MODELING CLIMATE CHANGE IMPACTS
ON THE THERMODYNAMICS OF ONEIDA LAKE:
APPLICATIONS OF A DYNAMIC RESERVOIR SIMULATION MODEL

A Thesis

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of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

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It was the grandest and most majestic sight I had seen. It was exquisitely beautiful. The sun in its full splendor at the western horizon gilding the enlightened clouds, the islands, the shores, the woods, and all seemed to vie with each other for preference. The evening was serene and delightful; a soft breeze curled the waves and fringed them with white while the sun, sinking toward the west beautified the whole scene.

Description of Oneida Lake
Francis Adrian VanderKemp (1792)

ABSTRACT

Substantial change in climate is predicted to occur across the globe this century. Understanding climatic impacts on lake ecosystems is highly relevant as they will have important effects on eutrophication, ecosystem processes, and aquatic biodiversity. Field-based monitoring and modeling were used to evaluate the impacts of predicted climate change on Oneida Lake temperature profiles and stratification. Oneida Lake is a 207 km^2 shallow, polymictic lake located in the center of an extensive 3,579 km^2 watershed in Central New York. Field data were collected on stream and groundwater temperature loading, weather, and lake temperatures at varying depths to calibrate and validate the Oneida Lake thermodynamics model. Downscaled climate data from three general circulation models and two emissions scenarios provided by the Northeast Regional Climate Center and maximum projections were used to assess the impacts of different anticipated climate scenarios on the lake for 2050 and 2099. Lake temperature profiles under current and anticipated conditions were modeled using a deterministic, one-dimensional model, Dynamic Reservoir Simulation Model (DYRESM), from the University of Western Australia Centre for Water Research. The sensitivity analysis confirmed the importance of meteorological variables, including solar radiation and wind speed, as drivers to the thermal regime of the lake. A best fit model was obtained by decreasing wind speed by 25%, mean albedo to 1%, and minimum layer thickness to 0.5 m. By the end of the century, the predicted increase in air temperatures and precipitation associated with the higher emissions scenario will be paralleled by an average increase in 2 m and 10 m water temperatures (April – November) of 2.47°C (SD 1.08) and 2.01°C (SD 1.43), respectively. Additionally, the higher emissions scenario indicated an increase of 15 consecutive days of stratification in Oneida Lake. This study contributes to our understanding of the thermal regime of polymictic lakes in a warmer world and provides broad-scale predictions of the effects of climate change on the thermal structure of the majority of global freshwater lakes.

BIOGRAPHICAL SKETCH

Water has always been the basis of Amy Lee Hetherington's life, from a childhood living, playing, and exploring on the shores of Cayuga Lake to an adulthood studying, understanding, and protecting this vital, limited resource. Early on, as an undergraduate at Cornell University, Amy participated in research-based internships through the National Science Foundation Research Experience for Undergraduates program at the University of Alaska, Fairbanks and the Cornell Biological Field Station in Bridgeport, New York. Also, as an undergraduate, Amy participated in the Cornell in Washington program and interned at the White House Office of Science and Technology Policy in the Clinton/Gore administration. In 1999, Amy earned a Bachelor of Science with Honors in Natural Resources from Cornell University.

After graduation, and prior to attending graduate school, Amy worked as an international management consultant for 10+ years assisting the public and private sectors adapt to change globally. Specifically, Amy worked with state environmental agencies in assessing federal and state permitting, compliance, and enforcement regulations for air, water, waste and also global pharmaceutical companies in evaluating international pharmaceutical regulations affecting human health. Amy's work with tens of Fortune 100 companies and governments spanned approximately 100 countries. To supplement her professional experience, Amy volunteered at the American Museum of Natural History leading tours in the Hall of North American Mammals and assisting with workshops, Central Park Conservancy learning about the history and ecology of the park and leading tours, and New York Cares organizing holiday gift giving and clothing drives for disadvantaged New Yorkers.

Amy decided to return to Cornell University for a Master of Science in Natural Resources with the goal of applying her professional skills to protect and benefit the natural environment. Amy's overall graduate research focuses on understanding climatic impacts on lake ecosystems as they will affect water quantity and quality and recommending watershed management practices for mitigating these impacts. Amy presented her research domestically and internationally at Cornell University, Cary Institute for Ecosystem Studies, Central New York Regional Planning and Development Board, New York State Federation of Lake Associations, American Water Resources Association, and the Global Lake Ecological Observatory Network and published her work in the 20ll American Water Resources Association Spring Specialty Conference Proceedings. Amy was awarded the Woodrow Wilson National Fellowship Foundation Doris Duke Conservation Fellowship, Andrew W. Mellon Student Research Grant, Cornell University Graduate School Research Award, and Mario Einaudi Center for International Studies International Research Travel Grant. In addition to her studies, Amy represented Cornell University at the 2010 United Nations Framework Convention on Climate Change conference in Cancun, Mexico and participated in the Dialogs for Water and Climate Change. This experience inspired Amy to intern with the Chief of the United Nations Department of Economic and Social Affairs, Sustainable Development Division, Small Island Developing States Unit in New York, New York. Also, Amy served as President of the Cornell University Department of Natural Resources Graduate Student Association and Community Service Chair of the Cornell University Kappa Delta Omega Chi Chapter Advisory Board. Upon graduation in January 2013, Amy will continue her studies for her doctorate in the Department of Natural Resources at Cornell University.

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New York Regional Planning and Development Board, and Jessica Breiten, Chief Planner at the Herkimer-Oneida Counties Comprehensive Planning Program. Special thanks to Dr. Art DeGaetano, Professor at Cornell University Department of Earth and Atmospheric Sciences, for providing the downscaled climate projections for Oneida Lake and its watershed and Jessica Rennells, Technician at Cornell University Department of Earth and Atmospheric Sciences, for supplying me with the Syracuse Airport meteorological data.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Warming of the climate system is “unequivocal” (Intergovernmental Panel on Climate Change [IPCC], 2007). The hydrologic cycle, a fundamental component of climate, is being altered in important ways by climate change. Indicators of climate change over the last century in the northeastern United States include warmer temperatures, increases in precipitation, and changes in the timing and intensity of precipitation (Huntington et al., 2009). Climate models suggest that these trends are expected to continue, with potential increases of as much as 9°C in mean annual temperature and 15% in annual precipitation by the end of the century in New York State (Rosenzweig et al., 2011). Potential increases in water temperatures between 1°C and 9°C have been predicted for a range of water courses in the United Stated and United Kingdom (Webb, 1996).

The main impacts of climate change on freshwater ecosystems result from changes in air temperature, precipitation, and wind regimes (Nickus et al., 2010). Freshwater systems respond by changes in their physical characteristics, including stratification and mixing regimes of lake water columns, catchment hydrology, and ice cover, all of which may induce chemical changes in habitats, e.g., alterations to oxygen concentrations and nutrient cycling (Nickus et al., 2010). Biological responses include changes in the abundance, composition, and distribution of many organism groups (Nickus et al., 2010). Climate changes have already been shown to translate into changes in hydrologic systems, with increased runoff and earlier spring peak discharge in many snow-fed rivers (Hodgkins et al., 2003; Hayhoe et al., 2007), decreased duration of ice cover in some lakes (Robertson et al., 1992; Magnuson et al., 2000; Futter, 2003; Hodgkins et al., 2003; Duguay et al., 2006; Korhonen, 2006; Hayhoe et al., 2007; Huntington et al., 2009), and effects on both thermal structure (Magnuson et al., 1997; Livingstone, 2003; Straile et al., 2003; Coats et al., 2006; Gaiser et al., 2009) and water quality of warming rivers and lakes (Magnuson et al., 1997; Jeppesen et al., 2009). In freshwater systems, changes in algal, plankton, and fish abundance have been associated with rising water temperatures, as well as related to changes in ice cover, oxygen levels, and circulation (McGinn, 2002; Winder and Schindler, 2004; Winder et al., 2009; O'Neil et al., 2012). Because of these links between changes in climate and ecological responses, ecological changes are predicted to continue under projected future climate scenarios (Robertson and Ragotzkie, 1990; Hondzo and Stefan, 1991; Stefan et al., 1996; Stefan et al., 1998; Hostetler and Small, 1999; Blenckner, 2005; Mooij et al., 2005).

