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Use of various remote sensing land cover products for PFT mapping over Siberia

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Abstract

High-latitude ecosystems play an important role in the global carbon cycle and in regulating the climate system and are presently undergoing rapid environmental change. Accurate land cover datasets are required to both document these changes as well as to provide land-surface information for benchmarking and initializing earth system models. Earth system models also require specific land cover classification systems based on plant functional types, rather than species or ecosystems, and so post-processing of existing land cover data is often required. This study compares over Siberia, multiple land cover datasets against one another and with auxiliary data to identify key uncertainties that contribute to variability in Plant Functional Type (PFT) classifications that would introduce errors in earth system modeling. Land cover classification systems from GLC 2000, GlobCover 2005 and 2009, and MODIS collections 5 and 5.1 are first aggregated to a common legend, and then compared to high-resolution land cover classification systems, continuous vegetation fields (MODIS-VCF) and satellite-derived tree heights (to discriminate against sparse, shrub, and forest vegetation). The GlobCover dataset, with a lower threshold for tree cover and taller tree heights and a better spatial resolution, tends to have better distributions of tree cover compared to high-resolution data. It has therefore been chosen to build new PFTs maps for the ORCHIDEE land surface model at 1 km scale. Compared to the original PFT dataset, the new PFT maps based on GlobCover 2005 and an updated cross-walking approach mainly differ in the characterization of forests and degree of tree cover. The partition of grasslands and bare soils now appears more realistic compared with ground-truth data. This new vegetation map provides a framework for further development of new PFTs in the ORCHIDEE model like shrubs, lichens and mosses, to better represent the water and carbon cycles in northern latitudes. Updated land cover datasets are critical for improving and maintaining the relevance of earth system models for assessing climate and human impacts on biogeochemistry and biophysics.

ESSDD
6, 255–296, 2013

The new PFT map at 5 km scale is available for download from the PANGAEA website, at: doi:10.1594/PANGAEA.810709.

1 Introduction

The Siberian region has been a focus of research attention in recent years because it is considered as a hot spot for climate change studies (see for example Lenton et al., 2008). The region is currently undergoing a warming trend with impacts already visible in the environment, its vegetation and soils (Lucht et al., 2002). Pronounced climatic warming in Siberia (Chapin et al., 2005) has had large implications on vegetation, changes which have been already confirmed by numerous studies at various scales. For example, Tape et al. (2006) demonstrated using aerial photography, an expansion of deciduous shrubs in tundra areas in northern Alaska during the last 50 yr. Satellite datasets and especially NDVI products have also documented landscape-scale greening signals and/or phenological changes, in relation with air temperature (see for example, Forbes et al., 2010; Huttich et al., 2007; Delbart et al., 2005, 2007; Myneni et al., 2001). However, the response of continental-scale vegetation shifts due to climate warming is not simple because different processes linked to snow, permafrost, soil moisture, albedo, and species competition (Chapin et al., 2005; Loranty and Goetz, 2012) interact and feedback, which lead to large uncertainties in predicting and attributing ecosystems and land-cover interact and feedback change dynamics.

One approach to better understand the role of interacting processes and how the various species compete for water, light, nutrients, is the use of ecosystem models. Ecosystem models are now able to represent the main high latitudes physical and biogeochemical processes and especially, permafrost and snow modeling and vegetation interactions, as well as vegetation dynamics, but these models require a correct representation of current land coverage as initial conditions or for benchmarking dynamic global vegetation models (Quaife et al., 2008).

ESSDD
6, 255–296, 2013

In Northern Eurasia, the main challenge for ecosystem modelers is to be able to differentiate short from high-statured vegetation, as well as deciduous from evergreen phenology. Even at this coarse thematic resolution, very different energy, water and carbon cycling processes are represented. For example, vegetation height is directly related to surface roughness and consequently affects turbulent fluxes; in addition, vegetation height can alter the effects of snow on ecosystem energy budgets with implications for surface albedo and related feedbacks. The deciduous character of shrubs or trees is also very important for the calculation of spring and autumn water and carbon fluxes and their seasonal variations.

Improved mapping of current land cover is a high priority for representation within earth system models, yet there are several challenges that need to be considered. Remote sensing instruments provide regular data at global scales, with increasing spatial resolution, and have been used for years to map land cover. Thus, a number of global products have been derived over the last 20 yr. They are used for a wide range of environmental studies and especially in climate models to characterize the land surface and its physical and biogeochemical properties and to determine the energy and matter transfers to the atmosphere. In such models, for simplification, to reduce the computer time, and to develop testable hypotheses, the various ecosystems are grouped in plant functional types (PFT), with a limited number of types, usually around 10 to 15. As an example, the ORCHIDEE Dynamic Global Vegetation Model (DGVM) (Krinner et al., 2005), part of the IPSL (Institut Pierre Simon Laplace) Earth system model (LMDZ, Hourdin et al., 2006; Dufresne et al., 2013), distinguishes 12 PFTs to represent the global land surface. Moreover, the reclassification in PFTs is done with constant, but qualitative rules defined across climate zones (Poulter et al., 2011), which can lead to significant uncertainty in the class fractions.

The current ORCHIDEE PFT map is based both on the IGBP 1 km global land cover map (Belward et al., 1999) reduced by a dominant-type method to 5 km spatial resolution, and on the Olson classification (96 types) (Olson et al., 1983). This spatial resolution is clearly not sufficient for future local-scale studies focused on the environmental

ESSDD
6, 255–296, 2013

impacts of global warming and land use in Siberia and for development perspectives in terms of biogeochemical processes parameterization. Therefore, our objective in this study is to develop a new map at 1 km resolution based on recent land cover products, suitable for earth system modeling which could be further refined if new PFTs are developed.

For that purpose, different remote sensing land cover products are available. They have been developed from multispectral and multitemporal imagery, in order to separate the various ecosystems presenting different spectral properties and seasonal variations. At medium resolution (hundred meters to kilometer), the most popular and most recent products are the GLC 2000 land cover database (Bartholomé and Belward, 2005) based on SPOT 4-VEGETATION instrument, the GlobCover land cover products (Arino et al., 2005, 2012) derived from Envisat/MERIS radiometer and the MODIS land cover datasets (Friedl et al., 2002, 2010), based on Terra and Aqua MODIS instruments.

These products have been compared in previous works and for some of them over Siberia. For example, Jung et al. (2006) developed the SYNMAP product dedicated to earth system modeling, based on the merging of GLC 2000 and MODIS 4.0 products. The final map, which separates 48 classes, is available at 30″ scale (~ 1 km). Frey and Smith (2007) inter-compared AVHRR and MODIS products at 1 km scale on West Siberia and highlighted the weaknesses of global LC products in northern wetland environments. Urban et al. (2010), focused on pan-arctic land cover mapping, and combine GlobCover, SYNMAP, MODIS LC and VCF and additional regional products like fire products, to create a new harmonized map separating 4 classes: trees, shrubs, herbaceous and barren areas. Sulla-Meneshe et al. (2011) developed the Northern Eurasia Land Cover (NELC) database from supervised classification of MODIS data which allows to separate 15 land cover classes including land use (urban, agriculture), wetlands and tundra classes. Meanwhile, Pflugmacher et al. (2011) cross-compared GLC 2000, GlobCover and MODIS products as well as Landsat-based reference maps on northern Eurasia. The map legends were converted to a common classification on the basis of

ESSDD
6, 255–296, 2013

dominant life form type (LFT). The results show regional disagreements among products and the difficulties to map shrubs and herbaceous vegetation types. More recently, Shepaschenko et al. (2011) produced a highly detailed land cover/land use dataset for Russia essentially based on GLC 2000 dataset at 1 km resolution combined with vegetation continuous fields (VCF) from MODIS, soil and vegetation databases and different inventories and statistics.

All these studies found significant differences between datasets and highlighted strengths and weaknesses of each product but none concluded on the superiority of one compared to the other. Moreover, since for most of these works, the final objective was not PFT mapping, and so the methodology developed for the cross-comparison and the final mapping could not be used directly for our study. Further, no comparison to date has included the MODIS 5.1 product, which benefits from a reprocessing of the complete MODIS archive, with an up-to-date training database, and an extension of the land cover data to 2011. Therefore, it was necessary to develop a new comparison of the most recent land cover products available on Siberia, to build dedicated aggregation rules for ORCHIDEE PFT mapping and to generate a new PFT map over Siberia at 1 km scale.

This paper presents the methodology used to compare medium-resolution remote sensing land cover products for Siberia. The evaluation was performed after aggregating the different land-cover datasets to the same spatial scale and under the same harmonized legend. A comparison of thematic differences was conducted to highlight areas of disagreement and we developed a methodology to generate the PFT distributions. Our results are presented in terms of product comparison and final PFT mapping, with uncertainties explicitly addressed.

