An Analysis Of Simulated Runoff And Surface Moisture Fluxes In The CCCma Coupled Atmosphere Land Surface Hydrological Model

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Abstract: The performance of Canadian Land Surface Scheme (CLASS) coupled to the Canadian Centre for Climate Modelling and Analysis (CCCma) atmospheric general circulation model (AGCM) is evaluated in an Atmospheric Model Intercomparison Project (AMIP II) simulation. In addition to the coupling between the atmospheric model and the land surface scheme, a variable velocity river flow routing model transports runoff from the land grid cells to the continental edges. Results from this atmosphere land surface hydrological model are analyzed to investigate how moisture is processed in the model and to compare model and observation-based moisture budget components. Runoff simulations and surface moisture fluxes are assessed for major river basins. Not surprisingly runoff is well simulated in river basins where GCM precipitation compares well with observations. In the model vegetation plays a major role in processing moisture at the land surface. It intercepts a large fraction of the precipitation and provides the medium for returning much of the moisture back to the atmosphere as evapotranspiration. Though important locally, the snow moisture reservoir plays a relatively minor role in the global moisture budget. The ground moisture reservoir also plays a major role and processes a similar fraction of precipitation as vegetation. The way moisture is processed at the land surface serves as a basis for model intercomparison and for understanding the modelled moisture budget and its variation as well changes with potential climate change.

Keywords: *GCM; Land-atmosphere interactions; Flow routing*

1. INTRODUCTION

The partitioning of precipitation into evaporation and runoff, and the partitioning of net radiation into latent and sensible heat fluxes at the land surface, plays a major role in determining surface climate. This partitioning is, to a large extent, determined by the soil moisture and the vegetation cover both of which characterize land surface. Studies of the coupled land-atmosphere system suggest how interactions between land and atmosphere may affect climate. Investigations of vegetation-atmosphere feedbacks depend on the use of increasingly complex soil-vegetation-atmosphere-transfer (SVAT) schemes which emphasize both the varying properties of soil and the direct role of vegetation in determining the surface energy and water balance, particularly by taking into account the physiological properties of vegetation (leaf area index, LAI, and stomatal resistance). SVAT schemes used in general circulation models (GCMs) and regional climate models (RCMs) are routinely assessed locally by forcing them with observed atmospheric data over small homogenous areas and comparing the model-simulated energy and water fluxes with observations. For example, atmospheric data from experimental sites such as HAPEX-Mobilhy, FIFE, Cabauw in the Netherlands, and Valdai in Russia have been used by the Project for Intercomparison of Land Surface Schemes (PILPS) and by modelers to validate their land surface schemes. Validation exercises conducted using local atmospheric forcing do not adequately test SVAT schemes at the large spatial scales at which they are applied in GCMs and researchers have attempted to perform validation exercises at river basin scales using streamflow as a diagnostic variable. While the local (e.g., based on locally measured quantities) and regional (e.g., based on streamflow) assessments of SVAT schemes give useful information about their behaviour they do not represent the two-way interaction between the land and the atmosphere which is important from a climate perspective. Analysis of the behaviour of a SVAT scheme in this context provides insight into the manner in which moisture and energy are processed at global scales.

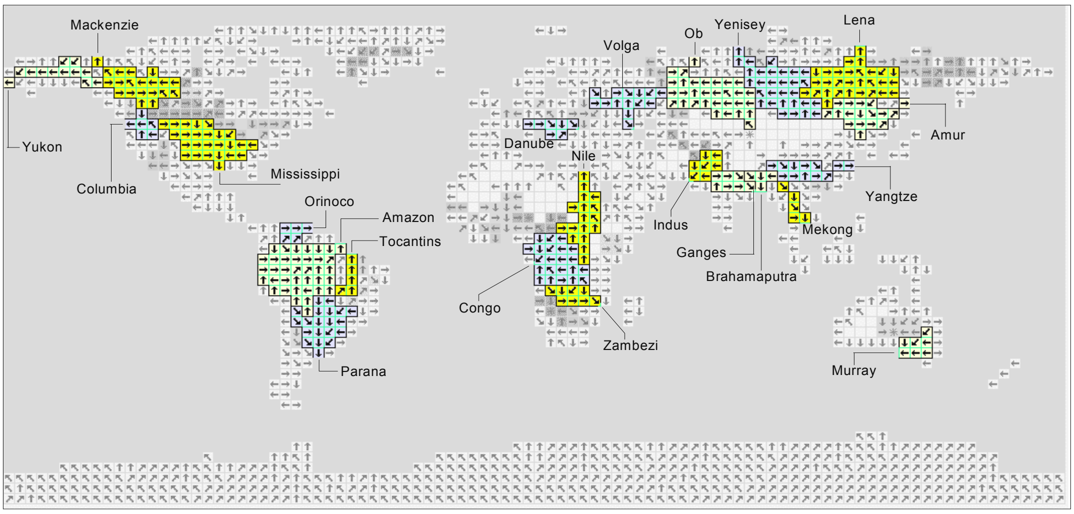

Figure 1. Model discretization of the 23 major river basins, at 3.75° resolution, considered in this study and their river flow directions as per Arora and Boer (1999).

