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Abstract	This chapter presents recent advances in the understanding of the effect of land cover/land use changes on the hydrologic cycle, and identifies current gaps in the knowledge needed for useful decision-making and water resource management. Research achievements within a framework of Earth System Models (ESM) are introduced, and research needs and future challenges are identified. Land surface provides the lower boundary condition to the atmosphere over continents by controlling the fluxes of momentum, heat, water, and materials such as carbon. In turn, land surface conditions are substantially influenced by atmospheric conditions on various temporal scales. As such, a land-atmosphere coupled system is established through biogeochemical feedbacks. Current land surface models exhibit a wide variety of responses to the same forcings, suggesting the need for increased research at the land-atmosphere interface. Indeed, all Earth System Models require the inclusion and validation of the processes that pertain to the biogeochemical feedbacks. Anthropogenic activities that result in land use and land cover changes affect the land surface characteristics and consequently the land-atmosphere feedbacks and coupling strength. Therefore, human activities play a role in the land-atmosphere coupling system, and thus, in the climate system. Water is essential to societal needs that require the construction of reservoirs, extraction of ground water, irrigation, changes in land use, urbanization among many other influences. The extent and sustainability of those interferences in the natural system remains to be assessed at global scales.

Keywords (separated by "-")	Land-atmosphere feedback - Vegetation - Ecosystem - Human impacts - Water - Energy - Carbon - Land cover/land use

Land Use and Land Cover Changes and Their Impacts on Hydroclimate, Ecosystems and Society

Taikan Oki, Eleanor M. Blyth, Ernesto Hugo Berbery, and Domingo Alcaraz-Segura

Abstract This chapter presents recent advances in the understanding of the effect of land cover/land use changes on the hydrologic cycle, and identifies current gaps in the knowledge needed for useful decision-making and water resource management. Research achievements within a framework of Earth System Models (ESM) are introduced, and research needs and future challenges are identified. Land surface provides the lower boundary condition to the atmosphere over continents by controlling the fluxes of momentum, heat, water, and materials such as carbon. In turn, land surface conditions are substantially influenced by atmospheric conditions on various temporal scales. As such, a land-atmosphere coupled system is established through biogeochemical feedbacks. Current land surface models exhibit a wide variety of responses to the same forcings, suggesting the need for increased research at the land-atmosphere interface. Indeed, all Earth System Models require the inclusion and validation of the processes that pertain to the biogeochemical feedbacks. Anthropogenic activities that result in land use and land cover changes

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affect the land surface characteristics and consequently the land-atmosphere feedbacks and coupling strength. Therefore, human activities play a role in the land-atmosphere coupling system, and thus, in the climate system. Water is essential to societal needs that require the construction of reservoirs, extraction of ground water, irrigation, changes in land use, urbanization among many other influences. The extent and sustainability of those interferences in the natural system remains to be assessed at global scales.

Keywords Land-atmosphere feedback • Vegetation • Ecosystem • Human impacts • Water • Energy • Carbon • Land cover/land use

1 Introduction

The land surface provides lower boundary conditions to the atmosphere: It receives downward short wave and long wave radiation, and emits or reflects upward short wave and long wave radiation. The net radiation is balanced by the fluxes of sensible, latent and ground heat to the atmosphere (Oki 1999). In terms of the water balance, precipitation is balanced by evapotranspiration and runoff (assuming that over long term periods there is no net water storage change on the soil). These exchanges also depend on the atmospheric conditions, including the surface pressure, temperature, humidity and wind. A balance mainly between precipitation, evapotranspiration and surface and deep runoff determines the land surface water cycle. Surface soil moisture, in turn, governs the partitioning of the sensible and latent heat fluxes into the atmosphere, and can affect daily, weekly, intraseasonal, seasonal, and interannual rainfall in various spatial scales through the impacts on development PBL (planetary boundary layers), its longer temporal auto-correlation ("memory" effect), and possibly through interactions with vegetation (see Table 1 of Taylor et al. 2011). Excess water from land discharges into the ocean changing its salinity and temperature, and possibly influences the formation of sea ice and thermohaline circulation at least on local scales (Oki et al. 2004).

The energy, water, and carbon balances determined by land surface processes are characterized by the land surface conditions such as topography, land cover, soil properties, and geological condition. Land cover can be characterized by the vegetation over it, such as forests, shrubs, grass, bare soil, or open water. Since vegetation types are dominantly determined by climatological conditions, land surface interacts with the atmosphere not only on the short time scales but also in longer temporal scales, such as decadal to centennial. Even though storage volumes are not as large as in the ocean, the land stores heat, water, and carbon, and thus, the land surface is one of the key components in the climate system on the Earth.

