GLACÉ:
Global Land-Atmosphere Coupling Experiment

**(An AGCM Intercomparison Study
Co-sponsored by GLASS[1] and WGSIP[2])**

Brief description: GLACÉ is a model intercomparison study focusing on a typically neglected yet critical element of numerical weather and climate modeling: the ability (or lack thereof) of land surface conditions to affect rainfall generation and other atmospheric processes. The proposed simple-to-perform AGCM experiment follows a design that was proven effective in a recent pilot project.

1 Introduction

1.1 Motivation

To what extent do land surface moisture and temperature states affect the evolution of weather and the generation of precipitation? How does a human-induced change in land cover affect local and remote weather, if at all? Such questions lie at the heart of much recent climatological research. This research is largely performed with atmospheric general circulation models (AGCMs) or mesoscale models, mostly because direct observations of the impact of land surface anomalies on atmospheric behavior are difficult (if not impossible) to obtain at regional to continental scales. AGCMs and mesoscale models are particularly useful tools because their process parameterizations can be manipulated easily in controlled experiments. Their use, though, introduces a number of additional important questions, also the subject of much research. Does a more realistic land surface model, for example, improve the numerical simulation of climate and climate change? Can knowledge of initial soil moisture or snow states improve the skill of short-term (days) or long-term (weeks to months) precipitation and temperature forecasts?

The list of published AGCM land-atmosphere interaction studies is extensive (e.g., Charney et al., 1977; Shukla and Mintz, 1982; Henderson-Sellers and Gornitz, 1984; Delworth and Manabe, 1989; Oglesby and Erickson, 1989; Dirmeyer, 1994; and Lau and Bua, 1998; to name only a few). Necessarily missing from single-AGCM experiments, however, is an analysis of the degree to which the experimental results are

[1]Global Land-Atmosphere System Study panel of GEWEX
[2]CLIVAR Working Group on Seasonal-to-Interannual Prediction

model-dependent. Model dependence in land-atmosphere interaction can bias results tremendously. Consider two AGCMs, one in which the atmosphere responds strongly to anomalies in land surface state via associated anomalies in surface fluxes, and one in which the atmosphere has an internal variability that overwhelms any signal from the land surface. Experiments with these two AGCMs would lead to contradictory conclusions about the importance of properly initializing soil moisture in forecast simulations, about the degree to which deforestation affects climate, and perhaps even about the need for a realistic treatment of land surface processes in climate simulations.

The degree to which the atmosphere responds to anomalies in land surface state, particularly at hourly to monthly timescales, is hereafter loosely referred to as the "land-atmosphere coupling strength". Coupling strength is not easy to quantify. It is not explicitly prescribed or parameterized; it is rather a net result of complex interactions between numerous complex process parameterizations in the AGCM, such as those for evapotranspiration, boundary layer development, and moist convection. The great majority of AGCM land-atmosphere interaction studies appear to take a given model's implicit coupling strength on faith, not addressing either its realism or how it compares with that in other models. This is arguably a major deficiency in the current state of the science. Simulated coupling strength clearly has a dominant impact on the conclusions reached in AGCM land impact studies. The quantification and documentation of the coupling strength across a broad range of models would be valuable, if only to serve as a frame of reference when interpreting the experimental results of any particular model.

A documentation of land-atmosphere coupling strength is indeed the goal of the present project, entitled GLACÉ (for Global Land-Atmosphere Coupling Experiment). GLACÉ will not be able to address the *realism* of simulated coupling strength, since again, direct measurements of land-atmosphere interaction at large scales are not available. GLACÉ will, however, show the extent to which coupling strength varies between models, and it will allow individual models to be characterized as having a relatively strong, intermediate, or weak coupling, for later use in interpreting various results obtained with those models. The range of coupling strengths uncovered by GLACÉ will serve to quantify the uncertainty inherent in our understanding of land-atmosphere coupling and our ability to model it.

GLACÉ is a broad follow-on to the four-model intercomparison study of Koster et al. (2002), hereafter referred to as K02. This study is now briefly summarized.

