WORLD CLIMATE RESEARCH PROGRAMME (WCRP)

REPORT OF THE ACSYS/GEWEX GLASS-PILPS 2E STAGE 1
ARCTIC HYDROLOGICAL MODEL INTERCOMPARISON STUDY
WORKSHOP
(SEATTLE, WA, USA, 18-20 MARCH 2001)

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EXECUTIVE SUMMARY

Climate modeling studies indicate that global warming may be larger at high latitudes than elsewhere, primarily due to reduced albedo associated with contraction of sea ice extent and seasonal snow cover (e.g., Holland and Curry, 1999; Manabe and Stouffer, 1994). The strength of the coupling between the ocean, land, and atmosphere in the Arctic is particularly important because of its influence on the net transfer of heat northward, and fresh water southward, which in turn affects global climate and weather (Sausen et al., 1994. Dumenil and Todini, 1992). All of these considerations motivate the improvement of high-latitude land surface representations within coupled land-atmosphere models used for numerical weather and climate prediction.

The Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) is the Local Off-Line Action Group within the GEWEX Global Land-Surface/Atmosphere System Study (GLASS). GLASS has been organized under the GEWEX Modelling and Prediction Panel (GMPP) to coordinate land-surface scheme development activities. The goal is to achieve improvements in land-surface schemes for the benefit of numerical weather prediction and climate models such that confidence in the simulated land-surface quantities will be enhanced. As a contribution to GLASS, the objective of the PILPS Phase 2e is to evaluate the performance of uncoupled land surface parameterizations in high latitudes, in a context that allows evaluation of their ability to capture key processes spatially. For this purpose, the study design must go beyond one-dimensional tests to evaluate model performance in the context of medium to large river basins.

The need for an evaluation of Arctic hydrology models was identified by the WCRP ACSYS Scientific Steering Group and by the GEWEX Hydrometeorological Panel (GHP) at their annual meetings in 1997. Subsequently a joint meeting of representatives of ACSYS and the GHP was held in Quebec City, Quebec, Canada (WCRP, 1999a). The proposed experiment was sanctioned by PILPS at its International Strategy Forum held in Honolulu, Hawaii in February 1999, which led to a planning meeting in Koblenz, Germany in March 1999, the result of which was an experiment plan (WCRP, 1999b). The experiment was initiated with release of data sets to participants in July 2000. This report summarizes results of a participants workshop held in Seattle, WA, USA from 18-20 March 2001.

The purpose of the PILPS 2e workshop was to provide a forum for discussion of preliminary results from Stage 1 of the experiment, and to develop the strategy for completion of the experiment and dissemination of the results to the scientific community. Topics for the meeting included:

1. Review of summary results;
2. Comments by individual participants about performance of their models, and any peculiarities experienced;
3. Discussion of possible need for, and nature of, additional model runs;
4. Discussion of participants’ experience with the new consistent data exchange formats developed and administrated by the GLASS Infrastructure/Assistance for Land-surface Modeling Activities (ALMA) Action Group and used for the first time in PILPS 2e; and
(5) Publication of results.

Appendix A contains a list of participants in the meeting.
1. INTRODUCTION

1.1 Background

The objective of PILPS Phase 2e was to evaluate the performance of uncoupled land surface parameterizations in high latitudes, in a context that allows evaluation of their ability to capture key processes spatially. These include snow accumulation and ablation, soil freeze/thaw and permafrost, and the existence of large seasonally frozen lakes and wetlands. For this purpose, the study design must go beyond one-dimensional tests to evaluate model performance in the context of moderate to large sized river basins. The design of the experiment roughly follows the PILPS 2c (Wood et al., 1998) experiment, modified as necessary to account for specific physical and observational characteristics of northern regions.

The Arctic Climate System Study (ACSYS) and the Global Energy and Water Cycle Experiment (GEWEX) Hydrometeorological Panel (GHP) are sponsoring the proposed model intercomparison. Within GEWEX the work is being coordinated between the GHP and the Modelling and Prediction Panel (GMPP). PILPS is now an important contributing element of the Global Land-surface/Atmosphere System Study (GLASS) under GMPP. The organization of the experiment is following the classic PILPS Local Off-Line framework (Henderson-Sellers et al., 1993, 1995) with the addition of a consistent data exchange format scheme that has been contributed for the first time to the PILPS-2e effort by the Infrastructure/Assistance for Land-surface Modeling Activities (ALMA) Action Group of GLASS.

One of the primary objectives of the ACSYS hydrology programme is the estimation of land surface runoff into the Arctic Ocean from ungauged catchments. It was the conclusion of the workshop on the status and directions of the Arctic runoff database, held in Koblenz, Germany in February 1998, that hydrological modeling offered the most plausible method of estimating runoff from these ungauged areas (IAPO, 1998). Similarly, GEWEX is concerned with the water and energy balance of two high latitude continental study areas as part of MAGS and GAME. The need for a joint evaluation of Arctic hydrology models was therefore identified by both the WCRP ACSYS Scientific Steering Group and by the GEWEX Hydrometeorological Panel (GHP) at their annual meetings in 1997. Subsequently, a joint meeting of representatives of ACSYS and the GHP was held in Quebec City, Quebec, Canada (WCRP, 1999a). The proposed experiment was sanctioned by PILPS at its International Strategy Forum held in Honolulu, Hawaii in February 1999, which led to a planning meeting in Koblenz, Germany in March 1999, the result of which was an experiment plan (WCRP, 1999b). The experiment was initiated with release of data sets to participants in July 2000. This report summarizes results of a participant’s workshop held in Seattle, WA, USA from 18-20 March 2001.

1.2 Purpose of the Workshop

The purpose of the PILPS 2e workshop was to provide a forum for discussion of preliminary results from Stage 1 of the PILPS 2e experiment. A total of 21 institutions from 10 countries participated in the Stage 1 experiment. All 21 groups were represented at the workshop, in addition to two groups interested in future participation. Each modeling group provided an overview of their results, as well as comments on the structure of the experiments, and recommendations for synthesis of the experiment results. The possible need for, and nature of, additional exploratory
runs was discussed, as was the publication of results. The workshop also served as a first assessment of the standardized output/interface for data developed by the ALMA component of GLASS (Polcher et al., 2000).

