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Detection of intensification of the global water cycle: the potential role of FRIEND

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Abstract Diagnostic studies of 14-year, $2 \times 2°$, Variable Infiltration Capacity (VIC) model off-line simulations of the global terrestrial water budget suggest that, given the annual variability in the major components of continental hydrological cycles (precipitation, evaporation, and runoff), several decades to perhaps centuries of measurements may be needed to detect with high confidence the intensification predicted by recent global climate model (GCM) studies simulating plausible global warming scenarios. Furthermore, these measurements may need to originate from a wider geographic expanse than is currently investigated within large-scale hydrological assessment programmes, such as the Global Energy and Water Experiment (GEWEX). Smaller, geographically dispersed basins, including many of those participating in the International Flow Regimes from International Experimental and Network Data (FRIEND) programme, could therefore play important roles in detection of an intensification in the global water cycle.

Key words climate change/variability; trend detection; hydrological cycle acceleration

INTRODUCTION

Based on plausible scenarios of atmospheric concentrations of greenhouse gases and aerosols, the mean annual global surface temperature is projected to increase 1–3.5°C by 2100 (Intergovernmental Panel on Climate Change, 2000). Two fundamental questions related to global warming are: (a) will the global hydrological cycle accelerate in response, and (b) where will the effects of an accelerated system, if any, manifest. Many global climate model (GCM) studies predict that over the next century warming will lead to increases in global precipitation (P) and evaporation (E) (e.g. Fig. 1, Table 1). Detection of acceleration in the hydrological cycle requires an understanding of variability in present-day water cycle components over a range of regional-to-continental scales. A key to early detection may be identifying indicator basins worldwide that collectively describe the statistical nature of the current hydrological cycle. If such basins exist, then monitoring them for change might be more feasible than examining the global or continental hydrological cycles as a whole.

In this paper, we report on diagnostic studies of global terrestrial water budget simulations using: (a) the Variable Infiltration Capacity (VIC) model (Liang *et al.*, 1994, 1996) and (b) the Parallel Climate Model (PCM). The studies are directed
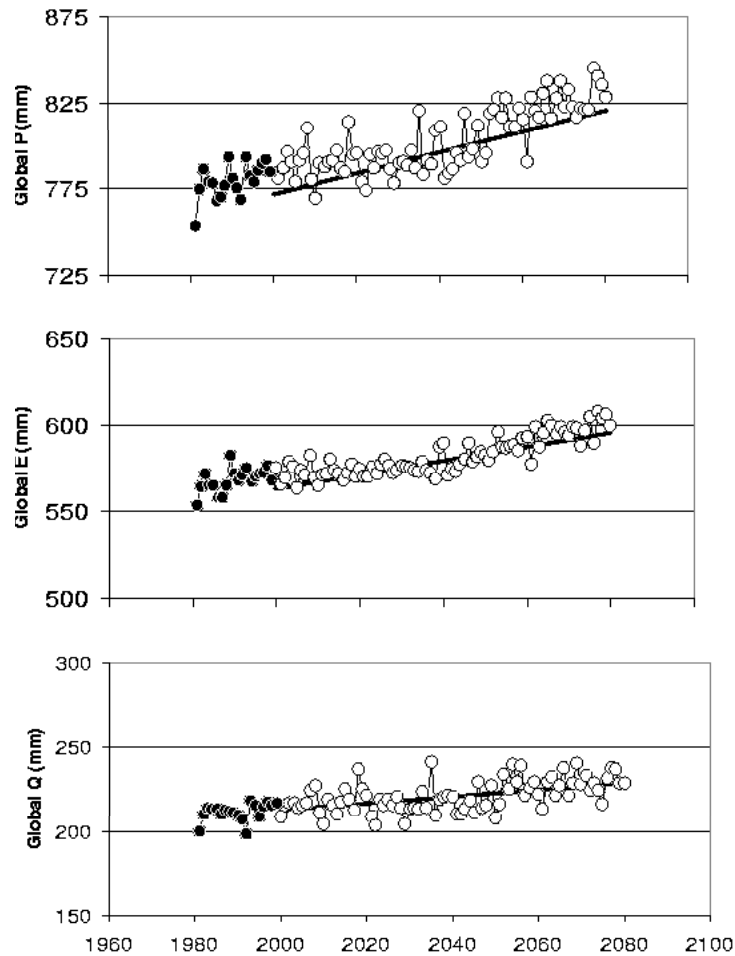
Fig. 1 Yearly, global terrestrial precipitation (*P*), evaporation (*E*) and runoff (*Q*) estimates from PCM model run B06.20 for the period 1980–2080 (interpolated to, then averaged over the VIC 2 × 2° grid domain). Trends were determined for the period 2000–2080 (open circles). The solid line is the Kendall–Thiel Robust Line (nonparametric slope, Helsel & Hirsch, 1992), for which each slope is the magnitude of the trend: 0.61, 0.42, and 0.21 mm year^{-1} for *P*, *E* and *Q*, respectively.

