Assessing soil moisture in global climate models: is radon a possible verification tool?

Ann Henderson-Sellers

Parvis Irannejad

Global Climate Model Evaluation

The natural greenhouse effect maintains the Earth's climate at temperatures hospitable to life. Human activities have been recognized as contributing radiatively active trace gases to the atmosphere for over a century (Henderson-Sellers and Jones, 1990). The potential impacts of human-induced global warming prompted the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to establish the Intergovernmental Panel on Climate Change (IPCC) in 1988. Open to all member nations of the UNEP and WMO, the IPCC has a mandate to assess the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change. It bases its assessment on published and peer reviewed scientific technical literature. Working Group I assesses the scientific aspects of the climate system and climate change. Working Group II addresses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it. Working Group III assesses options for limiting greenhouse gas emissions and otherwise mitigating climate change. The Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report published in 1996 stated:

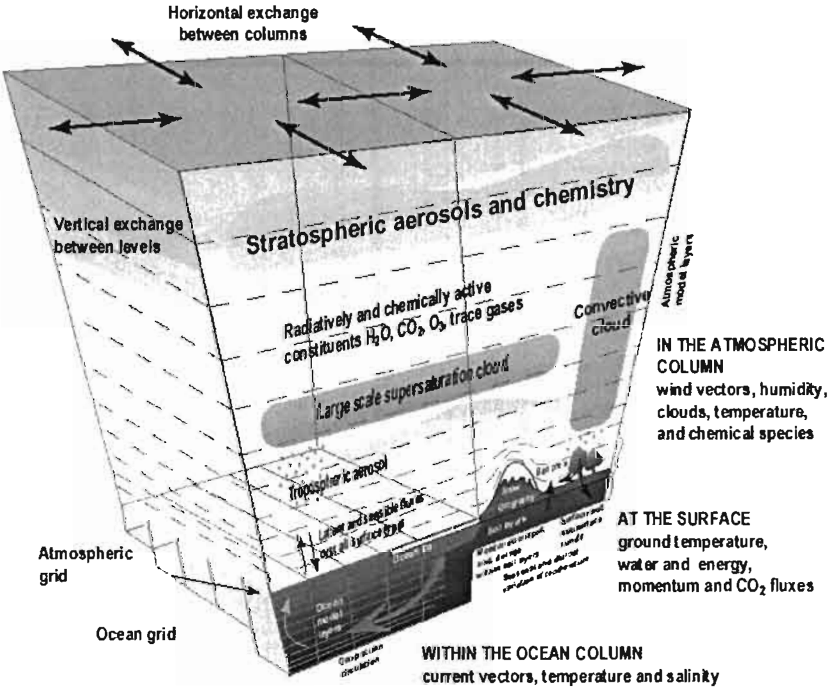
> "Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of evidence suggests that there is a discernible human influence on global climate." (Houghton *et al.*, 1996, p 5)

Thus it is established that human activities are impacting the climate system; in particular atmospheric concentrations of greenhouse gases are increasing at a rapid rate (e.g. Keeling *et al.*, 1976, 1995). Over the last few years, models and observations have combined to confirm that these increases are causing climate change (Houghton *et al.*, 1996). As a result, treaties and protocols are being developed and agreed which aim to reduce, and perhaps ultimately reverse, these human-induced disturbances to the climate system (e.g. Taplin, 1996; Wigley, 1998). The tools with which future climates are to be predicted are climate models. However, before models can be used with confidence, they must be tested against observations and their predictive skills verified (Gates *et al.*, 1996).

The IPCC includes a Task Force on National Greenhouse Gas Inventories which oversees the members' national efforts to account for and measure greenhouse gas sources and sinks. The IPCC has been at the forefront of international efforts to evaluate and verify global climate models. Its Second Assessment Report concluded that:

> "The most powerful tools available with which to assess future climate are coupled climate models, which include three-dimensional representations of the atmosphere, ocean, cryosphere and land surface... (and)... More detailed and accurate simulations are expected as models are further developed and improved." Gates *et al.* (1996, p 233)

Climate models are tools employed to enhance understanding of the climate system and to aid prediction of future climates. The aim of all global climate models (GCMs) is the calculation of the full three-dimensional character of the climate comprising at least the global atmosphere, the continental surfaces and the oceans. If a model were to be constructed which included the entirety of our knowledge on the atmosphere-ocean-land system, it would not be possible to run it on even the fastest computer. For this reason, GCMs, currently the most complicated numerical models, can only be simplifications of our current knowledge of the climate system (Figure 1).



