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Simulated 21st century changes in regional water balance of the Great Lakes region and links to changes in global temperature and poleward moisture transport

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[1] Simulations from eight climate models and two greenhouse gas emission scenarios are used to investigate changes in the hydrologic budget of the Great Lakes region of North America and the links to large-scale hemispheric/global changes. The ensemble average simulations indicate that increased net moisture (increased P-E) for the Great Lakes area is associated with a general increase in poleward moisture transport, which in turn is highly correlated with the sensitivity of each climate model to greenhouse-gas induced warming as measured by the global average increase of temperature. **Citation:** Kutzbach, J. E., J. W. Williams, and S. J. Vavrus (2005), Simulated 21st century changes in regional water balance of the Great Lakes region and links to changes in global temperature and poleward moisture transport, *Geophys. Res. Lett.*, *32*, L17707, doi:10.1029/2005GL023506.

1. Introduction

[2] Changes of temperature and water balance for the Great Lakes region and surrounding area may occur in response to increases in atmospheric CO_2 concentration. Both temperature (T) and precipitation (P) are likely to increase [*Gleick*, 2000]. The link between increased temperature and increased evaporation (E) has led to concern that lake levels and water resources might decrease [*Lofgren*, 2004]. However, the relative magnitudes of precipitation and evaporation increases vary from model to model, thus leaving uncertain the direction of change of the annual water balance. Most studies have employed regional energy and hydrologic budget models specifically designed for the Great Lakes basin, in conjunction with certain input variables from global climate models or climate scenarios for greenhouse gas increases [*Croley et al.*, 1998; *Kunkel et al.*, 1998]. The sign of the hydrologic budget change simulated by a regional model can depend upon the formulation of the global climate model; in one case, input variables from a global climate model that included lake/atmosphere interactions produced regional water balance increases [*Lofgren et al.*, 2002; *Lofgren*, 2004]. However, the causes of the uncertainty in the sign of net water balance change in the Great Lakes region remain poorly understood.

[3] One underlying large-scale dynamical feature of global warming simulations, first noted by *Manabe and Stouffer* [1980] and *Manabe and Wetherald* [1980], is that warming is accompanied by an increase in total atmospheric water vapor content and by an increase in poleward transport of water vapor across midlatitudes. This increased northward transport in turn implies a net convergence of water vapor in middle and polar latitudes (increased annual P − E or runoff, R) and a corresponding net divergence of water vapor in the subtropics (decreased P − E or R). The boundary between the opposite changes in water balance (wetter in the north, drier in the south) is somewhere in the midlatitudes, i.e., in the general latitude of the Great Lakes. In this region and elsewhere, regional circulations and processes can locally offset this large-scale pattern.

[4] This study uses global climate simulations from eight models for two emission scenarios to investigate both the water balance changes in the Great Lakes region and the links between the regional changes and the large-scale changes in temperature and poleward moisture transport. The ensemble average water balance for the Great Lakes region increases, and this increase is linked to increased moisture convergence north of 42–43N, i.e., in the vicinity of the Great Lakes. Intermodel variability in net water balance is due in part to the Great Lakes region being close to the crossover latitude separating more northern regions (trending wetter) from more southern regions (trending drier), and in part to differences in treatment of atmosphere/lake interactions by the various models.

2. Methodology

[5] We examined climate simulations for two emission scenarios produced for the Fourth Assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4); the eight models used for each scenario are listed in Table 1. The two scenarios, SRES A2 and B1, provide high-end (850 ppmv) and low-end (540 ppmv) projections of greenhouse gas concentrations. The greenhouse gas concentration in the A2 scenario has not stabilized by 2099 whereas the concentration in the B1 scenario has. Each model is represented by a single realization per scenario, which was chosen at random when multi-member ensembles were available. Climatic means were computed for the periods 1980–1999 and 2080–2099, with climate change defined as the difference between the two 20-year means. The results are reported as eight-member ensemble averages.

