EARTH OBSERVATION FOR LAND-ATMOSPHERE INTERACTION SCIENCE

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ABSTRACT

The European Space Agency (ESA), iLEAPS (Integrated Land Ecosystem-Atmosphere Processes Study, i.e. the land-atmosphere core project of the International Geosphere-Biosphere Programme), and the European Geosciences Union (EGU) jointly organized the "Earth Observation for Land-Atmosphere Interaction Science" Conference, which took place from 3rd to 5th November 2010 at the Italian premises of ESA in Frascati (Rome). The event represented an attempt to effectively draw together Earth-observation (EO) and Earth-system scientists investigating land-atmosphere processes in order to better understand the current gaps in science and derive recommendations to advance in the use of EO technology in the context of this important topic.

Around 200 people from more than 30 countries worldwide met and discussed for three intensive days. This paper reports keypoints and the main recommendations of the Symposium for each of the key Themes addressed during the Conference.

INTRODUCTION

Land-atmosphere interactions include a variety of critical feedbacks between radiative, hydrological, and biogeochemical processes resulting in complex exchanges of energy and matter that influence the overall Earth system and its climate. The observation, understanding and prediction of such processes and their impacts have been hindered in the past by the lack of suitable data at the required spatial and time scales. Over the last few years, EO data integrated with *in situ* networks and within suitable models have demonstrated the potential for EO to become a major tool for observing key variables and characterizing the main processes governing land-atmosphere interactions at global to local scales.

Over the next few years the capabilities of monitoring the Earth's land surface and atmosphere will further improve through the increasing number of new EO missions to be launched by the space agencies. The full exploitation of such increasing multi-mission observational capacity requires coordinated research efforts involving both EO and Earth-system scientists, modellers, and institutions to develop novel observations and robust biophysical products to be effectively integrated with *in situ* data and within appropriate coupled models.

In this context, the Conference aimed at bringing together the EO and Earth-system communities involved in the observation, characterisation and forecasting of land-atmosphere interactions and their impacts. In particular, the event provided an excellent opportunity to exchange information and enhance coordination to address the major scientific needs and priority areas for the future.

The specific objectives of the Conference were:

- To increase scientific understanding of the main land-atmosphere interactions and their impacts on the Earth system and climate;
- To review current advances in EO technology and its capacity to improve the characterisation of the complex land-atmosphere fluxes at different temporal and spatial scales;
- To accelerate the development of novel and robust multi-mission data products capable of exploiting the synergies of the increasing number of complementary EO missions;
- To foster the integration of EO data into advanced coupled models capable of describing and forecasting the main land-atmosphere fluxes;
- To consolidate a scientific roadmap outlining priorities and scientific requirements to further advance the development and exploitation of global observations and consistent data records capable of supporting the international scientific efforts of the iLEAPS community.

In the following, a review and summary of the main directions and recommendations for the future is provided for each of the 6 key Themes addressed during the Conference. In particular, Section 2 deals with methane fluxes, whilst Section 3 focuses on biomass burning emissions. In Section 4, land dynamics and carbon fluxes are discussed, whereas Section 5 is dedicated to modelling and data assimilation. Land surface models and heat fluxes are addressed in Section 6, whilst finally Section 7 focuses on aerosols. At the end, conclusions are drawn in Section 8.

METHANE FLUXES

EO is providing measurements of the column amount of CH_4 and key parameters which control its release at the surface. The progress made in the recent past is significant. The synergistic use of different parameters controlling the surface release of CH_4 and the observations of the dry columns of CH_4 are probing our ability to predict regionally and globally the changes of CH_4, which are poorly understood. Similarly we are now beginning to understand the impacts of topography and transport process on the modulation of the dry column of CH_4. It is worth pointing out that the challenges of understanding CH_4 dynamics in a changing climate and the need to provide accurate information to policy makers are drivers for the development of an adequate observing system for their total columns.