In many cases, particularly when dealing with extreme events, climatic variations and changes can have significant impacts on human activities; therefore it is critical that climate science includes and develops tools for monitoring and prediction of climatic variations. As climate affects human activities, in turn humans interfere with

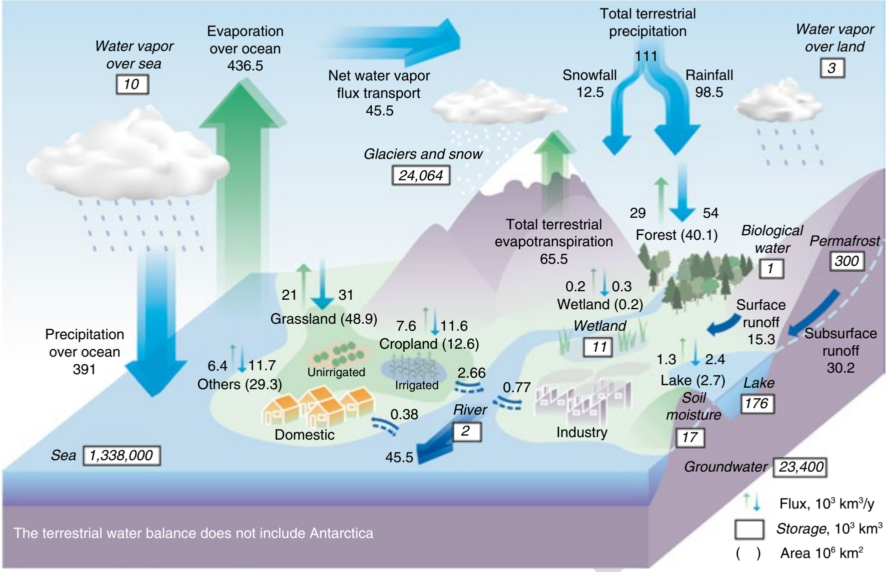

Fig. 1 Global hydrological fluxes (1,000 km^3/year) and storages (1,000 km^3) with natural and anthropogenic cycles are synthesized from various sources (Dirmeyer et al. 2006; Korzun 1978; Oki et al. 1995; Shiklomanov 1997). *Big vertical arrows* show total annual precipitation and evapotranspiration over land and ocean (1,000 km^3/year), which include annual precipitation and evapotranspiration in major landscapes (1,000 km^3/year) presented by *small vertical arrows*; *parentheses* indicate area (million km^2). The direct groundwater discharge, which is estimated to be about 10 % of total river discharge globally (Church 1996), is included in river discharge

the climate system from local to global scales. Apart from human influences through greenhouse gases (GHGs, not discussed in this chapter), human influences on the ecosystem service of climate regulation occur through changes in land use and land cover (Anderson-Teixeira et al. 2012), as well as through interventions on the water cycle components, for example by irrigation (Rosnay et al. 2003; Guimberteau et al. 2011) and storage in artificial reservoirs (Haddeland et al. 2006; Hanasaki et al. 2006, 2010).

The World Climate Research Programme (WCRP) emphasis on the role of land in the climate system has been mainly conducted through the Global Energy and Water Cycle Experiment (GEWEX). The GEWEX Hydroclimate Panel (GHP) has been promoting and synthesizing field campaigns measuring, estimating, and seeking to close the regional water balances in various climatic zones at continental and sub-continental scales. The Global Land-Atmosphere System Study (GLASS; van den Hurk et al. 2011) has been promoting and organizing numerical studies assessing the coupling between land and atmosphere, and the Global Data and Assessments Panel (GDAP) supports the creation and dissemination of comprehensive datasets of the climatic variables over land. The products from the Second Global Soil Wetness Project (GSWP-2; Dirmeyer et al. 2006) contributed to illustrate the global water cycles as shown in Fig. 1 (Oki and Kanae 2006).

In this chapter, we discuss the feedbacks and interactions between the land surface and the climate system, particularly with regard to land use and land cover change. The role of land use change in the hydro-climate system is presented in Sect. 2. The interactions with ecosystems are summarized in Sect. 3, and societal needs for research on water over land are introduced in Sect. 4. Section 5 identifies current gaps and future challenges for the research on land surface processes in the climate system.

2 Land Use Change and Hydroclimate

Long term changes to the land surface state occur when there is a significant change in the land cover, such as conversions from forest to crops. In cases like this, there will be changes in the biophysical properties of the surface, like its albedo, surface roughness length, and stomatal resistance. In addition, there will be changes to the hydrological functioning of the land surface, with changes in the amount of water available for storage and the runoff, possibly through changes in the soil properties and root uptake.

Many researchers have worked to quantify the impact that such changes have on the atmosphere. For instance, modeling experiments have been carried out to understand the regional climate impact of the wide-scale spread of agriculture that has occurred over the last century (see Pitman et al. 2009). Specifically, the goal was to assess if the current regional climate has been influenced by the anthropogenically altered landscape. The model results showed varying responses of the evaporation and rainfall to the deforestation, as the changes were small and of either sign. Part of the reason is due to difficulties in defining a consistent definition of vegetation characteristics for natural versus anthropogenic land use types and differences in parameterization in the models. However, the models were in better agreement on the changes in the air temperature: removing the forests and replacing them with crops and pasture cools the summer air by about 1° in the last 100 years in the two key regions of largest land use change: the middle of the USA and western Russia. This result is supported by an observational study of evaporation and sensible heat flux observations from a series of paired forest and grass sites across Europe by Teuling et al. (2010), which demonstrated, similar to the models, that the forests generally warm the atmosphere compared to grasses and crops. However, Teuling et al. (2010) also showed how this signal changes during drought conditions, when the grasses dry out and then warm the atmosphere more than the forests. Figure 2 is a schematic summarizing the findings of Teuling et al. (2010) and of Pitman et al. (2009), showing how the forests act to warm the overlying atmosphere under normal climatic periods, while grasses or crops warm the atmosphere during anomalously dry periods. This has important implications for the physical response to land use change and its impact on the regional meteorology, since an increasing cropped area may act to enhance the regional susceptibility to heat waves, while reforestation may act to reduce a heat wave. Clearly, more research and a combined approach to risks and hazards (such as wild fire) are necessary to support this conclusion.

