Numerical simulation of the geographical sources of water for Continental Scale Experiments (CSEs) Precipitation

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Koster et al. (1986) used passive tracers to follow incoming atmospheric water from surface evaporation through the atmosphere, until it was precipitated. In this way, the geographical source of water for all precipitation could be identified. While these simulations were very coarse ($8°\times10°$) and short duration (only one season long), the work demonstrated a methodology of numerical calculation of the local and remote sources of precipitation within the model's simulation. In this methodology, each source requires a new three-dimensional prognostic array in the General Circulation Model (GCM), which is often not feasible with limited computational resources. Since that study, the tracer methodology seen limited use (Druyan and Koster(1989) and Numagati(1999)). In recent years, there has been increasing focus on the atmospheric water cycle, especially with respect to the intensity and climate change of the regional water cycle (Morel, 2001). The water tracers provide a diagnostic link between evaporation, precipitation, moisture transport and the timescale that water resides in the atmosphere.

Recently, we have adapted the passive tracer methodology to the NASA Data Assimilation Office (DAO) Finite Volume GCM (FVGCM) to simulate the movement of regional sources of water (following Koster et al, 1986; and documented by Bosilovich and Schubert, 2002, in the NASA GEOS GCM). These passive tracers are termed Water Vapor Tracers (WVTs) because they simulate the model's water vapor prognostic variable at the model time step. The model dynamics and physics compute tendencies for the WVT in proportion to the model's water vapor. While the WVTs evolve according to the model dynamics and physical parameterizations, they are entirely passive, in that they do not affect the simulated hydrological cycle. Evaporation within a limited region is used as the source for a WVT. Figure 1 identifies 12 large-scale regions and each region represents a continental or oceanic source of water, in the form of evaporation, to the atmosphere. Following Bosilovich and Schubert (2002), we can diagnose the amount and location of precipitation that falls because of evaporation from each region.

The FVGCM uses semi-Lagrangian advection that is particularly useful for tracer calculation (Lin and Rood, 1996). The model uses the NCAR CCM3 physical parameterizations. We have run the FVGCM at $1°\times1.25°$ resolution for 15 years using real time varying SSTs from 1986-2000. In this paper, we present the simulation of large-scale continental and oceanic sources of water to precipitation in GEWEX Continental Scale Experiments (CSEs). The area of each CSE is defined identically to Roads et al (2002) (Figure 1). Table 1 shows the annual contribution to each CSE precipitation from the large-scale geographical region's evaporation. An exact estimate of precipitation recycling can not be identified in this table because the source regions are larger than the

CSEs. However, in all cases the local continental source of water is a major contributor to the precipitation. Some CSEs are relatively simple to understand, such as the MacKenzie River Basin where water comes either from the North American continent or from the Pacific Ocean. BALTEX seems to be more complicated with many sources of water contributing to precipitation, including European continental, North and Tropical Atlantic Oceanic and Polar (note that the Mediterranean Sea is included in Polar WVTs for convenience). Tibet and Lena are the only two CSEs where the continental sources of water exceed oceanic sources. Figure 2 shows the percentage of precipitation from continental sources over land. In general, coastal regions show less continental precipitation, especially where we would expect on-shore flow from the oceans. When averaged over all land points, 1.08 mm/day of precipitation from continental sources falls on land, while 1.50 mm/day precipitation from oceanic sources falls on land.

While the annual budgets of the moisture sources are useful, mean annual cycles can describe the seasonal variations of the moisture transport. Figure 3 shows the mean annual cycles of the major sources of each CSE. In the Mississippi River and MacKenzie River basins, the North American continental source dominates during summertime, while the winter Pacific Ocean source dominates. Likewise, BALTEX shows a transition from the local continental sources in summer to oceanic sources in winter. With its maximum Mississippi contribution in late summer, the tropical Atlantic Ocean has a smaller annual cycle than the Pacific Ocean. However, summertime precipitation is larger than winter, so the tropical Atlantic has a larger impact on the annual budget than the Pacific Ocean (Table 1). Continental sources for Amazonian precipitation are large throughout the year, but the oceanic sources vary with the seasonal change of the easterly flow. In the GAME Tropics region, the moisture sources shift from the Pacific Ocean to the Indian Ocean. Lena is largely dominated by the summertime Asia continental sources.

