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Validation of Land-Surface Processes in AMIP Models: A Pilot Study

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ABSTRACT

The Atmospheric Model Intercomparison Project (AMIP), an initiative of the World Climate Research Programme (WCRP) since 1990, is a standard experimental protocol for testing the performance of global atmospheric models. One of the many studies facilitated by the AMIP is the evaluation of model simulation of processes at the land surface, a key locus of human interaction with the climate system. In particular, the relationship between different continental climate simulations and the properties of the respective coupled land-surface schemes (LSSs) may be investigated. Studies of this type have been coordinated by the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS), organized as AMIP Diagnostic Subproject 12.

After recounting the history of the AMIP/PILPS collaboration to date, we describe a method for concisely displaying the spatio-temporal variability of a land-surface simulation relative to that of validation reference data. We apply this method to the continental simulations of 30 model entries in the first phase of the AMIP intercomparison.

We find that the overall agreement of simulated continental climate variability with that of selected reanalysis reference data is a function of the land-surface process considered. Of the monthly mean land-surface variables available from these AMIP simulations, the spatio-temporal variability of continental evaporation shows the greatest sensitivity to the LSS representation of hydrology. Moreover, in twin AMIP simulations where this representation is changed from a simple “bucket” scheme to a biophysically based formulation (while retaining the same atmospheric model and land-surface characteristics), there is a general reduction in the RMS errors of the continental climate simulation relative to the reference data. However, these LSS-related improvements are due almost exclusively to changes in the amplitude of the continental climate variability, suggesting that it is the atmospheric forcings and/or the land-surface characteristics that largely control the pattern of this variability. We plan to investigate such issues more fully in the second phase of the AMIP.

1. Introduction

The Atmospheric Model Intercomparison Project (AMIP), an initiative of the World Climate Research Programme (WCRP) since 1990, is a widely implemented protocol for testing the performance of atmospheric general circulation models (AGCMs) under common specifications of radiative forcings and observed ocean boundary conditions (Gates 1992, Gates et al. 1999). From the perspective of land-surface specialists, the AMIP affords a unique opportunity to study the interactions of a wide variety of land-surface schemes (LSSs) with their respective atmospheric host models. AMIP studies of this type, which have been coordinated by another WCRP initiative--the Project for Intercomparison of Land-surface Parmaterization Schemes (PILPS) (Henderson-Sellers et al. 1996)--address an overarching question: “To what extent does AGCM performance in simulating continental climate depend on the parameterizations of the coupled LSSs?”

The importance of answering this question is readily appreciated, since the impacts of climate variability on human populations are most keenly felt at the land surface; nevertheless, a definitive resolution remains elusive for several reasons. First, there is the dilemma of how to reliably validate simulation performance, given the present dearth of multi-annual global land-surface data sets. Moreover, even if observational data were more plentiful, some inherent ambiguities would remain. That is, validation of AGCM continental climate does not verify the workings of the LSS *per se* since, in addition to the “intrinsic” properties of the LSS (e.g. parameterizations of evaporation, runoff, soil moisture), the continental simulation also is impacted by atmospheric forcings (e.g. radiative fluxes, precipitation, surface winds) and by mediating land-surface characteristics (e.g. vegetation, albedos, roughnesses).

Despite these complications, there are preliminary indications that characteristic “signatures” of different LSSs can be detected in coupled climate simulations, provided that suitable diagnostics are chosen (e.g. Gedney et al. 1999). Thus, it seems the degree of correspondence between coupled model performance and LSS parameterizations will be clarified to the extent that a sufficiently penetrating validation methodology is applied; however, developing such a procedure almost certainly will entail considerable trial and error. In that spirit, we elaborate a provisional validation methodology, and present preliminary results of its application to AMIP land-surface simulations. First, however, we recount the history of the AMIP/PILPS collaboration.

2. PILPS in the AMIP

The initial phase of the AMIP (designated as AMIP I, circa 1990-1996) saw the participation of some 30 modeling centers and nearly as many diagnostic subprojects that analyzed various aspects of climate simulations of the decade 1979-1988 (Gates 1992, Gleckler et al. 1997). Among several investigations of land-surface processes in the AMIP models (e.g. Lau et al. 1996, Frei and Robinson 1998, Robock et al. 1998), PILPS constituted itself as AMIP Diagnostic Subproject 12 on Land-surface Processes and Parameterizations. Subproject 12 analyzed those AMIP simulations in which the coupled LSSs also were entries in off-line experiments that were the focus of other PILPS initiatives (e.g. Chen et al. 1997, Pitman et al. 1999).

At the outset, Subproject 12 confronted several substantial obstacles: little reliable global validation data were available; the standard set of land-surface variables provided by the AMIP modeling groups was quite limited (e.g. runoff was not included); and a rather narrow range of LSS complexity was represented, since the large majority of AMIP I models employed simple representations of land-surface processes (Table 1). In these circumstances, Subproject 12 implemented a "zeroth-order" validation, in the sense that it identified problematical features that could be readily discerned from inspection of the land-surface simulations.

The main findings were threefold:

- Every land-surface simulation was an outlier in some respects, i.e. no overall "best" model emerged (Love and Henderson-Sellers 1994).
- A number of simulations displayed pathological features such as nonconservation of continental moisture/energy and pronounced trends in moisture stores. These discrepancies were traced to errors in coding/coupling of the LSSs and/or to inadequate initialization/ spinup procedures (Love et al. 1995).
- At a regional scale, the inter-model scatter in energy/moisture partitionings in the AMIP models was substantially greater than in comparable PILPS off-line experiments. This result contradicted the prevalent expectation that two-way feedbacks in coupled atmosphere-land experiments would dampen inter-model differences in the simulation of continental climate (Irannejad et al. 1995) . (This outcome may merely reflect the large regional forcing differences in the AMIP simulations, in contrast to the common forcings that were imposed in the PILPS off-line experiments. Nevertheless, Qu and Henderson-Sellers 1998 found that the coupled-mode differences in energy/moisture partitionings still exceeded those from the off-line simulations even when the former were normalized by the respective AMIP model forcings.)