In this framework, main directions and recommendations are:

1) To improve and consolidate long term measurement capability to separate anthropogenic and natural fluxes and allow the quantification of emission hot spots.
2) To further improve the capability to measure CH_4 from space, with respect to precision, accuracy and spatial resolution and temporal sampling.
3) To effectively explore existing datasets available for characterizing the extent of flooded areas from where CH_4 is emitted.
4) To include additional EO measurements (e.g., temperature, soil moisture) as well as improved ancillary datasets (e.g., chemical and physical soil properties) in atmospheric transport models.
5) To exploit assimilation of EO-based land products (e.g., wetland dynamics) as well as atmosphere products (e.g., CH_4 concentration measurements) into novel land-atmosphere coupled models.

New observations are needed to address requirements of both scientists and policy makers. However, it is important to notice that after Envisat and GOSAT missions around 2015, there are no missions funded for measurements in the 0.75-2 micron absorptions of CO_2, CH_4 and O_2 required for the determination of the total dry columns of CO_2 and CH_4. In this context, a system providing daily coverage of the dry columns of these gases at 1-2 km and global daily coverage would be highly beneficial.

BIOMASS BURNING EMISSIONS

During the past century, biomass burning events have produced substantial emissions of trace gases and particles into the atmosphere. These emissions have resulted in significant perturbations in the radiative balance of the atmosphere and in air quality at regional and global scales. The definition of emission regulation policies and the evaluation of the effects of these policies require an accurate estimate of atmospheric emissions and of their temporal evolution. In this context the role of EO-based products has nowadays a great importance both for routinely identifying the location of fires and (since the last few years) characterizing the amount and biomass burning emissions and their evolution in time. However, several improvements are still needed:

1) Accurate estimates of pre- and post-fire fuel load are essential in order to refine emissions estimates derived using Fire Radiative Power (FRP) and burned area based emissions inventories. Improved fuel load estimates, particularly during senescence, are needed from EO sources and through field campaigns (e.g., prescribed fires). To leverage off these fuel load measurements, comparison between FRP and burned area emissions inventories is necessary to assess the benefits and limitations of each approach. This may indicate whether integrating these methods would be beneficial.

2) The increasing application of FRP observations to quantify biomass burning emissions may indicate it is at a stage where it could be recommended to GCOS (Global Climate Observing System) for inclusion as an Essential climate Variable (ECV).

3) There is a need to map tracers such as Formaldehyde and Ammonia to improve understanding of the influence of biomass burning on atmospheric chemistry. CO should be used as a surrogate for CO_2.

4) There is a strong requirement for a high spatial resolution MIR (3.9 µm) and TIR (10 µm) sensor. Such an instrument would complement the high spatial resolution visible and near-IR channels (1.6 µm and 2.2 µm) channels on Sentinel-2 and would be able to better define both the spatial extent of fires and the depth of burn of peat fires. This instrument would be also advantageous for other applications (e.g., detecting and quantifying gas and oil flaring).

5) Importantly, a high spatial resolution MIR instrument (see #4) would also provide the data required to quantify FRP underestimation by moderate spatial resolution sensors. MODIS, which has a minimum FRP detection threshold of ~10MW, is currently the only sensor that can be used to account for the underestimation of FRP by coarse spatial resolution instruments (e.g., geostationary). However, the degree to which MODIS underestimates fire activity is unknown. Quantifying this uncertainty is crucial for improved emissions forecasts such as those provided by the EU-FP7 MACC project.

6) Sentinel-3 instruments will allow the continuity of current developments in deriving smoke plumes injection heights from AATSR and MERIS. However, improvements may be limited due to the lack of at least 3 angles to derive smoke-plume top winds.

7) There is a need for EO products that better constrain the diurnal cycle of fire emissions, especially at high latitudes.

LAND DYNAMICS AND CARBON FLUXES

Understanding the role of the carbon cycle in the Earth system is crucial. Indeed, it is closely coupled to greenhouse gas induced climate change, the water cycle, marine and land productivity and biodiversity. A better understanding of the interactions of physical and biological processes in the carbon cycle and climate is a driver to predict future changes. Accordingly, there is a growing need to quantify the global carbon budget at different scales by combining space observations of surface processes with the atmospheric carbon and ground-based measurements.
In order to improve state-of-the-art estimations, the following recommendations and directions have been identified:

1) There are still some large gaps in the current EO product portfolio (e.g., biomass, land cover change). In particular, products from different sensors or projects are not consistent for most variables (i.e., LAI, fAPAR, land cover, etc.).