1.2 Background: Four-model Intercomparison

K02 describes a numerical experiment performed by four AGCM modeling groups: the NASA Seasonal-to-Interannual Prediction Project (NSIPP) AGCM, the Center for Ocean-Land-Atmosphere Studies (COLA) AGCM, the National Center for Atmospheric Research Community Climate Model Version 3 coupled to the Biosphere-Atmosphere Transfer Scheme (CCM3/BATS), and the Hadley Centre, Met Office AGCM (HadAM3). Figure 1 describes the two parts of the experiment. In the first part, the AGCM, fully coupled to its own land surface model (LSM) but forced by prescribed sea surface temperatures (SSTs), was run over July. At each time step in this simulation (hereafter labeled simulation W, for "write"), the values of all land surface prognostic variables at every grid cell were recorded into a special data file. The recorded prognostic variables include soil moisture contents at all vertical levels, temperatures at all vertical levels, canopy interception reservoir content, and various variables characterizing snow, if snow is present. The one-month experiment was then repeated 15 more times, using 15 different sets of atmospheric and land surface initial conditions, to obtain an ensemble of 16 one-month (July) simulations (simulations W1-W16). The prognostic variables, however, were only recorded during Simulation W1.

The second part of the experiment consisted of another 16-member ensemble of one-month (July) simulations, using the same prescribed SSTs. Again, the ensemble members used different atmospheric initial conditions. At every time step of every simulation, the updated values of all land surface prognostic variables were discarded and then replaced by the corresponding values for that time step from the data file written in Simulation W1. Thus, in this ensemble, all member simulations (simulations R1-R16, where R denotes "read") were forced to maintain precisely the same time series of (geographically-varying) land surface states.

The resulting precipitation data were processed into a diagnostic Ω_P, which measures the degree to which the sixteen precipitation time series generated by the ensemble members are similar. In essence, once the effect of sea surface temperature (SST) variations are accounted for, Ω_P is a useful measure of land-atmosphere coupling strength, being essentially equivalent to the ratio of land-explained precipitation variance to total precipitation variance. (The precise calculation is $\Omega_P = [16\sigma_{\hat{P}}^2 - \sigma_P^2]/[15\sigma_P^2]$, where σ_P^2 is the precipitation variance over all time periods and all ensemble members, and $\sigma_{\hat{P}}^2$ is the variance computed from the ensemble mean time series. See K02 for more details.)

Figure 2 illustrates the nature of Ω_P graphically. The top plot in the figure shows the time series of precipitation at a specific grid cell for each of the 16 simulations in the NSIPP R ensemble. Note that the precipitation is low for the month until day 20, when it becomes large for each simulation. This coherence must reflect the control of the prescribed surface boundary conditions over the precipitation (i.e., the coupling strength), since the sixteen ensemble members shared no other property that would cause them all to produce rain on that specific date. By definition, Ω_P can vary from

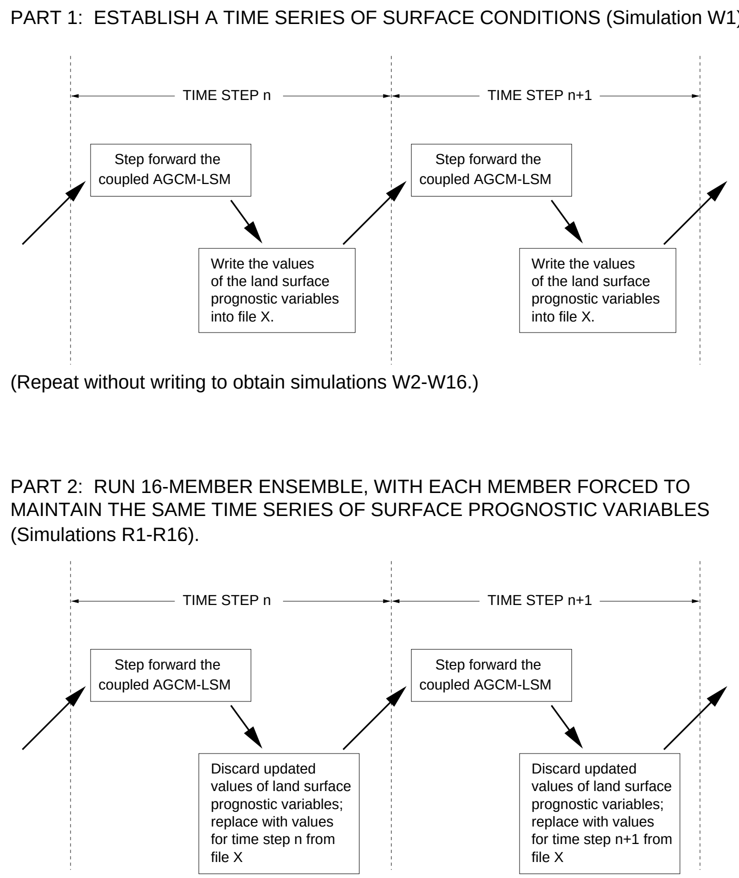

Figure 1: Basic design of the experiment, as performed by all participating models. (From Koster et al. (2002).)

