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1. Introduction

The Atmospheric Model Intercomparison Project (**AMIP**) is a commonly accepted protocol for testing the performance of the world's atmospheric general circulation models (**AGCMs**) under common specifications of radiative forcings (in solar constant and carbon dioxide concentration) and observed ocean boundary conditions (Gates 1992, Gates et al. 1999). From the standpoint of landsurface specialists, the **AMIP** affords an opportunity to investigate the behaviors of a wide variety of land-surface schemes (**LSS**) that are coupled to their "native" **AGCMs** (Phillips et al. 1995, Phillips 1999). In principle, therefore, the **AMIP** permits consideration of an overarching question: "To what extent does an **AGCM's** performance in simulating continental climate depend on the representations of land-surface processes by the embedded **LSS**?"

There are, of course, some formidable obstacles to satisfactorily addressing this question. First, there is the dilemna of how to effectively validate simulation performance, given the present dearth of global land-surface data sets. Even if this data problem were to be alleviated, some inherent methodological difficulties would remain: in the context of the **AMIP**, it is not possible to validate a given **LSS** *per se*, since the associated land-surface climate simulation is a product of the coupled **AGCM/LSS** system. Moreover, aside from the intrinsic differences in **LSS** across the **AMIP** models, the varied representations of land-surface characteristics (e.g. vegetation properties, surface albedos and roughnesses, etc.) and related variations in land-surface forcings further complicate such an attribution process. Nevertheless, it may be possible to develop validation methodologies/statistics that are sufficiently penetrating to reveal "signatures" of particular **LSS** representations (e.g. "bucket" vs more complex parameterizations of hydrology) in the **AMIP** land-surface simulations.

2. AMIP I Versus AMIP II

The first phase of the **AMIP**, designated **AMIP I**, spanned the years 1990 to 1996. Among several efforts to analyze various aspects of the land-surface climate of the **AMIP I** models (e.g. Lau et al. 1996, Frei and Robinson 1998, Robock et al. 1998), the GEWEX-initiated Project for Intercomparison of Land-surface Parameterization Schemes (**PILPS**) also contributed (Henderson-Sellers et al. 1996). In this **AMIP** study, **PILPS** participants organized as Diagnostic Subproject 12 on Land-surface Processes and Parameterizations.

Subproject 12 performed its work in the context of several significant limitations: little global data were available for validation; the set of model "standard output" variables was quite limited (e.g., runoff was not provided); and there was a narrow range of **LSS** complexity represented, since a large majority of **AMIP I** models used various forms of bucket schemes. In this context, Subproject 12 performed a "zeroth-order" land-surface validation, in the sense of identifying discrepancies that could be readily found from inspection of the **AMIP I** simulations. The main findings were threefold:

1) Every simulation of land-surface climate was an outlier in some respects, i.e. there was no one "best" model (Love and Henderson-Sellers 1994).

2) A number of simulations exhibited obvious flaws of execution such as nonconservation of soil moisture/energy and pronounced trends in continental moisture stores due to inadequate model initialization/spin-up (Love et al. 1995).

3) Contrary to expectation, the inter-model scatter in regional-scale energy/moisture partitionings was substantially larger than in comparable **PILPS** offline experiments--possibly as a consequence of different regional forcings in **AMIP I** models (Irannejad et al. 1995).

In the current **AMIP II** phase of the intercomparison, the experimental design remains fundamentally the same (i.e. commonly specified radiative forcings and ocean boundary conditions), but longer simulations (of length 17 years vs 10 years in **AMIP I**) are being run. There also are several refinements of the experimental protocol that address concerns expressed by land-surface specialists in **AMIP I**. These include a greater emphasis on ensuring adequate initialization/spin-up of continental moisture stores and conservation of energy/moisture; a broader representation of different types/complexities of **LSS**; and a more extensive set of required land-surface output variables (see **Table**). To date (October 1999), about 20 models have completed their **AMIP II** simulations, but model output data have only just been released to the diagnostic subprojects.