Climate model schematic

I Figure 1
Illustration of the basic characteristics and processes within a general circulation model, showing the manner in which the atmosphere and ocean are split into columns. The atmosphere, land and ocean are modelled as a set of interacting columns distributed across the Earth's surface. The resolutions of the atmosphere, land and ocean models are often different because the processes differ and have different timescales and equilibration times. Typically many types of clouds, soils and vegetation are treated. In this example, soil moisture is modelled in a number of layers and tropospheric and stratospheric aerosols are included climate model schematic (after Henderson-Sellers and McGuffie, 2000).

Although there have been great advances made in the discipline of climate modelling over its forty year history, even the most sophisticated models remain very much simpler than the full climate system (e.g. Henderson-Sellers and McGuffie, 2000). Indeed, such simplicity is an intended attribute of climate models (e.g. Washington and Parkinson, 1986; McGuffie and Henderson-Sellers, 1997). Modelling of a system that encompasses such a wide variety of components as the climate system is a formidable task and it requires co-operation between many disciplines if reliable conclusions are to be drawn. Intercomparisons such as the Atmospheric Model Intercomparison Project (AMIP) Phase II (AMIP II) are now an integral part of climate science and an important means for advancement of understanding of the climate system (Gates *et al.*, 1999). For climate models to be accepted as useful tools for climate analysis their evaluation must progress beyond simply intercomparison to verification.

This process of verification is now termed model "evaluation", although many researchers still use the term "validation". The former term has been chosen over the latter by Working Group I of the IPCC for its Third Assessment Report, because it is argued that "evaluation" denotes a comparison while "validation" appears to offer some form of approval. In this paper, a novel method for the evaluation of predictions of large-scale soil moisture by climate models is proposed.

Why Investigate Radon as an Evaluation Tool?

Large-scale (roughly an American or Australian state or a European nation) soil moisture variability is now recognized as an important cause of variability in weather & climate systems (e.g. Beljaars *et al.*, 1993; Sellers *et al.*, 1997; Douville and Chauvin, 2000). The Global Energy & Water Cycle Experiment (GEWEX) and the Biospheric Aspects of the Hydrologic Cycle (BAHC) are developing international programmes of soil moisture measurement, analysis & prediction (e.g. Sorooshian, 2000).

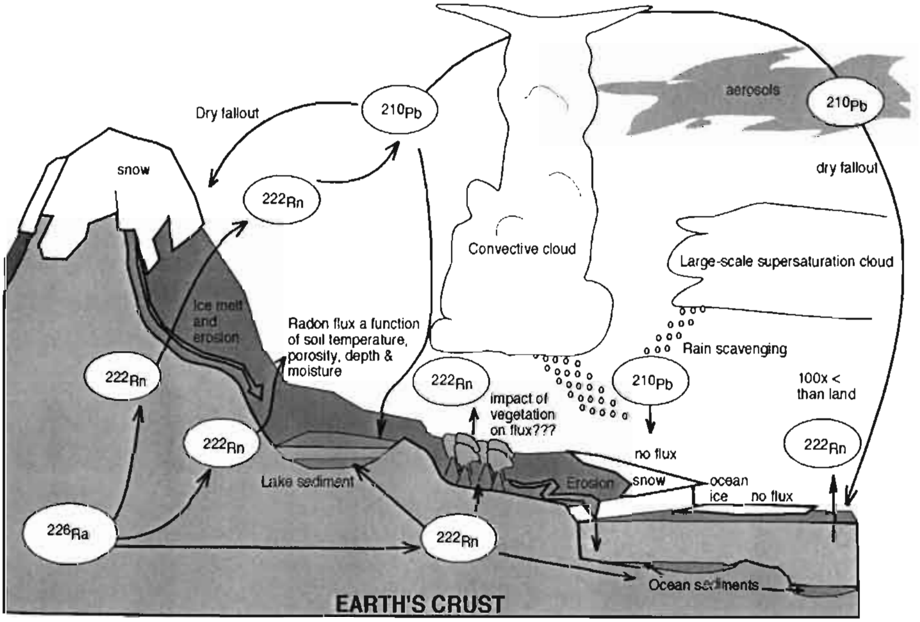
Arguably the most useful range of soil moisture verification for numerical model evaluation is for intermediate wetness conditions because very arid and permanently saturated soils behave in known and well-simulated ways (Shao & Henderson-Sellers, 1996; Wood *et al.*, 1998). Variations among land-surface simulations of latent heat fluxes are largest at intermediate soil wetnesses (Irannejad *et al.*, 1995). These temporally transient and spatially heterogeneous conditions are the most difficult conditions under which to try to measure "areal" soil moisture. Neither satellite-derived proxies for soil moisture nor summations of point-measured moisture contents can adequately deliver large-scale areal values of continental soil moisture (e.g. Robock *et al.*, 1998). The result is that the most important type of model prediction of continental soil moisture is the most difficult to evaluate because of the lack of appropriate observations.

