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Revisiting land cover observations to address the needs of the climate modelling community

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Abstract

One of the relevant processes driven by political discussion under the United Framework Convention on Climate Change is the monitoring of Essential Climate Variables. Land Cover is one of those variables and efforts are therefore to be made to develop land cover observation approaches which meet the climate modelling community expectations. This paper aims at contributing to this necessity. First, consultation mechanisms were established with the climate modelling 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 and products accuracy, stability and consistency that are currently not met. Based on this outcome, the paper calls into question the current land cover representation and for revisiting global land cover mapping approaches. Increasing the flexibility of current classification systems and making the mapping techniques less sensitive to the period of observation are proposed as two key aspects to enhance the usability of global land cover dataset.

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). Information on the state and the dynamics of land cover is indeed essential for a wide range of scientific purposes, for sustainable management of natural resources, and to address climate change mitigation and adaptation (Sutherland et al., 2009). Appropriate land cover maps are increasingly required by a broad spectrum of scientific, economic and governmental applications as essential input to assess ecosystem status and biogeochemical cycling, understand spatial patterns of biodiversity, parameterize land surface for modelling (water, climate, carbon, etc.) and develop land management policy (Townshend et al., 2008). With the development of Earth Observation (EO) technology and the increasing availability of satellite data, remote

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sensing approaches have progressively become one of the most efficient approaches to map land cover characteristics over a variety of spatial scales and over time.

In many different regions of the world, the land cover has been mapped and characterized several times, for instance through the Corine Land Cover databases in Europe (EEA, 2009, 2010a, b), the Greater Mesoamerica land cover database (Giri and Jenkins, 2005) or the AfriCover maps (FAO, 2003). On the other hand, many countries have some kind of land monitoring systems in place, dedicated for instance to forest change (INPE, 2008) or to cartographic information systems and inventories (the Spanish Land Cover and Use Information System) (Arozarena et al., 2006). In addition, a number of global land cover mapping activities exist. These activities have evolved with the availability of global moderate spatial resolution satellite observations since the early 1990s. Meanwhile, the development of the Land Cover Classification System (LCCS) of the United Nations Food and Agriculture Organization (FAO) has emerged as the most commonly accepted standard for land cover characterization (Herold et al., 2009) by providing a basic level of thematic land cover characterization (Di Gregorio, 2005). These efforts have yielded several global land cover products in the 300-m–1-km spatial resolution range (Bartholomé and Belward, 2005; Defourny et al., 2009a). All available global products, generated using more or less standard classification techniques based on single-sensor dataset (Loveland et al., 2000; Bartholomé and Belward, 2005; Defourny et al., 2009a; Friedl et al., 2010) have all around 68–73 % overall area weighted accuracy (Herold et al., 2008; Defourny et al., 2009b). Despite such limitations, many applications that use land cover data as proxy for different land surface characteristics are based on these global land cover maps. Clearly, improving accuracy and usability of the land cover data is essential. Longer time series data from multiple satellite sensors should be used to derive land cover data and associated dynamics including a consistent historical data record and direct interactions between data users and producers should be ensured to derive novel products targeted at specific user communities.

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One of the relevant processes driven by political discussion under the United Framework Convention on Climate Change (UNFCCC) is the monitoring of Essential Climate Variables (ECV) (GCOS, 2010). In this context, the European Space Agency (ESA) has initiated a programme driven by ECV monitoring requirements – known for convenience as the Climate Change Initiative (CCI) – which aims to provide an adequate, comprehensive, and timely response to the need for long-term satellite-based products in the climate domain (ESA, 2009). The essential feature of the programme will be to implement a coherent and continuous suite of actions that encompasses all steps necessary for the generation of such long-term satellite-based products which can serve the climate modelling and climate user community. The ESA-CCI programme focuses on 11 ECVs, the land cover being one of them. Indeed, land cover and change is as a pressing environmental issue acting as both a cause and a consequence of climate change. Accurate land cover data are thus required by the climate science and climate modelling communities for adequate modelling of climate relevant atmospheric and terrestrial processes (Hibbard et al., 2010; Hagemann, 2002).