Table: AMIP II Standard Model Output for Surface Variables (Ref: Gleckler 1996)

Required Monthly Mean Variables	**Required Six-Hourly Data**
Ground, screen temperatures	Total precipitation rate
Surface and mean sea-level pressure	Mean sea-level pressure
U-V winds and stresses	
Specific humidity	**Optional Six-Hourly Data**
Evaporation + sublimination	Screen temperature
Up/down shortwave/longwave radiative fluxes	Surface pressure
Latent and sensible heat fluxes	U-V winds/stresses
Convective and total precipitation rates	Specific humidity
Snowfall: rate, depth, cover, melt	Up/down shortwave/longwave radiative fluxes
10-cm depth, total soil moisture	Latent and sensible heat fluxes
Surface, total runoff	Snow depth
	Total runoff, soil moisture

Given the richer set of model land-surface variables in **AMIP II**, there is a commensurate demand for validation reference data. Concretely, there is a need for global, gridded data sets that span at least a decade within the **AMIP II** simulation period (from 1979 to 1995). The reality, however, is that many continental variables are not directly measurable at global scale, and there are mostly only a few years of data available from extant global remote-sensing initiatives. Until this data situation qualitatively improves, validation of the **AMIP II** models will need to rely heavily on model-derived estimates of land-surface variables such as are provided by various reanalyses, which conveniently span the entire **AMIP II** simulation period. (It should be noted that remotely sensed data are also model-derived, in the sense that algorithms must be used to translate the observed irradiances to the actual variables of interest.)

Because the reanalyses are known to be problematical for land-surface validation at regional scales (e.g. Betts et al. 1998), Diagnostic Subproject 12 will use these products only for large-scale validation of the **AMIP II** models, and will supplement this evaluation with alternative observational reference data sets, to the extent these are available for subperiods of the simulations (Phillips et al. 1998). In carrying out this validation exercise, Subproject 12 will emphasize land-surface "response" variables (e.g. evaporation, runoff, turbulent fluxes, etc.), viewing the evaluation of "forcing" variables (e.g. precipitation, radiative fluxes, momentum stresses) mainly in the context of interpreting this "response". (It is recognized, of course, that "forcing" and "response" are not cleanly separable in a coupled **AGCM/LSS**.) Further details of the planned validation methodology are discussed in the next section.

3. A Validation Methodology: Examples from AMIP I Models

In this section, the outlines of a validation methodology that is relevant for **AMIP II** are sketched and illustrated by application to selected land-surface variables in the **AMIP I** models. It is anticipated that as the validation of **AMIP II** models proceeds, this methodology both will be extended and refined.

In an intercomparison experiment as ambitious as **AMIP II** (30+ models, 17 year-simulations, ~ 20 land-surface variables), the calculation of summary statistics is essential for a practical validation effort. For each variable of interest, comparison of the annual-mean, global-mean climatology, or the "bias" <M> of a model, with that of an appropriate observational reference <O> is a natural first step in the validation process. Thereafter, it is more challenging to concisely summarize the model's spatio-temporal variation about its bias, {M(x,y,t) – <M>}, in relation to the corresponding reference variation, {O(x,y,t) – <O>}, when t ~ 200 months as in **AMIP II**.

As a starting point for such a validation exercise, it is useful to define a normalized spatio-temporal **RMS** error E/σ_O where

$$E = \left\{ \iiint \left([M(x,y,t) - \langle M \rangle] - [O(x,y,t) - \langle O \rangle] \right)^2 dx\,dy\,dt \right\}^{1/2}$$

and

$$\sigma_O = \left\{ \iiint [O(x,y,t) - \langle O \rangle]^2 dx\,dy\,dt \right\}^{1/2}$$

is the spatio-temporal standard deviation of the observational reference about its bias. The normalized **RMS** error E/σ_O is a dimensionless statistic that can be used to consistently compare the performance of a model across different variables (having different σ_O).

Other statistical measures of "goodness-of-fit" are also useful in this context. For example, the normalized **RMS** error may be viewed as consisting of errors in "amplitude" and "pattern". The amplitude error can be expressed by the deviation of σ_M/σ_O from unity, where the spatio-temporal standard deviation σ_M of the model is defined analogously to σ_O above. The pattern error can be captured by the deviation from unity of a spatio-temporal correlation statistic

$$R = \iiint [M(x,y,t) - \langle M \rangle][O(x,y,t) - \langle O \rangle]\, dx\,dy\,dt \,/\, [\sigma_M \sigma_O]$$