Radon (^{222}Rn) is produced by the radioactive decay of radium (^{226}Ra) ubiquitous in rocks and soils. It is a noble gas with a half life 3.8 days: chemically inert & short-lived enough for tracking, radon has been successfully used in atmospheric tracer studies for e.g. vertical mixing and air mass history (Genthon and Armengaud, 1995; Jacob *et al.*, 1997). Radon escapes from the soil by plant transpiration and diffusion through soil pores (Armengaud and Genthon, 1993). The emanation of radon from land surfaces is known to be a function of soil temperature and also believed to be dependent upon: (i) soil porosity; (ii) depth of soil; (iii) soil moisture; (iv) vegetation - these probably in decreasing importance (Pearson and Jones, 1966; Stockwell *et al.*, 1998). Ocean fluxes are at least 100 times less than land fluxes (Broecker *et al.*, 1967) while ice cover strongly inhibits radon emanations and frozen soils exhibit much lower fluxes than non-frozen (Feichter and Crutzen, 1990).

Radon is believed to have a mean global land emission rate of ~1 atom.cm^{-2}.s^{-1} (Lambert *et al.*, 1982) with a rough constraint that total global annual radon source is around 15 kg (Stockwell *et al.*, 1998). Measurements of fluxes of radon range typically from ~0.004 atom.cm^{-2}.s^{-1} in New Zealand to ~2.5 atom.cm^{-2}.s^{-1} in Illinois (Turekian *et al.*, 1977) although Schery (1986) found fluxes of up to 5 atom.cm^{-2}.s^{-1}.

There are conflicting reports regarding the possible impact vegetation might have on radon fluxes (cf. Schery *et al.*, 1989). Pearson and Jones (1966) found a major enhancement of radon flux due to transpiration. Hinton and Whicker (1985) reported that their measurements of enhanced flux from vegetated tailings was probably due to increased porosity (Strong and Levins, 1982); and Schery *et al.* (1984 and 1989) both find that the effects of transpiration are small. Finally, it is known that precipitation can clog soil pores and air pressure fluctuations affect radon emanation rates over short timescales (Schery and Gaeddert, 1982).

Figure 2 shows the routes followed by radon once released to the atmosphere from the soil. Its short half-life makes it an excellent



Half lives: $^{222}Rn = 3.8d, (0.33 \times 10^6 s)$; $^{210}Pb = 22.3y \ (0.694 \times 10^9 s)$; $^{226}Ra = 1{,}620$ y, $(0.511 \times 10^{11} s)$

▌ Figure 2
Schematic illustrating the sources of (^{222}Rn) radon in the atmosphere and the paths of its decay product (^{210}Pb) lead from the atmosphere into terrestrial, lacustrine and marine sediments. Half lives are 1,620 years for radium; 3.8 days for radon; and 22.3 years for lead.

tool for atmospheric tracing and global modelling studies (e.g. Rind and Lerner, 1996). ^{222}Rn decays to ^{210}Pb which is removed from the atmosphere either directly by dry fall-out or by wash-out or rain-out following incorporation of the lead into cloud droplets and hence precipitation.