Table 1: A listing of the land-surface hydrology representations of 30 AMIP I models. Here “prescribed soil moisture” signifies that a spatially and seasonally varying surface wetness is specified, while evaporation is predicted independently of runoff. The “simple bucket” land-surface schemes follow the approach of Manabe (1969): soil wetness, evaporation, and runoff are predicted in the context of a constant moisture field capacity. The “augmented bucket” schemes modify this paradigm (e.g. by including spatially variable field capacity, constrained evaporation, and/or a different runoff parameterization), but do not explicitly represent certain biophysical processes that are included in “vegetation canopy” schemes (e.g. precipitation interception and reevaporation by foliage, stomatal/canopy resistance to evapotranspiration, etc.) Reference: Phillips (1994)

Acronym	**AMIP Modeling Group**	**Hydrology Representation**
BMRC	Bureau of Meteorology Research Centre	Simple bucket
CCC	Canadian Climate Centre (now Canadian Centre for Climate Modelling and Analysis)	Augmented bucket
CCSR	Center for Climate System Research	Augmented bucket
CNRM	Centre National de Recherches Meteorologiques	Augmented bucket
COLA	Center for Ocean-Land-Atmosphere Studies	Vegetation canopy
CSIRO	Commonwealth Scientific & Industrial Research Organization	Augmented bucket
CSU	Colorado State University	Simple bucket
DERF	Dynamical Extended Range Forecasting (at GFDL)	Simple bucket
DNM	Department of Numerical Mathematics	Simple bucket
ECMWF	European Centre for Medium-range Weather Forecasts	Vegetation canopy
GFDL	Geophysical Fluid Dynamics Laboratory	Simple bucket
GISS	Goddard Institute for Space Studies	Vegetation canopy
GLA	Goddard Laboratory for Atmospheres	Vegetation canopy
GSFC	Goddard Space Flight Center	Prescribed soil moisture
IAP	Institute of Atmospheric Physics	Simple bucket
JMA	Japan Meteorological Agency	Vegetation canopy
LMD	Laboratoire de Meteorologie Dynamique	Simple bucket
MGO	Main Geophysical Observatory	Augmented bucket
MPI	Max-Planck-Institut für Meteorologie	Vegetation canopy
MRI	Meteorological Research Institute	Augmented bucket
NCAR	National Center for Atmospheric Research	Prescribed soil moisture
NMC	National Meteorological Center (now National Centers for Environmental Prediction, NCEP)	Augmented bucket
NRL	Naval Research Laboratory	Prescribed soil moisture
SUNYA	State University of New York at Albany	Simple bucket
SUNGEN	State University of New York at Albany/NCAR Genesis	Vegetation canopy
UCLA	University of California at Los Angeles	Prescribed soil moisture
UGAMP	UK Universities’ Global Atmospheric Modelling Programme	Augmented bucket
UIUC	University of Illinois at Urbana-Champaign	Augmented bucket
UKMO	United Kingdom Meteorological Office	Vegetation canopy
YONU	Yonsei University	Simple bucket

In the current AMIP II phase of the intercomparison, the experimental design remains fundamentally the same, except that the simulation period has been extended to 17 years (from 1979 to 1995). However, the AMIP II protocol also emphasizes the importance of adequate initialization/ spinup of moisture stores, and requires a more extensive set of land-surface output (Table 2). In addition, complex LSSs are likely to be much better represented than in AMIP I (Phillips 1999). These more auspicious conditions should allow the fuller investigation of the relationship between land-surface processes and parameterization schemes that the PILPS subproject plans to implement in AMIP II (Phillips et al. 1998).

Table 2: AMIP II Standard Model Output for Surface Variables. Reference: Gleckler et al. (1997)

Required Monthly Mean Variables	**Required Six-Hourly Data**
ground, surface air temperatures	total precipitation rate
surface and mean sea-level pressure	mean sea-level pressure
u/v winds and stresses	**Optional Six-Hourly Data**
specific humidity	surface air temperature
evaporation + sublimination	surface pressure
up/downward shortwave/longwave fluxes	u/v winds/stresses
latent and sensible heat fluxes	specific humidity
convective and total precipitation rates	up/downward shortwave/longwave fluxes
snowfall: rate, depth, cover, melt	latent and sensible heat fluxes
soil moisture: total columnar and at 10-cm depth	snow depth
surface, total runoff	total runoff and soil moisture

Given the richer set of model land-surface variables available in AMIP II, there is a commensurate need for global observational data that span a substantial portion of the 17-year simulation period. Such comprehensive data sets must be obtained by applying satellite remote-sensing techniques, with extensive quality-controlled postprocessing of the raw data. The reality, however, is that only a few years of such global land-surface data are presently available (e.g. Sellers et al. 1995). Pending the alleviation of this data shortage (e.g. ISLSCP 1999), validation of the AMIP II continental simulations will necessarily rely heavily on model-derived estimates such as are provided by reanalyses (e.g. Kalnay et al. 1996, Kanamitsu et al. 1999, ECMWF 1999, NASA 1999). (It should be acknowledged, however, that remote-sensing data also are model-derived, in the sense that algorithms must be used to translate observed radiances to the variables of interest.)

Because these model-derived products may be especially problematical in their representation of regional land-surface processes (e.g. Betts et al. 1998), the PILPS subproject will employ the reanalyses only for validation at continental-global scales, and also will use other “direct” observations such as are available for portions of the AMIP II simulation period. In this validation effort, the subproject will emphasize land-surface variables that are closely tied to the LSS parameterizations (e.g. turbulent fluxes and runoff), but also will evaluate other continental variables and atmospheric forcings (e.g. surface temperatures, radiative fluxes, and precipitation) in order to comprehensively survey all potential sources of error in the simulated land-surface processes.

3. A Provisional Validation Methodology: Application to AMIP I Models

In an intercomparison as extensive as the AMIP, summary statistics are essential to objectively validate simulation performance across many models and variables. As a starting point, for instance, the extent to which the global-mean, annual-mean climatological “bias” $\overline{M}$ of a spatio-temporal land-surface variable M(x,y,t) conforms to the observational reference bias $\overline{O}$ may be assessed. Model performance can be evaluated more meaningfully, however, by comparing the structure of a model’s spatio-temporal departures M' about $\overline{M}$ against those of the corresponding observational reference data:

$$\{M' = [M(x, y, t) - \overline{M}]\} \Leftrightarrow \{O' = [O(x, y, t) - \overline{O}]\}$$

The associated mean spatio-temporal variabilities are given by:

$$\sigma_m^2 = \frac{\sum_t \sum_y \sum_x (M')^2 \Delta x \Delta y \Delta t}{\Omega}$$

and

$$\sigma_o^2 = \frac{\sum_t \sum_y \sum_x (O')^2 \Delta x \Delta y \Delta t}{\Omega}$$

where the weight Ω is computed from the given spatial/temporal resolution $\Delta x \Delta y \Delta t$:

$$\Omega = \sum_t \sum_y \sum_x \Delta x \Delta y \Delta t$$

Shortcomings in model performance then can be summarized by the normed difference $\| M' - O' \|$, a standard measure of which is the root-mean-square (RMS) error statistic. In the context of the AMIP, a modified RMS error statistic

$$E = \left[\sum_t \sum_y \sum_x \frac{(M' - O')^2 \Delta x \Delta y \Delta t}{\Omega \sigma_o^2}\right]^{1/2}$$

that is normalized by $\Omega\sigma_o^2$ proves useful, since simulations of various land-surface processes with characteristically different natural variabilities then can be consistently compared across models.