Figure 3 suggests that in some regions, significant amounts of water are transported very long distances. For example, the Asia continental source for the MacKenzie basin in summer, and the North American source for BALTEX must traverse entire oceans. While a map of moisture transport may suggest the possibility that these are potential sources, the tracers provide a quantitative diagnostic. This also raises the question of residence time of the atmospheric water in the GCM. To evaluate the residence time, we initialized a special WVT equal to the initial atmospheric water content, but provide no source at the surface. This allows the precipitation to deplete the WVT atmospheric water content in time without being replenished. Again, this WVT is a diagnostic and the simulated precipitation and hydrologic cycle continue normally. Figure 4 shows the time series of the WVT water content as it is depleted. Fitting the data points with an exponential curve shows that the e-folding time of the atmospheric water is 9.2 days. For this period, the global mean precipitation is 3.33 mm/day and the global mean total precipitable water is 24.9 mm, which suggests an moisture depletion estimate (e-folding time of the water content) of 7.5 days. Trenberth (1998) points out that this estimated value of depletion is quite sensitive and neglects moisture transport (inherently included in the WVT estimate).

The WVTs provide a diagnostic tool to evaluate the hydrologic cycle in atmospheric numerical models. The diagnostic considers the instantaneous evaporation and precipitation rates as well as transport processes. Such diagnostics should be useful in evaluating the water cycle of extreme conditions such as flood and drought, as well as the intensity of regional water cycles in climate change experiments. Of course, the quality of the WVT diagnostics depends on the veracity of the GCM simulation. At present, we are implementing the WVT diagnostics in the NASA DAO Data Assimilation System to evaluate real data case studies and the impact of water vapor assimilation on the hydrologic cycle. These diagnostics may be useful in other studies, such as synoptic meteorology, mesoscale meteorology and paleoclimatology. It may also be possible to validate the WVT diagnostic data with precipitation isotope data. (This work is partially sponsored by the GAPP PACS Warm Season Precipitation Initiative and the NASA Global Water and Energy Cycle Program)

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Table Caption

Table 1 Percentage of precipitation that occurs in each GEWEX CSE from each of the source regions in Figure 1. The sum of continental and oceanic sources are included for convenience. CSE Annual mean precipitation is included in mm/day. Boldface indicates values greater than 10%. The percentages are computed from time averaged WVT precipitation divided by time average total precipitation.

Figure captions

Figure 1 Colored regions indicate the large-scale source regions for each of 12 WVTs. The Sources are NA, North America; Sam, South America; Eur, Europe; Afr, Africa; AsA, Asia-Australia; Npa, North Pacific; Spa, South Pacific, Nat, North Atlantic; Tat, Tropical Atlantic; INO, Indian Ocean and Pol, Polar (both north and south are included in one WVT for convenience). The area of each CSE is outlined on the map, and is based on Roads et al. (2002).

Figure 2 Percent of precipitation over land that originated as continental evaporation, annually averaged over 15 years of simulation.

Figure 3 Mean annual cycle of the dominant sources of water that occurred as precipitation in each of the CSEs. Colors correspond to the geographical regions in Figure 1.

Figure 4 Model simulated globally averaged WVT with no evaporative sources (daily average) divided by the initial water (dots) and the exponential fit of the model data (line). While there are no sources to replenish the WVT, transport terms can move the water and precipitation depletes the water.

