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Revisiting land cover observation to address the needs of the climate modeling community

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Abstract. Improving systematic observations of land cover, as an Essential Climate Variable, should contribute to a better understanding of the global climate system and thus improve our ability to predict climatic change. The aim of this paper is to bring global land cover observations closer to meeting the needs of climate science. First, consultation mechanisms were established with the climate modeling community to identify its specific requirements in terms of satellite-based global land cover products. This assessment highlighted specific needs in terms of land cover characterization, accuracy of products, as well as stability and consistency needs that are currently not met or even addressed. The current land cover representation and mapping techniques were then called into question to specifically focus on the critical need of stable products expressed by climate users. Decoupling the stable and dynamic components of the land cover characterization and using a multi-year dataset were proposed as two key approaches to allow generating consistent suites of global land cover products over time.

1 Introduction

Land cover is referred to as one of the most obvious and commonly used indicators for land surface and the associated human induced or naturally occurring processes (Herold et al., 2009). Land cover also plays a significant role in climate forcing. Indeed, land cover changes act as both a cause and a consequence of climate change by altering water, gas and energy exchanges with the atmosphere (Pielke et al., 1998; Bounoua et al., 2002). Information on the state and dynamics of land cover is therefore required for a broad spectrum of scientific, economic and governmental applications (Lautenbacher, 2006; Skole et al., 1997). Land cover maps are used to develop sustainable management policies for land and natural resources, to evaluate ecosystem status, to model and assess biogeochemical cycling (water, carbon, etc.) and to address climate change mitigation and adaptation (Townshend et al., 2008; Sutherland et al., 2009).

Earth Observation (EO) technology has progressively been recognized for its usefulness in mapping land cover characteristics over a variety of spatial scales and over time. On one hand, the unique global coverage of EO datasets enables the production of spatially-explicit land surface characterization (Singh, 1989; Defries and Townshend, 1999). On the other hand, their synoptic view makes possible repetitive and consistent image acquisitions over the same area (Singh, 1989; Defries and Townshend, 1999).

In many different regions of the world, land cover has been mapped and characterized several times using EO datasets. This is the case, for instance, with the Corine Land Cover databases in Europe (EEA, 2009, 2010a, b), the Greater Mesoamerica land cover database (Giri and Jenkins, 2005) and the Africover maps (FAO, 2003). Many countries also have particular land monitoring systems in place, dedicated to forest change (INPE, 2008), cartographic information systems or inventories (Arozarena et al., 2006).

A number of global land cover mapping activities exist. These activities have evolved along with the availability of global moderate spatial resolution satellite observations and the development of the Land Cover Classification System (LCCS) of the United Nations Food and Agriculture Organization (UN-FAO). These efforts have yielded several global land cover products in the 300-m–1-km spatial resolution ranges (Loveland et al., 2000; Bartholomé and Belward, 2005; Defourny et al., 2009a; Friedl et al., 2010; Bontemps et al., 2011). To date, the accuracies of four of them – the map from the International Geosphere-Biosphere Program (IGBP) Data and Information System (DISCover), the GLC2000 map, and the GlobCover 2005 and 2009 products – have been quantified through a rigorous validation exercise based on international standards (Scepan et al., 1999; Mayaux et al., 2006; Defourny et al., 2009b; Bontemps et al., 2011). In spite of the diversity of sources for remote-sensing data, classification methods and validation strategies, the overall accuracy figures weighted by area reached around 68–73 % for the four products.

Overall accuracy provides information on the agreement of the classification diagnostics with independent "reference" information. This is obtained by comparing the land cover type identified by the product and the "actual" land cover type (determined by the "reference" dataset). Weighting the accuracy value of each class by its proportional area avoids an over- or under-representation of the different land cover classes – depending on whether they cover small or large surfaces. Although area weighted overall accuracy is recognized to be the most all-encompassing figure (Strahler et al., 2006), it does not completely reflect the product's quality and usefulness. On one hand, it varies according to the thematic class and the region of interest. On the other hand, there are other valuable quality indicators, such as the product's stability (i.e. the consistency over time of successive products). However, this figure is not yet analyzed in current mapping and validation exercises.

Despite their limited accuracy (ceiling value around 70 %) and associated uncertainties in terms of stability, global land cover maps are used in many applications. Improving their quality is therefore of paramount importance in order to increase their usefulness. Recognizing that there is no unique definition of usefulness, it is necessary to establish interaction mechanisms with specific user communities in order to better understand their needs.

A strategic user community of climate modelers has been formed to provide guidance on the development of 50 Essential Climate Variables (ECVs), of which land cover is one, as defined by the Global Climate Observing System (GCOS). ECVs are variables that are technically and economically feasible for systematic observation of the climate system, and are currently ready for global implementation on a systematic basis (CEOS, 2008). Improving their systematic observation will support the United Nations Framework Convention on Climate Change (UNFCCC) efforts to reduce the uncertainties in our understanding of the climate system and to better cope with climate change (GCOS, 2010).

In this context, the European Space Agency (ESA) has initiated a new program of ECVs global monitoring – known for convenience as the Climate Change Initiative (CCI) – which aims to provide a comprehensive and timely response to the need for long-term satellite-based products in the climate domain (ESA, 2009). The essential feature of the program is to implement a coherent and continuous suite of actions that encompasses all steps (including data acquisition, calibration and validation, long term algorithm maintenance, data curation and reprocessing) necessary for the systematic generation and updating of relevant ECVs. The ESA-CCI program focuses, through individual projects, on 14 ECVs selected in the atmospheric, oceanic and terrestrial domains on the basis of ESA priorities. In the land cover project of the program, emphasis is put on the generation of successive and consistent global products at a moderate spatial resolution. The depiction of land cover categories and changes at a finer scale is beyond the scope of this project.