The effects of climate change on the physical and ecological dynamics in lakes can be diverse due to the specific conditions and individuality of lakes, including geographical position, catchment characteristics, lake morphology, lake history, and internal lake processes (Gerten and Adrian, 2001; George et al., 2004; Blenckner, 2005; Mooij et al., 2005; Tanentzap et al., 2008). Global warming scenarios generally indicate warmer epilimnetic waters increasing the stability of stratification in lakes (Livingstone, 2003); however, temperature in the hypolimnion may increase or decrease depending on the timing and onset of stratification (DeStasio et al., 1996; Hocking and Straskraba, 1999; Tanentzap et al., 2008; De Stasio et al., 2009). In the vast majority of lakes, the vertical temperature distribution and the intensity of vertical mixing are determined predominantly by meteorological forcing at the lake surface (Stefan et al., 1996; Peeters et al., 2002). Solar radiation and atmospheric long wave radiation heat the water column; whereas, evaporation and back radiation cool it. Convective heat transfer driven by the temperature difference between water and air can also warm or cool a lake. The differential radiative heat absorption throughout the lake depth causes thermal stratification creating a vertical density gradient. These density gradients are often observed at the metalimnion, a region of sharp change in water temperature which delineates the upper well-mixed epilimnion from a relatively quiescent, deep hypolimnion (Monismith and MacIntyre, 2009). Stratification can be transient or persistent, varying at time scales from hours to decades. This vertical partitioning of the water column has important implications for the availability of dissolved oxygen and nutrients, as well as vertical distribution, migration, and feeding of zooplankton and fish (MacIntyre and Melack, 2009). Eventually, wind and convection erode the stability of stratification and mix the water column. A change in climatic conditions affecting local meteorological forcing will therefore alter both thermal structure and vertical transport by mixing, which in turn will affect the flux of dissolved oxygen and nutrients, as well as the productivity and composition of lake ecosystems (Peeters et al., 2002).

Due to this complexity, predictions of climate change impacts for individual lakes need to be based on hydrodynamic models applied to specific lake conditions (DeStasio et al., In Press) to dynamically account for the distribution of heat in lakes in response to climate change (Trolle et al., 2011). Hydrodynamic and water quality models of lake ecosystems have become more sophisticated since the early models developed in the 1970s as a result of increased demand and improved computing technology (Jorgensen, 1995). The University of Western Australia Centre for Water Research's Dynamic Reservoir Simulation Model (DYRESM) is one such model that uses a one-dimensional representation of the vertical structure of the water body. This model has been successfully applied to a wide range of lakes and reservoirs globally (Patterson et al., 1984; Robertson and Ragotzkie, 1990; Gal et al., 2003; Tanentzap et al., 2007; Tanentzap et al., 2008;

Trolle et al., 2011; De Stasio et al., In Press). This model requires a large amount of input data but yields high resolution output leading to a more accurate description of the hydrodynamic processes.

In this study, DYRESM was used to study the impacts of climate change on the thermal stratification of Oneida Lake. This lake and its watershed, located in Central New York, is an ideal system for this project due to the wealth of historical climatic and hydrologic data. Oneida Lake is a shallow, 207 km^2 lake located in the center of an extensive 3,579 km^2 watershed. The lake is widely used for tourism, fishing, and recreation. The importance of the lake's healthy ecosystem was highlighted in a 2007 angler survey which demonstrated that approximately $12.5 million in revenue was generated in the surrounding communities from the lake's recreational fishery each year (New York State Department of Environmental Conservation, 2009). The Oneida Lake ecosystem has been studied for six decades resulting in approximately 250 scientific publications. A comprehensive, historic weather (1920's – present) and hydrologic (1950's – present) data set exists for Oneida Lake and its surrounding watershed, including long-term seasonal lake temperature profiles. Since Oneida Lake has frequently been used as a model system for understanding impacts of environmental change in the Great Lakes and other mesotrophic systems, be it invasive species or climate (Idrisi et al., 2001; Rudstam et al., 2004; Jackson et al., 2008), the results of my research could have relevance for lake management practices elsewhere, potentially globally.

To understand the impacts of climate change on the thermodynamics of Oneida Lake, the specific objectives of this study were as follows:

- Collect 2010 and 2011 lake and watershed field data as forcing inputs to the one-dimensional hydrodynamic model,
- Simulate the thermal structure of Oneida Lake with the DYRESM, and
- Evaluate the impacts of predicted climate change on lake temperature profiles and stratification.

METHODS

Field monitoring and modeling within Oneida Lake and its watershed were used to accomplish the objectives for this project.

Study Area

Oneida Lake (Latitude 43°10', Longitude -75°52') and its watershed are located in Central New York (Figure 1). Oneida Lake, the largest lake entirely within New York State, is a 207 km^2 shallow lake with a mean depth of 6.8 m and a maximum depth of 16.8 m. The lake basin is a spoon-shaped depression that deepens towards the eastern end. The lake is 33.6 km long and averages 6.1 km wide. Its long axis is oriented west-northwest to east-southeast and is fully exposed to the prevailing, west-northwesterly winds producing well-mixed and generally isothermal conditions throughout the ice-fee months (Mills et al., 1978). Normal elevation above sea level is 111 m during the winter and 112 m during the summer (Mills et al., 1978) with a lake volume of 1.56 x 10^9 m^3. Oneida Lake has one of the shorter hydraulic residence times ever reported for a lake of its large size (Kaste et al., 2003) with an annual average of 239 days (0.67 year) (Schneider et al., In Press). Lake level is regulated to provide sufficient water for navigation along the canal system that goes through the lake while minimizing potential for flood and winter ice damage to the many residential properties and marinas on the lake’s shoreline (Goebel, 2001; Schneider et al., In Press). Navigation season extends from the first Monday in May to the first Sunday in November (Goebel, 2001). Dam gates at Caughdenoy are opened at the end of the navigation season to lower the lake level in the winter and provide storage for spring snowmelt. As the navigation season approaches, the dam gates are closed to capture post spring runoff and gradually raise water levels to enable safe passage in the canals during the summer (Goebel, 2001).

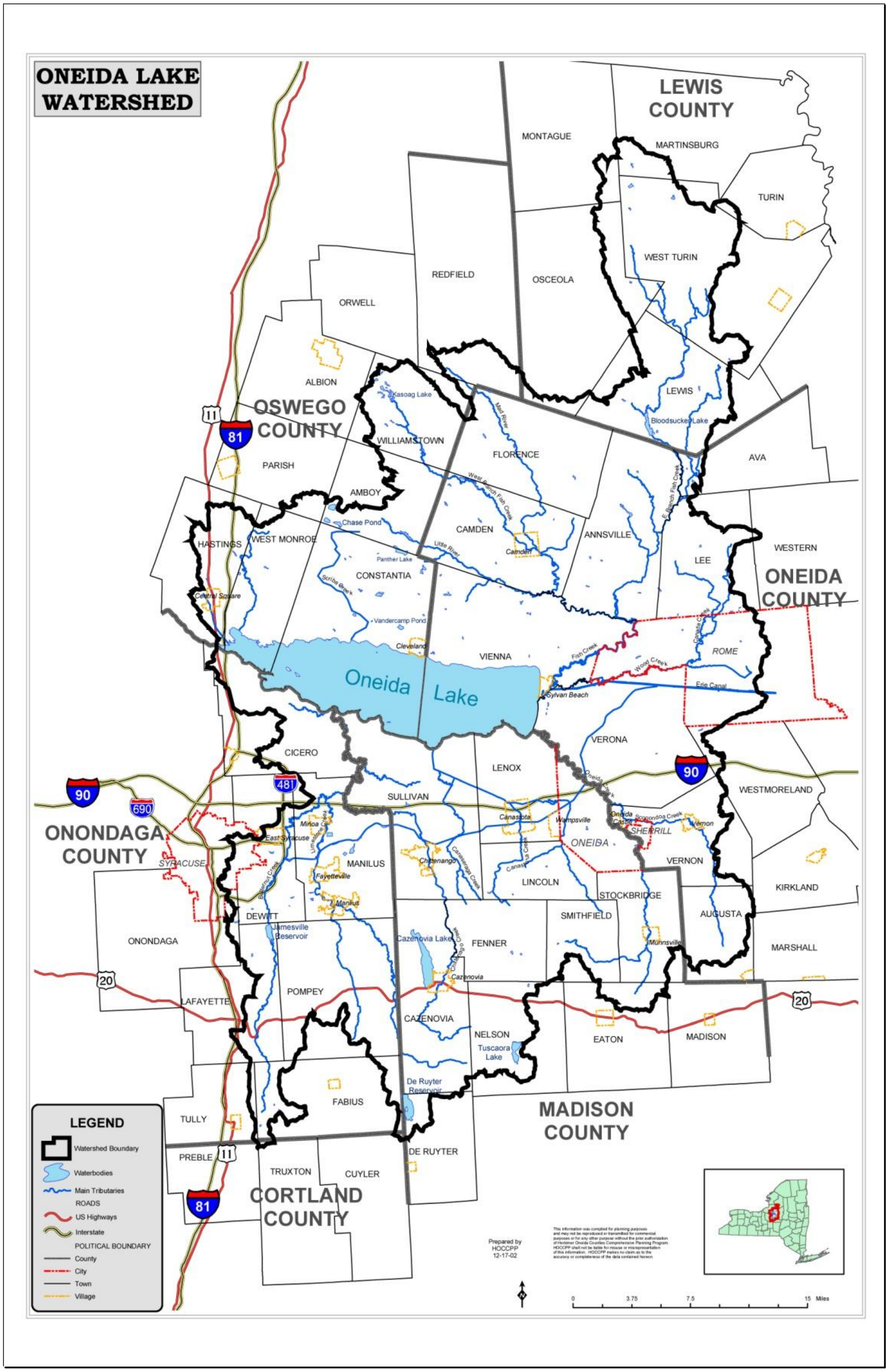

Figure 1. 207 km^2 Oneida Lake and Its 3579 km^2 Watershed Located In Central New York (Herkimer Oneida Counties Comprehensive Planning Program, 2002).

