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Reduction of Uncertainties in Remote Measurement of Greenhouse Gas Fluxes

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Abstract—As the U.S. and the International Community come to grips with anthropogenic climate change, it will be necessary to develop accurate techniques with global span for remote measurement of emissions and uptake of greenhouse gases (GHGs), with special emphasis on carbon dioxide.[1] [2] Presently, techniques exist for *in situ* and local remote measurements. The first steps towards expansion of these techniques to span the world are only now being taken with the launch of satellites with the capability to accurately measure column abundances of selected GHGs, including carbon dioxide. These satellite sensors do not directly measure emissions and uptake. The satellite data, appropriately filtered and processed, provide only one necessary, but not sufficient, input for the determination of emission and uptake rates. Optimal filtering and processing is a challenge in itself. But these data must be further combined with output from data-assimilation models of atmospheric structure and flows in order to infer emission and uptake rates for relevant points and regions. In addition, it is likely that substantially more accurate determinations would be possible given the addition of data from a sparse network of *in situ* and/or upward-looking remote GHG sensors. We will present the most promising approaches we've found for combining satellite, *in situ*, fixed remote sensing, and other potentially available data with atmospheric data-assimilation and backward-dispersion models for the purpose of determination of point and regional GHG emission and uptake rates. We anticipate that the first application of these techniques will be to GHG management for the U.S. Subsequent application may be to confirmation of compliance of other nations with future international GHG agreements.

ABBREVIATIONS AND ACRONYMS

AIRS Atmospheric Infrared Sounder
ARM Atmospheric Radiation Measurement
AVHRR Advanced Very High Resolution Radiometer
CH_4 Methane
CO Carbon monoxide
CO_2 Carbon dioxide
$^{13}CO_2$ Carbon dioxide containing ^{13}C carbon isotope
DOE Department of Energy
EPA Environmental Protection Agency
ESRL Earth System Research Laboratory
EVI Enhanced Vegetation Index
FPAR Fraction of absorbed Photosynthetically Active Radiation
FTS Fourier Transform Spectrometer
GHG Greenhouse Gas
GOSAT Greenhouse gas Observing Satellite
HFC Hydrofluorocarbon
H_2O Water
IASI Infrared Atmospheric Sounding Interferometer
LPJ Lund-Potsdam-Jena
MODIS Moderate-resolution Imaging Spectroradiometer
NASA National Aeronautics and Space Administration
NASA-CASA NASA-Carnegie-Ames-Stanford Approach
NDVI Normalized Difference Vegetation Index
N_2O Nitrous oxide
NOAA National Oceanic and Atmospheric Administration
O_3 Ozone
OCO Orbiting Carbon Observatory
PFC Perfluorocarbon
SCIAMACHY Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SF_6 Sulfur hexafluoride
SGP Southern Great Plains
SiB2 Simple Biosphere 2
TCCON Total Column Carbon Observing Network
TIROS Television Infrared Observation Satellite
TOVS TIROS Operational Vertical Sounder
TURC Terrestrial Uptake and Release of Carbon
UNFCCC UN Framework Convention on Climate Change
VPRM Vegetation Photosynthesis and Respiration Model
WMO World Meteorological Organization

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1. INTRODUCTION

National GHG management and international emissions treaty verification and monitoring will require a multi-component effort in modeling and measurements. This effort must include compilation and auditing of emissions inventories, as well as collection of remote and in situ GHG measurements and their interpretation using atmospheric models to confirm these inventories. Although self-reported national emissions inventories are required under the United Nations Framework Convention on Climate Change (UNFCCC), sufficiently accurate procedures for verifying the data provided have not yet been developed. Measurements with adequate coverage and resolution in time and space for verification are not yet available. Steps towards major expansion of the existing measurement network are now being taken with the launch of satellites with the capability to accurately measure column abundances of selected GHGs (carbon dioxide plus other gases; see Table 1). These satellite sensors do not directly measure emissions and uptake. The satellite data appropriately filtered and processed, together with GHG measurements by other techniques provide a necessary but not sufficient input for the determination of emission and uptake rates.