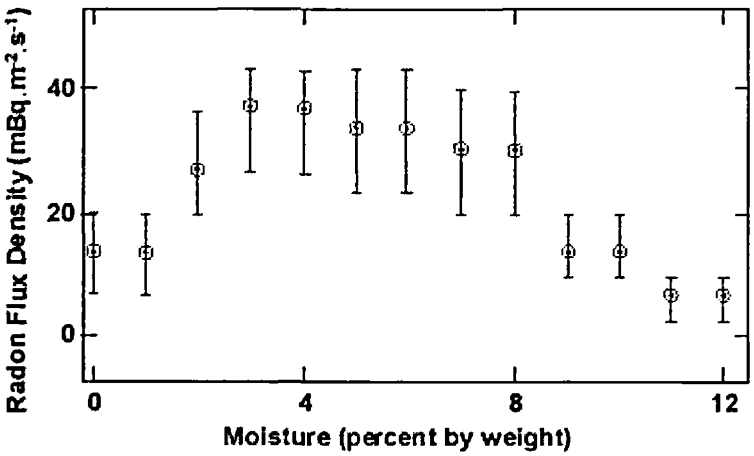
As well as the records of atmospheric radon from around the globe there are also archives of ^{210}Pb in ocean and lake sediments (e.g. Preiss *et al.*, 1996). Together, these radionuclide inventories form a powerful and synergistic archival record of continental-surface radon emanation to the atmosphere around the world and, thus, perhaps, of large-scale continental soil moisture variations over time.

Exploiting the Relationship between Radon and Soil Moisture for Climate Model Verification

Various initiatives of the UN-sponsored World Climate Research Programme (WCRP) are directed toward "validation and diagnosis" of GCM performance. Among these, the Atmospheric Model Intercomparison Project (AMIP) is an especially apt framework for assessing model performance at the atmosphere-land interface (Henderson-Sellers *et al.*, 1996; Gates *et al.*, 1999). Since 1992, for example, a Diagnostic Subproject on Land-surface Processes and Parameterizations has investigated AMIP model experiments with common specifications of radiative forcings and ocean boundary conditions. This subproject has analyzed selected 10-year climate simulations from the initial AMIP I phase of this intercomparison experiment (e.g. Love *et al.*, 1995, Qu and Henderson-Sellers, 1998), and currently investigations are being undertaken to validate and diagnose the 17-year simulations from the AMIP II phase that is in progress (e.g. Phillips *et al.*, 2000). AMIP II also has another Diagnostic Subproject specifically studying soil moisture simulations by participating AGCMs (Robock *et al.*, 1998).

There is a sound history of exploitation of various radionuclides in atmospheric model evaluation (e.g. Mahowald *et al.*, 1997). In particular, climate model intercomparisons have been conducted using radon surface emanations of: (a) two source strengths of 1 atom.cm^{-2}.s^{-1} (60° S to 60° N) and 0.5 atom.cm^{-2}.s^{-1} from 60° N to 70° N and (b) source strength a function of surface air temperature viz. 3.2 x 10^{-16} kg.m^{-2}.d^{-1} when the surface temperature is greater than 273 K and 1.0 x 10^{-16} kg.m^{-2}.d^{-1} when the surface temperature is less than or equal to 273° K (Rind and Lerner, 1996). These researchers found that radon proved to be a useful global circulation tracer.

Detailed observations have been made around the world of radon emanation rates as a function of soil moisture. Measurements of radon flux at 78 sites in Australia (Schery *et al.*, 1989), 42 Hawaiian sites (Whittlestone *et al.*, 1996) and 325 in Florida (Nielson *et al.*, 1996) give rise to expressions relating to radon emanation rates to soil moisture (Figure 3(a)). Detailed comparisons of radon emanation rates from similar soils with differing moisture and depth characteristics show that these factors can be segregated successfully and that the wetness (or dryness) of the soil is a significant factor in



I Figure 3a

Binned plot of radon emanation rates (mBq.m^{-2}.s^{-1}) and soil moisture content at 20 cm depth (percent by weight) (after Schery *et al.*, 1989).

radon release rates (Table 1). Strong and Levins (1982) find low radon emanation rates at both very low and medium soil moisture values with a turning point at about 8% water content by weight. From these sources, a functional dependence has been derived for use in global climate model studies (Figure 3(b)).

Soil	Radon flux (mBq.m^{-2}.s^{-1})		
Location/Moisture	Dry	Wet	Ratio (dry/wet)
Thin soil	1.3	0.006	21.7
Deep soil	6.5	1.1	5.9
E or W of island	5.7	1.1	5.1

Table 1
Radon flux as a function of soil moisture from Hawaii (compiled from Whittlestone *et al.*, 1996).

