Savarino, J., A. Romero, J. Cole-Dai, S. Bekki, and M.H. Thiemens, UV induced mass-independent sulfur isotope fractionation in stratospheric volcanic sulfate, *Geophys. Res. Lett*., **30** (21), 2131, doi:10.1029/2003GL018134, 2003.

Zielinski, G.A., Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the Greenland- Ice-Sheet-Project-2 ice core, *Journal of Geophysical Research*, Atmospheres, **100** (D10), 20937-20955, 1995.

Land–surface changes: feedbacks and climate forcing

Sandy P. Harrison
School of Geographical Sciences, University of Bristol, Bristol, UK, sandy.harrison@bristol.ac.uk

Climate changes affect vegetation productivity and distribution, surface hydrology including the extent of lakes and wetlands, and soil moisture regimes and, through these, susceptibility to erosion by wind and water. These changes in land-surface conditions in turn affect the physical properties which control water- and energy-fluxes between the land and the atmosphere, and hence can amplify or mitigate the impact of the original climate change. In this sense, land-surface changes can be regarded as feedbacks within the climate system. However, anthropogenic changes in land-surface conditions, caused for example by urbanization, deforestation or agricultural exploitation, produce similarly large changes in physical properties and such changes must be regarded as an independent forcing of the climate system.

The palaeorecord leaves us in no doubt that there have been substantial and often dramatic changes in land-surface conditions (e.g. Kohfeld and Harrison, 2000). The dramatic conversion of the Sahara into a landscape with large lakes, extensive wetlands and shrubby vegetation during the earlier part of the Holocene (ca 11,000 to 5500 years ago), or the large-scale replacement of boreal and temperate forests by steppe-tundra vegetation across Eurasia during the last glacial maximum (ca 21,000 years ago), are well documented. Palaeoenvironmental and isotopic evidence document the existence of freshwater lakes and moisture-demanding vegetation in central Australia between 30,000 and 65,000 years ago. During the last interglacial (ca 125,000 years before present) boreal forests extended to the Arctic coastline and wetter conditions associated with expansion of the northern hemisphere monsoons produced large lakes in northern Africa. Earlier periods in the Earth's history provide even more dramatic examples of land-surface changes, including the existence of forest in polar regions until ca 3 million years ago. It is hardly surprising, then, that some of the earliest work to demonstrate the importance of land-surface feedbacks in the climate system were concerned with past times.

Investigations of the role of land-surface changes on regional palaeoclimates have tended to focus on iconic features, for example, the amplification during interglacial periods of arctic warming by northward extension of boreal forest and of northern-hemisphere monsoons by the expansion of moisture-demanding vegetation (see e.g. Kutzbach et al., 2001; Wohlfahrt et al., 2004). Despite the very different types of models and experimental approaches used in these studies, a number of robust conclusions about the way land-surface changes affect climate have emerged.

In the high latitudes, the most important influence of land-surface conditions on the climate system is through changes in surface albedo. Albedo during the winter season is much lower in regions characterized by tall vegetation (high shrubs, trees) than in regions without such vegetation because of the masking effect of vegetation on the underlying snow. Northward expansion of forest vegetation, in response to orbitally-induced warming in the mid-Holocene or last interglacial, resulted in a reduction in albedo and hence increased surface warming. The impact of this vegetation-snow-albedo feedback is most marked during spring, when radiation receipts are increasing but the ground is still snow covered, but has a non-negligible effect during other seasons such that vegetation reduces the cooling due to orbital forcing in winter and produces year-round warming in the high northern latitudes. There is still considerable uncertainty about the magnitude of the warming due to vegetation feedback: early experiments suggested that vegetation-induced changes were substantially larger than those due to orbital forcing, but later studies indicate that realistic changes in vegetation cover produce a summer warming of 50-90% of that induced by orbital changes alone.

Albedo changes are also important in monsoonal regions. Studies of the impact of land-surface changes in northern Africa during the mid-Holocene, initially induced by orbitally-forced changes in the monsoon, indicate that vegetation-induced lowering of albedo led to warming of the continent, enhancing land-sea contrast and increasing onshore advection of moisture. When compared to the effects of mid-Holocene insolation changes, the presence of vegetation enhances warming in spring and hence initiates an early onset of monsoonal precipitation. Vegetation cover also prolongs the monsoon season in autumn, in large part because it decreases the reliance on moisture advection and maintains monsoonal conditions through enhanced moisture recycling. Other land-surface changes, including the expansion of lakes and wetlands, also increase moisture recycling. The impact of land-surface changes on the African monsoon is comparable in magnitude to the increase due to orbital forcing during the mid-Holocene.

