Atmospheric and Oceanographic Sciences Library 44

Nicole Mölders

Land-Use and Land-Cover Changes

Impact on Climate and Air Quality

Springer

Land-Use and Land-Cover Changes

ATMOSPHERIC AND OCEANOGRAPHIC SCIENCES LIBRARY

VOLUME 44

For further volumes:
http://www.springer.com/series/5669

Nicole Mölders

Land-Use and Land-Cover Changes

Impact on Climate and Air Quality

Springer

Nicole Mölders
Department of Atmospheric Sciences
College of Natural Sciences
and Mathematics
Geophysical Institute
University of Alaska Fairbanks
903 Koyukuk Drive
Fairbanks, AK 99775
USA
molders@gi.alaska.edu
cmoelders@alaska.edu

ISSN 1383-8601
ISBN 978-94-007-1526-4 e-ISBN 978-94-007-1527-1
DOI 10.1007/978-94-007-1527-1
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2011936018

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Acknowledgments

I would like to thank the most my father – Hermann W. Mölders – for evoking my interest in land-cover-related weather and climate change. He brought the climate–land-cover relations of the Sahel drought and potential climate impacts of irrigation to my attention when I was a teenager.

I also would like to express my thanks to Prof. Dr. Hantel and Prof. Dr. Kramm who encouraged me to write this book. I wish to thank my colleague Prof. Dr. Kramm and my graduate student Huy N.Q. Tran for fruitful discussions and helpful comments during the process of writing this book.

Thanks go also to my former mentors Prof. Dr. Raschke, Prof. Dr. Ramond, Prof. Dr. Pointin, Prof. Dr. Ebel, Dr. Laube, Prof. C. Walcek, Prof. Dr. Tetzlaff, and Dr. Raabe who helped me to become the scientist I am today.

Contents

Chapter 1

Introduction

Land-cover and land-cover changes (LCC) affect the moisture and temperature states as well as the composition of the atmospheric boundary layer (ABL). The often-unpleasant conditions in cities in summer are one of the most obvious examples of how land-use, that is the realization of the actual land-cover affects local weather and climate and, indirectly, air quality.

Land-cover changes can range from the modification of the landscape character without affecting the existing overall classifications to the extreme case, where one land-cover type completely replaces another. The latter is often referred to as land conversion (LC). Land-cover modification refers to anthropogenic (e.g., deforestation for agricultural expansion) or naturally caused (e.g., flooding, wildfire, disease, epidemics) LCC. In both cases, the replaced spatial entities can fall into a different land-cover category. In the first case, the replaced spatial entities may be just an alteration of extent, shape, and/or shift in location of the previous land-cover/use, or fragments or coalescence of a land-cover class. The location, temporal and spatial scales of various LCC differ among each other depending on the causes for the LCC.

Since humankind, the Earth's landscapes experienced naturally caused and anthropogenic LCC as well as local LC. Since on a small scale, in the sense of the micro-scale/meso-γ-scale classification by Orlanski (1975) (Fig. 1.1), all LCC can be viewed as LC, the distinction is not made any further throughout this book. Furthermore, no distinction between land-cover and actual land-use, and LCC or land-use changes will be made except if it serves for better understanding.

N. Mölders, *Land-Use and Land-Cover Changes*, Atmospheric and Oceanographic Sciences Library 44, DOI 10.1007/978-94-007-1527-1_1,

