ELSEVIER

Global and Planetary Change 13 (1996) 3–9

GLOBAL AND PLANETARY CHANGE

Soil moisture: A critical focus for global change studies

A. Henderson-Sellers *

Climatic Impacts Centre, Macquarie University, Sydney, Australia

Received 5 May 1995; accepted 28 August 1995

Abstract

The scientific and human dimensions of global change have many overlapping themes which offer a focus on processes occurring at the continental surface. Soil moisture is of critical importance to the physical processes governing energy and water exchanges at the land/air boundary. Soil moisture controls the extent to which plants can exploit sunlight in photosynthesis and the effectiveness with which agriculture, forestry and freshwater resources can be developed. The importance of the soil moisture to many, diverse communities has resulted in a very large collection of numerical models all of which simulate soil moisture. This paper outlines why and how a series of soil moisture simulation intercomparisons were conducted in a one-year exercise jointly sponsored by the International Geosphere Biosphere Programme and the World Climate Research Programme.

1. The landsurface and global change

Global change encompasses physical processes, biogeochemistry and human systems. This is particularly clear when near-surface continental processes are considered. The landsurface is where radiant energy is converted into living material through photosynthesis, into evaporation often via transpiration, into sensible heat and into radiant energy of longer wavelength. Moreover, human welfare depends critically upon climatic conditions near the continental surface as this is where crops are grown and fresh water is collected. The physics of the landsurface cannot be separated from its biochemistry nor from its potential to impact human social and economic systems.

The three international agencies responsible for global change research, the World Climate Research Programme (WCRP), the International Geosphere Biosphere Programme (IGBP) and the Human Dimensions Programme (HDP), all have research projects concerned with continental surface processes which, of necessity, overlap. In particular there are many areas of mutual interest between WCRP's Global Energy and Water Cycle Experiment (GEWEX) and IGBP's Biospheric Aspects of the Hydrological Cycle (BAHC) and synergistic research is being pursued.

It is now recognized that representation of continental surface processes affects both short-period meteorological prediction (e.g. Beljaars et al., 1993; Viterbo and Beljaars, 1995) and longer-term climatic projections (e.g. Dickinson and Henderson-Sellers, 1988; Xue and Shukla, 1993). Moreover, poor or

* Corresponding author: Deputy Vice-Chancellor (R&D), Royal Melbourne Institute of Technology, GPO Box 71, Bundoora, Vic. 3083, Australia, fax: +61 3 9466 9980, email: annhs@rmit.edu.au.

SSDI 0921-8181(95)00034-8

inadequate representation of both physical and biochemical processes at the continental surface can have significant impacts on future projections of carbon uptake by the biosphere and soil moisture available for crop production. Recognition of the potential importance of soil moisture and increased realism in the parameterization has led to a greater diversity among results. A recent submission to the Intergovernmental Panel on Climate Change's Working Group I 1995 Report has recommended reduction in the confidence "rating" given to soil moisture projections in future climatic scenarios compared with the IPCC Reports of 1990 and 1992 (e.g. Mitchell et al., 1990).

Within IGBP there is a Task Force whose goals include the facilitating of Core Project-derived modules into models of global change: the Global Analysis, Integration and Modelling group (GAIM). One of GAIM's four projects is entitled RICE: Regional Interactions of Climate and Ecosystems. RICE's goals are to:

- ascertain the regional effects of vegetation and soils on climates simulated by global models;
- establish the sensitivity of vegetation and ecological schemes to regional climates derived from global models; and
- facilitate the integration of new vegetation/ecological schemes into global models.

RICE's research therefore has synergistic overlap with GCTE (Global Change and Terrestrial Ecosystems) and BAHC within IGBP and, importantly, with GEWEX's Project for Intercomparison of Landsurface Parameterisation Schemes (PILPS) (Fig. 1).

PILPS aims are to improve understanding of current and future landsurface schemes used to represent regional to continental scales in weather forecast and global climate models. To do this PILPS has the following goals:

- document current schemes;
- acquire and disseminate data for testing;
- identify data gaps and propose means of acquiring additional/better data; and
- identify parameterisation inadequacies and propose solutions.