		Source Region													
		NA	SAM	AsA	Eur	Afr	Npa	Tat	INO	Sat	Nat	Spa	Pol	Cont	Oceanic	P(mm/dy)
GEWEX CSE	MRB	**39.7**	0.4	1.6	0.3	0.6	**30.1**	**22.9**	0.7	0.5	1.8	0.9	0.4	42.6	57.4	2.42
	MacKenzie	**26.8**	0.1	6.3	0.9	0.3	**60.1**	1.0	0.8	0.1	1.0	0.3	2.3	34.4	65.6	1.52
	Amazon	0.0	**43.5**	0.1	0.1	3.5	0.3	**13.5**	2.1	**34.7**	0.3	1.4	0.4	47.3	52.7	5.98
	BALTEX	5.8	0.1	1.6	**25.3**	1.2	4.2	**11.8**	0.3	0.2	**38.6**	0.1	**10.6**	34.0	66.0	2.44
	CATCH	0.5	0.9	0.8	1.4	**39.3**	0.9	**23.9**	9.5	**18.1**	1.2	0.4	3.2	42.8	57.2	2.70
	GAME Tr	0.1	0.1	**27.0**	0.4	1.9	**40.8**	0.6	**25.5**	0.3	0.2	2.8	0.4	29.5	70.5	4.75
	HUBEX	0.3	0.1	**46.6**	0.8	1.6	**32.8**	2.0	**12.2**	0.3	1.1	1.2	1.0	49.4	50.6	3.30
	Tibet	0.3	0.1	**51.8**	1.1	3.9	9.2	3.9	**26.4**	0.7	0.8	0.8	1.0	57.1	42.9	1.42
	Lena	2.2	0.0	**40.6**	**11.3**	1.6	**11.1**	4.7	1.3	0.1	**14.1**	0.1	**12.7**	55.7	44.3	3.80