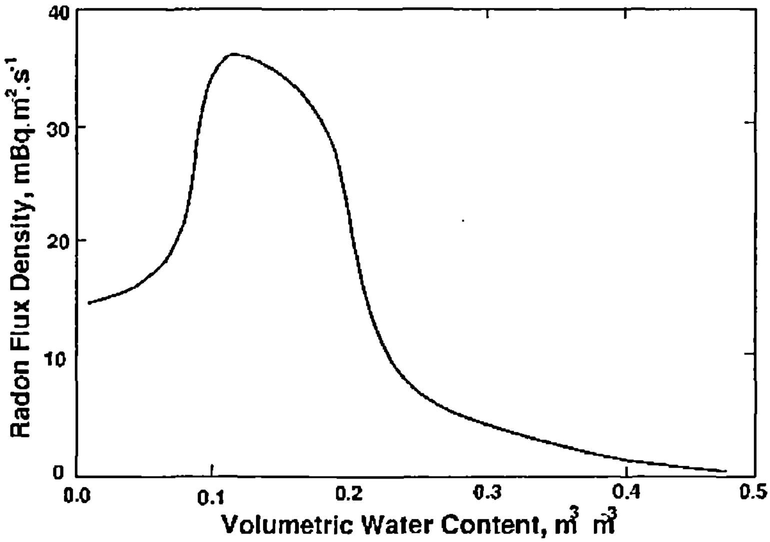


Figure 3b
Developed relationship between soil water (volumetric water content m^3 m^{-3} and radon release rates (mBq.m^{-2}.s^{-1}) used in the calculation of the near-surface radon maps shown in Figure 4.

As a result of many recommendations from project participants, the AMIP Co-ordinating Panel has provided for the possibility of some experimentation within the framework of Phase II of AMIP. In these global simulation sensitivity projects, the intention is to address fundamental issues associated with atmospheric GCMs and their development. It is envisaged that some working hypotheses warranting experimentation will result from the AMIP II Diagnostic Subprojects.

We propose that an AMIP II Experimental Subproject be performed in which the ^{222}Rn source strength is a function of simulated soil moisture. The nature of the relationship is open for discussion. Suggestions include: ^{222}Rn flux be inversely proportional to the square root of soil moisture (Nielson *et al.*, 1996); ^{222}Rn flux be given by the relationship in Schery *et al.* (1989) i.e. Figure 3(a); or the use of the function shown in Figure 3(b). Proposals for AMIP Experimental Subprojects are evaluated in terms of their capacity to address: 1) fundamental issues associated with AGCMs; 2) defined and practical questions; 3) implementation (demonstrated with at least one AMIP AGCM); 4) demonstrated need for intercomparative study; and 5) interest of at least three modelling groups participating in AMIP identified.

The first step in making such a proposal is to involve one AGCM group and ultimately two others. To this end, we propose the following hypotheses be examined by at least one AGCM in AMIP II:

(i) does the addition of a functional dependence of radon emanation on soil moisture improve the fit of predicted near-surface ^{222}Rn to observations?

(ii) does the addition of a functional dependence of radon emanation on soil moisture improve the fit of archived ^{210}Pb to observations? and, if either of these return an affirmative reply, then;

(iii) can ^{222}Rn or ^{210}Pb be used as a novel monitor of areal soil moisture and hence, ultimately, a tool for verification of global climate models?

The benefits of proposing a series of AGCMs experiments under the auspices of AMIP II are illustrated in Figure 4. This shows the simulated distributions of surface to atmosphere emanation rates of radon based on the soil moisture function given in Figure 3(b).

