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ABSTRACT:

This report discusses the potential impact of a lidar mission designed to monitor the fluxes of Carbon Dioxide at the regional scale. It compares the added value of several spaceborne missions in comparison to the current knowledge that can be derived either from inventory or from the measurements of the current surface network. The analysis is based on Observing System Simulation Experiments. The Observing system characteristics are i) the spatio-temporal sampling, ii) the vertical weighting function, and iii) the measurement error.
The results indicate that the thermal infrared measurements cannot provide useful information to constrain the CO_2 surface fluxes, due to their inadequate vertical weighting function. Shortwave infrared instruments do a better job. The performance is highly dependent on the measurement error. In that respect, OCO and A-SCOPE do a much better job than the other missions. If the 2-µm option is implemented, the A-SCOPE mission allows an excellent monitoring of the vegetation exchanges. Yet, the accuracy objective for ocean fluxes or anthropogenic emissions cannot be met. Finally, it was shown that improvement in atmospheric transport modelling is necessary to make use of the information provided by the satellites.

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Observation Techniques and mission concepts for Analysis of the Global Carbon Cycle

Executive Summary

For the attention of: Mr Paul INGMANN, ESA Technical Officer

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Acronyms

AIRS	Atmospheric Infrared Sounder
A-SCOPE	Advanced Space Carbon and Climate Observation of Planet Earth
ESAC	Earth Science Advisory Committee
ESTEC	European Space Research & Technology Centre
GOSAT	Greenhouse Gases Observing SATellite
IASI	Infrared Atmospheric Sounding Interferometer
LIDAR	LIght Detection And Ranging; or Laser Imaging Detection And Ranging
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics & Space Administration
OCO	Orbiting Carbon Observatory
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY
SNR	Signal to Noise Ratio
SWIR	Short Wave InfraRed
TIR	Thermal InfraRed

Executive Summary for the study: Observation Techniques and mission concepts for Analysis of the Global Carbon Cycle

This study discusses the potential impact of a Lidar mission designed to monitor the fluxes of Carbon Dioxide at the regional scale. It quantifies the added value of several spaceborne missions in comparison to the current knowledge that can be derived either from inventories or from measurements of the current surface network.