It can be shown that these three statistics share a law-of-cosines relationship, so that they may be simultaneously represented in a two-dimensional polar plot (K. Taylor, unpublished manuscript). An example of such a "Taylor diagram" for the land-surface temperature of ~ 30 **AMIP I** models (e.g. designated by acronyms "DNM", "IAP", etc.) is shown in Figure 1. Here the label "Observed" on the abscissa indicates the reference point, which in this case is the land-surface temperature estimated from the **NCEP/NCAR** Reanalysis (Kalnay et al. 1996) for the period of the decadal (1979-1988) **AMIP I** simulation. (The **NCEP** reanalysis model used radiative forcings and ocean boundary conditions very similar to those of the **AMIP I** models.) The radial dimension of the polar plot is proportional to the amplitude ratio σ_M/σ_O (where a value of unity is indicated by the dotted line), while the angular dimension is scaled proportional to the cosine of the spatio-temporal pattern correlation **R**. Finally, the distance between the temperature of the observational reference point ("Observed") and that of a given model ("DNM" etc.) is indicative of the model's normalized **RMS** error $\mathbf{E}/\sigma_O$. It is seen that, collectively, the land-surface temperature of the **AMIP I** models matches the observational reference quite well, with amplitude ratio $\sigma_M / \sigma_O \sim 1$, pattern correlation $\mathbf{R} > 0.95$, and correspondingly small normalized **RMS** error $\mathbf{E}/\sigma_O$.

A qualitatively different assessment obtains for the simulations of land-surface precipitation by the **AMIP I** models (Figure 2). Here the amplitude ratios range between ~ 0.6–2.0 (with correspondingly large scatter in the normalized **RMS** errors), while the pattern correlations are only ~ 0.5–0.6 for most of the models. The **AMIP I** simulations of land-surface evaporation (Figure 3) occupy an intermediate position within the performance bounds demarcated by the land-surface precipitation and temperature: the amplitude ratios range between ~ 0.6 and ~ 1.3, and the pattern correlations between ~ 0.7 and ~ 0.9.

Figure 1: A "Taylor diagram" for a 10-year time series of the land-surface temperature field in **AMIP I** models, plotted with respect to the observational reference (designated as "Observed"), as obtained from the **NCEP/NCAR** reanalysis estimate of this variable for the same time period. The radial dimension of this polar plot is scaled linearly proportional to the ratio of the integrated spatio-temporal standard deviations of each model (designated by acronym) and that of the observational reference: σ_M/σ_O (with a ratio of unity indicated by the dotted line). The angular dimension is scaled proportional to the cosine of the integrated spatio-temporal pattern correlation **R** of each model with the observational reference. The integrated normalized **RMS** error $\mathbf{E}/\sigma_O$ is proportional to the distance between each model and the "Observed" point. (See text for definitions of these statistics.)

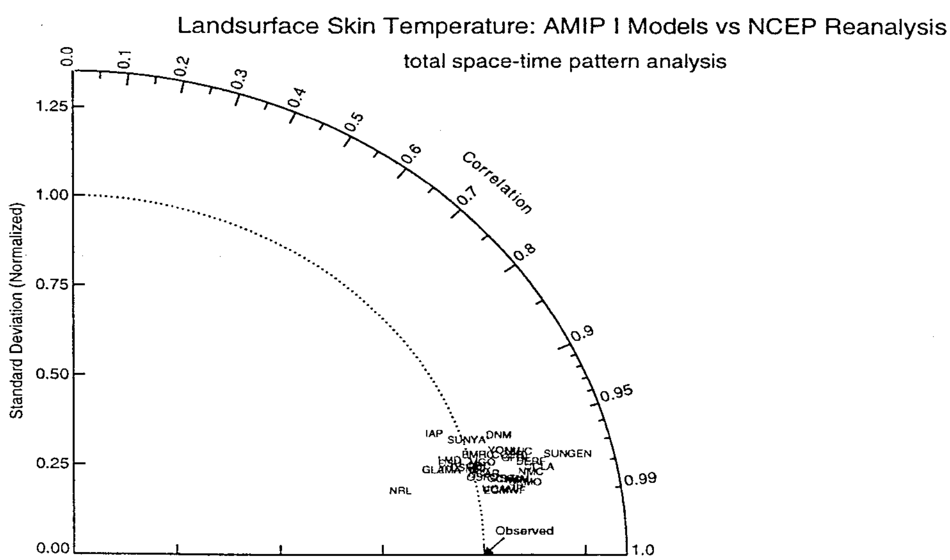


Figure 2: As in Figure 1, except for land-surface precipitation.