Assessing the climate modelling communities needs and investigating how the current land cover products are addressing them are objectives of this paper. First, it will present the results of consultation mechanisms with the climate modelling community built-up to derive more detailed characteristics and foundations to observe land cover as an ECV. Second, based on the outcomes of these users' consultations, it will document the temporal consistency of the current land cover observation and call for further development in land cover mapping.

2 Global land cover product requirements from climate modelling users

Three major climate modelling communities – the General Circulation Modelling, Earth System Modelling and Integrated Assessment Modelling communities – play an important role in the understanding and quantification of climate and Earth systems and specifically, in the understanding of the role of land use and land cover change in

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assessing impacts and vulnerabilities (Hibbard et al., 2010; Feddema et al., 2005). These three groups each have their specific modelling strategies. However, recent developments in the climate modelling communities have called for a much more integrated modelling and assessment framework, which fundamentally relies on information on land cover and land use (Hibbard et al., 2010). It can be argued that improvements in observing land cover and use can act as one of the most important catalysts to better integrate the efforts of the different communities.

Although there are significant overlaps in the systems modelled, there are also components that are unique to each modelling community. It results in different requirements for land cover data regarding spatial resolution, temporal detail, thematic representation and associated accuracies. As a result, land cover products would need to have a certain level of flexibility to serve climate modelling efforts for different scales and purposes.

2.1 User consultation

A user consultation mechanism was conducted to actively involve the climate modelling community. The overall objective of this consultation mechanism was twofold: (i) understand how land cover data is currently used by the climate modelling communities and what are the key land cover data characteristics of interest and (ii) what the future expectations for land cover data are for climate and Earth system modelling.

With this aim in view, specific surveys were set-up to distinctly focus on a restricted group of "key-users" that were partner in the Land Cover project of the ESA-CCI programme and on a broader group of "associated users" who are leading the development of relevant key climate models and applications. Key-users include the Max Planck Institute for Meteorology (MPI-M), the Met Office Hadley Center (MOHC) and the Laboratoire des Sciences du Climat et l'Environnement (LSCE). Regular and direct interactions with these users, thanks to their involvement in the project, have allowed in-depth analyses of the land cover data characteristics to be used in their models (spatial, temporal, thematic detail, accuracy requirements). Associated users have been targeted through a web-based user survey (85 groups invited to participate and 15 responses received (17.6 %)) and literature reviews carried out with special attention to innovative concepts and approaches to better reflect the evolution of requirements in the next generation of climate models. This broader assessment has ensured that the full range of needs was considered. This is illustrated in Fig. 1, which shows the variety of climate modelling applications covered by this survey.

A third survey was also addressed to the land cover data user community reflected in the scientific literature and represented by users of the ESA GlobCover product (Arino et al., 2008). Of the about 8000 registered GlobCover users, 372 replied to the user survey.

Next to the surveys, requirements from the Global Climate Observing System (GCOS) Implementation Plan 2004 (GCOS, 2004) and 2010 (GCOS, 2010) and associated strategic EO documents for land cover – Global Terrestrial Observing System (GTOS) (Herold et al., 2009), Integrated Global Observation of Land (IGOL) (Townshend et al., 2008), Integrated Global Carbon Observation (IGCO) (Ciais and Moore, 2004) and Climate Modelling User Group (CMUG) (http://www.cci-cmug.org/) – were considered and reviewed. Indeed, as a starting point of the land cover project of the ESA-CCI programme, activities have been closely aligned with specific land cover tasks listed in the GCOS Implementation Plans of 2004 and 2010 (GCOS, 2004, 2010 – Table 1).

2.2 Analysis of user requirements

The surveys were carried out in September and October 2010 and focused on three major ways land cover observations are used in climate models:

1. as proxy for a set of land surface parameters that are assigned based on Plant Functional Types (PFTs);

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2. as proxy for human activities in terms natural versus anthropogenic and tracking human activities, i.e. land use affecting land cover (land cover change as driver of climate change);

3. as datasets to validate model outcomes (i.e. time series) or to study feedback effects (land cover change as consequence of climate change).