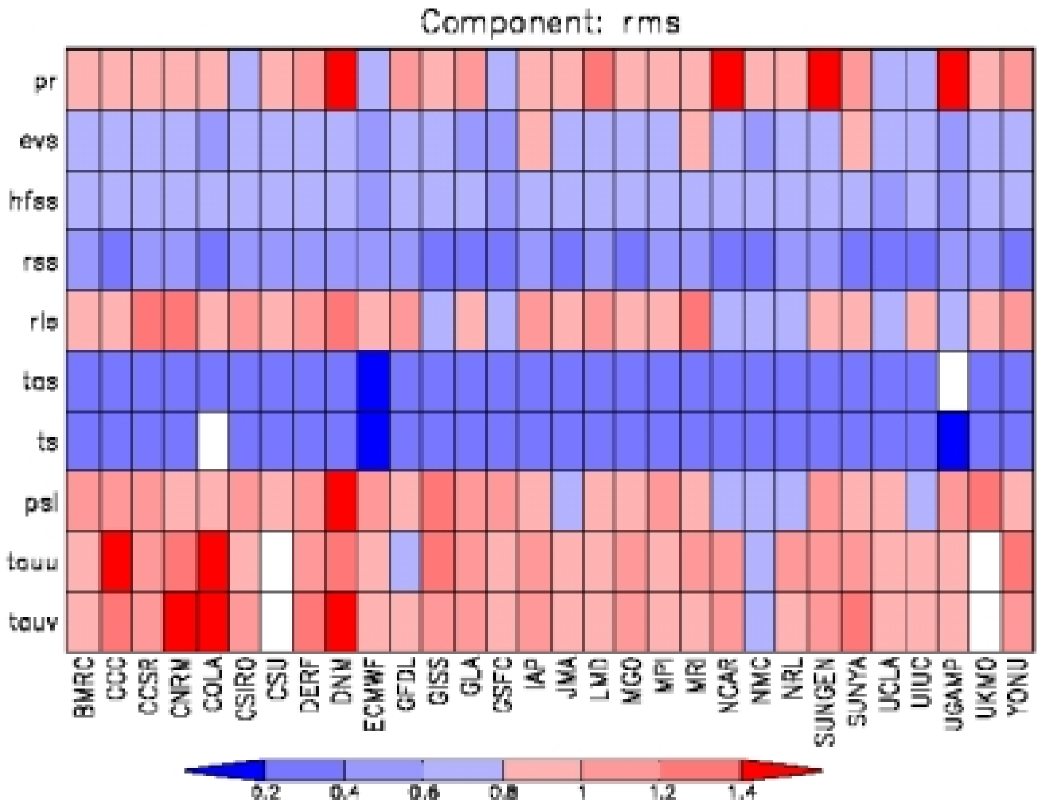

Figure 1**:** Normalized RMS error E of 10 land-surface variables with reference to NCEP Reanalysis-1 data for 30 AMIP I models. For each variable and model, E is calculated by summing over land grid boxes of area DxDy, where both model and reference data are interpolated to a common 2.5 x 2.5 degrees latitude-longitude grid, and by summing over monthly samples Dt of these data for the period 1979-1988. Relatively small values of normalized RMS error are depicted in blue, relatively larger values in red, and cases of missing data in white. The names of the land-surface variables are abbreviated as follows: **pr**: precipitation; **evs**: evaporation; **hfss**: sensible heat flux; **rss**: net shortwave radiative flux; **rls**: net longwave radiative flux; **tas**: air temperature at the lowest atmospheric level; **ts**: skin temperature; **psl**: mean sea-level pressure; **tauu**: u-wind stress; **tauv**: v-wind stress.

For example, Figure 1 depicts the normalized RMS errors of 10 simulated land-surface variables in 30 AMIP I models (see Table 1) relative to the corresponding data from the NCEP Reanalysis-1 (also known as the NCEP/NCAR Reanalysis--see Kalnay et al. 1996). It can be seen that land-surface skin and air temperatures (**ts** and **tas**), net shortwave radiation (**rss**), sensible heat flux (**hfss**), and evaporation (**evs**) are collectively simulated with lower normalized RMS errors than are continental mean sea-level pressure (**psl**) and wind stresses (**tauu** and **tauv**), precipitation (**pr**), and net longwave radiation (**rls**).

Because E consists of both errors in amplitude and pattern, other useful summary statistics include the ratio of variability amplitudes of model versus observations

$$A = \frac{\sigma_m}{\sigma_o}$$

and the corresponding pattern correlation

$$R = \frac{\sum_t \sum_y \sum_x (M' \cdot O') \Delta x \Delta y \Delta t}{\Omega(\sigma_m \cdot \sigma_o)}$$

It can be shown that E, A, and R share a law-of-cosines relationship (see the Appendix), and thus can be simultaneously depicted in a two-dimensional plot (Taylor, 2000). An example of such a “Taylor diagram” is shown in Figure 2 for the land-surface temperature (**ts**) from the AMIP I models, where the validation reference is again the NCEP Reanalysis-1 data (“Reference”). The radial dimension of this polar plot is proportional to the amplitude ratio A, while the angular dimension is scaled proportional to the cosine of the pattern correlation R. In addition, the distance between the reference temperature and that of a given model is indicative of the associated normalized RMS error E. There is little inter-model scatter in the A, R, or E statistics, perhaps because the simulated land-surface temperatures are constrained somewhat by the common AMIP specifications of solar constant and ocean surface temperature. In any case, there does not appear to be a sizeable global temperature sensitivity to the particular choice of LSS.