The time scales and goals of the seven-year GEWEX/PILPS project are shown in Fig. 2. Since its establishment in 1992, PILPS has been responsible for a number of complementary sensitivity studies (Pitman et al., 1993; Love and Henderson-Sellers, 1994). More details about PILPS, including its progress to date and future activities are described in Henderson-Sellers et al. (1993, 1995).

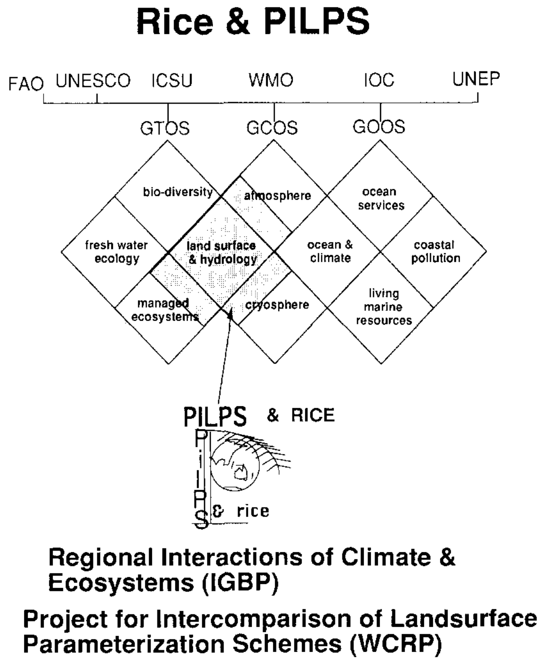

Fig. 1. Schematic representation of the way in which observational data required for both the World Climate Research Programme's Project for Intercomparison of Landsurface Parameterization Schemes and the International Geosphere Biosphere Programme's Regional Interactions of Climate and Ecosystems lie at the intersection of two global observing strategies: the Global Climate Observing System (*GCOS*) and the Global Terrestrial Observing System (*GTOS*). Other acronyms are the Global Ocean Observing System (*GOOS*) and the "parent" organizations: *FAO* = Food and Agriculture Organization; *UNESCO* = United Nations Educational, Science and Cultural Organization; *ICSU* = International Committee of Scientific Unions; *WMO* = World Meteorological Organization; *IOC* = International Oceanographic Commission; and *UNEP* = United Nations Environment Programme.

It is increasingly clear that different communities, particularly meteorologists, hydrologists, ecologists and agricultural scientists have different perceptions of the relative importance, the time constants and even the "laws" governing the processes occurring at the landsurface. These different perceptions are being encoded into numerical schemes, all of which capture some of the attributes of the soil and vegeta-