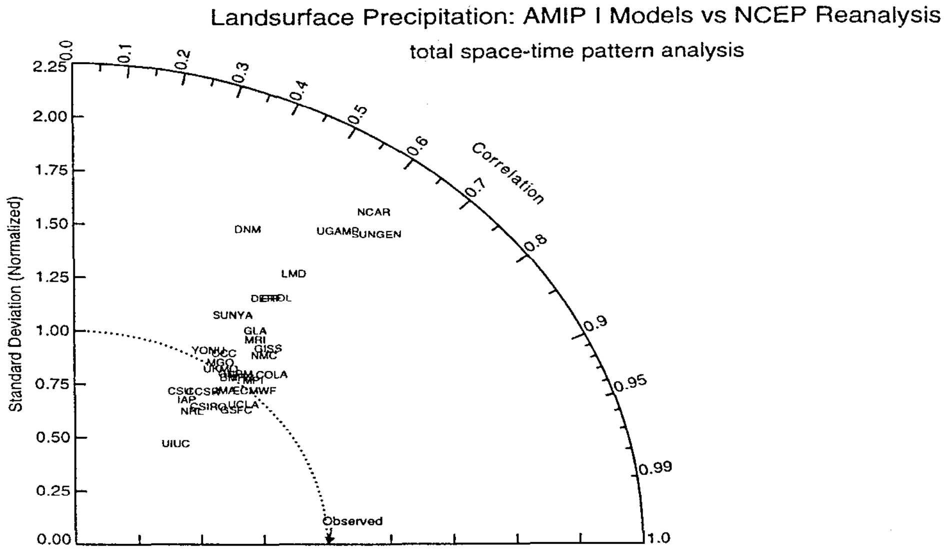
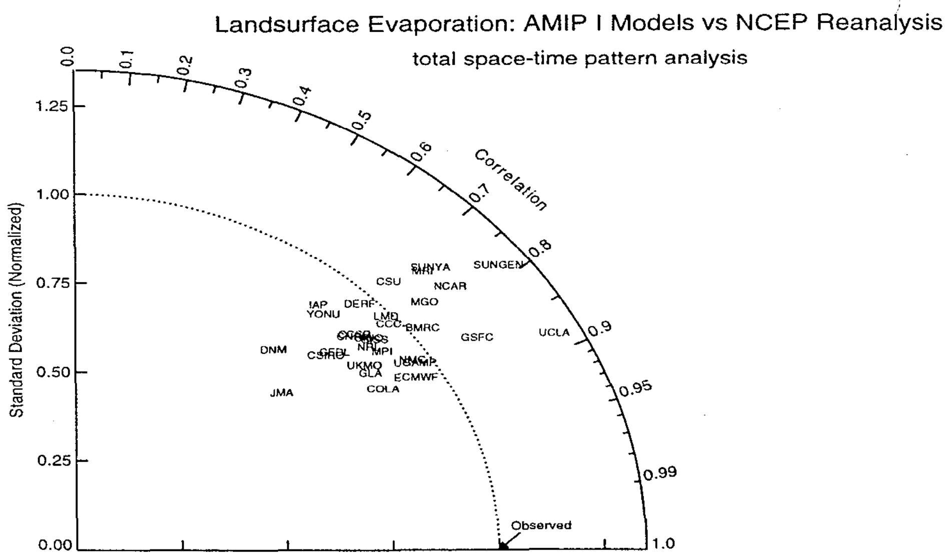


Figure 3: As in Figure 1, except for land-surface evaporation.



To some extent, the location of a land-surface evaporation point in the Taylor diagram of Figure 3 appears to depend on the respective **LSS** type (Figure 4), in that there is a tendency for most of the **LSS** of a similar complexity to cluster in the same statistical "neighborhood". Moreover, as a group, **LSS** with explicit representations of vegetation tend to exhibit lower **RMS** errors with respect to the **NCEP/NCAR** reference data than do simple-bucket **LSS**, while augmented-bucket **LSS** tend to show intermediate-sized **RMS** errors. (There are individual exceptions to this general tendency, however. For example, a few vegetation-canopy **LSS** show relatively large **RMS** errors, but these are mainly associated with errors of amplitude rather than of pattern.)