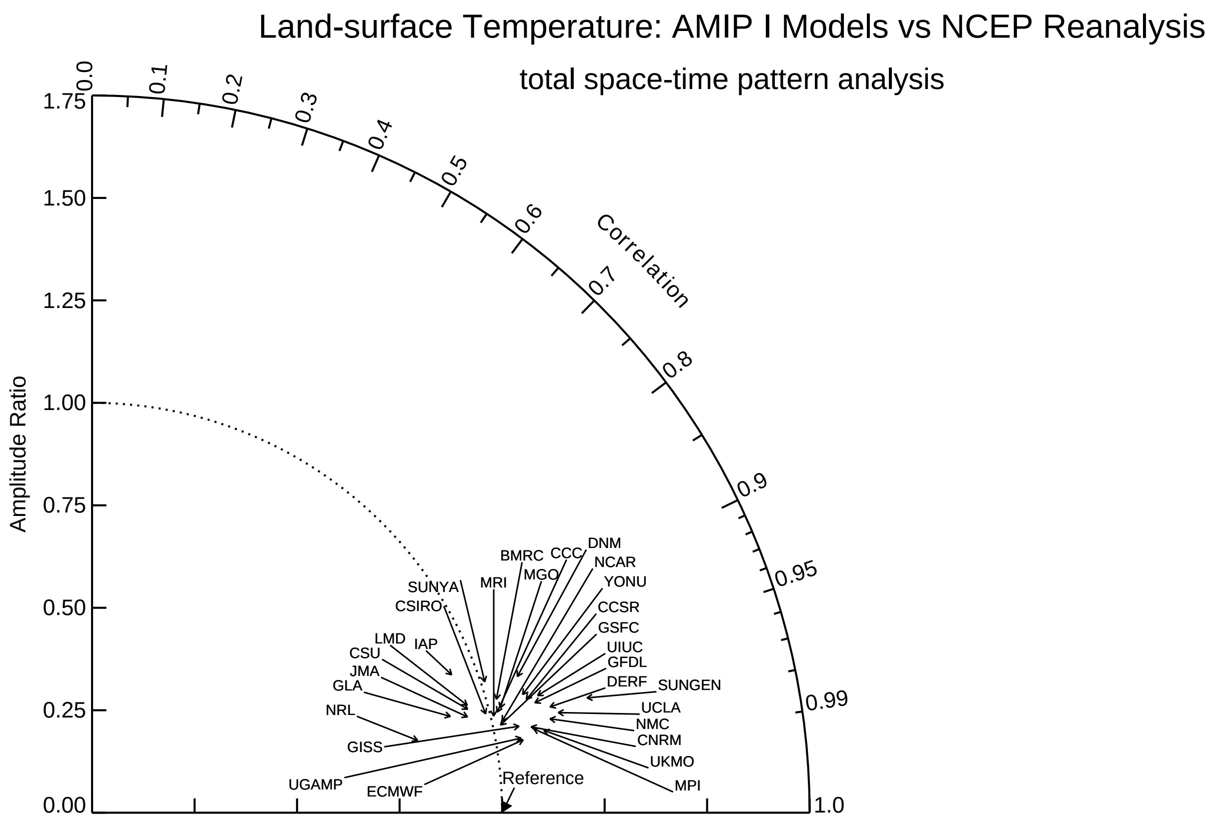

Figure 2**:** A Taylor diagram of the structure of the total variability of monthly mean land-surface temperature in 1979-1988 simulations of the AMIP I models relative to that of NCEP Reanalysis-1 ("Reference") estimates over the same time period. The distance between a particular model point (designated by the head of the arrow whose tail is labeled with that model's acronym--see Table 1) and the "Reference" is proportional to the model's normalized RMS error E with respect to the reference data. In this polar plot, the radial distance from the origin to a model point is proportional to the ratio A of variability amplitudes of the model vs reference data. (Values of A are indicated on the vertical axis, and the dotted quarter-circle is the locus of points where A = 1.) In addition, the angular displacement of a model point from the "Reference" is proportional to the cosine of the pattern correlation R, whose values are displayed along the edge of the outer quarter-circle. (See the Appendix for derivation of the relationships among the statistics A, E, and R.)

The simulated land-surface precipitation evinces a very different variability structure (Figure 3). Here the amplitude ratio A ranges widely (~ 0.6 to 2.0) relative to the reference data (but with A being close to unity for some models), while the pattern correlation R remains within a range ~ 0.5 to 0.7 across all the models. These results imply that the inter-model scatter in RMS precipitation errors (relative to the NCEP Reanalysis-1) that are displayed in Figure 1 are due more to differences in the amplitude of precipitation variability than in its pattern. An obvious global relationship to the respective LSS representations of land-surface hydrology (see Table 1) seems to be absent, however.

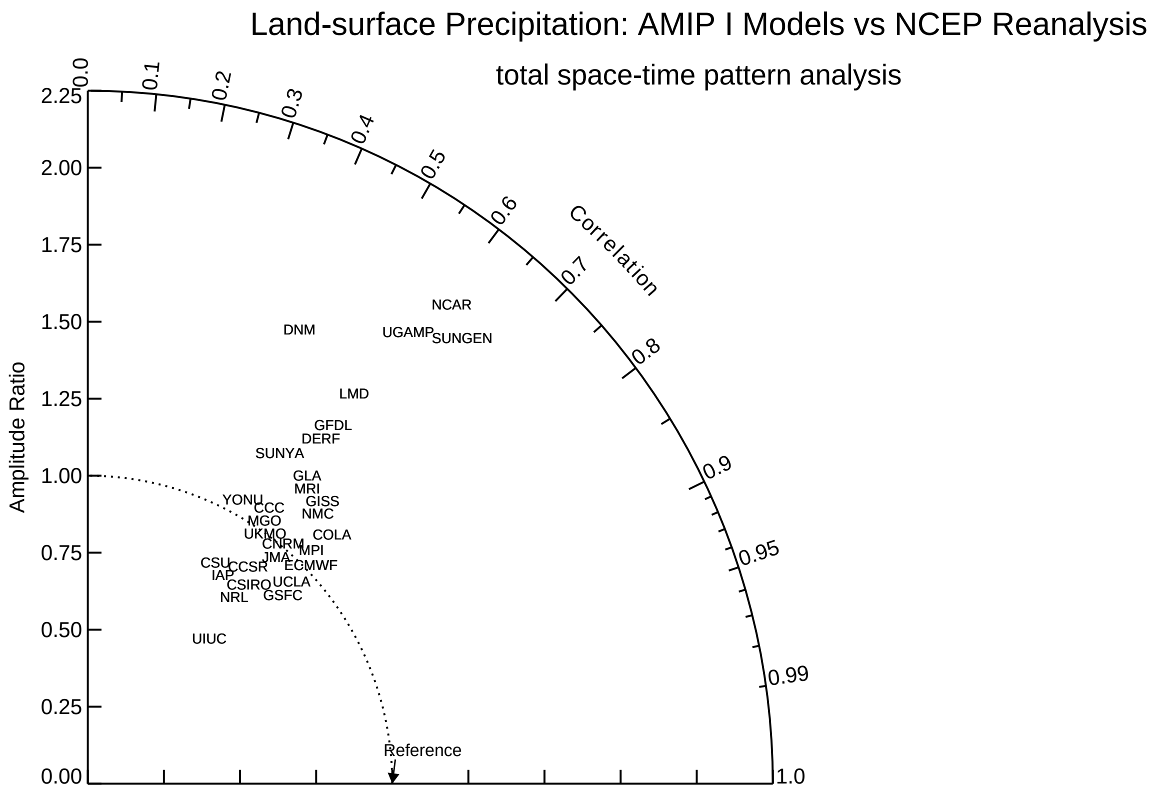

Figure 3: As in Figure 2, except for land-surface precipitation.