2) Consistency should also be sought for products coming from the same baseline data (i.e. albedo, fAPAR, LAI). Moreover, there is a strong need to improve baseline observations (atmosphere, cloud, calibration, cross-calibration, geolocation).

3) A commitment to long term data records is critical.

4) Uncertainty estimates are either not available or inappropriate (these should be fully traceable and translated into product measurement terms). In particular:
   a. Simple flags or standard deviations are not sufficient;
   b. Better characterisation of systematic errors is urgently needed (especially for land cover).

5) The interface between data and models remains an active area of research:
   a. Existing models shall be improved to meet the science need (LUE methods, complex DGVMs, etc.);

b. There is a urgent need for clarity on and consistency of definitions between the two domains.

6) Models of the biosphere and data assimilation interface require upgrading to better represent the complexity of vegetation canopies.

7) Scale issues affect the interface between models and data and between biosphere and atmosphere models and shall be properly taken into consideration.

8) Methods to characterise information change between scales and to retain information across scales require further development.

MODELLING AND DATA ASSIMILATION

The aim of data assimilation is to ascertain the best estimate of the state of a system by combining information of that system with an appropriate model of the system. Accordingly, it represents an important tool to help effectively combining EO data available from a wide variety of sources together with traditional *in situ* observations into Earth-system models. However, assimilation of data requires a careful inspection of both observations and models.

Nowadays, there is an intense discussion about the advantages and opportunities offered by the assimilation of Level 1 (L1) observations or Level 2 (L2) derived EO products (e.g. fluxes or state variables). In this context the main debate observations are reported in the following:

1) There is a growing need to have similar radiation transfer schemes in Soil-Vegetation-Atmosphere-Transfer (SVAT) models and in ground segments generating L2 products. The radiation transfer schemes implemented in SVAT models should ideally allow the accurate simulations of the scattered, transmitted and absorbed radiant fluxes. The latter are important drivers for representing, in regional and large scale models, the complex processes of exchanges of energy, mass and momentum between the atmosphere and the terrestrial environments but also between the vegetation layers and the soils underneath. Typically these SVAT modules implement their own radiative transfer schemes using their own set of state variables. The radiation transfer schemes that are used to simulate these processes in climate models and to retrieve the required state variables from EO data must be compatible with each other or at least physically equivalent with respect to the radiant fluxes they generate. Incompatibilities between the assumptions and approximations implicitly made by using different models, (e.g., one-dimensional versus three-dimensional radiation transfer models), may generate discrepancies and biases when EO products are heedlessly ingested by the climate models. As a matter of fact, the same class of radiation transfer schemes should be used in forward (when simulating surface processes in climate models) and inverse (when retrieving state variables from remote sensing data) mode.

2) There is a clear desire to assimilate L2 data. Indeed, on the one hand it should not be assumed that L1 products provides better results considering that the land surface is complex; whereas, on the other hand, the assimilation of L1 data requires that the model has sufficient information to interpret such data. Observational information plays a key role in reducing the large uncertainties associated with the state variables driving the radiation transfer processes in terrestrial environments. The accurate modelling of the radiance fields currently measured by a variety of space borne sensors remains a rather challenging task given the physical complexity of the coupling between the three-dimensional terrestrial and atmospheric environments. As an alternative, mapping the state variables of terrestrial systems onto products generated at top of canopy level, such as the surface albedo and, to some extent, the fAPAR as well, represents an achievable mid-term objective. It is noteworthy that the performance of assimilation techniques is strongly dependent on the accurate documentation of the correlation between the uncertainties associated with each component of these flux vectors.