2 Methods

We acquired recent land-cover satellite products available at medium spatial resolution (300 to 1000 m) and focused our comparison on Siberia. The datasets are presented

ESSDD
6, 255–296, 2013

C. Ottlé et al.

in Table 1 with their specifications in terms of spatial resolution, time of acquisition, geographic projection, and thematic information, including the classification legend and number of land-cover classes. They include the GLC 2000 product (Bartholomé and Belward, 2005) updated on Northern Eurasia by Bartalev et al. (2003), the GlobCover 2005 and 2009 products (Bicheron et al., 2006; Arino et al., 2005, 2012) and the MODIS Land Cover Type Collection 5.0 and 5.1 (Friedl et al., 2002, 2010). The first 4 products have been already compared and evaluated in various regions and at different scales, using ground truth measurements and have shown strengths and weaknesses (See and Fritz, 2006; Jung et al., 2006; Frey and Smith, 2007; Kaptué et al., 2010, 2011; Pflugmacher et al., 2011; Schepaschenko et al., 2011).

Our first goal was to identify the most suitable product for further PFT mapping. To achieve this, we assessed the land-cover classification methodology and land-cover class definition in terms of their capacity to represent the spatial heterogeneity and in terms of the spatial agreement between products. To assess these criteria, we compared various datasets at different temporal and spatial scales, including high-resolution optical images like Landsat-TM products.

2.1 Global land cover products

The GLC 2000 land cover map was developed for different parts of the world with regional experts before applying a generalized legend to create a global land-cover map. In this work, we used the regional product over Northern Eurasia developed by the European Commission's Joint Research Center and the Russian Academy of Science's Center for Forest Ecology and Productivity (Bartalev et al., 2003; Bartholomé and Belward, 2005). The land cover map was produced from daily observations provided by the SPOT4-VEGETATION instrument for the year 2000, at 1/112° ground sampling distance (GSD), corresponding to a ~1 km spatial resolution. The automated classification process allows separating 22 land cover types based on local expert opinion following the Land Cover Classification System (LCCS, Di Gregorio and Jensen, 1998) of the Food Agricultural Organization (FAO). The map is available from the JRC Land

ESSDD
6, 255–296, 2013

Resource Management Unit website (http://bioval.jrc.ec.europa.eu), in equal area projection (Plate Carrée) with map datum WGS84.

The GlobCover land cover products (GlobCover 2005 and GlobCover 2009) were developed within the framework of European Space Agency (ESA) projects (Bicheron et al., 2004; Arino et al., 2005, 2012). They are both based on Envisat/MERIS data acquired on years 2005 and 2009 respectively and available from the ESA GlobCover Project website (http://ionia1.esrin.esa.int). The maps are available in Plate Carrée (WGS84) projection with a 300 m spatial resolution (1/360° GSD), under the same class definition as GLC 2000, i.e. LCCS but with a larger number of classes (40) for the regional product available on eastern Eurasia in 2005, whereas GlobCover 2009 product is available only with a global legend which separates 22 classes, fully compatible with the GLC 2000 one. GlobCover uses a fully automated classification approach using GLC 2000 as training pixels.

Finally, the MODIS land cover products developed by the Boston University Department of Geography and Center for Remote Sensing (https://lpdaac.usgs.gov) are based on NASA MODIS instruments onboard AQUA and TERRA platforms. They are available at annual time step, from 2001 until 2007 for the C5.0 product (Friedl et al., 2002, 2010) with a spatial resolution of 500 m (1/240° GSD). The most recent product (C5.1) is available for the 2001–2010 period with the same spatial resolution of 500 m. The 2 products are available on an Integerized Sinusoidal Grid (ISG) projection, with a legend based on the IGBP classification system which separates 17 classes. The new product C5.1 is an update of C5.0 and an extension in time period. The same classification methodology was used but significant errors in the training dataset were adjusted as noted in the User Guide for the MODIS Land Cover Type Product, MCD12Q1 (which is available at http://www.bu.edu/lcsc/files/2012/08/MCD12Q1_user_guide.pdf).

2.2 Auxiliary datasets

Several auxiliary products representing different features of the land surface were used to assist in the evaluation of the global products (see Table 1). These products first

ESSDD
6, 255–296, 2013

helped us in the interpretation of the different legends and later assisted in the merging process, which permitted us to build the harmonized legend. Among them, two land cover maps based on aerial photointerpretation and ground truth data have been used to better understand the class significance and evaluate product accuracy and spatial variability representation. For these two products, the digital database was not available and only graphical maps have been used. The first one is the Circumpolar Arctic Vegetation Map (CAVM, Walker et al., 2005) which was developed within the National Science Foundation Arctic Transitions in the Land-Atmosphere System (ATLAS) project, and is presently the most precise mapping of the Arctic tundra. It is available at 1 : 7 500 000 scale at http://www.geobotany.uaf.edu/cavm, in Lambert azimuthal projection, and separates 18 classes describing very precisely the various tundra ecosystems. This dataset is based on photo-interpretation by vegetation experts of nine Arctic regions which allowed delineating the various biomes onto an NOAA-AVHRR image database.

The second one is the Yakutzk region land cover mapping provided by A. Fedorov (personal communication, 2013), which was derived from Landsat images acquired in 2002 combined with ground truth data. In this map, 12 land cover classes were separated including 6 different types of forest like larch and birch in different states and 3 types of grasslands (Alas, wet and dry valley meadows). These 2 maps have mostly been used in the following to evaluate the ability of the various land cover products to separate the shrubs/herbaceous classes and the broadleaf/needleleaf forests.

Lastly, the MODIS Global Vegetation Continuous Fields (VCF, Hansen et al., 2003, 2006) and the forest canopy height map proposed by Simard et al. (2011), complemented all these datasets. The VCF products derived from MODIS sensors, is provided at 500 m spatial resolution on an annual basis (2000–2010) and at global scales. The VCF is proportional estimates of vegetative cover types: woody vegetation, herbaceous vegetation, and bare ground. The Collection 4 (version 3) was downloaded at http://glcf.umiacs.umd.edu/data/vcf, where it is available in the same projection as the land cover product. Finally, the forest height product based on 2005 data from the

ESSDD
6, 255–296, 2013

Geoscience Laser Altimeter System (GLAS) onboard ICEsat (Ice Cloud and Land Elevation satellite), is available globally at 1km spatial resolution and provides an estimation of the canopy height. These two last products provided an independent mapping of the forested areas and were mostly used in the PFT maps generation. The data were obtained through the website http://lidarradar.jpl.nasa.gov in GeoTiff format.

2.3 Harmonized legend approach

Because these land cover products did not have the same spatial resolution and more importantly, did not use the same classification system, a harmonization procedure was developed. As already discussed by all the works dedicated to land cover map cross comparison (to cite but a few: See and Fritz, 2006; Frey and Smith, 2007; Urban et al., 2010; Sulla-Menashe et al., 2011; Pflugmacher et al., 2011; Kaptué et al., 2011), the classification method, the original data, the number of thematic classes chosen etc. can highly bias the classification results and the overall regional biogeographic characteristics.

For example, GLC 2000 and GlobCover legends give more weight to the dominant tree species than to the density character, compared to MODIS. This is probably the result of the classification methodology applied for the MODIS product, which is based on the combined use of surface reflectance and land-surface temperature (LST), contrary to the other products, which use only surface reflectance. The addition of LST, which is known to be highly sensible on vegetation fraction, could have increased the weight of the tree coverage in the class separation. Therefore, the LCCS legend used for GLC 2000 and GlobCover defines forest as greater than 15 % tree cover with trees defined as woody plants larger than 5 m, whereas IGBP used in the MODIS product, defines forest as greater than 60 % tree cover with trees defined as woody plants larger than 2 m. Two other IGBP classes of 8 and 9 (woody savannas/savannas) are then used to represent more open canopies with the same height thresholds but different cover thresholds down to 10 %. In the same way, for shrublands, LCCS distinguishes between evergreen and deciduous species, whereas IGBP considers open and closed

ESSDD
6, 255–296, 2013

types. Further, for barren lands, IGBP merges bare and sparsely vegetated soils, when LCCS separates sparse herbaceous, sparse shrubs and bare areas. Given all these features, a comparison work could not be performed before having converted all the study products in a common legend. For our final purpose of water and carbon cycle modeling, this common classification requires first, to be based on PFT features and secondly, to discriminate trees, shrubs, water and barren but also leaf type and senescence. This choice leads us to merge the IGBP and LCCS classes under the 16 classes listed in Table 3, which are in close agreement with the GlobCover 2009 legend. The merging rules and the allocation of the ambiguous classes have been driven by the comparison of the spatial distribution of the land cover classes and the help of the auxiliary products, especially the high resolution maps.

Afterwards, in order to allow the comparison, all the data have been reprojected to 1km scale, using a majority class criterion, on the same equal area (Plate Carrée projection), since GLC 2000 and GlobCover are already available in this projection.

