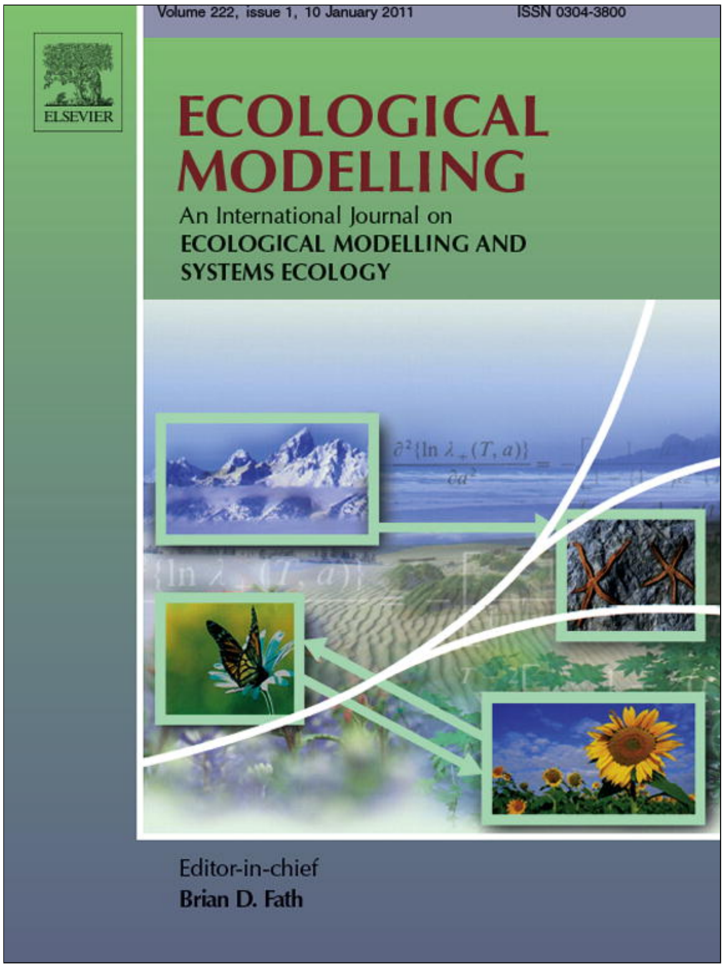
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Integrated model projections of climate change impacts on a North American lake

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ABSTRACT

Climate change is likely to impact terrestrial and aquatic ecosystems via numerous physical and biological mechanisms. This study outlines a framework for projecting potential impacts of climate change on lakes using linked environmental models. Impacts of climate drivers on catchment hydrology and thermal balance in Onondaga Lake (New York State) are simulated using mechanistic models HSPF and UFILS4. Outputs from these models are fed into a lake ecosystem model, developed in AQUATOX. Watershed simulations project increases in the magnitude of peak flows and consequent increases in catchment nutrient export as the magnitude of extreme precipitation events increases. This occurs concurrently with a decrease in annual stream discharge as a result of increased evapotranspiration. Simulated lake water temperatures increase by as much as 5 °C during the 2040–2069 time period, accompanied by a prolonging of the duration of summer stratification. Projected changes include shifts in the timing of nutrient cycling between lake sediments and water column. Plankton taxa projected to thrive under climate change include green algae and *Bosmina longirostris*. Responses for species at higher trophic levels are mixed. Benthic macroinvertebrates may either prosper (zebra mussels) or decline (chironomids), while fish (e.g., gizzard shad) exhibit high seasonal variability without any clear trend.

1. Introduction

Mean temperatures at the earth's surface are projected to increase by as much as 6 °C by the end of the 21th century, as a consequence of anthropogenic changes to atmospheric chemistry (Bates et al., 2008). Warming of the climate is expected to result in changes to the global hydrologic cycle, including changes in the amounts and spatial distributions of rainfall and snowfall, increased storm intensity, and rising sea levels (Huntington, 2006; Trenberth et al., 2003; US EPA, 2008). Lakes may act as sentinels by exhibiting signals that reflect influences of climate change, particularly given their role in sediment transport and carbon cycling (Williamson et al., 2009). Climate change affects lakes directly via atmospheric drivers, e.g. temperature increase, precipitation, wind speed and radition, and indirectly through changes to catchment properties. Temperature plays a driving role in most physicochemical processes in lakes, e.g. the presence and duration of ice-cover and thermal stratification (Fang and Stefan, 1999), dissolved gas concentrations and associated redox potential, and sediment–water nutrient dynamics (Jankowski et al., 2006; McKee et al., 2003). Warmer temperatures affect the physiology of organisms, altering food-web dynamics, biodiversity, and ecological productivity (Mooij et al., 2009; Winder and Schindler, 2004). Profound ecological changes due to climate change are shifts in the composition, seasonality and production of algae, changes in emergence and abundance of insect populations, and alterations of abiotic filters that determine the success of invasive or nuisance species (Blenckner et al., 2002; Jeppesen et al., 2007; Mooij et al., 2005; Rahel and Olden, 2008). Prolonged periods of thermal stratification, and in turn hypolimnetic hypoxia, stress benthic macroinvertebrate and fish populations (Carpenter et al., 1992). In general, under warmer temperatures fish grow faster, mature earlier and have shorter life-spans, with compositional shifts toward dominance of zooplantivorous and omnivorous species, and consequent increased predation of zooplankton and decreased predation of phytoplankton (Mooij et al., 2010). Increased variability in the volume, timing, intensity and type of precipitation change annual and seasonal patterns of river flows and influence lake retention times and depths (Chiew, 2007). These in turn alter expansion dynamics of submersed plants, and influence shifts between clear water and turbid states (Coops et al., 2003). Intensification of storm events results in increased nutrient, pathogen, and pesticide loads from watersheds (Arheimer et al., 2005; Chang et al., 2001; George

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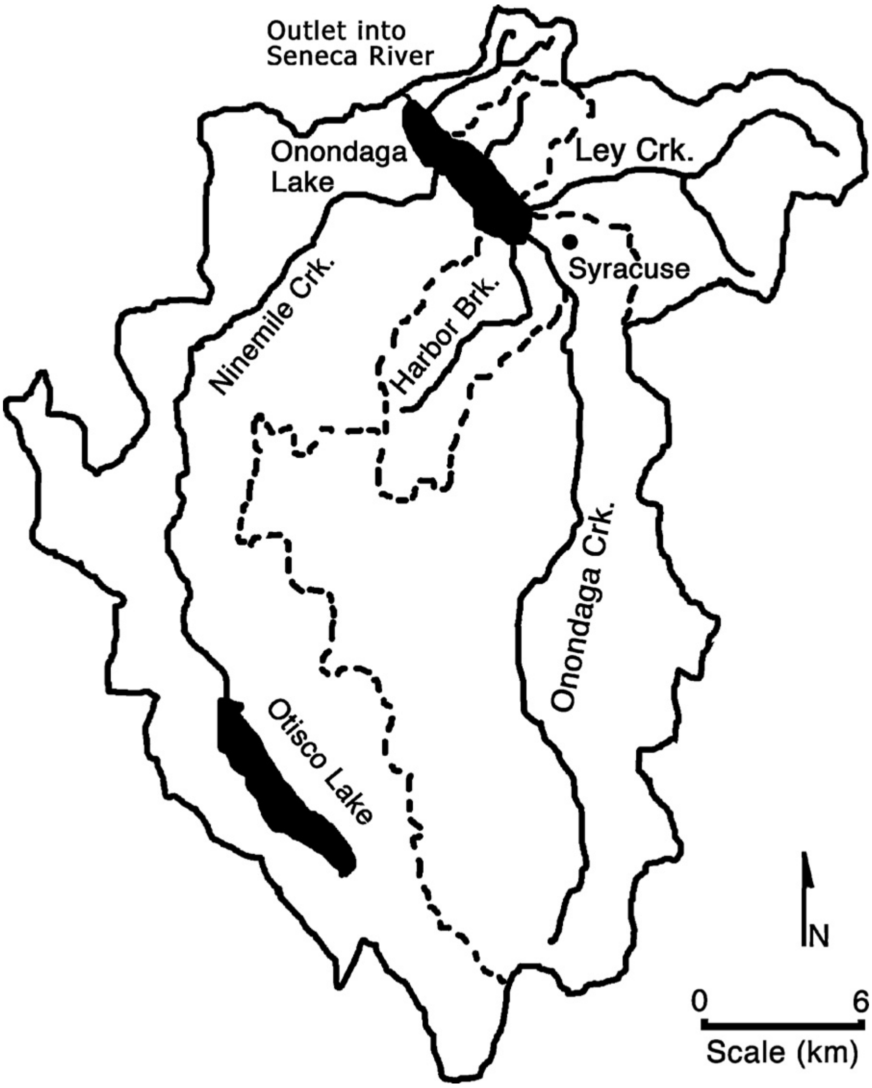

Fig. 1. Onondaga Lake and its watershed.

et al., 2007). Individual lakes may exhibit high variability in their responses to climate change, due to factors that are: (a) landscape related, i.e., geographic position, catchment characteristics, lake morphology; and (b) internal, i.e., lake history and biotic and abiotic interactions (Blenckner, 2005).

