Moisture Recycling

How important is evaporation to sustain rainfall?
Does landuse change affect rainfall significantly?

Yasir A. M. and H. H. G. Savenije. August 2002. IHE Delft, The Netherlands

1. Introduction

The components of the regional water cycle are: moisture in the atmosphere, precipitation, evaporation (in its all forms), infiltration, and runoff. The relation between these components is highly nonlinear and complicated by the different spatial and temporal scales of the components. Moisture recycling is a key process in the regional water cycle, and has direct implications on the management of land and water resources of the region. In climate modeling it is also known that the exchange of moisture with the land surface is relevant, if not crucial, to make realistic predictions of the atmosphere.

It is increasingly recognized, but not fully quantified, that landuse-changes can induce changes in climate, not only locally but also at continental scales. Recent research has shown that local evaporation contributes significantly to seasonal and annual rainfall in many regions of the world through moisture recycling. Hydrologists and water managers are becoming more aware of the importance of the atmospheric part of the regional water cycle. The classical approach of limiting a water resources system to only the land hydrological cycle (precipitation, evaporation, infiltration, and runoff) is advanced to a more inclusive approach. There is a lot of experience around among scientists and water managers: some anecdotal, some empirical, some as a result of modeling. There is however no consensus and no full picture on the relative importance of moisture feedback at different temporal and spatial scales.

A forum is planned that aims at raising discussion on moisture recycling issues: its importance to sustain regional rainfall, the available observational and computational experiences in the world, and what should be the direction of future research to better understand and quantify moisture recycling. This overview paper is formulated to start the discussion by presenting some of the key questions on the topic, followed by a description of the feedback mechanism as quoted by different researchers. Case studies on moisture recycling at some of the river basins are reviewed, in relation to the limitations of data and model techniques.

2. Key Questions:

The discussion forum is expected to be a good opportunity to share opinions and experience on the topic, not only among scientists, but also among water resources managers, and practitioners. To stimulate the discussion and limit it to a specific part of the land surface-climate interaction, a list of questions is presented here to start the discussion on the topic, viz.:

1. At what spatial and temporal scales does landuse change affect climate, particularly rainfall?
2. How realistic are the available methods in quantifying moisture feedback to the atmosphere?
3. Are the available data sufficient to quantify the significance of moisture recycling?
4. Can it be proved that drying of major wetlands will affect rainfall at regional scales?
5. What are the optimal landuse and water resources practices that conserve moisture recycling?
6. What is the scientific road map for better understanding of moisture recycling?

3. Moisture feedback mechanisms

Sources of precipitation in a given region are:

1. Moisture flux advected into the region by moving air masses.
2. Moisture flux supplied by evaporation from within the region itself.

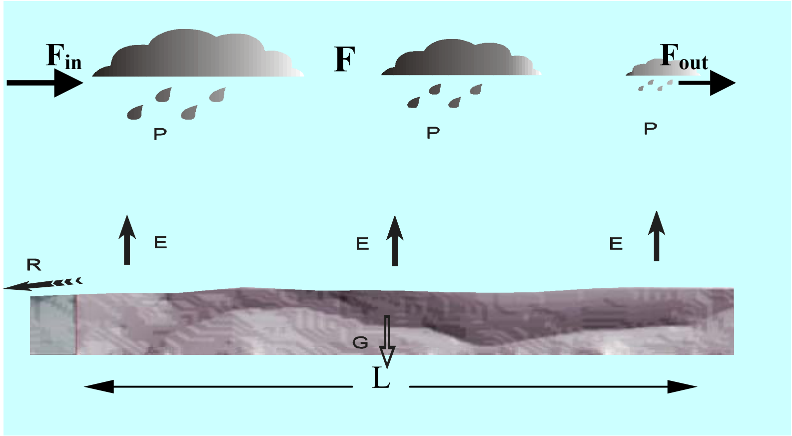

Fig. 1: The components of the water cycle in domain L (see the text for symbols).