3 Results

The various products have been compared over Siberia, with a focus on central and south-west Siberia (over Yakutia and around Omsk respectively, where high resolution data were available). The coordinates of these 2 domains are 55–75° N/104–163° E and 50–58° N/56–96.5° E, respectively. These 2 regions were chosen because they cover almost all the variety of Siberian ecosystems. The first region, Yakutia (Sakha Federal Republic of Russia, capital Yakutzk) covers a large area of about 3M square kilometer, with 40 % above the Arctic Circle. This region is one of the coldest continental regions in the world (outside Antarctica) with large annual temperature amplitude varying between −60 to +40 °C. It is all covered by permafrost and mainly drained by the Lena River and its tributaries. The vegetation is driven by these extreme climate conditions, which limits the extent of Arctic tundra, composed of lichens and mosses in the north, and the taiga forest mostly composed of deciduous trees (especially larch) in the south. The other region studied is situated in the south-west part of Siberia. It represents an area of about 2M square kilometer and is part of the Irtysh river catchment. The vegetation is mostly composed of croplands (wheat, barley, potatoes...) and deciduous forests with the predominant species being larch in the north taiga and birch and aspen in the south.

3.1 Comparison on central Siberia

Figure 1 presents the land cover maps extracted from the 5 global products (GLC 2000, GlobCover 2005 and 2009, MODIS 5.0 and 5.1) at 1 km scale under the harmonized legend discussed previously. The 5 products were compared considering their respective representative time period. Thus, GlobCover 2005 was compared with MODIS 2005 dataset, GlobCover 2009 with MODIS 2009 product and GLC 2000 with MODIS 2001.

The maps clearly show the latitudinal distribution of tree cover, with forested areas between the mountains of Verkhoyansk and Chersky on the East side and Stanovoi in the South, sparse vegetation in the northern latitudes and bare soils in the mountainous areas. In this large region, the main land cover classes are deciduous needleleaf forest (mostly larch) covering the middle latitudes, and shrubs often mixed with forests and sparse vegetation. Although present in the 5 products, the fraction and spatial distribution of forest differ significantly among them. Table 4 presents the fraction of each land cover class for each study product. The fractions were calculated excluding the water pixels in order to avoid the Arctic Ocean pixels which could have biased the statistics. In the table, values greater than 10 % have been highlighted (i.e., excluding vegetation types not well-represented in this region).

The main features are a larger representation of the sparse vegetation class in MODIS (50 % and 64 % for 5.0 and 5.1 products, respectively) compared to 8 and 21 % in GLC 2000 and GlobCover 2009, to the detriment of deciduous needleleaf forest (28 % in MODIS 5.1 compared to 58 % in GlobCover 2009). This disagreement was already pointed out by Frey and Smith (2007) when they compared MODIS product to

ESSDD
6, 255–296, 2013

land cover field-based observations. It can be noted also that the shrub class is represented in the north of the region only in the GLC 2000 product and that regularly flooded areas are more represented in GlobCover and MODIS products compared to GLC 2000, especially in the Lena river delta. The spatial agreements are quantified in Table 5 for the main classes present in this region (i.e., deciduous needleleaf, mixed forests, shrubs, sparse vegetation, herbaceous and bare soils). The statistics were calculated by comparing each product to the GlobCover 2005 one (values above 0.5 are shaded in the table). As previously, the total agreement percentages do not account for water pixels which could have biased the accuracy assessment. The results confirm the spatial comparisons: the best agreements are obtained for the 2 GlobCover products as expected, even though some classes like shrubs, mixed forests or herbaceous present some discrepancies. The comparison with GLC 2000 shows that the lower scores are obtained for the same ambiguous classes which probably present a larger heterogeneity and could suffer from the lower spatial resolution. The evaluation with MODIS maps displays worse statistics especially for shrubs, mixed forests and herbaceous and the total agreement values are all lower than 0.5 except when two products of the same family are compared. The comparison with the CAVM product (Walker et al., 2005) strengthens these conclusions, showing that the different types of tundra are better separated in the GLC 2000 and GlobCover 2005 products than in the other ones.

3.2 Comparison at finer scale on Yakutzk surroundings

In order to check the accuracy of the various products and the impact of the increased resolution of 300 m on the spatial representation of the land variability, we focused our comparisons around Yakutzk region taking advantage of a high resolution map provided by A. Fedorov's team (personal communication, 2013). The comparison presented in Fig. 2, indicates clearly that the GLC 2000 and GlobCover products offer a better description of the spatial variability of the land cover with a more precise separation of the evergreen needleleaf areas inside the broadleaf deciduous forests, on

ESSDD
6, 255–296, 2013

both sides of the Lena River. But the lower spatial resolution of GLC 2000 does not allow representing correctly the river bed and the flooded areas. As a conclusion, in that region, it seems that GlobCover 2005 better captures the main features of the land coverage.

3.3 Comparison in south-west Siberia

The second region where we focused our cross comparison is the south-west part of Siberia where we are interested in analyzing the evolution of agriculture in future works. This region is mostly covered by croplands, deciduous broadleaf and needleleaf forests, herbaceous and sparse vegetation. The grid cell fractions range between 0.3 and 0.43 for croplands, and are generally lower than 0.2 for the other cover types (Table 6).

The main difference among the LC products stems in the representation of the southern part of the region, covered by sparse vegetation and herbaceous in GlobCover and GLC 2000 maps, and by regularly flooded lands in MODIS. This area at the limit of Kazakhstan is drained by the Irtysh River and presents irrigated croplands which could be identified wrongly as flooded areas. The main cropland area in purple in Fig. 3 is well delimited between the forested areas in the north and the sparse vegetated lands southern. We also noted differences in the eastern part of the region which is classified as croplands by MODIS and as sparse vegetation in the other products. This disagreement was analysed more deeply, by looking at this region with Landsat images. The views show undoubtedly that this region is covered by agricultural fields presenting an unambiguous spatial structure. The classification discrepancies between crop and sparse vegetation highlight the difficulties in separating such ecosystems if only one year of data is used and if a pixel based classification technic is used. An object-based classification methodology should have been more performing in that case. Anyway, MODIS classification appears here, more accurate for crop mapping.

The spatial agreement statistics are presented for the main land cover classes in Table 7. The classes which appear in best agreement are the crops and the mixed forest

ESSDD
6, 255–296, 2013

(except for GLC 2000) with values larger than 0.5. The lowest values are obtained for sparse vegetation which can be mixed with crops or herbaceous ecosystems. Moreover, the deciduous needleleaf and broadleaf forests appear to be better separated in the GlobCover products compared to MODIS and GLC 2000, where all the forested areas are grouped in the mixed forest class. Finally, the overall agreement percentages are very low, with values never exceeding 0.4 like what has been previously shown on Yakutia (except when products of the same family are compared naturally).

3.4 Forest mapping accuracy

Our motivation being the development of PFT maps for land surface modeling, the characterization of biomes and the separation of forested areas from shrublands are particularly important. Indeed, the vertical structure of forests implies different ground shading, aerodynamic and roughness properties, and consequently significant impacts on surface fluxes. Therefore, a product of forest canopy height like the one proposed by Simard et al. (2011), appears interesting for the interpretation of the land cover products legend as well as for their accuracy assessment. This recent product, based on LIDAR measurements, provides at a global scale, the estimation of canopy height at 1 km resolution with an error evaluated against ground truth data, less than 6 m. For the comparison with land cover products, the forest classes were grouped together. Since the LIDAR product is based on 2005 data, and since the two GlobCover products are very similar, only GlobCover 2005 map was included in the comparison. Figure 4 presents the comparison of the current forest height product with GLC 2000, GlobCover 2005 and the two MODIS products extracted for the year 2005. Qualitatively, the extension of forested areas appears better represented in GlobCover 2005 if a threshold of 10m height is imposed to delineate trees and shrubs. The agreement with the forest class was calculated for the 4 land cover products (MODIS5.0, MODIS5.1, GLC 2000 and GlobCover 2005). The spatial agreements obtained (43.5 %, 37.4 %, 57.9 % and 76.1 %) for the 4 products respectively, show clearly that GlobCover 2005 better

ESSDD
6, 255–296, 2013

captures the degree of woodiness at the land surface, which is an essential parameter for vegetation characterization in carbon and water cycle modeling.

3.5 Discussion

The results of the cross comparison of the 5 land cover products studied, on two different regions of Siberia, show differences and similarities which can be explained either by the lack of resolution (for GLC 2000) or by the methodologies used to assess the class separation and interpretation. The agreement among the maps is highest in the zones which present more homogenous landscapes (for example inside the taiga region) and lower in the transition zones or in sparse ecosystems for which the class definition is determinant. The contribution of higher resolution products is therefore a significant improvement for discriminating vegetation types and for better mapping such regions. For our modeling purposes, since the most important is to identify the type of ecosystem whatever its density (which will be anyway, provided by the LAI variable used as forcing or prognostically computed by the big-leaf type DGVM), the definition provided by GlobCover or GLC appears more valuable. Furthermore, this class definition allows delineating forested areas more precisely, as was demonstrated in the comparison with the recent forest height product. In addition, GlobCover 2005 provides a more precise legend (compared to GlobCover 2009) and an increased spatial resolution (compared to GLC 2000).