Table 1

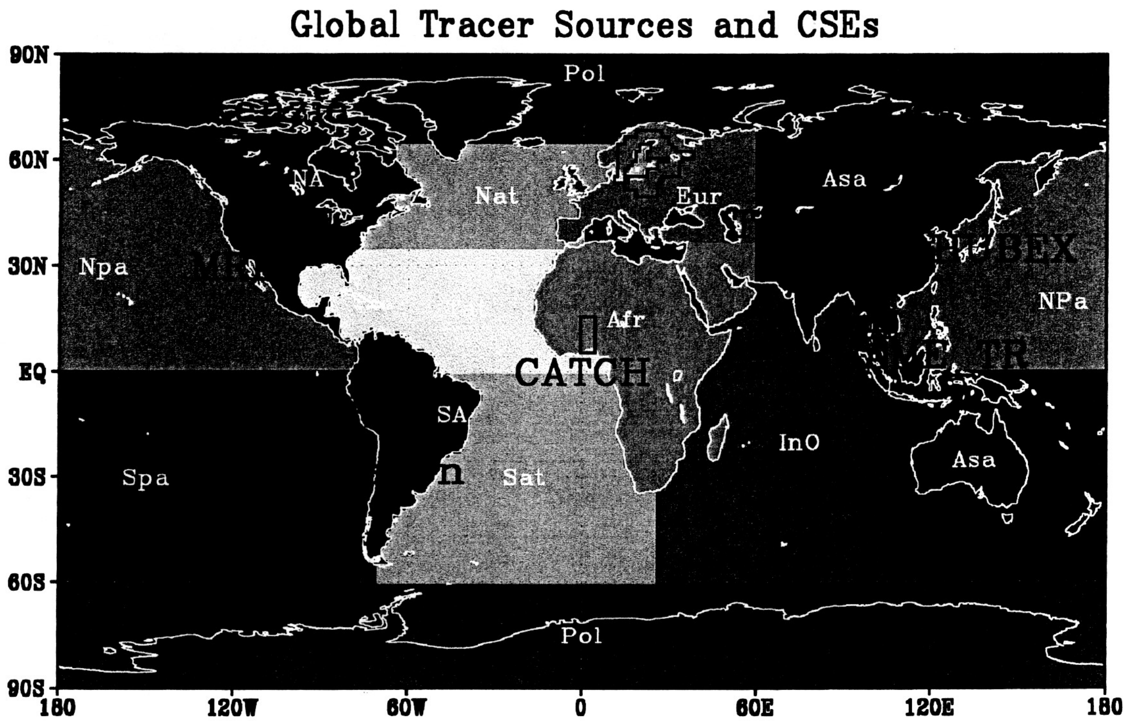


Figure 1

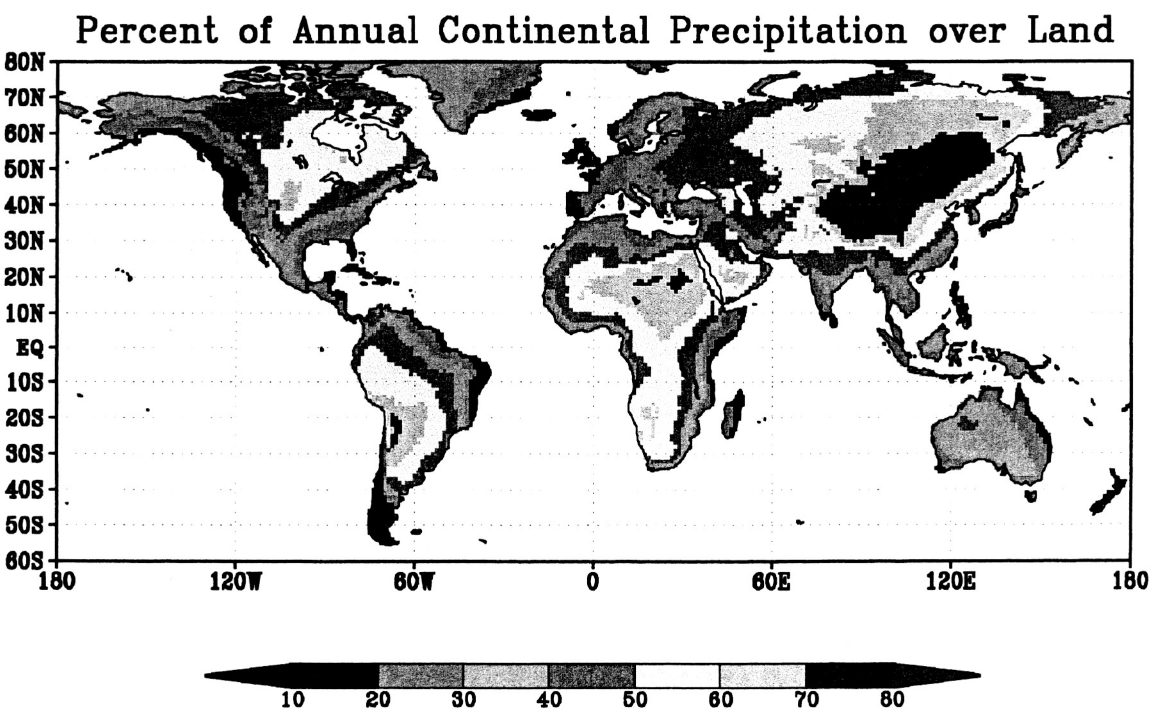