From the precipitated water in a region "P", part “E” evaporates from land surface (includes interception, evaporation from open water, from bare soil, and transpiration from vegetation). Part "R" drains at the outlet of the basin as runoff. Part “G” is the storage. The total precipitation P in a domain is composed of two components: P_l from a local source (local evaporation) and P_a from an advected source (oceanic evaporation). Moisture recycling is defined as the process by which part of the precipitated water which evaporated from a given area, contributes to the precipitation over the same area, also referred to as locally derived precipitation. The recycling ratio β is computed as the ratio P_l/P. Therefore, it is equal to one for the whole globe, and zero for a point location.

Moisture recycling characterizes a nonlinear relationship between regional evaporation, moisture transport, and precipitation. Evaporation in turn depends on the availability of moisture on the area, either as open water surface, or below surface within the unsaturated zone, which is evaporated directly or transpired via vegetation. The moisture transport into the region depends on the atmospheric dynamics and the sources of origin of the moisture. Therefore, moisture feedback and the related land use change are essential to the hydrology and water resources of a region. Subsequently, any modification of the processes overland can affect the amount of precipitation (for cases of $\beta \neq 0$).

It is known from both observations and numerical experiments, that evaporation from the land surface into the atmosphere has two effects:

1. It increases the atmospheric moisture, which favors more precipitation. Observational data over the Amazon and other regions (see e.g. Eltahir and Bras, 1994; Trenberth, 1999) shows a significant contribution of local evaporation to the atmospheric moisture. The relative importance depends upon the amount of the advected moisture into the region, i.e. it will have pronounced effects when the advected moisture is small. Bosilovich and Schubert (2001) computed a smaller recycling ratio of 20% over the central United States during the high flood of 1993, when large amounts of moisture were advected into the region. This ratio rises to more than 60% during the same month of the dry year of 1988, associated with smaller amounts of advected moisture.

2. Evaporation changes the thermodynamics of the vertical water column, favoring future precipitation. Higher evaporation (associated with wetter soils) reduces both albedo and Bowen ratio (Bastiaanssen, 1995; Brutsaert, 1982). This results in higher net radiation over the surface, and higher total heat energy to the atmosphere, which leads to larger moist static energy of the boundary layer. Moist static energy plays an important role in the dynamics of the local convective storms, and it strengthens the large-scale monsoon circulation ratio (see e.g. Schär et al., 1999; Eltahir, 1998). The correlation of soil moisture with net radiation, total heat flux, and evaporation, is confirmed in many earlier investigations (e.g. Soarės et al., 1988; Kustas, 1990; Humes et al., 1994), it can also be seen from a satellite observation over part of the Nile basin (see Fig. 2). This is a 1000 km*1000 km image of the Nile Basin on 26/01/2000, that has a clear land-cover contrast (dry land, Savannah, tropical forest, wetlands). The dry land (northern part of the image, and southeastern corner) shows lowest soil moisture, lowest net radiation, lowest total heat, and lowest evaporation, while the reverse is seen over the Sudd swamps (area between Juba, Wau and Malakal). The soil moisture in the root zone was computed by Scott (2002) and the surface fluxes were calculated using the SEBAL algorithm (Bastiaanssen et al., 1998) applied to a NOAA-AVHRR image (National Oceanic Atmospheric Administration – Advanced Very High Resolution Radiometer).

