Land-use/cover change and climate

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Over the last several thousand years humans have increasingly modified existing land use and land cover to meet various socioeconomic needs. It is noted that by 1990, 45.7–51.3 million km^2 of the global land surface (35–39%) was being cultivated, with forest cover decreased by approximately 11 million km^2 since 1750 (Pielke *et al.* 2011). By 2000, only a few desert regions, the central Amazon and Congo Basins, and the Arctic and Antarctic had not been affected by land-use/cover changes (LULCC). Over the last several decades LULCC has been increasingly recognized as a major forcing of local, regional, and global climate on multidecadal timescales (e.g., Mahmood *et al.* 2014; Pielke *et al.* 2011). Observations and modeling studies demonstrate that LULCC impacts meso-, regional-, and potentially global-scale atmospheric circulations, temperature, precipitation, and fluxes. These effects can be observed over multidecadal to longer timescales. Moreover, global climate modeling research demonstrates that the impacts of LULCC on extreme temperatures, for example at continental or smaller scales, can be equal to or greater than the radiative effect of a doubling of atmospheric CO_2.

In this context, the primary aim of this entry is to highlight the role of LULCC in the climate system. The impacts of LULCC can be both biogeophysical and biogeochemical in nature. Both biogeophysical and biogeochemical type responses of the climate, therefore, are discussed in the following sections. Biogeophysical changes can result in the modification of leaf area index (LAI), surface roughness, and albedo, while biogeochemical changes are changes that occur in the carbon and nitrogen budget, and the budget of other trace atmospheric constituents. The following discussion addresses the impacts of long-term systematic LULCC (e.g., agricultural land-use change, deforestation) and short-term abrupt changes (e.g., rapid urbanization).

Climate System and LULCC

LULCC has both biogeophysical and biogeochemical impacts on climate. Biogeophysical changes modify the radiation balance, energy partitioning, and exchanges of energy, mass, and momentum between the land surface and the atmosphere as well as the terrestrial water budget (Figure 1). Biogeochemical changes impact, for example, the nitrogen and carbon fluxes.

The surface energy and moisture budgets for bare and vegetated soils can be of help in understanding the impacts of LULCC and can be written as:

$$R_N = Q_G + Q_H + Q_E \quad (1)$$

$$P = E + T + RO + I \quad (2)$$

where R_N represents the net radiative fluxes, P is precipitation, E is evaporation, T is transpiration, Q_G is the ground heat flux, Q_H is sensible heat flux, Q_E is latent heat flux, RO is runoff,

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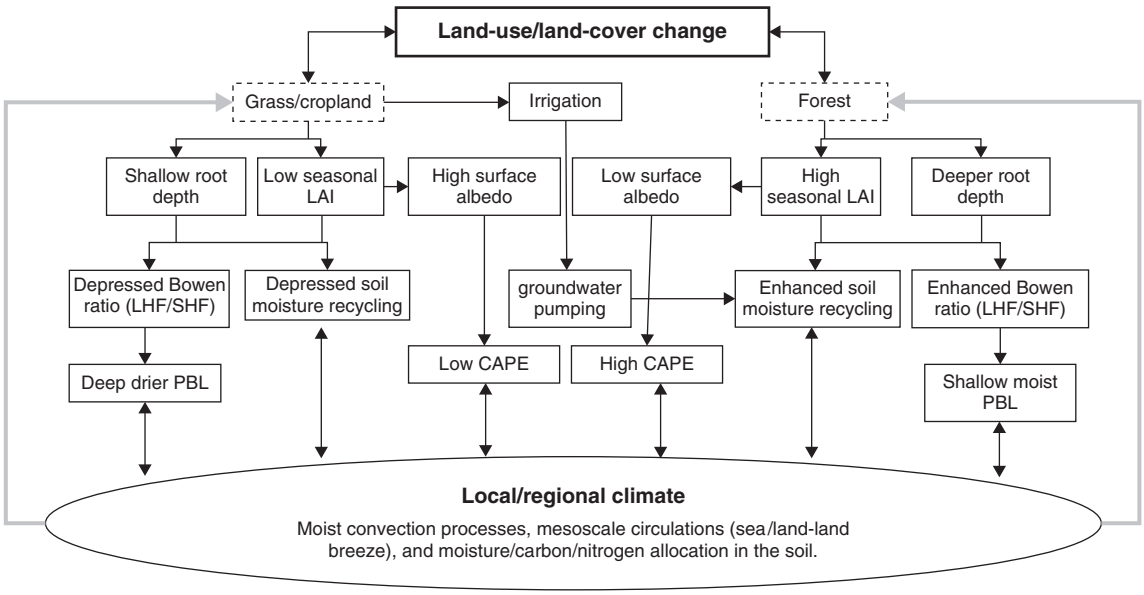