For all these reasons, the GlobCover 2005 product was chosen as a basis for the PFT mapping, keeping in mind its class definition, especially the forest classes which can include pixels with spatial coverage as low as 15 %. This definition more suitable for land cover type identification will require the merging with other indices to account for vegetation density. Otherwise, it could lead to a likely over representation of forests in transition zones with tundra in the northern latitudes and with herbaceous cover types in the south.

4 PFT mapping

Given the GlobCover 2005 land cover map, our next challenge is to define merging rules to build a PFT map for the ORCHIDEE dynamic global vegetation model (DGVM). For that purpose, we have followed the approach of Poulter et al. (2011) and associated to each GlobCover 2005 land cover class, the corresponding classification in the ORCHIDEE DGVM. In this work, we focused only on the PFTs present in Siberia. Given the previous studies and drawbacks highlighted in the GlobCover 2005 product, the reclassification rules proposed by Poulter et al. (2011), have been slightly modified and adjusted to boreal ecosystems.

4.1 ORCHIDEE model

ORCHIDEE land surface model is a mechanistic dynamic global vegetation model (Krinner et al., 2005), that is part of the IPSL Earth system model (Friedlingstein et al., 2006). It calculates the energy, momentum and hydrological budget of vegetation and soil and all the carbon and nitrogen cycle in the different soil and vegetation pools. Photosynthesis, phenology, allocation of carbon and nitrogen into the different organs, plant growth and mortality, and decomposition of litter and soil organic matter, are derived from primitive equations that depend on vegetation characteristics. ORCHIDEE is built on the concept of plant functional types (PFT) to describe vegetation distributions. Species with similar characteristics are re-grouped together and the model distinguishes 12 PFTs (tropical evergreen and deciduous forests, temperate broadleaf evergreen and deciduous forests, temperate needleleaf forest, boreal needleleaf evergreen and deciduous forests, boreal broadleaf deciduous forest, natural C3 and C4 grassland, and C3 and C4 crops) plus bare soil. In its standard version, the PFTs are defined from two databases, the AVHRR IGBP 1 km global land cover map (Belward et al., 1999) and Olson et al. (1983) biome classification including 96 land types (Vérant et al., 2004). The final map prescribes the fraction of each vegetation type over a resolution cell of 5 km. Therefore, different PFTs can coexist in every grid element, and

ESSDD
6, 255–296, 2013

their fraction can vary when the dynamic vegetation sub-module is activated. Figure 5 presents the standard PFT maps used in ORCHIDEE.

In Siberia, 9 PFTs are present in the standard land cover map. They include four types of forests (temperate and boreal needleleaf evergreen, needleleaf summergreen, broadleaf summergreen forests), C3 grass, C3 crops, unlikely (but very few) C4 crops and bare soils.

4.2 ORCHIDEE PFTs

Table 8 presents the merging rules that have been defined to reclassify the GlobCover 2005 classes present in Siberia, into the ORCHIDEE PFTs. The fractional distributions are based on Poulter et al. (2011) work, but have been adjusted to our model. For example, because of the absence of the boreal broadleaf evergreen class in the ORCHIDEE PFT classification, this class has been equally distributed between the broadleaf summergreen and the needleleaf evergreen PFT classes. For the same reasons, the lichens were merged with C3 grasses and the shrublands were spread among the C3 grass, the forests and bare soil classes. Further, the percentages of forests, bare soils and grasslands (only C3 in boreal zones), were adjusted with the support of the MODIS VCF products. These data, indeed, permit to assess the land surface heterogeneity and the amount of vegetation inside the pixels. Therefore, the VCF data for the year 2005 have been upscaled at 1 km scale and the fractions of trees, grasslands and bare soil have been extracted and averaged for each Globcover 2005 class. The PFT reclassification was then performed according to these new merging rules.

The new PFT maps have been generated from the GlobCover 2005 dataset, keeping the benefit of the high resolution of 300 m. The data were aggregated at 1 km scale in PFT fractions and the results are presented in Fig. 6. The results show the main features characterizing Siberia, i.e., the predominance of needleleaf summergreen forests in the center, broadleaf summergreen and then croplands southern, grasslands and larger fractions of bare soil in the northern latitudes. Compared to the previous maps (see Fig. 7 for the differences mapping), the temperate broadleaf PFTs and sparse C4

ESSDD
6, 255–296, 2013

crops have disappeared, and generally, the fractions are less contrasted. The amount of bare soil and grasslands is larger (up to 15 %) in central Siberia, better representing the sparse feature of Siberian forests, and the broadleaf summergreen forests abundance decreased in the northern part of the region, which seems to be more realistic. The boreal needleleaf summergreen forest covers now a larger area north and south of the previous limited location, where the abundance decreased from 100 to 60 %. The water surfaces are also more and better represented.

The agreement between the original Olson-based PFT map and the new GlobCover-based PFT map was quantified with the commonly used Euclidian distance between the PFT classes (Legendre et al., 2005; Poulter et al., 2011), calculated for each 1 km pixel. Equation (1) presents the expression of the dissimilarity index for a grid cell c, calculated between the 2 classifications (New and Standard) composed of 14 classes (12 PFT (including bare soils) + water and ice classes) and their corresponding fractional abundance P in the 2 classifications.

$$D_c = \left[\sum_{i=1}^{14} (P_{\mathrm{new}\,i,c} - P_{\mathrm{stan}\,i,c})^2 \right]^{0.5} \quad (1)$$

This index, which is 0 for full agreement and $\sqrt{2}$ for full disagreement is displayed in Fig. 8. The agreement is best in the northern latitudes and worse in the center of Siberia where the fractions of grasslands and forested PFTs have been the more modified.

5 Discussion and conclusion

Land cover mapping is crucial for many environmental studies and the re-gathering in PFT classes is necessary for the specific purposes of land surface modeling. In this study focused on Siberia, we compared five medium resolution land cover maps derived from remote sensing and highlighted some discrepancies mostly linked to the legend definition adopted. The strengths and weaknesses of each product were shown

ESSDD
6, 255–296, 2013

and the results led us to choose the GlobCover 2005 product because of its highest spatial resolution and more detailed legend. Therefore, a new PFT map at 1 km scale over Siberia has been generated for the ORCHIDEE DGVM. This map shows large differences compared to the standard maps in the differentiation of broadleaf and needleleaf forests and in the representation of the landscape heterogeneity. The fractions of the various ecosystems are smoothed and seem to better represent the vegetation diversity, thanks to the use of higher resolution datasets for the PFTs mapping.

These differences should significantly impact the DGVM simulations. Indeed, PFTs fractions are used to define the vegetation characteristics in terms of photosynthesis capacity, phenology, roughness, etc. All these properties are determinant for the calculation of the water and carbon fluxes, especially the evapotranspiration and the GPP fluxes. Consequently, such modifications should impact the biosphere-atmosphere exchanges and will be analyzed in further works.

This study also showed the difficulties to link vegetation classes to a limited number of PFT, constrained by global modeling and time computing issues. The absence of a shrub PFT and the solution to distribute the shrubs classes among grasslands, bare soils and forests is not satisfactory. Such vegetation types have so different properties that it appears difficult to well represent the energy and mass transfers with an aggregation of such variability. In the same way, mosses and lichen-dominant ecosystems are not represented in the final PFT map and are assimilated to bare soils, the same for regularly flooded areas and peatlands that have been spread between the grasslands and water classes, which in terms of carbon cycle could lead to significant errors. Therefore, the development of new PFT classes in ORCHIDEE, to better represent these specific northern ecosystems appear to be a priority if one wants to correctly represent boreal ecosystems and their future evolution.

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ESSDD

6, 255–296, 2013

Use of various remote sensing land cover products

C. Ottlé et al.

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ESSDD
6, 255–296, 2013

Use of various remote sensing land cover products

C. Ottlé et al.

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ESSDD
6, 255–296, 2013

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ESSDD

6, 255–296, 2013

Use of various remote sensing land cover products

C. Ottlé et al.

Table 1. List of the Land Cover products used and their characteristics.

Products	Satellite and sensor	Time period	Spatial resolution	Projection	Cover zone	Number of classes
Circumpolar Arctic Vegetation Map	NOAA (AVHRR)	1993–1995	1 : 7.5 M	Lambert Azimuthal	Circumpolar Artic zone	18
GLC2000 (v1.1)	SPOT-4 (VGT)	2000	1000 m	Plate-Carrée WGS84	Global map	22
MODIS MCD12Q1 (v5.0)	Terra Aqua (MODIS)	2001–2007	500 m	Sinusoidal	Global map	17
MODIS MCD12Q1 (v5.1)	Terra Aqua (MODIS)	2001–2010	500 m	Sinusoidal	Global map	17
MODIS VCF (V4)	Terra (MODIS)	2000–2010	500 m	Sinusoidal	Global map	3
GlobCover Eastern Eurasia (v2.2) 2005	Envisat (Meris)	2004–2006	300 m WGS84	Plate-Carrée (Eastrern Eurasia zone)	Regional map	40
GlobCover (v2.2) 2009	Envisat (Meris)	2009	300 m WGS84	Plate-Carrée	Global map	22

ESSDD
6, 255–296, 2013

Table 2. Aligning legends of global maps: dominant life form type (LFT) and corresponding land cover classes from GLC 2000, GlobCover and MODIS.

