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Spaceborne remote sensing of greenhouse gas concentrations

La mesure depuis l'espace de la concentration atmosphérique des gaz à effet de serre

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ABSTRACT

Despite their primary contribution to climate change, there are still large uncertainties on the sources and sinks of the main greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). A better knowledge of these sources is necessary to understand the processes that control them and therefore to predict their variations. Indeed, large feedbacks between climate change and greenhouse gas fluxes are expected during the 21st century. Sources and sinks of these gases generate spatial and temporal gradients that can be measured either in situ or from space. One can then estimate the surface fluxes, either positive or negative, from concentration measurements through a so-called atmospheric inversion. Surface measurements are currently used to estimate the fluxes at continental scales. The high density of spaceborne observations allows potentially a much higher resolution. Several remote sensing techniques can be used to measure atmospheric concentration of greenhouse gases. These techniques have motivated the development of spaceborne instruments, some of them already in space and others under development. However, the accuracy of the current estimates is still not sufficient to improve our knowledge on the greenhouse gases sources and sinks. Rapid improvements are expected during the forthcoming years with a strong implication of the scientific community and the launch of dedicated instruments, optimized for the measurement of CO_2 and CH_4 concentrations.

RÉSUMÉ

L'augmentation de la concentration atmosphérique des gaz à effet de serre est la cause principale de changement climatique. Les émissions anthropiques de ces gaz se superposent à des flux naturels, qui varient dans le temps et dans l'espace et sont sensibles aux modifications du climat. On ne connaît pas précisément la distribution spatiotemporelle des sources et puits des principaux gaz à effet de serre que sont le dioxyde de carbone (CO_2), le méthane (CH_4) et le protoxyde d'azote (N_2O). Pourtant, cette connaissance est nécessaire pour bien comprendre les processus qui les contrôlent, pour quantifier la vulnérabilité des cycles des gaz à effet de serre, et donc prédire correctement leur évolution. En effet, une rétroaction importante entre changement climatique et sources de gaz à effet de serre est attendue au cours du XXI^{e} siècle. Les sources et puits de ces gaz génèrent des gradients de concentration atmosphérique, qui peuvent être mesurés au sol ou depuis l'espace. On peut donc estimer les flux, positifs ou négatifs, à partir des gradients de concentration, par la modélisation inverse du transport atmosphérique. Avec cette technique, les mesures sol d'un réseau global de 100 stations environ ont été utilisées pour produire des bilans aux échelles

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continentales. Les mesures sol sont plus denses sur certains continents, comme en Europe ou en Amérique du Nord, ce qui permet de calculer des bilans régionaux, mais la plupart des autres régions du globe ne sont pas couvertes de mesures in situ. La mesure spatiale permet potentiellement d'accéder à des échelles plus fines sur toutes les régions du globe. Plusieurs techniques de mesure permettent d'estimer les concentrations atmosphériques des principaux gaz à effet de serre, en général intégrées sur la verticale. Elles ont motivé le développement d'instruments spatiaux en projet ou déjà en orbite. Cependant, la précision atteinte aujourd'hui n'est pas encore suffisante pour accéder à une meilleure connaissance des sources et puits. Des avancées importantes sont attendues dans les prochaines années grâce à un important investissement de la communauté scientifique et au lancement d'instrument dédiés, et donc optimisés pour la mesure de CO_2 et CH_4.

1. Introduction

It is well known that carbon dioxide (CO_2) concentration is rising in the atmosphere as a result of anthropogenic activities: Fossil fuel burning, cement production and forest clearing. Recent estimates are emissions of 7.9 GtC/yr due to fossil fuel and cement productions in 2005, while forest clearing leads to a net flux to the atmosphere of 1.5 GtC/yr (Raupach et al., 2007). On the other hand, the atmospheric load of CO_2 shows a net increase of 4.2 GtC/yr on average with very large annual fluctuations. There is, therefore, a natural net sink of CO_2 into the oceans and the land ecosystems. Best estimates lead to an almost even partition with 2.2 GtC/yr to the oceans and 2.3 GtC/yr to land surfaces, albeit with rather large uncertainties on each of the numbers (while their sum is rather well constrained).

A similar picture exists for methane (CH_4). Methane is emitted by human activities in the energy sector (coal and gas extraction), in the agricultural sector (rice paddies, animals) and by natural processes as well (wetlands, wildfires). However, unlike for carbon dioxide, the ocean-atmosphere flux of methane is insignificant. Methane is massively removed from the atmosphere by photochemical processes. After a rapid increase during the 20th century, the atmospheric concentrations of methane have levelled off a decade ago, for reasons that are still to be understood although some hypotheses exist (Bousquet et al., 2006) Large fluctuations in the growth rate of atmospheric methane are also observed from one year to the next, but their causes remain uncertain.

The spatial distribution of the CO_2 sinks is a matter of debate. It is not clear whether the largest sink of CO_2 is in the tropics, in the mid-latitudes or in boreal and arctic regions. The repartition in longitude among the continents is also a subject of large controversies. The spatial distribution of CO_2 emissions and sinks can be seen as a political question when a state claims that its natural sinks are larger than its net anthropogenic flux to the atmosphere. However, the need is mostly a scientific question for a better understanding of the processes that control the carbon flows between the various reservoirs, and their interactions with the climate system. A better knowledge of today's CO_2 fluxes at the regional scale would permit discriminating among various ecosystem and ocean models that claim rather different carbon exchanges.

This science question (i.e., the development and validation of accurate carbon cycle models for the natural exchanges between the various reservoirs) has a strong societal impact. Indeed, the current sink limits the growth rate of the greenhouse effect and therefore of climate change. The current sink is observed to decrease sharply during particularly dry years like 1998, 2002, 2003, 2005. There are reasons to fear that this sink could decrease in the future, and even reverse as a result of climate change. This is because vegetation could react negatively to temperature increases or drought in the tropics, and because high-latitude carbon stocks could decompose faster with warmer temperatures. Thus, for a prediction of the rate of climate change during the 21st century, there is a need for better models of the carbon cycle. Clearly, an accurate description of current fluxes and their variability would be a great help for the validation, the development and further improvement of such carbon models.

Beyond the scientific goal of monitoring carbon fluxes, there is also a political need to establish accurate observing systems for quantifying sources and sinks of greenhouse gases on national levels in the context of the Kyoto protocol and its likely successors. The accuracy requirements for this goal are substantially higher than for the scientific objectives mentioned above, because fluxes over relatively small geographical units and long time periods (e.g., 5-year commitment periods) have to be quantified. Furthermore, smaller changes in flux magnitudes have to be detected. Nevertheless, any global monitoring strategy has also to address this political objective.

Carbon dioxide is the main contributor to the radiative forcing of the Earth, which leads to climate change. The following contributors are methane and nitrous oxide (IPCC, 2007). Similarly to CO_2, there are large uncertainties on the sources of CH_4 and N_2O. Therefore, the discussion above also applies to these gases although their impact on climate change is less than that of CO_2 partly because of the magnitude of the emissions, and partly because of the shorter life times (in case of CH_4). Another significant difference between CH_4/N_2O and CO_2 is the large biogenic sink of CO_2 from photosynthesis and ocean uptake. Therefore, uncertainties on CH_4 and N_2O fluxes are primarily on the sources, and not on the sinks.

2. The need for a monitoring of greenhouse gas concentrations

There are several ways to estimate the fluxes of CO_2. One method is to make direct measurements from towers