0 to 1, with values closer to 1 indicating a greater coupling strength. Ω_P at this grid cell is 0.85.

For comparison, the bottom plot of Figure 2 shows the 16 time series at a different grid cell, where the coherence is absent – the precipitation generated in one simulation is essentially independent of that in any other simulation. The inferred coupling strength here is low; Ω_P is only 0.07. At this grid cell, atmospheric chaos overwhelms the land signal.

For each participating AGCM, Ω_P was computed for both the R ensemble and the W ensemble. The difference between the two fields isolates the impact of land-atmosphere coupling strength from that of all other external factors, including sub-monthly variations in SST. Plots of the differences are provided in Fig. 3 for all

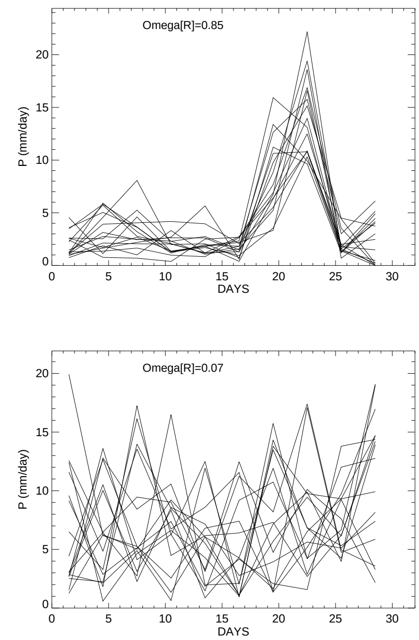

Figure 2: Superposed time series of precipitation (in mm day^{-1}), as produced by the NSIPP model's R ensemble. Top: Grid cell for which Ω_P is high. Bottom: Grid cell for which Ω_P is low. From Koster et al. (2002).

four AGCMs. The salient result is a wide disparity in the diagnostic between the models. Land-atmosphere coupling strength is clearly largest for the NSIPP model. The COLA and CCM3/BATS models have similar coupling strength distributions, with Ω_P values of 0.2 or less almost everywhere, and the HadAM3 model has what appears to be the weakest coupling strength.

1.3 Need for an Extended Study

The K02 study was a first step in the right direction. GLACÉ, the study proposed herein, aims to extend the analysis substantially:

– *Participation From a Wider Range of Models.* The intriguing intermodel variations in Fig. 3 are presumably indicative of the broad range of coupling strengths implicit in today's AGCMs. The goal of GLACÉ is to establish this range more precisely and (more importantly) to generate a compre-