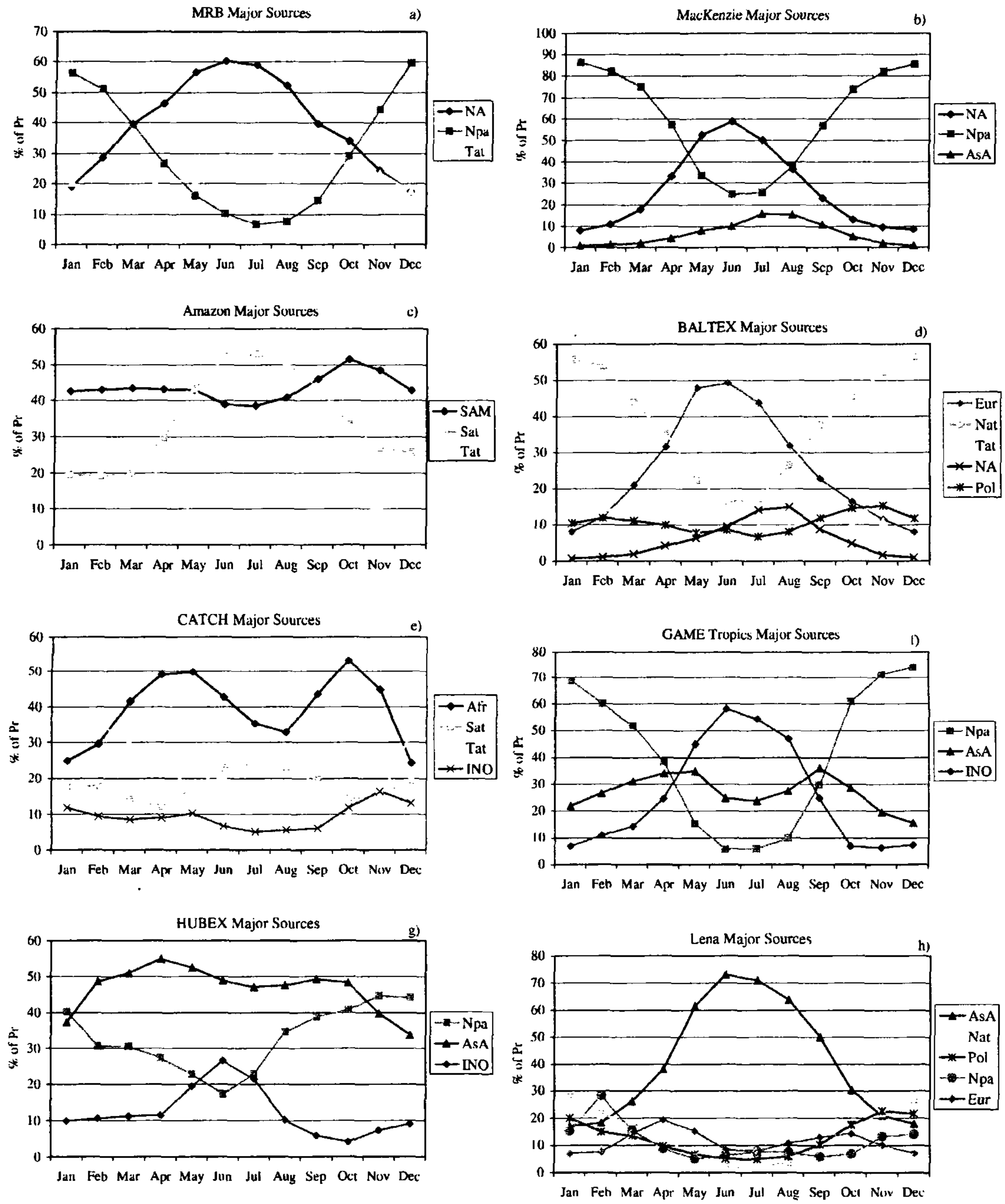
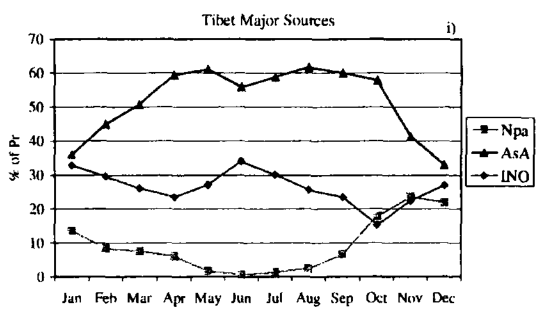