Dominant LFT	GLC2000	GlobCover 2005	GlobCover 2009	MODIS
Tree	[1] Tree Cover, broadleaved, evergreen	[40] Closed to open broadleaved evergreen or semi-deciduous forest	[40] Closed to open broadleaved evergreen or semi-deciduous forest	[1] Evergreen needleleaf forest
	[2] Tree Cover, broadleaved, deciduous, closed	[50] Closed broadleaved deciduous forest	[50] Closed broadleaved deciduous forest	[2] Evergreen broadleaf forest
	[3] Tree Cover, broadleaved, deciduous, open	[60] Open broadleaved deciduous forest/woodland	[60] Open broadleaved deciduous forest/woodland	[3] Deciduous needleleaf forest
	[4] Tree Cover, needle-leaved, evergreen	(70) Closed needleleaved evergreen forest	(70) Closed needleleaved evergreen forest	[4] Deciduous broadleaf forest
	[5] Tree Cover, needle-leaved, deciduous	[91] Open needleleaved deciduous forest		[5] Mixed forest
	[6] Tree Cover, mixed leaf type	[90] Open needleleaved deciduous or evergreen forest	[90] Open needleleaved deciduous or evergreen forest	[8] Woody savannas
	[7] Tree Cover, regularly flooded, fresh water	[92] Open (15–40 %) needleleaved evergreen forest		[9] Savannas
	[8] Tree Cover, regularly flooded, saline water	[100] Closed to open (> 15 %) mixed broadleaved and needleleaved forest	[100] Closed to open mixed broadleaved and needleleaved forest	
	[10] Tree Cover, burnt	[101] Closed (> 40 %) mixed broadleaved and needleleaved forest		
Shrub	[11] Shrub Cover, closed-open, evergreen	[130] Closed to open shrubland	[130] Closed to open shrubland	[6] Closed shrublands
	[12] Shrub Cover, closed-open, deciduous	[131] Closed to open (> 15 %) broadleaved or needleleaved evergreen shrubland		[7] Open shrublands
		[134] Closed to open broadleaved deciduous shrubland		
Herbaceous	[16] Cultivated and managed areas	[11] Post-flooding or irrigated croplands (or aquatic)	[11] Post-flooding or irrigated croplands (or aquatic)	[12] Croplands
		[12] Post-flooding or irrigated shrub or tree crops	[14] Rainfed croplands	[10] Grasslands
		[13] Post-flooding or irrigated herbaceous crops	[140] Closed to open (> 15 %) herbaceous vegetation	
		[14] Rainfed croplands		
		[15] Rainfed herbaceous crops		
		[16] Rainfed shrub or tree crops		
	[13] Herbaceous Cover, closed-open	[140] Closed to open (> 15 %) herbaceous vegetation		
		[141] Closed grassland		
		[143] Open grassland		

ESSDD
6, 255–296, 2013

Table 2. Continued.

Dominant LFT	GLC2000	GlobCover 2005	GlobCover 2009	MODIS
Barren	[14] Sparse herbaceous or sparse shrub cover	[150] Sparse (< 15 %) vegetation	[150] Sparse (< 15 %) vegetation	
		[151] Sparse (< 15 %) grassland		
		[152] Sparse (< 15 %) shrubland		
	[22] Artificial surfaces and associated areas	[190] Artificial surfaces and associated areas	[190] Artificial surfaces and associated area	[13] Urban and built-up
	[19] Bare Areas	[200] Bare areas	[200] Bare areas	[16] Barren or sparsely vegetated
		[201] Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)		
		[202] Non-consolidated bare areas (sandy desert)		
		[203] Salt hardpans		
	[21] Snow and Ice	[220] Permanent snow and ice	[220] Permanent snow and ice	[15] Snow and ice
Mosaic	[9] Mosaic: Tree Cover/Other natural vegetation	[20] Mosaic cropland (50–70 %)/ vegetation (grassland/shrubland/ forest) (20–50 %)	[20] Mosaic cropland (50–70 %)/ vegetation (grassland/ shrubland/ forest) (20–50 %)	[11] Permanent wetlands
	[15] Regularly flooded shrub and/or herbaceous cover	[21] Mosaic cropland (50–70 %)/ grassland or shrubland (20–50 %)	[30] Mosaic vegetation (grassland/shrubland/forest) (50–70 %)/ cropland (20–50 %)	[14] Cropland-natural vegetation mosaic
	[17] Mosaic: Cropland/Tree Cover/Other natural vegetation	[30] Mosaic vegetation (grassland/shrubland/forest) (50–70 %)/ cropland (20–50 %)	[110] Mosaic forest or shrubland (50–70 %)/grassland (20–50 %)	
	[18] Mosaic: Cropland/Shrub and/or grass cover	[32] Mosaic forest (50–70 %)/ cropland (20–50 %)	[120] Mosaic grassland (50–70%)/ forest or shrubland (20–50 %)	
		[110] Mosaic forest or shrubland (50–70 %)/grassland (20–50 %)	[160] Closed to open (> 15 %) broadleaved forest regularly flooded	
		[120] Mosaic grassland (50–70 %)/ forest or shrubland (20–50 %)	[170] Closed (> 40 %) broadleaved forest or shrubland permanently flooded	
		[170] Closed broadleaved forest or shrubland permanently flooded	[180] Closed to open (> 15 %) grassland or woody vegetation on regularly flooded or waterlogged soil	
		[180] Closed to open grassland or woody vegetation on regularly flooded or waterlogged soil		
		[185] Closed to open grassland on regularly flooded or waterlogged soil		
Water	[20] Water Bodies	[210] Water bodies	[210] Water bodies	[0] Water bodies

ESSDD
6, 255–296, 2013

Use of various remote sensing land cover products

C. Ottlé et al.

Table 3. Harmonized legend used and correspondance with original products classes.

Classes	GlobCover 2005	GlobCover 2009	MODIS	GLC 2000
Evergreen Needleleaf Forest	92, 70	70	1	4
Evergreen Broadleaf Forest	X	X	2	X
Deciduous Needleleaf Forest	90, 91	90	3, 8, 9	5
Deciduous Broadleaf Forest	50, 60	50, 60	4	2
Mixed Forest	32, 40, 100	40, 100	5	6
Mixed Forest-Shrubs	110, 12	110, 12	X	9
Shrubs	130, 131, 134	130	6	11, 12
Sparse Vegetation	150, 151, 152	150	7, 16	14
Herbaceous regularly flooded	180, 185	180	10	15
Herbaceous	30, 32, 140	30, 140	X	13
Urban	190	190	13	22
Bare Soil	200, 201, 202, 203	200	X	19
Snow/Ice	220	220	15	21
Water	210	210	0	20
Burnt areas	X	X	X	10
Croplands	11, 12, 13, 14, 15, 16, 20, 21	11, 14, 20	12, 14	16, 17, 18

ESSDD
6, 255–296, 2013

Table 4. Fraction of each class in each product for Yakutia.

Classes	GlobCover 2005	GlobCover 2009	MODIS5.0 (2005)	MODIS5.1 (2005)	GLC 2000
Evergreen Needleleaf Forest	0.03	0.00	0.01	0.01	0.04
Evergreen Broadleaf Forest	0.00	0.00	0.00	0.00	0.00
Deciduous Needleleaf Forest	0.56	0.58	0.42	0.28	0.45
Deciduous Broadleaf Forest	0.01	0.01	0.00	0.00	0.01
Mixed Forest	0.01	0.01	0.01	0.03	0.02
Mixed Forest-Shrubs	0.16	0.13	0.00	0.00	0.04
Shrubs	0.00	0.00	0.05	0.00	0.18
Sparse Vegetation	0.17	0.21	0.50	0.64	0.08
Herbaceous regularly flooded	0.01	0.02	0.02	0.04	0.04
Herbaceous	0.00	0.00	0.00	0.00	0.07
Urban	0.00	0.00	0.00	0.00	0.00
Bare Soil	0.05	0.05	0.00	0.00	0.06
Snow/Ice	0.00	0.00	0.00	0.00	0.00
Water	0.00	0.00	0.00	0.00	0.00
Burnt areas	0.00	0.00	0.00	0.00	0.00
Croplands	0.00	0.00	0.00	0.00	0.00

ESSDD
6, 255–296, 2013

Table 5. Agreement percentages on Yakutia (for the main classes and comparison of Globcover 2005 with Globcover 2009, GLC 2000, MODIS 5.0, MODIS 5.1.)

