Revised version of article published in: Sigurdsson et al., 1996, (Eds), Nordic Hydrological Conference, NHP-Report No. 40, pp. 360-368.

Hydroclimatic processes and spatiotemporal landscape patterns

Thomas Gumbricht, Royal Institute of Technology, Stockholm, Sweden

ABSTRACT

Hydroclimatic conditions are strongly related to the land surface and its vegetation cover. Changes in climate and carbon dioxide levels can lead to different rapid vegetation responses. By using a GIS-coupled model emphasising reciprocity between hydroclimatic processes and vegetation it is shown that inclusion/exclusion of different biosphere-atmosphere feedback mechanisms lead to different water cycles. Model results suggest that increases in vegetation growth and humic layer can lead to a more efficient vertical water cycle, increasing local energy dissipation and temperature control. It is concluded that present cause-effect models can not predict the effects of climate changes, and need to be substituted for holistic models relying on primary principles and heuristic methods. GIS and remote sensing can provide the necessary spatial data sets.

INTRODUCTION

The sun's energy received on Earth is transformed and dissipated exclusively at interfaces, notably the biosphere-atmosphere boundary. Over the ocean daily cycles of evaporation and condensation form a closed cycle. Over land energy partition is closely coupled to vegetation and moisture conditions (Collins and Avissar, 1994; Avissar, 1995). Natural landscapes with dense vegetation and thick humic layers lead to large water storage capacities (Gumbricht et al., 1996), with a subsequent large control over energy dissipation through latent heat fluxes (Ripl and Gumbricht, 1996).

Globally, clouds, ice and snow reflect approximately 30 % of the incoming radiation. Of the portion reaching the lower atmosphere, most is dissipated by the water cycle, and re-radiated as long wave radiation. A part of the re-emitted long wave radiation is trapped as heat by greenhouse gases, leading to a temperature increase of approximately 33 degrees Celsius (IPCC, 1990). The best estimate is that a doubling of pre-industrial carbon dioxide levels (expected to be reached in the mid 21st century) will lead to a further global temperature increase of about 2.5 (1.5-4.5) degrees Celsius. The measured temperature change during the last century is 0.3-0.6 degrees Celsius, which is less than could be expected, and subject to large uncertainties (cf. Barnett, 1990; Jones and Wigley, 1990). More detailed studies of cumulated anthropogenic influences (greenhouse gas emissions, ozone layer depletion and increases in aerosol production - Santer et al., 1996) estimate the climate variation up till now to a high degree, concluding a human fingerprint on global climate. Lately it has been proposed that increases in atmospheric dust following vegetation clearance is causing direct reflection to increase, mitigating part of the greenhouse effect (Sokolik and Toon, 1996; Tegen et al., 1996). These studies decrease the model uncertainties on a global scale (Nichols, 1996).

However, regional and local hydroclimatic equilibriums following changes are largely unpredictable and general circulation model (GCM) results are contradictory; Shukla et al. (1990) concluded that Amazonian forest clearing would lead to reduced precipitation, whereas Avissar (1993) showed that patchy deforestation could lead to increased convective precipitation. Local changes in water processes can trigger flip-flop events at larger scales, creating a new dynamic equilibrium (Holling, 1986; Lee et al., 1993), exemplified by the desertification of the Sahel region, droughts in Sudan and Ethiopia and the large floods in major European rivers (including Sweden and Norway) during the 1990´s.

Much of the uncertainties are stemming from different climatic feedback mechanisms (Dickinson, 1986; Lashof, 1989; IPCC, 1990). Water vapour is the most important greenhouse gas, and a potent magnifier of climate change as the water content of the atmosphere is predicted to increase with temperature (e.g. Raval and Ramanathan, 1989). Direct reflection is affected by clouds (a large uncertainty in predicting the climate system), and snow and ice cover. The latter is a positive feedback (through melting of polar ice caps and glaciers), and the basic hypothesis of ice age on- and offsets magnifying small changes in solar radiation (Milankowitch, 1941). The theory is corroborated by both measurements (Slowey et al., 1996) and model results (Gallimore and Kutzbach, 1996), but not enough to explain the magnitude of climate oscillations. From polar ice cores it has been revealed that historic global temperature has been tightly coupled to atmospheric carbon dioxide (CO_2) levels (Barnola et al., 1987), thus explaining an additional (but not a major) portion of the temperature fluctuations (e.g. Pisias and Shackleton, 1984). The explanation for the rapidness and magnitudes of climate and CO_2 changes are now sought in ocean carbon transfer related to its circulation pattern and biomass productivity (Lashoff, 1989; Gumbricht, 1992; Broecker, 1995), and, to a lesser degree, in changes in terrestrial biomass.