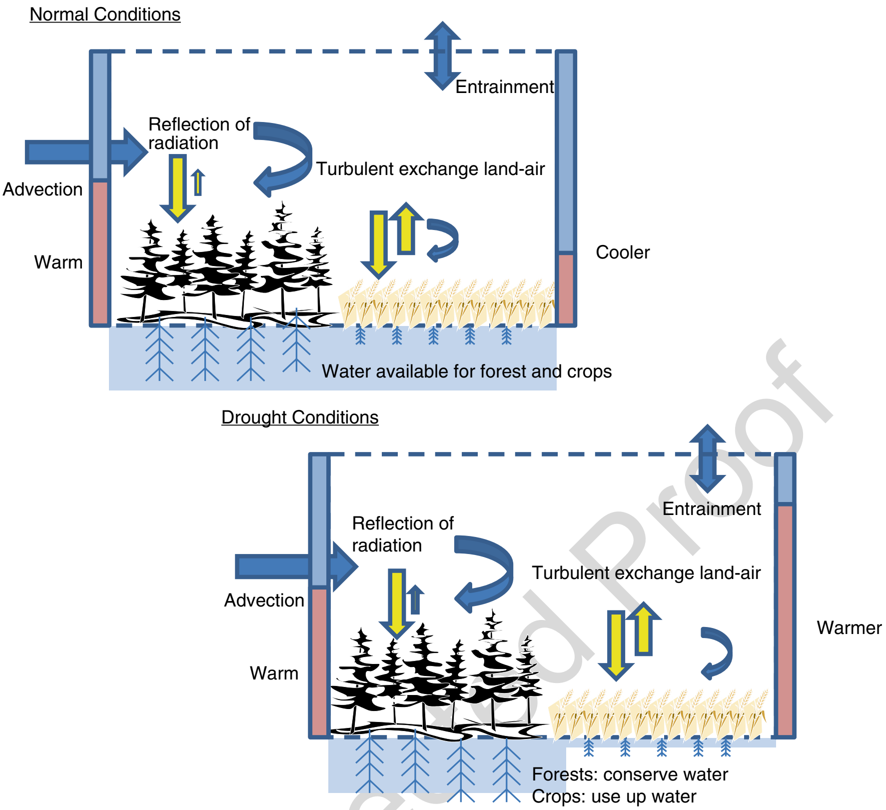

Fig. 2 Summary of impact of land-cover on atmospheric conditions

As well as impacts on the heat and temperature of a region, impacts of land cover change on the hydrological conditions should be expected due to feedbacks in the system. The relationships between the land and the atmosphere are part of the natural interplay that happens all around us: with a long term reduction in rainfall, the land dries out and this warms and dries the atmosphere which leads to further drying out of the land. This positive feedback means that a percentage drop in rainfall leads to a greater percentage drop in runoff and vice versa. Many articles have discussed the mechanisms by which a change in land cover can affect the overlying planetary boundary layer (PBL), its thermodynamic properties and circulation, and consequently the precipitation processes and regional climate (e.g., Pielke and Avissar 1990; Stohlgren et al. 1998; Kanae et al. 2001; Pielke et al. 2007, 2011; Lee and Berbery 2012). This feedback can be important for water resources, for instance, Cai et al. (2009) have demonstrated the role that land-atmosphere feedbacks have had on the recent Australian drought: their model results imply that feedbacks in the system act to exaggerate a drying period and that, during a warm, dry period, the feedbacks in the climate system act to extend the dry period. In contrast, there are areas where the land use change involves extensive moistening of the land through irrigation. This might be the case in India where the strength of the monsoon is determined by the land-sea temperature contrast and decreasing surface temperatures due to irrigation would be expected to reduce the intensity of the monsoon systems (Lee et al. 2009). Tuinenburg et al. (2011)'s study of the observed (from Radiosondes) atmospheric structures in the region show a potential alteration of the timing of the monsoon due to changes in PBL moisture from irrigated land. Douville et al. (2001) conclude that although precipitation does increase as a consequence of increasing evaporation this is somewhat counterbalanced, in the case of the Indian peninsula, by a reduced moisture convergence. Saeed et al. (2011) looked at these influences in more detail using a regional climate model, with and without irrigation. They found increased rainfall over the irrigated areas due to increased local moisture recycling and also an increase of the penetration of rain bearing depressions travelling inland from the Bay of Bengal, caused by a reduction in the westerly flows from the Arabian Sea.