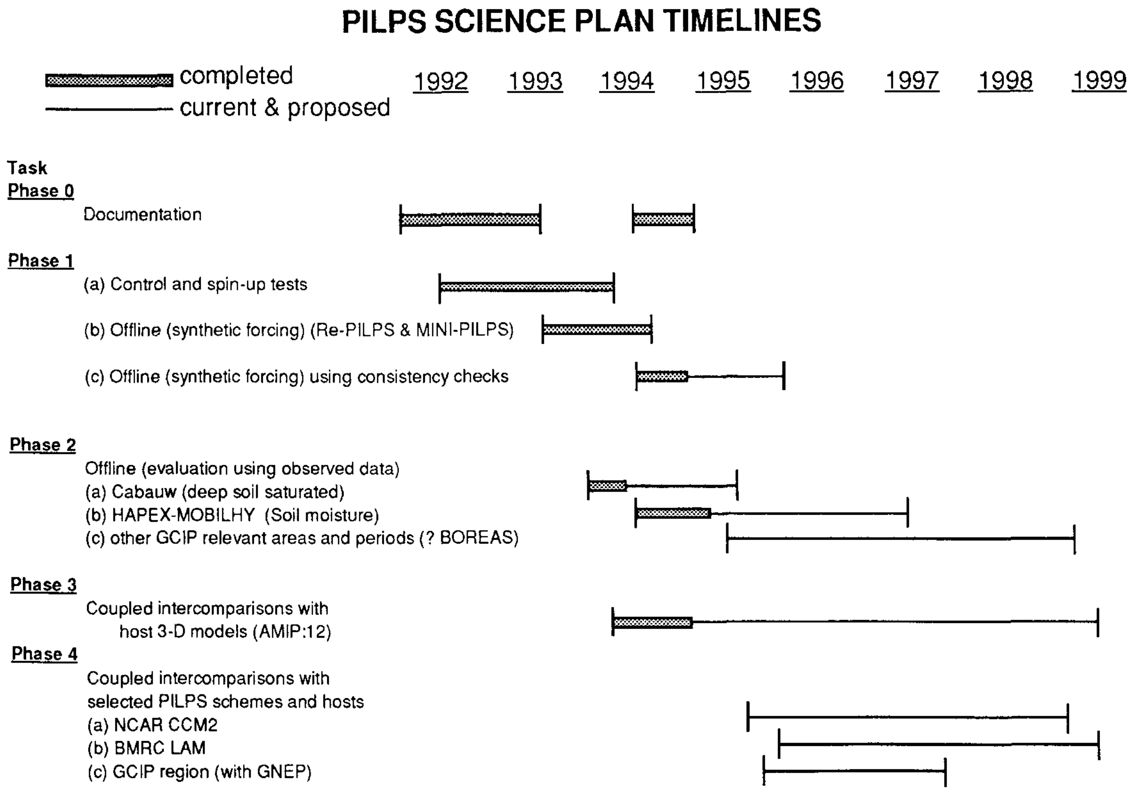

Fig. 2. Project of Intercomparison of Landsurface Parameterization Schemes science plan timelines. The workshop described in this special issue is Phase 2(b).

tion and the water, energy, momentum and carbon exchanges but none of which are exactly similar. A common element, and one of critical importance, is soil moisture, itself of critical importance to the physics, the biochemistry and the human development and exploitation of the continental surface. This recognition prompted the decision to hold a "Soil Moisture Simulation Workshop" in November 1994. This workshop was co-sponsored by IGBP/GAIM/RICE and WCRP/GEWEX/PILPS and also drew funding from IGBP/BAHC and the Climatic Impacts Centre, Macquarie University, the host institution.

This Special Issue of *Global and Planetary Change* describes the preparatory work (lasting about 9 months) which underpinned the workshop, the participating schemes, the two (very intense) weeks work during the workshop, and the 3–5 month analysis, outcomes and recommendations made by the participants. This collection of papers also serves as proof of the very great benefits to global change studies, and a few of the difficulties, of joint research and genuine collaboration.

2. Soil moisture: the workshop focus

A landsurface parameterisation scheme describes the energy, mass and momentum exchange at the Earth's continental surface. Originally, landsurface parameterisation schemes were required to provide boundary conditions for General Circulation Models (GCMs) (Budyko, 1956; Manabe, 1969). The last decade has seen a rapid development of landsurface schemes and a rapid expansion in their applications. Today, there are probably hundreds of landsurface schemes developed not only for global climate models, but also for atmospheric weather prediction, meso-scale numerical models, hydrological and water resource models, ecological models, models of global change and many others. It is widely recognized that the incorporation of realistic landsurface schemes into these models is necessary for improved predictive capability.

In an equilibrated climate, the atmospheric moisture convergence (precipitation minus evaporation or $P - E$) must equal the total runoff (R) in order that water is conserved in the landsurface submodel. Unfortunately, this fact does not offer any insight into the state of the soil moisture which is itself a determining factor in the evaporation and runoff partition (Shao et al., 1995). Since E and R are partially controlled by soil moisture, in different and highly non-linear ways, it is unlikely that they can both be correct if soil moisture is wrong unless there are exactly compensating errors or if the soil moisture is sufficiently ample or sufficiently meagre that E and R do not depend on it (wet and dry limits). Moreover, as different landsurface schemes exhibit different sensitivities to perturbations and achieve different equilibria when forced by the same meteorology, it is quite conceivable that different landsurface submodels will have different values of E and R for the same P (although feedbacks may also alter P) and hence different soil moistures. In addition, the effect of a disturbance, such as greenhouse warming, has the potential to produce different responses over continental regions i.e. different values of ΔE and ΔR (and different Δ soil moistures) even if the ΔP are the same (which is unlikely). Finally, as different landsurface schemes also have different time constants (e.g. Milly and Dunne, 1994), the dispersion in predictions for equilibrium climates has the potential to alter in transient climatic states (e.g. caused by interdecadal oscillations or transient changes in greenhouse gas concentrations).