toward (i) determining the variability in continental-scale *P*, *E* and runoff (*Q*); (ii) estimating the minimum number of years required to detect *P*, *E* and *Q* trends predicted in a recent PCM simulation of a plausible global warming scenario; and (iii) identifying several indicator basins within each continent that *collectively* mimic the statistical nature of the continental hydrological cycle.

METHODS

Trend detection

We examine the global, terrestrial (excluding Greenland and Antarctica) hydrological cycle simulations conducted by Nijssen *et al.* (2001). The simulations use daily observed *P* to drive VIC in calculating *E* and *Q* at a 2° resolution for the period 1980–1993. We employ a straightforward approach for estimating the minimum number of

Table 1 (a) Means and standard deviations (φ_ε) for VIC model precipitation (*P*), evaporation (*E*) and runoff (*Q*); (b) continental and global land surface trends (τ) predicted by PCM run B06.20 for 2000–2080; and (c) the minimum years (n_{min}, equation (3)) required to detect significantly ($\alpha = 0.05$, $\beta = 0.10$) each corresponding τ.

	Africa	Asia	Europe	North America	Oceania	South America	World
P							
Mean (mm year^{-1})	655	590	769	633	680	1449	727
φ_ε (mm year^{-1})	49.5	19.1	27.4	20.9	52.0	53.5	16.1
τ (mm year^{-1})	0.32	0.65	0.54	0.78	0.73	0.68	0.61
n_{min} (years)	143	48	69	45	86	92	45
E							
Mean (mm year^{-1})	537	330	484	375	486	876	459
φ_ε (mm year^{-1})	24.9	9.1	12.0	8.8	28.9	18.4	7.9
τ (mm year^{-1})	0.33	0.39	0.46	0.42	0.51	0.45	0.41
n_{min} (years)	89	41	44	38	51	34	36
Q							
Mean (mm year^{-1})	121	260	280	256	193	572	267
φ_ε (mm year^{-1})	16.8	12.8	24.7	14.6	29.4	39.7	10.9
τ (mm year^{-1})	0.05	0.26	0.06	035	0.27	0.23	0.21
n_{min} (years)	240	67	274	60	114	154	70

years required to detect trends in continental water cycle variables. This methodology utilizes: (a) the "natural" variability in *P*, *E* and *Q*, as determined from VIC water balance simulations; (b) PCM-predicted trends in *P*, *E* and *Q* for the first 80 years of the twenty-first century; and (c) statistical equations for determining the probability (β) of committing a type II error in one-sample testing.

For the typical hypothesis testing problem one often compares a null hypothesis (H_0: an event has *not* occurred) with an alternative hypothesis (H_1: an event has occurred). The *t*-test statistic is sometimes used to "chose" between H_0 and H_1, particularly for normally distributed data. The probability of choosing H_0 when H_0 is true is $1 - \alpha$; and the probability of choosing H_1 when H_1 is true is $1 - \beta$. These two probabilities are referred to, respectively, as (a) the confidence level of the test and (b) the power of the test. Trend detection is a special case of the hypothesis testing problem, for which the event in question is a trend. Power, which varies with record length, trend magnitude, and the distribution/form of the time series (see Lettenmaier, 1976, for a discussion on dependent *vs* independent series) plays an important role in trend detection because it gives the probability of detecting a trend at a fixed confidence level.

For the trend detection problem, the power of the test is given by the following equation (cf. Lettenmaier, 1976):

$$1 - \beta = 1 - F_x\left(W_{1-\alpha/2} - \frac{|\tau_{min}|}{\text{var}(\hat{\tau})^{1/2}} \right) \tag{1}$$

where $1 - \beta$ is the power of the *t*-test; F_x is the cumulative normal distribution; $W_{1-\alpha/2}$ is the normal deviate at cumulative probability $1 - \alpha/2$; τ_{min} is the minimum detectable trend per year for the time series in question (*P*, *E* or *Q*); and $\text{var}(\hat{\tau})$ is the variance of

the time series residual computed over n years of observation, calculated as:

$$\text{var}(\hat{\tau}) = \frac{\sigma_\varepsilon^2}{\sum_{i=1}^{n} (t_i - \bar{t})^2} \tag{2}$$

where σ_ε^2 is the variance of the "noise process" (assumed to be equal to the sample variance of the time series); values of t_i represent each year of data; and $\bar{t}$ is the mean year.