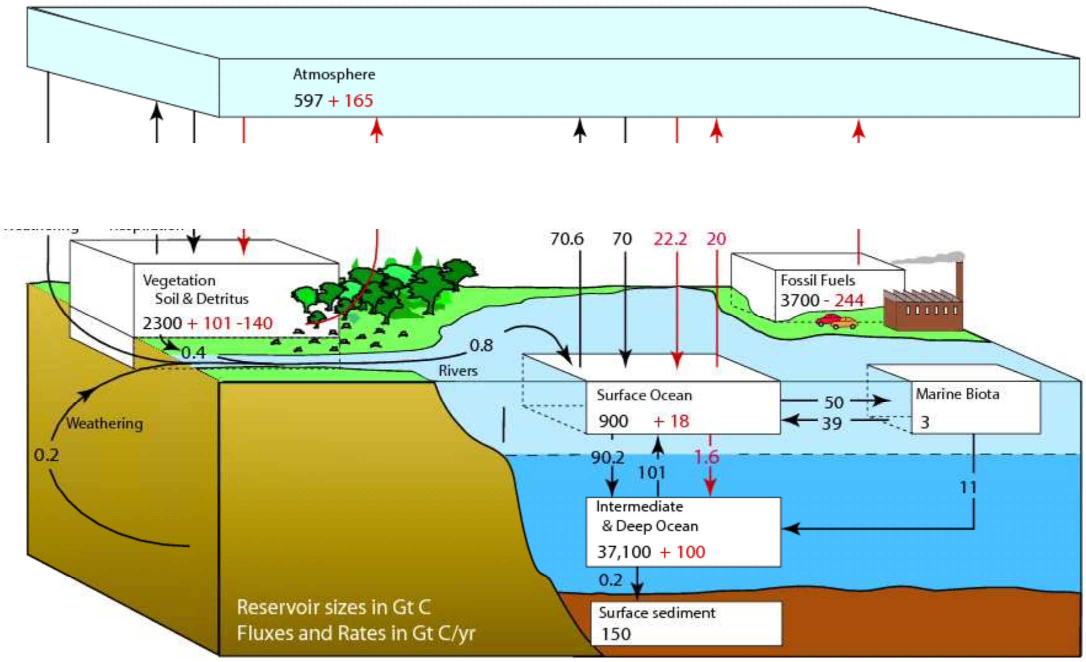

Figure 1. The Global Carbon Cycle

The context of this study is the rising levels of CO_2 concentrations resulting from anthropogenic activities. The increase of CO_2 concentrations leads to global warming, which may have devastating effects on some ecosystems. Interaction between climate and the carbon cycle may lead to a positive feedback, accelerating climate change. In this context, it is necessary to monitor the CO_2 surface fluxes in order to quantify the emissions and to understand the processes that link climate and carbon fluxes. This broad objective can be categorized into four main topics, with different spatial and temporal scales and accuracy requirements, which are detailed in this study:

- Monitor anthropogenic emissions in the context of the Kyoto protocol and its successors;
- Monitor the long-term fluxes over land areas;
- Monitor the long-term fluxes over ocean areas;
- Monitor vegetation dynamics and its impact on the Carbon cycle.

Surface fluxes (emissions and/or sinks) lead to atmospheric concentration gradients (both spatial and temporal). These gradients can be monitored at the surface (surface station), higher up in the mixing layer (tower), higher up in the atmosphere (airborne sampling), or from space. If the atmospheric transport is known, the measured gradients may be traced back to the surface fluxes. Clearly, this is an under-constrained problem as the number of variables (i.e. the fluxes for each grid point and temporal steps) is much higher than that of the observations. The inversion therefore requires additional information such as:

- An *a priori* for the fluxes, together with their uncertainties (variances);
- Co-variances for the flux uncertainties;
- Errors and co-variances of the errors for the observations. These may include atmospheric transport errors.

There are several mathematical methods to invert the fluxes from the atmospheric concentration measurements. Our initial plans were to use a variational approach which has the main advantage of resolving the fluxes at the resolution of the atmospheric transport model. However, the computer cost of this method was found prohibitive due to the large number of simulations required for the study. Besides, we encountered unanticipated convergence difficulties with this approach. These difficulties led us to use a matrix approach that does not allow the same spatial resolution but provides a full description of the uncertainties of the retrieved fluxes, together with their covariance.

The surface network provides concentration measurements at a given atmospheric level. On the other hand, satellite retrievals are representative of a weighted column. The various observing systems are therefore characterized by:

- the spatio-temporal sampling;
- the vertical weighting function;
- the measurement error.

We have assessed these characteristics for the current surface network (shown in figure 2), other networks that could realistically be built in the future, the existing spaceborne missions that can be used to estimate CO_2 concentrations, and potential missions including A-SCOPE that was proposed in the Earth-explorer program. Cloud cover limits the sampling of the spaceborne observations, depending on the Field of View. We have used high-resolution MODIS data to assess the contamination of the measurements by clouds. It was shown that thermal infrared instruments (TIR: AIRS, IASI) have a weighting function that peaks in the high troposphere, while that of the shortwave infrared instruments (SWIR: SCIAMACHY, OCO, GOSAT) is fairly constant along the vertical. The A-SCOPE mission shows a weighting function that is either similar to that of the SWIR instruments or weighted towards the low levels, depending on the choice of wavelength at 1.6 or 2 µm.