It was noted in the IPCC 1990 Assessment that "the representation (and validation) of soil moisture in current climate models is still relatively crude" (Gates et al., 1990, p. 109). At the same time, this assessment also noted the important impact of the present-day simulation of soil moisture on the predictions of greenhouse-induced changes in soil moisture noting that if "the soil in the $1 \times CO_2$ formulation is not close to saturation, (and) the enhanced winter precipitation in the $2 \times CO_2$ simulation is stored in the soil ... although the summer drying in the $2 \times CO_2$ experiments starts earlier, it starts from a higher level than in the control simulation, and may not become drier before the next winter season" (Mitchell et al., 1990, p. 149). Finally, the IPCC 1990 Assessment recognized the importance of correctly predicting changes in the surface hydroclimate: "since drying of northern mid-latitude continents in summer could have significant impacts, these changes warrant a close examination of the physical processes responsible and the fidelity of their representation in models needs to be carefully considered" (Mitchell et al., 1990, p. 149).

Landsurface schemes are developed based on different concepts and with different levels of complexity depending on the intended application of the scheme. Each scheme is intended to capture the most important physical and/or biochemical aspects of complicated landsurface processes relevant to the host model and important to the scheme originator. For global climate models, it is important for a landsurface scheme to correctly parameterize the energy and momentum transport from the surface on daily to annual scales, while weather forecast models and meso-scale models require a correct parameterisation on hourly to daily scales. For hydrological models, it is more important to correctly simulate the annual cycle of surface and subsurface moisture and detailed parameterisation of surface energy and momentum fluxes are less important. Ecological models are concerned primarily with carbon and nitrogen exchanges and tend to use energy and water processing as the "vehicle" for these exchanges. According to their purposes, the landsurface schemes tested in this workshop can be divided into schemes for global climate models, BATS (Dickinson et al., 1993), BEST (Pitman et al., 1991), CLASS (Verseghy, 1991 and Verseghy et al., 1993), CSIRO9 (Kowalczyk et al., 1991), SECHIBA2 (Ducoudre et al., 1993), SSiB (Xue et al., 1991), VIC (Liang et al., 1994), BUCKET (Manabe, 1969); for meso-scale models ISBA (Noilhan and Planton, 1989), LAPS (Mihailovic and Rajkovic, 1991), PLACE (Wetzel and Boone, 1995); and for ecological models BGC (Running and Hunt, 1993), BIOME2 (Haxeltine et al., 1994), CENTURY (Parton et al., 1993).

Landsurface schemes used in atmospheric models and ecosystem models have as their principal commonality the need to simulate soil moisture. While atmospheric models require accurate descriptions of the state and fluxes of water at the surface to assure the realistic partitioning of incoming energy into sensible and latent heat fluxes, terrestrial ecosystem models require this same information to predict the cycling of carbon and nutrients through various organic and inorganic phases. Both groups, insofar as model evaluation is concerned, are interested in accurate descriptions of soil water and hydrology in general as one of the best sources, in some cases the only source, of validation data.

Soil moisture is a key component in landsurface schemes and is of great significance to atmospheric models, hydrological models and ecological models. Soil and vegetation play an important role in the hydrological cycle and influence atmospheric systems on time scales from several hours to many years. Soil water content is closely related to evaporation and thus to the partitioning of sensible and latent heat fluxes at the surface. Soil moisture, the atmospheric boundary layer and convective clouds form a coupled system which prompts feedbacks in short term weather forecasting models and in longer-term climate variability and change. Apart from solar radiation and soil nutrients, the availability of soil moisture is the key to plant growth and to the net production of crops. For these reasons, the intercomparison of soil moisture simulation in landsurface schemes was the focus of the joint PILPS and RICE workshop.