Figure 1 Conceptual model of the impacts of LCC on local and regional climate (Pielke *et al.* 2007).

and I is infiltration. Physical evaporation plus transpiration is also known as evapotranspiration (ET) and can be expressed in energy terms (latent energy flux). Transpiration is a plant physiological process which is linked to photosynthesis and a variety of other plant functions. These equations (1 and 2) also show that the energy and water budgets are linked and that LULCC affects these budgets. Surface budgets could also be completed for carbon, nitrogen, and other chemical species. Each of these budgets will be changed if any characteristic of the land surface is altered. This includes changes caused by land management (e.g., deforestation) and also ones that arise from phenology, drought, and so forth.

Similar budget equations can be written for carbon and nitrogen fluxes. The carbon budget, for example, involves the assimilation of carbon dioxide into carbohydrates within vegetation, respiration of CO_2 from plants and animals, decay of animals and plants, industrial and vehicular combustion processes, outgassing from oceans and other water bodies, and volcanic emissions. The nitrogen budget has also been segmented into its different components. Among these components, for example, nitrogen deposition clearly has major LULCC interactions as the amount of material deposited on land is very large. However, more studies are needed because vegetation will be affected differentially by this inadvertent fertilization of plants, with resultant impacts on albedo, as well as transpiring leaf area.

Changes in the heat and water budget necessarily alter the carbon and nitrogen budget (and that of other trace constituents), and alterations in carbon and nitrogen budgets (and in the other trace gases and aerosols) change the surface heat and water budgets. A major reason for all of these fluxes are closely coupled is that the transpiration of water vapor through the stoma of plants is not only associated with changes in the heat budget,

as shown earlier in this section, but also intimately involved with the assimilation of carbon into plant leaf, roots, and stems through their stoma.

If the amount of plant material changes, this alters the transpiration of water vapor into the air and thus the amount of carbon that is assimilated. The amount of nitrogen compounds and other trace nutrients affects plant growth and vitality. The intimate coupling of all of the surface budgets is a fundamental aspect of the climate system. In short, land management practices and LULCC that alter any one of these budgets necessarily alter all of them.

The following sections highlight the climatic impacts associated with some of the most notable types of LULCC. They include impacts of agriculture, deforestation and afforestation, and urbanization. Due to their relevancy and importance, also included are the impacts of CO_2 and aerosols.

Agriculture

The concept of human-induced vegetation cover changes having an effect on climate is not new. Pioneers of the Great Plains of North America believed that "rain follows the plow." While there is evidence that human agricultural practices may have begun transforming the Earth's atmosphere thousands of years ago, direct large-scale anthropogenic impacts on the Earth's land cover are difficult to document before historical times. The possible first impacts of human activities were on vegetation through hunting and fires that may have led to extinction of many native species. Subsequently, agriculture and the domestication of grazing animals began to alter land cover. The following discussion includes examples illustrating impacts of LULCC due to agricultural activities.

It is found that the shift to agriculture often results in a cooling in daytime temperatures and presents the largest magnitudes of cooling. For instance, up to a 1.41 °C cooling of maximum temperatures was found at irrigated locations in the Ogallala aquifer region (Figure 2). In a subsequent assessment, a 1.56 °C increase was reported in average growing season dew point temperature over irrigated areas, and also up to a 2.17 °C increase was documented in dew point temperature for peak growing season months. These changes were primarily linked to modification of energy partitioning led by enhanced latent energy flux due to the availability of additional water through irrigation.

One study noted significant reductions in mid-June to mid-July maximum air temperatures, diurnal temperature range, and solar radiation of 1.7 °C decade^{-1}, 1.1 °C decade^{-1}, and 1.2 megajoules per meter squared per decade (MJ m^{-2} decade^{-1}), respectively, over Canadian Prairies associated with agricultural activities. This research also found a precipitation increase of 10.3 mm decade^{-1}. Again, the increased latent heat fluxes from increased agricultural vegetation could lead to increases in dew point temperature without necessarily resulting in increased precipitation.