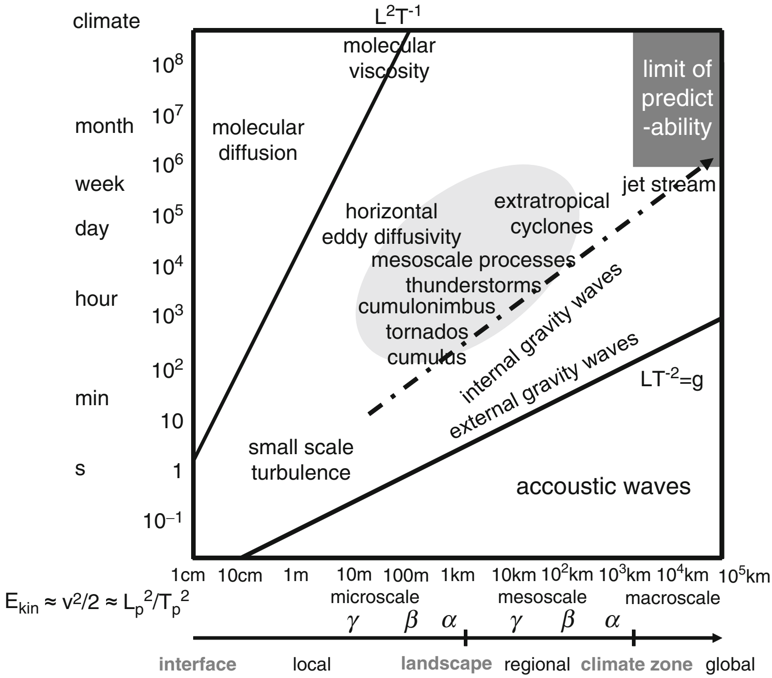

Figure 1.1. Definitions and different processes associated with characteristic temporal and spatial scales (Adapted from Orlanski (1975))

1.1 Natural Land-Cover Changes

Land-cover not only affects the local atmospheric conditions, but also is itself affected by local weather and depends on local climate. Consequently, land-cover may change naturally in response to extreme weather events that cause wildfires or lasting flooding, or multiple-year droughts. Land-cover changes in response to climate change include sea-level rise, invasion of non-native plants and shifts in ecosystem boundaries. Other driving forces for natural LCC are earthquake or otherwise induced landslides, and volcanic eruptions. In a broader sense of surface changes, we may consider break-off of ice shelves, glacier retreat, permafrost retreat and/or warming as near-surface responses to climate change.

Natural LCC may occur gradually or abrupt. Examples for gradually occurring LLC are desertification, non-native invasion of plants, shifts in ecosystem boundaries, or wildfire-succession landscapes. The Younger Dryas provides an example for LCC induced by climate change. The Younger Dryas was an abrupt cold event in the Northern Hemisphere during the last deglaciation between ∼12,800 and 11,500 BP. Once the ice had receded far enough, the continental runoff that formerly discharged into the Gulf of Mexico via the Mississippi River partly discharged to the St. Lawrence River. The increased freshwater inflow into the North Atlantic affected the thermohaline circulation and reduced the poleward ocean-heat transport. The resulting subsequently altered ocean-surface conditions led to more sea-ice and a decrease of about 5 K in near-surface temperatures. In response to the cooler "climate," glacial tundra replaced the forests in Scandinavia (Munro 2003).

Examples of rather abrupt surface changes are associated with glacier retreat and often-related ice-shelf break-off. Glaciers and shelves calf naturally; however, the frequency and amount may be affected by climate change. Time-series of the extent of nine Antarctic Peninsula ice shelves, for instance, show that the five northern shelves have retreated radically (Vaughan and Doake 1996) since the third International Polar Year (1957–1958). Between 1966 and 1989, the Antarctic Wordie Ice Shelf decreased by ≈1,300 km^2 (Rott et al. 1996). In January 1995, 4,200 km^2 of the northern Antarctic Larsen Ice Shelf broke off after a time of steady retreat in response to regional warming. Satellite radar images of the Larsen Ice Shelf and neighboring glaciers showed further retreat of several kilometers inland of the previous grounding line after the 1995 collapse (Rott et al. 2002).

Ice-shelf retreat/collapse is not unique to Antarctica. Between 2000 and 2002 the largest Arctic ice shelf, the Ward Hunt Ice Shelf in Canada, broke off; in consequence, an epishelf lake – a rare ecosystem type – was lost (Mueller et al. 2003).

Some natural LCC may be self re-enforcing, while most natural LCC are temporary and self-correcting. Prominent examples for self re-enforcing LCC are snow-covered land, ice caps and glaciers. A change in the extent of these land-surface types increases the region's albedo, which may lead to cooling. In the relatively cooler atmosphere, the partitioning of precipitation shifts further in favor of snow, which may further extend the area of snow-cover and glacier. Over oceans, lower temperature may enhance the formation of sea ice. This positive climate-feedback process is known as the snow-albedo or albedo-temperature feedback.

Fires are another example for self-correcting LCC despite the fact that they work through a biological rather than (geo)physical mechanism. Fires are the most important natural disturbance agent that leads annually to over $3 \cdot 10^6\,km^2$ of LCC worldwide. Since millennia, lightning-caused wildfires have initiated a natural gradual changing of landscapes with fire-adapted ecosystems. In such ecosystems, regrowth requires months to decades or longer depending on fuel type. All fire-succession landscapes show little to no biomass growth in the year of the fire. Grass and herbs start growing on the burned area in the first years after the fire followed by shrubs and, in naturally forest-dominated regions, trees (Mölders and Kramm 2007).