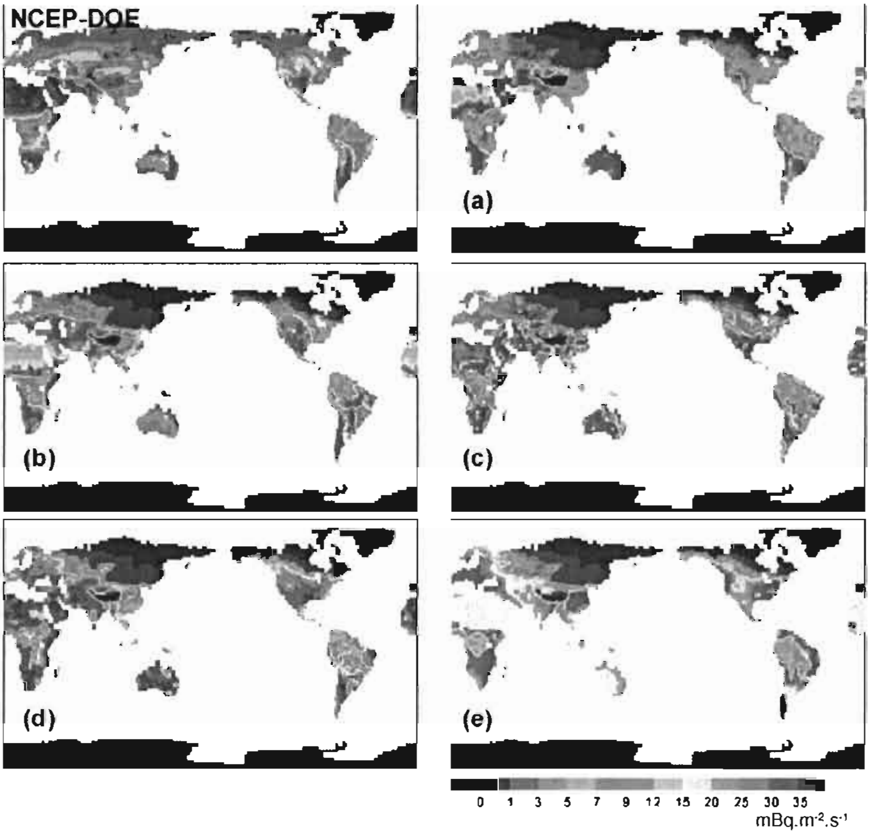


Figure 4

Computed global distributions of ^{222}Rn emanation rates from the surface (mBq.m^{-2}.s^{-1}) derived from 5 example AMIP II AGCMs (b)-(e) and one re-analysis data set (NCEP-DOE) (a). These distributions could form the basis for a global climate model soil moisture verification study using either the networks of atmospheric radon observations or archives of ^{210}Pb.

These maps have been derived using surface temperature and soil moisture conditions calculated by five example AMIP II models and one of the available reanalysis data sets (NCEP-DOE e.g. WCRP, 2000). The considerable variation in global radon distributions lends support to the proposal that comparison of such maps with global observations of ^{222}Rn could provide a novel and valuable means of verification of a poorly understood but critically important surface climate characteristic: soil water content.

Bibliography

ARMENGAUD A., GENTHON C., 1993 – "Modelling global distributions of ^{222}Rn, ^{210}Pb and ^{7}Be in the atmosphere with general circulation models ". *In: Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmosphere,* Vienna International Atomic Energy Agency, SM-329: 15-24.

BELJAARS A. C. M., VITERBO P., MILLER M. J., 1993 – The anomalous rainfall over the United States during July 1993: Sensitivity to land surface parameterization and soil moisture anomalies. *Mon. Wea. Rev.,* 124: 362-383.

BROECKER W. E., LI Y. H., CROMWELL J., 1967 – Radium-226 and radon-222: concentrations in Atlantic and Pacific Oceans. *Science,* 158: 1307-1310.

DOUVILLE, H., CHAUVIN F., 2000 – "Relevance of soil moisture for seasonal climate predictions", Procs. Second WCRP International Conference on Reanalyses, Geneva, WCRP-109, WMO/TD-NO. 985: 169-172.

FEICHTER J., CRUTZEN P. J., 1990 – Parameterisation of vertical tracer transport due to deep cumulus convection in a global transport model and its evaluation with ^{222}radon measurements. *Tellus,* 42B: 100-117.

GATES W. L., HENDERSON-SELLERS A., BOER G. J., FOLLAND C. K., KITOH A., MCAVANEY B. J., SEMAZZI F., SMITH N., WEAVER A. J., ZENG Q.-C., 1996 – "Climate Models – evaluation". *In* J.T. Houghton *et al.* (eds.) : *Climate Change 1995: The Science of Climate Change,* Cambridge University Press: 229-284.

GATES W. L., BOYLE J. S., COVEY C., DEASE C. G., DOUTRIAUX C. M., DRACH R. S., FIORINO M., GLECKLER P. J., HNILO J. J., MARLAIS S. M., PHILLIPS T. J., POTTER G. L., SANTER B. D., SPERBER K. R., TAYLOR K. E., WILLIAMS D. N., 1999 — An overview of the results of the Atmospheric Model Intercomparison Project (AMIP). *Bulletin of the American Meteorological Society,* 80: 29–55.