Assessing lake response to multiple stressors is difficult, as forcing factors may change simultaneously and unevenly. Aquatic ecosystems often respond to multiple driving forces non-linearly and in a delayed manner (Scheffer et al., 2001). Such changes may also occur dramatically, for example with rapid shifts in trophic state (Hecky et al., 2010). Process-based environmental models have become important tools for exploring complex interactions between climate drivers and water systems. Models have been developed and used to study climate change impacts on the global hydrological circle (Döll and Flörke, 2005), catchment hydrology (Arnell, 2004; Pietroniro et al., 2006), heat budgets (Fang and Stefan, 1999), water quality (Bangs et al., 2000; Komatsu et al., 2007; Malmaeus et al., 2006; Marshall and Randhir, 2008; Pierson et al., 2010), soil erosion and sediment loading (Bouraoui et al., 2004; Zhang and Jørgensen, 2005) and ecosystem dynamics (Markensten et al., 2010; Winder and Schindler, 2004). Recent developments in lake modeling, particularly better integration of ecosystem models with watershed and/or hydrodynamic models, provide means for holistic analyses (Jørgensen, 2010). However as yet, published analyses of climate change impacts on lakes are few. Studies have demonstrated the use of global or regional climate model outputs for simulating watershed runoff and nutrient discharges linked to simulations of lake and reservoir stratification and biochemistry (Arheimer et al., 2005; Elliott et al., 2005; Heerdt et al., 2007; Komatsu et al., 2007; Markensten et al., 2010). Whitehead et al. (2009) similarly evaluated climate change impacts on macrophytes and epiphytes in large river systems.

In this study, we present a framework for assessing potential impacts of climate drivers on lakes, using a linked series of environmental models. The primary objective is investigation of a method for conducting exploratory analyses of potential impacts of global climate change on aquatic ecosystems. Climate-related changes to stream flows and associated nutrient fluxes are simulated, as are direct influences of temperature changes on summer stratification. The influences of these changes on algal productivity and food web dynamics are in turn simulated. We apply our methodology to Onondaga Lake, New York. Climate change scenarios are developed using "Better Assessment Science Integrating point & Non-point Sources-Climate Assessment Tool" (BASINS-CAT) (US EPA, 2009) based on downscaled outputs of four Global Circulation Models (GCMs) for two IPCC "story lines", i.e. A2 and B2 (Nakićenović

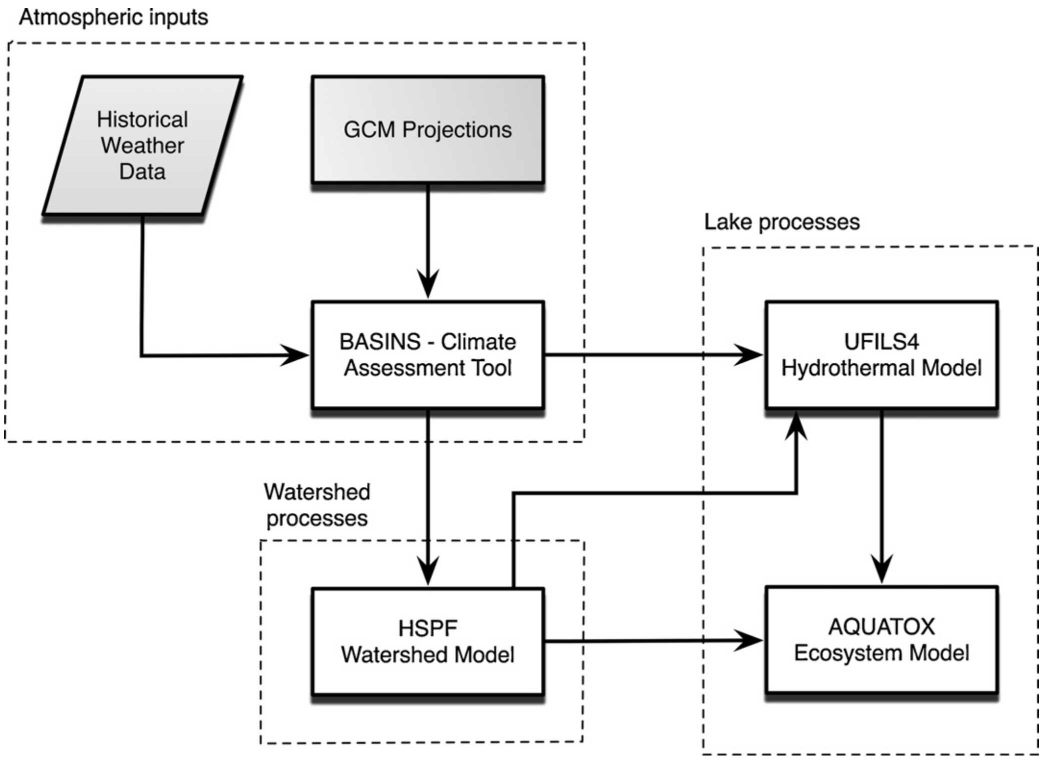

Fig. 2. Conceptual flow chart. Dashed lines show three interconnected systems and their subcomponents represented in the study. Grayed-out boxes represent readily obtained data sets and model outputs. Arrows indicate the direction of input–output linkages between components.

et al., 2000). Impacts of climate drivers on catchment hydrology and lake hydrodynamics are simulated using two mechanistic models, "Hydrological Simulation Program—FORTRAN" (HSPF) (Bicknell et al., 2005) and Upstate Freshwater Institute Lake Stratification Model No. 4 (UFILS4) (Effler, 1996), respectively. The ecosystem of Onondaga Lake itself is simulated using AQUATOX (Park et al., 2008) and climate change impacts on the lake are evaluated by linking in outputs from the watershed and hydrothermal models.

2. Material and methods

2.1. Study site: Onondaga Lake

Onondaga Lake is located southeast of Lake Ontario in the Great Lakes region, immediately northwest of the City of Syracuse in Onondaga County, New York, USA (Fig. 1). The lake has an approximate surface area of 12 km^2 and a maximum length and width of 8 km and 1.5 km, respectively. Lake mean depth is 10.9 m, and maximum depth ranges between 20.4 and 22.6 m (Effler, 1996). The major discharges to Onondaga Lake are Onondaga, Ninemile, Ley and Harbor Creeks, and effluent from the Metropolitan Syracuse Sewerage Treatment Plant (METRO), which totals 16 m^3/s as an annual average (Effler and Hennigan, 1996). The highest and lowest surface inflows to Onondaga Lake are observed during the March–April and July–September time periods. Onondaga Lake drains to the Seneca River (a tributary of the Oswego River) through a canal and dam system, although irregular inflows into Onondaga Lake from Seneca River are common during periods of low lake water level. The lake's hydraulic residence time averages 90 days. Onondaga Lake exists in a continental and humid climate, strongly influenced by Lake Ontario, located approximately 40 km away (Ecologic LLC, 2010). The lake receives an average annual precipitation of 40 in., with February being the driest and September the wettest months on average (NOAA, 2010).

Onondaga Lake is one of the most contaminated lakes in North America, due to the combined impacts of industrial and treated wastewater discharges, combined sewer overflows (CSOs), and agricultural and urban nonpoint source pollution. The lake is hypereutrophic, with excessive levels of phosphorus in the water column and bottom sediments, high turbidity, and prolonged periods of hypoxia during summer stratification. Major water quality problems include high concentrations of free ammonia (NH_3) and nitrate (NO_3^-), bioaccumulation of Hg in fish, elevated salinity in bottom waters, and accumulation of PCBs in lake sediments (Effler and Hennigan, 1996). Arguably the most significant pollution source had been a soda ash–chlor alkali plant, which operated from 1884 to 1986 (Effler, 1996). Onondaga Lake is dimictic, with strong stratification in summer, weak inverse stratification in winter, and turnover conditions in spring and fall seasons. Water temperatures vary throughout the year between 2.5 and 13 °C, and between 2.5 and 25 °C in the bottom and top layers, respectively (Effler, 1996). Elevated salinity accounts for about 30% of the lake's overall density stratification (Effler, 1996). The onset of summer stratification in the lake typically takes place in early May, and fall turnover occurs most often in mid-October, with the duration of thermal stratification varying between about 133 and 203 days (O'Donnell et al., 2010). In the 1990s, the lake was given "Superfund" status by USEPA, and restoration goals were set, including water quality improvement to allow fish consumption, and restoration of wildlife habitat (Ecologic LLC, 2006).