The surveys first revealed that a dozen of different available datasets are currently used by the climate modelling communities, where the most frequently mentioned are the IGBP Discover and GLCC datasets as respectively provided by USGS and FAO statistics (Fig. 2). In spite of the availability of more detailed dataset like GLC2000, MODIS land cover and GlobCover, the very first available products remain the most popular ones even years after the delivery of the more recent ones.

On the other hand, the user consultation mechanisms resulted in a series of outcomes that are described in the detail in Herold et al. (2011). The findings highlight that:

- there is need for both stable land cover data and a dynamic component in form of time series and changes in land cover;

- consistency among the different model parameters is often more important than accuracy of individual datasets, and it is important to understand the relationship between land cover classifiers with the surface parameters and the relative importance of different land cover classes;

- providing information on natural versus anthropogenic vegetation (disturbed fraction), tracking human activities and defining history of disturbance is of increasing relevance; in particular, information about land use affecting land cover is needed with most details to focus areas with large anthropogenic effects;

- in terms of land cover change and dynamics, most important information is required for vegetation phenology, agricultural expansion, forest loss/deforestation

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and urbanization. In addition but of less relevance, the needs for monitoring wetland dynamics, fire, land degradation and long-term vegetation trends are highlighted;

– land cover products should provide flexibility to serve different scales and purposes both in terms of spatial and temporal resolution;

– climate models and applications often run on broad spatial levels and a resolution of 300 m or coarser is sufficient to meet requirements for most users. However, for some and in particular for future periods and regional modelling, there are requirements for more detailed resolutions;

– 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 implementing multi-date accuracy assessments for land cover data;

– future requirements for temporal resolution refer to intra-annual and monthly dynamics of land cover including also remote sensing time series signals;

– more than 90 % of the general land cover users find the LCCS a suitable approach for thematic characterization and this approach is also quite compatible with the plant functional type concept of many models;

– quality of land cover products needs to be transparent by using quality flags and controls, and includes information on the probability for the land cover class or 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 modellers 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.

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3 User requirements and current land cover products

The user consultations have highlighted some requirements in terms of thematic content, spatial and temporal resolution, stability and accuracy that are not met by the global land cover datasets currently used by the climate modelling communities (Table 3).

In addition, the user assessment has highlighted that land cover remains a key and fundamental dataset that serves as consistency base for many other land surface parameters and characteristics and associated temporal variability. For example, global EO-driven progress for specific land surface variables (including other ECV's such as Leaf Area Index or Fraction Absorbed Photosynthetically Active Radiation) are commonly also not used by this user community although they provide more spatial and temporal detail than current model parameterizations. In this case, consistency of the products in space and over time and among a series of land surface parameters is often valued higher than the accuracy of individual parameters. However, this aspect of consistency is even not addressed by the land EO domain.

Significant advancement could come from calling into question and revisiting the current mapping approaches and even the current understanding of the land cover itself.

3.1 Land cover representation issues

The real world is infinitely complex and any interpretation of EO data involves processes such as abstraction, classification, aggregation and simplification. For a long time, there has been some diversity of opinion about what the land cover is and how it is distinct from the land use. 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.

Most of the major land cover mapping initiatives created their own classification system and described it in great details. To ensure full interoperability between typologies

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and provide common grounds for land assessment, the Africover programme led by FAO developed the LCCS as a conceptual tool for the legend definition. Through a dichotomous modular-hierarchical system based on several sets of descriptors, namely the classifiers, this LCCS tool aims at explicitly clarifying each land cover class and therefore allows translating from one typology to another (Di Gregorio, 2005). This system is based on independent and universally valid land cover diagnostic criteria rather than on a pre-defined set of land cover classes. Its output is a comprehensive land cover characterization, regardless of mapping scale, land cover type, data collection method or geographic location (Di Gregorio, 2005).