The core objectives of this paper are to assess the needs of the climate modeling community in terms of global land cover products, to investigate how these needs are met by existing products and to propose a new approach to help land cover observation to evolve. First, it presents the results of consultations established with the climate modeling community to derive more detailed specifications for observations of land cover as an ECV. Further, it investigates how current global land cover products meet the particular need expressed by modelers for stable land cover information. Finally, the land cover observation approach, developed in the land cover project of the ESA-CCI program in order to address this stability issue, is presented.

2 Global land cover product specifications from climate modelers

Land cover products are relevant to three major climate modeling groups: general circulation modeling, Earth system modeling and integrated assessment modeling. All of them are specifically interested in the role of land use and land cover change in assessing impacts and vulnerabilities (Hibbard et al., 2010; Feddema et al., 2005). Each of the three groups has specific modeling strategies, but also has to respond to new policy needs and to the increasing requirement for integrated data (Overpeck et al., 2011). Recent developments in climate science have called for a much more integrated modeling and assessment framework, where land surface information includes both land cover and land use aspects (Hibbard et al., 2010). It can therefore be argued that improvements in observing land cover will act as an important catalyst to better integrate the efforts of the different modeling groups.

2.1 User consultation

A user consultation was conducted with a twofold objective: to understand (i) current land cover data usage by climate modelers and what their key characteristics are, and (ii) future expectations for land cover data in the context of climate and Earth system modeling. The consultation was set up through surveys (carried out in September and October 2010) focusing on three major uses of land cover observations in climate models:

1. as a proxy for a set of land surface parameters that are assigned based on Plant Functional Types (PFTs);
2. as a proxy for human activities in terms of natural versus anthropogenic changes, and to track human activities;
3. as datasets to validate model outputs (i.e. time series) or to study feedback effects (land cover change as consequence of climate change).

With this aim in mind, specific surveys were defined to distinctly focus on three types of users:

- Key users: being partners of the ESA-CCI land cover project, they are central to all phases of the consultation. Regular and direct interactions have allowed in-depth analyses of the land cover data characteristics to be used in their models (spatial and temporal resolution, thematic detail, accuracy requirements). Key users include 3 institutions, which are the Max Planck Institute for Meteorology (Germany), the Laboratoire des Sciences du Climat et de l'Environnment (Fance) and the Meteorological Office Hadley Center (United Kingdom).
- Associated users: they belong to the climate modeling community but are not project partners. A group of 85 users was approached to participate in the survey and 15 of them (from a broad range of countries all over the globe) accepted to be actively involved.
- Broad users: this group does not refer only to users, but also to information. It has been considered by gathering material through the World Wide Web and by reviewing scientific literature with special attention to innovative concepts and approaches to better reflect the evolution of requirements in the next generation climate models. Broad users also include "climate concerned users" who, although not being climate modelers, make use of land cover information for other societal benefits or national reporting and accounting. The feedback of these "climate concerned users" was collected thanks to a survey addressed to the land cover data user community, represented by users of the ESA GlobCover product (Arino et al., 2008). Out of the about 8000 registered GlobCover users, 372 filled in the questionnaire.

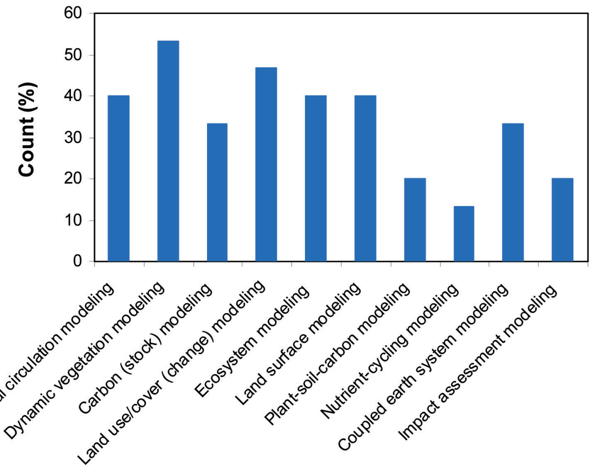

Fig. 1. Earth system or climate modeling focus of respondents to the associated users' survey (each respondent having the possibility to have more than one focus).

Specific questionnaires were prepared for each group. Their format varied according to the question (multiple choice questions or open questionnaire). For the key users, the questionnaire was longer and disseminated via e-mail, while for the associated and broad users, a more concise form was made available online.

This broad consultation ensured that the full range of needs was considered. This is illustrated in Fig. 1, which shows the variety of climate modeling applications covered by the associated users' survey.

Alongside the surveys, requirements from other international activities were also gathered. First, activities of the land cover project of the ESA-CCI program have been closely aligned with specific land cover tasks listed in the GCOS Implementation Plans of 2004 and 2010 (GCOS, 2004; GCOS, 2010 – Table 1). The project focuses on the generation of successive and consistent global land cover maps (action T26 (or T27) in Table 1).

Second, a key document on ECV standardization (Herold et al., 2009), the most recent summary report highlighting key gaps in current land observation programs (Townshend et al., 2008), as well as the user requirement document written by the "Climate Modeling User Group" of the whole ESA-CCI program (CMUG, 2011) were also considered. A complete description of the consultation mechanism (user description, consultation methodology and outcomes) is provided in Herold et al. (2011).

2.2 Analysis of user requirements

While the frequency of responses varied, the amount and quality of feedbacks were found to be suitable to obtain a good synthesis on what climate modeling users need and expect from a new land cover product. A first outcome to highlight is the confirmation that there was quite some

Table 1. Key tasks for land cover theme from GCOS Implementation Plan (2004 and 2010) and how these tasks are taken up by the CCI land cover project.