Inversion methods can be used to infer area emissions and uptake rates by coupling measurements of atmospheric distributions of GHGs with atmospheric transport models. The accuracy of these estimates is limited, however, by uncertainties in the transport models and by the limited spatial and temporal coverage of atmospheric GHG measurements. Of course, the transport models critically depend upon meteorological measurements. The strengths of natural sources and sinks can also be inferred from flux measurements using eddy covariance techniques, but these measurements are highly local in nature.

Emissions from anthropogenic point sources, such as power plants, and anthropogenic area sources like cities can also be inferred more directly from abundance distributions in their plumes under known meteorological conditions. Extensive measurements of GHGs from selected large point sources could provide valuable data to validate emissions inventories and would lend support to treaty verification. The current ground station network is not adequate for measuring such sources, and the extension of this ground measurement network for treaty verification purposes would require extraordinarily extensive international cooperation. Emissions from natural or agricultural sources can be estimated by scaling directly measured local fluxes from a biome to larger areas using land-use maps constructed using satellite data, but the limited resolution of these maps and a lack of information about fluxes from particular plant types grown under specific conditions lead to large uncertainties in scaled emissions estimates. Current technology does not allow surface fluxes of GHGs to be measured directly with spatial resolution and coverage sufficient to accurately account for the carbon budget. Transport models with data assimilation must, therefore, be relied upon to estimate surface fluxes from datasets with incomplete measurement

Table 1. Satellite Instruments for Use in GHG Emissions Estimates [1]

	OCO	GOSAT	SCIAMACHY	AIRS	IASI
GHG measured	CO_2	CO_2, CH_4, O_3, H_2O	CO_2, CH_4, O_3, H_2O, CO, N_2O	CO_2, CH_4, O_3, H_2O, CO	CO_2, CH_4, O_3, H_2O, CO, N_2O
CO_2 sensitivity	Total column	Total column	Total column	Mid-troposphere	Mid-troposphere
Horizontal resolution (km)	1.29×2.25/5.2	10.5/80-790	30×60/960	15/1650	12/2200
CO_2 uncertainty (ppm)	1-2	4	14	1.5	2
Instruments	3-channel grating spectrometer	Fourier transform spectrometer	8-channel grating spectrometer	Grating spectrometer	Fourier transform spectrometer
Samples/day	500,000	18,700	8,600	2,916,000	1,296,000
Revisit time/orbits	16 days/ 233 orbits	3 days/ 72 orbits	35 days	16 days/ 233 orbits	72 days/ 1037 orbits
Local time	13:30	13:00	10:00	13:30	21:30
Launch date	Failed	Jan 2009	March 2002	May 2002	Oct 2006

coverage [2].

We have investigated ways to overcome the deficiencies in measuring or estimating GHG sources and sinks. A great deal of work has been done and is presently underway in this area. We have reviewed the state of knowledge in the field, initiated more detailed evaluations of two models used in attribution studies, and have begun to develop a conceptual design for a mobile GHG laboratory. This laboratory is designed to complement existing fixed ground-based measurement networks for estimating emissions and studying carbon-cycle science. It includes remote measurement instrumentation similar to that used on satellite platforms, as well as *in situ* measurement instrumentation. It also includes limited cloud and aerosol characterization instrumentation to aid in interpreting satellite GHG column measurements. It can also be viewed as a prototype of a likely necessary element of a GHG emissions inventory verification system. We have also investigated alternative GHG sampling and measurement techniques to assess where the field will likely go from here. This was done for a short internally-funded project at Sandia National Laboratories aimed at producing a preliminary understanding of how satellite data could best be integrated with existing GHG measurement networks to reduce uncertainties in emissions and uptake of greenhouse gases.

2. SATELLITE GHG DATA COUPLED WITH MODELS

First, it's useful to describe briefly how GHG-sensing satellites work. For specificity, we focus upon the Orbiting Carbon Observatory (OCO), an attempted U.S. launch in February 2009. OCO failed to achieve orbit, but will likely be replaced. We describe how OCO was intended to measure carbon dioxide column-averaged dry mole fraction. OCO, like GOSAT (Greenhouse Gas Observing Satellite, a Japanese satellite in orbit since January 2009) measures absorption in the near infrared using reflected sunlight from the surface as a source. The mole fraction is obtained by comparison of absorption in the near infrared of carbon dioxide and oxygen [3]. The measurements over land are typically made with the sensor pointing in the nadir direction (although other modes are possible). Each measurement is made over a single location of known dimensions (1.29 by either 2.25 or 5.2 km). The result is a sequence of column–averaged, dry-air, mole-fraction measurements below and in the plane of the satellite orbit. For OCO, this planned sequence of measurements will typically provide 200 soundings per degree of latitude with a ground track repeat cycle of 16 days. Sequential ground tracks are separated by approximately 24 degrees of longitude, but adjacent ground tracks taking account of all tracks acquired during the 16 day cycle are separated by only about 1.5 degrees of longitude. OCO does no imaging. Some imaging satellites have limited GHG-sensing capabilities, but they are much less sensitive and have other limitations as well.