Several researchers have managed to capture this large-scale long-term relationship between climatological precipitation (P), evapotranspiration (E) and potential evapotranspiration (PE) and, by implication, runoff (R), but possibly the most famous empirical equation was derived by Budyko (1974); see also Choudhury (1999):

$$E = \frac{P\,PE}{\left(P^{\mathrm{n}} + PE^{\mathrm{n}}\right)^{\frac{1}{\mathrm{n}}}} \tag{1}$$

Where 'n' is a catchment specific dimensionless factor (Roderick and Farquhar 2011). The shape of this curve for various values of 'n' is shown in Fig. 3. Roderick and Farquhar (2011) examined the effect of this relation on freshwater flows at the global scale and how well the climate models are able to represent it. They note that there are different regional responses to the large scale forcing of the water balance: in some regions where 'n' is high, changes in runoff follow closely the changes in precipitation. In other systems or regions where 'n' is low, changes in runoff are always greater than the changes in precipitation. Part of the reason for the differences is associated with different rainfall types (see Porporato et al. 2004) and different topographic and land-cover responses to rainfall. Other influences include atmospheric feedbacks with the atmosphere as outlined in the previous section. In addition, an analysis by Zhang et al. (2004) showed that the land cover is a factor in defining 'n' with forests displaying a higher 'n' compared to data from grass sites (see their Figure 8). This result is confirmed by Yang et al. (2009). The change from forest to grass decreases the 'n' from 2.12 to 1.83. Since it is logical that the value of 'n' is affected by the strength of the land-atmosphere feedbacks, the results from Zhang et al. (2004) suggest that forests have a higher feedback strength than crops, a point that has also been made by Bonan (2008). This is consistent with the result of Teuling et al. (2010) who showed that forests have a conservative approach to the water use, so as precipitation drops and evaporative demand increases, the evaporation decreases quickly. Grasses and crops however do not drop their evaporation so quickly (they have a more linear response to precipitation decrease) and they lose the water, thus leading to hotter drier conditions in drought conditions. The larger feedback strength of forested regions is also consistent with

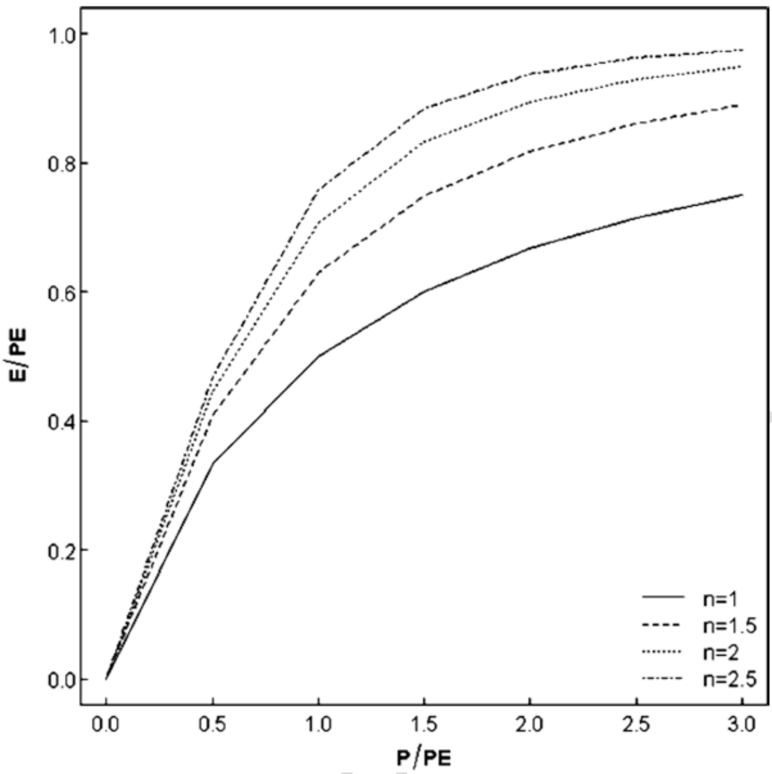

Fig. 3 Ratio of evaporation to potential evaporation as a function of the ratio of precipitation to potential evaporation (aka the Budyko Curve) for different values of 'n'

the finding of McNaughton and Spriggs (1989), who used a PBL model and found that the Priestley-Taylor parameter – which is a measure of the strength of land-atmosphere interactions – should be higher for forests than for grasses.

According to this analysis, the impact of having a decreased level of feedback between the surface and the atmosphere when changing the land cover from forest to crops and pastures is to reduce the sensitivity of the change in runoff to changes in precipitation. This will mean a more linear relationship between changes in precipitation and river flow, with less conservation of water and more drought vulnerability. These conclusions need to be more thoroughly examined with large scale observations and models.

3 Land Use Change and Ecosystems

Climate is the main regional driver of ecosystem structure and functioning through the timing and amount of energy and water that is available in the system (Stephenson 1990). In turn, ecosystems influence climate by determining the energy, momentum, water, and chemical balances between the land-surface and the atmosphere (Chapin et al. 2008). Hence, extensive impacts on ecosystems, both from natural origin and human made (e.g., land use changes), alter one or several pathways of the ecosystem–climate feedbacks, which ends up affecting the regional and global climate.