Onondaga Lake's biodiversity is relatively low due to its polluted condition. Predominant sestonic phytoplankton taxa present are chlorophyta (green algae), bacillariophyta (diatoms), and cryptophyta (cryptomonads). Diatoms are dominant in the spring, green algae in summer and cyanobacteria in late summer and fall, although the latter organisms rarely exceed 5% of total plankton biomass (Effler, 1996). The lake's zooplankton community is poor compared with similar lakes elsewhere. Dominant species are the cladocerans *Bosmina longirostris* and *Daphnia retrocurva*,

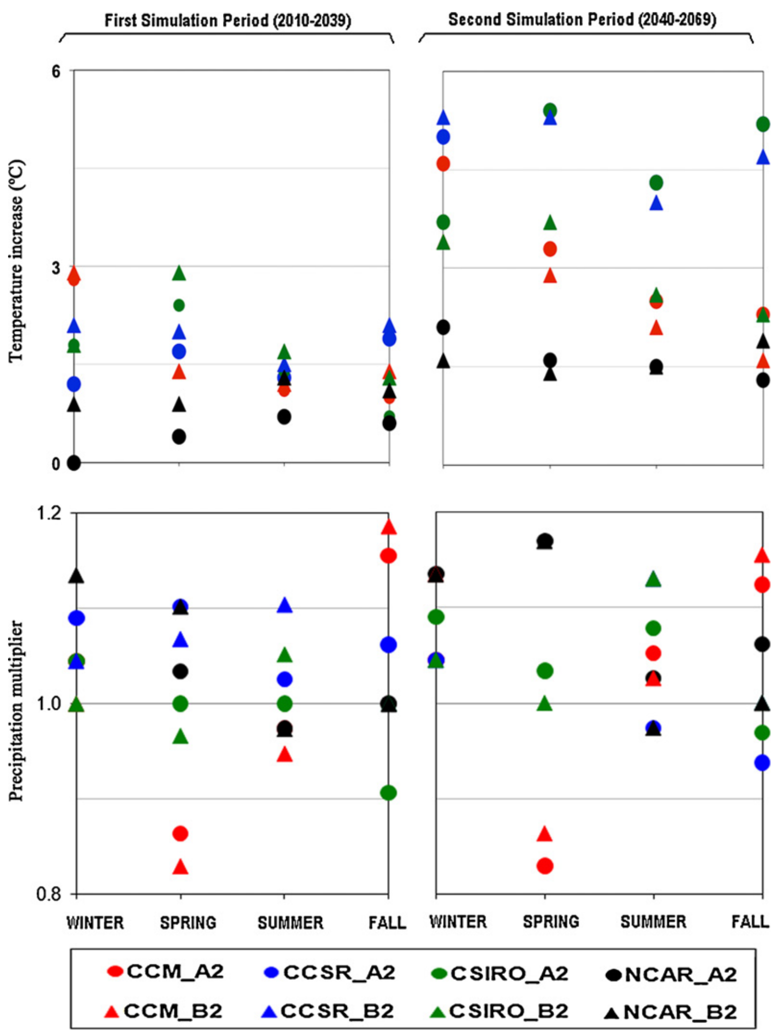

Fig. 3. Changes in temperature and precipitation in climate scenarios. Temperature changes show the seasonal increases applied to the scenarios. Precipitation multipliers show the seasonal multiplicative factor applied to the top 10% of the precipitation events in the scenarios.

and the copepod *Diachyclops thomasi*. Benthic macroinvertebrate diversity is actually greater, and has improved in recent decades, with more than 60 taxa (oligochaetes, chironomids, amphipods and zebra mussels (*Dreissena polymorpha*)) identified in the littoral zone in 2005 (Ecologic LLC, 2006). The non-native zebra mussels were first detected in1992, and remained low in number initially. However, in the last decade their populations have increased substantially in apparent response to improvements to lake water quality, especially a decrease in ammonia concentrations (Matthews et al., 2001). The lake's fish community is mostly composed of pollution-tolerant, warm water species, including a high proportion of planktivores. Clupeids, alewife (*Alosa pseudoharengus*) and gizzard shad (*Dorosoma cepedianum*) comprise about 90% of the lake's electrofishing catch (Ecologic LLC, 2006).

2.2. Integrated modeling approach overview

The modeling framework incorporated linked watershed, thermal balance and ecosystem models. Climate change scenarios were developed in BASINS-CAT by modifying historical air temperature and precipitation data sets based on downscaled GCM projections. A previously calibrated HSPF application was run using each scenario's simulated precipitation and temperature time series as drivers, to obtain corresponding tributary flows, water temperatures and constituent loadings. For each climate scenario, the hydrothermal model UFILS4 employed the simulated air temperatures and hydrologic outputs to calculate vertical water column temperature profiles. The HSPF and UFILS4 outputs were then used as inputs to a newly developed ecosystem model study in AQUATOX, and the responses of biotic and abiotic variables for each scenario were evaluated (Fig. 2).

2.3. Scenario development using BASINS-CAT

Climate change scenarios were developed using "Better Assessment Science Integrating point & Non-point Sources" (BASINS), a non-proprietary, multi-purpose environmental analysis system developed by US EPA (2007). The "Climate Analysis Tool" (CAT) within BASINS provides users with a flexible ability to generate meteorological time series reflecting user-determined changes in temperature and precipitation, for use as input to watershed models (US EPA, 2009). Application of BASINS-CAT requires a pre-existing, calibrated HSPF simulation. Recent applications of BASINS-CAT have included examination of watershed hydrology and nutrient loadings in the Patuxent and Monocacy Rivers in Maryland (Johnson and Kittle, 2006; Johnson and Weaver, 2009). Scenarios were developed using historical weather data over the period 1996–2008 (Coon and Reddy, 2008) from three weather stations in Onondaga Lake's watershed, and downscaled global circulation model (GCM) projections for Syracuse, NY produced by the

Table 1
Prey and predators are listed in the far left column and on the top row respectively. Listed values show the prey consumption preference of predators (in percentages).

Biotic & Abiotic Variables	Oligochaetes	Chironomid	Daphnia	Bosmina Longirostris	Zebra Mussels	Rotifer 1	Copepod	Predatory Zooplankton	Gizzard Shad	Alewife	Pumpkinseed	Largemouth Bass, YOY	Largemouth Bass, Lg
R detrsed													
L detrsed	100	90			35								
R detr part									5				
L detr part			30	30		30	23.5		40				
Diatom				30	15		23.5						
Green			30	10	5	50	18.						
Blue-Green				5	5								
Cryptomonad			40	25	10	20	35						
Oligochaetes									10	5	10	20	
Chironomid									5	10	10	20	
Daphnia					5			35	5	45			
Bosmina L.					10			15	10				
Zebra Mussels											40		
Rotifer					10			20					
Copepod					5			30		10			10
Pred. Zooplankton		10							25	30	5		25
Gizzard Shad											15	27.5	20
Alewife											15	27.5	35
Pumpkinseed												5	10
LM Bass, YOY											5		
LM Bass, Lg													

Consortium for Atlantic Regional Assessment (CARA, 2010). Within CARA's database, four GCMs that give a reasonably broad range of climate projections for Syracuse, NY were selected, namely the Canadian Centre for Climate Modeling and Analysis (CCCM), the University of Tokyo's Center for Climate System Research – National Institute for Environmental Studies (CCSR), Australia's Commonwealth Scientific and Industrial Research Organization (CSIR), and the National Center for Atmospheric Research model (NCAR). Each GCM covers two Intergovernmental Panel on Climate Change, Special Report on Emission Scenarios (IPCC SRES) story lines, i.e. A2 and B2, and two time periods, 2010–2039 and 2040–2069. Thus altogether a total of 17 scenarios were generated, including a "base scenario" which assumes no change over the historical weather data. For all other scenarios, projected temperature increases were added to the corresponding seasonal values in the base scenario. For precipitation, GCM projections were applied to the largest 10% of all storm events in a particular season through the use of a multiplier between 0.8 and 1.2, which simply scaled the corresponding precipitation magnitudes accordingly. In this way, large storm intensity was increased while gentler rainfall remained unchanged. Overall, the downscaled GCM results projected air temperature increases of up to 3 °C and 6 °C for the 2010–2039 and 2040–2069 time periods, respectively, and precipitation changes of between 80% and 120% (Fig. 3).

2.4. Watershed responses

The Hydrological Simulation Program-Fortran (HSPF) Release 12.2, developed under joint sponsorship of U.S. EPA and USGS, is a lumped-parameter, semi-distributed, continuous-simulation model designed to simulate hydrologic and water-quality processes in natural and manmade water systems. HSPF represents landscape and stream flow hydrology and pollutant transport at an hourly or smaller time step (Bicknell et al., 2005). In HSPF, the response of the land phase of the hydrologic cycle is simulated using elements called "segments" that are classified either as pervious (PERLND) or impervious (IMPLND). Surface water bodies (e.g. streams, river, lakes, and impoundments) are represented as completely mixed "reaches" (RCHRES), which may be connected to represent networks of linked streams of various orders.