2. EXPERIMENT DESIGN

The domain of the experiment was the Torne-Kalix River system in northern Scandinavia. Most of the basin can be characterized as low topography forest and mire areas (Carlsson, 1990). The mountains in the northwest make up 7-8% of the total drainage basin and include Mount Kebnekaise, the highest point in Sweden (maximum elevation 2117 m), see Figure 1. Approximately 1/3 of the basin lies between 200 meters above sea level (m.a.s.l.) and 500 m.a.s.l. The runoff regime is characterized by a seasonal maximum following snowmelt in the forest and swamp regions. Both the Torne and the Kalix are essentially unregulated. A natural bifurcation of the Torne River diverts an average of 57% of the discharge above Junosuando/Tarendo (near the mid-point of Figure 1) to the Kalix River (Carlsson, 1990).

![Figure 1. Torne-Kalix river basin with observation station locations.](image)

The basins have a combined area of 58,000 km\(^2\), which was represented, by 218 1/4° computational grid boxes, as shown in Figure 2. Model forcing data were available from 1979-1998. Forcing data from 1979-1988 were available for model 'spin-up', while the period 1989-1998 was used for the intercomparison. The simulations were conducted at an hourly (or finer) time step.
To evaluate the goals and objectives of PILPS 2e, three different types of model runs were requested from the participants. For all experiments forcing data were supplied for the entire ten year time period, 1989-1998. The three categories are:

1) Calibration and validation runs. Model forcing data and streamflow observations were provided to each modeling group for two sub-catchments of the Torne/Kalix system, the Övre Abiskojokk and the Övre Lansjarv (see Figure 3). The catchments were selected to encompass a range in elevation and a range in characteristics of vegetation cover. For two similarly selected validation catchments (Pello and Kaalasjarvi), only model forcing data were provided to the participants. Parameters were transferred to the validation catchments, and to the basin as a whole, at the modelers’ discretion.

2) Base-runs. For these runs, the modelers simulated the energy and moisture fluxes of each of the 218 1/4° grid cells. The core diagnostics were intended to evaluate the importance of the identified cold regions processes at the scale of the Torne-Kalix River basin, and to determine whether they are adequately represented (or compensated for by other model characteristics).

3) Re-runs. Due to problems with the original forcings, updated forcing data was supplied for a rerun of experiment 1, as described in Section 2.2.

### 2.1 Original Forcing Data

Table 1 summarizes the surface forcings, at an hourly time step for the period 1989-1998. Station data and basin descriptions were provided by the Swedish Meteorological and Hydrological Institute (SMHI) and processed for these purposes by the University of Washington. Station locations are also shown in Figure 1.
Precipitation catch correction for the Swedish manual gauges was based on mean monthly correction coefficients. These include corrections for wind, adhesion and evaporation, based on previous studies (Eriksson, 1983). All stations were assigned to one of seven classes according to how their situation in the field, as summarized in Table 2. Adjustments were made for each station to the original corrections proposed by Eriksson so that they are not quite as extreme for the most exposed stations (Alexandersson, 2001). The mean monthly coefficients from Alexandersson, were applied directly to the daily observations.

Automatic recorders were installed at seven of the stations beginning in 1995. These stations have higher undercatch than the standard manual stations. Alexandersson (2001) has estimated the monthly ratio of automatic stations to manual stations for the period 1996-1999 (ranging from 0.78 to 0.935). The corresponding monthly corrections were first applied to the automatic station data to
make them similar to manual measurements. Data from automatic stations subsequently were
treated the same as observations from the manual stations. Given the limited number of automatic
stations, the gridded precipitation are expected to be reasonably consistent over time.

The distribution of precipitation stations in the mountainous areas of the study region is sparse and
is unable to capture the variations of precipitation with elevation. Based on the recommendation of
SMHI scientists, the catch corrected precipitation was lapsed to the grid cell elevation at a rate of
0.1% per meter.

Table 1. Surface Forcing Data Description

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainf</td>
<td>Mean rainfall rate</td>
<td>Interpolated gauge-corrected daily data from 37 SMHI stations and lapsed with elevation, using the SYMAP interpolation scheme (Shepard et al., 1984). A constant rate is assumed to disaggregate from daily to hourly data.</td>
</tr>
<tr>
<td>Snowf</td>
<td>Mean snowfall rate</td>
<td>Same as Rainf, for precipitation falling at hourly air temperatures &lt;= 0°C</td>
</tr>
<tr>
<td>Tair</td>
<td>Near surface mean air temperature</td>
<td>Interpolation and lapsing with elevation of gauge-corrected daily mean data from 19 SMHI stations, using the SYMAP interpolation scheme (Shepard et al., 1984). Disaggregated to sub-daily based on three-hourly data from gridded 1° data set of SMHI, while maintaining daily mean. Temperature linearly interpolated over 3 hours. The observation height is typically two meters.</td>
</tr>
<tr>
<td>Psurf</td>
<td>Mean pressure above ground surface</td>
<td>Gridded dataset of mean sea level pressure from SMHI (1°, 3 hourly), optimally interpolated from station data (<a href="http://www.smhi.se/sgr0102/bhdc/metdata_3h_grid.htm">http://www.smhi.se/sgr0102/bhdc/metdata_3h_grid.htm</a>), linearly interpolated to ¼ degree, hourly data, and adjusted to grid cell elevation by the University of Washington.</td>
</tr>
<tr>
<td>Qair</td>
<td>Mean near surface specific humidity</td>
<td>Specific humidity converted and linearly interpolated from 1° (3 hourly) SMHI gridded 2 meter relative humidity data set.</td>
</tr>
<tr>
<td>SWdown</td>
<td>Mean surface incident shortwave radiation</td>
<td>Hourly clear sky surface radiation computed using relationships that include an optical depth derived from surface humidity (TVA, 1972). Clear sky radiation was adjusted for cloud cover using an attenuation formula (TVA, 1972). Cloud cover at 1/4° was linearly interpolated from the 1° (3 hourly) data set of SMHI.</td>
</tr>
<tr>
<td>LWdown</td>
<td>Mean surface incident longwave radiation</td>
<td>Hourly downward longwave radiation was computed using the derived hourly surface air temperature, interpolated cloud cover and humidity (TVA, 1972).</td>
</tr>
<tr>
<td>Wind_E</td>
<td>Mean daily near surface eastward wind component</td>
<td>Daily surface wind (10 m) from NCEP/NCAR reanalysis, linearly interpolated in space, held constant for each 24 hour period.</td>
</tr>
<tr>
<td>Wind_N</td>
<td>Mean daily near surface northward wind component</td>
<td>Daily surface wind (10 m) from NCEP/NCAR reanalysis, linearly interpolated in space, held constant for each 24 hour period.</td>
</tr>
<tr>
<td>CloudFn</td>
<td>Cloud cover Fraction</td>
<td>Gridded dataset of SMHI (1°, 3 hourly), optimally interpolated from station data, linearly interpolated to ¼ degree, hourly data, by the University of Washington.</td>
</tr>
</tbody>
</table>
Table 2. Division of the precipitation stations into different classes due to the wind exposure of the gauges