Given the importance of land-surface feedbacks in regional palaeoclimates, it is natural to expect that climate-induced changes in natural vegetation will play a role in future climate change. Recent warming in the Arctic has indeed led to reductions in snow cover and the expansion of shrub and tree cover. Chapin et al. (2005) have suggested that these changes in land-surface conditions have led to local increases in atmospheric heating by up to 3 Wm-2 per decade. However, considerably more attention has been focused on the potential impacts of direct anthropogenic modification of land-surface conditions on the climate system. There have been large changes in the nature of the land surface during the last 300 or so years of the post-industrial period. Estimates suggest 20% of the world's forests and woodlands have disappeared during this period, and that some 33% of the natural land surface has been cleared. Today, some 3 million km2 are occupied by urban areas, 18 million km2 is in permanent cultivation, and 34 million km2 is used for grazing. Individual studies have shown that the growth of urban areas, deforestation and re-afforestation, and the expansion of agricultural and grazing land affect surface temperature, precipitation and atmospheric circulation at a regional scale. There is, also, a growing appreciation that these regional changes have an impact on the global circulation and hence on global climate regimes. However, there is still controversy about the importance of land-use changes in affecting both regional and global climates. Model studies (see e.g. Betts et al., 2004) suggest, for example, that the effect of the reduction and fragmentation of forest cover in Amazonia is to reduce evapotranspiration, which in turn reduces rainfall because some 25-30% of the precipitation falling over Amazonia is due to recycling, raises surface temperatures and changes regional circulation patterns. The simulated changes in atmospheric circulation have an impact on precipitation patterns in the mid- to high-latitudes of the northern hemisphere. Both meteorological observations and satellite data confirm some aspects of these simulations, most notably the increase in surface temperature but are less clear about the simulated reduction in precipitation over Amazonia.

In the IPCC Third Assessment Report, the change in global, annual mean climate forcing due to changes in land cover during the industrial era (since ca 1700 A.D.) was estimated as between -0.1 to -0.2Wm-2, corresponding to a global cooling of a few tenths of a degree (Ramaswarmy et al., 2001). More recent estimates based on simulations with several different models indicate that the radiative forcing due to historical land cover changes could be up to -0.5 Wm-2 (Brovkin et al., in press). However, focusing on the radiative impacts of changes in land cover does not provide a realistic assessment of the importance of land-surface changes for climate forcing, since it fails to take vegetation-induced changes in the water- and carbon-cycles into account. Although there are many studies that have demonstrated the potential significance of these effects for regional and global climate, there are still many open questions that will need to be addressed before we have a comprehensive understanding of the influence of natural and anthropogenic changes in land-surface conditions on the climate.

References

Betts, R.A., Cox, P.M., Collins, M., Harris, P.P., Huntingford, C. and Jones, C.D. 2004 The role of ecosystem–atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. *Theoretical and Applied Climatology* **78:** 157–175.

Brovkin, V., Claussen, M., Driesschaert, E., Fichefet, T., Kicklighter, D., Loutre, M.F., Matthews, H.D., Ramankutty, N., Schaeffer, M. and Sokolov, A., in press. Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity. *Climate Dynamics* (doi 10.1007/s00382-005-0092-6)

Chapin III, F.S., Sturm, M., Serreze, M. C., McFadden, J. P., Key, J. R., Lloyd, A. H., McGuire, A. D., Rupp, T. S., Lynch, A. H., Schimel, J. P., Beringer, J., Chapman, W. L., Epstein, H. E., Euskirchen, E. S., Hinzman, L. D., Jia, G., Ping, C. L., Tape, K. D., Thompson, C. D. C., Walker, D. A., Welker, J. M., 2005. Role of Land-Surface Changes in Arctic Summer Warming. *Science* **28**: 657-660

Kohfeld, K.E. and Harrison, S.P., 2000. How well can we simulate past climates ? Evaluating the models using global palaeoenvironmental data sets. *Quaternary Science Reviews* **19:** 321-346.

Kutzbach, J.E., Harrison, S.P. and Coe, M.T., 2001. Land-ocean-atmosphere interactions and monsoon climate change: a paleo-perspective. In: Global Biogeochemical Cycles in the Climate System (Schulze, E.-D., Heimann, M., Harrison, S.P., Holland, E., Lloyd, J., Prentice, I.C. and Schimel, D., Eds) Academic Press, pp. 73-86.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G.Y. and Solomon, S., 2001. Radiative Forcing of Climate Change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 351-416.

Wohlfahrt, J., Harrison, S.P. and Braconnot, P., 2004. Synergistic feedbacks between ocean and vegetation on mid- and high-latitude climates during the mid-Holocene. *Climate Dynamics* **22**: 223-238. ISSN: 0930-7575 (paper), 1432-0894 (on-line)