The amount of carbon in the terrestrial biosphere approximately equals the atmospheric content, with soil organic carbon about three times larger. With temperature rise oxidation of frozen soils, peatbogs and wetlands will potentially increase, leading to releases of both carbon dioxide and methane (Nisbet, 1989; Schimel, 1990). Vegetation will be fertilised by increases in $p\mathrm{CO}_2$ through increased water and nitrogen efficiencies, and lower sensitivity to atmospheric pollution (e.g. Strain and Cure, 1985; Jones et al., 1996). This leads to secondary effects including less leaf area needed for sustained growth, and changes in C:N ratios in humic matter with subsequent slower break down rates (Strain and Cure, 1985; Melillo et al., 1990). An important effect might be that respiration (and break down) increases faster than photosynthesis following temperature increases. The effects of $p\mathrm{CO}_2$ changes on vegetation is uncertain, and dependent on species, and method and scale of study (Houghton et al., 1990; Norby, 1996). However, the potential amplitude of the climatic feedback is large (Lashof, 1989).

To evaluate vegetation interaction "big leaf - big stomata" models, including the Land-Ecosystem-Atmosphere-Feedback Model (LEAF), the Biosphere-Atmosphere Transfer Scheme (BATS) and the Simple Biosphere Model (SiB) have been coupled to GCMs (summarised in Lee et al., 1993). The purpose of these models is physical realistic determination of the exchange of radiative, momentum, and sensible and latent heat fluxes across the soil-plant-atmosphere continuum. The time step is usually seconds to days, and most models use Leaf Area Index (LAI - defined as the leaf area per unit ground area) as an important parameter relating to stomata processes. Models incorporating key biogeochemical processes, vegetation growth and the water cycle usually have a longer (daily-monthly) time step and include RHESSys (Nemani et al., 1993), and SPUR (Hanson and Baker, 1993). Geographic Information Systems (GIS) are increasingly used for nesting different scales and models, for instance for superimposing GCM output on hydroclimatic (Hay et al., 1993) and ecological (Nemani et al., 1993) models. The smaller scale models in turn are used for sub-grid parametisation of the GCMs (Avissar, 1993; Moore et al., 1993). A major interest has been to use GIS and remote sensing for defining surface characteristics (e.g. relief, vegetation) and to estimate hydroclimatic processes (e.g. evapotranspiration).

In this article a GIS-coupled hydroclimatic model emphasising the reciprocal relations between vegetation, climate and water has been used for analysing potential changes in the water regime of Cyprus following CO_2 induced changes in climate and subsequent vegetation changes.

MATERIALS AND METHODS

The PHASE model (Gumbricht, 1996; Gumbricht et al., 1996) has been used as a simplifying (but more transparent) substitute for models with a daily time step. Compared to the more elaborated models PHASE is simple to parametise and needs much less data. It focuses on vegetation-water dynamics, and emphasises reciprocity rather than cause-effect relations. PHASE is regionally calibrated by 3-7 lumped parameters for soil moisture accounting and routing. Local calibration is done by extraction of data on vegetation distribution (LAI) and relief through a tight coupling to GIS and remote sensing data. Vegetation acts like a sponge with local water control; both storage volumes and transpiration rates are parametised by vegetation cover (i.e. LAI). A part of the transpired water is allowed to return as fractal precipitation. Vegetation growth and decay (i.e. LAI dynamics) is a function of temperature and transpiration.

The study was undertaken for a natural catchment on Cyprus (Limnitis) described in an adjoining article (Gumbricht et al., 1996). The model was run for a five year historical hydroclimatic time series, where changes were allowed to happen at an instant at the starting date. The following different scenarios were simulated:

A. present situation,
B. temperature increase of three degrees Celsius,
C. and increases in vegetation growth by 20 % through increased water efficiency,
D. and decreased respiration rate of organic matter with 20 %.