3) The assimilation of L2 products will add relevant constraints to the land-surfaces processes that are still crudely parameterized in SVAT modules. The most advanced representation of radiation transfer processes is still confined to one-dimensional approaches. This leads to some significant inconsistencies and biased results when assimilating for instance directly state variables by contrast to radiant fluxes. It is noteworthy that multiple years of medium resolution (i.e., close to 1 km spatial resolution) L2 products such as albedo and FAPAR are already available from various space agencies. In the meantime the radiation transfer modelling tools needed to interface large scale models with albedo and FAPAR values derived from space measurements have become available (http://rami-benchmark.jrc.ec.europa.eu/HTML/RAMI4PILPS/RAMI4PILPS.php). The capability of using these L2 products, especially the surface albedo, as input to inverse schemes for partitioning the solar radiant flux absorbed in the vegetation and soil

components have been demonstrated. Only a few SVAT modules implemented in dynamic vegetation models currently incorporates radiation transfer schemes (across all wavelengths from shortwave up to microwaves) with a sufficient degree of detail to fully benefit from the ingestion of accurate L2 products. This, however, is a mandatory task to accomplish if L2 products are to be used for driving simulations of the water and carbon cycles based on these dynamic vegetation models.

Other relevant recommendations are summarized below:

1) There is a need for realistic uncertainty estimates for each measurement at pixel level and not just an overall single error measurement.

2) A clear characterisation of temporal and spatial correlations in the errors is necessary.

3) In order to make data assimilation systems capable of improving EO products by detecting and quantifying inconsistencies, physically based models are needed which have been verified against *in situ* data.

4) Models could be particularly useful to assess the consistency between different observation types (ideally ensembles of multiple model runs should be used).

LAND SURFACE MODELS AND HEAT FLUXES

Being located at the edge between the atmosphere and hydrology, the land surface represents the link between several scientific disciplines and land-surface modelling has been largely investigated in the hydrological, atmospheric, and EO communities in the last decades. Combining these efforts is of vital importance for the successful predictions of future changes.

The total radiation absorbed at the land-surface is balanced by emission of thermal infrared radiation to the atmosphere, latent heat loss associated with evaporation and transpiration, sensible heat losses and diffusion of energy into the soil. Accordingly, the basic task of any land-surface model is to accurately simulate the partitioning of net radiation at the land surface into these component fluxes. In this framework, relevant information on land surface and climate available from EO data and products is of paramount importance. Moreover, the conversion of EO data into surface fluxes to improve validation of land-surface models is subject to intense research.

Current main recommendations are listed below:

1) The main requirement is for investment in analysis techniques, leading to a strong collaboration between the EO community and the modelling community.

2) Due to the LandFlux initiative (focused on developing an operational approach for routine production of a multi-decadal global land based surface flux data set) significant steps forward have been taken in terms of accessing a large range of EO products that deliver the kind of data which the land surface modellers need to test their algorithms against. However, it is important that the analysis evolves beyond a simple “root mean square error” assessment.

3) In order to define new useful metrics to assess model performance, it is necessary to clearly identify what phenomena we are interested in.

4) A useful test would be to quantify if the global hydrological cycle is accelerating or not. Another test would be to quantify the ability of the models to locate large-scale floods and droughts. Long-term data sets are required for such an assessment and the availability of 30 years of data now allows the analysis of decadal variations (although it is not possible to derive trends from these records as they are not long enough).

5) There is a need for thermal infrared data with a high temporal frequency and high spatial resolution.

6) Land surface temperature is one of the few variables we can actually measure both from space and on the ground is a mature product and should be recommended to GCOS for inclusion as an ECV. While it is true there are scaling issues, say comparing 100m with 1km with 4 km, these issues are no different than other products.

7) While there are a number of numerical modelling based approaches that seek to describe terrestrial water and energy cycles, an operational, observationally based and temporally consistent data set for continental scale evapotranspiration is not currently available. Such a dataset would provide an independent means to assess the capacity of different modelling schemes to reproduce surface heat fluxes and contribute to model evaluation.