<table>
<thead>
<tr>
<th>Class</th>
<th>Wind shelter of the gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Well protected, e.g. small glade in a forest. Wind protection is at least 20° over the horizon in all directions.</td>
</tr>
<tr>
<td>2</td>
<td>Well-protected in a forest settlement (e.g. near a dwelling), at least 10 km from the coast. Wind protection up to 20° in at least 75% of the horizon.</td>
</tr>
<tr>
<td>3</td>
<td>Somewhat protected, at least 10 km from the coast. Wind protection not more than 20° in more than 50% of horizon or well-protected in the coast zone.</td>
</tr>
<tr>
<td>4</td>
<td>Poor wind protection in most directions with open areas nearby. Only a few obstacles up to 20° over the horizon or protected area near the coast.</td>
</tr>
<tr>
<td>5</td>
<td>Poorly placed location, e.g. on a slope or hill or somewhat protected near the coast.</td>
</tr>
<tr>
<td>6</td>
<td>Unprotected near the coast or in the mountains near tree-line.</td>
</tr>
<tr>
<td>7</td>
<td>Extremely unprotected near the coast or above the tree line in mountainous areas</td>
</tr>
</tbody>
</table>

2.2 Re-run Forcing Data

After the experiment was underway, it became clear from annual energy balance computations (average annual net radiation less average energy required for snowmelt), that there was not enough energy available in the Ovre Lansjarv catchment (see Figure 3) to match the observed annual water balance. Daily average solar radiation was observed for the period January 1969 through December 1993 at Kiruna in the Torne/Kalix basin and archived as part of the World Radiation Data Centre (WRDC). As indicated in Figure 4a, the PILPS incoming shortwave radiation computed using the method outlined in Table 2 has a low bias in comparison with the Kiruna data. The bias resulted from the calculations that reduced radiation at the top of the atmosphere to clear sky radiation at the ground surface, based on TVA (1972) without calibration. Figure 4b shows the results of the Eagleson (1970) method to estimate clear-sky radiation, as follows:

\[ I_c = I_0 \exp(-n a_1 m) \]

Where \( a_1 \), the molecular scattering coefficient, and \( m \), the optical air mass, are both calculated as a function of solar altitude. The turbidity factor, \( n \), was calibrated based on the Kiruna station data to a value of 1.25. Solar radiation was also calculated at Luleå, a station on the coast just south of the Kalix basin (Figure 4), using the same turbidity factor of 1.25. Figure 5 shows that the turbidity factor estimated for Kiruna appears to be appropriate at Luleå as well.

In addition, several modeling groups expressed concern regarding the effects of using daily precipitation interpolated to finer (e.g., hourly) time steps using a constant (1/24) apportionment. In some models, small quantities of constant precipitation may cause instabilities in interception evaporation. This is especially true if the precipitation occurs on days with hours of low cloud cover. Particularly problematic for some models was that the constant apportionment did not preclude artificial occurrence of precipitation during periods of high radiation. To address these
concerns we distributed a sub-daily precipitation data set generated using a simplified statistical disaggregation technique of 6-hourly precipitation from four automatic stations in the Torne-Kalix basin. A cumulative distribution function (CDF) of event duration and start time, in 6 hour increments, was created for each of the four stations. The derived CDF of the nearest station is used for each grid cell in the data set. For each six-hour bin with precipitation, the signal is further disaggregated to hourly values using a uniform distribution. Based on observations at the four stations, 90% of the precipitation falls when the cloud cover exceeds 60%, so this method does not assign precipitation to hours with less than 60% cloud cover.

An error in the originally distributed wind fields due to incorrect regridding of reanalysis winds, was also resolved in the re-release of the data. Experiment participants were asked to complete re-runs of their models using the re-released data prior to the workshop, as resources permitted. Approximately one-half of the modeling groups were able to complete the model reruns before the workshop and 20 (of 21) submitted results at the time of writing this report. All modeling groups

Figure 4. Daily average solar insolation at Kiruna: A) versus the PILPS forcing data and B) versus a calibrated relationship.

Figure 5. Daily average solar insolation at Luleå: A) versus the PILPS forcing data and B) versus a calibrated relationship.
have indicated an intention to submit results from the rerun experiments prior to final publication of results.