By re-arranging equation (1), the minimum number of years ($n_{\min}$) needed to detect a trend for a specified significance level α and power $1 - \beta$ can be derived iteratively from the left-hand side of the following:

$$\sum_{i=1}^{n_{\min}} (t_i - \bar{t})^2 = \frac{\sigma_\varepsilon^2}{\tau^2} \left(W_{1-\alpha/2} - W_\beta \right)^2 \tag{3}$$

where τ is the trend magnitude, determined from the PCM-predicted annual time series; σ_ε^2 is calculated from the VIC water balance simulation forcing/output; and W_β is the normal deviate at cumulative probability β. To clarify our detection framework, α can be regarded as the probability of detecting intensification when there is none; β, the probability of not detecting intensification when it is indeed occurring.

For each of P, E and Q, $n_{\min}$ is calculated for τ values derived from run B06.20 of the USA Department of Energy (DOE) Parallel Climate Model (PCM, www.cgd.ucar.edu/pcm/). These simulations correspond to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) "global warming" scenario A2, which is included in the Third Assessment Report of IPCC (Intergovernmental Panel on Climate Change, 2000); A2 is generally regarded a worst-reasonable-case scenario. We first interpolate the PCM P and E fields (Gaussian grid, 128×64 cells, roughly 2.8°) to the VIC model $2 \times 2°$ grid domain (land areas only), then average over the same cells used in the Nijssen simulations. Discharge (not available for PCM runs) is calculated as $P - E$, or "residual discharge", for which we assume the year-to-year changes in soil moisture are negligible. For all variables, values of τ are calculated for the 81-year period 2000–2080 as the Kendall–Thiel Robust Line (nonparametric slope, Helsel & Hirsch, 1992).

Indicator basins

To investigate the existence of hydrological indicator basins, we select n grid cells (equal to 5% of the grid cells comprising each continent), for which the mean of the 14-year monthly VIC P time series is "closest" to the continental mean. Closeness is quantified by calculating the mean squared error for all the months ($T = 180$) in P time series:

$$\text{MSE} = \frac{1}{T} \sum_{t=1}^{T} \left(\bar{p}_{\text{all\_cells},t} - \bar{p}_{n,t} \right)^2 \tag{4}$$

where $\bar{p}$ is the mean precipitation of the grid cells comprising either the entire continent (all_cells) or the n indicator basins (5% for each continent). Prior to calculating MSE, we normalize all data by dividing by the largest value in the 180-month time series. The n indicator "basins" (here, simply $2 \times 2°$ grid cells) are determined using a genetic-type algorithm (A C++ Library of Genetic Algorithm Components; http://lancet.mit.edu/ga/) that generates a set of solutions to the objective function represented by equation (4). Each solution is analogous to a binary strand of genetic material, having an associated MSE value. New generations of solutions are created by "mating" two of the better solutions, and by allowing mutations (solutions chosen at random). Our potential indicator basins are those producing the lowest MSE after 10 000 generations.

RESULTS AND DISCUSSION

Assuming that the variability in the VIC P, E and Q forcing/output data are consistent with their "real-world" counterparts, data records having lengths of the order of decades to more than a century are needed to detect (significantly) the magnitude of trends that are predicted to occur if continental hydrological water cycles are intensified by projected global warming (Table 1). For example, if 0.3–0.8 mm year^{-1} increases in P were to occur over the six continents during the next 80 years, roughly 40–140 years of data are needed to detect this change, with Africa, South America, and Oceania requiring the longest records for detection.

An important factor affecting the time required to detect significantly intensification in the global water cycle is the level of risk one is willing to accept in making the determination. For instance, the estimates of $n_{\min}$ reported in Table 1 are calculated using low values for the probability of making type I and II errors (i.e. $\alpha = 0.05$, $\beta = 0.10$). These conservative criteria equate to a "low risk" of: (a) detecting intensification when it is not occurring, and (b) not detecting intensification when it is occurring. If we allow α and β to increase (i.e. if we increase the risk of making an error in detection), $n_{\min}$ decreases to time periods that may be more conducive for making prompt policy decisions regarding global warming.