The overall precipitation pattern of Cyprus was hypothesised to remain stable; a logical consequence of regarding Cyprus as the only terrestrial land mass influencing the regional patterns of energy dissipation and water cycling. However, the IPCC (1990) best estimate for the Mediterranean area is that winter precipitation will increase slightly, but with a 5-15 % reduction in summer.

RESULTS

Predicted changes in runoff following the four scenarios (A-D) are shown in Fig. 1. Changes in vegetation and humic layer dynamics are shown in Fig. 2. The decrease in runoff is adjoined by an increase in evapotranspiration (Fig. 3). This increase is larger than the decrease in runoff, except for scenario B. In scenarios C and D higher water efficiency and increases in biomass (Fig. 2) lead to a more closed vertical water cycle. The change in precipitation is -5 %, +20 % and +30 % respectively in the 3 scenarios compared to the present situation.

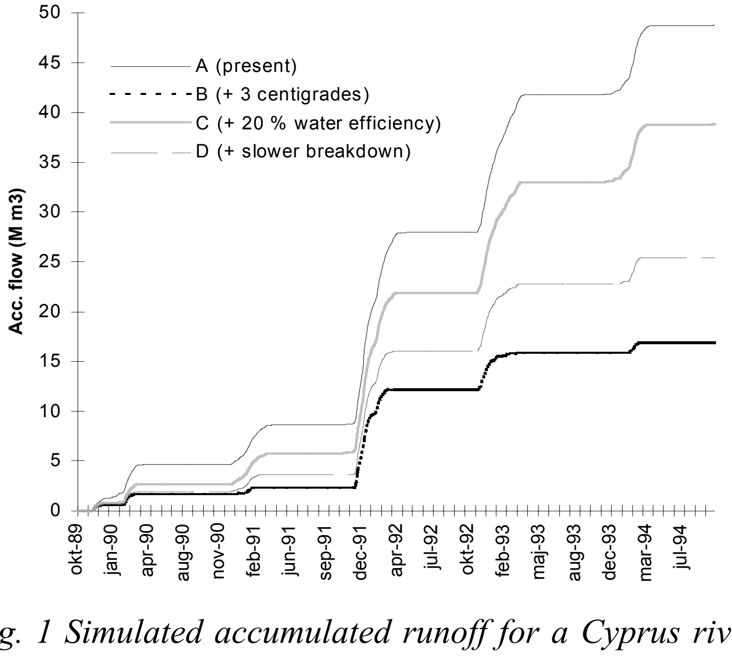

Fig. 1 Simulated accumulated runoff for a Cyprus river basin following climate change scenarios with allowance for different vegetation effects (see text).

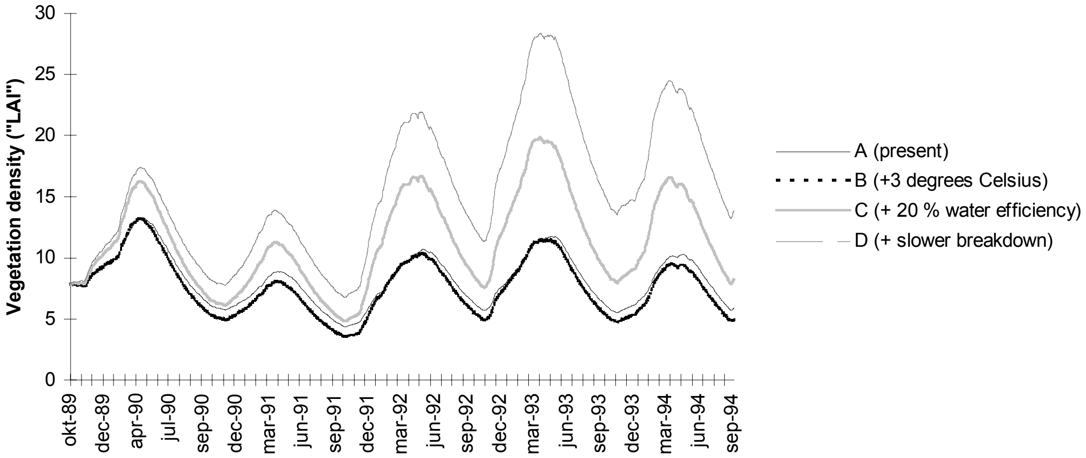

Fig. 2 Simulated vegetation effects in a climate change scenario (see text).