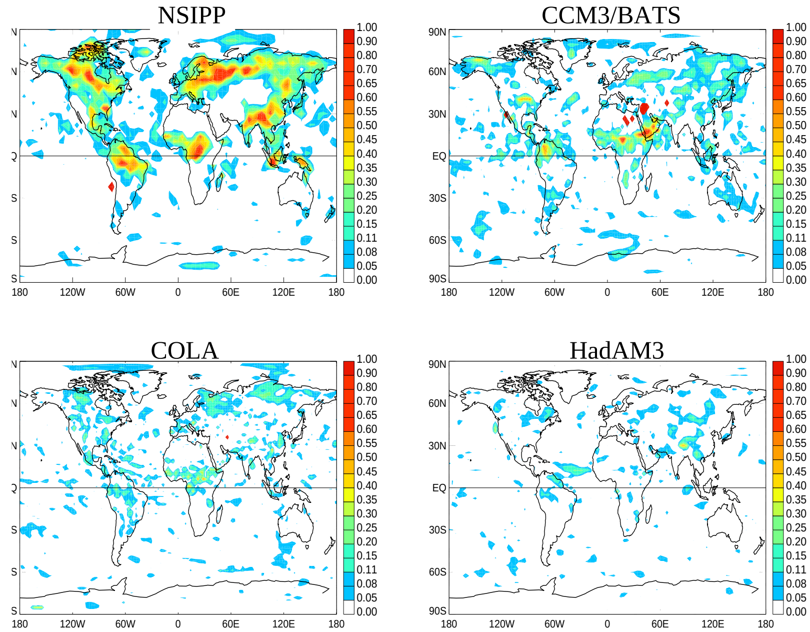

Figure 3: Global fields of $\Omega_P(R) - \Omega_P(W)$, as generated by each of the participating AGCMs. From Koster et al. (2002).

hensive "table" of AGCM coupling strengths, a table that can help in the interpretation of the published results of a wide variety of climate models.

– *Separation of the Effects of "Fast" and "Slow" Reservoirs.* The experimental set-up used in K02 was limited; the prescribed diurnal surface temperature variations had as much an effect on Ω_P as anything else. Since diurnal variations in temperature and storage in "fast" moisture reservoirs (e.g., canopy interception) have little potential for prediction, the noted differences in Fig. 3 may have limited practical application. Of much greater relevance to many land impact questions is whether some of the "slower" state variables (in particular, soil moisture in the root zone and lower reservoirs) have an impact on the evolution of weather. This aspect of coupling strength will be examined in GLACÉ through some simple modifications to the experimental plan.

– *Effect on Air Temperature.* K02 focused on how the land surface boundary affects the generation of precipitation. Also of interest is the control of the land boundary on air temperature fluctuations, particularly when only root zone (and lower) soil moisture is prescribed. GLACÉ will provide the means to address this issue.

– *Correction of Miscellaneous Technical Issues.* K02 was a pilot study of sorts, in preparation for GLACÉ. Numerous technical problems were encountered in the course of doing that study. Appropriate corrections are incorporated into the initial design of GLACÉ. The resulting model intercomparison should, as a result, be cleaner.

1.4 Practical Constraints

In K02, each modeling group performed two ensembles of 16 one-month integrations, amounting to almost 3 years of GCM simulation. A desire to extend the study can lead to numerous temptations, e.g., to ask modelers: (a) to repeat the July simulations for a number of different years (with the associated different SSTs), (b) to repeat the simulations for a boreal winter month, (c) to extend all simulations to a full season, (d) to update different combinations of "slower" states in supplemental R ensembles. While all of these ideas are potentially valuable, GLACÉ is necessarily subject to a very strong logistical constraint: many AGCM groups will not be able to participate if too many simulations are required. The computational expense behind the 3 years of simulation required for K02 was not negligible. A substantial increase in the required simulations could easily kill the project; the value of the project, after all, rests largely with the breadth of participation from the modeling community. While the required runs will extend beyond the K02 framework (e.g., the full boreal summer will indeed be simulated), the experiment is designed with tractability in mind.

Another issue to consider is the amount of output data requested by the project. In K02, modeling groups provided daily precipitation and evaporation fields for each 1-month simulation, a quite manageable amount of data that was sufficient to produce, for example, the Ω_P values in Fig. 3. Data requirements for GLACÉ will be expanded, but not excessively. Provision of sub-daily data will not be required in order to avoid overwhelming the patience of the AGCM modelers and the capabilities of those who will be processing it.

2 Experiment Overview

Each AGCM participating in the experiment will generate three 16-member ensembles of 3-month simulations. (Approaches for generating the ensemble members are

Ensemble Identifier	# of Simulations in Ensemble	Period Covered by Each Simulation	Description
W	16	June 1 - August 31, 1994	Standard AGCM simulations with fully interactive land surface model.
R	16	June 1 - August 31, 1994	As W, except all surface state variables replaced at every time step, from values in file.
S	16	June 1 - August 31, 1994	As W, except root zone and lower soil moisture variables replaced at every time step, from values in file.

Table 1: Brief summary of GLACÉ ensembles.

discussed in section 3.2.) In CPU terms, this is equivalent to a 12-year AGCM simulation.