The Onondaga HSPF application, developed by Coon and Reddy (2008) conceptualizes Onondaga Lake's watershed as 107 subbasins, each apportioned among 19 pervious and impervious land types based on topographic and soil characteristics. Model segmentation is primarily based on: (1) locations of weather stations, (2) confluences of major tributaries, (3) reach lengths and (4) significant changes in channel slopes. The model was extensively calibrated against USGS flow and water quality monitoring data, and model performance was judged "good" for stream flow (mean error less than 10%), water temperature (mean error less than 7%) and PO_4, TP, NO_3^- and Org. N (mean errors less than 15%), and "acceptable" for dissolved Oxygen (DO) and total suspended solids (TSS) (mean errors less than 40%). Ammonia NH_3-N was not explicitly simulated, but was approximated as 43% of Org. N (Coon and Reddy, 2008).

2.5. Lake thermal processes

Climate change-based changes to the lake's vertical temperature profile and thermocline depth were represented with UFILS4, a mechanistic model of density stratification and vertical transport that evolved from CE-THERM-R1, the stand-alone thermal component of the U.S. Army Corps of Engineers' one-dimensional reservoir model CE-QUAL-R1 (Environmental Laboratory, 1982). UFILS4 has four modules for calculating heat budget, tributary flows and vertical mixing in epilimnion and hypolimnion layers. A surface mass and heat transfer module estimates evaporative losses at the lake's surface based on average wind conditions, air moisture and air temperature, and net heat flux at the water surface (Environmental Laboratory, 1982). UFILS4 is capable of representing both neutrally buoyant inflows, where the total flow is evenly distributed over the depth of the epilimnion, and negatively buoyant (plunging) inflows. UFILS4 has been successfully applied to simulate water quality and stratification and constituent transport in Cannonsville Reservoir, New York (Owens, 1998), as well as in Onondaga Lake (O'Donnell et al., 2010).

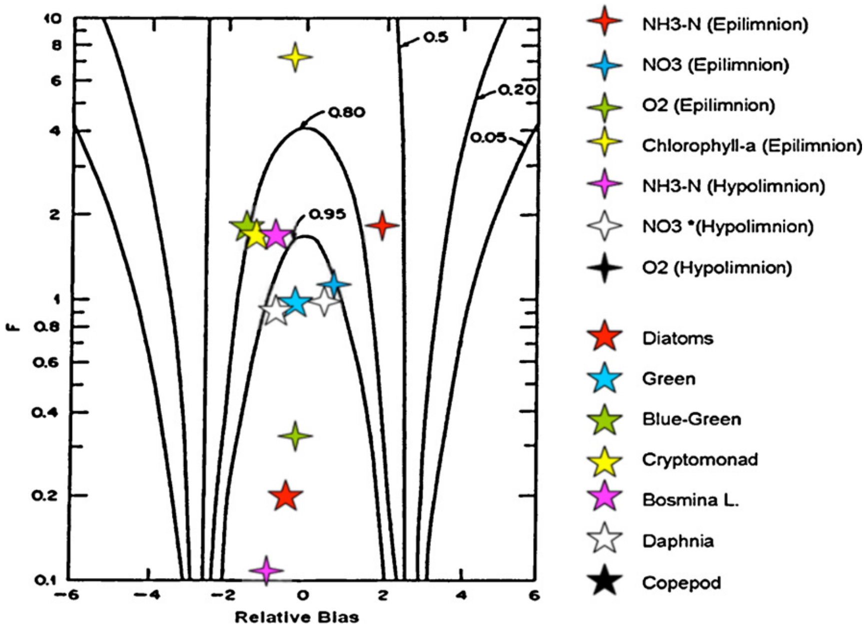

Fig. 4. Relative bias and *F* test for biotic and abiotic variables. Isopleths correspond to probability that distributions of simulated and observed values, as defined by combination of the rB and *F* statistics, are the same. Isopleths assume that data are normally distributed.

For our purposes, the existing model simulation period was extended from 9 months (i.e. March–November) to 1 year for providing a gapless input time series to AQUATOX. Unfortunately no temperature profile data were available to evaluate the model's performance for the additional period. The analysis was also restricted to model variables for which estimates were readily available, either from downscaled GCM projections or HSPF simulation outputs. Thus, variables that may show significant sensitivity to climate change (e.g. water elevation (m), lake density (g/m^3) and light extinction (m^{-1})) were kept constant in all 17 scenarios. To address the absence of a measured set of values that could be employed as initial conditions, a "spin-up" approach was used. This entailed running a preliminary simulation with an arbitrary set of initial values, and then re-running the model with a second set of initial values based on the results at the last simulated day of the prior simulation run.

2.6. Lake ecosystem model

A model application was developed using AQUATOX for representing recent biological conditions in Onondaga Lake. AQUATOX Release 3, is a general aquatic ecological risk assessment model intended to be used to evaluate direct and indirect effects from various stressors including nutrients, sediments, toxics, flow, and temperature (Park et al., 2008). AQUATOX has been applied to simulation of pesticide impacts in reservoirs, accumulation of PCBs and biomass dynamics in streams (Rashleigh, 2003; Rashleigh et al., 2009; Sourisseau et al., 2008), and nutrient-related algal dynamics in rivers (Carleton et al., 2009). Abiotic variables in AQUATOX include DO, nutrients, detritus (disaggregated as refractory or labile and dissolved or suspended), and toxics. AQUATOX simulates biota as algae and macrophytes (further classified as suspended, attached and submerged), invertebrates and fish (either as forage, bottom feeding, and game), with each component represented by a set of growth and loss equations. For instance, phytoplankton biomass is modeled as a function of upstream loading, photosynthesis, respiration, excretion, mortality, predation, sinking, turbulent diffusion and sloughing. Food-web relationships in AQUATOX are specified in a feeding preference matrix (Table 1).

Onondaga Lake was modeled as essentially one-dimensional, with two linked, well-mixed layers representing epilimnion and hypolimnion. The lake's physical conditions were set based on the available data (Coon and Reddy, 2008; Ecologic LLC, 2010; Effler, 1996). Tributary flow rates and loadings of NH_3, NO_3^-, PO_4, organic carbon, chemical oxygen demand (COD) and DO were obtained from Onondaga County Department of Water Environment Protection (OCWEP). For providing daily input time series to AQUATOX, OCWEP's biweekly nutrient and DO data were converted to daily estimates by using FLUX, an interactive program that maps the flow/concentration relationship from a sample record and estimates daily mass discharges and associated error statistics (Walker, 1999). Lake biota were represented by 16 variables in total: diatoms, green algae, blue-green algae and cryptomonads as phytoplankton; rotifers, daphnia, *B. longirostris*, copepods (representing *D. thomasi*), and predatory zooplankton (representing *Cercapagis pengoi*) as zooplankton; oligochaetes, chironomids and zebra mussels as benthic macroinvertebrates, and gizzard shad, alewife, pumpkinseed, and largemouth bass as fish.

Model performance was evaluated by comparing simulation results to OCWEP's monitoring data from 2005 to 2006, both visually and statistically. The visual comparison of observed against simulated NH_3-N, NO_3^-, and DO were generally good. Predicted chlorophyll-a concentrations were higher than the observed, and the predicted phytoplankton and zooplankton dynamics were acceptable. The relative bias versus variances test was applied to compare simulation results with OCWEP's 1-year water quality and biological sampling data, for a sub-set of biotic and abiotic variables (Ecologic LLC, 2006). Relative bias (rB) (Eq. (1)) and variances (*F*) (Eq. (2)) are defined as (Park and Clough, 2009):

$$\mathrm{rB} = \frac{\overline{\mathrm{Sim}} - \overline{\mathrm{Obs}}}{S_{\mathrm{Obs}}} \qquad (1)$$