This tendency for surface evaporation to stratify according to **LSS** type is magnified when the validation methodology is applied only to a subcomponent of the total spatio-temporal variability of the models, and especially to the zonally asymmetric part of the seasonal cycle (Figure 5). On the other hand, when only the interannual component (a small fraction of total spatio-temporal variability) of surface evaporation is considered, all the **AMIP I** models exhibit very high **RMS** errors with respect to the reference data (Figure 6). In general, these are associated with very low pattern correlations, possibly an irremediable outcome of the models' chaotic behavior. A few models, however, replicate the amplitude of the reference's interannual component fairly well, but in this respect an obvious relationship to **LSS** type appears to be absent.

Figure 4: As in Figure 3, except that the **LSS** type corresponding to each **AMIP I** model is indicated.

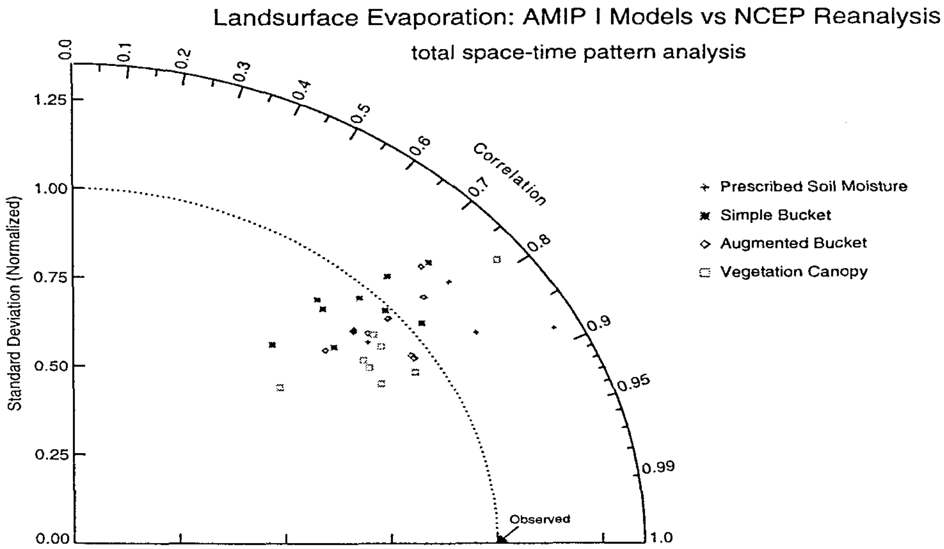


Figure 5: As in Figure 4, except for the zonally asymmetric component of the climatological seasonal cycle of land-surface evaporation.

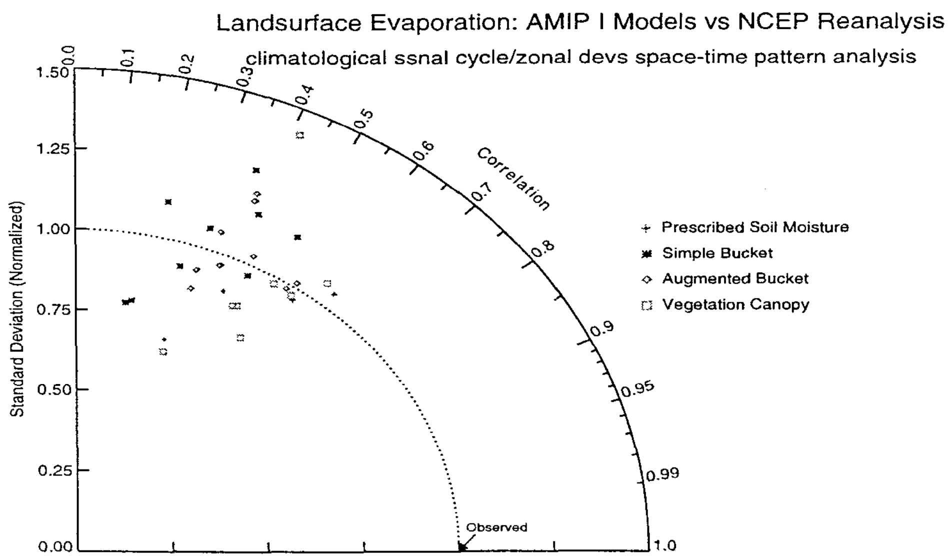


Figure 6: As in Figure 4, except for the interannual departures from the climatology of land-surface evaporation.