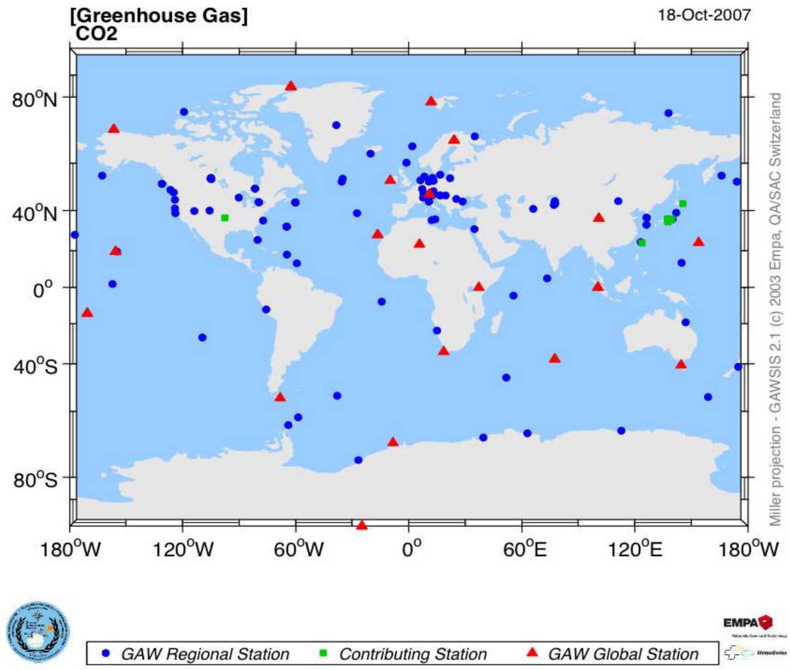

Figure 2. The Current Surface Network

In the context of flux inversion, the usefulness of *in situ* measurements is mostly limited by representativity errors because of the variability of surface concentrations generated by local conditions. These representativity errors were quantitatively assessed using atmospheric transport simulations at high resolution and depend on the station type: oceanic, coastal or continental. Satellite estimates are less affected by such errors but the accuracy is much lower due to noise in the measurements and the inversion. These noises were quantified through radiative transfer simulations. The CO_2 estimates from the TIR instruments are mostly affected by the uncertainties on the temperature profiles, while the SWIR observations are limited by radiometric noise and the impact of aerosols. The A-SCOPE measurements are mostly affected by radiometric noise. Surface conditions, and in particular the impact of mis-registrations of the channels, also have a significant impact that was carefully assessed. The radiative transfer simulations and inversions indicate that the typical error for the OCO observation is smaller than that of A-SCOPE. These simulations indicate that the large impact of aerosol on the apparent CO_2 column can be accurately corrected using the measurements acquired in the O_2 absorption band. Although based on state-of-the-art simulations and a proper analysis of their results, one may question the high performance of OCO. The aerosol correction is critical in the success of such mission based on the passive differential absorption technique.

The addition of an oxygen channel on passive CO_2 missions is needed for the aerosol correction but also for the normalization of the column density (to provide a concentration rather than a number of molecules along the path). This may not be necessary on an active mission because the atmospheric path length could be known accurately. It requires nevertheless some information on sea-level pressure. An analysis of current outputs from Numerical Weather Centers demonstrated that the accuracy of this parameter is sufficient except for very specific mountain areas.

Atmospheric transport simulations were then used to assess the impact of observing systems on the knowledge of surface fluxes. We have quantified the error reduction as well as the final error on the fluxes. The TIR instruments are poorly suited to provide constraints on the surface fluxes, as a result of their weighting function that does not provide significant information in the low atmosphere. SWIR instruments, such as SCIAMACHY, GOSAT or OCO are better suited in this respect. However, the current satellite systems are not adequate to meet the objectives set above. This includes GOSAT, even though this satellite was designed to monitor CO_2 and its gradients. The inadequacy of GOSAT results from the relatively poor performance of its CO_2 retrievals compared to OCO. It seems that the SNR of the Japanese instrument is smaller than that of its NASA counterpart (however the actual relative performance of the instruments cannot be compared as only the GOSAT instrument has successfully reached its orbit). Also, the performance of the algorithm designed for GOSAT seems to be not as good as that of OCO. With the loss of their mission, the OCO algorithm team is putting some effort on GOSAT data, and one may expect a better performance due to the team experience in spectroscopy, atmospheric radiative transfer, and inversion techniques.

The A-SCOPE system allows an error reduction of the weekly fluxes of more than 80% over most vegetated areas (see figure 3b below). This number is consistent with the scientific requirements for the monitoring of the vegetation dynamics. Measurements such as those provided by A-SCOPE would help the development of new models of the vegetation and its interaction with the atmosphere. On the other hand, the posterior uncertainties on the fluxes are still too large to properly monitor anthropogenic fluxes in the context of Kyoto-like protocols. This conclusion is reinforced by the fact that the measurements provided by the mission would not allow to distinguish natural and anthropogenic fluxes. Nevertheless, the accuracies appear sufficient to monitor long-term natural fluxes, such as those expected over large regions as a response to climate change. There are growing worries on the potential disturbance to ecosystems such as the Amazonian or Siberia that may lead to additional fluxes to the atmosphere and a carbon monitoring mission is urgently needed in this context.