2.3  Land Surface Characteristics

The land surface characteristics provided to the participants include both spatially distributed (cell-specific) data and look-up table parameters. No attempt was made to specify all parameters required by each model. Rather, the organizers tried to provide a basic set of characteristics and sufficient descriptive information from which each modeling group could derive the parameters they required. Specific values were required for some parameters and “suggested” values for several additional parameters were provided for convenience. Free calibration of model parameters was only permitted for the two calibration basins, Ovre Lansjarv and Ovre Abiskojokk.

Spatial parameters were derived from the following databases:

1. Basin boundaries for the Torne and Kalix River basins and four sub-basins were provided by SMHI.
2. The mean elevation of each ¼° grid cell was calculated based on the Global 30 Arc Second Elevation Data Set (GTOPO30) acquired from the US Geological Survey.
3. Soil textural information and soil bulk densities were obtained for each model grid cell using the SoilProgram (Carter and Scholes 1999), which combines the 5 minute FAO-UNESCO digital soil map of the world (FAO, 1995) with the WISE pedon database (Batjes, 1995).
4. Vegetation types were determined using the 1 km AVHRR-based global land classification of Hansen et al. (1999) (see Figure 3).
5. Leaf area index (LAI) values were based on the 15 minute global data set of Myneni et al. (1997), as processed by Nijssen et al. (2001).

2.4  ALMA Conventions for Data Handling

The GLASS project has set up an infrastructure, the Assistance for Land-surface Modelling Activities (ALMA), in order to support four areas of land-surface scheme intercomparisons (Polcher et al., 2000). The aim is to provide the community with the means to perform these intercomparison projects more efficiently. PILPS 2e was the first test case for the ALMA standards for data exchange, which were initially drafted by the workshop organizers and the GLASS science panel in April 2000. Data distributed to participants in July 2000 followed the ALMA formats which are based on netCDF, and participants were required to provide model output in the specified netCDF formats as well. At the workshop, Jan Polcher reported on the evolution of the ALMA protocols and improvements that were made as a result of the PILPS 2e experiment for a planned aggregation experiment in the Rhône River basin. The variable definitions in use for the PILPS 2e experiment, as well as the most recent developments can be found at the ALMA web-site: www.lmd.jussieu.fr/~polcher/ALMA/dataex_main.html.

ALMA also intends to provide the community with general diagnostic tools for the analysis of results and standard interfaces for the coupling of land-surface schemes with atmospheric models. As a first step in this direction, diagnostic programmes were distributed to the PILPS 2e participants to check the variable definitions and the closure of the water and energy balance.
Use of the ALMA protocols was an integral part of the design of the PILPS 2e experiment. This required specification of specific data formats, and choosing a meta-data convention that facilitated unambiguous description of the data files. A key part of this process was specification of variable definitions, sign conventions, and names and units of the forcing variables. In the same manner an extensive list of possible output variables was established. The idea was to construct a general list so that future intercomparison experiments can select the variables they wish to have reported. The use of standard formats ensures that all experiments will use the same units, standard sign conventions and that the definitions of output variables will not change among projects.

The initial ALMA convention used in PILPS 2e contained a few errors and misleading definitions. In order to correct for these problems and to allow the introduction of new variables, a second version of the convention was introduced. The first version will remain available as a reference. To facilitate the transition to the second version a detailed description of the changes has been made. Most of the corrections that were made deal with the consistency within the list of variables. Definitions of some variables like surface temperature had to be reformulated to avoid possible ambiguities.

Additional changes to the reporting conventions were made so that processes represented by some schemes could be better documented. In the revised conventions, for instance, it is possible to close the budget of liquid water in the snow pack. The three-dimensional structure of snow can also be archived in the new version of the convention. In order to allow future GLASS experiments to validate the model output with satellite observations, a new table dedicated to this topic was created. The first variable in this new table is the upward longwave flux.

3. PRELIMINARY INTERCOMPARISON RESULTS

3.1 PILPS 2e energy balance and cold season processes

3.1.1 Energy balance components

The surface energy balance was calculated for all 21 models for all grid cells in the model domain. Initial checks were made of water and energy balance closure over the period 1989-1998. Many of the models showed significant energy balance deficiencies for the base run. Although the reported results for the reruns improved the energy balance deficiencies, problems remained with some models. Discussions with the workshop participants made it clear that most of these errors were related to confusion with the ALMA reporting protocols for some of the energy balance terms, in particular, the heat storage change terms and the surface ground heat flux. In addition some errors seemed to have occurred when model results were converted into the common NetCDF format that was adopted for this study. It was agreed with all participants that at the very least these problems would be resolved in the final reruns, and many participants volunteered to re-submit the energy balance files for the base run as well.
Net radiation

Like other arctic basins, the Torne basin is characterized by low available energy (see Figure 6). Mean annual incident shortwave radiation ranges between 85 and 105 W/m², while mean annual incident longwave radiation ranges between 265 and 280 W/m². A significant portion of the basin lies above the Arctic Circle and wintertime incident shortwave radiation is consequently very small. The presence of snow during a large part of the year, roughly from October till June, and the associated high albedo, resulted in a simulated mean annual net incoming shortwave radiation averaged over the basin ranging from about 38 to 52 W/m² for the participating models for the base run and from 54 to 73 W/m² for the rerun. Simulated mean annual net longwave radiation also varied considerably between the models, ranging from -26 to -43 W/m² for the base run and from -27 to -46 W/m² for the rerun.

Net annual radiation (net shortwave plus net longwave) was very small for all models in the base run, varying between 2 and 23 W/m², and was somewhat higher in the rerun, ranging from 16 and 41 W/m². The mean monthly cycle of net radiation shows that the spread in the model-predicted net radiation is largest in the springtime, when the incident shortwave radiation increases and snow starts to melt. Differences in the simulation of snow ablation and snow albedo led to large differences in net radiation during this period. Differences in surface temperature, and consequently net longwave radiation, were most marked during the winter months (shown in Figure 7), and were much smaller during the summer months when snow was absent.