$$F = \frac{S^2_{\mathrm{Sim}}}{S^2_{\mathrm{Obs}}} \qquad (2)$$

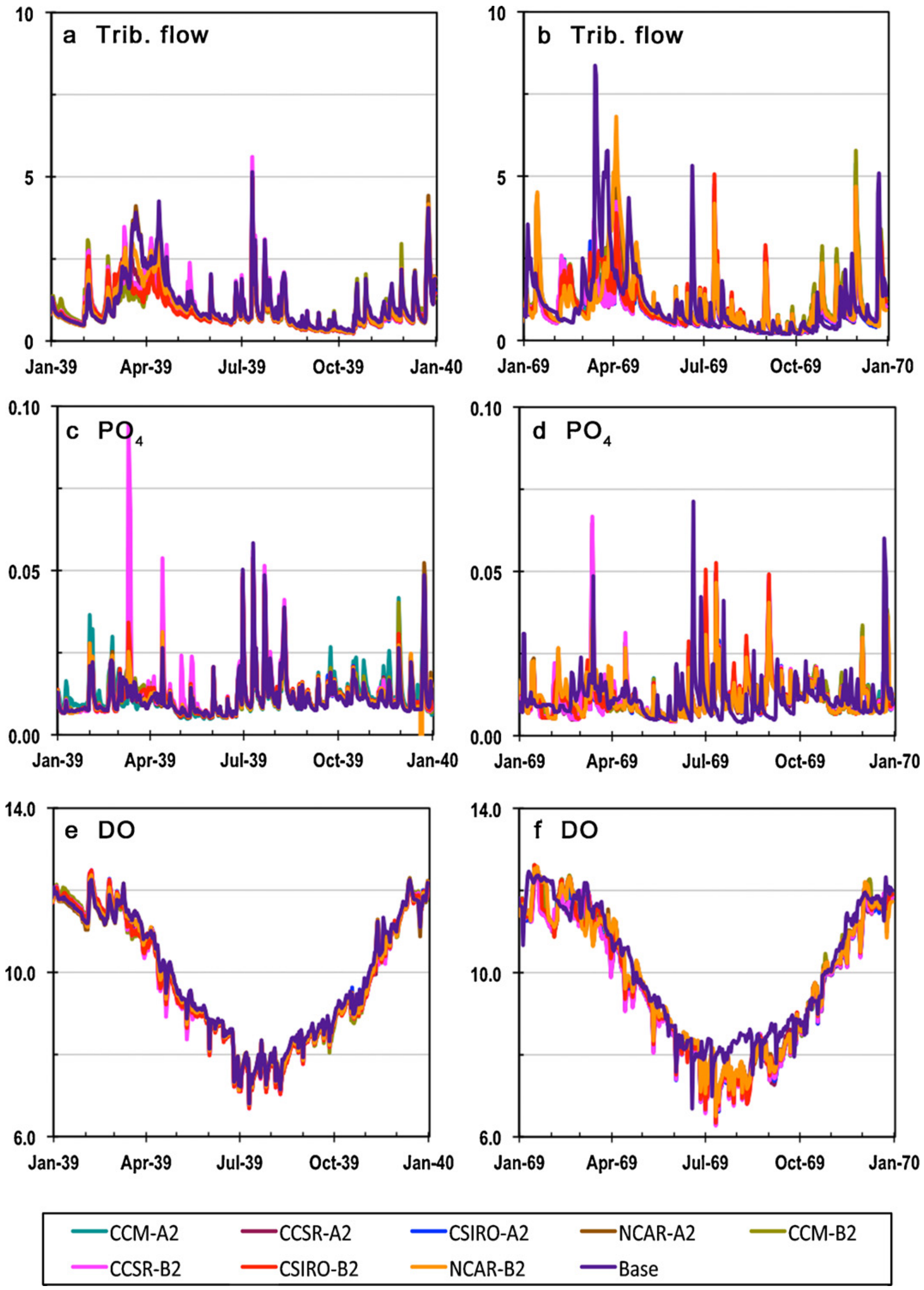

Fig. 5. Simulated average discharges to Onondaga Lake: (a) tributary flow during 2010–2039 (in million m^3/day); (b) tributary flow during 2040–2069 (in million m^3/day); (c) PO_4 concentration during 2010–2039 (in mg/l); (d) PO_4 concentration during 2040–2069 (in mg/l); (e) DO concentration during 2010–2039 (in mg/l); and (f) DO concentration during 2040–2069 (in mg/l). Charts show final year results of entire simulation period.

where $\overline{Sim}$ is the mean of simulated values, $\overline{Obs}$ is the mean of observed values, S_{Sim} is the variance of observed values and S_{Obs} is the variance of simulated values. The rB and F values indicated that the simulated distributions of NH_3-N, NO_3^-, DO, diatoms, greens and *Daphnia* spp. were very similar to the observed distributions (i.e. within the 95% isopleth) while blue-green, cryptomonad and *B. Longirostris* were in the 80% isopleth. The only exception was chlorophyll-a, whose simulated distribution had a higher difference in variances (less than 8% isopleth) (Fig. 4).

3. Results

3.1. Watershed processes

Scenarios yielded substantial variations in simulated stream flows and in-stream nutrient concentrations. For the 2010–2039 period, average stream discharges slightly increased in winter, and decreased by up to 50% in spring as a result of higher air temperatures and earlier snow melt (Fig. 5a). Changes in stream flow

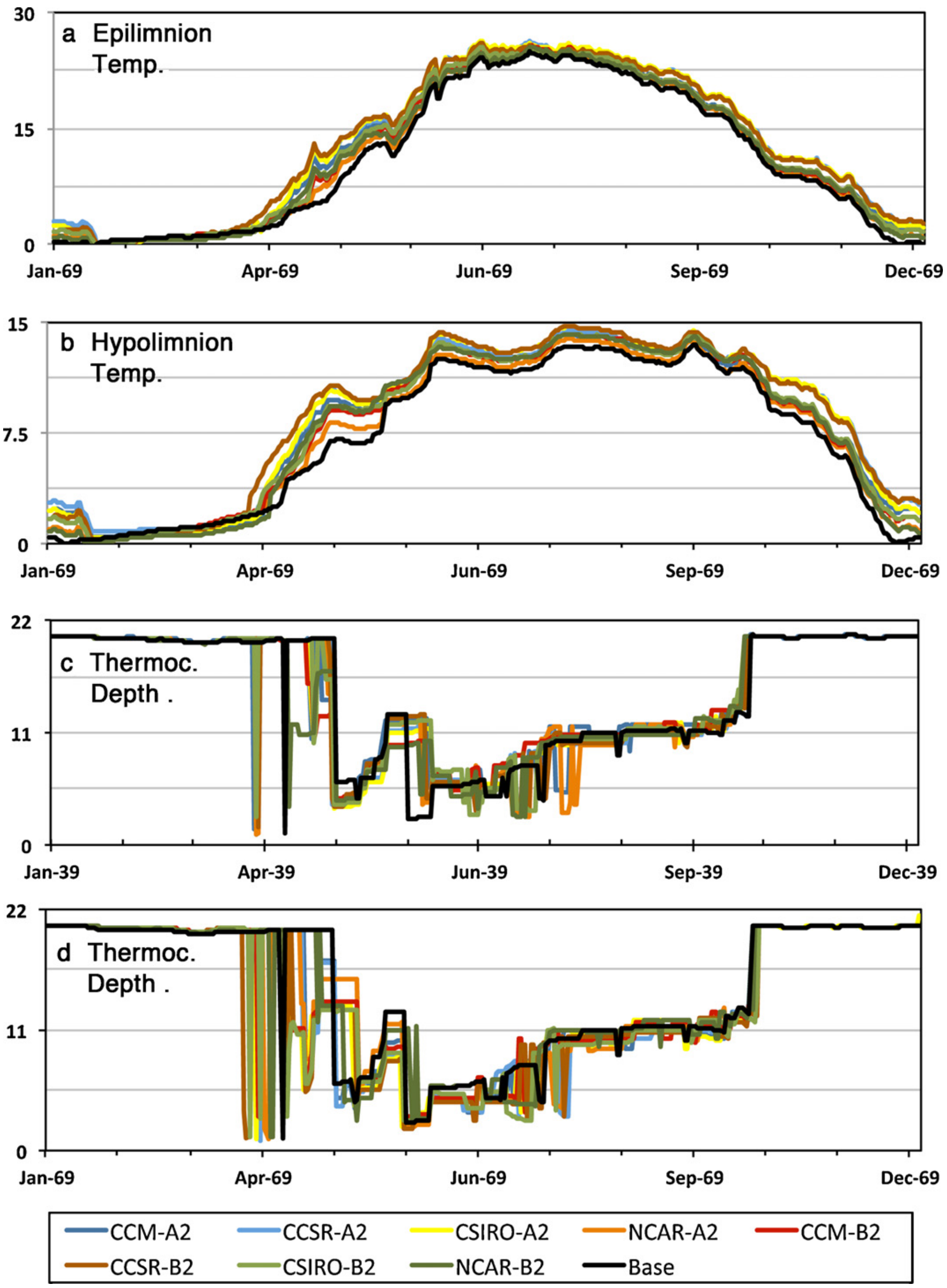

Fig. 6. (a) In-lake epilimnion temperatures during 2040–2069 (°C), (b) in-lake hypolimnion temperatures during 2040–2069 (°C), (c) thermocline depth during 2010–2039 (m), and (d) thermocline depth during 2040–2069 (m). Charts show final simulated year's results. .

patterns were more dramatic during the 2040–2069 period, when peak stream flows shifted from March to April, and the frequency of high flows during summer notably increased (Fig. 5b). Simulated total annual stream flows decreased in the 2040–2069 period, even for the CCSR-A2 and CCSR-B2 scenarios in which precipitation rates increased in all seasons. This suggests that increases in precipitation may not be sufficient to offset losses caused by increased evaporation brought about by higher temperatures (e.g. potential evapotranspiration rates increased up to 40% for the CCSR-A2 and CCSR-B2 scenarios, whereas precipitation increased by no more than 30%). The greatest variability in NO_3^- concentrations occurred in the spring season, although no clear trend in annual NO_3^-–N loading was observed. Higher concentrations of PO_4 were observed in spring for the 2010–2039 period, particularly for CCSR-B2 (Fig. 5c), and the frequency of peak PO_4 concentrations increased in late summer for the 2040–2069 period (Fig. 5d). Average simulated DO concentrations were insensitive to GCM projections for the 2010–2039 period (Fig. 5e), but slight decreases in DO were noted for the 2040–2069 period (i.e. average 8 mg/l in the base scenario and 7 mg/l in other scenarios, Fig. 5f).