However, the objective of land cover scheme standardization is challenged by Comber et al. (2008), which argue that land cover is by essence a socially-constructed concept and that data producers use a classification scheme that is appropriate for their own context and related to their specific socio-political and technical setting. In parallel, Ahlqvist (2008) proposed a set of modifications to improve the LCCS flexibility with unbounded classifiers and a richer class description. According to these authors, the LCCS imposes a view of land cover categorization which is strictly and precisely hierarchical and which thus often imposes crisp univariate distinctions.

Next to this debate around land cover typologies, the question of the spatial observation unit is another important issue. If the question of units or objects is self-evident in many scientific fields, it is somewhat not the case for land disciplines. Raster made of pixels and vector made of objects are the two main conceptual models designed to describe the spatial dimension of the world. The land is discretized in pixels by satellite imagery. When the pixel size is close or larger than the land cover features to map, land cover information is generally presented as pixels. For very high spatial resolution imagery providing pixels much smaller than the land cover features, the vector model is usually preferred and land cover objects are then delineated.

The meaning of an object is a complex problem since the description of a part of the Earth's surface pre-supposes that the area is clearly defined in space (Duhamel and Vidal, 1999). Although many objects are easily identifiable and have boundaries

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corresponding to physical discontinuities (e.g. plots of farmland or built-up areas), these boundaries become blurred typically in natural landscapes. In this case, the approach by continuous field is much more suitable to depict natural gradient over space. Along these lines, an interesting concept is the hybrid one of fiat and bona fide boundaries according to the properties of the geographic objects (Smith and Varzi, 2000; Smith and Mark, 2001). An advanced land cover representation model should obviously take the best out of these two worlds by using a pixel structure where pixel clusters would be handled as objects described by attributes but would still support continuous fields for objects showing some gradient.

3.2 Land cover mapping approach

Current land cover mapping systems (mainly based on "single-sensor" and "single-year" approaches) seem to be hardly able to meet the general expectations of the climate modelling communities and in particular, their need for products continuity and consistency in the long-term.

Thanks to the accumulation of global multi-year time series of EO data, recent initiatives (Friedl et al., 2010; Defourny et al., 2009a) have allowed delivering successive global land cover products derived from the same sensor. While representing a big step forward, these initiatives have also raised new issues since significant year-to-year variations in land cover labels, not associated with land cover change, were observed (Friedl et al., 2010; Bontemps et al., 2010).

This outcome has been deeper investigated by generating a suite of annual global land cover products from 2000 to 2010, using the 1-km spatial resolution SPOT-VEGETATION (SPOT-VGT) archive as input and the GlobCover classification chain as mapping approach (Fig. 3). The GlobCover processing system is based on different seasonal composites according to the region as described by Arino et al. (2008) and Defourny et al. (2009a). It automatically delivers a global product depicting 22 land cover classes fully documented according to the LCCS standard.

As a result, 11 consecutive but slightly different land cover maps were produced at global scale. Figure 4 illustrates Africa results for the years 2000, 2005, 2009 and 2010.

Differences between successive products have been quantified by analyzing the succession over the 11 yr of the land cover labels, for a same pixel, in order to derive the maximum occurrence of a same label. Those results, aggregated at the global scale are provided Table 4 and are illustrated for Africa in Fig. 5. 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. At the opposite, for 12 % of the land, no majority label can be derived.

As shown in Fig. 5, classification instabilities are located in areas known to be either heterogeneous (i.e. with fragmented landscapes) and/or showing contrasted seasonal cycles. The difference between successive annual products is more probably related to the inter-annual variability of the biome seasonality or to a certain incompatibility between the sensor resolution and the landscape complexity, rather than to the detection of any land cover changes. In any case, this issue of global land cover products stability over time clearly prevents to derive, from the direct comparison of such products, any land cover change information or consistent historical data record. Indeed, at global scale, the annual rate of any land cover change corresponds to a different magnitude order with less than one percent even for the fastest land conversion processes like deforestation.