AEROSOLS

Tiny dust particles and droplets suspended in the atmosphere have a definite influence on our climate, but we are a long way from defining precisely the role that aerosols play. That they do have an effect was established more than a decade ago.

The majority of aerosols reach the atmosphere by natural means (i.e., salt condensed from ocean waters, fine sand from desert dust storms, ice crystals over the poles and ash from fires as well as eruptions), but human activities account for 10% of global aerosol loading, mostly concentrated in the Northern Hemisphere.

EO provides a global census of aerosol loads, following them through from their origins, their interaction with atmospheric components and the energy budget, and finally their deposition on the surface.

Aerosols are largely absent from current climate models, and their effects are difficult to quantify. Many aerosols reflect sunlight, and so cool down the atmosphere immediately below them. But black carbon aerosols do just the opposite, acting to absorb heat energy.

In this context, identified priorities and further research developments are presented in the following:

1) As far as chemical transformations and gas–particle interactions of aerosols and clouds are concerned, one of the most important prerequisites for efficient further investigation and scientific progress is the establishment of a common basis of consistent, unambiguous, and universally applicable terminologies and model formalisms.

2) Aerosols, both through their direct radiative impact and their influence on cloud properties, remain one the largest sources of uncertainty in our understanding of the climate system. This uncertainty is due to the high temporal and spatial variability of aerosol properties and loading, combined with the complexity of their interactions with cloud. The requirement for long term, global datasets to aid in quantifying the radiative impact of aerosol is then straightforward.

3) Although emission sources of fine particulates are generally known, knowledge about their chemical composition is still inadequate. Integrated studies are hence necessary for identifying the processes whereby aerosols are formed, with co-planned emphases on characterizing the radiative properties that influence the climate system (by radiation scattering-absorption and via aerosol-cloud interactions) and the chemical properties that influence human health.

4) The identification and characterization of hazardous aerosol components and their sources and sinks (emission, transformation, deposition) should allow the optimization of air-pollution control and medical treatment of aerosol effects on human health.

5) Novel techniques need to be developed for distinguishing anthropogenic from natural aerosols. Current satellite-based estimates of anthropogenic aerosol fraction rely on retrievals of aerosol type. These estimates suffer from limited information content of the data under many circumstances. More needs to be done to combine satellite aerosol type and vertical distribution retrievals with ancillary information (e.g., from back trajectories and inverse modelling or from *in situ* measurements).

6) A synthesis of data from multiple sensors would in many cases be a more effective resource for characterizing aerosol than data from individual sensors alone. Nevertheless, techniques for achieving such synthesis are still preliminary, and multi-sensor products have only begun to be developed. The full information content of existing data, even with individual sensors, has not been realized. Accordingly, there is a need to refine retrieval algorithms and extract greater information about aerosols from joint data sets, to quantify data quality, and to generate uniform climate-quality data records.

CONCLUSIONS

The ESA-iLEAPS-EGU joint Conference brought together a unique combination of scientists providing an excellent opportunity to 1) review the current state-of-the-art in land-atmosphere interactions science; 2) to better understand the current gaps in observations and scientific requirements of both EO and Earth-system communities and 3) to derive recommendations to advance in the use of EO technology in the context of this important topic.

The Conference covered different topics including methane fluxes, biomass burning emissions, land dynamics and carbon fluxes, modelling and data assimilation, land surface models, heat fluxes and aerosols.

The results of the three days of discussions have demonstrated the significant advances achieved in the last years to retrieve from satellites several of the key parameters and variables governing land-atmosphere interactions as well as the significant efforts carried out by the international community to integrate these observations within suitable models in order to better describe and characterise such key processes.

The Conference offered a wide panorama of practical experiences and scientific results demonstrating the potential of EO for land-atmosphere interactions science, while pointing out the still many gaps and the scientific challenges for the future.

In this context, this paper offers a collection of some of the major findings and conclusions from the discussions carried out in each of the main sessions of the Conference. These recommendations represent a guideline to better coordinate the international efforts required to further advance in the use of EO technology to characterize and understand the chemical, physical and biological processes occurring at the land-atmosphere interface.

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