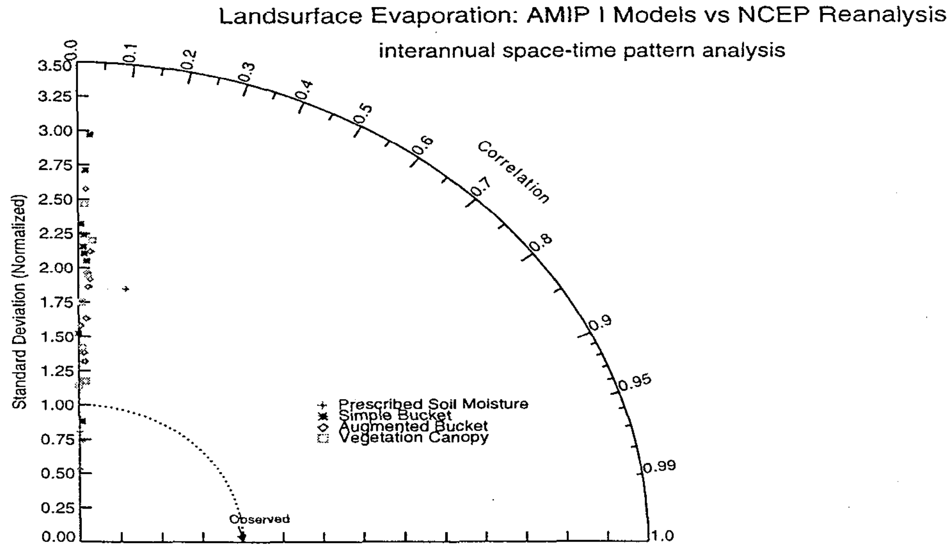
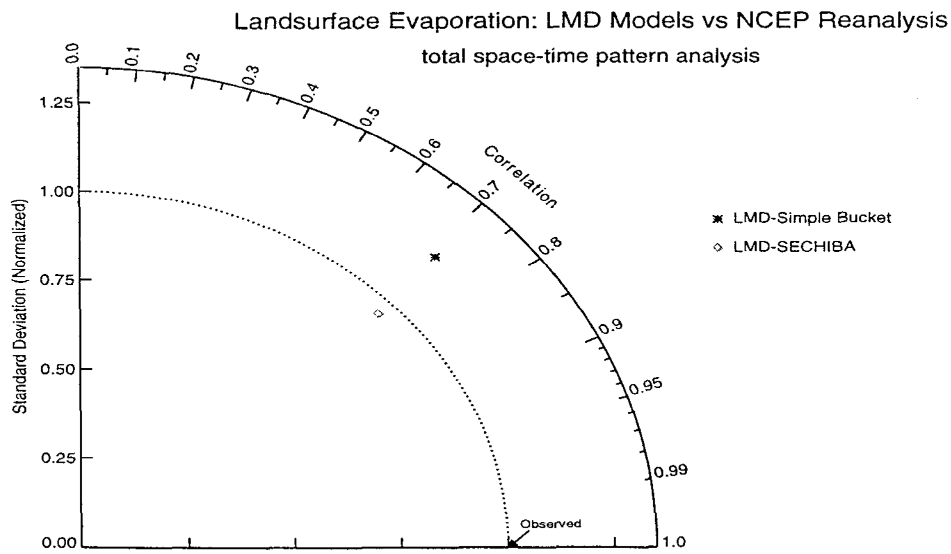
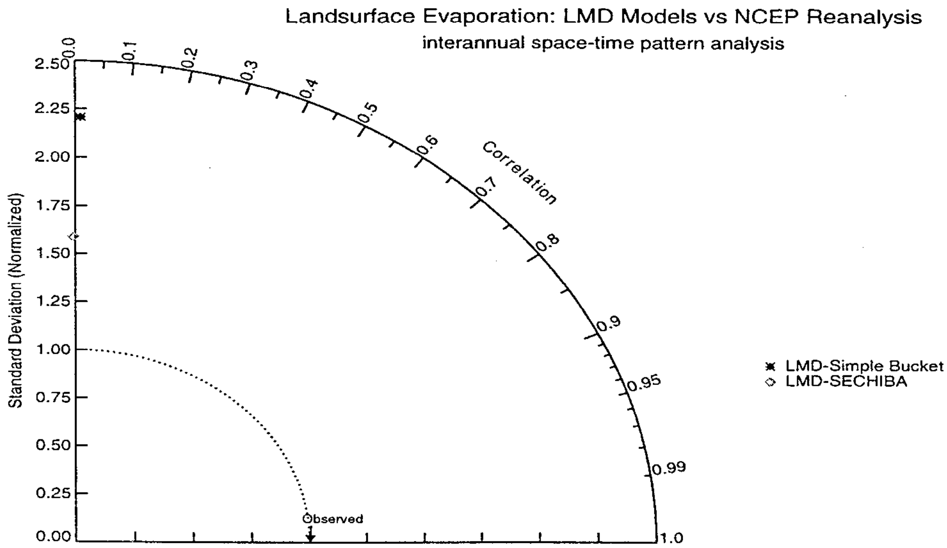