[6] We summarized climate statistics for the region extending from 95W to 75W and from 35N to 55N. This region includes the Great Lakes Basin, bounded between 40 and 50N, and adjacent lands to the north and south (Figure 1). Using the larger area has the advantage of

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Table 1. Models Used[a]

Model Name	Modeling Group	Citation
CCSM3	National Center for Atmospheric Research	*Collins et al.* [2005]
CSIRO-Mk3.0	CSIRO Atmospheric Research	*Gordon et al.* [2002]
ECHAM5/MPI-OM	Max Planck Institute for Meteorology	*Roeckner et al.* [2003]
GFDL-2.1	US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	*Delworth et al.* [2005]
GISS-ER	NASA/Goddard Institute for Space Studies	*Schmidt et al.* [2005]
IPSL-CM4	Institut Pierre Simon Laplace	*Marti et al.* [2005]
MRI-CGCM2.3.2	Meteorological Research Institute	*Yukimoto et al.* [2001]
PCM	National Center for Atmospheric Research	*Washington et al.* [2000]
UKMO-Had3	Hadley Center for Climate Prediction and Research/Met Office	*Gordon et al.* [2000]

[a] Scenarios A2 and B1 were available for seven of the nine models. The B1 scenario was available for the CCSM3 and the A2 scenario was available for the CSIRO model. Other models are contributing to the IPCC assessment but results from other models for these scenarios were not available in time for this study. Four models reported fractional lake area information. Two models (GISS-ER, UKMO-Had3) reported lake ice changes.

calculating changes over a reasonably large domain. We also calculate the global average temperature change and the zonally-averaged poleward moisture transport to enable us to compare regional changes with large-scale hemispheric/global changes.

[7] In the Great Lakes region, we examined surface air temperature (T), precipitation (P) and evaporation (E); we also examined soil moisture and runoff when available. The climate models differed somewhat in grid resolution, but a resolution of 2.8 degrees latitude by 2.8 degrees longitude was typical; at this resolution Great Lakes water in a particular grid cell could be represented by a water fraction, with appropriate atmosphere/lake interactions included. Four models reported fractional lake area information; if atmosphere/lake interactions were included in the simulations, we used the combined (fractionally-weighted) surface hydrologic budget for the land and water portions of the model grid cells. Information about lake ice changes and the nature of cold air outbreaks are useful to assess changes in wintertime evaporation from the lakes [*Croley et al.*, 1998]. Only two models (Table 1) included output on lake ice changes and these simulated maximum decreases in winter/spring lake ice cover of 30 and 90%, amounts consistent with decreases calculated by a regional model [*Lofgren et al.*, 2002].

3. Annual Average Comparison of Simulations With Observations

[8] We compared the AR4 simulations with observations (1961–2000) [*Climate Research Unit* (*CRU*), 2002]. The simulated ensemble averages of annual T (5C) and P (2.5 mm/day) for years 1980–1999 for the Great Lakes region (Table 2 and Figure 1) are close to the CRU observations: T (6.3C), P (2.5 mm/day). The simulated (and observed) annual precipitation (about 900 mm) is only slightly higher than the estimated annual precipitation for the Great Lakes Basin (about 820 mm) [*U. S. Environmental Protection Agency* (*EPA*), 1995].

[9] The simulated annual P-E for the Great Lakes region is positive for all models; the average value is 0.8 mm/day