GENTHON C., ARMENGAUD A., 1995 – Radon-222 as a comparative tracer of transport and mixing in two general circulation models of the atmosphere. *J. Geophys. Res.,* 100: 2849-2966.

HENDERSON-SELLERS A., JONES M. D. H., 1990 – History of the greenhouse effect. *Progress in Physical Geography,* 14: 1-18.

HENDERSON-SELLERS A., MCGUFFIE K., 2000 – Forty years of numerical climate modeling. *Int. J. Climatol.,* in the press.

Henderson-Sellers A., McGuffie K., Pitman A. J., 1996 – The Project for Intercomparison of Land-surface Parametrization Schemes (PILPS): 1992 to 1995. *Climate Dynamics*, 12: 849-859.

Hinton T. G., Whicker F. W., 1985 – A field experiment on Rn flux from reclaimed uranium mill tailings. *Health Phys.*, 48, 421-427.

Houghton J. T., Mera Filho L. G., Callander B. A., Harris N., Kattenberg A., Maskell K., 1996 – *Climate Change 1995, The Science of Climate Change: Contribution of Working Group 1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, Cambridge University Press: 572 p.

Irannejad P., Henderson-Sellers A., Shao Y., Love P. K., 1995 – "Comparison of AMIP and PILPS off-line landsurface simulations". *In: Procs. of The First International AMIP Scientific Conference*, Monterey, CA, USA, 15-19 May 1995, (ed. W.L. Gates), WMO/TD, 732, Geneva, WCRP: 465-470.

Jacob D. J., *et al.*, 1997 – Evaluation and intercomparison of global atmospheric transport models using ^{222}Rn and other short lived tracers. *J. Geophys. Res.*, 102: 5953-5970.

Keeling C. D., Bacastow R. B., Bainbridge A. E., Ekdahl C. A., Guenther P. R., Waterman L. S., Chin J. F. S., 1976 – Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus*, 28: 538-551.

Keeling C. D., Whorf T. P., Wahlen M., van der Plicht J., 1995 – Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature*, 375: 666–670.

Lambert G., Polion G., Sanak J., Ardouin B., Buisson A., Jegou A., LeRoulley J. C., 1982 – Application à l'étude des échanges troposphère-stratosphère. *Annal. Geophys.*, 48: 497-531.

Love P. K., Henderson-Sellers A., Irannejad P., 1995 – "AMIP diagnostic subproject 12 (PILPS Phase 3): Land-surface Processes". *In: Proceedings of the First International AMIP Scientific Conference*, , Monterey, CA, USA, 15-19 May 1995, (ed. W.L. Gates), WMO/TD, 732, Geneva, WCRP: 101-106.

McGuffie K., Henderson-Sellers A., 1997 – *A Climate Modelling Primer*, Chichester, 2nd edition, John Wiley and Sons, 254 p.

Mahowald N. M., Rasch P. J., Eaton B. E., Whittlestone S., Prinn R. G., 1997 – Transport of ^{222}radon to the remote troposphere using the model of atmospheric transport and chemistry and assimilated winds from ECMWF and the National Center for Environmental Prediction. *J. Geophys. Res. (Atmosphere)*, 102 D23 (28): 139-157.

Nielson K. K., Rogers V. C., Holt R. B., 1996 – Measurements and calculations of soil radon flux at 326 sites throughout Florida. *Env. Int.*, 22 (1): S471-S476.

Pearson J. E., Jones G. E., 1966 – Soil concentration of emanating radium-226 and the emanation of radon from soils and plants. *Tellus*, 18: 655—662.

Phillips T. J., Henderson-Sellers A., Irannejad P., McGuffie K., Zhang H., 2000 – On validation and diagnosis of land-surface climate simulations.

Climate Change Newsletter, 12(1): 3-5 and http://www.brs.gov.au/publications/ccn/ccn12v1/research.html.

Preiss N., Mélières M-A., Pourchet M., 1996 –
A compilation of data on lead 210 concentration in surface air and fluxes at the air-surface and water-sediment interfaces.
J. Geophys. Res., 101 D22 (28): 847-862.

Qu W., Henderson-Sellers A., 1998 –
Comparing the scatter in PILPS off-line experiments with that in AMIP I coupled experiments.
Global and Planetary Change, 19 (1-4): 209—223.