Latent and sensible heat

The mean annual simulated latent heat flux averaged over the basin ranged from 12 to 44 W/m² in the base run and from 18 to 45 W/m² in the rerun (see Figure 8). Given the low net radiation values, all models reported a negative sensible heat flux in the base run, meaning that the atmosphere acted as a source of energy for evaporation and sublimation. The sensible heat flux ranged from -23 and -3 W/m² in the base run. As shown in Figure 9, all models showed an increase in the sensible heat flux in the rerun compared to the base run, with some models transitioning to a positive mean annual sensible heat flux. Mean annual sensible heat fluxes in the rerun ranged from -11 to +8 W/m².
3.2 PILPS 2e water balance and the effect of water storage

3.2.1 Water Balance Components

Water balance errors were generally less pronounced than energy balance errors, but many models still encountered problems. As for the energy balance, the problems were most commonly caused by errors in definition of the storage change terms. These problems are expected to be resolved prior to final publication of results.

3.2.2 Evaporation and snow water equivalent (SWE)

The latent heat flux peaked for all models during the summer months, but significant differences existed among the models during all months. For most models, the annual evaporation is greatest in the more southerly, lower elevations, rather than the high elevations that receive greater precipitation (e.g., Figure 8). This suggests that on an annual basis evaporation is limited by the available energy in the north.

Perhaps the most important finding of the experiment was the large variations in predicted snow sublimation among models, and the effect of these differences on the modeled energy and moisture fluxes throughout the year. Averaged over the ten years, maximum simulated SWE varied between 40 and 300 mm for both the base and the reruns, as shown in Figure 10. The maximum mean SWE of all models was 220 mm. For some models, virtually all of the snow sublimated, whereas for other models most of the snow accumulated through the winter until the onset of the spring melt.
Figure 8: Mean annual latent heat flux for the model reruns

Figure 9: Annual average sensible heat flux for both the base runs and reruns
Mid-winter melt events are infrequent over most of the basin and have relatively little effect on maximum snow accumulation.

Figure 10: Mean monthly snow water equivalent for the base runs (black) and reruns (blue).

3.2.3 Runoff and Storage

Snowmelt is the single largest factor controlling annual runoff production in the Torne-Kalix basin. The spatial variability in runoff production is low, and was fairly consistent between models (Figure 11). This reflects the importance of snowmelt, which has a great deal of spatial consistency in comparison with summer rainstorms, which are responsible for relatively little of the annual runoff.

In contrast, the predicted seasonal runoff hydrographs were quite variable among models, with annual runoff ranging from 159 to 489 mm for the reruns. Peak monthly runoff ranged from under 1 to over 7.5 mm/day. The observed mean annual discharge of the Torne-Kalix system is 403 mm. Among-model variations in mean annual runoff were found to be primarily related to the model-predicted winter snow sublimation -- models with higher rates of sublimation (hence lower accumulations of snow on average) predicted lower annual runoff (see Figure 12). On the other hand, models with similar snow accumulations simulated different mean monthly hydrographs due to differences in the treatment of surface and subsurface storage. A few of the models explicitly simulated surface storage in lakes, and while these models tended to simulate less moisture storage in the soil column, the resulting shape of the simulated hydrographs for these models did not differ much from those without lakes.
The effect of calibration on the simulated water balance was explored for the two calibration sub-basins, Ovre Abiskojokk and Ovre Lansjarv. In almost all cases, the fit of the simulated hydrographs, as measured by the root mean squared error, was improved through calibration. The total simulated runoff volumes, however, did not change much. This is consistent with the trends found in the basin-wide runs. In general, changes in model soil parameters had the effect of changing the timing of runoff production, but had much less effect on the amount of annual runoff generated by the models. The reason for this relative lack of sensitivity of the annual runoff ratio to model parameters appears to be that evapotranspiration is primarily energy-limited in this environment.

4. SUMMARIES OF WORKING GROUP DISCUSSIONS

4.1 Policy on model anonymity and data access

In a plenary session, the following data policy was agreed upon:

(1) It is anticipated that the results of the experiment will be published in three papers to be submitted to a refereed journal (most likely *Global and Planetary Change*). These papers will be co-authored submissions by the PILPS 2e community.

(2) Prior to submission of final results by all modeling groups, no models will be identified explicitly in any publications or presentations of the intercomparison results. A version of the diagnostic plots without model labels will be provided via the PILSP 2e website for participants to use in personal presentations in the interim.

(3) Models will be identified by name and modeling group when the results of the experiment are published.

(4) The forcing data set and model results will be archived at ALMA, at some reduced temporal resolution, following the conclusion of this experiment. These data sets will be freely available to other researchers.
Observed data will not be available to the modelers in digital form until all modelers have submitted final results. However, after discussion by the group, some observed benchmarks were included on preliminary diagnostic plots at the workshop in order to further assess model performance.

![Figure 12: Winter (January and February) latent heat flux versus mean annual discharge for the reruns](image)

4.2 Experiment Protocol

Discussion of the experimental design for PILPS 2e centered around two primary components: the appropriateness of the forcing data and the size of the output files requested.

1) Output file size – Each model was requested to return hourly output for the entire ten year period for the 46 defined variables. Total data volume was over 6 Gb for each model without compression (approximately 2.5 Gb with compression). Although there is interest in having variables such as the energy components at a sub-daily time step, it was the consensus that several variables could be identified, such as albedo and snow cover fraction, that could be returned at a coarser time interval.

2) Forcing data – In addition to the issues with solar radiation and precipitation disaggregation, three variables were identified in particular for additional diagnostics:
   (a) Relative humidity – potential seasonality in bias of the gridded product?
   (b) Bias in snow fall – how does gauge catch correction compared to WMO procedures?
   (c) Radiative fluxes – both longwave and shortwave

3) Vegetation data – more precise vegetation maps were requested for some of the models.

4.3 Experience with NetCDF and the ALMA conventions

The PILPS 2e experiment was the first test of the standard data exchange protocol defined by ALMA (see Section 2.4). The protocol is based on the NetCDF data format and a standard set of variable definitions. As noted in Section 2.4, Jan Polcher presented a summary of changes to the
ALMA protocols that are being implemented in response to the PILPS 2e experience, for use in the upcoming Rhône-Agg experiments.