Oneida Lake is located in the center of an extensive 3,579 km^2 watershed. The watershed is large in comparison to the lake with a lake to watershed surface area ratio of only 0.06. The nearly equal in size northern and southern drainage basins are similar in geologic origin, which consists of limestone, shale, dolomite, sandstone, and glacial till, but differ considerably in land cover and climatic characteristics. The land use in the northern basin consists largely of forests and pocket wetlands; whereas, the southern basin is a mix of suburban and agricultural land (Schneider et al., In Press). The Oneida Lake watershed has a continental climate characterized by warm, dry summers and cold, snowy winters. Major climatic influences on the watershed include topography, prevailing westerly wind direction, and proximity to Lake Ontario. Annual precipitation varies across the watershed ranging from approximately 100 cm/year in the southern to approximately 130 cm/year in the northern portion of the watershed (Central New York Regional Planning and Development Board, 2003). The watershed is located in the eastern Lake Ontario snowbelt and is subject to lake effect snow events (Central New York Regional Planning and Development Board, 2003). Average seasonal snowfall in the Oneida Lake watershed varies from more than 508 cm in the Tug Hill region which receives the greatest annual snowfall east of the Rockies (Tug Hill Commission, 2010), between 404 and 508 cm in the eastern portion of Oswego County, and 292 cm in the City of Syracuse (Central New York Regional Planning and Development Board, 2003).

The Oneida Lake watershed has an extensive surface water network. Seven tributaries, three in the north, Scriba Creek, Fish Creek, and Wood Creek, and four in the south, Oneida River, Canaseraga Creek, Cowaselon Creek, and Chittenango Creek provide significant surface water inputs to the lake (Figure 1). According to Greeson (1971), the total annual discharge of water from the Oneida Lake watershed via the Oneida River is approximately 213 x 10^7 m^3/year, an estimate based on discharge for the period 1931-1960. Greeson estimated precipitation to be 379 x 10^7 m^3/year in the watershed. If evapotranspiration is assumed to be the difference between precipitation and outflow from the watershed, it would then be equal to 166 x 10^7 m^3/year or 48.8 cm/year. Thus, approximately 56% of the precipitation that falls in the watershed reaches the lake through surface and groundwater inflow. The rest is lost through evaporation, and absorption by trees and plants. The Tug Hill region in the northern portion of the watershed contributes approximately 67% of total surface inflows largely due to the volume of snowfall (Greeson 1971). The Oneida River, along the western shoreline, forms the only outflow.

Portions of six counties and 69 municipalities are located within the Oneida Lake watershed. According to the U.S. Census Bureau's 2000 statistics, approximately 262,000 people live in the watershed and are dependent on the lake for drinking water and wastewater disposal. A variety of tourism and recreation opportunities are available in the Oneida Lake watershed with Oneida Lake's fishery functioning as a major contributor to the region's tourism industry. Oneida Lake has been identified as the most important inland fishery and the second most important sport fishery in New York State after the much larger Lake Ontario. The 2007 net economic value of Oneida Lake's freshwater fishery was estimated to be over $12.5 million, ranking it first among New York State's inland waters (NYS Department of Environmental Conservation, 2009). People from all over New York State and beyond annually spend millions of dollars throughout the watershed as they recreate on Oneida Lake and its tributaries. For this reason, the integrity of the lake and the watershed has a direct impact on the economic livelihood of local municipalities.

Field Monitoring

Temperature loading contributed by both tributary streams and groundwater seepage into Oneida Lake was measured from June 2010 through November 2010 and March 2011 through November 2011. Automated HOBO TidBit® data loggers measured incoming stream temperatures every 4 hours daily beginning at 0:00 in two northern basin streams, Scriba Creek and Fish Creek, two southern basin streams, Oneida Creek and Chittenango Creek, and the outlet, Oneida River at approximately 0.5 m depth (Figure 2). Discharge was periodically measured at the Scriba Creek, Fish Creek, and Chittenango Creek sites at the time of temperature measurements. Total water loading was determined using a combination of an automated TruTrack and manual stream gauge for monitoring water level (stage) and converting these stage data to discharges by measuring stream cross-sectional area and velocity with a Marsh-McBirney Flo-Mate 2000 electromagnetic velocity meter to create a rating curve for each monitored site. In addition, groundwater wells were installed on the northern and southern shores of Oneida Lake at Cleveland, NY and Bridgeport, NY, respectively for monitoring hydraulic head gradients and temperature of inflowing seepage waters. Additional groundwater temperature data were collected in residential groundwater wells at Cleveland, NY and Shackelton Point in Bridgeport, NY (Figure 2). Groundwater temperatures were similarly recorded every 4 hours beginning at 0:00 using automated HOBO TidBit® data loggers.

Continuous lake water temperature, air temperature, light intensity, precipitation, and evaporation were measured at Shackelton Point in Bridgeport, NY (Figure 2). In a shallow bay, surface water temperature was measured every 4 hours beginning at 0:00 using an automated HOBO TidBit® data logger suspended from a float and secured with an anchor. Additionally, air temperature, light intensity, precipitation, and evaporation were measured from a grey 1.2 m x 0.6 m Styrofoam raft anchored in the bay. Air temperature was measured every 4 hours beginning at 0:00 using an automated HOBO TidBit® data logger hung from a screen within a grey 30 cm PVC pipe mounted upright on the raft. Likewise, light intensity was measured every 4 hours beginning at 0:00 using an automated HOBO Pendant® data logger mounted directly on the raft. For validation purposes, air temperature and light intensity were also measured in an open meadow approximately 18 m from the shoreline. Precipitation and evaporation were measured daily from a Tru-Check® rain gauge and 38 cm diameter stainless steel pan containing 4 L of water mounted on the raft, respectively. The bottom half of the stainless steel pan was submerged in the water and a screen placed over the pan to deter birds from interfering with the water. The amount of water in the pan was measured and refilled every day without precipitation at 20:00. Measured meteorological data were compared with those collected at the Syracuse Hancock International Airport (Latitude 43°7'12", Longitude -76°7'12", Elevation 128 m above MSL) located in the Oneida Lake watershed on average 21 km from Oneida Lake (Figure 2). Minimum and maximum distances from Syracuse Hancock International Airport to Oneida Lake are 9.5 km and 33 km, respectively.

In 2010 and 2011, lake temperatures were recorded at 5 locations within Oneida Lake approximately weekly at 1 m intervals throughout the water column using a Hydrolab DataSonde 3 (Data available in Rudstam and Mills, 2012) (Figure 2). Additionally, for April – November 2010, lake temperatures were recorded every 60 minutes at 2 m and 10 m using automated HOBO TidBit® data loggers at Shackelton Point in Bridgeport, NY (Figure 2). Likewise, lake temperatures were recorded every 60 minutes at 1 m intervals using a thermistor string equipped with automated HOBO TidBit® data loggers at Shackelton Point in Bridgeport, NY for May – November 2011 (Figure 2). Lastly, at the 5 locations within Oneida Lake, approximately weekly light profiles using a LiCor LI-2000 were recorded for the duration of the study (Figure 2).