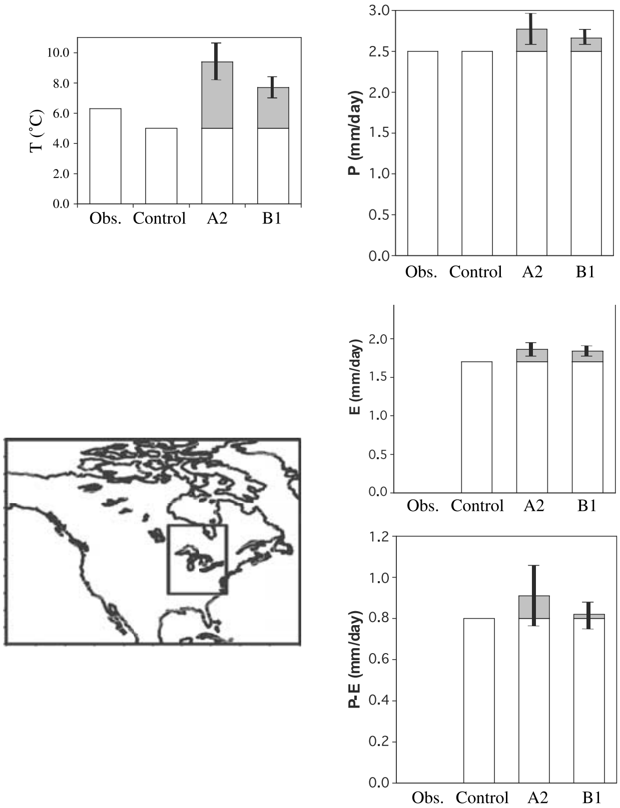

Figure 1. Annual average T, P, E, and P -E for the Great Lakes region (area enclosed within rectangle in North America; lower left). The annual average observations (Obs.) are from *CRU* [2002]. The eight-model ensemble average climate simulations of annual T and P (Control) are for the period 1980–1999. The ensemble average changes in annual T, P, E, and P-E are indicated in gray for emission scenarios A2 and B1 (see text); based upon differences in 20-year means (2080–2099 minus 1980–1999). Variability about the ensemble average is indicated by the standard deviation.

Table 2. Comparison of Annual Average Observations and Eight-Model Ensemble Annual Average Simulations for 1980–1999 for the Great Lakes Region[a]

	Obs.	Control	Std. Dev.
T, C	6.3	5.0	1.3
P, mm/day	2.5	2.5	0.4
E, mm/day		1.7	0.2
P-E, mm/day		0.8	0.3

[a] Obs are from *CRU* [2002]. The simulated control values are from 1980–1999. The standard deviation about the ensemble average is also indicated.

and the range is from 0.4 to 1.2 mm/day (Table 2). Annual P-E is nearly identical to annual R (available for most but not all models). The annual P-E (290 mm) is nearly identical to the estimated net basin supply for the Great Lakes Basin (about 300 mm) [*EPA*, 1995].

4. Annual Average Response to CO_2 Increases

[10] The ensemble average increase of T for the region is 4.4C for the A2 scenario and 2.7C for the B1 scenario, with all models simulating increases (Table 3 and Figure 1). The increase of P is 11% for A2 and 6% for B1, with seven of the eight models simulating increases (the increases were significant at the 5% level or higher (t-test), the one decrease was not statistically significant). The increase of E is 9% for A2 and 8.5% for B1, with all eight models simulating increases. The moisture balance (P-E) increased 14% (0.11 mm/day) for A2 but only 3% (0.02 mm/day) for B1 (Table 3 and Figure 1). P increased more than E for 6 of 8 models for A2, and for 4 of 8 models for B1. The increased P-E for A2 is statistically significant (t-test, 5% level). Changes in annual R, available for some but not all models, were nearly identical to the changes in annual P-E, implying minimal rates of change in annual soil moisture or other storage.

5. Links Between the Regional and Large-Scale Changes

[11] We used changes in global average temperature and poleward moisture transport to evaluate the relationship between these variables that was noted by *Manabe and Stouffer* [1980] and *Manabe and Wetherald* [1980] and described in the Introduction.

[12] The ensemble average global temperature increase is 2.9C for A2 and 1.7C for B1. Correspondingly, the change in zonal and annual average P-E (Figure 2) shows increased moisture in middle and polar latitudes of both hemispheres, and in the equatorial zone, and decreased moisture in the subtropics. This pattern implies increased moisture convergence at both high and low latitudes and increased moisture divergence in the subtropics. The area-weighted increase in annual and zonal average P-E from the North Pole to 42N (the crossover latitude) is 0.14 mm/day for A2 and 0.08 mm/day for B1 (Figure 2). This increase in P-E provides an index of the increase in poleward moisture transport across 42N: an increase of 19% for A2 compared to 10% for B1. These changes in P-E (Figure 2) are very similar to the changed distribution of zonal-average P-E reported by *Manabe and Stouffer* [1980].