We assess the runoff and surface moisture fluxes simulated by the Canadian Land Surface Scheme (CLASS) coupled to the Canadian Center for Climate Modelling and Analysis (CCCma) third-generation atmospheric general circulation model (AGCM3). In addition to the coupling between the atmospheric model and the land surface scheme, a variable velocity river flow routing model transports runoff from the land grid cells to the continental edges. Our aim is to understand how vegetation, snow, and ground moisture reservoirs process moisture at the land surface, and to compare model and observational moisture budget components.

2. METHODS

The CCCma third generation atmospheric GCM is the latest in the series of AGCMs described in Boer et al. (1984) and McFarlane et al. (1992). The results analyzed here are obtained with the T47 L32 version of the model. The horizontal resolution of the model is approximately 3.75° and the vertical domain extends to 1 hPa with the thicknesses of the model's 32 layers increasing monotonically with height from approximately 100 m at the surface to 3 km in the lower stratosphere.

Primary features of CLASS (Verseghy et al., 1993) include three soil layers, liquid and frozen soil moisture, a snow layer where applicable and a vegetative canopy. Soil surface properties (e.g., surface roughness heights and surface albedo) are functions of soil moisture conditions and the soil and vegetation type. The variable velocity flow-routing algorithm of Arora and Boer (1999) is applied in the coupled model to obtain streamflow at the continental edges. Major river basins at the GCM resolution are shown in Figure 1. Streamflow simulations are assessed in Arora (2001a). Here we assess the mean annual runoff and other surface moisture fluxes for major river basins.

We analyze results from an AMIP II simulation made with AGCM3. The Atmospheric Model Intercomparison Project (AMIP), initiated in 1989, undertakes the systematic validation, diagnosis, and intercomparison of the performance of atmospheric GCMs (Gates et al., 1999). In AMIP II simulations, an atmospheric GCM is integrated for the 17 year period (1979-1995) with observed monthly sea surface temperatures (SST) and sea-ice concentrations specified but with a freely evolving atmosphere and land surface.

3. RESULTS

3.1. The Global Hydrological Cycle

Figure 2 compares simulated and observation-based components of the global annual mean hydrological cycle. The observation-based estimates are those of Baumgartner and Reichel (1975) and L'vovich (1979). AGCM3 simulates a slightly more active global hydrological cycle than the estimates of Baumgartner and Reichel (1975) but compares well with the estimates of L'vovich (1979). The simulated value of vapour transport from the ocean to the land surface is slightly higher than both observation-based estimates, while the runoff from the land surface to the ocean compares well with them. The 3000 km^3/year difference between the vapour transport and river flow represents the conversion of accumulating snow to ice and the storage of moisture in the permanent ice cover of Antarctica and Greenland. This value may be compared with observation-based iceberg discharge estimate of

2604 km^3/year from Antarctica and Greenland, respectively (Vaughan et al., 1999 ; Reeh , 1994).

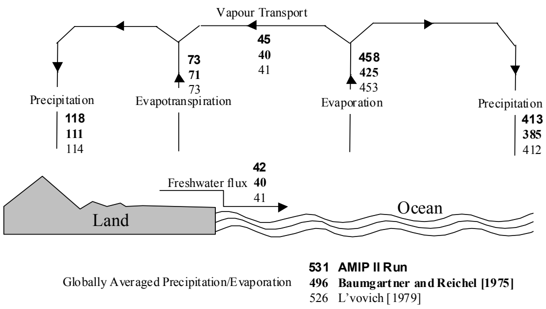

Figure 2. Comparison of annual mean components of global hydrological cycle with observation-based estimates. The units are 10^3 km^3/year.

Table 1 compares model values of mean annual precipitation and runoff over land with observation-based estimates. The model value of annual mean precipitation falls within the range of observation-based estimates and the modelled estimate of annual mean runoff also compares well with the observations although all values are lower than those of Cogley (1998).

Tab1e 1: Mean annual model and observed, precipitation and runoff (mm/year) over land.