3.3 Call for an innovative land cover model

Previous sections have strived to show that the inaccuracy and instability issues of current global land cover products could – to some extent – be explained by the sensitivity of the mapping approach to the observation period and by the attempt to classify the infinite variety of landscapes into a limited number of discrete classes. This conclusion calls for the development of a new land cover observation model, which would explicitly address these topics of land cover representation and observation. Indeed, it must be recognized that land cover cannot, at the same time, be defined as the physical and biological cover on the Earth's surface like in the LCCS approach (Herold et al., 2009; Di Gregorio, 2005) and remains stable and consistent over time as expected by most users.

The time dimension should be integrated in the land cover representation, in order to be able to distinguish between the stable and the dynamic components of the land cover. This would contribute to define the land cover in a more integrative way than just categories (e.g. forest or open water) or more continuous variables classifiers (e.g. fraction of tree canopy cover). In parallel, a maximum of flexibility in a classification system should be preserved by defining a minimum set of descriptive primitives that would act as building blocks. Land cover would then be classified, starting from a very simple group of descriptive primitives and assembling them in different ways to describe the more complex semantic in any separate application ontology (legends).

In this respect, it shall be noted that, building on the classifiers' experience, the LCCS team is aiming to develop a Land Cover Meta Language (LCML) which should be able to work as "boundary object" to mediate and support negotiations of different ways to represent land cover. This means that classes derived by this LCML could be customized to user requirements but should have common identities between users. Such a LCML approach should also allow extending similarity assessment and semantic distance expression as requested by Ahlqvist (2008). The challenge of such an approach is twofold: (i) to define appropriate descriptive primitives which provide a common ground to all users and thus guarantee a global standardization and in the same time, (ii) to limit the number of these blocks as much as possible to open possibilities to represent very distinctive land cover situations. Beyond the descriptive primitives, the object-based orientation of this new LCCS (version 3) should allow enriching this predefined set of land cover basic blocks on their semantic significance with external qualities and attributes.

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4 The CCI land cover observation concept

The overall objective of the ESA-CCI programme land cover project is to revisit approaches and algorithms required for the generation of global land products matching the needs of the climate change community. More specifically, global land cover databases for three epochs centred around 2000, 2005 and 2010 shall be delivered. An important objective will be to generate global land cover maps combining both stable and dynamic information about land cover. In order to ensure spatial and temporal harmonization, the legend will be built on the LCCS, which is compatible with the PFT concept used by many models.

It should be noted that, in spite the fact that the proposed global successive land cover products are expected to be more consistent than the previous global single-year products, any land cover change detection is not expected through simple inter-comparisons of products. Some land cover change will likely be depicted over certain hot-spot areas but change detection will not be achieved neither in a systematic, nor a consistent way. Mapping the land cover change requires specific processing methods such as proposed by Bontemps et al. (2008, 2011) and Verbesselt et al. (2010).

A specific effort will focus on the error characterization and the validation. Indeed, the need to improve quantification of uncertainty in land cover mapping has also been 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 could thus be incorporated into future assessments, allowing climate (and numerical weather prediction) scientists to understand the effect of uncertainty in the land cover on the climate system.

Therefore, an independent validation will be implemented in order to provide confidence in the products quality and ultimately, to contribute to their acceptance by the GCOS and the climate communities. More precisely, the overall validation process relies on 4 complementary pillars: (i) a confidence-building procedure, which consists in

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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. Unlike previous global land cover exercise, the Land Cover project of the ESA-CCI programme will deliver several products corresponding to different epochs (2000, 2005 and 2010). A one-shot effort for the thematic validation is therefore not appropriate and a longer-term data validation tool (allowing validating future land cover products but also historical ones) is designed. Finally, the usability of the produced land cover data will be targeted through a phase of products assessment by the climate users themselves. By allowing users testing the generated land cover products, this mechanism has the objective to provide evaluation and a set of recommendations to improve the global observation of land cover as an ECV.