Adapting the terminology of K02, the three ensembles are referred to here as the W (for "write states"), R (for "read states"), and S (for "read slow states") ensembles. Table 1 and ensuing discussion summarizes the similarities and differences between the three ensembles:

Ensemble W (Control). Ensemble W is the most straightforward of the three ensembles, since it essentially involves running the AGCM in the way it is normally run. The only difference is in the writing of state variables during one of the 16 simulations. The approach is equivalent to that shown in the top half of Fig. 1. In one of the simulations, chosen randomly but referred to here as "W1" for convenience, the value of every land surface state variable is written to a special data file at every time step. (How this is done, and what format to use, will be up to the individual AGCM group.) This special data file is hereafter referred to as W1_STATES. W1_STATES thus includes global fields of all soil moisture contents, all soil temperatures and freeze/thaw states, all canopy interception reservoir contents and temperatures, and all snow state variables – one global field per state variable per time step.

Ensemble R (Experiment 1). The approach used for this ensemble is shown in the bottom half of Fig. 1. At every time step in each of the 16 simulations, the updated values of all land surface state variables are "thrown away" – all land surface state variables are reset to values read in from W1_STATES. The approach used for reading in the data and resetting the variables will be AGCM-specific, and each AGCM group will need to develop their own strategy. The end result of the resetting, though, must be a set of sixteen simulations that have the same time-varying land surface boundary condition. If simulation W1 in ensemble W (the simulation that wrote data into W1_STATES) produced a very wet soil in southern France on July 27, then the atmosphere in every simulation of ensemble R should feel the same very wet soil in southern France on July 27.

Ensemble S (Experiment 2). Ensemble S has the same design as ensemble R, except for one thing: in ensemble S, not all of the land state variables are reset with values from W1_STATES during the course of the simulations. Some of the variables are allowed to evolve freely, as they did in ensemble W. In ensemble S, the *only* variables to be reset are the soil moisture contents associated with the rooting depth and below. If a model has a soil moisture variable(s) corresponding to a depth of 5 cm or less from the surface, then this variable should not be reset. Again, the motivation for this experiment is to isolate and quantify the impact of a relatively predictable state (deep soil moisture) on the evolution of weather. (Send any questions regarding the resetting of soil moisture variables to the experiment organizers (see section 6).)

3 Technical Details

3.1 Model Resolution

The spatial resolution and the time step used will necessarily vary amongst the AGCMs. Each group should use a resolution that is typical for their model.

3.2 SST Boundary Conditions

SST boundary conditions should correspond to June-August 1994. (This year was chosen because neither El Niño nor La Niña conditions are strong.) Different SST datasets are available, but for consistency, modeling groups should use the AMIP-2 SST dataset if at all possible. The K02 study, by the way, suggests that the impact of SSTs on derived Ω_P values is small.

3.3 Initialization of Ensemble Members

The members of an AGCM ensemble typically differ only in their initial atmospheric and land surface conditions. The approach for assigning the initial conditions cannot be specified by GLACÉ; doing so would undoubtedly make the project too complicated for some groups and would thereby quell participation. The only requirement GLACÉ can impose is that the initial conditions be fully consistent with the AGCM being used. They should not, for example, be imported from some other model.

Several approaches for initializing land and atmosphere states can be considered; they are listed in order of preference below. (That is, approach (a) is preferred most.) The key is to produce sets of initial conditions that sample the full range of possible land and atmosphere states. Initial land conditions between ensemble members, for example, should not be allowed to be artificially similar, as can happen through the commonly used approach (e). If a group has an alternative approach to producing acceptable initial conditions, the organizers of the experiment would be happy to consider it. Contact the experiment organizers (see section 6) with a description of the approach.

(a) Some groups may have available an archived series of 16 or more parallel multidecade AMIP-type simulations (i.e., simulations using SSTs prescribed from observations) from which to extract 16 different sets of land and atmosphere states for June 1, 1994. These states can be used to initialize the W, R, and S ensembles. If daily data from the 16+ parallel AMIP-type simulations are archived, then in effect ensemble W is already almost finished; only one more simulation – the one that writes the time step information to W1_STATES – needs to be performed for that ensemble.

(b) If the number of archived multidecade AMIP-type simulations is less than 16 but greater than 1, they can still be used, as long as the years from which the June 1 land and atmosphere states are extracted belong to the set of "quiescent" years (i.e., years with little El Niño or La Niña signal). For the purposes of this experiment, these years are 1951, 1952, 1959, 1960, 1961, 1963, 1977, 1979, 1980, 1981, 1986, 1990, and 1994, years for which the Nino3 anomaly has an absolute value less than 0.5 for the three months preceding the initialization date. As an example, suppose a group can draw from four archived parallel AMIP simulations. Extracting restart files for June 1 of 1977, 1979, 1990, and 1994 from each of the 4 simulations would give a total of 16 sets of initial states for the experiment.