3. Workshop plan and goals

The RICE and PILPS workshop took place between 14–25 November 1994, at the Climatic Impacts Centre, Macquarie University, Sydney, Australia. The major objective of the workshop was to increase the understanding of the parameterisation of soil moisture in climate and vegetation models. The major goals of the workshop were:

- to quantify the differences in soil moisture predictions among the landsurface parameterisation schemes;
- to determine whether these differences are important for atmospheric and/or ecological models (vegetation models, hydrological models, atmospheric boundary-layer models and GCMs); and
- to understand whether differences occur because of:
  theory;
  numerical implementation;
  coding; or
  choice of parameters.

These goals were to be achieved in the time frame of the workshop as a whole: including the 9 month preparation, the workshop itself and subsequent and continuing evaluation of the results. Fifteen scientists from overseas and Australia, representing 14 landsurface schemes, participated in the workshop (Table 1). Carefully designed numerical experiments were carried out before the workshop and during the two week period of the workshop additional experiments were conducted as well as the analysis of results. Intensive scientific discussions continued throughout.

The time scale problem is an important issue in comparing and evaluating landsurface schemes. The two most important time scales in landsurface processes are reflected in diurnal changes of surface energy fluxes, photosynthetic activities of the plants, surface temperature and soil moisture in the upper soil layers, and in the annual changes of surface energy fluxes, growth of vegetation, soil moisture and temperature in deeper soil layers. In recent years, most landsurface scheme developers have been striving to parameterize the diurnal variations of landsurface processes. Among the landsurface

Table 1
Workshop participants and landsurface parameterisation schemes studied in the RICE and PILPS workshop

Participant	Landsurface schemes
Zong Liang Yang	[BATS]
Andy Pitman	[BEST]
Peter Thornton	[BGC]
Alex Haxeltine	[BIOME2]
Parviz Irannejad	[BUCKET]
William J. Parton	[CENTURY]
Diana Verseghy	[CLASS]
Eva Kowalczyk	[CSIRO9]
Jean-Francois Mahfouf, Joel Noilhan	[ISBA]
Dragutin T. Mihailovic	[LAPS]
Peter Wetzel	[PLACE]
Agnes Ducharne	[SECHIBA2]
Yong Kang Xue	[SSiB]
Xu Liang	[VIC]

schemes participating in the workshop, the bucket model, BGC, BIOME2 and CENTURY are not developed for the purpose of capturing the diurnal variations of the landsurface processes, while all other schemes have been developed to parameterize landsurface variations from (fast) hourly to (slow) annual time scales.

The treatment of these processes in a particular model is largely determined by the spatial and temporal resolution of the model employed. Atmospheric models have short time steps (less than 0.5 hours), but large spatial resolution of tens to hundreds of kilometers because of the numerical and dynamical constraints. Hydrological and ecosystem models operate under other constraints, and have time steps on the order of days to months. Because the numerics involved are relatively simple compared to atmospheric models, there is more flexibility in specifying the spatial resolution which is often constrained by the availability of spatially explicit data sets and the aims of the particular application rather than by numerical considerations.

This polarity between spatial and temporal resolution for atmospheric and hydrological models, when considering the application of each over large spatial domains, leads to a polarity in the treatment of the soil moisture processes. With very short time steps, the landsurface schemes used in atmospheric models must treat the vertical movement of water and heat in the soil mechanistically. However, with a horizontal spatial resolution on the order of tens to hundreds of kilometers, explicit treatments of the horizontal movements of water at the surface are necessarily very coarse and simplistic. On the other hand, with longer time steps, on the order of days to months, it is neither necessary nor possible for hydrological models to assess the details of vertical water movements in the soil column, but with a greater flexibility in the definition of the horizontal spatial resolution of the landsurface, these models can and occasionally do incorporate much more sophisticated diagnoses of horizontal movements of water at and under the surface. Ecosystem modellers are concerned with some aspects of both the atmosphere and hydrologic processes but tend to consider time and space scales closer to those of hydrology than those of meteorology. Although, to date these communities seem to have been fairly well served by this arrangement, these simple divisions are disintegrating rapidly. Hydrologic models and ecosystem models are being "plugged into" GCMs and the space and time scale incompatibilities must be recognized and overcome. The precise horizontal distribution of fluxes at the surface may be less important to the accurate assessment of long-term patterns of atmospheric dynamics than is an accurate assessment of the magnitude of those fluxes at short time steps. On the other hand, knowing the relative horizontal distribution of the quantities and fluxes of surface (including subsurface) water is critical to the accurate assessment of the major drainage features and structural and dynamic aspects of terrestrial ecosystems, while the exact magnitude of these quantities and fluxes may not be as critical. These remains one crucial, common factor: soil moisture.