	Precipitation	Runoff
This study	747	265
Baumgartner and Reichel (1975)	743	268
L'vovich (1979)	763	274
Xie and Arkin (1997)	710	
Cogley (1998)		307

Figure 3 shows the differences between modelled and observation-based mean annual precipitation and runoff over land. The observed precipitation and runoff estimates of Xie and Arkin (1997) and Cogley (1998), respectively, are used. While the simulated globally averaged precipitation and runoff estimates compare well with observations over land (Figure 2 and Table 1) there remain discrepancies in regional precipitation and consequently in runoff estimates. The model apparently produces somewhat more precipitation over northern North America, Central America, central Africa, south-west China, and southern South America than is observed. For regions where model precipitation is less than observed, the difference is most significant in the Amazonia region. As expected, the land surface scheme produces more (less) runoff in areas characterised by high (low) GCM precipitation. The model runoff is less than observed in Amazonia, and greater in northern North America, central Africa, and south-west China. The differences in regional precipitation and runoff lead to differences in basin-wide averaged values calculated for individual river basins.

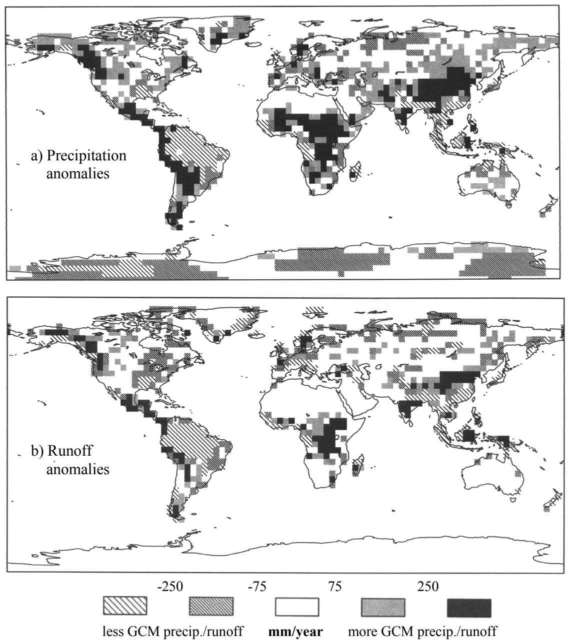

Figure 3. Differences between model and observed, mean annual precipitation and runoff estimates over land (mm/year).

3.2. Basin-wide Average Precipitation and Runoff

Table 2 compares the basin averaged values of precipitation and runoff for the 23 major river basins with observation-based estimates from Xie and Arkin (1997) and Cogley (1998), respectively. Out of 23 major river basins considered in this study, model precipitation is within 20% of the observed estimates for 15 river basins. The differences between simulated values and observed estimates are bigger for runoff than for precipitation because of the errors associated with the land surface scheme. Consequently, model runoff is within 20% of the observed estimates for only 5 of these 15 river basins. For most river basins high (low) GCM precipitation results in high (low) runoff. However, there are river basins for which the precipitation estimates are close to observations, such as the Mississippi and the Yukon, but where model runoff simulations differ from observations. The simulated precipitation for the Yenisey, Lena, and the Amur is higher than observation-based estimate, while the simulated runoff is lower because of higher simulated evapotranspiration (Arora, 2001b). Model runoff ratios compare reasonably well with observed estimates for many but certainly not all river basins.

Table 2: Comparison of basin averaged precipitation and runoff for the 23 major river basins with observation-based estimates.

River basin	Precipitation (mm/year)		Difference in model and observed precipitation (%)	Runoff (mm/year)		Difference in model and observed runoff (%)	Runoff Ratio	
	Model	Observed		Model	Observed		Model	Obs.
Tocantins	1002	1892	-47.0	206	878	-76.5	0.21	0.46
Amazon	1437	1771	-18.9	493	1029	-52.1	0.34	0.58
Ganges	789	935	-15.6	119	323	-63.2	0.15	0.35
Orinoco	1363	1565	-12.9	432	609	-29.1	0.32	0.39
Mekong	1350	1549	-12.8	473	677	-30.1	0.35	0.44
Ob	390	424	-8.0	125	143	-12.6	0.32	0.34
Volga	537	551	-2.5	175	146	19.9	0.33	0.27
Mississippi	699	698	0.1	95	188	-49.5	0.14	0.27
Yukon	688	673	2.2	562	479	17.3	0.82	0.71
Yenisey	443	424	4.5	169	266	-36.5	0.38	0.63
Murray	417	384	8.6	5	15	-66.7	0.01	0.04
Zambezi	973	886	9.8	169	96	76.0	0.17	0.11
Lena	403	355	13.5	188	196	-4.1	0.47	0.55
Congo (Zaire)	1743	1514	15.1	726	431	68.4	0.42	0.28
Danube	867	743	16.7	354	700	-49.4	0.41	0.94
Amur	568	480	18.3	144	157	-8.3	0.25	0.33
Parana	1325	1061	24.9	294	232	26.7	0.22	0.22
Indus	516	393	31.3	149	243	-38.7	0.29	0.62
Mackenzie	572	424	34.9	324	228	42.1	0.57	0.54
Brahamaputra	2009	1363	47.4	1448	1008	43.7	0.72	0.74
Yangtze	1548	985	57.2	907	650	39.5	0.59	0.66
Columbia	1014	645	57.2	544	398	36.7	0.54	0.62
Nile	1057	599	76.5	356	59	503.4	0.34	0.10

