized fluxes each 15 days over the large western European region and the response of R to aggregation (Fig. 3c) is similar to that of S0 but weaker. Almost independent of the temporal aggregation scale, the NSD steeply drops toward 1.1, i.e. the inversion accuracy is dramatically improved, when increasing the spatial aggregation scale from 40 to 200 km. For spatial aggregation higher than 200 km, only marginal NSD changes are found (Fig. 3c). This indicates that in SP2, the spatial aggregation is the limiting factor controlling the inversion accuracy at scales smaller than 200 km (see also discussion in CA08).

SP3. Including only spatial error correlations in the prior NEE, we obtain R values that are slightly degraded compared to the case with temporal prior error correlations only (SP2). A maximum value of $R=0.55$ is reached for the western European region, given a temporal aggregation of 15 days (Fig. 3d). This result is very similar to SP2. The response of NSD to aggregation is also similar to SP2, except for small spatial scales (< 200 km) where NSD remains close to 1. In this case, the spatial prior error correlation plays an important role in correcting for large prior NEE variability compared to the truth, which was not the case in SP2.

The significance analysis shows no statistical difference between SP2 and SP3 cases. The correlation differences are always smaller to 0.2 (the 95% interval confidence is ± 0.1) and both variances are not statistically different from the true variance at all aggregation levels. The similarities between SP2 and SP3 show that temporal and spatial correlations play

a comparable role in spreading the atmospheric information to neighboring grid-points in the inversion.

SP4. In this more complex sensitivity test, the flux error correlations are patterned according to the NEE differences between truth and prior (see Sect. 2.2). The value of R is smaller than in the control inversion S0, reaching up to 0.5 only (Figs. 3e and 6d). Correlations are statistically different between S0 and SP4 only for time aggregations longer than 9 days and spatial aggregations larger than 1000 km. The NSD as function of aggregation has about the same shape as in S0, with a slight improvement at large spatial (>1000 km) and small temporal (<7 days) scales compared to S0 but a deterioration at small spatial scale (<300 km). The significance analysis indicates no statistical difference for the residual variances between S0 and SP4 with both cases not being statistically different to the variances of ORCHIDEE true residual fluxes for time aggregation longer than 3 days at all spatial aggregations. At small spatial scales (<300 km) the inversion accuracy in SP4 is worse than in S0, with NSD isolines parallel to the temporal axis (Fig. 3e). Overall, at small spatial/small temporal scales, the NSD improves similarly in space and in time in SP4 and S0, indicating a balanced contribution of temporal and spatial error correlations to improve the flux variability retrieval.

It is rather surprising that the SP4 sensitivity test, with “physically-based” error correlations based on differences between TURC and ORCHIDEE, degrades on average the inversion accuracy as compared to the “isotropic” error correlations of S0, both in terms of R and NSD. The reasons for this are linked to the computation of the error correlations in SP4 (using the variation of true minus prior fluxes over 5 days) and also because 1) prior and true fluxes are generated using two very different models, and 2) these models calculate daily NEE forced by two different years of meteorology. Regarding point 2, different synoptic weather events affecting NEE in TURC and ORCHIDEE induce day-to-day changes in error correlation between grid-points, which have a poor coherence during a 5-day window. The resulting NEE error correlations thus strongly vary with time, and may show some sudden swings between large positive and large negative values, even across grid-points that are far apart from each other. In this case, inconsistencies between prior minus true NEE and prior error covariances might occur when considering all European grid-points. On the contrary, a smoother and isotropic prior flux error structure, such as prescribed in S0 always produces correlations that are constant in time and rapidly decrease with increasing distance across grid points (R is only 0.3 at 1000 km). For this case, inconsistencies between prior minus true NEE and prior error covariances are likely to be more restricted in space. It is also important to keep in mind that each R or NSD value in Fig. 3 represents the mean of an ensemble of values corresponding to all possible spatial/temporal groups of grid points at a given aggregation scale during one year. We found, when calculating R and NSD in the SP4 sensitivity test, that for

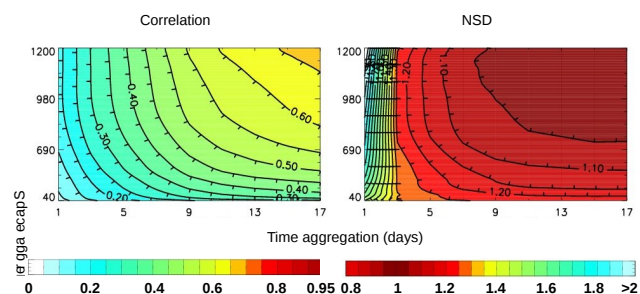


Fig. 4. Same as Fig. 3 for posterior fluxes of “dist_correl” inversion of “transport error” case.