Two working groups were formed at the workshop to discuss user-experience with the ALMA protocols. The findings of these working groups are:

1. In general, the participants were pleased with the ALMA variable definitions.

2. The ALMA web page should contain better documentation of the NetCDF interface. Example subroutines from different models to read and write NetCDF directly should be archived.

3. The ALMA web page should have an example script to convert between NetCDF and ASCII for basic input/output.

4. The programmes that calculate the energy and water balance errors need to be revised for different computer platforms.

5. A mailing/discussion list would be desirable for exchange of questions/information regarding the use of the conventions.

4.4 Discussion of additional sensitivity analyses

The discussion of additional model sensitivity runs opened with a proposal for a sensitivity study by Randy Koster, detailed below. Two working groups further discussed the Koster proposal, as well as any other sensitivity runs that might further explain the observed intermodel differences. The ideas of these working groups are summarized in Section 4.4.2. The conclusions of the working groups are summarized in Section 4.4.3.

4.4.1 Proposal for an aerodynamic resistance/albedo sensitivity experiment (Randy Koster)

The Torne-Kalix River system has an ample moisture supply over the year but is energy-limited, at least on an annual average basis. We can then hypothesize that most of the intermodel differences in evaporation and runoff in the PILPS 2e results from intermodel differences in the aerodynamic resistance formulation (drag coefficient formulation) and albedo. Intermodel differences in snow, canopy, runoff, soil water stress, etc., arguably can have only a secondary impact. We propose that interested groups (on a voluntary basis) can redo their simulations making two very simple changes:

1. Prescribe the aerodynamic resistance (drag coefficient) to a fixed, uniform value;

2. Prescribe the snow and snow-free albedos to fixed values.

If the above hypothesis is correct, then the intermodel differences for the new runs will be much smaller than those for the old runs.

4.4.2 Additional proposed sensitivity analyses

Further discussion of sensitivity analyses centered on four primary areas, as follows:

1. Model sensitivity to downward radiation:
(a.) Partitioning of additional solar energy – most models seem to put additional energy into sensible heat in the summer, is this caused by Jarvis type evapotranspiration parameterizations?

(b.) Longwave radiation sensitivity. What is the error range of longwave radiation?

(2) Sensitivity of snow models to simulated latent and sensible heat:
   (a.) Snow melt experiment with precipitation eliminated.
   (b.) Explore modeled differences in snow sublimation.

(3) Sensitivity of simulated runoff and soil moisture to the presence of simulated lakes.

(4) Sensitivity of the simulated runoff and SWE to other uncertainties in the input data:
   (a.) Model time step and forcing data interpolation.
   (b.) Seasonality in error of relative humidity?
   (c.) Snowfall bias due to gauge catch correction.

4.4.3 Conclusions
As indicated in Section 4.4.2, sensitivities were identified that could be explored to help quantify the error propagated by uncertainties in forcing data and variability in parameter selection. However, the consensus was that the potential gain from the additional model runs implied in Section 4.4.2 would not currently warrant the additional effort. Rather, an attempt will be made to identify and quantify the error in the forcing data set and to explore how the uncertainty in the input data results in an uncertainty of the model output.

4.5 Analysis of the intercomparison models and publication of results
4.5.1 Intercomparison Analyses
The breakout groups further discussed what analyses of the intercomparison data should be undertaken immediately and how the findings could be best presented to the scientific community. It was agreed that previous experiments, such as PILPS 2c and 2d have been insightful, but the analyses fall short of fully identifying mechanisms for the observed scatter. The groups identified several questions to be addressed by the intercomparison of model results, as follows:

(1) Aerodynamic resistance is not an output variable in PILPS 2e, is it needed? Could it be pre-calculated for Milly/Koster type analysis (PILPS 1c) for some grid cells where validation data are available?

(2) Is output needed for each tile? Models that use a mosaic approach are difficult to compare to other models.

(3) What are the most significant output variables from PILPS 2e that should be compared? Can the differences in SWE (or snow melt) be explained by differences in model physics?

(4) Can we decide what the necessary complexity of a snow model is? (multi-layer model versus models which imply horizontal fractional coverage).
(5) Are 2 meter forcings inappropriate? Is a boundary layer model needed as discussed in previous PILPS/GEWEX/GLASS meetings?

4.5.2 Journal Publications

Based on the workshop discussions, the experiment results will be published in three articles in a refereed journal. Ideally all three will appear in one volume. It was suggested that the Journal for Global and Planetary Change might be a viable option. The contents of the papers are roughly defined as follows:

(1) Paper 1: Experiment Design

Purpose: To introduce the experiment design, basin description, and to provide as comprehensive an analysis of the input forcing data set as possible.

Outline:
I. Introduction - PILPS/GLASS/ALMA background
II. Experiment background/design
III. Site Description
IV. Data Preparation
   A. processing/approximating/gridding, etc. (correction of precipitation)
   B. data verification/sensitivity/interpretation (particular attention to shortwave and longwave radiation, precipitation (with respect to the WMO gauge intercomparison) and humidity)
V. Models’ description, including snow model, runoff model, tile vs. dominant vegetation types, last published documentation
VI. Summary Results (motivation for following two papers)
VII. Working hypothesis from observed basin hydrology, PILPS 2d results and literature.

(2) Paper 2: Model Validation

Purpose: Explore results in the context of data accuracy, describe the seasonal hydrological cycle, and establish sensitivity of the models to the forcing data.