3.3. Moisture Processing at the Land Surface

Runoff and precipitation are the only two quantities which can be compared with observation-based estimates. Insight into the manner in which precipitation is processed at the land surface is of interest and the ability of the model to simulate the interactions and feedbacks between the land surface and the rest of the climate system is basic to simulating forced climate change and is an area of model validation and intercomparison.

The CLASS land surface scheme processes heat and moisture via three reservoirs: the ground, the canopy and snow. A GCM grid cell is further divided into four sub-areas: bare soil, snow covered ground, canopy covered ground, and canopy covered snow, for each of which heat and moisture balance is evaluated separately.

Figure 4 shows how precipitation is processed at the land surface via the three moisture reservoirs in the coupled atmosphere and land surface model. Mean annual values of the inputs, outputs, and exchanges to, from, and between the three moisture reservoirs are shown in mm/year and as a percentage of mean annual precipitation. P_c, P_g, and P_s are direct precipitation inputs into the canopy, ground, and snow moisture reservoirs, respectively. I_{cg}, I_{sg}, I_{cs} are the moisture exchange fluxes from the canopy to ground, from the snow to ground, and from the canopy to snow reservoirs, respectively. E_s, E_g, and E_c are evaporative fluxes from the snow, ground, and canopy reservoirs respectively. E_g is divided in evaporation (E_{soil}) and transpiration (E_t) from soil. Finally, R_o and R_g represent the surface runoff and drainage runoff .

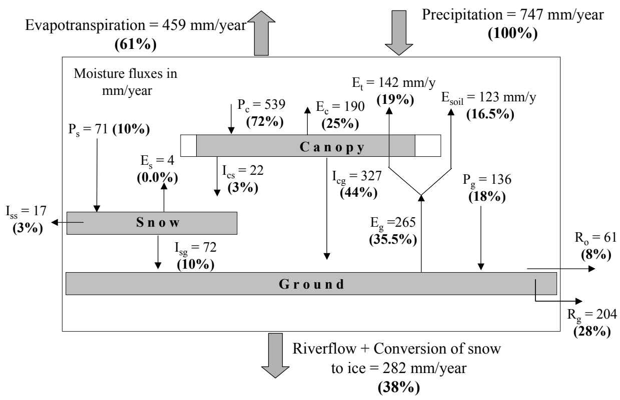

Figure 4. Mean annual values of inputs, outputs, and moisture exchanges to, from, and between the three moisture reservoirs over land in mm/year and as a percentage of annual precipitation.

In the model, and by inference in the real system, the canopy plays a major role in moisture processing. It intercepts 72 units of the total precipitation of which 25 units are evaporated and 47 units are exchanged with the underlying ground and snow. It also plays an indirect role in the evapotranspiration of 19 units from the ground moisture reservoir. In terms of moisture fluxes, the snow moisture reservoir plays only a modest role in the global moisture budget although, of course, an important role locally. About 10 units are processed, mainly by direct moisture input into the snow reservoir and subsequent snow melt. Compared to soil moisture and canopy moisture reservoir, however, the snow offers the largest moisture storage. The ground reservoir processes a similar amount of moisture as the canopy, although in a different manner. It receives about 72% of precipitation as moisture input from drip via the canopy and snow melt combined, and partitions this almost equally into evaporation and runoff.