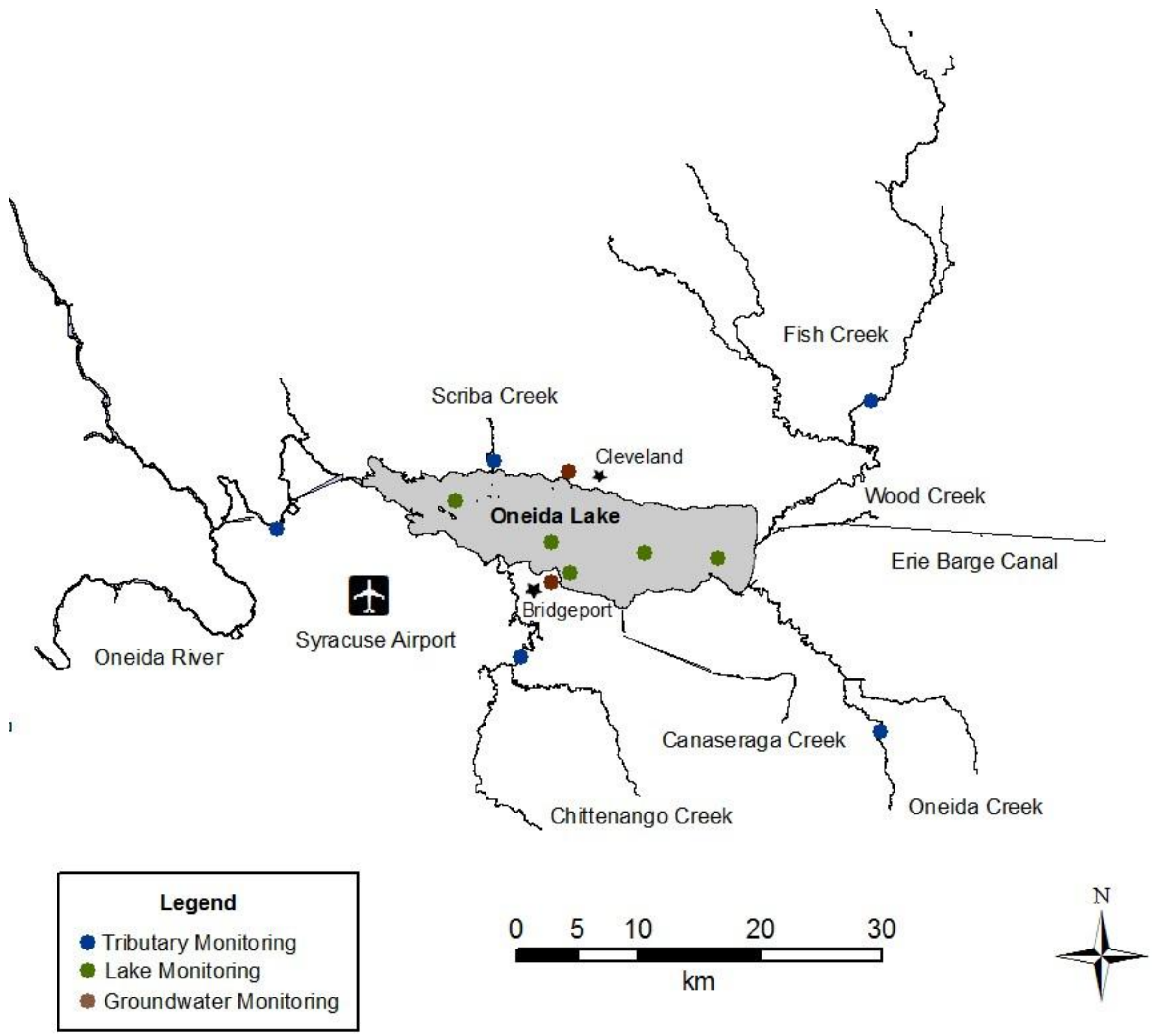

Figure 2. Oneida Lake and Its Watershed Field Monitoring Sites. Five tributary monitoring sites located in Scriba Creek at Constantia, NY, East Branch Fish Creek at Taberg, NY, Oneida Creek at Sherrill, NY, and Chittenango Creek at Bridgeport, NY. Five lake monitoring sites located at Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point. Two groundwater monitoring sites located at Cleveland, NY and Bridgeport, NY.

Modeling

Model Description

The University of Western Australia (UWA) Centre for Water Research's (CWR) Dynamic Reservoir Simulation Model (DYRESM) Version 4.0.0-38 was used to model Oneida Lake's thermal structure. DYRESM is a one-dimensional thermodynamics model for predicting the vertical distribution of temperature and density in lakes and reservoirs. This model is widely accepted as a standard for lake modeling (Imberger et al., 1981; Patterson et al., 1984; Gal et al., 2003; Tanentzap et al., 2007). DYRESM simulates vertical water temperature and density with horizontal Lagrangian layers that vary in thickness and number. The model's predictions are driven by volume changes produced by inflows, outflows, and mixing, and are dependent on the thickness of the horizontal layers to detect changes in vertical density stratification (Imberger et al., 1978). The model adopts a one-dimensional layer structure based on the importance of vertical density stratification over horizontal density variations, with destabilizing forces such as wind stress and surface cooling abbreviated to ensure a one-dimensional structure (Tanentzap et al., 2007; Imerito, 2010a; Imerito, 2010b). Mixing and surface layer dynamics are modeled at the confluence of adjacent layers and are dependent on a turbulent kinetic energy budget and potential energy required for mixing (Hamilton and Schladow, 1997).

Simulations

DYRESM 4.0.0-38 was configured to simulate temperature for Oneida Lake on a daily interval during the ice-free season for 2010 and 2011. This version does not include an ice module; therefore, dates were selected within the ice-free periods of 2010 and 2011 for Oneida Lake. Simulations were conducted for 251 days in 2010 from March 22 to November 27 and 238 days for 2011 from April 4 to November 27. Simulation start dates were the first day of ice-out; whereas, simulation end dates were selected as November 27 to avoid errors with the United Nations Educational, Scientific and Cultural Organization (UNESCO) density function of water (Imerito, 2010a). Model inputs were based on data collected from monitoring of Oneida Lake and its watershed or constants provided by the UWA CWR (Table 1). The model was run at one hour time steps, daily output, and a vertical resolution within the range specified during model setup while the model determined the actual layer thickness. Model output data consisted of the temperature for each of 100 depth layers in the 17 m water column. The average modeled output was compared to an average of temperature field data collected at 1 m intervals throughout the water column at 5 stations in Oneida Lake (Figure 2). Model performance was first assessed based on visual inspection of time series plots of daily simulated and weekly observed data. Subsequently, for a more rigorous analysis, the simulated and observed mean daily water temperatures at 2 m and 10 m were compared and r^2 values calculated. Furthermore, the average deviation (SD) and mean absolute difference (SD) between the simulated and measured temperatures and root mean square error were calculated at 2 m and 10 m. Lastly, the difference between 2 m and 10 m for the simulated and observed average daily water temperatures were compared.

Table 1. Initial DYRESM Parameter Value Constants (Imerito, 2010b).

File	Parameter	Default Value	Units
Parameter	Bulk Aerodynamic Momentum Transport Coefficient	1.3E-3	-
Parameter	Mean Albedo of Water	0.08	-
Parameter	Emissivity of Water	0.96	-
Parameter	Critical Wind Speed	3.00	m/s
Parameter	Entrainment Coefficient Constant	2.0E-3	-
Parameter	Bubble Entrainment Coefficient	0.012	-
Parameter	Buoyant Plume Entrainment Coefficient	0.083	-
Parameter	Shear Production Efficiency	0.06	-
Parameter	Potential Energy Mixing Efficiency	0.20	-
Parameter	Wind Stirring Efficiency	0.40	-
Parameter	Effective Surface Area Coefficient	1.0E+7	-
Parameter	Vertical Mixing Coefficient	200	-
Configuration	Benthic Boundary Thickness	0.2	m
Configuration	Minimum Layer Thickness	1.5	m
Configuration	Maximum Layer Thickness	3.0	m
Configuration	Activate Bubbler	FALSE	-
Configuration	Activate Non-Neutral Stability	FALSE	-

Inputs

Lake Morphometry

These data include a matrix of height (m), area (m^2), and volume (m^3) values which describe the hypsographic curve for Oneida Lake. These values were calculated with ArcGIS 9.3 using an updated bathymetric raster dataset for Oneida Lake (Fitzgerald et al., In Press).

Initial Conditions

These data include a temperature and salinity profile according to the Practical Salinity Scale (pss) for the first days of the simulations. Due to limited spring monitoring in Oneida Lake, the initial conditions were based on the temperature profiles conducted at Shackelton Point in Bridgeport, NY (Figure 2) on March 22, 2010 and April 8, 2011. Oneida Lake salinity is below 0.2 pss; therefore, the salinity profiles were set to zero for this study.

Meteorological Data

Meteorological inputs consisted of hourly short wave radiation (W/m^2), cloud cover (%), air temperature (°C), vapor pressure (mb), wind velocity (m/s), and precipitation (m) measured at the Syracuse Hancock International Airport (Latitude 43°7'12", Longitude -76°7'12", Elevation 128 m above MSL). The shortest and longest distances between the airport and Oneida Lake are 9.5 km and 33.0 km, respectively (Figure 2). Given the relative proximity of the airport to the lake, meteorological data from the airport were used as input to the model with few adjustments. Short wave radiation, cloud cover, air temperature, relative humidity, wind velocity, and precipitation at the Syracuse Airport for 2010 and 2011 were obtained from Cornell University's Northeast Regional Climate Center. DYRESM estimates long wave radiation from cloud cover and the water surface temperature calculated during the simulation (Imerito, 2010b). For 2010 and 2011, the minimum air temperature was raised to 0.1°C to avoid errors in the UNESCO density function of water within DYRESM (Centre for Water Research, 2012). Vapor pressure was approximated from relative humidity and air temperature as follows:

$$e_a = (h/100)\exp[2.303((a \cdot q_D/(q_D + b)) + c)]$$

where
e_a = Vapor Pressure (hPa)
h = Relative Humidity of Air (%)
q_D = Dry Bulb Air Temperature (°C)

Additionally, the coefficients for over-water calculations are as follows:
a = 7.5
b = 23.3
c = 0.7858 (Tennessee Valley Authority, 1972).

Inflow Data

DYRESM requires daily volume (m^3/day), temperature (°C), and salinity (pss) of major inflows. Oneida Lake salinity is below 0.2 pss; therefore, inflow salinity was set to zero for this study. According to Greeson (1971), seven tributaries contribute significant inflow volumes to Oneida Lake: Scriba Creek, West Branch Fish Creek, East Branch Fish Creek, Wood Creek, Oneida Creek, Canaseraga/Cowaselon Creek, and Chittenango Creek (Table 2). Greeson (1971) calculated the average annual discharge (m^3/s) and percentage of total discharge using gauged flows for these tributaries from 1931-1960 (Table 2); however, these gauged inflows were not sufficient to balance the water budget of Oneida Lake given measured outflow, direct precipitation, and calculated evaporation. Greeson (1971) attributed additional inflow to ungauged streams (Table 2) to balance the water budget. Alternatively, this additional inflow could be attributed to groundwater inflow which has since been documented as a significant contributor throughout the shoreline of Oneida Lake (Schneider et al., 2004; Schneider et al., In Press).