Classes	GlobCover2005 – GLC2000	GlobCover 2005 – GlobCover 2009	GlobCover 2005 – MODIS 5.0	GlobCover 2005 – MODIS 5.1	GLC 2000 – MODIS 5.0	GLC 2000 – MODIS 5.1	MODIS 5.0 – MODIS 5.1
Deciduous Needleleaf Forest	0.65	0.95	0.64	0.42	0.68	0.70	0.61
Mixed Forest	0.24	0.73	0.25	0.33	0.31	0.23	0.73
Mixed Forest-Shrubs	0.09	0.74	0.00	0.00	0.00	0.00	0.00
Shrubs	0.66	0.29	0.50	0.00	0.18	0.12	0.00
Sparse Vegetation	0.36	0.90	0.88	0.85	0.14	0.11	0.86
Herbaceous regularly flooded	0.18	0.97	0.20	0.22	0.04	0.04	0.31
Herbaceous	0.24	0.58	0.00	0.00	0.00	0.00	0.00
Bare Soil	0.49	0.83	0.00	0.00	0.00	0.00	0.00
Total Agreement	0.60	0.89	0.61	0.52	0.49	0.43	0.76
Total Agreement without Water	0.38	0.68	0.40	0.31	0.28	0.21	0.55

ESSDD
6, 255–296, 2013

C. Ottlé et al.

Table 6. Fraction of each class in each product for South Siberia.

Classes	GlobCover 2005	GlobCover 2009	MODIS 5.0 (2005)	MODIS 5.1 (2005)	GLC 2000
Evergreen Needleleaf Forest	0.05	0.02	0.06	0.02	0.07
Evergreen Broadleaf Forest	0.00	0.00	0.00	0.00	0.00
Deciduous Needleleaf Forest	0.08	0.12	0.05	0.06	0.04
Deciduous Broadleaf Forest	0.13	0.11	0.0	0.0	0.01
Mixed Forest	0.03	0.06	0.23	0.26	0.24
Mixed Forest-Shrubs	0.05	0.03	0.00	0.00	0.0
Shrubs	0.00	0.00	0.01	0.00	0.02
Sparse Vegetation	0.17	0.13	0.02	0.01	0.03
Herbaceous regularly flooded	0.01	0.01	0.19	0.27	0.17
Herbaceous	0.17	0.10	0.00	0.00	0.0
Urban	0.01	0.00	0.00	0.0	0.00
Bare Soil	0.0	0.01	0.00	0.00	0.0
Snow/Ice	0.00	0.00	0.00	0.00	0.00
Water	0.00	0.00	0.0	0.00	0.00
Burnt areas	0.00	0.00	0.0	0.00	0.00
Croplands	0.3	0.41	0.43	0.37	0.43

ESSDD
6, 255–296, 2013

Table 7. Agreement percentages on South Siberia (for the main classes and comparison of Globcover2005 with Globcover2009, GLC2000, MODIS 5.0, MODIS 5.1).

Classes	GlobCover 2005 – GLC2000	GlobCover 2005 – GlobCover 2009	GlobCover 2005 – MODIS 5.0	GlobCover 2005 – MODIS 5.1	GLC 2000 – MODIS 5.0	GLC 2000 – MODIS 5.1	MODIS 5.0 – MODIS 5.1
Evergreen Needleleaf Forest	0.65	0.13	0.54	0.71	0.56	0.71	0.34
Deciduous Needleleaf Forest	0.16	0.68	0.13	0.07	0.10	0.07	0.29
Deciduous Broadleaf Forest	0.55	0.50	0.02	0.02	0.69	0.75	0.03
Mixed Forest	0.56	0.50	0.88	0.90	0.36	0.39	0.80
Mixed Forest-Shrubs	0.01	0.32	0.00	0.00	0.00	0.00	0.00
Sparse Vegetation	0.24	0.72	0.03	0.02	0.08	0.01	0.22
Herbaceous regularly flooded	0.20	0.76	0.03	0.05	0.00	0.00	0.93
Herbaceous	0.08	0.46	0.00	0.00	0.00	0.00	0.00
Croplands	0.54	0.96	0.79	0.70	0.42	0.67	0.80
Total Agreement	0.42	0.65	0.31	0.27	0.32	0.39	0.74
Total Agreement without Water	0.40	0.64	0.30	0.26	0.31	0.38	0.72

ESSDD
6, 255–296, 2013

C. Ottlé et al.

Table 8. Merging rules from GlobCover classes to ORCHIDEE PFTs.

ID	Globcover description	Bare Soil	Boreal Needleleaf Evergreen	Boreal Broadleaf Summer	Boreal Needleleaf Summer	C3 Grass	C3 Agri	Water	Snow/Ice
11	Post-flooding or irrigated croplands		0.0	0.0	0.0		100.0		
12	Post-flooding or irrigated shrub or tree crops		0.0	0.0	0.0		100.0		
13	Post-flooding or irrigated herbaceous crops		0.0	0.0	0.0		100.0		
14	Rainfed croplands		0.0	0.0	0.0		100.0		
15	Rainfed herbaceous crops		0.0	0.0	0.0		100.0		
16	Rainfed shrub or tree crops		0.0	0.0	0.0		100.0		
20	Mosaic cropland (50–70 %)/vegetation (grassland/shrubland/forest) (20–50 %)		10.0	15.0	0.0	15.0	60.0		
21	Mosaic cropland (50–70 %) / grassland or shrubland (20–50 %)		10.0	0.0	15.0	25.0	50.0		
30	Mosaic vegetation (grassland/shrubland/forest) (50–70 %)/cropland (20–50 %)		13.8	21.3	0.0	25.0	40.0		
32	Mosaic forest (50–70 %) / cropland (20–50 %)		10.0	0.0	50.0		40.0		
40	Closed to open broadleaved evergreen or semi-deciduous forest		47.5	52.5	0.0				
50	Closed broadleaved deciduous forest		0.0	85.0	0.0	15.0			
60	Open broadleaved deciduous forest/woodland	10.0	0.0	55.0	0.0	35.0			
70	Closed needleleaved evergreen forest		77.5	7.5	0.0	15.0			
90	Open needleleaved deciduous or evergreen forest	15.0	20.0	5.0	15.0	45.0			
91	Open needleleaved deciduous forest	10.0	0.0	0.0	60.0	30.0			
92	Open needleleaved evergreen forest	15.0	47.5	7.5	0.0	30.0			
100	Closed to open mixed broadleaved and needleleaved forest	10.0	27.5	37.5	10.0	15.0			
110	Mosaic forest or shrubland (50–70 %)/grassland (20–50 %)		17.5	32.5	10.0	40.0			
120	Mosaic grassland (50–70 %)/forest or shrubland (20–50 %)		12.5	22.5	5.0	60.0			
130	Closed to open shrubland	10.0	30.0	30.0	0.0	30.0			
131	Closed to open broadleaved or needleleaved evergreen shrubland	10.0	45.0	15.0	0.0	30.0			
134	Closed to open broadleaved deciduous shrubland	15.0	0.0	40.0	0.0	45.0			
140	Closed to open herbaceous vegetation	40.0	0.0	0.0	0.0	60.0			
141	Closed (> 40 %) grassland	40.0	0.0	0.0	0.0	60.0			
143	Open (15–40 %) grassland	60.0	0.0	0.0	0.0	40.0			
150	Sparse (< 15 %) vegetation	35.0	9.4	9.4	6.3	40.0			
151	Sparse (< 15 %) grassland	35.0	0.0	0.0	0.0	65.0			
152	Sparse (< 15 %) shrubland	35.0	7.5	7.5	5.0	45.0			
160	Closed to open (> 15 %) broadleaved forest regularly flooded		15.0	45.0	0.0	20.0		20.0	
170	Closed (> 40 %) broadleaved forest or shrubland permanently flooded		40.0	40.0	0.0			20.0	
180	Closed to open (> 15 %) grassland or woody vegetation on regularly flooded		15.0	15.0	0.0	40.0		30.0	
185	Closed to open (> 15 %) grassland on regularly flooded or waterlogged soil		0.0	0.0	0.0	70.0		30.0	
190	Artificial surfaces and associated areas	75.0	2.5	2.5	0.0	15.0		5.0	
200	Bare areas	100.0	0.0	0.0	0.0				
201	Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)	100.0	0.0	0.0	0.0				
202	Non-consolidated bare areas (sandy desert)	100.0	0.0	0.0	0.0				
203	Salt hardpans	100.0	0.0	0.0	0.0				
210	Water bodies		0.0	0.0	0.0			100.0	
220	Permanent snow and ice		0.0	0.0	0.0				100.0

ESSDD
6, 255–296, 2013

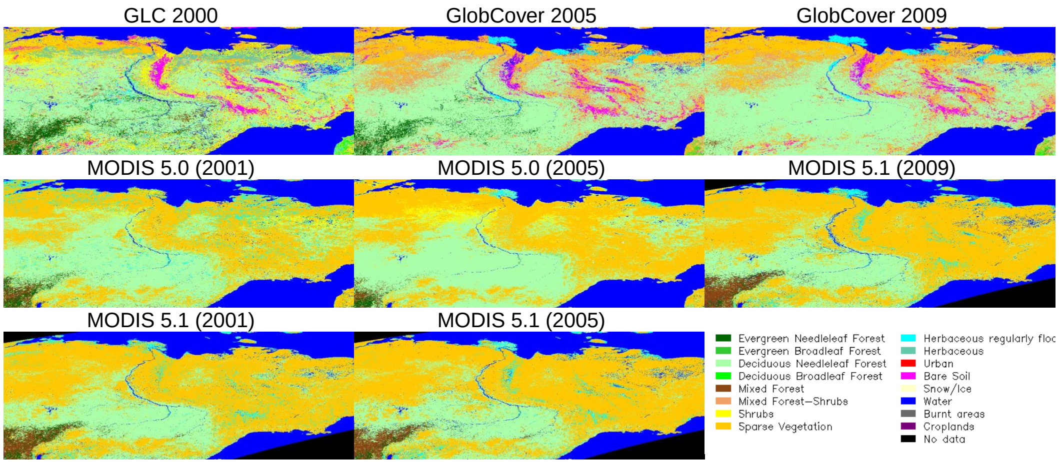

Fig. 1. Comparison of 5 Land Cover products on Yakutia: GLC2000, GlobCover 2005 and 2009, MODIS 5.0 and 5.1 for 2001, 2005 and 2009, are aggregated at 1 km scale to a common legend.