Indeed, several studies (e.g., Pielke et al. 2002; Kalnay and Cai 2003; Weaver and Avissar 2001; Werth and Avissar 2002) have concluded that the contribution of land-use changes to climate change might be about 10 % of the total global change, but that regionally the relative contribution of land-use change may be notably larger, even larger than that from greenhouse gas emissions. There are conspicuous known cases showing how land-use changes may end up altering the regional climate, such as the aridification of the Mediterranean basin during the Roman Period (Reale and Dirmeyer 2000; Reale and Shukla 2000), or changes in the hydrometeorology of Amazonia after deforestation (Baidya Roy and Avissar 2002; Gedney and Valdes 2000). In South America, inter-annual variability in climate conditions significantly affects vegetation structural and functional properties (Phillips et al. 2009; Brando et al. 2010; Zhao and Running 2010), whose effects may end up influencing the regional climate.

The ecosystem-climate feedbacks are a central problem not only for modeling the land-atmosphere interactions of the climate system (e.g., Mahmood et al. 2010), but also for many other biological and environmental issues. Ecosystem-atmosphere interactions and feedbacks depend on the physical properties of the underlying surface, like surface albedo, surface roughness, and stomatal resistance, among others. These properties affect the radiation balance at the surface as well as the exchange of momentum, heat, moisture, and other gaseous/aerosol materials. Changes in the structure and functioning of the ecosystems will thus have an impact on those exchanges that may end up affecting the climate regulation service that ecosystems provide to societies (Anderson-Teixeira et al. 2012).

Many land surface models do not consider the inter-annual dynamics of ecosystems. Models of intermediate complexity have static vegetation or land-cover classes with look-up tables to identify their corresponding biophysical properties (Chen and Dudhia 2001; Ek et al. 2003). Land cover types are assumed to remain constant but, in reality, they may experience important changes. For instance, the biophysical properties of a typical vegetation type during a wet period should be very different during a drought. The same is true during anomalous periods of intense rain that can create numerous ponds, or flooding. A model that assumes constant surface properties will still be able to represent in general changes in soil moisture content and water stress, but will be unable to represent the different conditions that emerge, e.g., when a field is flooded affecting land-atmosphere interactions, the radiation budget, and the surface water, energy and carbon cycles. Dynamical vegetation models that include the carbon cycle are an attempt to advance in the area of ecosystem-atmosphere interactions, since they allow for changes in vegetation composition and have advanced assumptions regarding surface processes that will feed back into the atmosphere. Yet, direct human-imposed land use change, as deforestation and land cover conversions may have an immediate impact on the atmosphere, as opposed to the slower effects included in a dynamical vegetation model.

Traditionally, land-cover maps are mainly driven by vegetation structure and composition but do not formally include ecosystem functional aspects such as the dynamics of carbon gains. Ecosystems functional attributes (i.e., different aspects of the exchange of matter and energy between the biota and the atmosphere) add some advantages to the traditional use of structural variables. First, variables describing ecosystem functioning have a faster response to disturbances than vegetation structure (Milchunas and Lauenroth 1995). Second, functional attributes allow the quantitative and qualitative characterization of ecosystems services (e.g., carbon sequestration, nutrient and water cycling) (Costanza et al. 1998). Additionally, they can be more easily monitored than structural attributes by using remote sensing at different spatial scales, over large extents, and utilizing a common protocol (Foley et al. 2007). Functional descriptors of ecosystems have been successfully used to define Ecosystem Functional Types (EFTs) (Alcaraz-Segura et al. 2006, 2013; see also Körner 1994; Valentini et al. 1999; Paruelo et al. 2001). In ecology, such classifications into functional units aim to reduce the diversity of biological entities (e.g. ecosystems) on the basis of processes, and allow for the identification of homogeneous groups that show a specific and coordinated response to the environmental factors. EFTs are groups of ecosystems that share functional characteristics in relation to the amount and timing of the exchanges of matter and energy between the biota and the physical environment. In other words, EFTs are homogeneous patches of the land surface that exchange mass and energy with the atmosphere in a common way (Valentini et al. 1999; Paruelo et al. 2001; Alcaraz-Segura et al. 2006, 2013a, 2013b). EFTs are computed from satellite information (e.g., spectral vegetation indices), so they do not identify the functions of a given plant species (as it occurs with plant functional types; see Wright et al. 2006), but instead identify a patch of land that has homogeneous properties in terms of exchanges of energy and mass over a given region. EFTs can thus be considered a top-down functional classification directly based on ecosystem processes.

The definition of EFTs relies in three metrics derived from the NDVI (Normalized Difference Vegetation Index) time series. First, the average of NDVI over 1 year (NDVI-mean) is a linear estimator of the amount of solar energy that is used for photosynthesis, formally called the Fraction of Absorbed Photosynthetically Active Radiation (fAPAR), and is empirically (Paruelo et al. 1997) and conceptually (Monteith 1972) related to net primary production (NPP; Tucker and Sellers 1986). Second, the seasonal coefficient of variation (CV) is a measure of the intra-annual variation of photosynthetic activity, which has been used as an indicator of the seasonality of carbon fluxes or the amplitude of the annual cycle (Oesterheld et al. 1998; Potter and Brooks 1998; Guerschman et al. 2003). Third, the phenology, or date of the absolute maximum of NDVI (DMAX), indicates the intra-annual distribution of the period with maximum photosynthetic activity (Lloyd 1990; Hoare and Frost 2004). These three metrics capture important features of ecosystem functioning for temperate ecosystems (Pettorelli et al. 2005; Lloyd 1990; Paruelo and Lauenroth 1995; Nemani and Running 1997; Paruelo et al. 2001; Virginia et al. 2001) and up to 90 % of the variability of the NDVI temporal dynamics (Paruelo et al. 2001; Alcaraz-Segura et al. 2006, 2009).