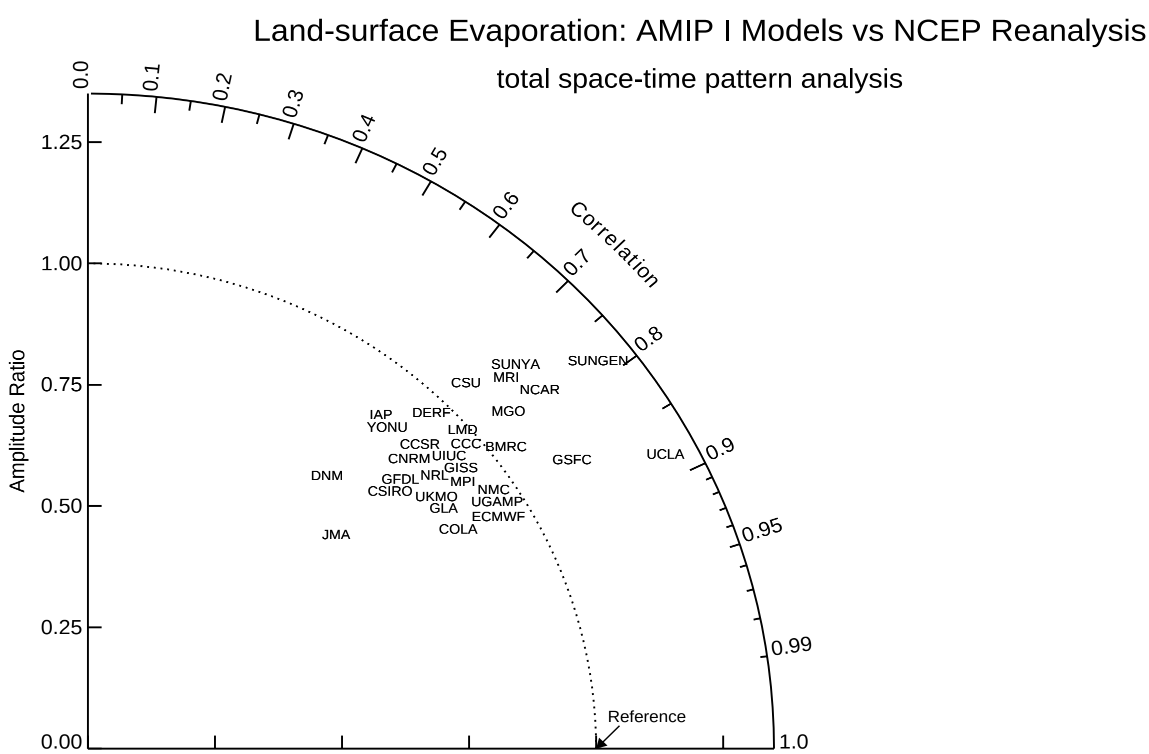

Figure 4: As in Figure 1, except for land-surface evaporation.

Relative to the reference data, the simulations of land-surface evaporation (Figure 4) occupy an intermediate position within the performance bounds demarcated by land-surface temperature and precipitation: amplitude ratios A range between ~ 0.6 and 1.3, with pattern correlations R between ~ 0.7 and 0.9. However, these reference evaporation data are influenced not only by the reanalysis model's atmospheric parameterizations and by its LSS, but also by the adopted procedure for "nudging" deep-layer soil moisture toward an assumed climatology (Mahrt and Pan 1984, Pan and Mahrt 1987, Kalnay et al. 1996). The NCEP Reanalysis-1 data therefore provide only a rough estimate of the actual variability of land-surface evaporation.

The degree of current uncertainty in estimating the global variability of land-surface evaporation from reanalyses is conveyed by Figure 5, which compares the estimate from the NCEP Reanalysis-1 for the AMIP I simulation period 1979-1988 ("Reference") with that of the NCEP Reanalysis-2 ("NR2", also known as the NCEP-DOE Reanalysis--see Kanamitsu et al. 1999) and of the European Centre for Medium-Range Weather Forecasts Reanalysis ("ERA"--see ECMWF 1999). It is noteworthy that the RMS difference between the two NCEP estimates is substantial, in spite of the presence of the same LSS in the respective reanalysis models. This divergence is thought to be due primarily to the replacement of soil-moisture nudging in NCEP Reanalysis-1 by a procedure that predicts soil moisture from precipitation observations, and secondarily to various changes in model parameterizations (M. Kanamitsu, personal communication). The ERA estimate of evaporation variability has a substantially lower amplitude than either of the NCEP reanalyses, and its pattern correlates somewhat less with the NR1 reference than does NR2.

On physical grounds, there are reasons to expect that the structure of a model's continental evaporation variability should depend on its representation of land-surface hydrology (see Table 1). Such a relationship seems to hold most conspicuously for those AMIP I models with biophysically based LSSs (Figure 6): the RMS differences relative to the NR1 reference for most of the models with vegetation-canopy LSSs are lower than those of nearly all the models with simpler representations of land hydrology. Most models with complex LSSs also have RMS differences with respect to the reference that are similar to those shown by the NR2 and ERA reanalyses. However, two models with biophysically based LSSs display relatively large RMS differences, mainly because the amplitude (not the pattern) of evaporation variability deviates substantially from that of the reference data.