ESSDD
6, 255–296, 2013

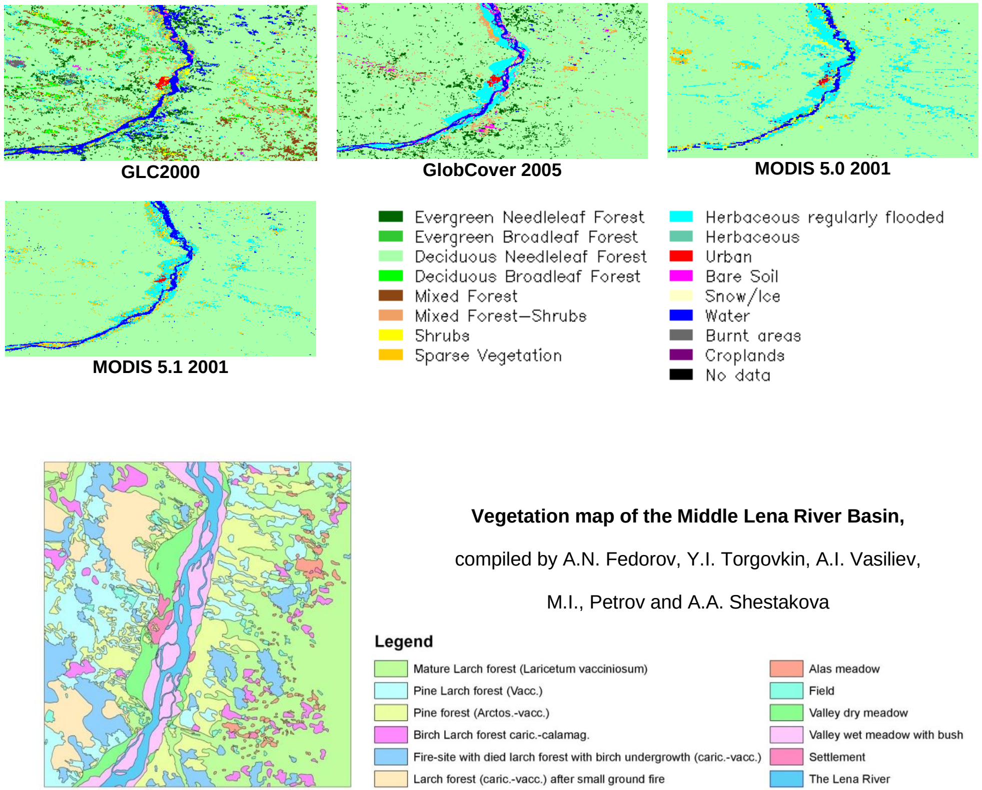

Fig. 2. Comparison of 5 Land Cover products on Yakutsk region: GLC2000, GlobCover 2005, MODIS 5.0 and 5.1 for 2001, aggregated at 1 km scale to a common legend with the land cover map provided by A. Fedorov (Melnikov Permafrost Institute, Russia).

ESSDD
6, 255–296, 2013

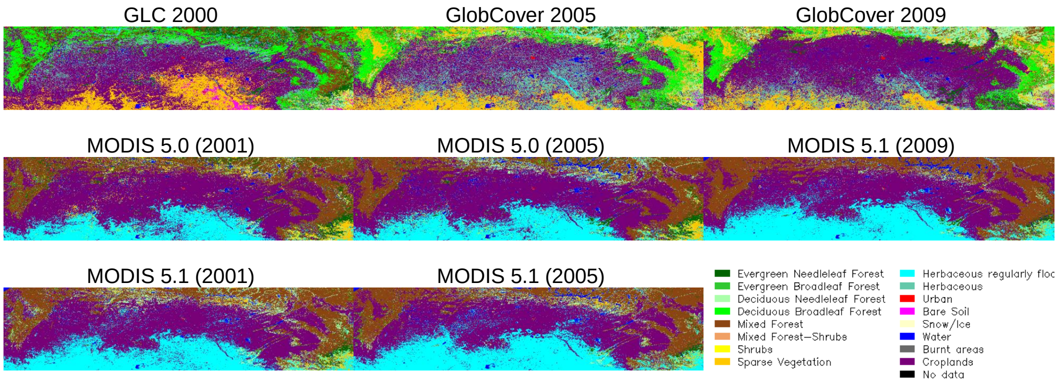

Fig. 3. Comparison of 5 Land Cover products on south-west Siberia: GLC2000, GlobCover 2005 and 2009, MODIS 5.0 and 5.1 for 2001, 2005 and 2009, are aggregated at 1 km scale to a common legend.

ESSDD
6, 255–296, 2013

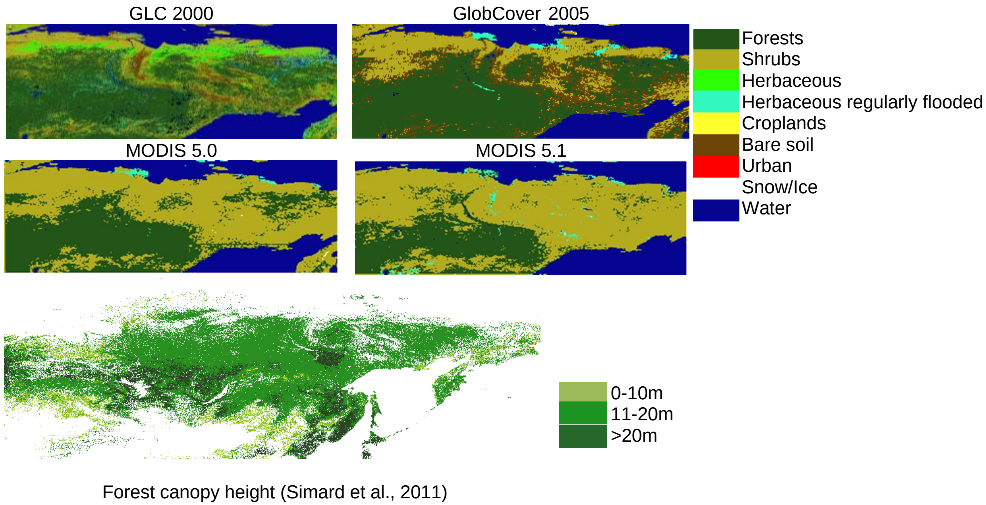

Fig. 4. Comparison of 4 Land Cover products on Yakutia: GLC2000, GlobCover 2005, MODIS 5.0 and 5.1 for 2001, with the forest canopy height product provided by Simard et al. (2011). The forests classes were grouped together at 1 km scale.