In northwestern India, up to a 0.34 °C cooling of growing season maximum temperatures was determined to be due to the introduction of irrigation. For individual growing season months, up to a 0.53 °C decrease of maximum temperature was reported and long-term temperature trends were largely negative and also statistically significant. These changes in temperature were associated with increased latent energy flux (Figure 3). Subsequent studies also suggest modification of dry season precipitation associated with irrigation and increased soil moisture and latent energy flux. Other modeling studies suggest changes in circulation over the

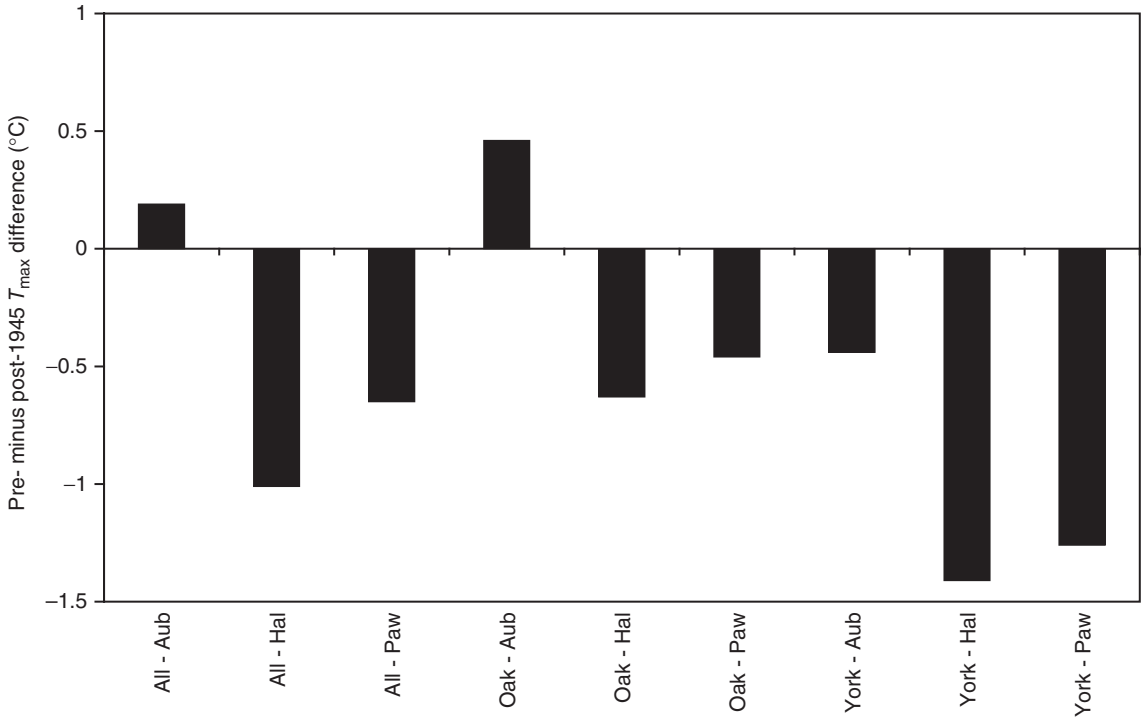

Figure 2 Cooling at irrigated locations in Nebraska, USA, during the post-1945 period. Negative values show cooling. Alliance (All), Oakland (Oak), and York are irrigated locations while Halsey (Hal), Auburn (Aub), and Pawnee City (Paw) are nonirrigated locations. Source: Reprinted from Mahmood *et al.* (2006) with permission from Elsevier.

Asian continent due to the widespread adoption of irrigation.

In a modeling study for modern-day land cover, there was a statistically significant warming for the austral summer (December–February) for mean surface temperature of 0.1–0.6 °C in eastern Australia and a warming of 0.1–0.4 °C for the coastal southwest corner of Western Australia, which is still largely covered by tall native forests. However, there was a significant cooling of 0.2–0.4 °C over the inland wheat belt for summer and austral winter (June–August). Further analysis of daily rainfall events indicates an increase in the number of dry and hot days, an increase in drought duration, and a decrease in daily rainfall intensity and wet day rainfall in southeast Australia.