GCOS Implementation Plan task (2004 and 2010)	Status reported in recent progress report (2009)	Issues addressed by Land Cover CCI
Action T22: International standards for land cover maps. *In the 2010 plan, T22 was removed.*	The UN LCCS (under ISO) provides the required standards and specifications (good progress).	LCCS classifiers, generic classes and related legends targeted at user requirements will be used to develop the product.
Action T23: Methods for land cover map accuracy assessment. *In the 2010 plan, defined as T26.*	Standard validation protocols, methods and best practices have been developed by the CEOS Working Group on Calibration and Validation (WGCV), working with GOFC-GOLD (good progress).	The project is using a comprehensive validation approach that is independent, internationally agreed upon and repeatable.
Action T25: Development of in situ reference network for land cover. *In the 2010 plan, T25 is reflected in ecosystem observing network.*	As a start, GOFC-GOLD and CEOS WGCV have developed the framework for an in situ reference network for operational global land cover validation (low progress).	For the product validation, a comprehensive approach making best use of existing resources and aiming at developing an operational reference network is applied.
Action T26: Annual land cover products. *In the 2010 plan, defined as T27.*	There are several global land cover products at the requested resolution including GlobCover and MODIS (moderate progress).	The activities are building upon the GlobCover heritage, cooperating with the MODIS team and aiming at multi-date global products.
Action T27: Regular fine-resolution land cover maps and change. *In the 2010 plan, defined as T28.*	No concerted action towards a global product at the required fine resolution (10–30 m) has been achieved (low progress).	The issue of fine-scale land cover/land cover change is not specifically addressed here, but some methodological steps could be extended to higher spatial resolution datasets.

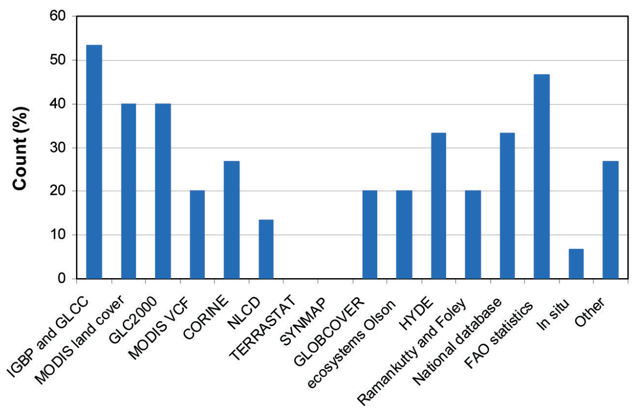

Fig. 2. Distribution of land cover dataset used in the different climate modeling applications, according to the respondents to the associated users' survey.

congruency among the different users groups that were assessed. A second interesting result lies in the fact that 12 different datasets are currently used by the climate modeling groups. The most frequently mentioned are the IGBP Discover and the Global Land Cover Characterization (GLCC) datasets, respectively provided by USGS and FAO statistics (Fig. 2). In spite of the availability of more detailed datasets like GLC2000, MODIS land cover and GlobCover, the products that were available first thus remain the most popular ones. This suggests that the more recent products are not considered to add sufficient value in the context of climate modeling. This could be due to the fact that the main progress in global land cover product evolution is mainly an increase in spatial resolution while regional and global climate models still run at resolutions ranging from 0.25 to 2.5 degrees. Conversely, no major improvement was observed in the fields of product stability or change detection, which are of particular interest for climate modelers.

The user consultation also resulted in a series of outcomes listed below:

- There is a need for both stable land cover products (free from any temporary variability as they are often used as a consistent basis for land surface parameterization) and a dynamic component reflecting land cover change and vegetation dynamics such as phenology;

- Consistency among the different model parameters is often more important than accuracy of individual datasets. It is important to understand the relationship between land cover classifiers and the surface parameters to know the relative importance of each land cover class;

- The relative importance of different class accuracies significantly varies depending on which surface parameter is estimated. The need for stability in accuracy should be reflected in the implementation of multi-date accuracy assessments for land cover data;

- Providing information on natural versus anthropogenic vegetation (disturbed fraction), tracking human activities and defining the history of disturbance is of increasing relevance. Information about land use affecting land cover is particularly needed, with most detail focusing on areas with large anthropogenic effects;

- In terms of land cover change and dynamics, the user survey showed that information need is the largest for vegetation phenology, agricultural expansion, forest loss/deforestation and urbanization. With less importance in terms of user requests, the needs for monitoring wetland dynamics, fire, land degradation and long-term vegetation trends were also highlighted;

- Requirements for land cover data regarding spatial and temporal resolution, thematic representation and associated accuracies largely vary among modeling groups. Land cover products thus need to have a certain level of flexibility to serve climate modeling efforts for different scales and purposes;

- Even if there is not one spatial resolution that fits all purposes, a resolution of 300 m or coarser is sufficient to meet the requirements of most users. However, for some applications (in particular for the coming years and for regional modeling), there are requirements for resolutions higher than 100 m (i.e. higher than those specific to the action T26 (or T27) in Table 1);

- Future requirements for temporal resolution refer to intra-annual and monthly dynamics of land cover. A better use of the increasing length and detail of remote sensing time series data is also expected;

- More than 90 % of the general land cover users find the UN LCCS a suitable approach for thematic characterization and quite compatible with the PFT concept of many models;

- The quality of land cover products needs to be transparent by using quality flags and controls, and include information on the probability for the land cover class, anticipated second class or even the probability distribution function for each class (coming from the classification algorithm).

Furthermore, the user consultations have shown that although the range of expectations coming from the climate modelers is broad, there is a good match among the expectations coming from the different user groups and the broader guidelines derived from GCOS, CMUG and other relevant international panels, as shown in Table 2.