Figure 7: As in Figure 4, except for twin **AMIP I** simulations of land-surface evaporation by the **LMD AGCM** with embedded simple-bucket and biophysically based **SECHIBA** schemes.



In addition, there are many other parameterization differences among the **AMIP I** models, so that the apparent stratification of surface evaporation according to **LSS** type may be merely coincidental. However, a few **AMIP I** simulations where the same atmospheric model was coupled to different **LSS** can provide some preliminary answers to this question. For example, twin **AMIP I** experiments were run with the **LMD** model, the first simulaton with a simple bucket scheme (Laval et al. 1981), and the second with the biophysically based **SECHIBA** scheme (Ducoudre et al. 1993). In both simulations, the surface characteristics (vegetation, albedos, surface roughnesses) remained the same, so that only the effects of "intrinsic" **LSS** differences were manifested. The relevant Taylor diagram for surface evaporation is shown in Figure 7, with the the **NCEP/NCAR** Reanalysis again serving as a validation reference. It is seen that virtually no change in pattern correlation results from varying the **LSS**, but there are discernable improvements in the amplitude of the total spatio-temporal variability of surface evaporation. A similar improvement is seen in the amplitude of the interannual component of this variability (Figure 8).

Figure 8: As in Figure 7, except for the interannual departures from the climatology of land-surface evaporation.



4. Initial Conclusions and Future Directions

The following initial conclusions can be drawn from this validation exercise :

- The assessment of model performance in simulating continental climate is colored by the choice of land-surface variables for validation. For example, the **AMIP I** models collectively simulate land-surface temperature much better than precipitation.
- At global scale, the spatio-temporal variability of land-surface evaporation appears to be sensitive to the **LSS** type.
- When operated in coupled mode, simple-bucket **LSS** *can* produce simulations of the spatio-temporal variability of surface evaporation that are "competitive" with those obtained from **AGCMs** with more complex **LSS**. However, for the same **AGCM**, the replacement of a simple bucket scheme by a biophysically based **LSS** *may* globally improve some aspects (e.g. reduction of amplitude errors) of the simulation of surface evaporation variability.
- The simple-bucket schemes seem to have more difficulty simulating the zonally asymmetric component of the land-surface evaporation field, when compared with more complex **LSS**. However, this may reflect the absence of explicit vegetation and related surface characteristics (e.g., albedos and surface roughnesses) more than "intrinsic" deficiencies of the simple-bucket schemes.

- In general, the spatio-temporal pattern of the interannual component of the land-surface evaporation is poorly simulated (possibly due to the models' chaotic behavior), but a few **AMIP I** models are better able to replicate its amplitude. In the latter respect, however, there does not appear to be an obvious relationship to **LSS** type.

Because of the limited scope of this validation exercise, these conclusions must be regarded as quite preliminary. In particular, they may depend on the peculiarities of the **NCEP/NCAR** Reanalysis that were used as a validation reference. At this point, therefore, these conclusions should be viewed as working hypotheses to guide the work of Subproject 12 in **AMIP II**. A similar methodology will be employed, for example, to evaluate whether there has been a change in performance in the simulation of land-surface climate resulting from parameterization changes in **AMIP I** vs **AMIP II** versions of a model. In addition, future directions that also seem worth exploring include:

- Use of other reanalyses (e.g. those of the **ECMWF** and **NASA**) and remote-sensing data sets as alternative validation references.
- Application of this methodology to continental-scale variability.
- Investigation of the utility of other validation summary statistics.
- Assessment of the relative weight of land-surface characteristics vs **LSS** parameterizations in determining the coupled simulation of continental climate (possibly realized by means of a future **AMIP II** experimental subproject).

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