5 Conclusion and perspective

Consultation mechanisms established with the climate modelling community have permitted to identify specific needs in terms of satellite-based global land cover products. Interestingly, this assessment has highlighted some requirements that cannot be met using the current global land cover approaches (e.g. the needs for a temporal representation of the land cover or for stability between products) or event that are not yet properly addressed (such as the needs for products consistency or transparent quality control with error characterization).

Indeed, current global land cover products are found to be sensitive to the content of the annual time series, which prevents from reaching a satisfactory level of accuracy, stability and consistency. Addressing this issue would ask calling into question a rather ambiguous land cover definition and developing new mapping approaches.

In addition, the use of a minimum set of "descriptive primitives" to describe the land cover would allow preserving a maximum of flexibility in the classification system. Land

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cover could then be classified, starting from a very simple group of landscape elements (the descriptive primitives) and assembling them in different ways to be suitable for different applications, thus increasing the usability of the products.

Finally, it was found remarkable that a quantitative and precise users requirements assessment targeting a specific community clearly highlights the current shortcomings of the commonly used land cover observation approach and calls for further development of such a popular concept.

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

GCOS Implementation Plan task (2004 and 2010)	Status reported in recent progress report (2009)	Issues addressed by the Land Cover project of the ESA-CCI programme
Action T22: international standards for land cover maps In the 2010 plan, T22 was removed	The 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 Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV), working with the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) (good progress).	The project is using a comprehensive validation approach that is independent, internationally agreed 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 while some methodological steps could be extended to higher spatial resolution dataset.

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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	$> 85\,\%$

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Table 3. Capabilities of four global land cover products currently used by the climate modelling communities.

	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	Yearly cycle	Yearly cycle	Yearly cycle	Yearly 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

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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-VGT 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 %

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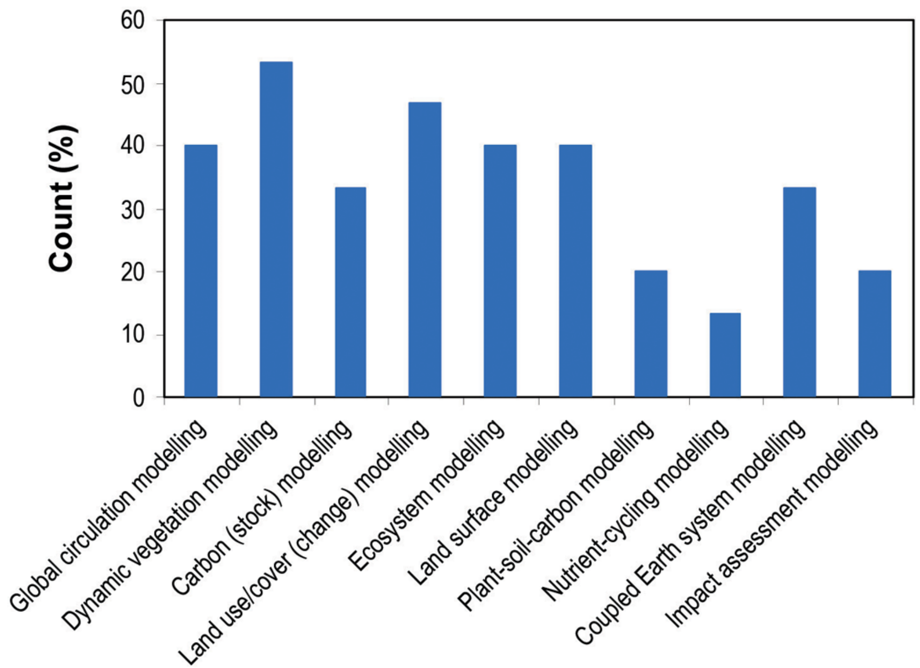

Fig. 1. Earth system or climate modelling focus of respondents to the user survey.