It is relatively easy to conceive of how, under ideal conditions, OCO data could be used to measure the carbon dioxide emission from a sufficiently large isolated point source. We'll call this the "brute force" method. For an OCO ground track at an appropriate downwind distance, OCO would measure a plume profile superimposed on the background carbon dioxide abundance. With knowledge of the meteorology, and use of a transport model which takes into account dispersion and removal or contribution of carbon dioxide at the ground surface, that profile could be compared with the anticipated profile as a function of emission rate, and the best fit to emission rate determined. While this approach is conceptually straightforward and works reasonably well for much higher spatial resolution aircraft and surface-based remote sensors deployed close to strong point sources, there are many obstacles to actually implementing it with satellite data. To name a few:

First, since background carbon dioxide concentrations are high, it takes a massive source of carbon dioxide to produce a plume accurately measureable from orbit any significant distance downwind.

Second, most carbon dioxide sources are not sufficiently isolated to have flat background carbon dioxide abundance fields. Upwind sources and sinks introduce gradients that are not accounted for in the simplistic approach described above.

Third, the atmosphere contains clouds. It is estimated that only about 1 in 10 OCO measurement pixels will be sufficiently cloud free to produce a useable column-averaged dry mole fraction for carbon dioxide. Hence, most OCO plume profiles would likely be poor candidates for plume profile fitting.

So the "brute force" approach is not generally useful.. A more sophisticated approach is to make use of modeling in a more fundamental way, making initial "first guess" assumptions on global point and area source and uptake strengths based on whatever information is in hand, and then minimizing the discrepancies with the satellite observations. This is analogous to, but much more complex than "curve fitting" with two dimensional data sets.

A variety of different transport models and data assimilation approaches have been used. A general method for data assimilation is based on recursive Bayesian inference. The inadequacy of measurements to resolve all the flux sources and sinks dictates the need to infer surface fluxes from available data using models. For practical purposes direct measurements of CO_2 fluxes can only be made with footprints of about one square kilometer or less at some number of sites representing only a tiny fraction of the total land mass. Measurements of CO_2 mixing ratio can be made with much larger footprints using towers, aircraft, or satellites. Models must be used to relate these measurements to surface fluxes. Because the problem of estimating CO_2 source fluxes is poorly constrained by the measurements,

additional information is needed to perform the inversion. A common approach used in atmospheric science is to use a set of first guesses of source fluxes (*a priori* flux estimates), a set of measurements that are typically abundance measurements at discrete points (or column-averaged measurements), and a Bayesian inference scheme that generates updated estimates of source fluxes (*a posteriori* flux estimates). The *a priori* quantities can come from inventories, models of ecosystem behavior, or direct measurements. For global-scale CO_2 surface flux estimation, prior estimates are needed for all major natural sources and sinks including both the oceans and landmasses. In addition, estimates of anthropogenic contributions from fossil fuel burning are needed. A number of different databases and models exist for these different categories of fluxes which provide regional data on emissions. The *a posteriori* flux estimates are chosen to minimize the differences between the first guesses and *a posteriori* estimates, and also to minimize the differences between the actual mole fraction measurements and model-calculated mole fractions based on the *a posteriori* fluxes.

The reference standard for global CO_2 levels is derived from flask measurements with calibrations traceable to the World Meteorological Organization (WMO). GLOBALVIEW-CO_2 is a data product of NOAA ESRL that incorporates well-calibrated CO_2 measurements from a large number of sites and provides global CO_2 average abundance estimates. CO_2 levels have distinct seasonal variations and vary more strongly with latitude in the northern hemisphere than in the southern [4].