Table 3. Eight-Model Ensemble Average Changes in Annual T, P, P-E for Emission Scenarios A2 and B1 for the Great Lakes Region[a]

	A2	Std. Dev.	B1	Std. Dev.
ΔT, C	4.4	1.2	2.7	0.7
ΔP, mm/day	0.27 (11%)	0.20	0.16 (6%)	0.10
ΔE, mm/day	0.16 (9%)	0.10	0.14 (8%)	0.06
ΔP–E, mm/day	0.11 (14%)	0.14	0.02 (3%)	0.07

[a] Water budget changes are indicated in percent. Variability about the ensemble mean is indicated by the standard deviation.

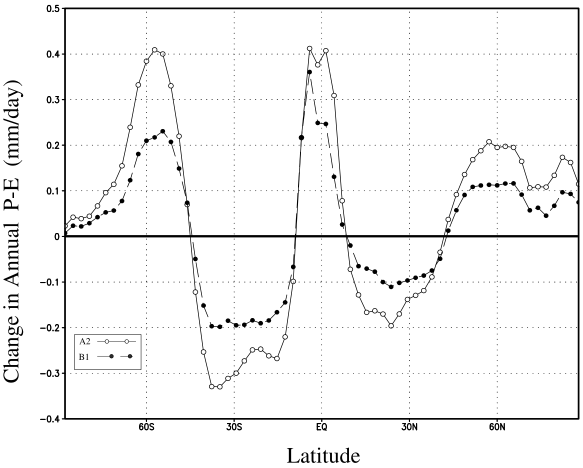

Figure 2. Change in annual average and zonal average P-E for eight-member ensembles of simulations for emission scenarios A2 and B1; based upon differences in 20-year means (2080–2099 minus 1980–1999).

[13] The zonal-average crossover latitude (42–43N) separating the changes toward wetter or drier climates is not uniform for all longitudes. The zero-change line is located around 40N in N. America, around 50N in Europe, and in the subtropics in parts of the monsoon lands of Asia (A2 scenario, Figure 3). This pattern of change in annual P-E, in response to greenhouse warming scenarios, is similar to the patterns of change in annual R [*Wetherald and Manabe*, 1999] and annual P in these (not shown) and other simulations [*Cubasch et al.*, 2001; *Meehl et al.*, 2005]. Assessments of inter-model agreement in the sign of regional precipitation change in N. America find increased P in two subpolar regions, decreased P in one subtropical region (central America), and some inconsistency (between models) in three middle latitude regions [*Giorgi et al.*, 2001].

[14] The results for individual simulations and emission scenarios (not shown) deviate from the ensemble pattern of change in annual P-E (Figure 3); for example, the zero-change line in N. America is as far south as the northern Gulf of Mexico coast and as far north as James Bay, but is frequently near the Great Lakes.

[15] The positive correlation between global temperature increase and inferred poleward moisture transport increase that is apparent in the ensembles of the two emission scenarios (Figure 2) holds for the individual simulations as well. The correlation between global temperature increase and poleward moisture transport increase is 0.92 (16 cases, i.e., 8 models and 2 emission scenarios/model), a correlation that is significant at the 1% level (F test; analysis

of variance, see Figure 4). Correlations within each scenario (8 cases each) are equally significant. The correlation between global temperature increase and the change of P-E for the Great Lakes region is somewhat lower, 0.42 (16 cases), significant only at the 10% level. [The correlation between the regional P-E and the poleward moisture transport is 0.46 (significant only at the 10% level.)]