From an observational study, (the 2005–2007 Bunny Fence Experiment (BuFex)) in southwest Australia, a favored area of cloud formation was found that was linked to land-use change (Nair *et al.* 2011). The cooling effect was most prominent during the summer when the land use in the agricultural area deviates most from the native land in terms of albedo, leaf area, vegetation cover, and surface roughness. Analysis of radiosonde observations showed, on average, the noontime planetary boundary layer (PBL) height was found to be higher by approximately 260 m over the native vegetation during summertime,

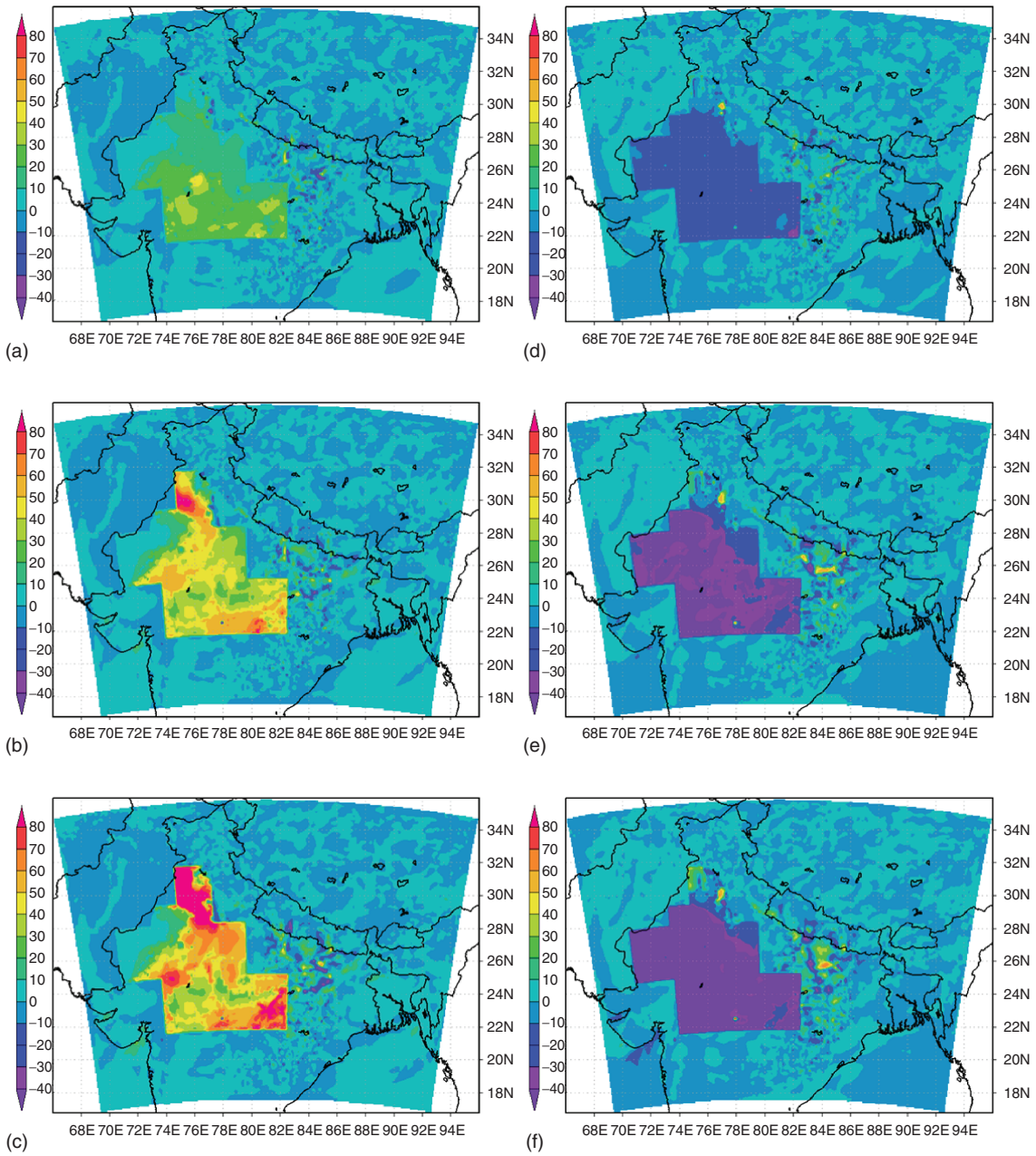

Figure 3 Latent energy flux differences (W m^{-2}) for March 23, 2000: (a–c) CTRL-DRY05, 10, and 15 and (d–f) CTRL-WET05, 10, and 15. Soil moisture was systematically decreased (DRY) and increased (WET) up to 15% with 5% interval (Sen Roy *et al.* 2007).

while over winter time the difference was approximately 189 m. Observations of energy fluxes from aircraft show that the enhanced boundary layer development was driven by sensible heat fluxes that were consistently higher over the native vegetation areas, with peak differences of approximately 200 W m^{-2} and approximately 100 W m^{-2} observed during the summer and winter seasons, respectively.