(c) A more tractable approach for many groups will be to access restart files (initial conditions) from a preexisting *single* 16+ year simulation. In particular, if such a simulation exists in which SSTs do not vary from year to year (i.e., they are set to seasonally-varying climatological values), then the land and atmosphere states produced on 1 June in each of 16 years of the simulation can be used to initialize the 16 ensemble members.

(d) If the only 16+ year simulation available is an AMIP-type simulation (one with interannually-varying SSTs), then the June 1 conditions determined for the different years in this simulation can be used to initialize the June-August 1994 simulations. With this approach (as with approach (b)), the calendar years for the AMIP simulation are forced to lose their meaning. For example, suppose the restart files produced by an AMIP-type simulation covering 1979-1994 are available. The 1 June 1979 atmosphere and land states can be used to initialize one member of ensemble W (and of ensembles R and S), the 1 June 1980 states can be used to initialize another ensemble member, and so on.

(e) A common approach to assigning initial conditions to the different members of an ensemble is to run the AGCM for, say, 16 June days and write out the atmosphere and land states at the beginning of each day. Each daily set of fields would then be used as initial conditions. This type of approach, however, is highly undesirable for the present experiment, since the land surface states would not have time to vary much during the short simulation – the initial land conditions amongst the different members of ensemble W would not represent the broad range of states the model is capable of achieving.

Note that, given the design of the experiments, the initialization of all land states for ensemble R and the deeper soil moisture states for ensemble S is actually irrelevant. Note also that in all cases, the atmosphere may feel a "shock" at the beginning of the R and S simulations, since initially it will not be in equilibrium with the prescribed surface state. K02 examined the effect of this shock on Ω_P and concluded that it was small. Nevertheless, the first 10 days or so of each 3-month simulation can be excluded from the data analyses, to avoid its effects altogether.

3.4 Energy and Water Balance Considerations

The design of ensembles R and S necessarily precludes the maintenance of a strict energy and water budget below the land-atmosphere interface. Note, however, that energy and water in the atmosphere and across the interface are still perfectly conserved; conservation of energy and water is only "neglected" within the land reservoirs themselves. Since these specialized experiments focus solely on the atmospheric response to land conditions, the lack of conservation below the interface is deemed acceptable.

3.5 Redundancy of Simulations

If the initial conditions used by simulation W1 (the simulation that wrote out its state variables into file W1_STATES) are also used to initialize one of the members of ensemble R (say, simulation "R1"), then by the construct of the experiment, the weather (and thus the precipitation) generated in simulations W1 and R1 should be identical. The same holds true if W1's initial conditions are used to initialize a member of ensemble S. Modeling groups can, if they wish, take advantage of this redundancy by using simulation W1 as a member of both the R and S ensembles. In other words, in reality only 15 new simulations need to be performed for both the R and S ensembles. (Note that truncation errors may, in fact, allow simulation R1 or S1 to diverge from simulation W1. These truncation effects are irrelevant; the point is that simulation W1 can properly serve as a member of both the R and S ensembles.)

4 Diagnostics Required

The following 6 global fields will be required each day from each simulation of each ensemble:

– Daily total precipitation (*Rainf*)
– Daily total evaporation (*Evap*)
– Daily-averaged air temperature in GCM layer closest to the surface (*Tair for lowest level*)
– Daily-averaged soil wetness in the column: the vertically integrated soil moisture above the wilting point divided by the maximum allowable soil moisture above the wilting point (*SoilWet*)

– Daily-averaged specific humidity in GCM layer closest to the surface (*Qair for lowest level*)
– Daily averaged outgoing longwave radiation at the top of the atmosphere

The variable names in parentheses are ALMA conventions. All ALMA conventions (see http://www.lmd.jussieu.fr/ALMA) regarding units, direction of flux, and so on should be followed in the reporting of the variables. Note that in the ALMA standard, *Tair* and *Qair* are 3-dimensional fields, with values provided at multiple vertical levels. For GLACÉ, however, *only the values closest to the land surface* are requested. If the values can be post-processed into 2-meter height values, so much the better; in any case, the height associated with the *Tair* and *Qair* data should be made clear. Also, the daily averaged outgoing longwave radiation at the top of the atmosphere is not an ALMA variable, but it is a standard AGCM diagnostic. Values should be provided in units of Wm^{-2}.