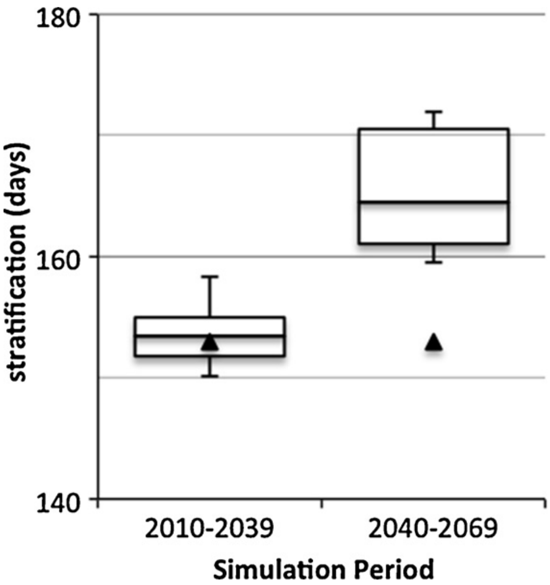

Fig. 7. Average duration of thermal stratification for the simulated climate scenarios. Symbol Δ shows thermal stratification in base scenarios. The Box-and-whisker diagram depicts the 10th percentile, lower quartile (25th percentile), the median, the upper quartile (75th percentile) and the 90th percentile of stratified period for all climate change scenarios. Chart is based on the final simulated year's results.

3.2. Lake thermal balance

Lake water temperatures were primarily affected by changes in air temperatures, thus differences in the hydrothermal profiles were more apparent in the (warmer) 2040–2069 period. Increases in average water temperature in the epilimnion and hypolimnion were up to 2.3 °C and 1.5 °C, respectively, in the 2010–2039 simulation period, and 5.2 °C and 3.7 °C in the 2040–2069 period (Fig. 6a and b). These increases are comparable to previous findings for the Great Lakes region, with estimated increases of up to 7 °C by the 2090s (Kling et al., 2003). For both simulation periods, lake warming was greater during fall than winter. The highest water temperature increases were projected for the CSIRO-A2 and CCSR-B2 scenarios, parallel to the projected increases in air temperature. The summer thermocline deepened in all scenarios, particularly during the 2040–2069 period. This deepening took place earlier, concurrent with the earlier on-set of thermal stratification (Fig. 6c and d). Thermal stratification lasted from 150 to 155 days during the 2010–2039 period, and increased to 172 days in the 2040–2069 period (Fig. 7). The duration of thermal stratification, defined for our purposes as taking place when the temperature difference between epilimnion and hypolimnion exceeds 3 °C, was particularly of interest as it is relates to the duration of hypolimnetic anoxia (Wetzel, 2001).

3.3. Lake ecosystem

3.3.1. Abiotic variables

Water quality variables related to system eutrophication (e.g., NH_3, TSP and DO) are evaluated in this section. Simulation results indicate that a period of epilimnetic NH_3 depletion shifts from June to May in all of the 2040–2069 scenarios, and that summer epilimnetic NH_3 concentrations are notably higher (e.g., approximate doubling in scenario CCSR-A2 as compared with the base scenario) as an apparent consequence of earlier thermal stratification onset. Hypolimnetic NH_3 concentrations increase in all seasons except summer, when slight decreases are observed for the NCAR-A2 and NCAR-B2 scenarios. Similarly, a period of spring time epilimnetic TSP depletion shifts by up to one month earlier in the year, as compared with the base scenario (Fig. 8a). Magnitudes of epilimnetic TSP concentrations appear to correspond directly with temperatures, e.g. the highest TSP concentrations between 2040 and 2069 are observed in CCSR-B2, a scenario with high projected temperature increases (Fig. 8a). Hypolimnetic TSP concentrations generally increase during fall by up to 30% of the base scenario values (Fig. 8b). Epilimnetic DO exhibits high variability during spring and the summer for all scenarios in both simulation periods. Peak epilimnetic DO concentrations tend to happen earlier in the year, and the magnitude of the spring DO increases to as much as 16 mg/l, paralleling increases in primary production (Fig. 8c). Timing shifts in peak DO are greater during 2040–2069 in all scenarios (Fig. 8d). Hypolimnetic DO concentrations are substantially affected in all climate change scenarios, e.g. the duration of periods when hypolimnetic DO is below 6 mg/l increases up to 15 and 30 days in the 2010–2039 and 2040–2069 simulation periods respectively. Decreases in hypolimnetic DO are apparent during both spring and early summer (Fig. 8e and f).

3.3.2. Plants

Total phytoplankton biomass increases in all climate change scenarios in both simulation periods, especially 2040–2069. Peak biomass concentrations are comparable in the two simulation periods, however the frequency and the timing of algal blooms show notable variations (Fig. 9a and b). The sensitivity of modeled phytoplankton groups varies among scenarios in both periods, and the magnitude of change shows prominent seasonal differences. For example, phytoplankton biomass increases more in summer in scenario CCSR-B2 (Fig. 9a), but more in fall in CCM-B2 (Fig. 9b). Diatom blooms exhibit a time shift from June to May in the 2040–2069 period, as an apparent consequence of earlier warming of the lake (Fig. 9c). Green algae appear to strongly benefit from the simulated changes in climate, particularly in the 2040–2069 period, with frequent blooms occurring in summer (Fig. 9d). Increases in green algal biomass are dramatic in scenario CSIRO-A2, as concentration increases from 0.1 mg/l in the base scenario to nearly 3 mg/l (Fig. 9d). Cryptomonads also benefit from the simulated changes, as their biomass and blooming frequency increase to different degrees in different scenarios (Fig. 9e). Blue-green algal biomass increases by about 25% on average during the growth season, particularly in the CSIRO-B2 and CCSR-B2 scenarios (Fig. 9f). Nevertheless blue-green algal biomass remains relatively low as a fraction of overall phytoplankton biomass.

3.3.3. Animals

Increases in zooplankton biomass are relatively small during the 2010–2039 period, but dramatic during the 2040–2069 period. *B. longirostris*, a small cladoceran, continues to be the dominant zooplankton in both simulation periods for all scenarios. Peak biomass of *B. longirostris* dramatically increases in CCSR-A2 and CSIRO-A2 as compared with the base scenario, from 0.1 mg/l to 1 mg/l (Fig. 10a). Dynamics of *Daphnia* sp., a larger cladoceran preferentially grazed by alewife, resemble those of *B. longirostris*; with peak biomass increasing by up to eight fold in CCSR-A2 and CSIRO-A2 (Fig. 10b). Despite these proportional increases, *Daphnia* sp. biomass is still negligible compared to *B. longirostris* (e.g., less than 0.001 mg/l at the peak), and remains an insignificant factor in the control of phytoplankton biomass (Fig. 10b). Other zooplanktons in the model also remains at low levels (i.e., less than 0.001 mg/l) and are not found to cause major changes in food-web structure.