This Special Issue of *Global and Planetary Change* has been developed with the intention of documenting the workshop as completely as possible. It contains three major sections: (1) an introductory review of the workshop, the HAPEX data and the parameters used in the numerical experiments and the design, rationale and instructions for the experiments; (2) the results and analysis of the experiments as they represent the seasonal cycle of soil moisture; and (3) the participating schemes and problems their users observed during the workshop itself and the improvements, including this documentation, that flowed from these.

Acknowledgements

This research was funded in part by grants from the NOAA Program of Global Change, through the University of Arizona, the Model Evaluation Consortium for Climate Assessment, the Department of the Environment, Sport and Territories, by the Australian Research Council and IGBP/GAIM's Project Office at the University of New Hampshire. This is Contribution no. 95/7 of the Climatic Impacts Centre.

References

Beljaars, A.C.M., Viterbo, P., Miller, M.J., Betts, A.K. and Ball, J.H., 1993. A new surface boundary layer formulation at

ECWMF and experimental continental precipitation forecasts. GEWEX News, 3(3): 1, 5–8.

Budyko, M.I., 1956. The Heat Balance of the Earth's Surface. Gidrometeoizdat, Leningrad, 255 pp. (in Russian).

Dickinson, R.E. and Henderson-Sellers, A., 1988. Modelling tropical deforestation: a study of GCM land-surface parameterizations. Q. J. R. Meteorol. Soc., 114(B): 439–462.

Dickinson, R.E., Henderson-Sellers, A. and Kennedy, P.J., 1993. Biosphere–Atmosphere Transfer Scheme (BATS) Version 1e as coupled to the NCAR Community Climate Model. NCAR Tech. Note., NCAR/TN-387 + STR.

Ducoudre, N.I., Laval, K. and Perrier, A., 1993. SECHIBA, a new set of parameterizations of the hydrologic exchanges at the land–atmosphere interface within the LMD atmospheric general circulation model. J. Climate, 6: 248–273.

Gates, W.L., Rowntree, P.R. and Zeng, Q.-C., 1990. Validation of climate models. In: J.T. Houghton et al., (Editors), Climate Change, The IPCC Scientific Assessment. Cambridge Univ. Press, pp. 93–130.

Haxeltine, A., Prentice, I.C. and Creswell, I.D., 1994. Use of a coupled carbon and water flux model to predict vegetation structure: An Australian case study (manuscript available from authors).

Henderson-Sellers, A., Yang, Z.-L. and Dickinson, R.E., 1993. The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS). Bull. Am. Meteorol. Soc., 74(7): 1335–1349.

Henderson-Sellers, A., Pitman, A.J., Love, P.K., Irannejad, P. and Chen, T., 1995. The project for inter-comparison of landsurface parameterisation schemes (PILPS): Phase 2 & 3. Bull. Am. Meteorol. Soc., 76: 489–503.

Kowalczyk, E.A., Garratt, J.R. and Krummel, P.B., 1991. A soil–canopy scheme for use in a numerical model of the atmosphere-1D stand-alone model. CSIRO, DAR Tech. Pap., 23, 56 pp.

Liang, X., Lettenmaier, D.P., Wood, E.F. and Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res., 99(D7): 14,415–14,428.

Love, P.K. and Henderson-Sellers, A., 1994. Land surface climatologies of AMIP–PILPS models and identification of regions for future investigation, GEWEX/WCRP Rep. IGPO Publ. Ser., 13 (Nov. 1994), 48 pp.