Table 2. 1931 – 1960 Oneida Lake Watershed Tributaries Discharge (Greeson, 1971).

Tributary	**Average Annual Discharge (m^3/s)**	**Percentage of Total Discharge (%)**
Scriba Creek	2.3	4
West Branch Fish Creek	14.1	21
East Branch Fish Creek	15.7	23
Wood Creek	4.0	6
Oneida Creek	4.9	7
Canaseraga/Cowaselon Creek	3.5	5
Chittenango Creek	12	18
Ungauged	11.2	16
TOTAL Outflow (Caughdenoy Dam)	67.7	-

For DYRESM presented here, this system was simplified to four stream inflows. The East Branch Fish Creek, West Branch Fish Creek, and Wood Creek merge to form Fish Creek and Cowaselon Creek is a tributary of Canaseraga Creek. Because of the limited contribution and relative proximity of Canaseraga Creek to Oneida Creek and Chittenango Creek, its inflow volume was distributed equally across the two major south shore creeks, Oneida Creek and Chittenango Creek. The 16% ungauged inflow was distributed to the four streams, Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek, based on their relative volumetric contributions to Oneida Lake.

Discharge data for 2010 and 2011 were obtained from the USGS continuous gauges for the East Branch of Fish Creek at Taberg, NY (Latitude 43°18'06", Longitude -75°37'09") and Oneida Creek at Oneida, NY (Latitude 43°05'51", Longitude -75°38'22"). Missing data values were rare with gaps between measurements ranging from 1 to 3 days. These inconsistencies were resolved by averaging the previous and next values. The volumetric contribution weightings for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek combined with the 2010 and 2011 Fish Creek and Oneida Creek daily discharge data from USGS were used to determine daily relative inflow volumes for the four stream inflows. Average daily discharge for East Branch Fish Creek and Oneida Creek were examined for the length of the historical record in conjunction with the 2010 and 2011 discharge data. For 2010 and 2011, measured and calculated discharges were compared for East Branch Fish Creek, Chittenango Creek, and Scriba Creek. In addition, the 2010 and 2011 average annual discharges and volumetric contributions were compared with historical values from 1931-1960.

Inflow temperature data for 2010 and 2011 were obtained from field monitoring for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek as described above. Regression relationships between air and water temperature were developed to estimate temperatures for each of the four inflow streams in early spring and late fall when monitoring was not conducted.

Withdrawal Data

These data included the volume (m^3/day) of the Oneida River at the USGS gauge at Euclid, NY (Latitude 43°12'18", Longitude 76°13'05"). Oneida Lake is drained by this single outlet located on the western edge of the lake. Missing data values were rare with gaps between measurements ranging from 1 to 41 days. These inconsistencies were resolved by averaging the previous and next values for gaps of 3 days or less. Missing data values for more than 3 days were resolved by developing a regression relationship between a 7 day backwards moving average of the East Branch of Fish Creek inflow discharge and the Oneida River average daily outflow discharge. Average daily discharge for the Oneida River was examined for the length of the historical record in conjunction with the 2010 and 2011 discharge data.

Water Budget

A water budget accounts for the inputs and outputs of water where input must balance output and changes in water storage over a specified time period. For this study, inputs of water consist of tributary inflows and direct precipitation while outputs are from the Oneida River outflow and evaporation. Residual inflow was derived from a daily water balance for Oneida Lake. The water balance included recorded data for lake heights at Cleveland, NY provided by the NYS Canal Corporation adjusted to volume from lake surface area, inflows, outflows, direct precipitation estimated from Syracuse Hancock International Airport, and theoretical evaporation. Evaporation was derived as follows:

$$E = 6.25 \bullet 10^{-4} u_8 (e_0 - e_8)$$

where
E = Evaporation (cm/3 hours)
u_8 = Wind Speed at 8 m Level (Knots)
e_0 = Saturation Vapor Pressure at Water Surface Temperature (mb)
e_8 = Saturation Vapor Pressure of Air at 8 m Level (mb) (Tennessee Valley Authority, 1972).

The saturation vapor pressure of water at standard atmospheric pressure over water's surface was computed by the Magnus-Tetens formula:

$$e_0 = \exp(2.3026\,(((7.5\,\Theta_o)/(\Theta_o + 237.3)) + 0.7858))$$

where
e_0 = Saturation Vapor Pressure at Water Surface Temperature (mb)
Θ_o = Surface Water Temperature (°C) (Tennessee Valley Authority, 1972).

Additionally, saturation vapor pressure of air based on relative humidity and air temperature was computed as follows:

$$e_8 = (h/100)\exp[2.303((7.5 \bullet q_D/(q_D + 237.3)) + 0.7858)]$$

where
e_8 = Saturation Vapor Pressure of Air at 8 m Level (mb)
h = Relative Humidity of Air (%)
q_D = Dry Bulb Air Temperature (°C) (Tennessee Valley Authority, 1972).

Balancing the water budget required increasing the daily inflow by 7% in 2010 and increasing the outflow by 26% in 2011. In 2010, this water was added to the four inflows in proportion to their known contributions because the source of this additional water was not known. Additionally, the effect on the model of assuming this water was primarily from groundwater was explored by adding a fifth inflow with measured groundwater temperatures from the northern and southern shores and residential wells.

Light Extinction Coefficient

Light extinction coefficients were calculated from April-November 2010 and 2011 irradiance measurements throughout the water column. Water column irradiance was measured with a LI-COR 4π sensor coupled to a LI-COR 2000 data logger at 0.5 m intervals from the surface to the bottom at the five stations (Figure 2). Light attenuation coefficients were calculated from the light intensity definition according to the Beer-Lambert law:

$I_z = I_o\, e^{(-KZ)}$

where

I_z = Light Intensity at Depth Z
I_o = Light Intensity at Surface
K = Light Attenuation Coefficient (m^{-1})
Z = Depth Distance (m) (Wetzel, 2001).

Baseline Simulation

The baseline is the initial DYRESM simulation for Oneida Lake in 2010 using inputs based on data collected from monitoring of Oneida Lake and its watershed and default parameters (Table 1). Model performance was assessed as described in the Simulations section.

Sensitivity Analysis

Input required for model simulations included forcing data (meteorological conditions, inflows, and withdrawals), initial conditions, and a series of parameters. While the forcing data and initial conditions were largely dependent on available data collected from the lake and watershed, the model parameters were based on published values, results of experiments when available, and the experience of DYRESM modelers. Therefore, there was a degree of uncertainty associated with the parameter values when applied to Oneida Lake. This uncertainty in parameter values, along with any measurement error associated with the forcing data, lead to errors in the model and its ability to successfully reproduce field conditions for the lake. A sensitivity analysis was performed to examine the sensitivity of the model to changes in the parameter's or forcing variable's values and assisted in identifying ways to calibrate or reduce discrepancies between model simulations and actual measurements.

Forcing variables and input parameters were tested for their influence on heating and mixing in DYRESM by comparing with a baseline simulation using the 2010 input data for forcing variables and the default input parameters (Table 1). The forcing variables tested were solar radiation, wind speed, and groundwater while the parameters examined included the effective surface area coefficient, mean albedo, minimum layer thickness, and critical wind speed. The range of values selected was based on our knowledge of the certainty of the parameters and appropriate limits from previous applications of DYRESM (Burt, 1954; Gal et al., 2003; Hamilton[1], personal communication, 2011). Simulations for 2010 were performed while varying one of the tested parameters or variables at a time and comparing the daily temperature output with the baseline simulation using r^2, average deviation (SD), mean absolute difference (SD) and root mean square error.

Calibration

Based on the sensitivity analysis, several sets of parameters and variables were tested for 2010 and the various model outputs were compared with measured values of temperature to obtain a best fit model. Refer to the Simulations section for a description of model performance

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assessment. The parameter and/or variable set that produced the best agreement between model output and measured values was selected for validation.

Validation

The calibrated model was tested against an independent set of data from 2011 to determine the fit between these modeled and observed data and validate the calibrated or best fit model. Model performance was tested as described in the Simulations section. Additionally, model performance was assessed based on comparisons of daily simulated and both daily and weekly observed data.

Climate Scenarios

The potential impacts of climate change on the thermal structure of Oneida Lake were investigated by performing DYRESM simulations driven by two altered meteorological scenarios of increasing temperature and precipitation for 2050 and 2099. Meteorological input data for 2011 were replaced with daily high-resolution (5 km) regional temperature and precipitation projections for Central New York provided by collaborators at Cornell University's Northeast Regional Climate Center.

The statistically downscaled projections were based on two emissions scenarios, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1fi and B1, and three General Circulation Models (GCMs), the U.S. National Atmospheric and Oceanic Administration's Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1, the United Kingdom Meteorological Office's Hadley Centre Climate Model Version 3 (HadCM3), and the National Center for Atmospheric Research's Parallel Climate Model (PCM).