A file naming convention for the submission of output will help in the analysis. The 92 daily global fields of a given variable (e.g., total precipitation) for a given simulation should be merged into a single file with the name aaaa_ENSb_SIMcc_dddd, where aaaa is the AGCM identifier, b is the ensemble identifier (W, R, or S), cc is the ensemble member (01, 02, 03, ..., 15, or 16), and dddd is the variable name (Rainf, Evap, Tair, SoilWet, Qair, or OLR). With 3 ensembles, 16 simulations per ensemble, and 6 files per simulation, a total of 288 files are to be submitted. Again, each file has 92 global fields (one for each day of June-August), so that a total of 26496 global fields will be provided by each group.

Different AGCMs have different resolutions and different ways of describing a global gridded dataset. Use of the ALMA format should automatically ensure that when submitting the data, each group is also providing the ancillary information needed to interpret a given global field (e.g., resolution, whether the first data item begins at the dateline or at 0°, whether it begins at the north or south poles, whether or not latitude divisions are irregular, and so on). If this is not true for any reason, the information should be provided separately. The land-sea mask assumed by the AGCM should also be provided, as should an orography field, if available.

5 Proposed Analyses

The precipitation data alone will be sufficient to compute Ω_P, as outlined in K02. Comparisons of Ω_P between the models (after subtracting out the effects of SSTs and other forcing, as in K02) should reveal, to first order, the models' relative land-atmosphere coupling strengths. The daily values of evaporation will be used as in K02 to help determine if the intermodel differences relate to differences in the LSMs themselves or to differences in the atmospheric models above them. The daily values of the other variables should provide further information in this regard.

The analysis, however, will not stop with the quantification and interpretation of Ω_P. The daily data will be aggregated to monthly and seasonal totals, and the probability density functions (pdfs) of precipitation, air temperature, and so on from the W ensemble will be compared to those from the R and S ensembles. Significant differences in the pdfs (based on established statistical tests) will point to an impact of the land boundary condition on the evolution of the atmospheric fields, an impact that can be measured even if the surface state variables do not vary much over the 3-month period. (Under certain conditions, slowly varying state variables may limit the usefulness of the Ω_P diagnostic.)

The quantification of coupling strength through Ω_P and through the pdf analysis will be the key contribution of this project. Intermodel comparisons of precipitation variance itself, however, are also possible with the provided data. Note that these variances can be compared directly to observations, allowing a first-order evaluation of a critical aspect of simulated precipitation – an aspect that can be considered in tandem with the diagnosed coupling strengths. A model, for example, that has a relatively high coupling strength (a high Ω_P) and an underestimated total variance relative to observations may be underestimating the purely random contributions to variability. Such analyses will not be conclusive, since again, the relative contributions of externally-forced and chaotic contributions to variability have never been quantified in the real world. Nevertheless, modelers should find the joint analyses of Ω_P and total variance instructive.

6 Timetable and Management Plan

Participating AGCM groups will be given 6 months to complete the GLACÉ experiments. GLACÉ should not suffer from a problem that has slowed the progress of most land model intercomparison projects in the past, namely, the occasional need to correct and re-provide input and forcing datasets. Because no such datasets are needed for GLACÉ, AGCM groups can perform the experiments immediately without worrying about having to redo them later.

Output from all of the models will be processed at COLA by Zhichang Guo, a post-doctoral research associate, with help and supervision from Randal Koster of NASA/GSFC and Paul Dirmeyer of COLA. Participants will be able to deposit their data at COLA via an ftp site.

The processing and analysis of the submitted AGCM data will proceed as discussed in section 5 above. This should take about 3 months, at which time a draft of a summary journal paper, co-authored by all participants, will be written. During this period, preliminary findings will be communicated electronically, and e-mail discussions will keep all groups involved and up-to-date. No physical workshop is planned.

All questions regarding the set-up of the experiment can be directed to Randal Koster (301-614-5781; randal.koster@gsfc.nasa.gov).

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