Figure 4 shows that of the 265 mm/year of runoff, surface runoff accounts for 61 mm/year (or about 23% of the total runoff) and, drainage accounts for 204 mm/year (or about 77%). CLASS generates surface runoff when the amount of ponded water exceeds a specified limit and ponds form when the precipitation intensity exceeds the infiltration capacity of the soil. Deep soil percolation or drainage from the bottom-most soil layer is assumed equal to the hydraulic conductivity of the soil, which itself is a function of soil moisture. L'vovich (1979) provides globally-averaged estimates of the partitioning of total runoff into surface runoff (~70%) and drainage (~30%) based on an analysis of hydrograph data from around the world using a baseflow separation method. He attributes the rapidly varying discharge in a hydrograph to surface runoff, and the slowly varying discharge to baseflow (or drainage). No other global estimates are available. While the modelled global runoff agrees well with the estimates of L'vovich (1979) and others as referenced in Figure 2 and Table 1, the relative fraction of surface runoff and drainage differ. This is an area that requires more observations and modelling studies.

Regional values of primary input and output quantities for the three moisture reservoirs for selected major river basins are used to illustrate the different ways in which precipitation may be processed at the land surface in Figure 5. Three river basins characterized by different environments are selected as an example. They are (1) the Mackenzie basin, characterized by large amount of snow, (2) the Lake Eyre basin in Australia, characterized by arid and dry climate and relatively sparse canopy, and (3) the Amazon basin, characterized by thick canopy cover. The location of these river basins is shown in Figure 1.

Figure 5 shows how the large spatial extent of the canopy in the Amazon basin results in a large fraction (92%) of precipitation being intercepted, compared to only 41% for the Lake Eyre basin which is characterized by a sparse canopy. Consequently a large fraction of precipitation (41%) is evaporated from the canopy in the Amazon basin, compared to only 16 % for the Mackenzie and the Lake Eyre River basins. In the model, 33% of the precipitation contributes as direct moisture input to the snow moisture reservoir in the Mackenzie River basin. Here, the canopy moisture reservoir also contributes to the snow reservoir via snow drip from the canopy leaves. The model simulated basin averaged snow-melt amounts to 47% of precipitation, which contributes to the ground reservoir. In the absence of snow there is no interaction between the snow, and the canopy and ground reservoirs in the Amazon and the Lake Eyre River basins. In the Lake Eyre basin a larger fraction of precipitation (59%) falls directly on the ground because of a relatively sparse canopy. About 60% of the evaporation occurs directly from the ground in the Lake Eyre basin, compared to only 8% from the Amazon.

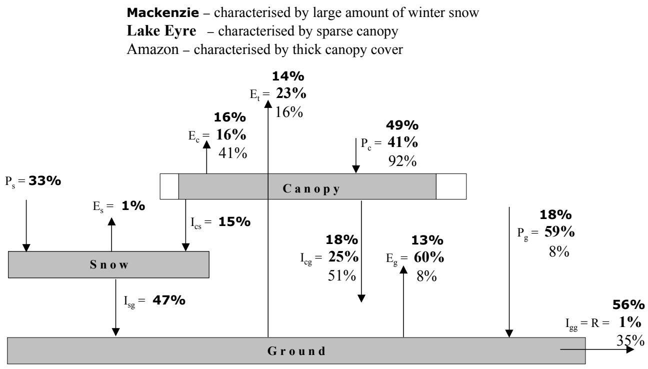

Figure 5. Mean annual values of the moisture components, for the canopy, the ground, and the snow moisture reservoirs, expressed as a percentage of precipitation for the Amazon, the Mackenzie, and the Lake Eyre river basins.

Figure 5 serves as a basis on which to understand the manner in which the land surface scheme processes moisture for different river basins. However, only the percentage of precipitation converted into runoff (the runoff ratio) can be compared with observationally-based estimates (Table 2). Basin-wide averaged estimates of various moisture budget quantities also provide a basis for model validation and intercomparison at regional scales.

4. SUMMARY

From a climate perspective, it is important to assess the response of SVAT schemes at global scales where the land-atmosphere feedbacks are integrated. Such global analyses help provide insight and understanding into the manner in which SVAT schemes process energy and moisture at large spatial scales. Here, the global moisture budget and the behaviour of its various components over land is evaluated for an AMIP II simulation made with the CCCma third generation AGCM. Related results are provided also in Arora and Boer (2002).

The global hydrological cycle is reasonably well simulated in the model with globally averaged precipitation and evapotranspiration within 4% of the observation-based estimates. Globally averaged precipitation and runoff over land are also simulated well while there remain differences in the regional estimates of these quantities which lead to differences in basin-wide average estimates of precipitation and runoff for individual river basins. The analysis of moisture budget components for the canopy, the ground, and the snow moisture reservoirs show that the canopy plays a major role in processing precipitation at the land surface. This emphasizes the importance of vegetation for climate. Currently of the components of moisture budget only precipitation and runoff and the partitioning of runoff into surface runoff and drainage, can be compared with observation-based estimates. The establishment of a more complete budget remains an important need.

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