ESSDD
6, 255–296, 2013

Use of various remote sensing land cover products

C. Ottlé et al.

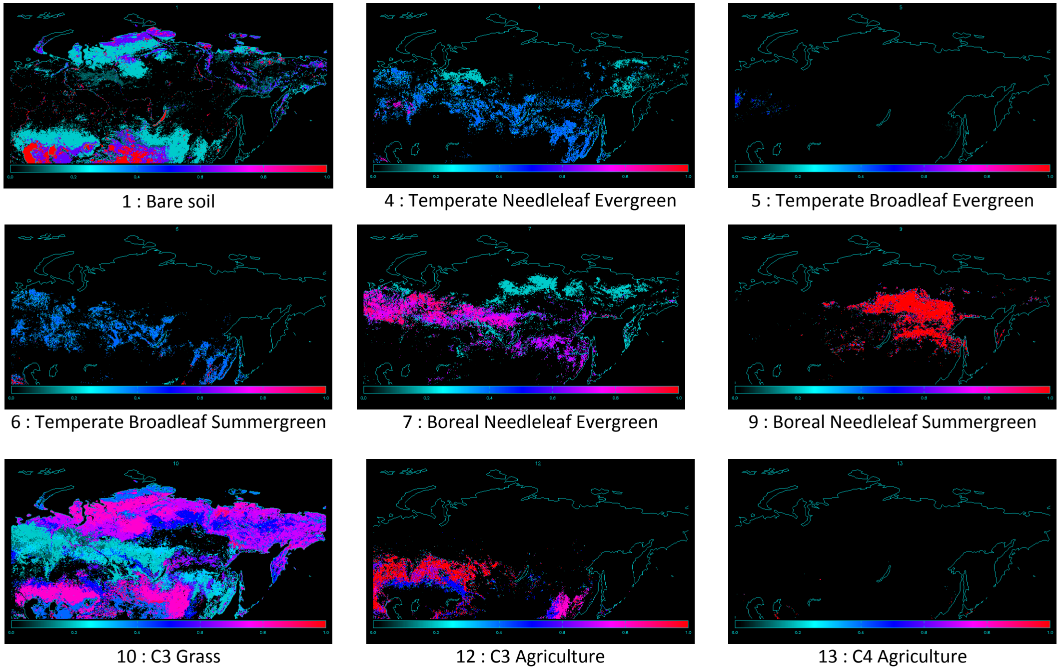

Fig. 5. Standard ORCHIDEE PFT maps. The respective fractions of the following 9 classes: Bare soil (PFT1), Temperate Needleleaf Evergreen (PFT4), Temperate Broadleaf Evergreen (PFT5), Temperate Broadleaf Summergreen (PFT6), Boreal Needleleaf Summergreen (PFT9), C3 Grass (PFT10), C3 Agriculture (PFT12), C4 Agriculture (PFT13), are represented in color scale, from blue (0 %) to red (100 %).

ESSDD
6, 255–296, 2013

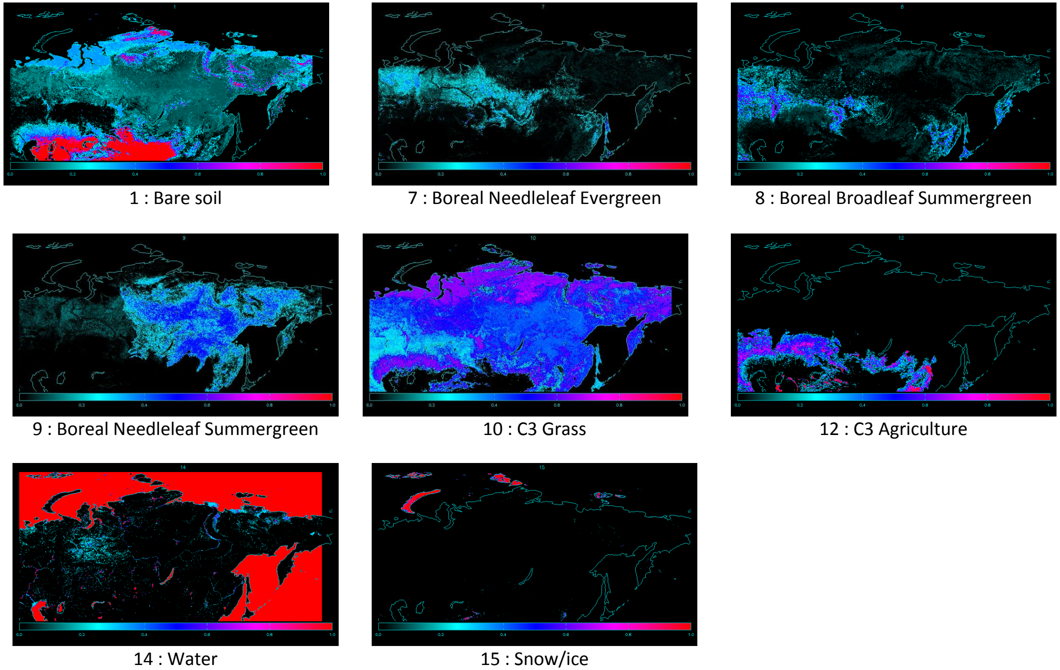

Fig. 6. New ORCHIDEE PFT maps. The respective fractions of the following 8 classes: Bare soil (PFT1), Boreal Needleleaf Evergreen (PFT7), Boreal Broadleaf Summergreen (PFT8), Boreal Needleleaf Summergreen (PFT9), C3 Grass (PFT10), C3 Agriculture (PFT12), Water (PFT14), Snow/Ice (PFT15), are represented in color scale, from blue (0 %) to red (100 %).

ESSDD
6, 255–296, 2013

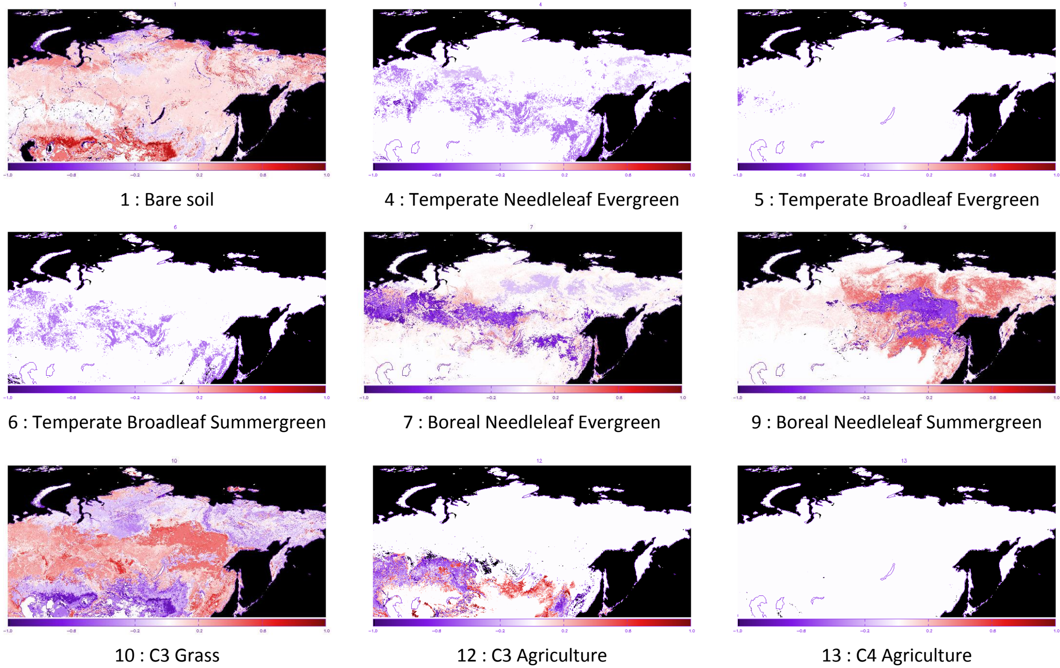

Fig. 7. Difference (New-Standard) PFT maps. The percentage differences are represented in color scale, ranging from −1 (blue) to +1 (red).

ESSDD
6, 255–296, 2013

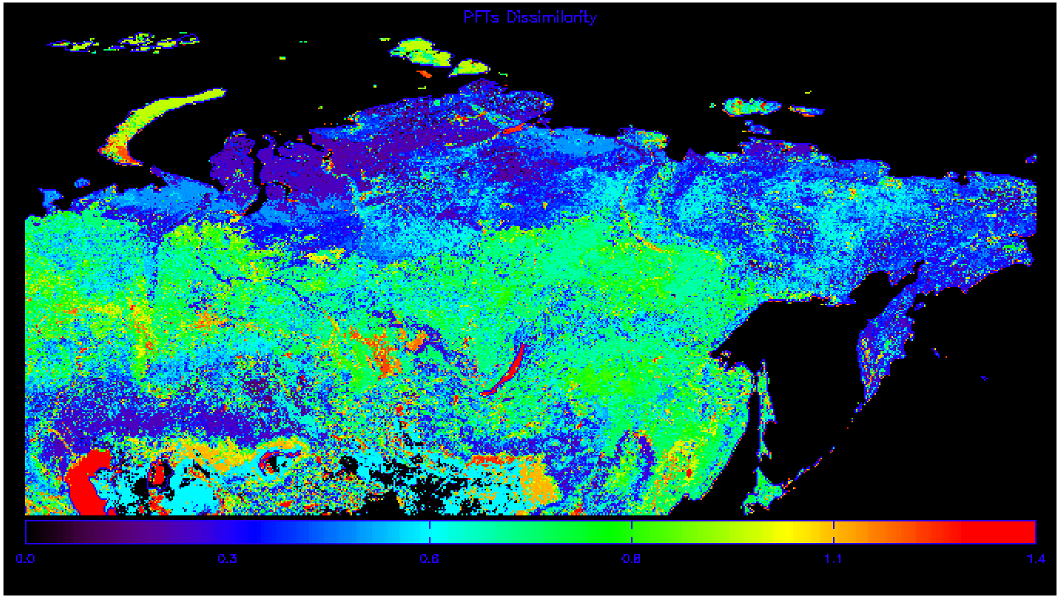

Fig. 8. PFT dissimilarity index ranging from 0 (full disagreement) to $\sqrt{2}$ (full agreement).

ESSDD
6, 255–296, 2013

Use of various remote sensing land cover products

C. Ottlé et al.