3 User requirements and current land cover products

The user consultations highlighted some requirements in terms of thematic content, spatial and temporal resolution, accuracy (i.e. agreement between the classification and independent “reference” information) and stability (i.e. freedom of the product from variability not related to land cover changes). Some of these requirements are not met by the existing global land cover products (Table 3).

In addition, the user assessment highlighted that land cover remains a key dataset that serves as a consistent basis for many other land surface parameters and for the associated temporal variability. For instance, the users have emphasized that there is some reluctance to take up new land surface variables (including other ECVs such as Leaf Area Index or Fraction Absorbed Photosynthetically Active Radiation) coming from EO datasets although they provide more spatial and temporal details than current model parameterizations. Since many users are relying on a common land cover map to estimate a series of land surface parameters, introducing new datasets may result in inconsistencies with the existing model inputs. That is the reason why consistency (i) of the input parameters in space and over time and (ii) among a series of land surface parameters is higher valued than the accuracy of individual parameters. However, this aspect is not addressed by the EO land domain.

The next sections of this paper will specifically focus on the first requirement expressed by the users: the need to decouple the stable and dynamic components of the land cover in order to produce global land cover maps which do not reflect temporary conditions. Generating such stable maps would address, at the same time, the second requirement in providing a consistent basis for land surface parameterization. Before proposing any alternative, this section investigates how current land cover observation approaches deal with this requirement.

Table 2. Comparison of GCOS, CMUG and surveyed users expectations for different characteristics of global land cover products.

	Geometric accuracy	Temporal resolution	Accuracy	Stability
GCOS	250 m–1 km (accuracy better than 1/IFOV with target IFOV 250 m)	Yearly	< 15 % omission and commission errors for individual classes	> 85 %
CMUG	300 m–1 km	2–5 yr	5–10 % omission and commission errors for individual classes	> 90 %
Surveyed users	300 m–1 km	5 yr	5–10 % omission and commission errors for individual classes	>85 %

Table 3. Capabilities of four global land cover products currently used by the climate modeling community.

	IGBP DISCover (AVHRR sensor)	GLC2000 (SPOT-Vegetation sensor)	MODIS land cover v5 (MODIS sensor)	GlobCover (MERIS sensor)
Period	April 1992–March 1993	2000	2002 to 2009	2005 and 2009
Temporal resolution	Annual cycle	Annual cycle	Annual cycle	Annual cycle
Spatial resolution	1 km	1 km	500 m	300 m
Geometric accuracy	∼1 km	300 m	50–100 m	70 m
Accuracy	67 % weighted across all classes	69 % weighted across all classes	*(75 % cross validation accuracy)*	73 % weighted across all classes
Stability	Not specified	Not specified	Not specified	Not specified

3.1 Current land cover representation

The real world is infinitely complex and any interpretation of EO data involves processes such as abstraction, classification, aggregation and simplification. As land observation has no agreed fundamental unit, land cover mapping must be understood as a process of information extraction governed by rules which are grounded in individual or institutional objectives.

At the very beginning of the satellite observation era, the US Geological Survey (USGS) had established a standardized land use and land cover classification system based on 40 yr of mapping experience using aerial photographs (Anderson et al., 1976). With the increasing expectations of users and the ever-growing data availability, this kind of documentation effort is still going on all over the world (e.g. the land use oriented typology of the European CORINE classification, European Commission, 2001).

To ensure compatibility between typologies and provide common grounds for land assessment, the Africover program led by the FAO developed the LCCS as a conceptual tool for the legend definition. In the LCCS context, land cover refers to the "physical and biological cover over the surface of land, including water, vegetation, bare soil, and/or artificial structures" (Di Gregorio, 2005). The Integrated Global Observation for Land (IGOL) theme more recently reported the land cover definition as "the observed bio-physical cover on the Earth's surface" while recognizing the confusion between land cover and land use in current practices (Townshend et al., 2008). It must be admitted that these land cover definitions are somewhat incompatible with the basic requirement of temporal stability expressed by users. Indeed, land cover cannot remain stable over time if it is (i) defined as the biological cover on the Earth's surface (and thus affected by living processes such as growth, senescence, seasonality, etc.) and (ii) related to the observation process (i.e. sensitive to instantaneous conditions).

3.2 Current land cover mapping approach

Since the early nineties, several global land cover products have been delivered, all based on "single-year" and "single-sensor" approaches (Loveland et al., 2000; Bartholomé and Belward, 2005; Defourny et al., 2009a; Friedl et al., 2010; Bontemps et al., 2011). More recently, the accumulation of global long-term time series of EO data has allowed the delivery of several global maps derived from the same sensor. This is the case for the ESA GlobCover and MODIS products. This capacity to produce successive maps based on data acquired by a single sensor is certainly a major advance, but it also raises new issues.

In the suite of MODIS products, Friedl et al. (2010) reports significant year-to-year variations in land cover labels not associated with land cover change. Similarly, the comparison between the GlobCover 2005 and 2009 maps highlights discrepancies between products (Bontemps et al., 2011). Friedl et al. (2010) indicates a 10 to 30 % proportion of pixels which are associated with different labels from one year to another.