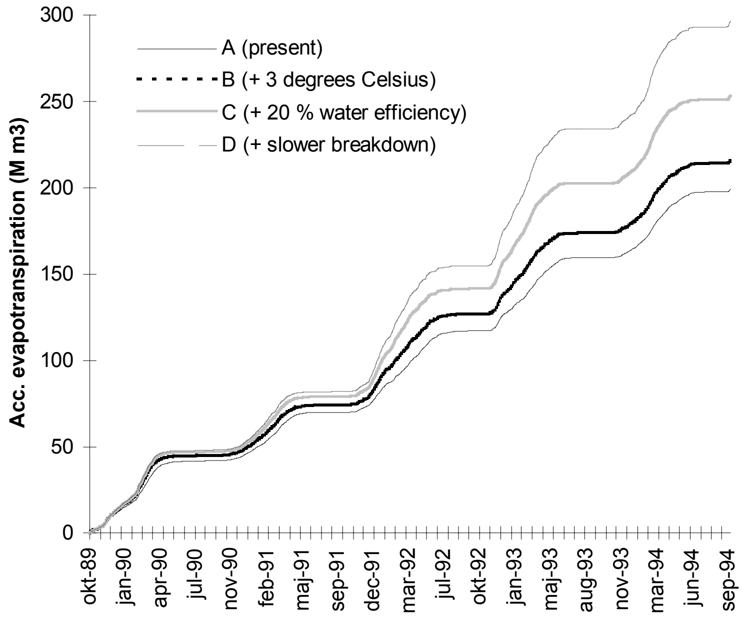

Fig. 3 Simulated accumulated evapotranspiration increase in a climate change scenario (see text).

DISCUSSION

Response to changes in climate and $p\text{CO}_2$ in vegetation can lead to large changes in hydroclimatic conditions; capable of both magnifying and mitigating the initial change. Disregarding different response mechanisms will generate very different water budgets (cf. Chiew et al., 1995; Gärdenäs and Jansson, 1995).

The modelling results herein support the results of IPCC (1990) and others that runoff and soil wetness will decrease with increased temperature, and potentially perpetuate themselves. However, the results also suggest that higher water efficiency in plants, and accumulation of organic matter can lead to a

Revised version of article published in: Sigurdsson et al., 1996, (Eds), Nordic Hydrological Conference, NHP-Report No. 40, pp. 360-368.

higher degree of local closure of the vertical water cycle (i.e. increases in fractal precipitation). This means higher efficiency in local energy dissipation, and thus a lowering of the initial temperature increase. This again indicates the intricate cybernetic pathways of the biosphere-atmosphere system, and also points at a negative feedback mechanism, to the author's knowledge not previously considered. A back of an envelope calculation reveals that the thermal effect of the increase in latent heat partitioning, assuming a lower planetary boundary at 1000 m above ground (Avissar, 1995), approximately corresponds to 0.1, 0.5 and 0.8 degrees Celsius for scenarios B, C and D respectively (disregarding the condensation heat release).

The increase in vegetation growth-decay rates as a response to increases in temperature and $p\mathrm{CO}_2$ (Fig. 2) is consistent with both direction and amplitude as inferred from measured CO_2 fluctuations during the last 40 years (Keeling et al., 1996). The increase in soil organic carbon, a sequestering of the atmospheric increase (Fig. 2), is also in agreement with recent findings on soil carbon storage in the Northern hemisphere (Bird et al., 1996).

The assumption of instant changes in temperature and carbon dioxide levels is of course a simplification. The modelled changes are believed to take approximately a century. "Intermediate scale" effects in biological and ecological adjustments will most likely occur; notably changes in species in food webs with short turnover (including the detritus food web). The different competitiveness of C3 and C4 plants under such scenarios can also create unpredictable shifts in *inter alia* water efficiency. Model results can thus not be used for predicting the quantitative changes of the dynamic system following climate induced changes. Nevertheless understanding the coupling of vegetation, water processes and climate is crucial for a proper management of the life supporting land surface.