Currently there are several large-scale experimental watershed studies conducted within the GEWEX framework that are dedicated, in part, to understanding variations in regional hydrological processes and their response to environmental changes, including anthropogenic warming. Although GEWEX objectives likely include gathering data useful for detection of intensification of the global water cycle (cf. Morel, 2001), the locations of our hydrological indicator basins (again, based initially on precipitation only) suggest that the geographical extent of the GEWEX basins may not span sufficient biomes or climate zones to allow for the most rapid detection possible of continental-scale hydrological changes. In Fig. 2, our indicator basins are shown to be widely distributed across the continents, with many located outside the boundaries of principal GEWEX-related projects (Baltic Sea Experiment (BALTEX), GEWEX Asia Monsoon Experiment (GAME), GEWEX Continental-Scale International Project (GCIP), Large-Scale Biosphere–Atmosphere Experiment in the Amazon (LBA), and the Mackenzie GEWEX Study (MAGS)) and the GEWEX-
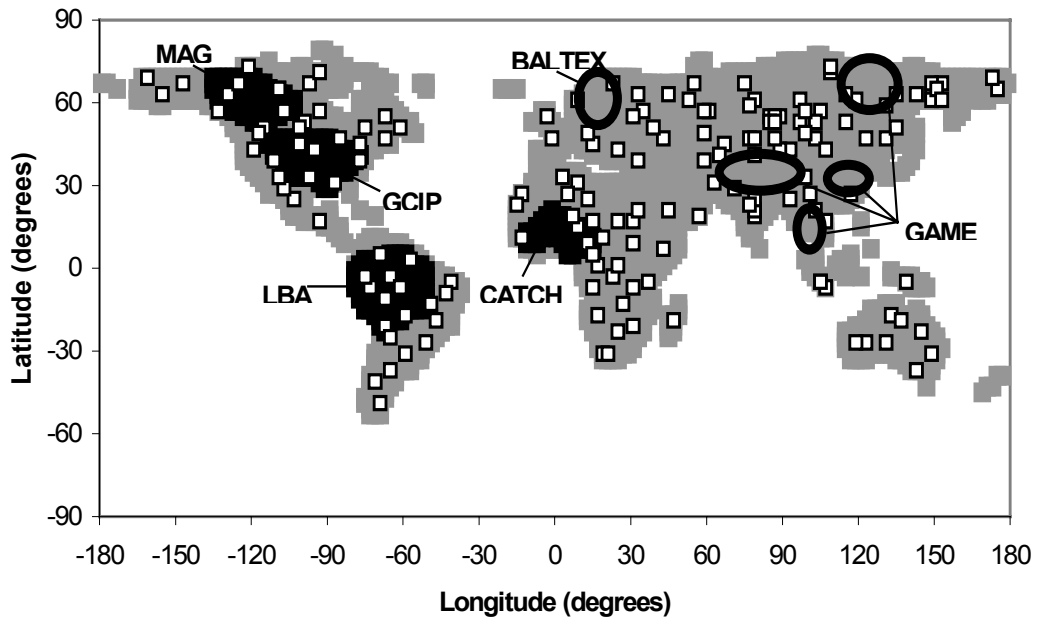
Fig. 2 For each continent, the *n* grid cells that most closely describe (collectively) the statistical nature of the continental precipitation during the period 1979–1993. Africa, Asia, Europe, North America, Oceania, and South America, have 31, 62, 18, 34, 9, and 19 cells, respectively. MSE errors (from equation (4)) for each continent are: Africa, 0.000 79; Asia, 0.016 47; Europe, 0.005 85; North America, 0.000 39; Oceania, 0.003 02; and South America, 0.003 07. Land areas shown correspond to the 2 × 2° grid cells in the VIC model domain. Each indicator basin location corresponds to a unique VIC grid cell; apparent overlaps result from using an exaggerated symbol size for better visualization. The indicator basins are shown in reference to principal continental-scale GEWEX projects.

affiliated Coupling Tropical Atmosphere and Hydrologic Cycle (CATCH) project. Detecting and understanding the hydrological consequences of global warming may, therefore, be improved through the collaboration of GEWEX with small watershed studies (e.g. each smaller than 2° grid cells). In this respect, many current/proposed FRIEND watersheds could play important roles in the evaluation of continental hydrological changes, in addition to addressing their current objectives of improving understanding of spatio-temporal variability in regional hydrological systems, and aiding in the development of international hydrological science.

CONCLUSIONS

Variability in VIC model *P*, *E* and *Q* forcing/output data suggest that several decades to more than a century of measurements may be needed to the detect an intensification of continental water cycles, as predicted by GCM studies simulating greenhouse gas-enhanced global warming scenarios. Hydrological assessment programmes such as GEWEX, which are a vital first step to assessing/detecting global hydrological changes, may not alone cover a large enough geographical expanse to detect rapid changes to continental-scale hydrological cycles. Smaller experimental watersheds, such as those participating in FRIEND, along with emerging remote sensing techniques, potentially play important roles in detecting an intensification in the global water cycle.

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