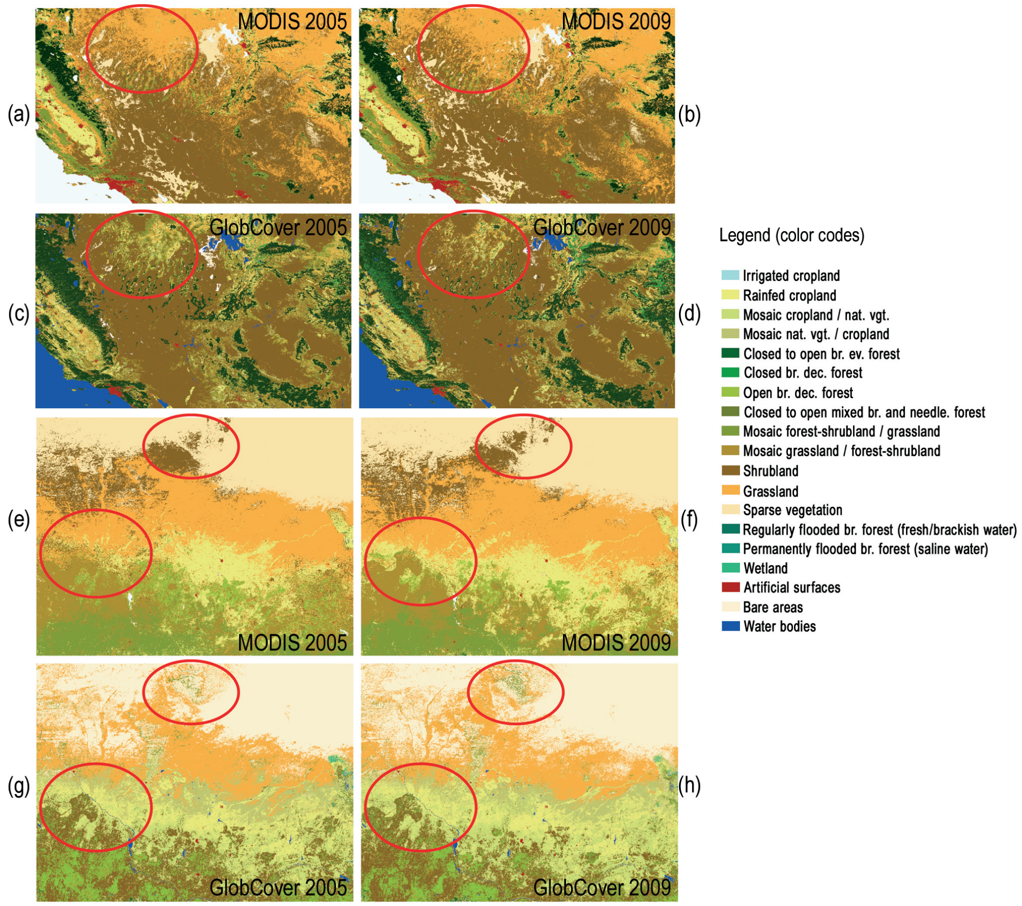

Fig. 3. Illustrations over United States (**a** to **d**) and Africa (**e** to **h**) showing the existence of spurious inter-annual variability between successive products.

For the GlobCover maps, year-to-year variations in labels concern around 25 % of the pixels. Illustrations of instabilities of the GlobCover and MODIS products are provided in Fig. 3.

These classification instabilities do not affect all land cover classes in the same way. With regard to the GlobCover products, mosaic classes (between cropland and natural vegetation, as well as between different natural vegetation types) and forest classes are the most affected ones. Furthermore, this issue is mostly observed between classes that are ecologically related. This is exemplified in Fig. 4, which focuses on the pixels classified as forest in the GlobCover 2005 product but associated with a different label in 2009. Most of the instability corresponds to variations in land cover labels between different forest classes.

This problem can be partly explained by the fact that many landscapes include mixtures of classes at 300- or 500-m spatial resolution and because the spectro-temporal signatures of some land cover classes are not easily separable in MERIS and MODIS data. Year-to-year variability in phenology and disturbances such as fire, drought and insect infestations also make a consistent annual characterization rather difficult.

4 CCI land cover observation approach

4.1 Multi-year classification strategy

Previous sections have strived to show that current land cover observation techniques are not able to efficiently extract the stable land cover component. Spurious year-to-year variability is observed in successive maps and needs to be reduced (Friedl et al., 2010). This phenomenon is investigated by generating a suite of annual global land cover products from 2000 to 2010, using the 1-km spatial resolution SPOT-Vegetation archive as input and the GlobCover classification chain as the mapping approach.

The GlobCover classification chain was designed to combine the spatial consistency of the class delineation obtained from well-selected multispectral composites with the discrimination power of temporal profile analysis. More precisely, the classification automatically delivers a global

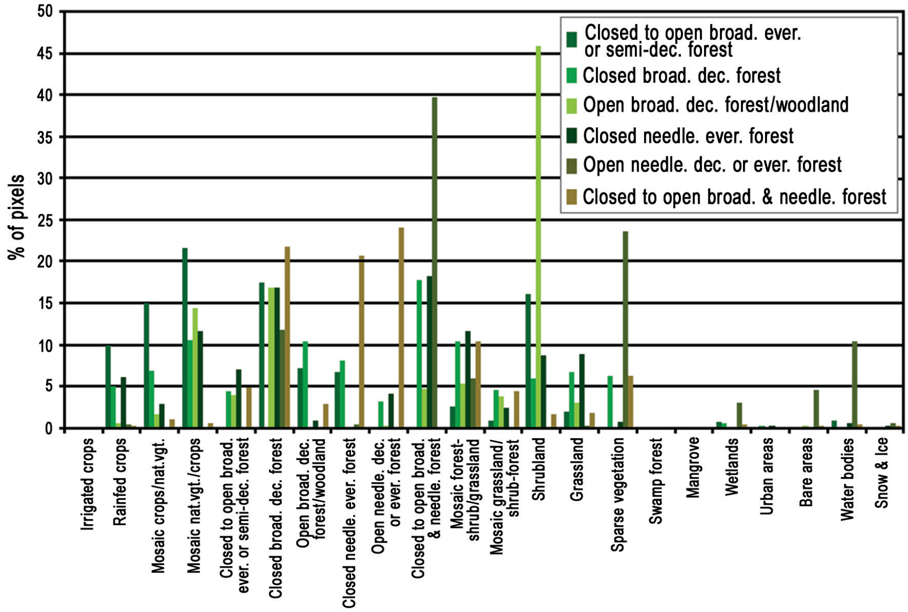

Fig. 4. Classification trajectories of the pixels belonging to a forest class in the GlobCover 2005 product, but which were not identically classified in the GlobCover 2009 map.

product depicting 22 land cover classes by interpreting a set of seasonal and annual composites into land cover classes through a spectro-temporal classification algorithm and an automated labeling procedure. Before that, an a priori stratification of the world allows equal-reasoning regions to be processed separately. The great but much controlled flexibility of this classification strategy allowed defining an automatic process tackling both the regional diversity and the local heterogeneity of land cover characteristics. This successfully dealt with the threefold challenge of data handling, production of globally consistent land cover maps and timeliness of the results (Arino et al., 2008; Defourny et al., 2009a), which justifies its use in this study.