each level of space/time aggregation, the spread between the individual R and NSD values is larger than in the control inversion S0. This indicates that the SP4 error correlation patterns happen to be more favorable for some groups of grid points during specific periods. On average, the prior error correlation matrix defined with the SP4 sensitivity test is more selective in terms of possible directions for the NEE error corrections, as compared to the isotropic S0 case, which does not favor any particular spatial direction at any time. It turns out that the simpler isotropic choice is more neutral, and appears to be more robust for obtaining an accurate retrieval of the daily fluxes in our framework. Finally, we also checked that, using a longer time window to build the spatial flux error correlations (10 days), the SP4 prior error correlation matrix becomes closer to the matrix of S0, so that the R statistics are then more comparable between the two setups.

In addition, we note that the NSD close to 1 for all aggregations in SP2 and SP3 contrasts with the large NSD observed in S0 and SP4 cases for small temporal and space aggregations. This suggests that larger prior flux error correlations (spatially or temporally) effectively constrain flux variations at high resolution. The implementation of a full prior flux error correlation matrix, including cross-correlation between space and time, in the inversion might thus be a potential way to improve the results at small aggregation scales. It could be interesting to study a correlation matrix with cross-correlations in future work to estimate the validity of this assumption.

3.3 Sensitivity to data errors (SD test)

For the SD1 sensitivity test, where the data errors are larger and more realistic than in the control inversion, Fig. 4 shows the dependency of R and NSD as a function of space and time aggregation. The results of SD1 are close to those obtained when assuming a smaller data error in S0, with only a small degradation of the inversion accuracy. On a daily basis, the R values in SD1 are smaller for all spatial aggregation scales (by roughly 0.1) as compared to S0. The NSD values are only degraded (compared to S0) for small aggregation scales (NSD becomes 0.15 larger at scales smaller than 700 km and

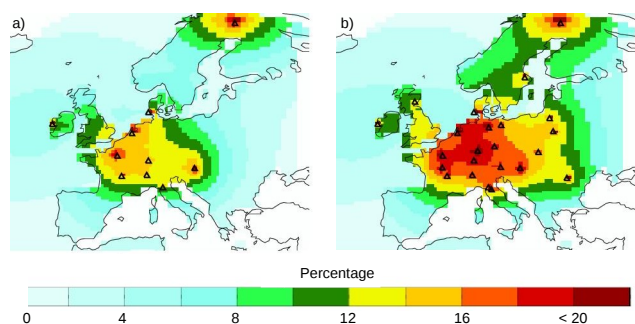


Fig. 5. (a) Three monthly average of daily error reduction for June–July–August for the “dist.correl” inversion of “transport error” case. (b) Same as (a) for an extended network.

shorter than 7 days). However, at the scale of the Western European region, and for a 10-day aggregation, both R and NSD come very close to the results obtained in S0. This finding is encouraging for using inversions to determine regional fluxes, because if a larger data error worsens the retrieval of daily fluxes, it has no strong consequences in the retrieval of weekly spatially-aggregated fluxes. However, the results of the SD1 test should not be generalized to the full impact of transport model uncertainties on inversion results. We only considered random data errors here, whereas a large part of the model-data mismatches arise from unresolved local processes/topography (representation error) or from wrong mixing parameterizations. Such errors may not disappear with averaging.

3.4 Sensitivity to the atmospheric network density (SN test)

In order to estimate the potential of added atmospheric stations, we consider the flux error reduction (ER, or inversion precision). ER is a measure of the network and method adequacy. It is defined by:

$$\text{ER} = \frac{V_{\text{prior}} - V_{\text{poste}}}{V_{\text{prior}}} \times 100, \quad (1)$$

where V_{prior} (resp. V_{poste}) is the daily prior variance at a grid cell (resp. daily posterior variance).

Error reduction is complementary to the R /NSD diagnostics used above to assess the inversion accuracy, related to the difference between true and optimized fluxes. We could not produce R and NSD variations as a function of space and time aggregation, because this test is limited to a 3-months summer period (June–September) for computational reasons.