The higher emissions scenario, A1fi (fossil fuel-intensive), represented a world with fossil fuel-intensive economic growth and a global population that peaked mid-century and then declined with new and more efficient technologies introduced towards the end of the century. In this scenario, atmospheric carbon dioxide concentrations reach 940 parts per million (ppm) by 2100—more than triple pre-industrial levels. The lower emissions scenario, B1, represented a world with high economic growth and a global population that peaked mid-century and then declined. However, this scenario included a shift to less fossil fuel-intensive industries and the introduction of clean and resource-efficient technologies. Emissions of heat-trapping gases peaked around mid-century and then declined. Atmospheric carbon dioxide concentrations reach 550 ppm by 2100—about double pre-industrial levels.

Additionally, DYRESM simulations driven by altered forcing variables likely affected by climate change, including air temperature, precipitation, water temperature, and inflow volume were performed for 2050 and 2099. Daily air temperature and precipitation data for 2011 were modified based on the average annual projections under the higher (A1fi) emissions scenario for 2040-2069 and 2070-2099 (Union of Concerned Scientists, 2006). The average annual air temperature and precipitation are predicted to increase by 5.8°C and 5% by 2050 and 9.5°C and 10% by 2099, respectively. These increases were added to each day of 2011 for the simulation period. Predicted water temperatures for the inflowing streams were estimated by developing regression relationships between air and water temperatures for each of the four inflow streams using the predicted air temperatures for 2050 and 2099. Lastly, inflows and withdrawals were increased based on predicted precipitation increases for 2050 and 2099.

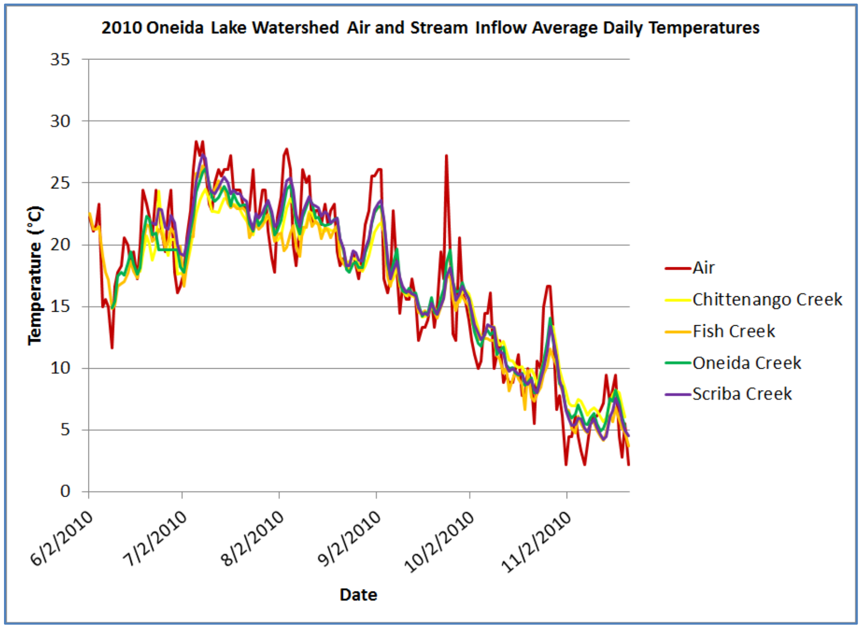
The simulated climate scenarios were compared with 2011 best fit mean daily water temperatures at 2 m and 10 m. In addition, the average deviation (SD) and mean absolute difference (SD) between the simulated and best fit temperatures and the root mean square error were calculated at 2 m and 10 m to assess the potential impact of climate change on the thermal structure of Oneida Lake. Lastly, the difference between 2 m and 10 m for the simulated climate scenarios and 2011 best fit average daily water temperatures were compared.

RESULTS

Field Monitoring

Stream Inflow Temperatures

The average daily stream inflow temperatures generally tracked with the average daily Syracuse Airport air temperatures for the 2010 and 2011 sampling periods (Figure 3). As expected, the air temperatures were more variable than the water temperatures (Figure 3). The maximum air temperatures of 28.33°C and 31.67°C occurred on July 6th and 8th in 2010 and July 21st in 2011 (Figure 3 and Table 3). The maximum water temperatures for the four stream inflows in 2010 occurred on July 8, 2010 for East Branch Fish Creek (26.43°C) and Scriba Creek (27.29°C) and July 9, 2010 for Chittenango Creek (24.51°C) and Oneida Creek (26.14°C) (Figure 3 and Table 3). In 2011, the maximum stream inflow temperatures occurred on July 22nd for East Branch Fish Creek (24.42°C), Oneida Creek (26.49°C), and Scriba Creek (27.00°C) and July 23rd for Chittenango Creek (25.30°C) (Figure 3 and Table 3). The minimum, maximum, and average air and stream inflow temperatures were generally higher in 2011 than 2010 with statistical significance for Chittenango Creek, Oneida Creek, and Scriba Creek (Table 3). In 2011, the Oneida Creek sampling period ended on August 29th and the Chittenango and Scriba Creek sampling periods ended on October 4th due to vandalism which accounts for the higher minimum temperatures and a portion of the higher average temperatures.



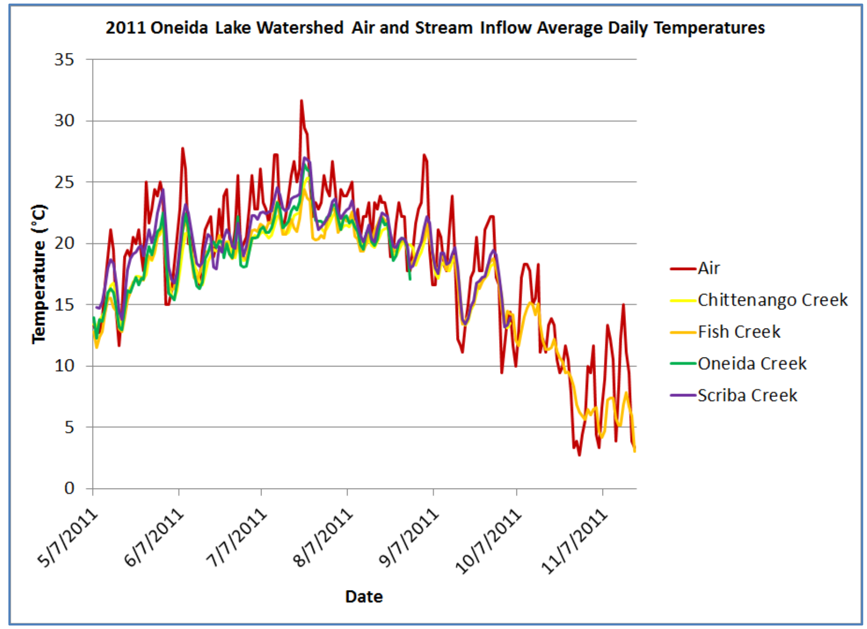


Figure 3. 2010 and 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and Stream Inflow Temperatures for 6/2/2010 to 11/21/2010 and 5/7/2011 to 11/18/2011. Average daily air temperature obtained for Syracuse Airport. Average daily water temperatures calculated from water temperatures measured every 4 hours for Chittenango Creek at Bridgeport, NY, East Branch Fish Creek at Taberg, NY, Oneida Creek at Sherrill, NY, and Scriba Creek at Constantia, NY.

Stream Discharge

Field data used for comparison or modeling are included in the Results section with additional data located in Appendices A-F. See Appendix A for Stream Discharge.

Groundwater Inflow Temperatures

Groundwater temperatures from 0.61 m (2 ft) wells in 2010 aligned with air temperatures more so than groundwater temperatures from 3.66 m (12 ft) wells in 2011 on the northern and southern shores of Oneida Lake (Figure 4 and Figure 5). A regression relationship between 2010 air temperatures and 0.61 m (2 ft) groundwater temperatures produced a good correlation with $r^2 = 0.83$ and N=153 for 6/20/2010 to 11/19/2010 (Figure 6). As expected, the average groundwater temperature from the 0.61 m (2 ft) wells of 18.51°C (SE 0.42) was significantly greater than the average temperature from 3.66 m (12 ft) wells of 14.61°C (SE 0.17) (Paired T-Test; t=8.60, df=203, p=2.15E-15) (Table 3). Also, the groundwater temperature range (8.44°C to 25.81°C) was greater for the 0.61 m (2 ft) wells than the 3.66 m (12 ft) wells (8.89°C to 17.62°C) (Table 3).