As a result, eleven consecutive but slightly different land cover maps were produced at global scale. Figure 5 illustrates Africa results for the years 2000, 2005, 2009 and 2010.

In order to further analyze the issue of year-to-year variability between successive products, the pixel classification trajectories (i.e. the successive land cover classes associated with the pixel over the 11 yr) have been extracted. Stable and unstable pixels have been distinguished, based on the number of times a same label was observed (more than 5 or less than 6, respectively). Results are illustrated in Fig. 6. The random character of the variability in land cover labels, both for stable and unstable pixels, clearly prevents the user from interpreting this variability as land cover changes. It should also be noted that Fig. 6 (more precisely, the suite of land cover classes that constitute the classification trajectories) confirms the fact that inter-annual variability is mostly observed between classes that are thematically related (see Sect. 3.2 and Fig. 4).

Differences between successive products have been quantified by analyzing the succession over the 11 yr of the land cover labels, for the same pixel, in order to derive the maximum occurrence of a given label. Areas where no majority label could be derived have been considered as “unstable”. Those results are illustrated for Africa in Fig. 7.

An aggregated global land cover map corresponding to the epoch 2000–2010 has been built by summarizing the eleven consecutive land cover maps using a majority voting strategy. In this way, 41 % of the world is always consistently mapped throughout the years and about 60 % can be considered as quite stable allowing one or two discrepancies among the 11 successive global land cover products. In contrast, for 12 % of the land, no majority label can be derived. Those results are provided in Table 4.

According to Fig. 7, classification instabilities are located in areas known to be either heterogeneous and/or showing contrasted seasonal cycles. This confirms that the difference between successive annual products could be related to a certain incompatibility between the sensor resolution and the landscape complexity or to the inter-annual variability of the biome seasonality. In this second case, this would mean that current land cover mapping approaches are quite sensitive to the period of observation. Accordingly, the use of a multi-year EO dataset can contribute to reducing this sensitivity to the period of observation and then, to better extracting the stable land cover component. Advanced techniques should

Table 4. Percentages of the world indicating the occurrence of a same land cover label in the 11 yearly global land cover products obtained by the GlobCover processing chain from the SPOT-Vegetation archive (figures obtained without considering the water class).

Occurrence of a same land cover label	1	2	3	4	5	6	7	8	9	10	11
Global land proportion	0 %	0 %	1 %	4 %	7 %	10 %	9 %	9 %	8 %	10 %	41 %

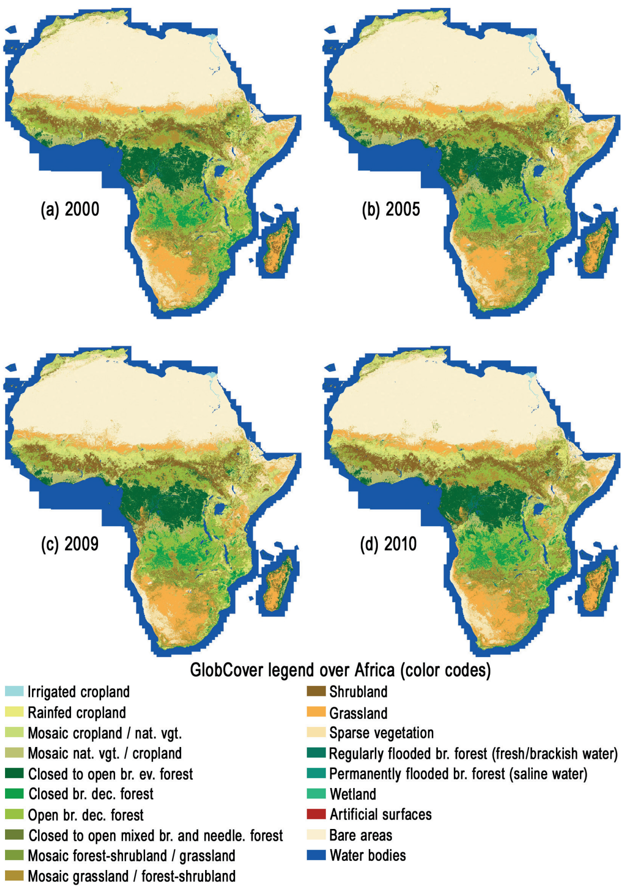

Fig. 5. Land cover products over Africa for the years 2000 **(a)**, 2005 **(b)**, 2009 **(c)** and 2010 **(d)**, obtained by running the GlobCover classification chain over the corresponding SPOT-Vegetation time series.

now be developed to refine the mapping strategy and take better advantage of these multi-year time series.

Despite this improvement in stability, land cover change detection is not expected through simple inter-comparisons of products. Such a strategy would only allow depiction of some land cover changes over certain hot-spot areas, but change detection would not be achieved in a systematic or consistent way. Indeed, the annual rate of any land cover change measured at global scale with moderate spatial resolution time series corresponds to a different order of magnitude (less than 10 %), even for the fastest land conversion processes like deforestation.