CONCLUSION

Hydroclimatic conditions are not random processes independent of the surrounding land surface characteristics. Analysing trends of e.g. precipitation and floods from hydrological records without considering changes in the land surface over scales relevant for the process investigated seems pointless. Present cause-effect model results can not be trusted to even describe the direction of change properly. Non-linearities and cybernetic (water carried) communication across different scales lead to unpredictability. There is a need to use simple heuristic methods for analysing the complex and reciprocal relation between land surface patterns and hydroclimatic processes. This means taking a step back from today's elaborate models, and instead relying on the primary principles of thermodynamics and life as a dissipative structure. GIS and remote sensing are important tools for relating spatial patterns with process distribution. The GIS-coupled and remote sensing parametised model presented in this article can assist as a simple hypothesis testing tool. Primary results suggest that increases in vegetation growth and humic layer can lead to a more efficient vertical water cycle, increasing local energy dissipation and temperature control.

REFERENCES

Avissar, R., 1993. An approach to bridge the gap between microscale land-surface processes and synoptic-scale meteorological conditions using atmospheric models and GIS: potential for application in agriculture. In: M. Goodchild, B. Parks and L. Steyaert (Eds.), Environmental modelling with GIS. Oxford University Press, pp. 123-134.

Avissar, R., 1995. Recent advances in the representation of land-atmosphere interactions in general circulation models. Reviews of geophysics, supplement, U.S. national report to international union of geodesy and geophysics 1991-1994, pp. 1005-1010.

Barnett, T.P., 1990. Beware greenhouse confusion. Nature, 343: 696-697.

Barnola, M., D. Raynard, Y. Korokevich and C. Lorius, 1987. Vostok ice core provides 160,000-year record of atmospheric CO2. Nature, 331: 675-679.

Bird, M.I., A.R: Chivas and J. Head, 1996. A latitudal gradient in carbon turnover in forest soils. nature, 381: 143-145.

Broecker, W.S., 1995. Chaotic Climate. Sci. Am., Nov. pp. 44-50.

Chiew, F., P. Whetton, T. McMahon and A. Pittock, 1995. Simulation of the impacts of climate change on runoff and soil moisture in Australian catchments. J. Hydrology, 167: 121-147.

Collins, D. and R. Avissar, 1994. An evaluation with the Fourier Amplitude Sensitivity Test (FAST) of which land-surface parameters are of greatest importance for atmospheric modelling. J. Climate, 7: 681-703.

Dickinson, R.E., 1986. Impact of human activities on climate - a framework. In: W.C. Clark and R.E. Munn (Eds.), Sustainable development of the biosphere. Cambridge University Press, pp. 252-289.

Gallimore, R.G. and J.E: Kutzbach, 1996. Role of orbitaly induced changes in tundra area in the onset of glaciation. Nature, 381: 503-505.

Gumbricht, T., 1992. The role of ocean biota in the CO_2 drama. Royal Institute of Technology, Division of Land and Water Resources, Stockholm.

Gumbricht, T., 1996. Landscape pattern and transparency to hydrological processes. In: K. Kovar and P. Nachtnebel (Eds.), Application of geographic information systems in hydrology and water resources management, HydroGIS ´93, IAHS publ. No. 235, pp. 115-121.

Gumbricht, T., M. Hessling and J. McCarthy, 1996. Hydrological modelling integrating landscape pattern - a case study of Cyprus. In: O. Sigurdsson, K. Einarsson and H. Adalsteinsson (Eds), Proc. Nordic Hydrological Conference 1996, NHP-report No. 40, 529-537.

Gärdenäs, I. and P.E. Jansson, 1995. Simulated water balance of Scots pine stands in Sweden for different climate change scenarios. J. Hydrology, 166: 107-125.

Hanson, J. and B. Baker, 1993. Simulation of rangeland production: future applications in system ecology. In: M. Goodchild, B. Parks and L. Steyaert (Eds.), Environmental modeling with GIS. Oxford University Press, pp. 305-313.

Hay, L., W. Battaglin, R. Parker and G. Leavesley, 1993. Modeling the effects of climate change on water resources in the Gunnison River basin, Colorado. In: M. Goodchild, B. Parks and L. Steyaert (Eds.), Environmental modeling with GIS. Oxford University Press, pp 173-181.

Holling, C.S., 1986. Resilience of ecosystems: local surprise and global change. In: W.C. Clark and R.E. Munn (Eds.), Sustainable development of the biosphere. Cambridge University Press, pp. 292-317.

Intergovernmental Panel on Climate Change (IPCC), 1990. J.T. Houghton, G.J. Jenkins and J.J. Ephraums (Eds.): Climate change - The IPCC Scientific Assessment. Cambridge University Press, 364 pp.