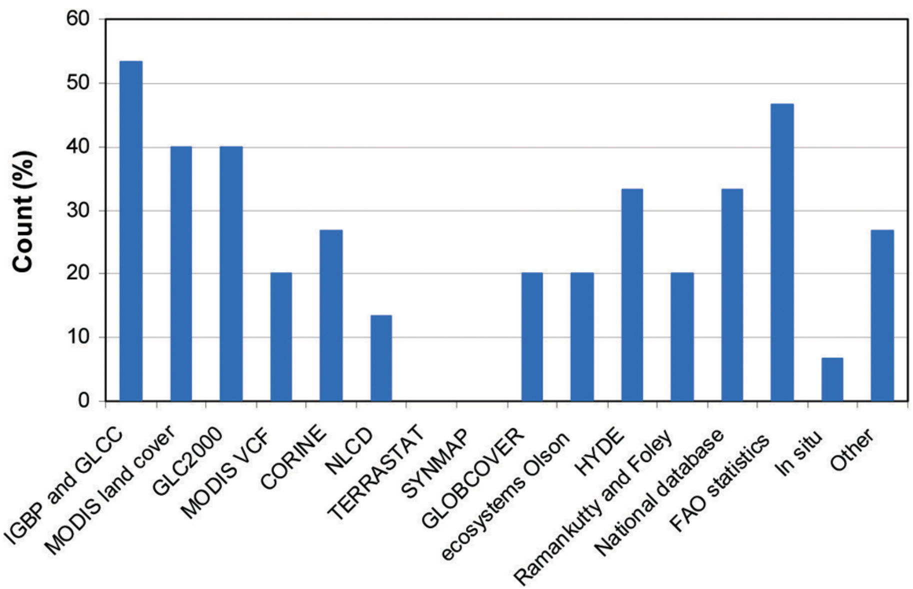

Fig. 2. Distribution of land cover dataset used in the different climate modelling applications covered by the user survey.

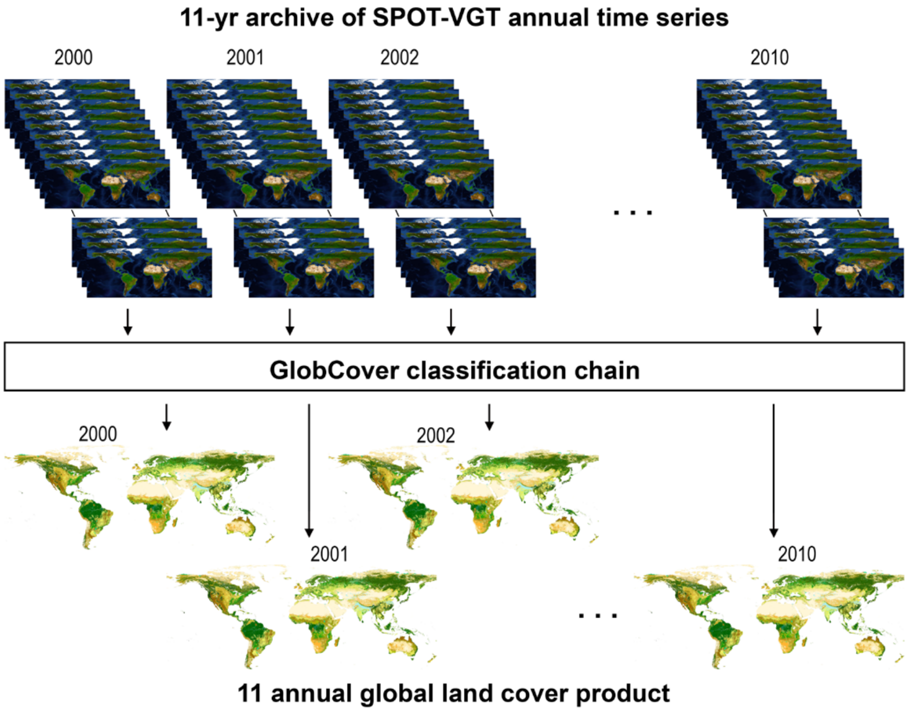

Fig. 3. Flowchart of the methodology developed to investigate the temporal stability of global annual land cover products, based on the 11-yr SPOT-VGT archive using the GlobCover classification chain.