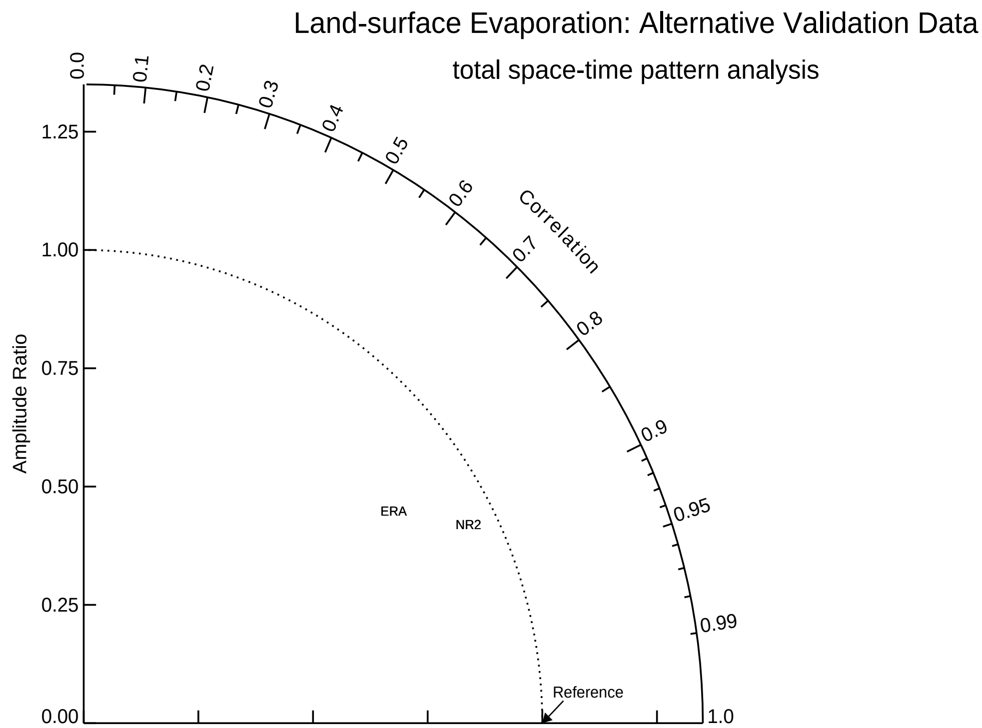

Figure 5: Differences in the structure of the spatio-temporal variability of land-surface evaporation among several reanalyses: the NCEP Reanalysis-1 (“Reference”), the NCEP Reanalysis-2 (“NR2”), and the ECMWF Reanalysis (“ERA”).

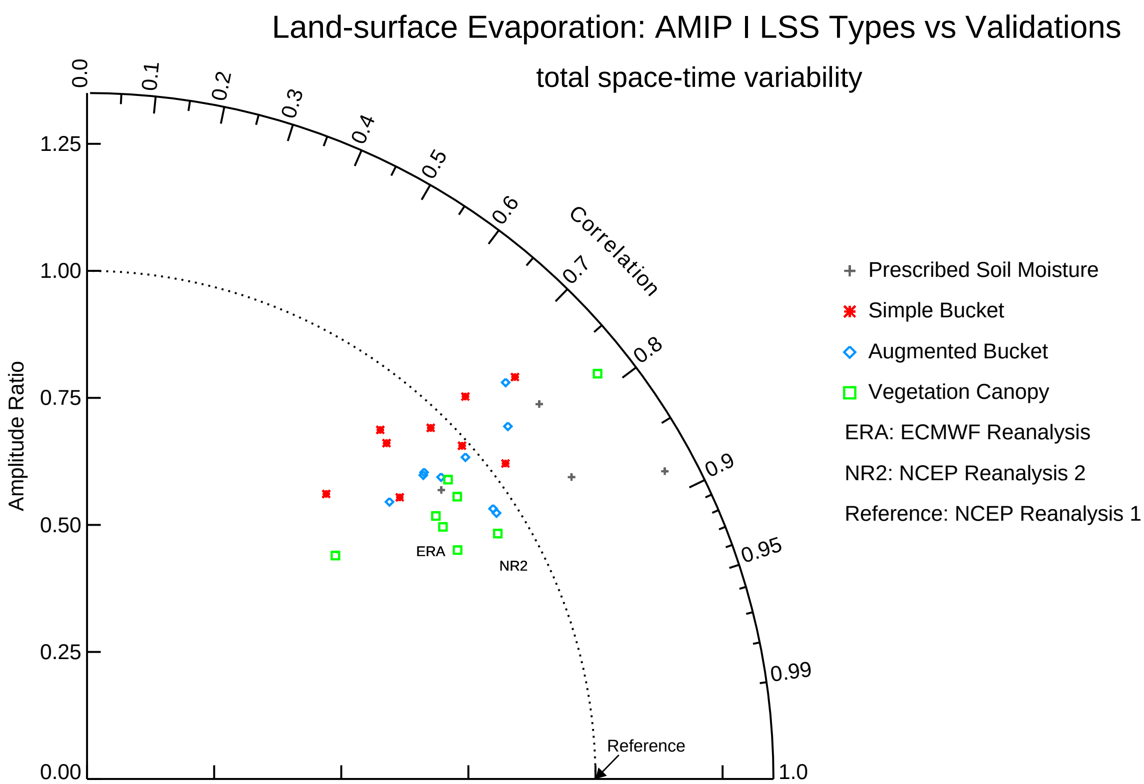

Figure 6: As in Figure 4, except that the type of land-surface scheme corresponding to the respective AMIP I model is indicated and the estimates from the NR2 and ERA reanalyses also are included.

On the other hand, a few simulations corresponding to simple and augmented bucket schemes, as well as one with prescribed soil moisture, also show relatively low RMS differences with the reference data. This result suggests that the global monthly variability statistics associated with complex LSSs *can* be matched by using simpler schemes. In nearly all the latter cases, however, the effects of vegetation on surface roughnesses and albedos are accounted for, even though canopy biophysics are not explicitly represented (Phillips 1994). (Because these land-surface characteristics are not included in the standard AMIP I output data, it is not possible to precisely estimate their impact on the simulations.) These results are reminiscent of the off-line LSS experiments of Desborough (1999), wherein a simple parameterization of continental evaporation that included a constant surface resistance was able to approximate the results of more complex formulations on monthly time scales.