In case of self-correction of land-cover after fires, the time for self-correction depends on the climate zone and original land-cover and has implications for the frequency of wildfire occurrence. Boreal forest, for instance, requires about 80 years for recovery. Burned tundra recovers 50–100% after 5–6 years, while concurrently the thawing of soil stabilizes (Racine et al. 1987). Since grass and shrubs regenerate fast, landscapes with high presence of fine fuel may experience fires with larger horizontal extent and in shorter intervals between fires than landscapes dominated by woody fuel.

Economic and political changes may affect natural LCC, too. For instance, fire-management policies and changes thereof affect the annual area burned and the location where LCC due to wildfires occur. Invasive fire-prone species, fire suppression, prescribed burnings and related fuel changes, clearance, and intensive grazing increase fire susceptibility. Economic changes affecting subsistence and agricultural economies, tourism and recreation have led to an increase in population at the wildland-rural border. Consequently, the extension of areas with different fire-management degrees has changed over time. Such changes may have consequences for the disturbance regimes, ecosystem dynamics, biodiversity, carbon storage, emission of trace gases and particles, and atmospheric composition.

1.2 Anthropogenic Land-Cover Changes

Anthropogenic LCC or LC occur because of changing management practices or altered purpose (e.g., logging, ranching, cropping, construction, water storage) of land-use (e.g., forest, grassland, cropland, urban land, artificial lakes). Typically, anthropogenic LCC will persist for long time if the purpose of the LCC is a new land use. Anthropogenic LCC occur for food production (agriculture, grazing), biofuel production, establishing and/or growth of settlements and industrial areas, forest harvest and managing, and creation of water reservoirs, just to mention a few purposes. The reasons for LCC and their extension differ regionally and temporally. Since 1850, about $4.7 \cdot 10^6\,\mathrm{km}^2$ of savannahs, grasslands, and steppes and $6 \cdot 10^6\,\mathrm{km}^2$ of woodlands and forests were converted to croplands (Sivakumar 2007).

Anthropogenic LCC may occur in response to natural LCC and/or climate changes. The Younger Dryas – despite its initial LCC were caused naturally – provides also an example for climate-induced anthropogenic LCC. The cold and dry conditions of the Younger Dryas reduced the availability of food and forced the population into a more mobile subsistence life style. The continuing climatic deterioration may have led to cereal cultivation at the end of the Younger Dryas (Munro 2003). Concurrently, settlements started along rivers.

Today's landscapes developed from the natural landscapes mainly due to regional anthropogenic LCC. In North America, for instance, agriculture was introduced gradually westward with the land demands of new settlers, while in Europe, agriculture is millennia old. The long history of agriculture established the predominantly cultural character of the European landscapes (Klijn 2004). The cultural landscapes range from semi-natural (often-subsidized) grassland in the high Alps and overdrained marshes and wetlands for extensive grazing in Middle and Eastern Europe to completely man-made and high-maintenance polders in The Netherlands.

Worldwide, the extension of cultivated areas changed over time due to changes in local or regional climate, demographic, economic, political and/or natural conditions and agricultural techniques (e.g., introduction of the plough, artificial fertilizer, irrigation). In Europe, for instance, agriculture employed more than 80% of the work force at the beginning of the Middle Age. The population decline due to the pest caused land abandonment (Klijn 2004). Between 1400 and 1800, the agriculturally used area increased. After 1800, the application of agricultural science, and improved education and technology increased the agricultural production. The increase in production and cheap imports from the USA, Canada, Australia and Third World countries led to a decrease of the extent of agriculturally used land. In the first half of the last century, the food demands of the rapidly growing population required to convert formerly poor, less suitable soils into agriculturally used land by means of artificial fertilizer. After the foundation of the European Union (EU), subsidies frequently changed the percentage fraction of what crops were grown. Moreover, the yields per hectare increased due to various economic incentives and policies.

In America, for instance, the settling of the contiguous USA required fertile land for agricultural purpose and wood for construction. Since 1600, these demands led to deforestation of 90% of the virgin forests (Fig. 1.2). In the last century, the vast majority of deforestation in the Tropics occurred for economic reasons. In Amazonia, the deforestation