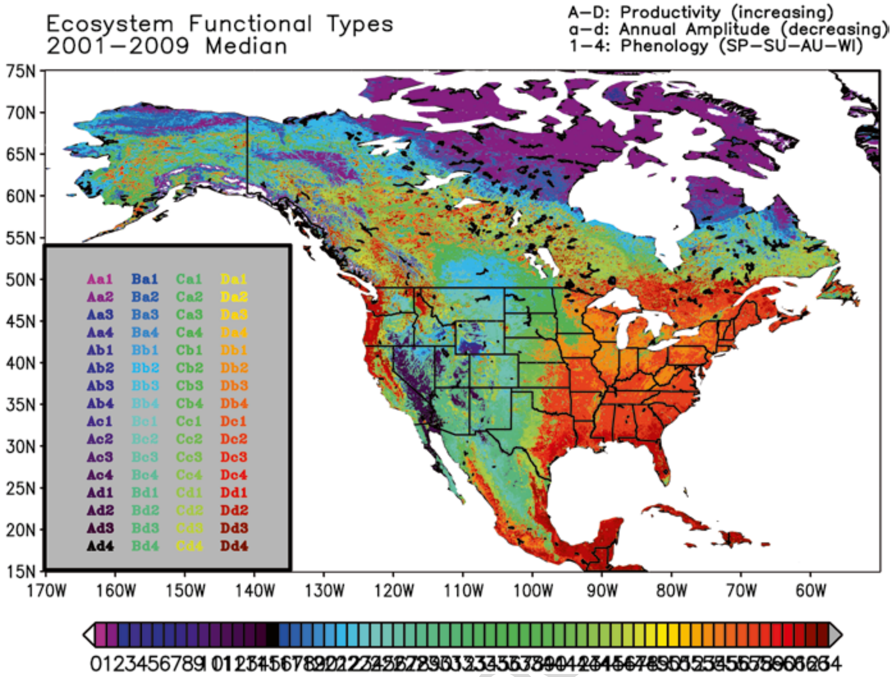

Fig. 4 Ecosystem Functional Types based on three descriptors of the seasonal dynamics of the NDVI estimated from MODIS images for the period 2001–2009

Figure 4 is an example that presents the median of the 64 EFTs for North America as computed from MODIS (or Moderate Resolution Imaging Spectroradiometer) NDVI. The warm colors indicate greatest exchanges of mass and energy between the ecosystems and the atmosphere. As expected, these regions include the coastline of the Gulf of Mexico extending over the Great Plains, subtropical forests surrounding the Gulf of Mexico and the Caribbean, the Pacific coast, the North American Monsoon in northwestern Mexico and the East Coast states. On the other hand, desert regions in Arizona and Nevada, where the net productivity is very low, are depicted with dark colors; tundra is distinctly identified in light purple. The figure depicts the median EFTs for 2001–2009, but since EFTs can be defined on a year-to-year basis, they can give a much better representation of time-varying surface states. Since EFTs are identified from time-series of satellite-derived estimates of the carbon gains dynamics (e.g. spectral vegetation indices such as NDVI and EVI), differences between sensors and datasets may occur due to the corrections applied (Alcaraz-Segura et al. 2010a). Such differences can be used to evaluate the uncertainty of the approach and the sensitivity to different databases (e.g. Alcaraz-Segura et al. 2010b).

Another advantage of Ecosystem Functional Types is that their definition is exclusively based upon the carbon gain dynamics estimated from time-series of satellite images, so EFTs are able to capture differences between natural ecosystems (e.g. native oak forest) and managed ecosystems (e.g. tree plantations) when they differ in their carbon gain dynamics. For instance, Volante et al. (2012) showed how the intrusion of cattle rising and croplands on natural dry forest and shrublands of NW Argentina significantly changed satellite-derived ecosystem functional attributes related to productivity and seasonality and, subsequently, the EFTs composition (Paruelo et al. 2011).

4 Societal Needs for Research on Water Over Land

All organisms, including humans, require water for their survival. Therefore, ensuring that adequate supplies of water are available is essential for human well-being (Millennium Ecosystem Assessment 2005; Oki and Kanae 2006; Vörösmarty et al. 2010). Water issues are related to poverty, and providing access to safe drinking water is one of the key necessities for sustainable development (WHO/UNICEF 2012). However, better information on the hydro-climate system is necessary to understand the issues of supply and demand of water, both in the current climate and the future. Substantial changes to the Earth's climate system, hydrological cycles, and social systems have the potential to increase the frequency and severity of water-related hazards, such as: storm surges, floods, debris flows, and droughts (IPCC 2011). Global population is growing, particularly in the developing world and is accompanied by migration into urban areas, and could be associated with large scale land use/land cover changes. The urbanization threatens to increase the risks of urban flash floods and reduce per-capita water resources. Global economic growth is increasing the demand for food, which further drives demands for irrigation water and drinking water, demands more cropland, and potentially changes land use/land cover. Therefore it is critically important to consider both the social and climate changes in a concerted framework (Kundzewicz et al. 2007) as illustrated in Fig. 5.