To address the effects of increasing cropped areas and afforestation on atmospheric processes in South America, Beltrán-Przekurat *et al.* (2012) performed sensitivity experiments using a fully coupled atmosphere-biospheric regional climate model. The general effect of agriculture was cooling when the shift was from grasses (with C3 metabolism) to crops, and warming when the shift was from grasses (with C4 metabolism), wooded grasslands, or trees. Near-surface temperatures decreased when crops (such as wheat and soybean) replaced C3 grasslands. Increases in temperature were found when crops replaced evergreen trees and wooded grasslands (e.g., in Brazil) and C4 grasslands (e.g., in the central region of the Pampas). The coolest (up to −0.8 °C) and warmest (higher than 0.6 °C) 2 m temperature differences (the difference at 2 m above the ground) appeared in the spring (October–November) averages. Maximum temperatures showed a larger decrease than minimum temperatures. Minimum temperatures slightly increased in summer in the southern Pampas. This also means a decrease in the diurnal amplitude of temperature. The results are consistent with the observed trends in temperature over Argentina.

Based on the observed responses of the climate system to agriculture-related LULCC, these regions where cooling occurs can be considered as "Agricultural Cool Islands" (ACI). This terminology could be applied to the landscapes dominated by both rain-fed and irrigated agriculture.

Deforestation, afforestation, and desertification

In many parts of the world, vast regions of original forest have been cut to permit agriculture, urbanization, and other human activities. Large areas of the Amazon are currently being clear-cut for agriculture or burnt by fire. This land-use change is referred to as *deforestation*. To reverse this deforestation, in some regions trees have been planted either to recreate an originally forested area or even to introduce forests where none exists. An example of the latter is Nebraska National Forest in the United States. Moreover, in response to various policy responses related to conservation efforts and to increases in carbon sink, some regions in the world have made efforts to plant vegetation and create new forests. This type of land-use change is called *afforestation*.

Observational studies have shown that deforestation results in changes in regional temperature, cloud cover, convection, and precipitation and is linked to changes in albedo, surface roughness, and land surface hydrology. Deforestation has been shown in a modeling study to cause changes in regional and mesoscale wind circulations and cloud formation in the Amazon. The dynamics involved in LULCC-driven climate change in the subtropics are slightly different from those in the tropics. Land surface and atmospheric radiation balance plays an important role in the establishment and maintenance of semi-arid regions. Positive feedbacks from a reduction in vegetation cover and its concomitant albedo increase can further exacerbate desertification. It is suggested by the scientific community that the interplay between vegetation, moisture, and

weather in the subtropics may create preferred modes of variability and preferred states of stability of climate in these areas.

Desertification occurs when a region that was covered in grassland or even forests is replaced by sparse desert plants or even bare soil. Studies have shown that changes in albedo are key to the climate response. Moisture is an important limiting factor in the subtropics, and modeling studies show that reductions in surface moisture tend to disrupt further precipitation by inhibiting moisture recycling. Modeling research shows that vegetation degradation in the Sahel produced rainfall anomalies consistent with the observed multidecadal drought in that area.

Model simulations were completed to assess modern era vegetation and that of earlier times. Restoring vegetation for the times of the Roman Empire, for example, caused summer rainfall in the model to increase in southern Europe and the Atlas Mountains, the lower Nile Valley, and the Levant (e.g., Reale and Dirmeyer 2000). Model responses to LULCC in the mid-latitudes tend to be more subtle and complex, because agriculture displaces both forest and prairie/steppes, with opposite effects on albedo and roughness, making the response highly sensitive to the details of the experiment's implementation.

As expected, afforestation also inadvertently modifies biogeophysical and biogeochemical characteristics of a region and thus regional climate. Afforestation in temperate and tropical South America has led to cooler and wetter near-surface atmospheric conditions over most of the afforested areas, associated with higher and lower latent and sensible heat, respectively, than in current land cover conditions (Beltrán-Przekurat *et al.* 2012). Modeling research found temperature differences between current and afforested conditions were 0.6 °C and 0.8 °C in spring and summer, respectively. Higher evaporation and transpiration rates and lower temperatures in forest compared to grasslands were also found in an observational study of the area.