The *a priori* surface flux estimates for soils and vegetation are typically derived from models of surface behavior driven by meteorological data, but they may also incorporate satellite data. A variety of different vegetation and soil flux models exist with varying degrees of computational complexity. Models that resolve different leaf and soil biochemical processes such as the Lund-Potsdam-Jena (LPJ) model [5] have been used to produce prior estimates for inverse transport studies, e.g. [6]. More commonly used in inversion studies are simpler models such as the NASA-Carnegie-Ames-Stanford Approach (NASA-CASA) [7], and Vegetation Photosynthesis and Respiration Model (VPRM) [8], Terrestrial Uptake and Release of Carbon (TURC) [9] and a revised land surface parameterization for atmospheric general circulation models (SiB2) [10]. A common approach of NASA-CASA, VPRM, TURC and SiB2 is the use of satellite measurements of vegetation to calculate the fraction of absorbed photo-synthetically active radiation (FPAR), which is presumed to be correlated with ecosystem production [11]. FPAR has been derived from Normalized Difference Vegetation Index (NDVI) data products from the NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite and also from the Moderate-resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) product.

The NASA-CASA biosphere model simulates net primary production (NPP) and soil heterotrophic respiration using monthly gridded air surface temperature, precipitation, and surface solar irradiance measurements and produces outputs of net exchange for CO_2 and other major trace gases.

Net CO_2 flux at ocean surfaces can be estimated from dissolved ocean surface CO_2 and wind speed using an ocean model maintained by NOAA [12].

In principle this "Bayesian synthesis" method can be used to solve coupled sets of linear equations to find the flux estimates and their uncertainties from the measurements and *a priori* estimates, but this approach becomes intractable for large problems. For estimation using large numbers of observations and large numbers of flux sources (grid cells) an alternative approach is needed. Variational methods are typically employed. The variational approach involves minimizing a cost function. The solution is reached through an iterative process.

A number of studies have been conducted to investigate the degree to which uncertainties in global CO_2 emission estimates can be reduced through the use of satellite observations. Studies have been conducted using SCIAMACHY, TOVS, and AIRS with marginal results because of the non-ideality of the satellite measurements for the task. Much effort has been put into estimating the ability of the planned OCO mission to address needs for CO_2 flux data. A number of studies were performed with synthetic OCO data to model the ability of inversion schemes to accurately estimate surface fluxes. The general approach of these computational experiments was to generate a time-dependent 3-dimensional model of atmospheric CO_2, which was used as the "true" atmosphere, and the 'satellite measurements" were generated by sampling this "true" atmosphere and perturbing the sample results to represent noise and biases. The "truth" for the experiment was generated through the use of surface fluxes derived from surface models and propagation of the carbon dioxide using an atmospheric transport model. A set of synthetic OCO measurements was generated by sampling the reference, "true", atmosphere with perturbations added to represent measurement errors. A set of first guesses of surface fluxes were also generated either by a perturbation of "true" surface fluxes [13, 14], or by using an independent model of surface fluxes [6].

The degree of uncertainty reduction in these simulations of OCO inversions by Chevallier *et al*. [13], Miller *et al*. [14], and Baker *et al*. [6] generally depended on the uncertainties assumed for the satellite measurements, but they all indicated that errors in flux estimates from OCO would likely be low enough to produce scientifically useful results. For instance OCO should be able to detect a 1 GtC yr^{-1} sink in a Northern Hemisphere area smaller than 100 x 100 km [14], and the European summer anomaly of 2003 of 0.5 GtC [13]. Chevallier *et al*. [13] point out, however, that using available and currently planned surface and satellite

Table 2. Selected Networks of Surface and Aircraft GHG Measurement Sites [1]

Network	Measurement	Number of sites	Timeframe (yrs)
GLOBALVIEW-CO_2	CO_2 abundance	277	30
GLOBALVIEW-CH_4	CH_4 abundance	216	25
GLOBALVIEW-CO	CO abundance	143	18
GLOBALVIEW-CO_2C13	$\delta^{13}CO_2$	74	15
TCCON	Column CO_2, CH_4, CO, H_2O, N_2O	19	7
ARM/SGP	CO_2, CO abundance, CO_2 flux, CO_2 isotope ratios	1	17
AmeriFlux	CO_2, H_2O, energy, momentum fluxes	89	13
FLUXNET	CO_2, H_2O, energy, momentum fluxes	500	
EPA Registry	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6	13,000	

measurements, that it is still unlikely that carbon dioxide measurements can be attributed with sufficient precision to support treaty verification [13]. As their example, they indicate that uncertainties over Europe would remain as high as 0.16 Gt C yr^{-1}, which they compare to an accuracy of approximately 0.01 Gt C yr^{-1} needed to verify European compliance with the agreed-upon Kyoto protocol reductions. So, if their conclusions are correct, an improvement of more than an order of magnitude in uncertainty will be required for treaty verification.