Outline:
I. Overview of types of results submitted (refer to 1st paper for description)
II. Description of Validation Data (streamflow, snow extent, point snow depth/swe, freezing depth, soil temperatures, lake ice, and other)
III. Results Summary - Water
   A. Snow
      1. Snow line retreat (contour lines), average over 10 years
      2. Partition of snowfall into melt and sublimation (sublimation vs. melt scatter plot)
      3. Mean monthly snow and mean monthly runoff; compare with observations, average over area with observations; divide into two classes of models
   B. Runoff
      1. RMSE/NS vs. volume ratio for calibration and validation catchments
      2. Ratio of surface runoff or dynamic storage vs. rms discharge
IV. Results Summary - Energy
A. Energy components and sensitivity to radiation forcing
   1. Net radiation, LW, SW bar plot; base and rerun
   2. Latent and sensible heat bar plot; base and rerun
   3. Evolution of latent vs. sensible "PILPS scatter"

B. Intermodel variance
   1. Seasonal ANOVA of Ts, Rnet and albedo
   2. Spatial, effect of canopy vs. no canopy, etc.
   3. Box and whisker diagrams for each season for explained variance
   4. Surface T depression.

(3) Paper 3: Koster-Milly type sensitivity analysis

Purpose: Condense model results into a few calibration parameters of a simple budget model, in order to stratify elementary model properties.

Outline:
I. Preamble - summarize papers 1 and 2
II. Review Koster/Milly; Gedney and Cox et al..
III. Structure of this model
   A. Interception evaporation must be subtracted from available energy
   B. Add snow budget model
   C. Take into account snow cover fraction for evaporation
   D. Calibrate over 3 catchments, "homogeneous" areas of vegetation and topography
IV. Application; results
   A. Calibrated parameters vs. RMSE
   B. Explain differences between models (sublimation, runoff, etc.)
V. Explore sensitivity - is response in simplified model the same as between base and reruns?
   A. Additional energy (by season)
   B. Additional precipitation.

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EXPERIENCE STATEMENTS FROM MODELING GROUPS

CHASM
Three modes of the CHASM land surface model were compared in the PILPS 2e experiment. These modes include EB mode with one composite tile, Slam-1T mode with one composite tile, and Slam mode with two tiles. The results show that Slam can basically catch the seasonal variability of daily runoff at the two calibration sub-basins, but Slam-1T cannot.

CLASS
We have continuing questions about the errors associated with the estimated input fields of incoming shortwave and longwave radiation and precipitation. We would like to see further sensitivity testing to investigate the effects of possible alternative parameterizations.

Some groups at least should investigate the effects of sensitivity between the Clapp, Cosby and Rawls sets of soil properties.

Finally, our group would be interested in investigating the effects of including peatlands and shallow till soils in the simulation; CLASS version 3.0 (scheduled for release in a few months) will be able to handle such soils (as well as lakes).

ECMWF
The ECMWF model is a recently developed mosaic-version of the operational European Center for Medium-Range Weather Forecasts (ECMWF) land surface scheme. In particular, the change of the treatment of snow in boreal forest areas improved significantly the winter and springtime simulation of surface evaporation and precipitation in the higher latitude areas. During PILPS 2e, deficiencies remained apparent in the sublimation rate of snow outside the forest areas. Also, a fast-response component of the total runoff was absent, resulting in an anomalous simulation of the catchment discharge.

HY-SSIB
HY-SSiB, the LSM used at NASA Goddard in the GEOS 2 GCM has in the past several years undergone major developments to its snow physics and soil hydrology. The current scheme, with a diurnal layer above a bulk snow layer, very well reproduced observed snow melt timing, soil moisture, and runoff in the GSWP 1 and Valdai datasets, whereas previous versions of SsiB produced too late snowmelt, too little soil moisture, and too high and too late runoff. In the Torne/Kalix PILPS 2e experiment base runs with HY-SSiB, the simulated discharge in the Ovre Lansjarv was generally well-simulated, if a bit too high, while in the Ovre Abiskojokk, the simulated discharge was too early. In the re-runs, both basins may show too early runoff peaks (and thus too early melt), although these reruns have yet to be re-calibrated. The affect of the new forcing data in the reruns was to increase summer evaporation and spring/summer sensible heat, as well as reduce runoff, especially in the sub-surface.
IBIS
I certainly enjoyed participating in this experiment. I had some difficulties of technical order, mainly because of the amount of data files to deal with, but this is a 'part' of science. By participating in this experiment, I learned a lot on the performance of the model I am using for my research. I hope, however, that my participation was useful in assessing the performance of current Land Surface Schemes in northern cold environments.

IHAS
Our model (IHAS) is a simple land surface model based energy balance that includes a river break-up sub-model. The surface state (land cover types) is presented by a big-leaf, so some variables for surface state and evaporation components (e.g. vegetation canopy temperature, bare soil temperature, vegetation transpiration, bare soil evaporation, open water evaporation and so on) can not be separated. For subsurface state variables, the output from the model include soil temperature and soil moisture but the range of depth of soil thaw is over the expected range, so we decided do not submit it in this step.

ISBA
ISBA used its new 3-layer snow scheme for this application. We had problems simulating the two calibration basins with the same quality. First we thought it was due to a quality problem with the forcing data. Therefore, we made no calibration, except to activate "the subgrid subsurface runoff", with default value parameters, in order to sustain summer streamflow. We still had some problems simulating the Abiskojokk basin with the rerun forcing data, but we do not yet know what is the problem with this basin.

MATSIRO
MATSIRO was developed for use in climate studies and has a similar structure to SiB2. The calibration for PILPS2e was conducted in such a way that two surface runoff parameters (surface storage capacity and ratio of river channel to the saturated area) depend on topography. The annual runoff was closer to the observation after calibration, but subsurface flow needs to be examined further since it is underestimated in the simplified TOPMODEL.

MECMWF
A modified version of the ECMWF scheme, labeled MECMWF, addressed deficiencies in the ECMWF scheme. Sublimation of exposed snow was suppressed by reducing the surface roughness of this particular grid box fraction. Fast response surface runoff was created by adopting a variable infiltration capacity parameterization, routing a portion of the precipitation and snow melt directly into runoff prior to infiltration. MECMWF appeared to be significantly more successful in simulating discharge for the averaged basin, as well as the mountainous calibration catchment (Abisko). Discharge from the flat area appeared to contain too much fast-response components, implying that appropriate calibration may be desirable.