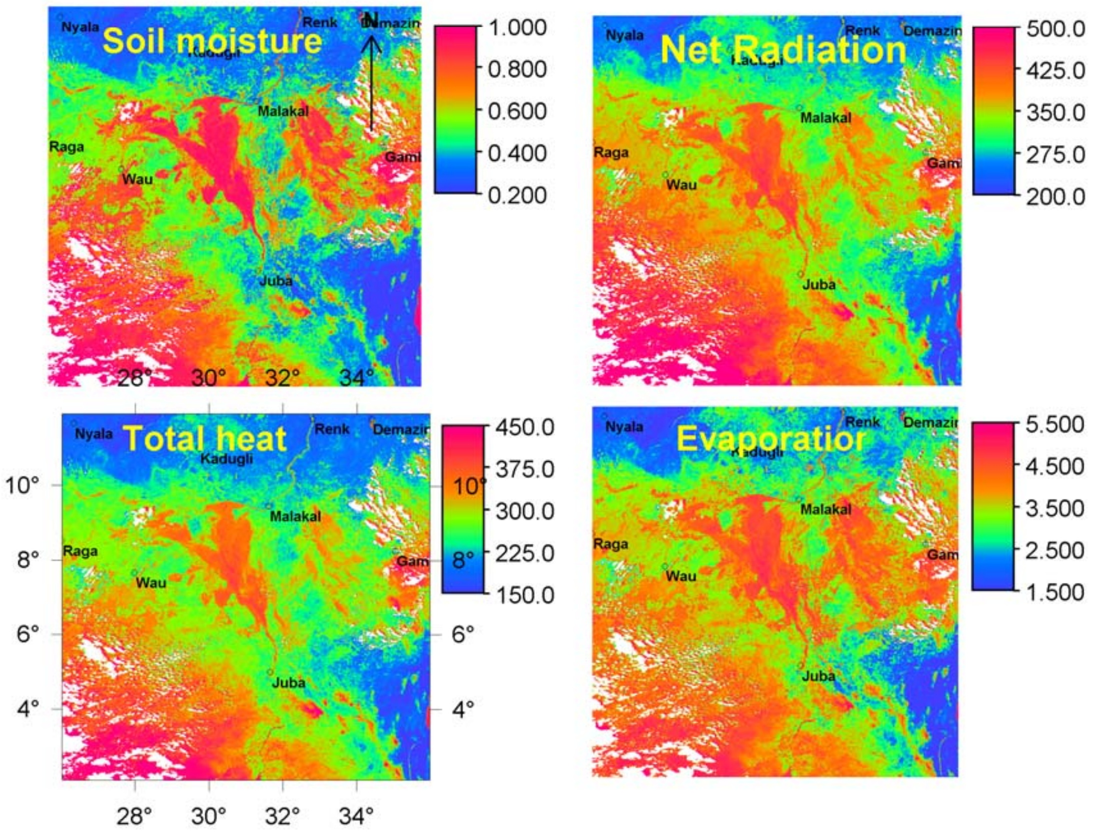

Fig. 2: Instantaneous Soil moisture (%), net radiation (W/m2), total heat (W/m2) and daily evaporation (mm/day) over part of the Nile Basin on 26/01/2000.

4. Methods to compute moisture recycling

Almost all researchers agree on the definition of moisture recycling, as the ratio of locally generated precipitation to the total precipitation, yet, different approaches are used to formulate the recycling method. In general, the methods in use to compute moisture recycling can fall in one of the following groups:

1. Methods based on the atmospheric moisture balance, (e.g. Budyko, 1974; Eltahir and Bras, 1996; Savenije, 1995). Data used in the calculations can be direct observations, reanalysis data, or pure results from numerical experiments.

2. Methods based on following trajectories of water molecules from source origin through the atmosphere and then as precipitation (e.g. Koster et al., 1986; Dirmeyer and Brubaker, 1999).

A summary is given below of some of the widely used methods.