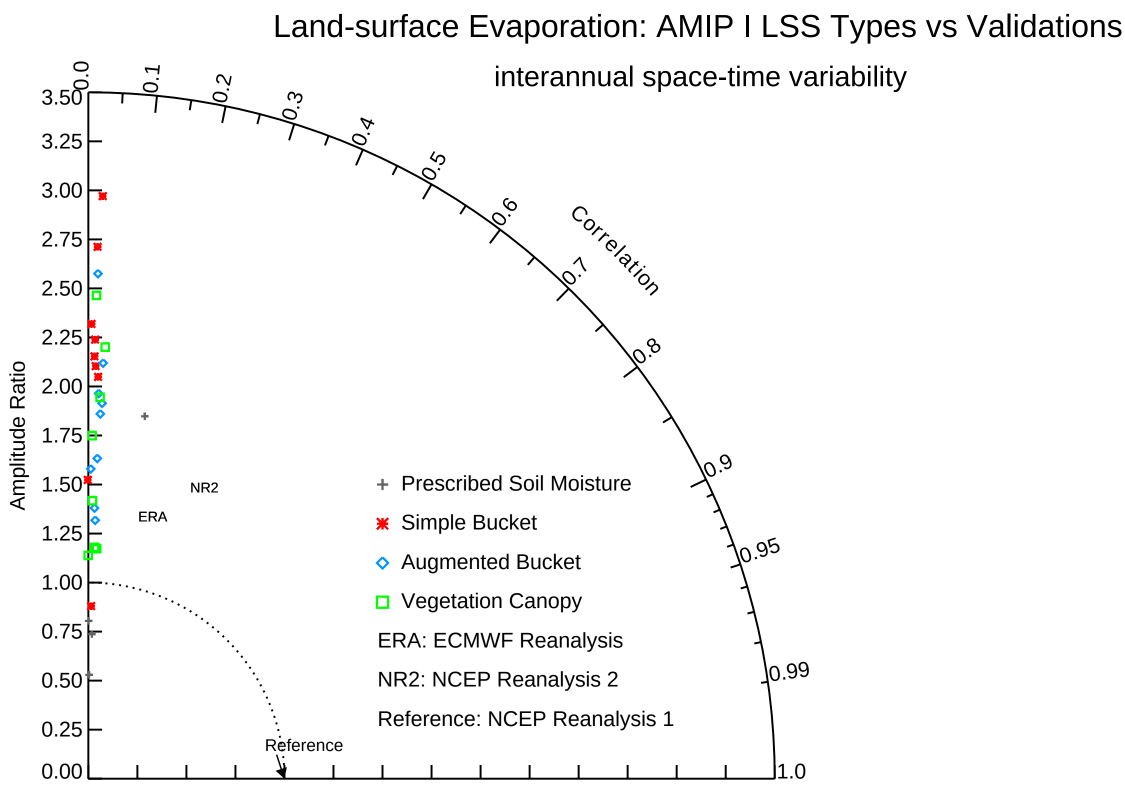

Figure 7: As in Figure 6, except that the interannual spatio-temporal variability of land-surface evaporation as a function of the type of land-surface scheme is indicated relative to that of the NCEP Reanalysis-1 (“Reference”). The relationship of the NR2 and ERA reanalyses to this reference also are indicated.

When only the interannual variability of continental evaporation is considered (Figure 7), there is neglible pattern correlation between each AMIP I model and NR1, and there is a wide range of amplitude ratios. The ERA and NR2 reanalyses display marginally better agreement with the NR1 reference. There also is an apparent lack of differentiation according to LSS type, probably because the interannual component of variability is globally chaotic--that is, more sensitive to the different model initial conditions than to their common ocean boundary conditions. (It is noteworthy, for example, that the model with the best correlation to the reference is one with prescribed *land* boundary conditions.)

Since there are many parameterization differences among the AMIP I models apart from their LSSs (Phillips 1994), the apparent sensitivity of surface evaporation variability to LSS type (e.g. as displayed in Figure 6) may be coincidental. A clearer indication of the degree of sensitivity of land-surface evaporation that can result only from changing the LSS type is provided by a supplemental pair of AMIP I simulations made with a version of the Laboratoire de Meteorologie Dynamique (LMD) AGCM. In these twin experiments, a simple bucket (Laval et al. 1981) and the biophysically based SECHIBA scheme (Ducoudre et al. 1993) were alternatively coupled to the AGCM, but with the same land-surface characteristics (i.e. the surface albedos and roughnesses associated with the SECHIBA vegetation types) being specified.

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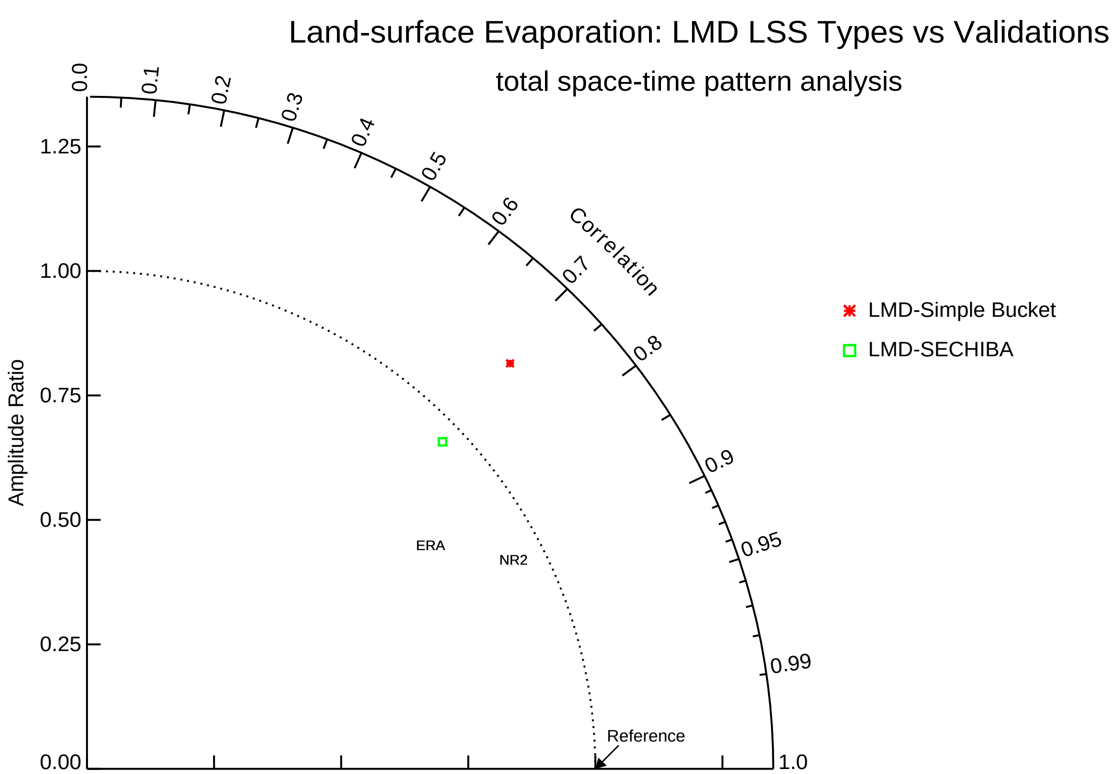


Figure 8**:** As in Figure 6, except for twin AMIP I simulations of land-surface evaporation by a version of the LMD model with an embedded simple-bucket scheme and the biophysically based SECHIBA scheme.

Figure 8 shows the Taylor diagram for the variability of continental evaporation in these experiments relative to estimates from the various reanalyses. By substituting the SECHIBA scheme for the simple bucket, the amplitude of the variability is reduced, thereby improving its agreement with the estimates of the various reanalyses. Analogous but less dramatic results (not shown) are obtained for other land-surface variables in these paired simulations. A similar impact on the amplitude of the interannual component of continental climate variability is also evident (Figure 9). In all such cases, little change in the correlation R results from modifying the LSS, suggesting that it is the atmospheric forcings and/or the land-surface characteristics that largely control the pattern of continental climate variability.