In the past, water issues remained local; however, they are becoming a key global issue due to the increased awareness that human induced global warming has large impacts on the water cycle. Further, due to the increase in international trade and mutual interdependence among countries, water issues now often need to

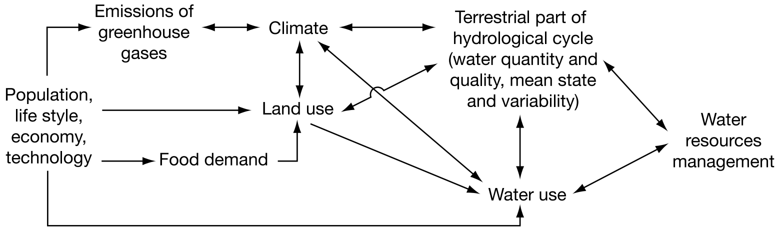

Fig. 5 Impact of human activities on freshwater resources and their management, with climate change being only one of multiple pressures (Modified after Oki 2005)

be dealt on a global scale, and thus require information on global hydrological conditions and their changes associated with climate changes. In trans boundary river basins and shared aquifers, it is necessary to share not only hydrological information but also any development plan that implies modifying LULC to reduce conflicts between relevant parties. In addition, quantitative estimates of recharge amounts or potentially available water resources will assist in implementing sustainable water use.

Global hydrology is not only concerned with global monitoring, modeling, and world water resources assessment. Owing to recent advancements in global earth observation technology and macro-scale modeling capacity, global hydrology can now provide basic information on the regional hydrological cycle which may support the decision making process in the integrated water resources management.

The use of offline land surface models at very fine spatial and temporal scales, e.g., 1-km grid spacing and hourly time intervals, is yet to be fully assessed (Oki et al. 2006; Wood et al. 2011). For such research efforts, observational data from regional studies can provide significant information for validation, and efforts to integrate datasets from various regional studies should be promoted. The recent Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative (Giorgi et al. 2009) from the World Climate Research Program (WCRP) promotes running multiple RCM simulations at higher spatial resolution for multiple regions, and current and future estimates of atmospheric conditions will be provided, although at much lower resolution than that of the offline land surface models.

Certainly another societal need is to assess the impacts of human interferences on the hydrological cycle due to land use changes, such as deforestation and urbanization, reservoir constructions, and water withdrawals for irrigation, industry, and domestic water uses (e.g., Haddeland et al. 2006; Hanasaki et al. 2006, 2010; Pokhrel et al. 2012a).

Withholding water in reservoirs may result in a drop in the sea level. On the other hand, over exploitation of ground water, particularly “fossil water” which has virtually no or very little recharge at present, would have contribution to sea level rise. These effects are studied based on in-situ observations (Gornitz et al. 1997; Konikow 2011), satellite observations (Rodell et al. 2009; Moiwo et al. 2012), and modeling studies (Wada et al. 2010; Pokhrel et al. 2012b). Satellite information like that provided by GRACE (Gravity Recovery and Climate Experiment) serves to monitor the long term changes of these major water storages over land, and provides a powerful tool to assess and validate the global estimates from models.

5 Current Gaps, and Future Challenges

Current global land surface modeling has begun integrating most of the latest achievements in process understanding and regional- or local-scale modeling studies. For example, there are emerging efforts in global simulation of the occurrence, circulation, and balance of solutes and sediments. In addition, improvements to the