1. The method derived by Budyko (1974), and extended into two dimensions in Brubaker et al. (1993) and Trenberth (1999), defines the recycling ratio β as, (see Fig. 1):

$$\beta = \frac{P_l}{P} = \frac{EL}{EL + 2F_{in}} = \frac{EL}{PL + 2F}$$

where "F_{in}" and "F_{out}" are the in and out moisture flux in a given domain of length L. The average flux along the domain "L" is "F" given by "$0.5(F_{in}+F_{out})$". The average horizontal advective flux is "$F_{in}-0.5P_aL$", where "P_a" is the precipitation component from the advected moisture. The horizontal flux of local origin is "$0.5(E-P_l)L$". The basic assumption is that the atmosphere is well mixed and the change of atmospheric moisture storage is negligible compared to the other terms. The recycling results of course depend on the length of the domain (L), which may involve the difficulty of defining the areal extent of the region. To avoid dependence on domain length, Trenberth (1999) computed the recycling ratio for the whole world based on two length scales 500 km and 1000 km, which allows comparison of the different regions.

2. Eltahir and Bras (1994) developed a recycling ratio based on conservation of mass of a control volume in the given region. Similar to Budyko's model, two basic assumptions are imbedded: the atmospheric moisture is well mixed, and the rate of change of atmospheric moisture is negligible on a monthly time scale. The spatially distributed moisture recycling ratio is defined as:

$$\beta = \frac{P_l}{P} = \frac{F_l + E}{F_l + F_a + E}$$

   where the flux moisture F_{in} into the control volume, e.g. into a model grid is composed of F_l (moisture flux from recycled moisture) and F_a (moisture flux of oceanic origin). E, P and P_l respectively are: evaporation, total precipitation and local precipitation in the control volume. For the whole region $\beta = E/(F_{in}+E)$, where E and F_{in} are the regional evaporation and inflow flux respectively.

   Through a different approach Eltahir (1998) described precipitation recycling through the relation between soil moisture condition and future rainfall. He proposed that the wet soil moisture condition over a large region should be associated with relatively large boundary layer moist static energy, which favours the occurrence of more rainfall. This is based on the fact that, the albedo and Bowen ratio of moist soil are higher, implying increased net available radiation at the surface, and hence increased heat energy from the surface to the planetary boundary layer.

3. Koster et al. (1986) used tracers of water molecules in General Circulation Model (GCM) simulations to trace the route of evaporated moisture from land surface through the atmosphere and then as precipitation on a different location. Results obtained could show the relative importance of the source regions to regional precipitation. However, as a typical modeling result, the accuracy is dependent on the model parameterization and the associated temporal and spatial scales.

4. Savenije (1996) assumes a Lagrangian movement of the air mass over the Sahel region, where he applies a one dimensional moisture balance of the atmosphere to define moisture recycling. In the rainy season, the net advective moisture along distance L is equivalent to the precipitation component from advection P_a, while local rainfall is equivalent to wet season evaporation E_w. It is assumed that $F_{out} << F_{in}$. Therefore moisture recycling over the rainy season is given by:

$$\beta = \frac{E_w}{P} = 1 - \alpha$$

where α is the loss coefficient from the system, which equals the runoff coefficient C_R plus the part of the rainfall which evaporates during the dry season e_d, $\alpha = C_R + e_d$. It is assumed that E_w is completely removed as precipitation, and no part leaves the region at the downstream end.

5. Schär et al. (1999) assume the feedback mechanism to be composed of two processes: direct (recycling), whereby extra precipitation is caused by addition of evaporative moisture into the atmosphere, and an indirect process (amplification), whereby extra precipitation, originating from outside the region is due to an enhanced precipitation efficiency caused by local evaporation. The recycling formula used over large regions (e.g. France) is:

$$\beta = \frac{E}{E + F_{in}}$$

This is the same as the Eltahir and Bras (1996) formula applied to a region, with the inflow flux at the boundary originated from local evaporation "F_l" is zero. Note the difference as compared to the formulae given in (Budyko, 1974; Brubaker et al., 1993; Trenberth, 1999). Implicit assumptions, which can be drawn from this formula, are: no part of evaporation is leaving the domain, since all E is consumed as local precipitation; total $P=E+F_{in}$, implies negligible atmospheric outflow moisture from the region.