[16] The high correlation between the increase in global temperature and the increase in poleward moisture transport provides a strong link between the large-scale hydrologic changes and the regional changes near the Great Lakes. The location of the Great Lakes near the crossover latitude between increased moisture convergence and increased moisture divergence indicates that some of the intermodel variability in the water balance of the Great Lakes region, noted above, may be due to intermodel differences in large-scale dynamics as well as differences in treatment of local processes.

6. Seasonal Response of Model Subset to CO_2 Increase

[17] We did not summarize the seasonal response of these models to the A2 and B1 emission scenarios. However, we examined the seasonal response of a subset of three of the models (GFDL, PCM, and GISS) to a doubling of CO_2 (a 1% per year increase of CO_2 for 70 years followed by 180 years with constant (doubled) CO_2); we compared the final 30 years of the 250-year simulations to the initial 30 years for the Great Lakes region. T increased in all seasons. The largest increase in P was in MAM. The six-month period DJF-MAM contributed most to the increase in annual runoff. Changes in P were smallest in JJA when two of the three models simulated decreases and all three simulated a drawdown of soil moisture.

7. Summary

[18] Simulations from eight climate models for two greenhouse gas emission scenarios, extending to 2099, were used to investigate changes in the hydrologic budget of the Great Lakes region and links between the regional changes and the large-scale hemispheric/global changes. The ensemble average simulations indicate increased net moisture (increased P-E) for the Great Lakes region, especially for the scenario with the largest CO_2 increase (A2), and link the changes in this region to increased poleward moisture transport, which in turn is highly correlated with the sensitivity of each model to greenhouse-gas induced warming as measured by the global average increase of temperature. This result helps confirm the overall mechanism linking global and regional scales. The location of the Great Lakes region near the crossover latitude separating the more northerly regions (trending wetter) from the more southerly regions (trending drier) implies that intermodel differences in treatment of large-scale processes may contribute to intermodel differences in regional water balance for this region. Moreover, not all of the climate models included explicit treatment of atmosphere/lake exchange processes and this factor could also contribute to intermodel differences.

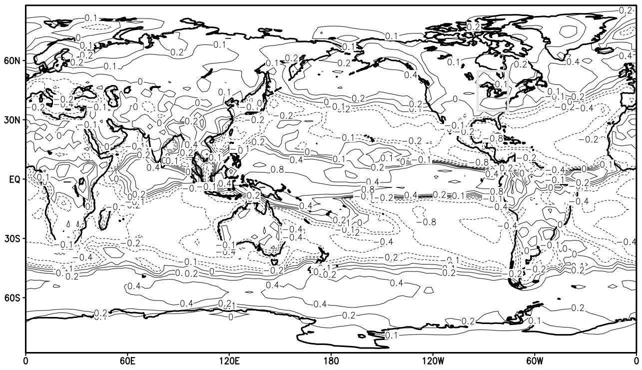

Figure 3. Global pattern of changes in annual average P-E for the eight-member ensemble of simulations for emission scenario A2; based upon differences in 20-year means (2080–2099 minus 1980–1999). The area representing the Great Lakes region used in the regional averages is outlined.

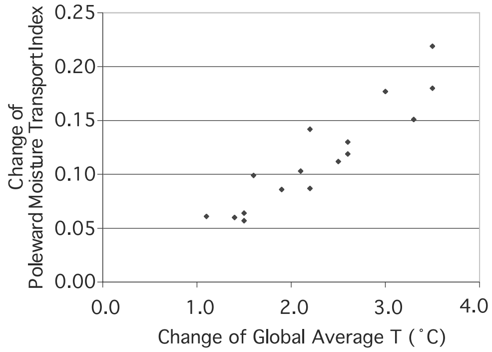

Figure 4. Scatterplot of changes in global average temperature and changes in an index of poleward moisture transport across 42N based upon individual simulations by eight climate models for two emission scenarios, A2 and B1; based upon differences in 20-year means (2080–2099 minus 1980–1999). The correlation between the 16 pairs of variables is 0.92.

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