We first estimate the error reduction associated with the network of 10 continuous stations used in SD1. This error reduction is independent of the observation values themselves and only relies on network geometry, transport properties, and error covariance matrices associated to the data

and to the prior fluxes. Although the absolute value of the error reduction depends on the prior error setup, the relative differences between grid-points can be considered as a robust indication of the network’s ability to retrieve fluxes. The map of error reduction in summer 2001 (Fig. 5a) shows small values at the grid-point scale, lying between 0 and 22%, with an average of only 7.6% across Europe. The error reduction is maximal around each station and decreases smoothly with distance. This is clearly illustrated for the Pallas station in Finland in Fig. 5a. The largest error reductions ($\sim 20\%$) are found in the vicinity of surface stations. This is shown in Fig. 5a around Saclay, Hungary, Westerland, Cabauw and Pallas. Mountain stations show smaller error reductions ($\sim 14\%$) as compared to the surface stations. Mountain stations being more influenced by large-scale transport in the free troposphere tend to have a more widespread influence function than surface stations. The information brought by each mountain station is thus more evenly spread in space. In the western European “ring of stations” formed by Saclay, Cabauw, Westerland, Schauinsland, Plateau Rosa and Puy de Dôme, a spatially coherent region of error reduction $> 14\%$ appears on Fig. 5a. The proximity of these six stations enhances the flux constraints on this region, leading to consistently larger error reductions than elsewhere. Daily fluxes over other regions of Europe remain poorly constrained by the 10 stations network. This is the case for Mediterranean regions, for Central and Eastern Europe and for most of Scandinavia (see discussion in CA08).

The error reduction for a network with 13 additional sites (see Sect. 2.2) is shown in Fig. 5b. The mean daily error reduction can be compared with the control case S0. With the denser network, the error reduction is significantly increased over Western and Central Europe. Areas with error reduction $> 14\%$ increase from $6.8 \cdot 10^5 \text{ km}^2$ up to $11 \cdot 10^5 \text{ km}^2$, extending eastward in Hungary and Poland. However, the error reduction on daily fluxes remains much larger in the vicinity of the stations, and regions with poor coverage remain under-constrained. Although encouraging, these results show that even with 23 stations delivering continuous data assumed to be well captured by the transport model (no bias in data errors), the atmospheric constraint on European daily fluxes remains small (error reduction at the grid cell level $< 25\%$). This result is consistent with the inversion accuracy analyses of CA08 showing poor inversion performances at the daily/grid-point resolution.

4 Closing remarks

The sensitivity tests conducted in this work highlight some critical aspects of an inversion of daily fluxes over Europe. Improving the retrieval accuracy of NEE would require more efforts in three main directions, 1) improving the coverage of atmospheric stations as mentioned above and also in the companion paper of this work (CA08), 2) improving the

incorporation of prior information (prior error covariance) in inversions, and 3) improving the description of transport model errors.

4.1 Prior error covariances

The estimation of a priori spatial and temporal error correlations is a key issue that needs further developments. Solving fluxes over large regions as in most previous inversions implies that “hard constraints” are imposed between model grid-points (Engelen et al., 2005). In this case, the error reduction on estimated fluxes is larger but the so-called “aggregation error” (Kaminski et al., 2001; Peylin, 2001) linked to the use of incorrect prior patterns can generate estimates that strongly deviate from the truth. Solving for individual grid-points with prior flux error correlations is a way to turn “hard constraints” into “soft constraints” (Engelen et al., 2005). These error correlations should be small enough to allow individual grid-points to be adjusted, but also significant enough to account for existing correlations in order to limit the null space of the inverse problem. Recent work by Michalak et al. (2004) allows estimating some error parameters, both in the flux space and the observation space, using information from the atmospheric data and the transport in a maximum likelihood approach. Although they only inferred variances, the methodology could be used to estimate non-diagonal terms of the prior flux error covariance matrix. Our attempt to use differences between the true and prior fluxes to define spatial elements of the prior flux error matrix produced worse results in terms of inversion accuracy as compared to the use of a simpler isotropic distance-based correlation (control case). This result suggests that the conservative choice of an isotropic spatial error correlation structure might be a reasonably robust choice, unless more information is known about the spatial error correlations. However, this result can not be generalized as it is critically linked to the temporal and spatial resolution of the inverted fluxes (daily and ~ 50 km in our setup) and to the distinct patterns we choose between prior and true fluxes in the SP4 test (two independent models, each driven by meteorology from a different year). Further investigations need to be conducted as these error correlations are crucial in inversions, considering the insufficient density of observations.

4.2 Transport model errors

With the attempt to assimilate continuous CO_2 measurements at continental stations, errors in transport models are likely to be the most severe source of errors. This is illustrated in Geels et al. (2007), with a twofold increase in the spread of model results between marine and continental stations. This implies a model error twice larger at continental stations than at marine sites. In particular, night-time (and winter) accumulations of CO_2 near the surface because of reduced mixing are generally underestimated by models.