One basic assumption in all these methods, is that the atmosphere is well mixed both temporarily and spatially (Budyko, 1974). Vertical mixing can be attained in a relatively short time compared to the advective time scales due to the planetary boundary layer turbulence (see e.g. Eltahir and Bras, 1994; Harris et al., 1988). However, in the horizontal direction the assumption of well mixing is weak because of the spatial variations of the atmospheric parameters (e.g. variations of temperature, humidity, local conditions) over a wide range of distances.

It should be emphasized (Brubaker et al., 1993; Trenberth, 1999; Eltahir and Brass, 1996) that the precipitation recycling ratio as defined above is a diagnostic measure that defines the contribution of local evaporation to local precipitation in a given climate condition. It has no prognostic value, i.e. it is not a fixed value for all climate conditions in a region, because of the non-linear relationship of precipitation and evaporation in the given climate system of a region. So quantitative results of moisture recycling should not be taken too literally.

If you know a method to compute moisture recycling not reported above, please forward to the discussion forum.

5. Case Studies

Worldwide, there are many studies aiming at quantifying the regional moisture recycling. Most of the studies showed increase of precipitation with increasing evaporation. However, there are substantial variations depending on the model used, data source, location and season of the year. Prove of the results with real life observations is restricted by the limitations of data availability and reliability. As a result it is not abnormal to find different recycling ratios for a given region e.g. for the Amazon or the Sahel computed by different researchers. Or even different results in the same basin, with the same input data, but using different definition of moisture recycling formula. E.g. Bosilovich and Schubert (2001) have computed two different summer time recycling ratios over the Central United States with exactly the same data set, by two methods: using Brubaker et al. (1993), the recycling ratio is 25%, and it is 36% using the Eltahir and Bras (1996) method.

In the following (Table 1) is presented a comparison of some of the results in the literature of the annual regional moisture recycling. See Fig. 3 for the approximate location of the regions. It should be emphasized that, most of these results were originally derived on monthly bases showing large seasonal variations, which were smoothened out in the annual results.

Table 1: Example of average annual moisture recycling over different regions

Basin	**Amazon**	**Mississippi**	**West Africa**	**Eurasia**[1]	**Method and data**
Budyko (1974)				11%	Budyko model along a streamline, and observed data of various sources.
Molion (1975)	56%				Based on the ratio of total evaporation to total precipitation in the Amazon basin.
Brubaker et al. (1993)	24%	24 %	31%	11%	Extended the 1 D Budyko model, and analyzed observations. West Africa is the Niger Basin.
Eltahir and Bras (1994)	25% 35%				Using spatially distributed recycling model, and two data sources: the ECMWF[2] gives (25%), and GFDL[3] gives 35%.
Savenije (1995)			63%		This is point recycling ratio in the Sahel, based on atmospheric and terrestrial water balance analysis. It is applicable during rainy season only.
Trenberth (1999)	34%	21%			Using spatial model based on 500 km length scale. Amazon length is 2750 km, and Mississippi is 1800 km. Data from CMAP[4], NVAP[5] and NCEP[6].

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[1] European part of the former Soviet Union
[2] European Centre for Medium-range Weather Forecasts
[3] Geophysical Fluid Dynamics Laboratory
[4] Climate Prediction Center Merged Analysis of Precipitation
[5] NASA Water Vapor Project
[6] National Centers for Environmental Prediction