More generally, it should be noted that change detection requires specific processing methods based on the direct analysis of full time series, as proposed by Bontemps et al. (2008, 2012) and Verbesselt et al. (2010a, b). On one hand, these specific methods avoid error propagation, which particularly affects the post-classification comparison methods (Cardille and Folley, 2003). On the other hand, they account for both phenological variability and trends in the change detection. Change detection would also require a higher spatial resolution dataset (below 30 m). If moderate to coarse spatial resolution time series constitute a key dataset for global land cover mapping, they are of poor use for the precise changes delineation and quantification (Defries et al., 2002; Morton et al., 2005). Accordingly, land cover mapping and change detection correspond to two different ways of characterizing the land cover ECV (actions T26 (or T27) and T27 (or T28) in Table 1). The challenging aspect of the action T27 is explicitly recognized by the GCOS implementation plan due to the fact that its implementation assumes success in all other land cover observation domains. Addressing the action T26 – as it is done by the CCI land cover project – is therefore seen as a first essential step towards addressing the action T27. This is confirmed by climate users, who have also advocated for fine-scale satellite observations coming from action T27-type data (e.g. Sentinel-2) in the coming years for future modeling and assessment efforts.

4.2 An innovative land cover model

The issue of sensitivity of annual land cover products to the "instantaneous" conditions of observations call for the development of a new land cover observation concept. Section 4.1 has shown that the use of a multi-year EO dataset can help to improve global land cover products' stability. These stable but multi-year products have to then be reconciled with the need for resolving temporal variability associated with intra-annual dynamics of land cover also expressed by the users (see Sect. 2.2). To do so, a time dimension needs to be introduced in land cover characterization.

The stable component of the land cover definition would refer to the set of land elements that remain stable over time and thus define the land cover independently of any sources of temporary variability. Conversely, the dynamic component would be directly related to this temporary or natural variability that can induce some variation in land observation over time but without changing the land cover in its essence. Describing the stable component can easily build on recent

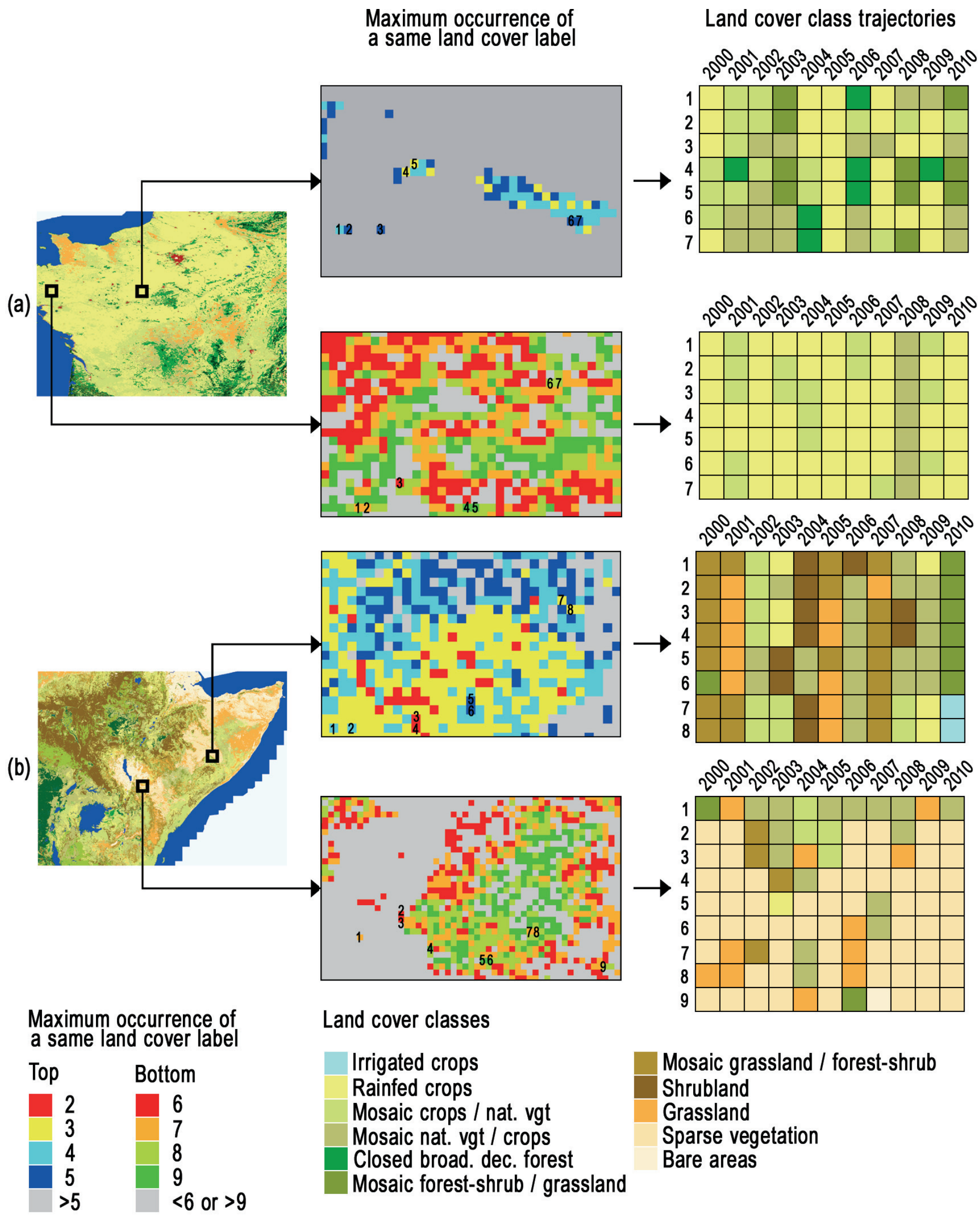

Fig. 6. Classification trajectories, over the 2000–2010 period, of pixels located in Europe **(a)** and Africa **(b)**. For both examples, trajectories of unstable and stable pixels are provided in top and bottom illustrations of **(a)** and **(b)**, respectively.

developments around the LCCS and rely on classifiers to depict the most permanent aspect of the landscape. The dynamic component encompasses the inter-annual processes – typically driven by biogeophysical processes – which temporally modify the land surface throughout the year. The inter-annual processes can be defined as an annual time series mode of "instantaneous observations" of the land cover.