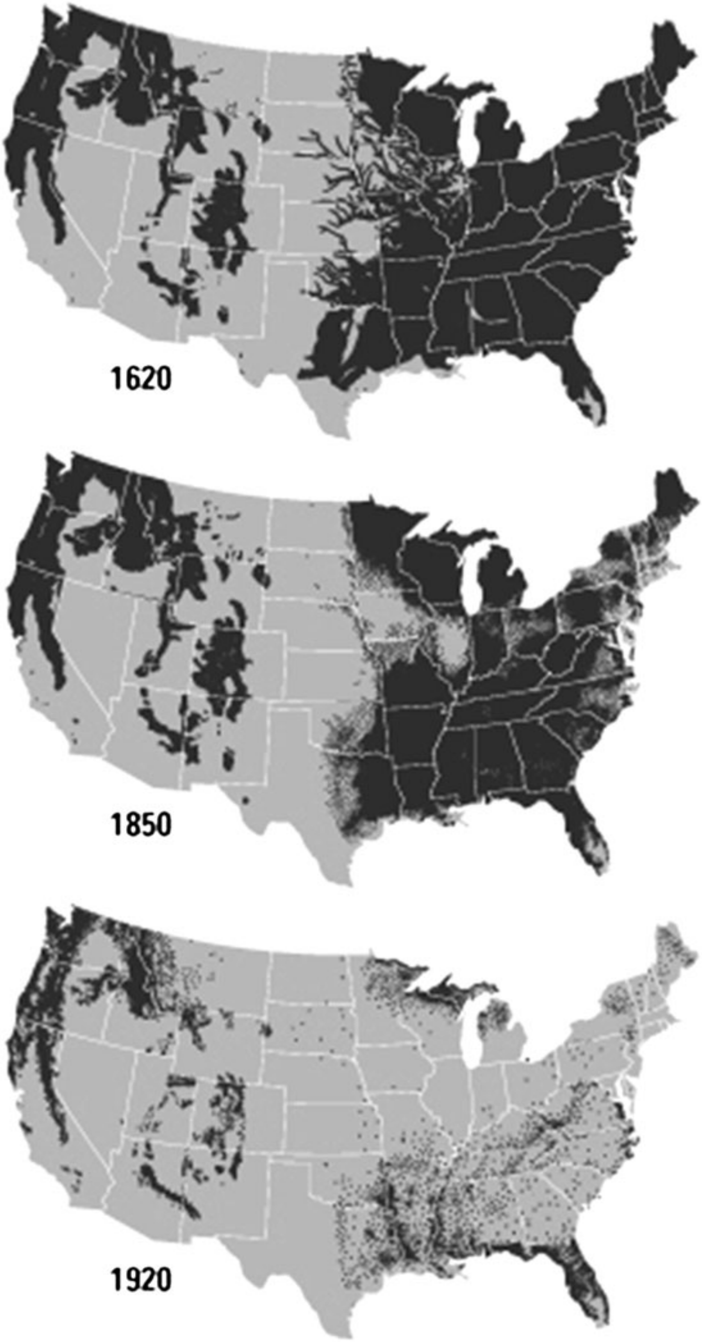

Figure 1.2. Example of historic land-cover changes for the contiguous USA. The *dark gray* area indicates natural forests (Modified after: http://www.globalchange.umich.edu/globalchange2/current/lectures/deforest/defores9.JPG)

served to provide land for the poor, while in Asia, powerful families and local governments benefited from harvest concessions. The Tropics of Africa, Latin America, and Asia still have a deforestation rate about 0.8%, 2% and 2% per year, respectively (http://www.globalchange.umich.edu/globalchange2/current/lectures/deforest/deforest.html).

Over time, political changes and subsidence policies led to LCC and/or land-use change. The collapse of the Eastern Block, for instance, meant a shift from large monocultures to individually managed fields. This change in agricultural production increased the heterogeneity of the landscape and altered the pattern of biogenic emissions. Another example for LCC due to political changes is related to the unification of the German states. The new economic conditions led to construction of commercial areas and housing and rearrangement of agriculturally used land in East Germany. Due to the poor quality of the lignite coal, the open-pit mining activities were reduced appreciably. Some of the open-pit mines were closed, and flooded or re-cultivated. These LCC affected local weather (Mölders 1998), anthropogenic and biogenic emissions and, hence, air quality.

An example for the impact of subsidence policies on land-cover and/or land-use is biofuel production. The EU, for instance, set targets of replacing 2% of the union's fossil fuel needs with biofuel. This policy increased the fraction of land-cover used for rapeseed, corn and beet fields. In the USA, grants, loans and tax incentives for biofuel production increased rapidly the fraction of land used for corn production that serves to produce ethanol.

Anthropogenic land-use changes may also occur in response to short-term climate variability. Three to five years of favorable weather for a certain crop (e.g., winter wheat) typically encourage more farmers to sew this crop in the next season. A few years of weather-conditions leading to low yields of a certain crop reduce the fraction of land used to grow this crop. The resulting shortage may cause an increase in the fraction of land used for this crop later on.