MOSES
The new version of MOSES used for PILPS 2e differs from versions used for 2d and earlier studies through the introduction of surface tiling and a prognostic snow albedo scheme. A four-layer soil model is used; snow is lumped with the surface soil layer, but tiles can have differing snow cover.
MOSES-CEH
Run by CEH Wallingford, MOSES-CEH is the same model as MOSES which has participated in previous PILPS experiments, but with runoff calculated using a soil moisture probability distribution function for the surface layer.

NSIPP
A general deficiency of offline simulations, the inability to model the adjustment of the overlying atmosphere due to sensible heat from the land surface, was discussed. The sensitivity of adjusting atmospheric temperature to annual total runoff prediction was presented at the workshop.

NOAH
The NOAH (NOAA, OSA, Air Force and Office of Hydrology) land-surface model uses Richard's equation for soil water movement and resolves the soil temperature profile to calculate ground heat flux. It was necessary to perform a simple temporal interpolation to generate forcing data at the required 15 minute time step required for the NOAH model. A triangular linear interpolation scheme was used which preserves the hourly mean of the 15 minute data. We experienced no problems with NetCDF, but did neglect to include one term in the cold content for closure of the energy balance.

RCA
An outstanding problem that has been seen in the RCA simulations is excessive sublimation. This is especially seen at Abisko, whereas the extra resistance from the forest reduces the problem at Lansjarv. This problem could depend on the use of too small an aerodynamical resistance over snow.

SAST
When we were doing our calibration, we changed the soil depth from 5 meters to 1.1 meters in order to fit the observed runoff. The forest region's runoff is more sensitive to this parameter than the mountain region's. We increased the albedo for the short grass grid box so phase of mountain region's runoff is postponed. The surface runoff was too large in our original model so we used the largest hydraulic conductivity, which made the surface runoff decrease.

SEWAB
The PILPS2E experiment was the first time that I have done a hydrologic simulation. The model SEWAB was also quite new to me, so my ideas about the abilities of SEWAB to simulate especially the cold season processes were vague. I thought that because SEWAB includes a snow and frozen soil model it should be possible to get adequate results. The biggest part of the basin cannot be characterized as 'flat low land', so the TOPMODEL soil model of SEWAB seemed to fit to the shape of the landscape. On the other hand, in the simulation basin (very lovely, I've been there some years ago) there are some areas of rock instead of soil and a lot of swamp. SEWAB doesn't handle these areas very well.

The biggest problem I had was that the evapotranspiration in areas with vegetation class 1, 6 and 7 seemed to be too low, so that the runoff was too high. The second problem was reproducing the smaller discharge peaks in summer. Using the given soil parameters I was not able to produce enough surface runoff during short rain events.
SPONSOR

Significant surface temperature differences (between models) in winter might result from parameterizations of snow albedo, snow thermal conductivity, or turbulence under stable stratification in the surface air layer. Spatial disaggregation of the forcing should be of special attention within PILPS 2e, probably with revision of some forcing parameters. In particular, the longwave radiation should be corrected for the effect of diminishing air emissivity (i.e. air density) in mountains. A major technical concern for SPONSOR was dealing with large files in NetCDF format on a PC. Probably the operations with NetCDF format (to and from ASCII) could be taken away from the experimenters with limited technical resources and given to the organizers of the given PILPS stage.

SSiB

SSiB uses a 3-layer snow model, which enables it to better predict vertical snow temperature distribution, the melting/freezing cycle, and the timing of snow ablation. It can better describe internal heat conduction and compaction processes and take into account properties of new snow. The energy and water balances are checked at every time step. To calibrate to observed discharge, one parameter was modified to slow the melting rate of snow. A stability adjustment was ignored for the Ovre Lansjarv catchment to decrease total runoff, and albedo was increased for the Ovre Abiskojokk catchment to increase total runoff. These changes were applied in the validation and base runs to sites with similar vegetation.

SWAP

For this application the old version of SWAP was modified in the following manner:

(1) The concept of seasonally thawed soil was used.
(2) Subsurface runoff was neglected. Two mechanisms of formation of surface runoff (Hortonian runoff and bucket runoff) were included.
(3) Tall vegetation was incorporated in the cold season sub-model.

When performing the PILPS 2e experiment, we tried to calibrate soil parameters, but without any progress. So, we decided to refrain from any calibration and used the first set of soil data (Clapp et al. 1978).

Nine types of land surface were aggregated into four types:

(1) bare soil and water (the lakes were neglected);
(2) grassland;
(3) evergreen needleleaf forest;
(4) the rest vegetation (mixed forest, woodland, wooded grassland, closed and open shrubland) because of uncertainties in vegetation parameters.

VIC

Several new features of the VIC model were tested for the first time for the PILPS 2e experiment. These include:

(1) The representation of sub-tile variability in SWE and soil ice content;
(2) The calculation of heat fluxes from a canopy layer above an underlying snow layer; and
(3) The representation of open water evaporation from a 'lake' tile, and the storage of runoff in the lake tile.
We found that it was easier to calibrate to the discharge of the lower-elevation Ovre Lansjarv catchment. We believe the difference is primarily due to the existence of a large percentage of lakes in the Ovre Abiskojokk catchment. Tuning of the rate of runoff from the lake tiles for the Ovre Abiskojokk catchment resulted in a much better fit of the spring freshet peak.

VISA
This model is sensitive to the ground snow cover fraction, especially in less vegetated areas. We propose a formula to compare snow covered fraction among PILPS 2e models and to remote sensing data, where SCF is equal to the ratio of the total area less the snow free area to the snow covered area less the snow free area.

We have also found that the Ksat decay factor, f, is crucial for controlling the water table depth (larger f, faster decay of Ksat, resulting in a shallower water table) and the phase of subsurface runoff. We have developed a formula for f as a function of elevation for the PILPs 2e application.