4.3 Land cover project of the ESA-CCI program

Based on this new land cover model, the land cover project of the ESA-CCI program plans to deliver three global land cover databases for three epochs, centered around 2000, 2005 and 2010. These databases will be made of global multi-year land cover products associated with dynamic information about land cover.

Simultaneously, a specific effort will be needed for the validation of such databases. Indeed, the need to better quantify uncertainty in land cover mapping was also emphasized in the user assessment. Perturbed physics experiments are now commonly used in climate science to understand the effect of uncertainties in our knowledge of atmosphere/land/ocean interactions on the climate system. Uncertainties in land cover products could thus be incorporated into future assessments,

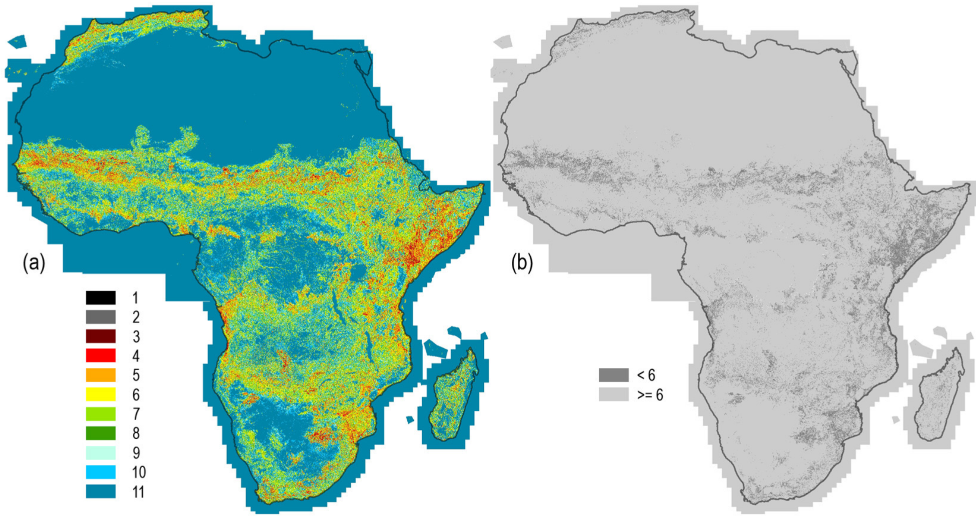

Fig. 7. Spatial representation of the maximum occurrence of a same land cover label over the 11 yr, over Africa. **(a)** illustrates the exhaustive distribution of maximum occurrence while **(b)** summarizes this information in a binary stable – unstable map.

allowing climate (and numerical weather prediction) scientists to understand the effects of uncertainty in the land cover on the climate system.

An independent validation will thus be implemented in order to quantify the accuracy and stability of the global land cover databases, to provide confidence in their quality, and ultimately, to contribute to their acceptance by the GCOS and the climate community. More precisely, the overall validation process will rely on 4 complementary pillars: (i) a confidence-building procedure, which consists in a systematic quality control of the products in order to eliminate macroscopic errors and increase the products' acceptance by users; (ii) a statistical accuracy assessment, which should allow a potential user to determine the "map's fitness for use" for his/her application; (iii) a comparison with other global land cover products; and (iv) a temporal consistency assessment. Finally, usability of the produced land cover data will be targeted through a phase of product assessment by the climate users themselves. Allowing users to test the generated land cover products will provide an evaluation and a set of recommendations to improve the global observation of land cover as an ECV.

5 Conclusions

Improving the systematic observation of land cover, as an ECV, should contribute to an improved understanding of the global climate system. Consultation mechanisms established with the climate modeling community have permitted identification of specific needs in terms of satellite-based global land cover products. This assessment has highlighted some requirements in terms of thematic content, spatial and temporal resolution, and accuracy that are not met by the existing global land cover products. It also identified a need for stable maps (which do not reflect temporary conditions), while the existing suite of global land cover maps are found to be contaminated by significant inter-annual variations due to phenology and disturbances rather than land cover changes. This paper examines this stability issue by calling into question a rather ambiguous land cover definition and by proposing a new mapping strategy.

First, the time dimension has been introduced into the land cover characterization in order to decouple the stable and dynamic components of land cover. This revisited land cover concept should contribute to addressing the critical requirements of stability between successive global products while integrating the dynamic dimension at the intra-annual and seasonal levels. It would also allow defining land cover in a more integrated way, as opposed to simple categories (e.g. forest or open water) or more continuous variable classifiers (e.g. fraction of tree canopy cover).

Second, an innovative land cover mapping approach, based on a multi-year EO dataset, has been proposed. Using multi-year time series as a source of data for classification has proved efficient in reducing the sensitivity of the mapping approach to the period of observation, and therefore produces more stable land cover products. However, further research is needed to optimize the integration of a multi-year time series into a single land cover product. At the same time, the use of multi-sensor EO data should also be investigated to increase the spatial, temporal and spectral resolution of the input data. Finally, higher spatial resolution imagery is also expected to bring significant improvements by reducing the amount of mixed pixels. To this end, major progress is expected to result from the Sentinel-2 mission.

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