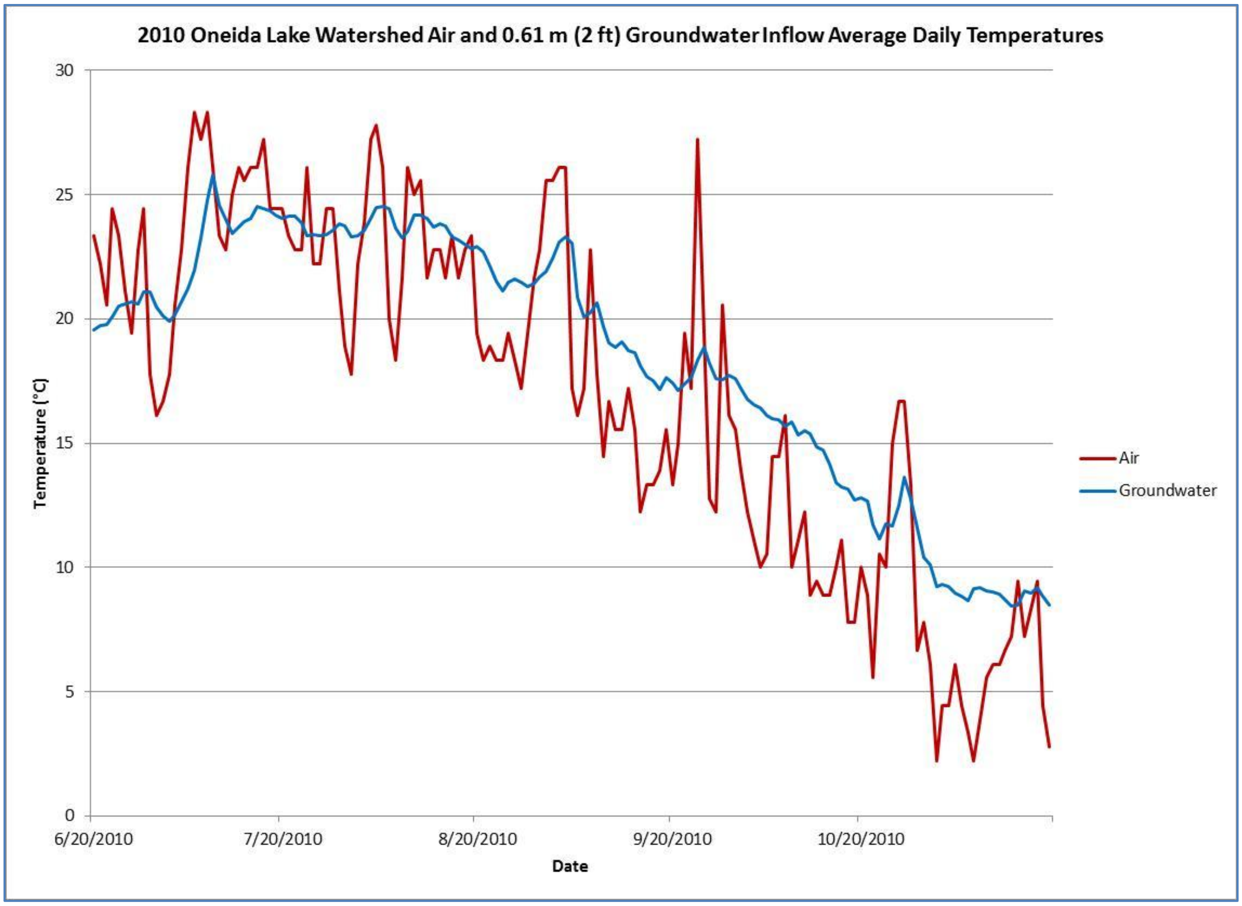


Figure 4. 2010 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and 0.61 m (2 ft) Groundwater Inflow Temperatures at Cleveland and Bridgeport, NY for 6/20/2010 to 11/19/2010. Average daily air temperature obtained for Syracuse Airport. Average daily 0.61 m (2 ft) groundwater temperatures calculated from groundwater temperatures measured every 4 hours 8 m from north and south shores of Oneida Lake.

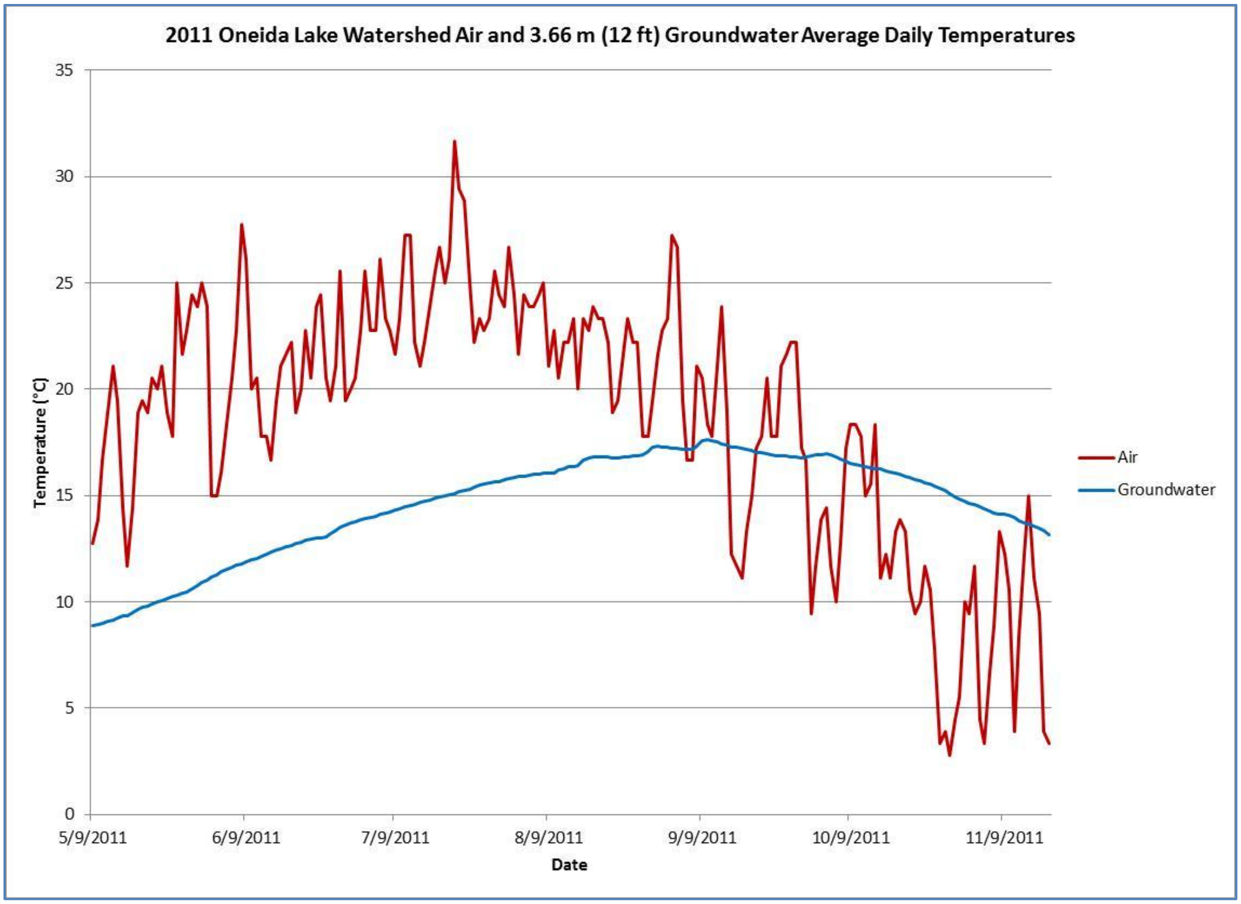


Figure 5. 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and 3.66 m (12 ft) Groundwater Temperatures at Cleveland and Bridgeport, NY for 5/9/2011 to 11/18/2011. Average daily air temperature obtained for Syracuse Airport. Average daily 3.66 m (12 ft) groundwater temperatures calculated from groundwater temperatures measured every 4 hours at residential wells on north and south shores of Oneida Lake.