3. EXISTING GHG NETWORKS

There are currently several extensive ground- and aircraft-based networks that provide measurements for monitoring GHGs in selected locations across the globe. A selection of these networks is summarized in Table 2. The GLOBALVIEW GHG climatologies produced by NOAA ESRL use interpolated and extrapolated datasets collected by many institutions at a large number of sites.[3] GLOBALVIEW-CO_2, for instance, provides estimates of average monthly CO_2 distributions derived from stationary or mobile (from ships or aircraft) measurements from 277 sites covering all continents collected by 23 laboratories over 30 years. GLOBALVIEW-CH_4 includes measurements of methane abundances from 216 sites from 13 laboratories made over 25 years. GLOBALVIEW-CO incorporates measurements of CO abundances from 143 NOAA ESRL sites made over the past 18 years. GLOBALVIEW-CO_2C13 is derived from observations of $^{13}CO_2$ made over the past 15 years at 74 sites managed by the University of Colorado. A more recently developed ground-based network, the Total Carbon Column Observing Network (TCCON), is composed of 19 current and future sun-viewing, Fourier transform infrared spectrometers that measure column abundances of CO_2, CH_4, CO, H_2O, and N_2O at sites to be located in 12 countries.[4] The DOE Atmospheric Radiation Measurement (ARM) program has a small network of sites with an array of instruments for measurements of a variety of climate-related species and parameters. Only the Southern Great Plains (SGP) ARM site includes routine observations of carbon-cycle GHGs.[5] Measurements at this site include CO_2 abundance and flux, CO abundance, and CO_2 isotope ratios. Several of these networks are interrelated. Some of the TCCON spectrometers are or will be co-located with NOAA tall towers, one of them is located on the ARM SGP site, and one of them is located at the ARM Darwin, Australia site.

Except for the CO_2 flux measurements at the ARM SGP site, all of the measurements mentioned above are abundance measurements, which require inverse models to infer emission source strengths. There are, however, corresponding networks of flux towers devoted to direct measurements of emission source/sink strength. AmeriFlux is a network of 89 active towers established in 1996 to provide measurements of CO_2, H_2O, energy, and momentum fluxes for ecosystem exchange studies in North America.[6] This network is part of a much larger international flux network called FLUXNET, which includes 500 tower sites globally.[7]

In general, these measurement sites have been designed to study carbon-cycle science or validate satellite observations under clear-sky conditions and have been deliberately located in remote locations away from large sources of GHGs. This distribution of sites severely restricts their utility in verifying emissions from large sources of GHGs. Note that as of January 1, 2010, however, EPA will require facilities that emit at least 25,000 metric tons of GHGs (~13,000 facilities) to monitor and report their emissions of CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6, which will fill data gaps related to large sources in the U.S. Nevertheless, there remain severe limitations in information in other countries about large point sources and urban areas that produce a majority of anthropogenic GHGs.

[3] http://www.esrl.noaa.gov/gmd/ccgg/globalview/
[4] http://www.tccon.caltech.edu/index.html
[5] http://www.arm.gov/
[6] http://public.ornl.gov/ameriflux
[7] http://www.fluxnet.ornl.gov/fluxnet/index.cfm

Satellite observations of GHG abundances can be used to fill the spatial gaps left by sparse and remote placement of surface sites, but these measurements must have high precision and adequate spatial resolution. Such space-based measurements can also help circumvent resistance to emissions verification from uncooperative countries. In addition, satellite observations that produce high-resolution land-use maps are extremely useful for verifying statistics for emissions inventories. Nevertheless, it appears unlikely that present GHG measurement networks, even augmented with current and planned GHG measurement satellites, will be adequate to the task of verifying potential GHG treaties. Hence, consideration of yet further augmentation is appropriate.