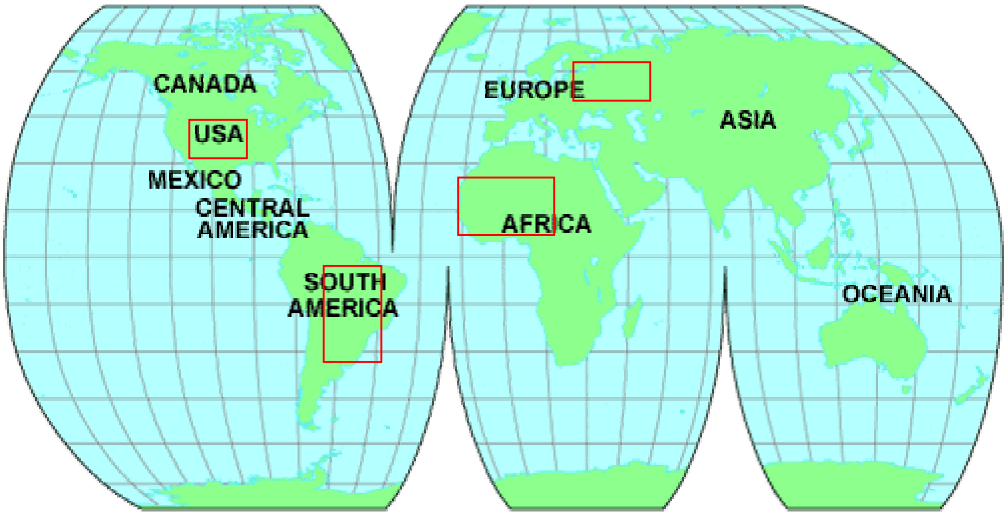

Fig. 3: Regions of calculated moisture recycling given in Table 1.

To compare the results of moisture recycling by the formulae given in section 4, we make use of the data on the annual hydrological cycle of the Amazon, Mississippi and the Sahel (see Table 2). The data on the Amazon were derived from ECMWF reanalysis data (Eltahir and Bras, 1996) and for the Mississippi are from (Benton et al. 1950). For West Africa the data were derived from the model of Savenije (1995). Numbers are yearly totals normalized by the yearly precipitation (index = 100). The calculated annual recycling ratio for the two basins are given in Table 2.

Table 2: Annual moisture recycling ratio over the Amazon, Mississippi and the Sahel by different methods.

Basin	**Amazon**	**Mississippi**	**West Africa**
Input data (annually)			
Fin	141	466	
Fout	99	444	
P	100 = 1950 mm	100 = 750 mm	100=870 mm
E	58	78	xx%
R	42	22	
Ew	58		63
Recycling ratio			
Brubaker et al., 1993; Trenberth, 1999	17%	8%	
Eltahir and Bras (1994)	29%	14%	
Savenije (1996)	58%		63%
Schär (1999)	29%	14%	

The method of Savenije (1996) given in section 4, which is E_w/P, could not be applied for the Mississippi as E_w is missing. E_w for the Amazon assumed similar to E. It is to be noted that there can be substantial spatial variation of the moisture recycling ratio within the basin itself. Based on the spatially distributed calculation of the recycling ratio for the 500 km length scales, Trenberth (1999) gives double the ratio for the Amazon and Mississippi basins (see Table 1). While Eltahir and Bras (1994), based on 2.5*2.5° grid, the recycling ratio (given in Table 1) is not very much different from the value of the basin as a whole (see Table 2). The annual recycling ratio as computed in Table 2 smoothened out substantial seasonal variations, e.g. Brubaker et al. (1993) computes for the Mississippi a ratio of 15% during the winter season, and up to 34% during the summer months.

Difficulties and constraints in attaining a unified result of moisture feedback are obvious, and due to several reasons. First, there are assumptions utilized in the methods that may not be fully satisfied in reality, e.g. most of the methods (Budyko, Eltahir, Savenije, Schär) assume a well mixed atmosphere in the region under consideration, implying that advected and evaporated moisture are well mixed. It is well possible that, at least horizontally, this assumption is not well justified, i.e. there can be variations in temperature, humidity, orographic effects, along the trajectory of atmospheric moisture. As moisture recycling is direcly dependent on the length of the domain, different results are obtained with different definitions of areal extents of the regions. This can be partly overcome through the use of spatially distributed computations (e.g. Trenberth, 1999).