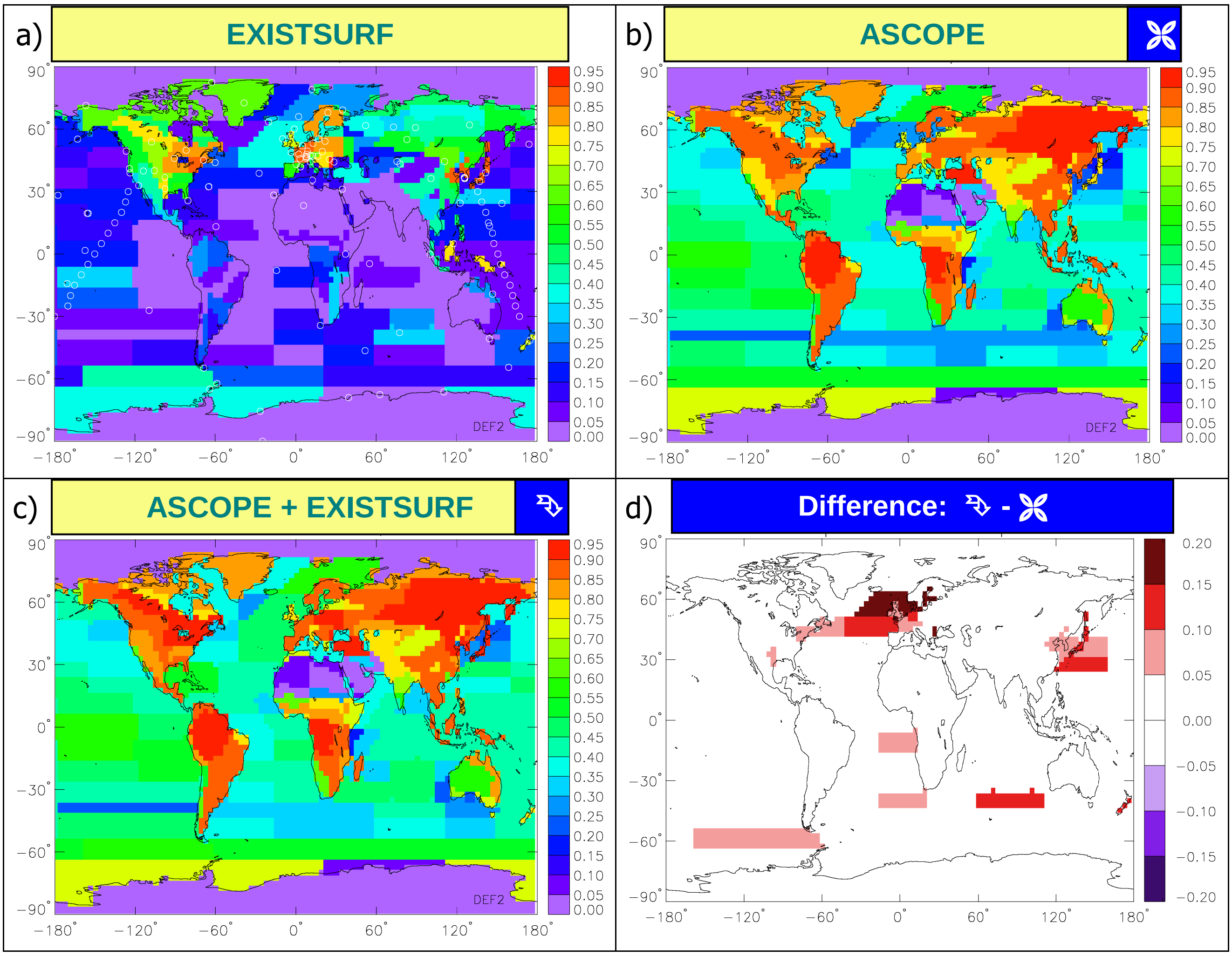

Figure 3. Comparison of the error reduction for weekly fluxes for A-SCOPE and the existing Surface Network – (a) existing surface network, (b) A-SCOPE, (c) combining the existing surface network with A-SCOPE and (d) comparing (c) and (b)

Another important finding is that, if an extension of the current surface network could be funded with the same amount of money as the satellite system, it would provide a similar performance. Clearly, as the surface network is not significantly better than the satellite system, the latter is preferable as it is free from local pressure and allows a global and consistent monitoring.