Precipitation is also affected by the vegetation changes in temperate and tropical South America. Domain-averaged precipitation showed an increase in natural versus afforested simulations: absolute mean values were higher, up to 30 mm month^{-1} in summer, compared to current conditions. Relative changes were up to 30% in the afforested condition. Spatially, areas of increased rainfall were associated with changes in latent heat, roughness length, and areas of moisture convergence. Some dependency of afforestation pattern and moisture flux convergence was also observed, indicating that interannual variability in the fluxes may also affect the simulated patterns and magnitudes (Beltrán-Przekurat *et al.* 2012).

Urbanization

Humans tend to concentrate in cities. Although covering less than 0.5% of the Earth's land surface, cities still exert a significant effect, out of proportion to their fractional coverage, on regional and global climate both from their LULCC, through their effects on the surface energy budgets, the water cycle, and surface biogeochemical cycles (e.g., carbon, nitrogen), and from their aerosol and gas emissions. This type of LULCC is referred to as *urbanization*.

The urban heat island (UHI) (Figure 4) is probably the most well-studied process with respect to weather and climate processes. A net surplus of surface energy over urban regions can be explained by enhanced surface sensible heat flux, ground heat storage, and anthropogenic heating as well as changes in physical evaporation and transpirational cooling. Because urban

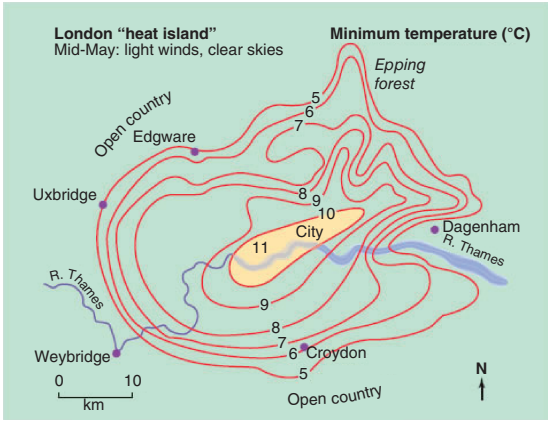

Figure 4 Urban Heat Island of London (Pielke 2013).

regions typically have lower albedo values than rural areas (except, for instance, for urban areas embedded in coniferous forests), they absorb more shortwave radiation energy at the surface. Smaller values of the sky view factor (SVF) below roof level result in decreased radiative loss and turbulent heat transfer and add to the UHI anomaly.

UHI's impacts can vary depending on existing climate regime and the vegetation type both within and surrounding the urban area, latitude, seasons, and even time of day. For example, over temperate regions, UHI can produce urban–rural sensible heat flux differences leading to a city center as a significant heat source. This is linked to the removal of forests, vegetation, and wetlands and the replacement by the built environment. On the other hand, over arid and semiarid regions urbanization may result in the introduction of irrigation and the resultant increase of latent heat fluxes. Moreover, it is found that over high latitudes, the urban–rural temperature differences are the highest during winter.

Urban land use can also modify, amplify, reduce, or initiate precipitation cloud systems since the surface heat, moisture, and momentum fluxes are altered from the surrounding non-urban landscape. Rainfall is often, therefore, different over the urban regions and downwind compared to nonurban areas, as verified by both in situ and satellite datasets. Thunderstorm rainfall can be increased over urban areas, for example, when the added heat from urban areas invigorates these storms. In semiarid irrigated urban areas, the cities also add water vapor to fuel the thunderstorms. UHI is a well-studied process; however, uncertainties still exist and a better understanding of the built-up environment and its effects on various aspects of the Earth's weather and climate system is still emerging (e.g., Shepherd *et al.* 2013).

Carbon dioxide (CO_2) and LULCC

The association of LULCC and the carbon cycle is well known. Eastman, Coughenour, and Pielke (2001) investigated regional weather conditions in the central grasslands of the United States for three experimental scenarios using a model: (i) land cover was changed from current to potential vegetation; (ii) radiative forcing was changed from $1 \times CO_2$ to $2 \times CO_2$; and (iii) biological CO_2 partial pressures were doubled. Results indicate that the biological effect of enriched CO_2 and of land-use change exhibit dominant effects on regional meteorological and biological variables, which were observed for daily to seasonal timescales and grid to regional spatial scales. Simulated radiation impacts of $2 \times CO_2$ were minimal on these space- and timescales, with interactive effects between the three experimental scenarios as large as the radiational impact alone. Model results highlight the importance of including $2 \times CO_2$ biological effects when simulating possible future changes in regional weather.