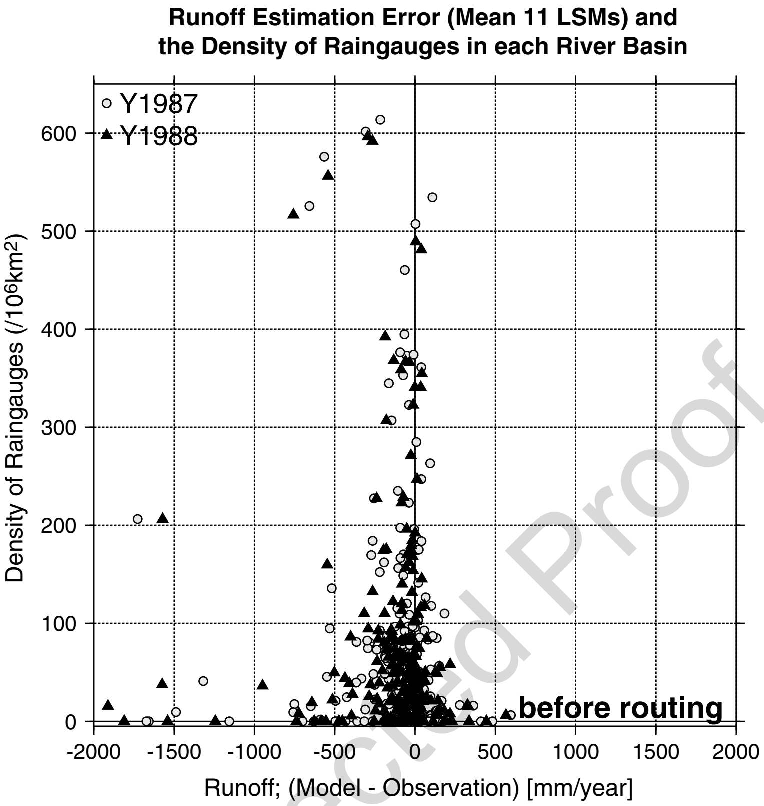

Fig. 6 Comparisons between the density of rain gauge [/10^6 km^2] used in preparing the forcing precipitation and the mean bias error [mm year^{-1}] of 11 LSMs for 150 major river basins in the world in 1987 and 1988 (Oki et al. 1999)

modeling of hydrology and groundwater are being incorporated into the models. Less developed are efforts to consider both natural and anthropogenic sources for nutrients, as well as their coupling to agricultural models that simulate crop growth and yield. Precise information on land use/land cover (LULC) is essential to have better estimates on nutrient, carbon and water cycles. Coupling of the LULC changes with biogeochemical and biogeophysical land surface model would be necessary for better future projections considering both climate and societal changes.

Hydro-meteorological monitoring networks need to be maintained and further expanded to enable the analysis of hydro-climatic trends at the local level and the improvement in the accuracy of predictions, forecasts, and early warnings. As clearly illustrated in Fig. 6 (Oki et al. 1999), global hydrological simulations are relatively poor in areas with little in-situ observations. Basic observational networks on the ground are critically crucial for proper monitoring and modeling of global hydrology; they are also needed to validate remotely sensed information that in turn is needed in order to fill the gaps of in-situ observations. Reliable observational data are essentially necessary not only as the forcing data for global hydrological modeling, but also for the validation of model estimates. River discharge and soil moisture data are critically important for global hydrological studies. Hence the cooperation and coordination of operational agencies in the world need to be prioritized and promoted.

Some key land surface processes, such as hydrology, have been represented in only simple ways in the current global climate models or earth system models due to their relatively minor impacts on the climatic feedbacks from the land surface to the atmosphere on global scales. It has also been pointed out that differences between land surface models is the major source of uncertainty in water balance estimates and multiple impact models are recommended to be used in this type of studies (Haddeland et al. 2011). However, land surface models with higher spatial resolution information are now being developed as impact assessment tools to support decision-making. Integrated land surface models that consider biogeochemical cycles and anthropogenic interventions explicitly (e.g., Hanasaki et al. 2010; Pokhrel et al. 2012a, b) need to be developed and implemented in order to provide more realistic impact assessments and to support the design of practical adaptation measures. In the WCRP conference held in Denver, CO, USA, in October 2011, these research needs and gaps were identified in the Land session. The identified research needs are outlined next:

- The observed and modeled feedbacks between land cover change induced by human activities needs to be assessed. Furthermore, the impact of deforestation on river flow, heat waves and wild fires should be investigated.
- There is a need to check that the earth system models are reproducing the simple signals that have been observed with large scale land use change, such as the cooling effect of deforestation under normal climate conditions, and the opposite warming effect under drought conditions.
- Current earth system models need to include and improve their representation of crop growth in order to better understand the role of land use change on the regional climate and subsequent impacts.
- WCRP, through efforts in GEWEX, has made great advances in understanding the land-atmosphere coupling and its relation to the hydrologic cycle. Yet, there are several areas that currently are poorly covered or not covered at all in the WCRP structure. Two GEWEX panels, GHP and GLASS, are the closest to the themes discussed in this paper, and could either assume or partner with other groups to lead efforts in the following areas: (a) Impacts of irrigation and water management on the hydrologic cycle of large basins; and (b) Effects of LULC on land-atmosphere feedbacks and its subsequent impact on river flows.
- For future states of the climate system, future assessments of the evolution of land use will require an interdisciplinary approach that considers not only the physical science but also societal aspects and economy information.
- A very challenging issue is that of prediction of land use changes based on society's future needs and responses to change. Assessments of future land use are important for climate prediction and climate change scenarios, and in this case

WCRP will have to partner with human dimensions groups (e.g., IHDP) in order to advance our knowledge of future states. Initiatives promoting interdisciplinary research that includes the physical aspects as well as human dynamics will be needed.

6 Concluding Remarks

Land use has had a large impact on water cycles and carbon changes over the twentieth century, and consequently understanding land surface processes is crucial for research of the climate system, and more so in relation with delivering policy relevant knowledge. The choices we make in LULCC will likely influence future climate through the water, carbon and energy balances and cycles.

Major advances in recent Earth System Models (ESMs) include state of art global scale land surface models that include anthropogenic activities such as irrigation, reservoirs and the carbon cycle. They are very promising to assess past, current and future global water crisis and may provide valuable information supporting better policy-making in crop and water management. The relation between biophysical effects of regional LULCC and global GHG is still unclear. For these reasons, LULCC matters at regional scale and so must be included in studies of climate change.

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