4. SATELLITE AND SURFACE DATA AUGMENTATION

The lack of observations of GHG abundances near urban areas and near large point sources is one of the most significant deficiencies in the current network of monitoring stations. Augmentation of the fixed surface measurement network to remedy this lack would be helpful. But in addition, a whole constellation of GHG measurement satellites will likely be necessary to multiply the available data by a factor of ten or more. In addition, some GHGs (such as methane and fluorocarbon compounds) are much more effective absorbers of thermal IR radiation, and quantification of the uncertainty in their abundances is necessary to reduce the uncertainty in the CO_2 measurements.

Aircraft-based and mobile surface measurement capabilities could, to some extent, minimize the additional satellite systems required. It would be particularly useful to equip current and future fixed and mobile measurement facilities with automated vertical profiling capabilities. Currently most tropospheric GHG vertical profiles are derived from *in situ* instruments on aircraft and from flask samples at a limited network of NOAA tall towers (in the planetary boundary layer). A new NOAA sampler, the AirCore[8], is capable of producing a vertical GHG profile using a single very long coiled sampling tube when flown on an aircraft executing the required altitude profile. However, the sampler must be analysed using an appropriate real time instrument shortly after landing. The advantage is that the instrumentation carried on the aircraft itself can be dramatically simplified. The AirCore also lends itself to measurements using stratospheric balloons which are capable of profiling 99% of the atmosphere. In the longer term, GHG measuring lidar systems of adequate accuracy and precision may also provide needed vertical profile data.

With regard to a mobile GHG measurement capability, we have developed a conceptual design for a mobile laboratory that could be used to augment current ground-based networks (Fig. 1). This laboratory includes instruments to measure abundances of important tracers for attribution, such as isotopes of CO_2 and H_2O, as well as CH_4, CO, NO_x, SO_2, and black carbon.

Figure 1 – Existing Mobile Laboratory which will be equipped over the next several months for *in situ* and remote sensing of GHGs to facilitate emissions and uptake rate uncertainty reductions.

The mobile laboratory design also includes instruments to measure fluxes of CO_2 and its stable carbon and oxygen isotopes. These measurements would be compared and combined using transport and mixing models for attribution. In addition, the mobile lab design includes a mobile solar Fourier Transform Spectrometer (FTS) to be linked into the TCCON to observe column greenhouse gas (GHGs: CO_2, CH_4, N_2O) and signature species (CO) mixing ratios. The mobile lab can be deployed in either urban or rural environments for emissions estimates, verification, and carbon-cycle science. The conceptual mobile lab design will be developed on a vehicular platform for deployment to sites of interest, for rapid redeployment as winds change to gain better access to emissions of interest, or for following a plume through space and time as it ages. The mobile lab will also be equipped and likely deployed to analyse AirCore samplers so as to minimize the time between profiling, aircraft landing, and AirCore analysis. The shorter that time delay, the higher the fidelity of the GHG profile obtained. It is also possible for this mobile lab to be deployed on a ship for coastal or open-ocean measurements. We view this mobile lab as a potential prototype for a fleet of such labs which could compose one element of an eventual GHG treaty verification system.

It is difficult to foresee other major advances in technology that will enable novel *in situ* or remote measurements with better precision, accuracy, or applicability to a wider range of species. One area in which advances are recognized and anticipated, however, is in space-based instrumentation that will allow measurements of vertical profiles of GHGs on a global spatial scale. The future Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)

[8] Patent pending by P. Tans

satellite lidar instrument will collect 100,000 clear-sky soundings of CO_2 per day with a precision of 2-4 ppm. This instrument will be a good complement to the future OCO instrument, which has better precision but lacks vertical resolution [15]. Advances in *in situ* instrument capabilities are currently being made with the development of new laser-based light sources for absorption measurements, which allow for either increased precision or better affordability and thus expansion of ground-based networks.

5. CONCLUSIONS

It is apparent from this review that we are at present a long way from having the technical capability to remotely verify any GHG treaty that may eventually be agreed upon. However, the development of that capability is well started. It may be that any agreement to a GHG treaty will depend upon confidence that such a capability can and will be developed. If so, our global climate future may depend upon these and similar efforts.

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