Rind D., Lerner J., 1996 –
Use of on-line tracers as a diagnostic tool in general circulation model development. 1. Horizontal and vertical transport in the troposphere.
J. Geophys. Res., 101 (12): 667-683.

Robock A., Schlosser C. A., Vinnikov K. Ya., Speranskaya N. A., Entin J. K., Qiu, S., 1998 –
Evaluation of the AMIP soil moisture simulations. *Glob. Plan. Chng.*, 19: 181-208.

Schery S. D., Gaeddert D. H., 1982 –
Measurements of the effect of cyclic atmospheric pressure variation on the flux of ^{222}Rn from soil.
Geophys. Res. Letts., 9: 835-838.

Schery S. D., Gaeddert D. H., Wilkening M. H., 1984 –
Factors affecting exhalation of radon from a gravelly sandy loam.
J. Geophys. Res., 89: 7299-7309.

Schery S. D., 1986 –
Studies of thoron and thoron progeny: implications for transport of airborne radioactivity from soil to indoor air.
Indoor Radon, SP-54, Air Poll. Cont. Assoc., Pittsburgh PA: 25-36.

Schery S. D., Whittlestone S., Hart K. P., Hill S. E., 1989 –
The flux of radon and thoron from Australian soils. *J. Geophys. Res.*, 94(D6): 8567-8576.

Sellers P. J., Dickinson R. E., Randall D. A., Betts A. K., Hall F. G., Berry J. A., Collatz G. J., Denning A. S., Mooney H. A., Nobre C. A., Sato N., Field C. B., Henderson-Sellers A., 1997 –
Modeling the exchange of energy, water and carbon between continents and the atmosphere.
Science, 275: 502-509.

Shao Y., Henderson-Sellers A., 1996 –
Modelling soil moisture: a Project for Intercomparison of Land Surface Parameterisation Schemes Phase 2(b). *J. Geophys. Res.*, 101 (D3), 7227-7250.

Sorooshian S., 2000 –
GEWEX Phase II, (editorial).
GEWEX News, March 2000: 2-3

Stockwell D. Z., Kritz M. A., Chipperfield M. P., Pyle J. A., 1998 –
Validation of an off-line three-dimensional transport model using observed radon profiles. 2 Model results. *J. Geophys. Res.*, 103 (D7): 8433-8445.

Strong K. P., Levins D. M., 1982 –
Effect of moisture content on radon emanation from uranium ore and tailings. *Health Phys.*, 42: 27-32.

Taplin R., 1996 –
"Climate science and politics: the road to Rio and beyond".
In Giambellucca, T. and Henderson-Sellers, A. (eds): *Climate Change: Developing Southern Hemisphere perspectives*, Chichester, John Wiley & Sons: 377–396.

Turekian K. K., Nozaki Y., Benninger L. K., 1977 –
Geochemistry of atmospheric radon and radon products. *Ann. Rev. Earth Plant Sci.*, 5: 227-255.

WASHINGTON W. M., PARKINSON C.L., 1986 – *An Introduction to Three-Dimensional Climate Modelling.* Mill Valley, CA, University Science Books, 422 p.

WCRP, 2000 – "Second WCRP International Conference on Reanlaysis". *Proceedings, WCRP-109*, World Meteorological Organisation, Geneva, 452 p.

WHITTLESTONE S., SCHERY S. D., LI Y., 1996 – Thoron and radon fluxes from the island of Hawaii. *J. Geophys. Res.*, 101(D9): 787-794.

WIGLEY T. M. L., 1998 – The Kyoto protocol: CO_2, CH_4 and climate implications, *Geophys. Res. Lett.*, 25: 2285-2288.

WOOD E. F., LETTENMAIER D. P., LIANG X., LOHMANN D., BOONE A., CHANG S., CHEN F., DAI Y., DICKINSON R. E., DUAN Q., EK M., GUSEV Y. M., HABETS F., IRANNEJAD P., KOSTER R., MITCHEL K. E., NASONOVA O. N., HOILHAN J., SCHAAKE J., SCHLOSSER A., SHAO Y., SHMAKIN A. B., VERSEGHY D., WARRACH K., WETZEL P., XUE Y., YANG Z.-L., ZENG Q.-C., 1998 – The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase 2(c) Red—Arkansas River basin experiment: 1. Experiment description and summary intercomparisons. *Global and Planetary Change*, 19(1-4): 115-135.