Benthic macroinvertebrate dynamics appear complex and nonlinear, with the direction and magnitude of responses showing substantial variability among different scenarios. In general, zebra mussels are projected to benefit from climate change, while chironomids are projected to decline. Zebra mussel biomass generally increases compared with the base scenario (e.g., more than three-

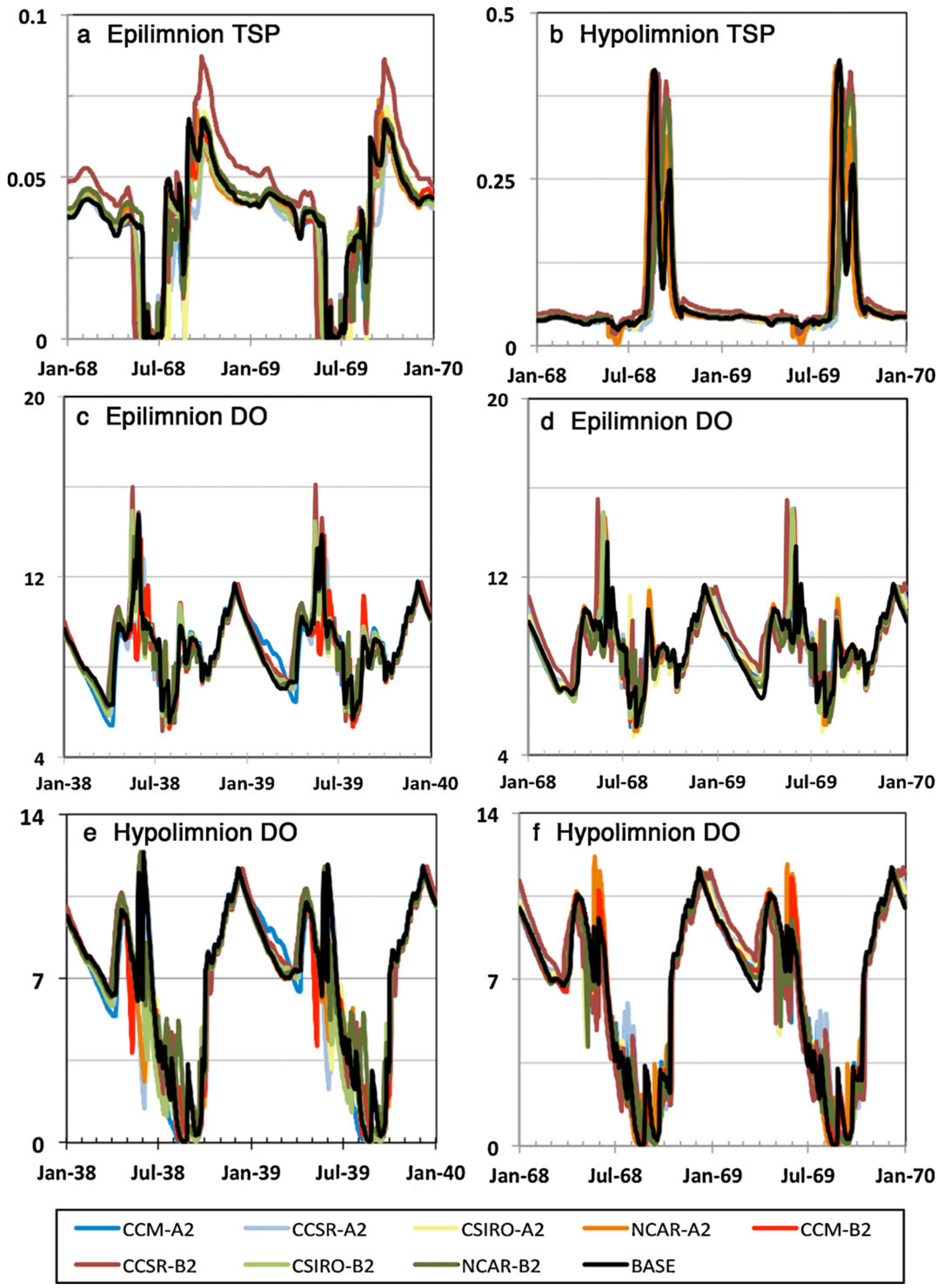

Fig. 8. Constituent concentrations (mg/l) for simulated climate change scenarios in Onondaga Lake: (a) epilimnetic TSP, 2040–2069; (b) hypolimnetic TSP, 2040–2069; (c) epilimnetic DO, 2010–2039; (d) epilimnetic DO, 2040–2069; (e) hypolimnetic DO, 2010–2039; and (f) hypolimnetic DO, 2040–2069. Charts show final two simulated years' results.

fold in NCAR-A2 in summer), though decreasing for NCAR-B2 – a relatively low temperature increase projection (Fig. 10c). Prominent differences between similar scenarios (e.g., NCAR-A2 and NCAR-B2) appear primarily related to prey availability. For example the duration of a May diatom bloom in NCAR-A2 is approximately twice that in NCAR-B2, and *B. longirostris* biomass in the NCAR-A2 scenario is more than ten times that in NCAR-B2. Chironomid biomass shows high year-to-year variation, with significant reductions in CCSR-A2 and CSIRO-A2 (from 1.5 mg/l to 0.25 mg/l) (Fig. 10d).

Fish dynamics resemble those of benthic macroinvertebrates, i.e. complex responses with high seasonal and annual variations. Biomass dynamics of two dominant fish species, alewife and gizzard shad are discussed in this section (Fig. 10e and f). Optimum growth temperature (T_{opt}) and maximum tolerated temperature (T_{max}) are found to be effectively controlling alewife biomass (16 and 27 °C, respectively), as highest biomass concentrations are observed in NCAR-B2 (i.e., up to 2.5 mg/l) (Fig. 10e). The other important clupeid, gizzard shad, also benefits from small increases in water temperature (e.g., NCAR-A2 and NCAR-B2), but

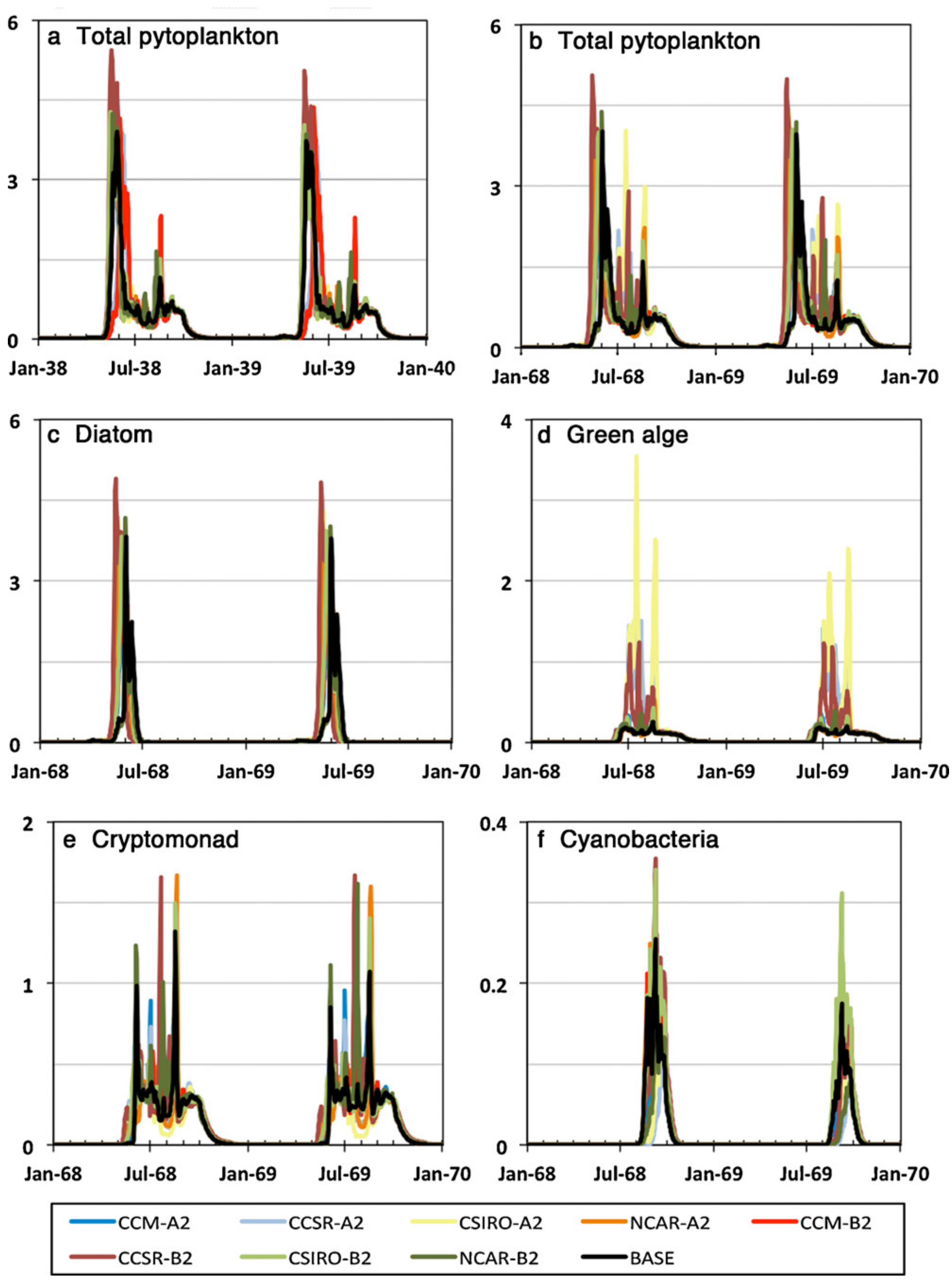

Fig. 9. Phytoplankton biomass concentrations (mg/l dry) for simulated climate scenarios in Onondaga Lake: (a) total phytoplankton, 2010–2049; (b) total phytoplankton biomass, 2040–2069; (c) diatom biomass, 2040–2069; (d) green algae biomass, 2040–2069; (e) crytomonad biomass, 2040–2069; and (f) blue-green algae biomass, 2040–2069. All graphs are 2 year excerpts from the simulation periods.

is negatively affected at higher increases (e.g., CCSR-A2) (Fig. 10f). Pumpkinseed, in the sunfish family, exhibit a response similar to that of their prey zebra mussels, in that biomass increases more than three-fold for scenarios NCAR-A2 and CCSR-B2. Unlike the clupeids, another sunfish, largemouth bass, apparently benefit from greater temperature increases, but show no significant changes in the lower temperature increase scenarios.