Other modeling studies have shown that the inclusion of biospheric feedbacks due to increased CO_2 impacts the LULCC simulations. These studies have noted that these impacts are non-negligible and could be compared to changes associated with radiative forcing. Separate modeling research suggests that the impacts of LULCC initially remain over the areas of change and subsequently could be found over remote areas as well. In addition, it has also been noted that increased CO_2 does not negate the impact of LULCC but rather produces statistically significant regional effects. Regional modeling studies show that LULCC and increased CO_2 impact temperature and precipitation in China. It was found that increases in CO_2 resulted in increases in both maximum and minimum temperatures. Precipitation intensity has also changed due to LULCC and accompanying increases in CO_2. Moreover, modeling research demonstrated that LULCC and increased CO_2 modify return values of extreme maximum temperature and convective precipitation over Europe and China.

Aerosols and LULCC

It is well known that the impacts of aerosols on atmospheric processes, especially PBL layer evolution, are strongly coupled to surface processes and thus underlying land use. Depending on the albedo of a surface, aerosols can result in either warming or cooling of the PBL. Typically, aerosols over a high albedo surface result in warming, while those over a low albedo surface lead to cooling of the boundary layer.

Different atmospheric responses to aerosol radiative forcing over different land-cover types imply that aerosols modify horizontal temperature gradients and mesoscale circulations induced by land surface heterogeneity. Numerical simulations found that radiative forcing resulting from Saharan dust is rapidly reflected in the surface energy budget for land, causing a daytime reduction in downwelling radiation at the surface, and a corresponding reduction in sensible heat flux and boundary layer air temperature. However, over the ocean, since the radiation is absorbed over a deep layer compared to land, radiative forcing has little impact on the surface energy budget at short timescales. As a result, over the ocean, direct heating of air by the dust aerosols dominates and leads to an increase in air temperature. The net effect of aerosols, therefore, is to reduce the land–ocean thermal gradient in the PBL.

The coupled aerosol and land-cover change impacts on the modulation of mesoscale circulations may thus be especially significant in maritime environments. Sea breeze circulations, for example, are an important driver of convective activity tied to small islands. As a result, concurrent land-cover change and biomass burning in maritime settings and the combined impact of these two forcing mechanisms will influence deep convection, but this is not well understood.

A recent work by Junkermann *et al.* (2009) shows that land-cover change can affect the atmospheric distribution of aerosols and cloud condensation nuclei (CCN) which thus impact cloud microphysics. Aircraft observations over southwest Australia show that the differing biogeochemistry of salt lakes in the cleared areas and emission of aerosol precursors lead to approximately doubled CCN concentrations over this region compared to adjacent native vegetated regions. Corresponding differences in cloud particle size distribution are also observed in the clouds over the native vegetation region. Higher concentration of cloud droplets with diameters greater than 10 μm were found over native

vegetation, while the cleared agricultural regions showed higher cloud droplet concentrations for particle diameters less than 10 μm.

Final remarks

This entry clearly demonstrates many impacts of LULCC on the climate system at all spatiotemporal scales through a variety of pathways and mechanisms. Moreover, after decades of scientific work around the globe, LULCC is now considered as a first-order climate forcing. However, additional research needs to be conducted to permit a further understanding of the pathways through which LULCC affects the climate system. This requires the establishment of in situ observational platforms in areas of rapid LULCC and also in and around where LULCC has already occurred, for example, in and around irrigated areas. It is also important that sustained funding be available for already established high quality in situ networks. Examples of such networks are the US Climate Reference Network (USCRN), and the Oklahoma, Kentucky, Nebraska, and Delaware mesonets. Similar funding stability should be provided to maintain the continuity of various satellite missions (e.g., Landsat). These observational capabilities should be complemented by simultaneous efforts for the improvement in modeling of the weather and climatic impacts of LULCC. We conclude that observational capabilities are essential for improvement and validation of modeling of LULCC effects.

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SEE ALSO: Agroclimatology; Climatology; Desertification; Land change science; Urban climatology

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