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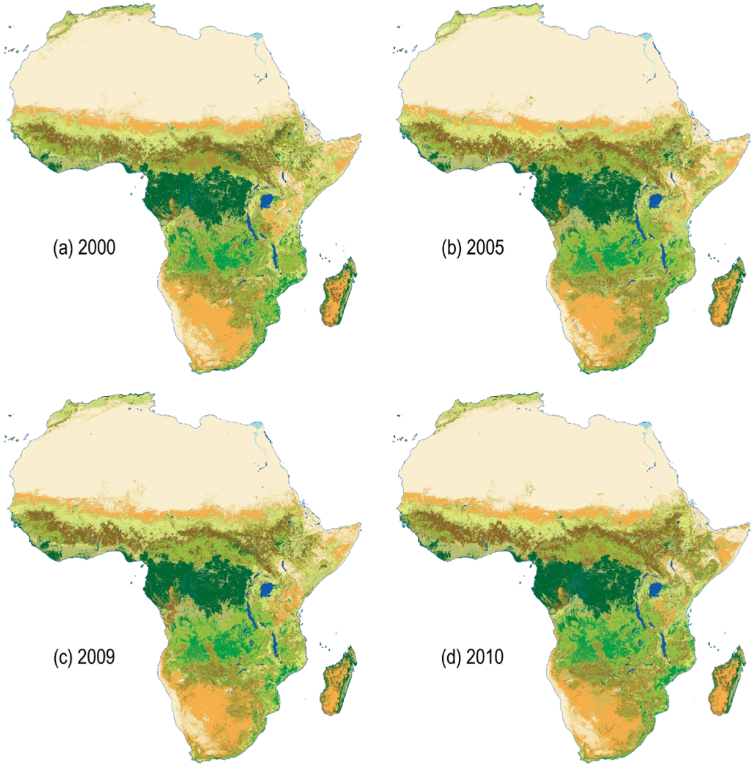

Fig. 4. Land cover products over Africa for the years 2000 **(a)**, 2005 **(b)**, 2009 **(c)** and 2010 **(d)**, obtained by running the GlobCover classification chain over the corresponding annual SPOT-VGT time series.

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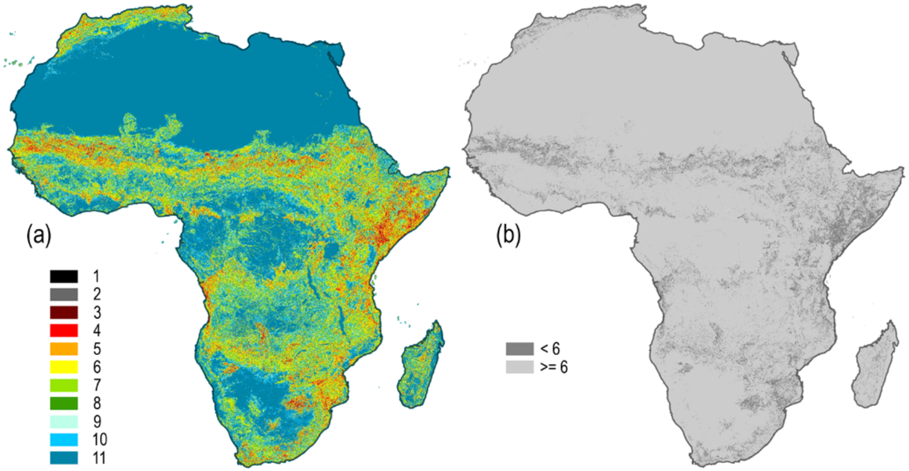

Fig. 5. Spatial representation of the maximum occurrence of a same land cover label over the 11 yr, over Africa. Left figure **(a)** illustrates the exhaustive distribution of maximum occurrence while right figure **(b)** summarizes this information in a binary majority – no majority map.

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