4. Discussion

Our study demonstrates the utility of coupling disparate environmental models together to project impacts of stressors on ecosystems. When used with HSPF, the Climate Assessment Tool in BASINS offers a mechanism to project impacts of climate change on watersheds. Among other applications, AQUATOX was intended to be applied in assessing climate change impacts on aquatic ecosystems; however, to our knowledge, it has not previously been utilized for that purpose. We concurrently used a hydrothermal model, UFILS4 to compensate for AQUATOX's limited capabilities for representing physical processes. The results in three simulated realms – watershed, heat balance and aquatic ecosystem – indicate more pronounced impacts in the second half of the 21st Century, in line with IPCC projections (Bates et al., 2008).

Our results suggest that despite increasing precipitation (projected in several scenarios), net stream discharge may actually decrease, and drought frequency and duration increase, as a consequence of increased evapotranspiration. Simultaneously, intensification of precipitation results in projected increases in

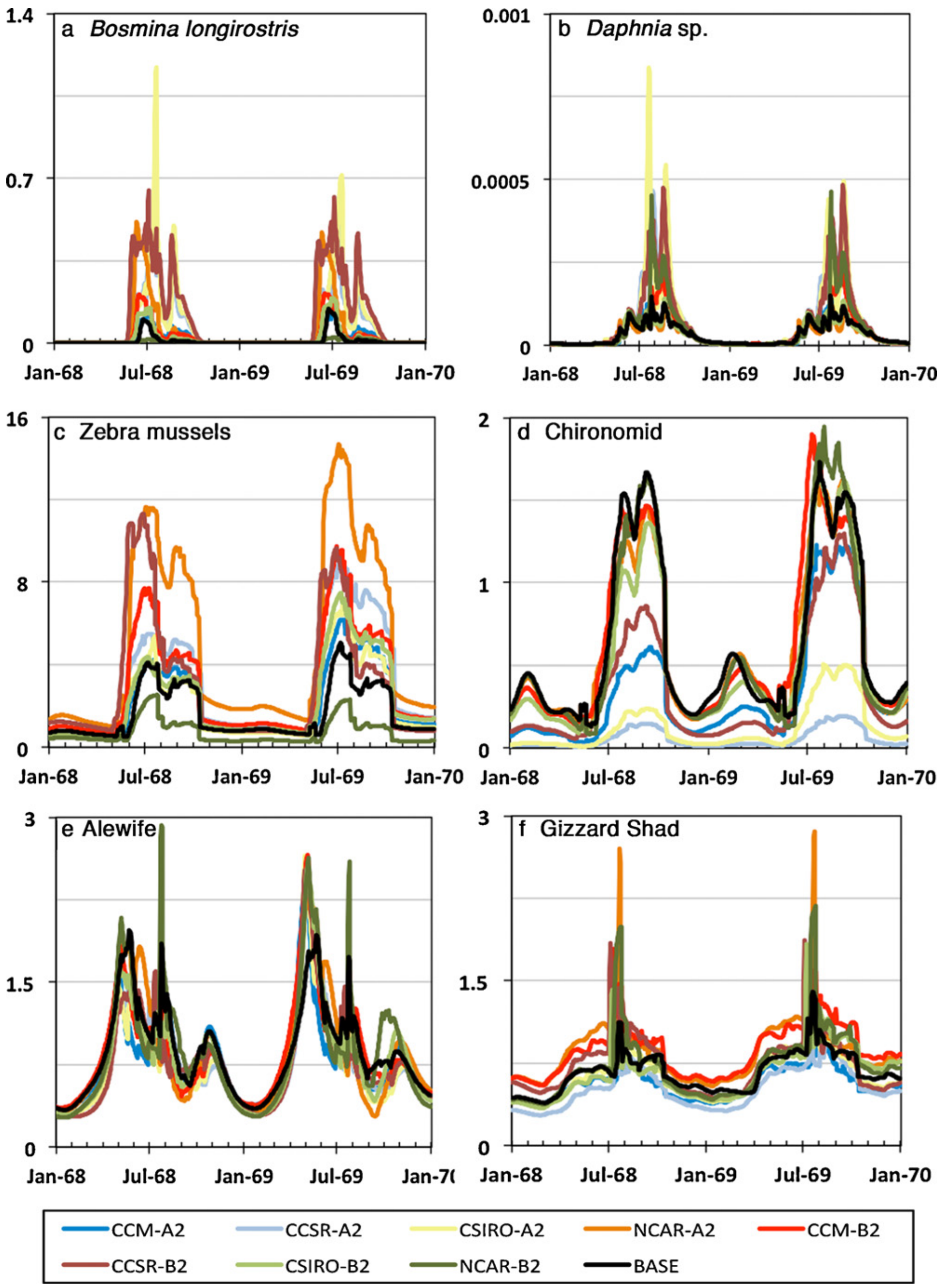

Fig. 10. Animal biomass concentrations (g/m^2 dry) in Onondaga Lake for the simulated climate scenarios: (a) *Bosmina longirostris*, 2010–2049; (b) *Daphnia* sp., 2040–2069; (c) zebra mussels, 2040–2069; (d) Chironomids, 2040–2069; (e) Alewife, 2040–2069 period; and (f) Gizzard shad, 2040–2069. All graphs are 2-year excerpts from the simulation periods.

loading of nutrients (especially P) to Lake Onondaga. Increasing nutrient and sediment discharges associated with increasing magnitude and frequency of storm events are generally expected to accelerate eutrophication in freshwater systems (Jeppesen et al., 2007). Water temperatures in Onondaga Lake are projected to follow changes in air temperature, with increases of up to 5.2 and 3.7 °C for epilimnion and hypolimnion, respectively.

The ecological impact of modified loadings (hydrologic and pollutant) combined with lake warming is a projected increase in eutrophication frequency and duration, with peak phytoplankton biomass occurring earlier and at greater magnitude (Adrian et al., 2006; Gerten and Adrian, 2002). Our results suggest that green algae may benefit at the expense of other phytoplankton species. By contrast, it is generally believed that cyanobacteria stand to benefit most from warmer temperatures (De Senerpont Domis et al., 2007; Jeppesen et al., 2007). Our results stand apart from those based purely on temperature, in that they project the combined impacts of multiple interacting stressors which are likely to accompany anthropogenic climate change in the future.

Our integrated modeling approach necessitated some simplifications. First, certain important atmospheric drivers including dew point temperature, solar radiation, wind speed and cloud cover were not changed from baseline scenarios, due to lack of projected values of these entities. Wind speed may have a particularly significant impact in larger lakes, on hydrodynamics and biotic processes (Blenckner, 2008). For watershed modeling, land-use patterns in Onondaga Lake's watershed were kept constant.

We did not represent macrophytes in the ecosystem model due to lack of reliable data. In order to utilize the current modeling framework for regulatory or planning purposes, potential improvements could include: (1) re-development of downscaled climate change scenarios incorporating additional atmospheric drivers (e.g., wind speed), (2) improvement in the temporal span of the hydrothermal model, providing long-term simulation results, and (3) implementing a rigorous validation for the ecosystem model against long term hydrological and water quality monitoring data. Future improvements to the study could include a sensitivity analysis implemented in all three models for the key climate drivers, using synthetic scenarios (e.g., changing the drivers by arbitrary amounts within realistic ranges).

5. Conclusions

The coupling of BASINS-CAT, HSPF, UFILS4 and AQUATOX shows promise as a method for projecting combined impacts of changes in air temperature and precipitation patterns on aquatic ecosystems.

Our results project that changes to watershed and lake ecosystem attributes will occur primarily after the 2040s.

These changes include increases in the magnitude of peak stream flows and higher loadings of nutrients and sediments, prolonged periods of thermal stratification due to warming of lake waters, and a general increase in primary production and zooplankton biomass in response to climate change.

Indirect impacts such as modified nutrient fluxes might be as important as direct climate change impacts (i.e. increasing water temperatures) in terms of influence on aquatic ecosystems.

Linking models through an input–output approach, as done in this study, inherently neglects certain feedback loops that might have significant impacts on long-term system behavior (e.g. impacts of biota on thermodynamics). Newer, more sophisticated tools that are fully capable of simulating interactions between hydrodynamics, thermodynamics and biology may provide enhanced means for conducting climate change impact assessment studies in the future.

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