Jones, P. and T. Wigley, 1990. Global warming trends. Sci. Am., August, pp. 66-73.

Jones, M.B., M. Jongen and T. Doyle, 1996. Effects of elevated carbon dioxide concentrations on agricultural grassland production. Agriculture and Forest Meteorology, 79: 243-252.

Keeling, C.D., J.F.S. Chin and T.P. Whorf, 1996. Increased activity of Northern vegetation inferred from atmospheric CO_2 measurements. Nature, 382: 146-149

Lashof, D.A., 1989. The dynamic greenhouse: feedback processes that may influence future concentrations of atmospheric trace gases and climate change. Climate change, Vol. 14, pp. 213-242.

Lee, T., R. Pielke, T. Kittel and J. Weaver, 1993. Atmospheric modeling and its spatial representation of land surface characteristics. In: M. Goodchild, B. Parks and L. Steyaert (Eds.), Environmental modeling with GIS. Oxford University Press, pp. 108-122.

Melillo, J.M., T.V. Callaghan, F.I. Woodward E. Salati and S.K. Sinha, 1990. Effects on ecosystems. In: J.T. Houghton, G.J. Jenkins and J.J. Ephraums (Eds.): Climate change - The IPCC Scientific Assessment. Oxford University Press, pp. 283-310.

Milankovitch, M., 1941. Kanon der Erdbestrahlung und seine Andvendung auf das Eiszeitproblem. Royal Serbian Academy, Special Publication, 133.

Moore, I., A. Turner, J. Wilson, S. Jenson and L. Band, 1993. GIS and land-surface-subsurface process modeling. In: M. Goodchild, B. Parks and L. Steyaert (Eds.), Environmental modeling with GIS. Oxford University Press, pp. 196-230.

Nemani, R., S. Running, L. Band and D. Peterson, 1993. Regional hydroecological simulation system: An illustration of the integration of ecosystem models in a GIS. In: M. Goodchild, B. Parks and L. Steyaert (Eds.), Environmental modeling with GIS. Oxford University Press, pp. 296-304.

Nichols, N. 1996. An incriminating fingerprint. Nature, 382: 27-28.

Nisbet, E.G., 1989. Some northern sources of atmospheric methane: production, history and future implications. Can. J. Earth Sci., 26: 1603-1611.

Norby, R.J., 1996. Forest canopy productivity index. Nature, 381: 564.

Pisias, N.G. and N.J. Shackleton, 1984. Modelling the global climate response to orbital forcing and atmospheric carbon dioxide changes. Nature, 310: 757-759.

Raval, A. and V. Ramanathan, 1989. Observational determination of the greenhouse effect. Nature, 342: 758-761.

Ripl, W. and T. Gumbricht, 1996. Integrating landscape structure and clean water production. Presented at 1995 Stockholm Water Symposium, accepted for publication in Ambio.

Santer, B.D., K.E. Taylor, T.M.L. Wigley, T.C. Johns, P.D. Jones, D.J. Karoly, J.F.B. Mitchell, A.H. Oort, J.E. Penner, V. Ramaswamy, M.D. Schwarzkopf, R.J. Stouffer and S. Tett, 1996. A search for human influence on the thermal structure of the atmosphere. Nature, 382: 39-45.

Schimel, D., 1990. Biogeochemical feedbacks in the earth system. In: J. Leggett (Ed.), Global warming - The Greenpeace report. Oxford University Press, pp 68-82.

Slowey, N.C., G.M. Henderson and W.B. Curry, 1996. Direct U-Th dating of marine sediments from the two most recent interglacial periods. Nature, 383: 242-244.

Shukla, J., C. Nobre and P. Seller, 1990. Amazon deforestation and climate change. Science, 247: 1322-1325.

Sokolik, I.N and O.B. Toon, 1996. Direct radiative forcing by anthropogenic airborne mineral aerosols. Nature, 381: 681-683.

Strain, B.R. and J. Cure (Eds.), 1985. Direct effects on increased carbon dioxide on vegetation, DOE/ER-0238. U.S. Department of Energy, Washington D.C.

Tegen, I., A. Lacis and I. Fung, 1996. The influence on climate forcing of mineral aerosols from disturbed soils. Nature, 380: 419-422.