Results of regional moisture recycling based on numerical experiments are limited to model validity in simulating the interaction process. Temporal and spatial resolution has direct impact on the results. Modeling results based on monthly data will ignore the diurnal cycle variation (Bosilovich and Schubert, 2001). Orography may not be captured by a model resolution of 5°*5° or even 2.5°*2.5°. The land surface-climate coupling schemes imbedded in the AGCM vary between the models, and hence will vary the derived results. In their comparison of the coupling strength in 4 AGCM's, Koster et al. (2002), showed significant variations among those models.

A continuing problem in the determination of moisture recycling and other hydroclimatological parameters as well, is the availability of data needed to compute the fields on which they are based. Error sources arise from both data sampling and analysis techniques. Despite of its extreme importance to the recycling process, soil moisture data is very scarce in the world: only limited localized sample observations are available. The use of remote sensing techniques for soil moisture measurements is only at its infancy (see e.g. http://lshp.gsfc.nasa.gov/Post2002/smm3.html#exec; van den Hurk, 2001) Because of data scarcity in many regions of the world, the reanalysis data may also reflect some of the model bias.

Although far more studies and model experiments support positive moisture feedback, there exist some studies concluding opposite results, or at least do not support positive moisture climate feedback. Giorgi et al. (1996) in their numerical experiments over the Central Unites States for the two climatic extremes (1988 drought and 1993 flood) found that the effect of local recycling of evaporated moisture is not important as compared to the large scale moisture fluxes and synoptic cyclonic activity. It is even concluded that a dry initial soil condition provides increased sensible heat flux, causing greater air buoyancy, enhancing convective systems and hence providing more precipitation (i.e. a negative moisture feedback process). The hypothesis of Eltahir (1989) that an increase of the wetlands area over part of the Nile Basin (Sudd and Bahr el Ghazal swamps) would favor increased rainfall over central Sudan, and also the argument of Eagleson (1986) that the evaporation from the Sudd would surely be felt climatically over a wider region, is argued by Sutcliffe (1999 p. 76) that there was no extra rainfall caused by the increase of the Sudd wetland area after 1961. Contemplating that a reduction of the wetland area (e.g. by Jonglei canal) is likely not to effect the rainfall in central Sudan or in the Blue Nile Basin. The area of the Sudd swamps was tripled in size after the 1961 high rainfall over the Lake Victoria.

6. Final Remarks

The water balance approach used in many studies to define regional moisture recycling is too simple to define accurately the physics of the land surface–climate interaction. Land surface climate interaction is a nonlinear and complex process. Still the available Soil Vegetation Atmosphere Transfer SVAT schemes used in the GCM can not capture the interaction appropriately, and significant differences in the coupling strength of the AGCM's were reported. It will be highly beneficial if the forum points out specific areas on land surface climate interaction for further research to better understand, and hence simulate moisture recycling in a more sound basis.

In weather prediction models, feedback mechanism may not be fully captured in current climate models, and thus may be responsible for part of the distortion in the precipitation patterns simulated by those models (Trenberth, 1999). This is a key problem in predicting the impacts of climate change on the earth water resources, which are primarily regional in scale and extent.

Over the land surface, the hydrological processes are not less complex than the interaction with the atmosphere. Landuse change, rainfall, evaporation, runoff and recharge of groundwater are closely interrelated. Vegetation affects the hydrological cycle in several ways: it contributes to the amount of evaporation in the region through interception and transpiration, and it indirectly affects the amount of infiltration to the groundwater storage and the runoff at the exit of the basin. Therefore, in addition to the research in the physics of moisture recycling, there is an important need for research into policy implications of the link between land and water use, climate and water resources availability. What are the good landuse/water resources management options that yield sustainable development and yet positive climate feedback.

We hope the forum to be a good opportunity to raise a discussion and share experience amongst scientists and practitioners on moisture feedback and its relevance to regional land and water resources management.

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