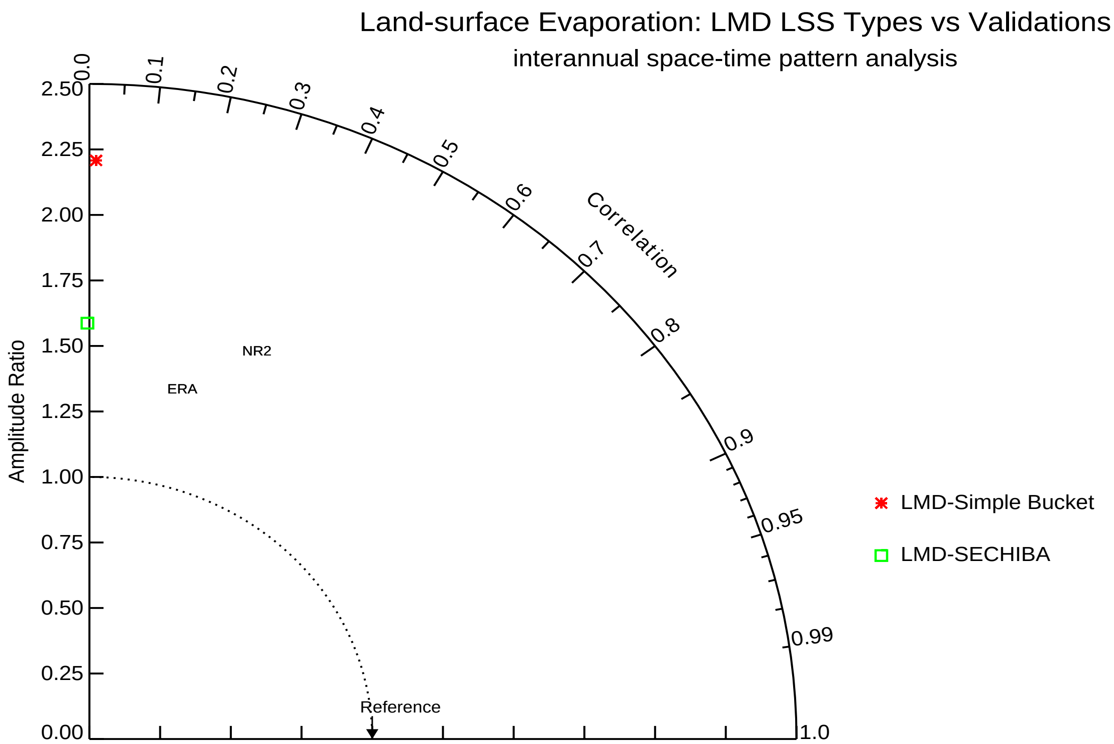


Figure 9: As in Figure 8, except for the interannual variability of land-surface evaporation.

4. Conclusions and Future Directions

We draw the following provisional conclusions from this pilot study:

- The perceived performance of an AGCM in simulating continental climate is a function of the land-surface variables and reference data chosen for the evaluation. Of the available AMIP I land-surface variables, most do not display obvious *global* sensitivity to LSS type.
- Nevertheless, the simulated land-surface evaporation variability does seem to exhibit such sensitivity, insofar as most models with biophysically based LSSs generally show lower RMS differences with the chosen reference data than do models with simpler representations of hydrology. In part, however, these inter-model differences undoubtedly also reflect diverse representations of land-surface characteristics (e.g. surface albedos and roughnesses) as well as atmospheric physics.
- For paired AMIP I experiments in which the same atmospheric model and land-surface characteristics are retained, the replacement of a simple bucket scheme by a biophysically based LSS (while retaining the same land-surface characteristics) reduces the RMS differences of the land-surface variables with respect to selected reference data. However, these LSS-dependent improvements are almost completely associated with reductions in variability amplitude, suggesting that the atmospheric forcings and/or the land-surface characteristics largely control the pattern of continental evaporation variability.

Because of the uncertain quality of the available reference data and the restricted scope of this study (limited selection of variables, globally aggregated statistics, etc.), these “conclusions” should instead be regarded as hypotheses to guide future work of Subproject 12 in AMIP II (Phillips et al. 1998). That effort will include not only an extension of the pilot validation methodology to a broader selection of land-surface variables and reference data sets, but also regional-scale diagnosis of the coupled behaviors of the LSSs in AMIP II models.

Acknowledgments

The validation methodology and related computer software applied herein were developed by Karl Taylor and Charles Doutriaux of PCMDI. We greatly appreciate their assistance in the production and interpretation of the displayed figures. This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Appendix: Relationships Among Summary Statistics

Here we derive the relationships among the normalized RMS error E, the amplitude ratio A, and the pattern correlation R that are represented pictorially by a Taylor diagram.

First, recall that if M' and O' are spatio-temporal departures of model and observations from their respective annual-mean, global-mean biases $\overline{M}$ and $\overline{O}$, the normalized mean-square error of model M relative to observational reference O is defined as

$$E^2 = \sum_t \sum_y \sum_x \frac{(M' - O')^2 \Delta x \Delta y \Delta t}{\Omega \sigma_o^2}$$

where the normalization factors are a spatio-temporal weight

$$\Omega = \sum_t \sum_y \sum_x \Delta x \Delta y \Delta t$$

and total variability of the observational reference data

$$\sigma_o^2 = \frac{\sum_t \sum_y \sum_x (O')^2 \Delta x \Delta y \Delta t}{\Omega}$$

Thus, the mean-square error may be expressed in expanded form as

$$E^2 = \frac{\sum_t \sum_y \sum_x (M'^2 - 2M' \cdot O' + O'^2) \Delta x \Delta y \Delta t}{\sum_t \sum_y \sum_x (O')^2 \Delta x \Delta y \Delta t}$$

Then, by defining the model's total spatio-temporal variability analogously to σ_o^2

$$\sigma_m^2 = \frac{\sum_t \sum_y \sum_x (M')^2 \Delta x \Delta y \Delta t}{\Omega}$$

and by utilizing the spatio-temporal amplitude ratio

$$A = \frac{\sigma_m}{\sigma_o}$$

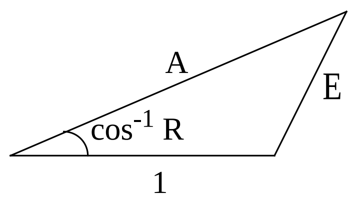
and pattern correlation

$$R = \frac{\sum_t \sum_y \sum_x (M' \cdot O')\Delta x \Delta y \Delta t}{\Omega(\sigma_m \cdot \sigma_o)}$$

the normalized mean-square error is reducible to

$$E^2 = A^2 - 2R \cdot A + 1$$

This is equivalent to a law-of-cosines relationship among E, A, and R if we make the following geometrical assignments::



A Taylor diagram exploits this geometry in order to express the relationships among E, A, and R in a single two-dimensional polar plot.

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