Manabe, S., 1969. Climate and ocean circulation: 1. The atmospheric circulation and the hydrology of the earth's surface. Mon. Weather Rev., 97: 739–805.

Mihailovic, D.T. and Rajkovic, B., 1991. A coupled soil moisture and surface temperature prediction model. J. Appl. Meteorol., 30: 812–822.

Milly, P.C.D. and Dunne, K.A., 1994. Sensitivity of the global water cycle to the water-holding capacity of land. J. Climatol., 7(4): 506–526.

Mitchell, J.F.B., Manabe, S., Tokioka, T. and Meleshko, V., 1990. Equilibrium climate change—and its implications for the future. In: J.T. Houghton et al. (Editors), Climate Change. The IPCC Scientific Assessment. Cambridge Univ. Press, pp. 131–172.

Noilhan, J. and Planton, S., 1989. A simple parameterisation of land surface processes for meteorological models. Mon. Weather Rev., 117: 536–549.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J.-C., Seastedt, T., Garcia Moya, E., Apinan Kamnalrut and Kinyamario, J.I., 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles, 7: 785–809.

Pitman, A.J., Yang, Z.L., Cogley, J.G., and Henderson-Sellers, A., 1991. Description of bare essentials of surface transfer for the Bureau of Meteorology Research Centre AGCM. BMRC Res. Rep., 32, 117 pp.

Pitman, A.J., Henderson-Sellers, A., Abramopoulos, F., Avissar, R., Bonan, G., Boone, A., Cogley, J.G., Dickinson, R.E., Ek, M., Entekhabi, D., Famiglietti, J., Garratt, J.R., Frech, M., Hahmann, A., Koster, R., Kowalczyk, E., Laval, K., Lean, L., Lee, T.J., Lettenmaier, D., Liang, X., Mahfouf, J.-F., Mahrt, L., Milly, C., Mitchell, K., deNoblet, N., Noilhan, J., Pan, H., Pielke, R., Robock, A., Rosenzweig, C., Running, S.W., Schlosser, A., Scott, R., Suarez, M., Thompson, S., Verseghy, D., Wetzel, P., Wood, E., Xue, Y., Yang, Z.-L. and Zhang, L., 1993. Results from the off-line control simulation phase of the project for intercomparison of landsurface parameterisation schemes (PILPS). GEWEX Tech. Note, IGPO Publ. Ser., 7, 47 pp.

Running, S.W. and Hunt, E.R., Jr., 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: J.R. Ehrlinger and C. Fields (Editors), Scaling Physiological Processes: Leaf to Globe. Academic Press, New York.

Shao, Y., Anne, R.D., Henderson-Sellers, A., Irannejad, P., Ciret, C., Thornton, P., Liang, X., Desborough, C. and Chen, T.H., 1995. Soil moisture simulation. A report of the RICE and PILPS Workshop, GEWEX/GAIM Report. IGPO Publ. Ser., 130 pp.

Verseghy, D.L., 1991. Class-a Canadian land surface scheme for GCMs I. Soil model. Int. J. Climatol., 11: 111–133.

Verseghy, D.L., McFarlane, N.A. and Lazare, M., 1993. Class-a Canadian land surface scheme for GCMs, II. Vegetation model and coupled runs. Int. J. Climatol., 13: 347–370.

Viterbo, P. and Beljaars, A.C.M., 1995. An improved land surface parameterization scheme in the ECMWF model and its validation. J. Climate, 8: 2716–2748.

Wetzel, P. and Boone, A., 1995. A parameterisation for land–atmosphere–cloud exchange (PLACE): documentation and testing of a detailed process model of the partly cloudy boundary layer over heterogeneous land. J. Climate, 8: 1830–1837.

Xue, Y. and Shukla, J., 1993. The influence of landsurface properties on Sahel climate, Part I: Desertification. J. Climatol., 6: 2232–2245.

Xue, Y., Sellers, P.J., Kinter, J.L. and Shukla, J., 1991. A simplified biosphere model for global climate studies. J. Climate, 4: 345–364.