Figure 2





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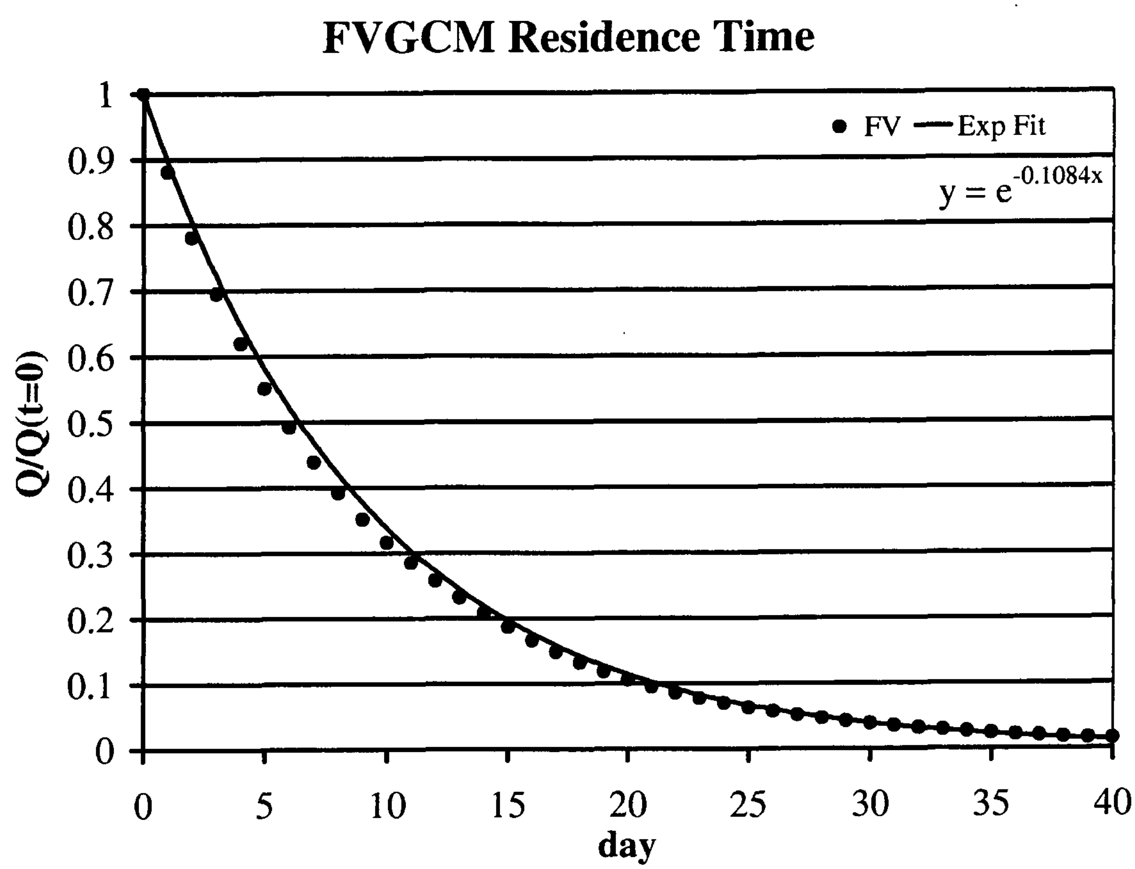
FVGCM Residence Time
FV
Exp Fit
$y = e^{-0.1084x}$
Q/Q(t=0)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
day

Figure 4

Popular Summary

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This short paper will be submitted to the Global Energy and Water Cycle Experiment (GEWEX) Newsletter.

There are several important research questions that the Global Energy and Water Cycle Experiment (GEWEX) is actively pursuing, namely: What is the intensity of the water cycle and how does it change? And what is the sustainability of water resources? Much of the research to address these questions is directed at understanding the atmospheric water cycle. In this paper, we have used a new diagnostic tool, called Water Vapor Tracers (WVTs), to quantify the how much precipitation originated as continental or oceanic evaporation. This shows how long water can remain in the atmosphere and how far it can travel. The model-simulated data are analyzed over regions of interest to the GEWEX community, specifically, their Continental Scale Experiments (CSEs) that are in place in the United States, Europe, Asia, Brazil, Africa and Canada.

The paper presents quantitative data on how much each continent and ocean on Earth supplies water for each CSE. Furthermore, the analysis also shows the seasonal variation of the water sources. For example, in the United States, summertime precipitation is dominated by continental (land surface) sources of water, while wintertime precipitation is dominated by the Pacific Ocean sources of water. We also analyze the residence time of water in the atmosphere. The new diagnostic shows a longer residence time for water (9.2 days) than more traditional estimates (7.5 days). We emphasize that the results are based on model simulations and they depend on the model's veracity. However, there are many potential uses for the new diagnostic tool in understanding weather processes and large and small scales.