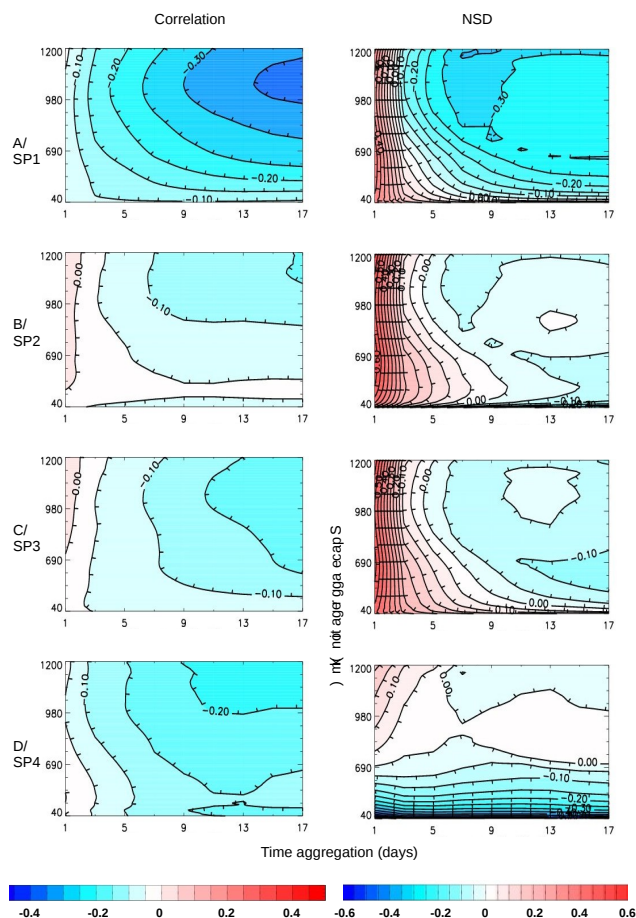


Fig. 6. Evolution with spatial and temporal aggregation of the difference of correlation between the sensitivity cases and the control case, for the posterior flux residuals (left panel). Evolution with spatial and temporal aggregation of the difference of the distance to 1 of the NSD between the sensitivity cases and the control case: $|\text{NSD}_{\text{Cont}} - 1| - |\text{NSD}_{\text{Sen}} - 1|$, for the posterior flux residuals (right panel). On both panels, a value of 0 indicates estimated flux residuals are equivalently good. A negative, resp. positive, value indicates the control case is better, resp. worse.

The representation of vertical mixing in the continental planetary boundary layer has also received much interest in recent years as more aircraft vertical profiles observations become available to check model performances (Stephens et al., 2007).

In this study, we consider transport model errors as random noise, which is included in the data error, whereas in reality models have significant biases both in space and time (Gerbig et al., 2003). Tarantola (2005, Eq. 1.74) has described how such transport errors can be included in the Bayesian formalism but first the errors must be characterized. Complementary efforts are also required to reduce these errors. The use of global models with finer grids over particular regions (Krol et al., 2005, this study) helps to improve the representation of CO_2 observations over continents in complex

terrain with heterogeneous sources, the presence of mountains, or the proximity of oceans. The use of atmospheric mesoscale models coupled with more realistic land-surface physics is also investigated as a promising way to reproduce properly atmospheric concentrations of trace gases (Lauvaux et al., 2008).

5 Conclusions

In this paper we investigated the performance of an inversion system under a range of assumptions about the setup. We assessed the performance by the ability to recover known fluxes in a pseudo-data experiment. Our control inversion assumed a perfect transport model and prior flux error correlations in space and time. All correlations of the control case follow an exponential decrease. We tested four other prior flux error correlation matrices. The first one assume no correlation at all. The second includes only temporal correlations. In the third matrix, we consider only spatial correlations. Finally the fourth matrix has temporal and spatial correlations but spatial correlations are based on the knowledge of the true flux error. We tested also the sensitivity to model error by increasing the data uncertainty to a more realistic one. Eventually, we examined the effect of the network of stations by adding projected stations. The performance at highly resolved spatial and temporal scales are generally bad but very sensitive to the setup. The prior flux covariance matrix plays a critical role at these scales and the use of a more complex structure, including in particular cross-correlation between space and time, needs further investigations. As we aggregated to larger scales, both in space and time, performance improved and the details of the setup became less important. This was true both for assumptions about the structure of the prior or background error and also of the data uncertainty (although our exploration of this was more limited). There thus seems a reasonable chance of setting up an inversion system using real data to recover fluxes at the scales suggested by CA08 i.e. about 1000 km and 10 day means.

The case with an extended network showed with no surprise a better error reduction than in the control case, simply because of an increase number of observations to constrain the inversion. However, the error reduction stays globally low showing that even more ground stations or additional constraints (airborne or spaceborne measurements) are needed in order to infer highly spatial and temporal scales. The most important (and very large) caveat is the assumption about the uncorrelated nature of data errors. It is now imperative that efforts switch to the reduction and characterization of such errors. A useful by-product is likely to be an increase in the amount of data we are able to use in atmospheric inversions.

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