1.3 Land-Cover Changes and Weather and Climate

Research on LCC began in the 1960s and 1970s, as the public raised concerns about urban climate, the climate impact of tropical deforestation, and the causes of the great droughts in the Sahel and how to overcome them (Budyko et al. 1971; Potter et al. 1975; Loose and Bornstein

1977). Deforestation was also of concern since a long time, because it reduces the carbon storage and modifies the carbon cycle. Research related to the great droughts in the Sahel led to the hypothesis of biometeorological feedback cycles. The increased albedo due to vegetation loss in the Sahel would trigger sinking motion, additional drying and would foster the arid conditions (Charney et al. 1975).

Today, it is well accepted that LCC can modify local climate conditions significantly (in a statistical sense). However, the full significance of LCC impacts on large-scale (i.e., macro-scale in the classification by Orlanski (1975); Fig. 1.1) climate is still under scrutiny. Land conversion, land-cover and/or land-use changes at all scales have been found to feed back to weather and climate. The impacts of LCC occur highly regionalized and mainly coincide with the population distribution. The anomalies caused by LCC vary with climate region, season, extension of area changed, type of LCC, distance from the LCC and duration over which the LCC persist.

The urban heat-island effect is the most prominent example for impacts of local LCC on local weather and climate. Studies focusing on urban climate showed that urban areas affect the energy budgets (e.g., Kerschgens and Drauschke 1986) and, hence, the distribution of temperature, clouds and precipitation (e.g., Changnon and Huff 1986) and may affect frontal systems (Loose and Bornstein 1977). Examples of regional impacts of LCC are the increased humidity, moderate diurnal temperature cycle, and altered distribution and amount of precipitation after the establishing of large water reservoirs (e.g., Stivari et al. 2005).

Any LCC affect the atmosphere via altered surface characteristics and altered biogenic emissions. The change in surface characteristics modifies the physical conditions of the atmosphere via shifts/changes in biogeophysical processes (e.g., albedo feedback, cloud-evapotranspiration (i.e., the sum of evaporation and transpiration) feedback. The altered biogenic emissions modify the atmospheric composition. If the emitted species are greenhouse gases (GHG), the LCC may affect climate also via altered absorption. Therefore, the increased methane emissions associated with the expansion of rice production are of great public concern.

In case of LCC due to wildfire or slash-and-burn land clearance, the direct process of the LCC affects the atmospheric composition notably at the time the LCC actually occur. Biomass burning, for instance, contributes probably to about 40% of the carbon dioxide, 32% of the carbon monoxide, 20% of the particulates, and 50% of the highly carcinogenic poly-aromatic hydrocarbons emissions worldwide (Sivakumar 2007).

From a scientific point of view, questions related to LCC impacts on the atmosphere are:

- How do LCC affect the atmosphere and its composition and by which mechanisms?
- Do the same LCC produce the same atmospheric responses independent of where they occur?
- What is the critical extent of LCC to produce a significant atmospheric response?
- Do LCC impacts remain locally, or do they affect areas far remote from the LCC? If so, what are the mechanisms causing local and/or remote changes?
- Do simultaneously occurring LCC enhance or diminish each others' responses?
- Do LCC have the same atmospheric responses under altered climate conditions?
- How do the concurrent LCC and GHG impacts on the atmosphere interact with each other?
- Are there possibilities to offset LCC impacts on the atmosphere?
- How does a warming climate affect or trigger natural LCC?
- What are the driving atmospheric forces for natural and anthropogenic LCC?

This book summarizes structures and presents the current knowledge on LCC and land-use change impacts on weather, climate and atmospheric composition, to address these questions. Chapter 2 reviews briefly the theoretical background of atmospheric processes that react sensitive to LCC and the atmospheric anomalies caused by LCC. Chapter 3 presents land-cover impacts on the atmosphere found for current climate conditions from major field campaigns and modeling studies reaching from the local to global scale. Chapter 4 reviews studies on LCC under future climate conditions, including biogeochemical feedbacks; elucidates the challenges related to future LCC and their impact on weather, climate and air quality; elaborates the uncertainties and discusses potential solutions. Chapter 5 presents conclusions and suggests future investigations to explore variables, key parameters and processes that were found to be important. It also poses critical hypotheses that need to be tested in the future.

References

Budyko MI, Drozdov OA, Yudin MI (1971) The impact of economic activity on climate. Sov Geogr Rev Trans 12:666–679

Changnon SA, Huff FA (1986) The urban-related nocturnal rainfall anomaly at St. Louis. J Clim Appl Meteorol 25:1985–1995