Another key finding of this study concerns the uncertainty in atmospheric transport modelling and how biases may impact the retrieved fluxes. For this objective, the outputs of several models were inter-compared and compared to *in situ* measurements. It showed differences among models of the order of 0.5 ppm on the weighted columns of CO_2. The difference among models was interpreted as an estimate of the modelling error. In one experiment, a transport model was used to simulate A-SCOPE pseudo measurements, and another one was used to estimate the surface fluxes. The difference between the prior and retrieved fluxes can be interpreted as the impact of the transport modelling error. The results showed biases in the annual CO_2 flux of the order of 0.1 PgC yr^{-1} per 10^6 km^2 over land and 0.03 PgC yr^{-1} per $10^6 km^2$ over the ocean. These uncertainties are large in comparison to the accuracy requirements that were formulated above. Therefore, it appears that uncertainties in the atmospheric transport modelling alone do not permit to reach the demanding accuracy objectives on the surface fluxes.

There are other uncertainties, although of lesser importance, in the main conclusions presented above. We are fairly confident on the observing system characteristics concerning the sampling and the vertical weighting function. On the other hand, there are several hypotheses behind the estimate of measurement error, a critical parameter for the observing system performance. The experience with SCIAMACHY (and others) shows that the performance of a satellite mission may not be as good as the pre-launch estimate. There is little doubt that the GOSAT measurements are better suited than those of SCIAMACHY for CO_2 monitoring. Similarly, the OCO measurements would have been of better quality than those of GOSAT (SNR and spectral resolution). However, the actual performance of GOSAT and an OCO-like instrument remain to be demonstrated. The CO_2 estimates from these two instruments rely on a complex correction of the impact of scattering in the atmosphere. There are significant uncertainties on whether the theoretical performance can be achieved. The active mission, on the other hand, does not require such a complex correction so that its performances are more reliable.

Positive surprises are unlikely. It can therefore be said with some certitude that objectives, that cannot be reached according to theoretical simulations, will not be reached. On the other hand, one must be careful with the objectives that are marginally met according to the simulations.

Based on these findings, the following **recommendations** are made:

i) There is still a lack of experience with CO_2 concentration measurements that are integrated over the vertical. One should therefore extend instruments suitable for column concentration measurements (using spectroscopy techniques, aiming at the sun) and analyze their measurement time series in conjunction with modelling results. Such an analysis may provide information on the dynamic and vertical exchanges in the atmosphere and lead to the necessary model improvements;

ii) A large effort should be undertaken to improve atmospheric transport modelling. One key element is the vertical mixing in the atmosphere. A better understanding of the model-to-model differences is needed. One should then devise means to select the most accurate model;

iii) Some effort should be devoted to the analysis of the GOSAT measurements. A primary task would be to analyze the data in well-controlled easy cases (very clear atmosphere in an area where the CO_2 profile is known, high sun, large surface albedo or in sun glint geometry). This will mostly validate the spectroscopy as well as the instrument characteristics (signal to noise, instrument spectral response). If the spectra model-measurement comparisons are successful, one may attempt similar comparison in more difficult cases, in particular where aerosol loading is significant. Finally, one should attempt to retrieve CO_2 column concentration from the measurements, and validate these estimates against independent data;

iv) Based on the GOSAT measurement analysis, it should be possible to build a tool that would provide the CO_2 column typical error as a function of the instrument characteristics for Shortwave Infrared Spectrometers. It would then be possible to provide a better assessment of the respective advantage of passive and active instruments for the monitoring of CO_2 and other greenhouse gases from space;

v) In parallel, ESA should pursue the efforts on the hardware development around the A-SCOPE concept. Indeed, the technology is not yet mature which led to the non-selection of the mission by ESAC. There is therefore a strong need to pursue studies on the elements that were evaluated as critical and non mature by industry.