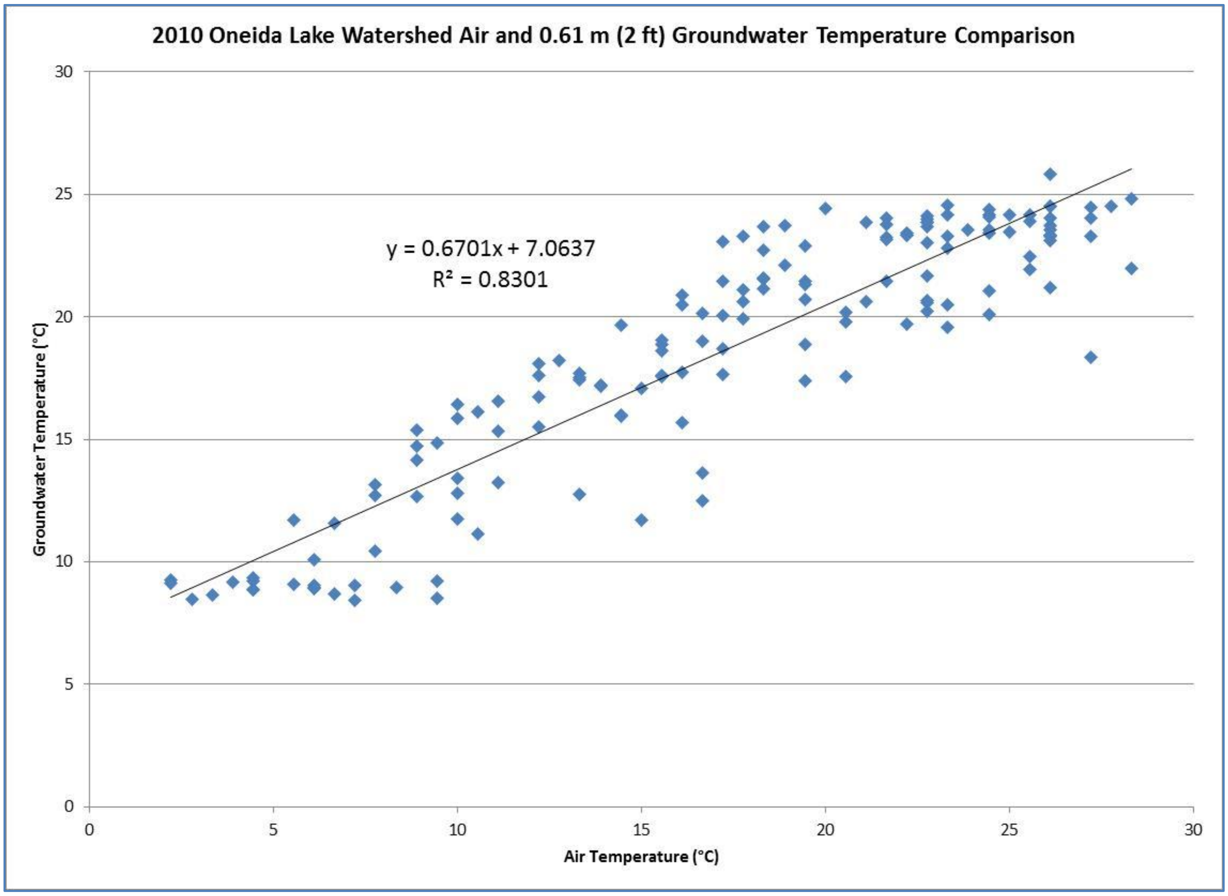


Figure 6. 2010 Oneida Lake Watershed Air (Syracuse Airport) and 0.61 m (2 ft) Groundwater Temperatures at Cleveland and Bridgeport, NY Comparison for 6/20/2010 to 11/19/2010 (Groundwater Temperature (°C)=0.670*Air Temperature (°C)+7.064, R^2=0.830, N=153). Average daily air temperature obtained for Syracuse Airport. Average daily 0.61 m (2 ft) groundwater temperatures calculated from groundwater temperatures measured every 4 hours 8 m from north and south shores of Oneida Lake.

Groundwater Discharge

Field data used for comparison or modeling are included in the Results section with additional data located in Appendices A-F. See Appendix B for Groundwater Discharge.

Outflow Temperatures

The outflow temperatures of the Oneida River at Euclid, NY corresponded with the air temperatures in 2010 and 2011 (Figure 7). The average, minimum, and maximum temperatures of the outflow were similar in 2010 and 2011 (Table 3) which could indicate that the average lake temperature in 2010 and 2011 was similar (Table 3).

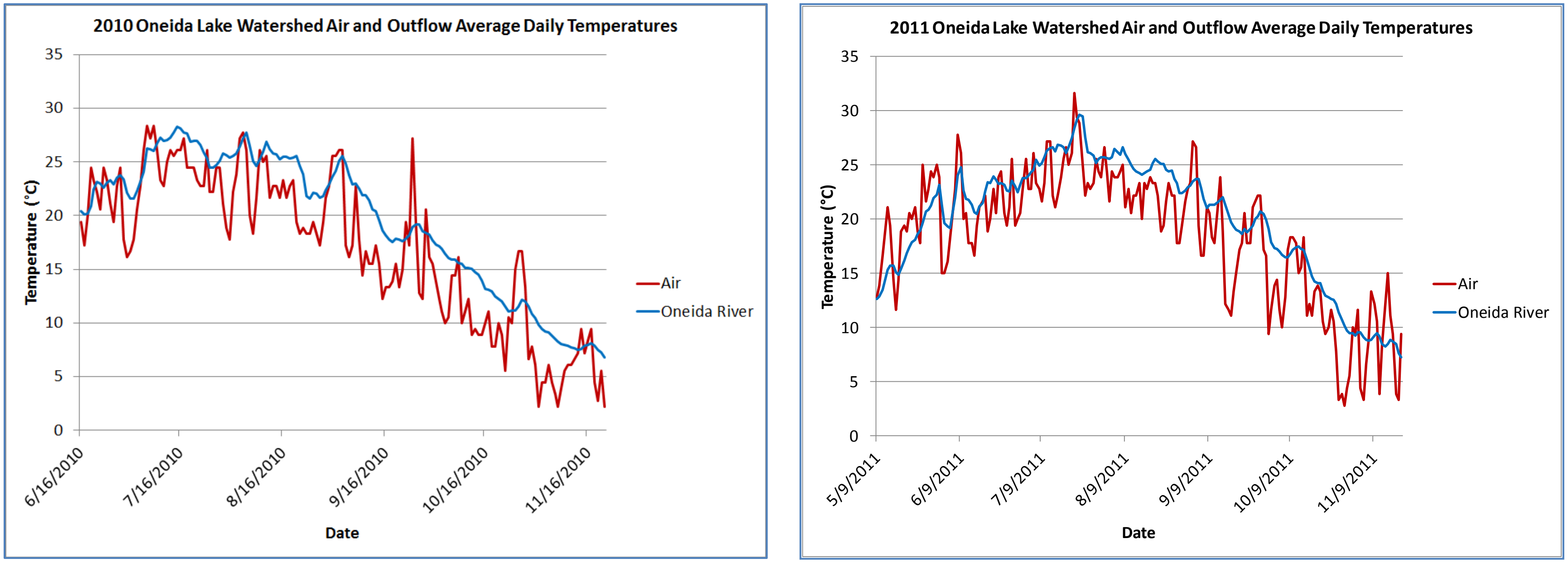
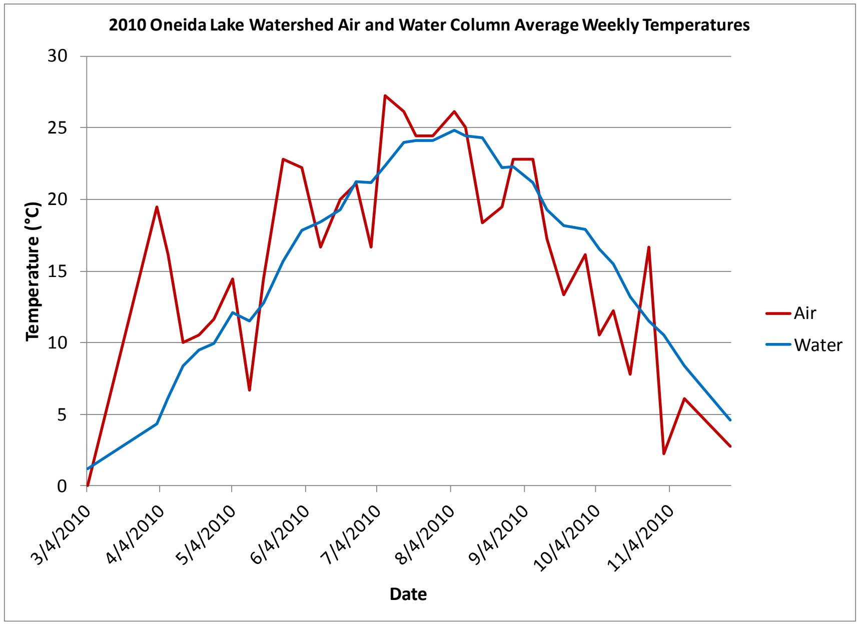


Figure 7. 2010 and 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and Oneida River Outflow Temperatures for 6/16/2010 to 11/21/2010 and 5/9/2011 to 11/19/2011. Average daily air temperature obtained for Syracuse Airport. Average daily Oneida River outflow temperatures calculated from water temperatures measured every 4 hours at Euclid, NY.

Lake Temperatures

Overall, lake and air temperatures followed the same seasonal pattern (Figure 8). However, on closer examination, air temperatures exceeded lake temperatures in the spring for several weeks and then water temperatures exceeded lake temperatures in the fall. This pattern differed slightly between 2010 and 2011 such that, in 2011, average weekly air temperatures were greater than average weekly water column temperatures during the late spring and early summer; however, average weekly water column temperatures exceeded average weekly air temperatures in mid to late summer (Figure 8). This pattern continues in the fall; however, there are periods when the average weekly air temperatures were greater than the average weekly water column temperatures (Figure 8). Overall, this trend occurs in 2010; however, the length of time the average weekly water column temperatures exceeded average weekly air temperatures in summer is shorter (Figure 8). For 2010 and 2011, the Oneida Lake average, minimum, and maximum weekly water column temperatures were similar (Figure 9 and Table 3) with 2010 and 2011 average monthly water temperatures at the higher end of the range for 1984-2009 (Figure 10).

As expected, average daily water temperatures at 2 m tracked average daily air temperatures better than average daily water temperatures at 10 m (Figure 11). In 2010, the deviation of average daily 2 m and 10 m water temperatures from late spring to late summer indicated periods of stratification punctuated by mixing events (Figure 11). In Fall 2010, the average daily 2 m and 10 m water temperatures were similar indicating overturn and a well-mixed lake (Figure 11). Likewise, in Fall 2011, the average daily 2 m and 10 m water temperatures were similar; however, this trend begins approximately one month earlier in 2011 (Figure 11).



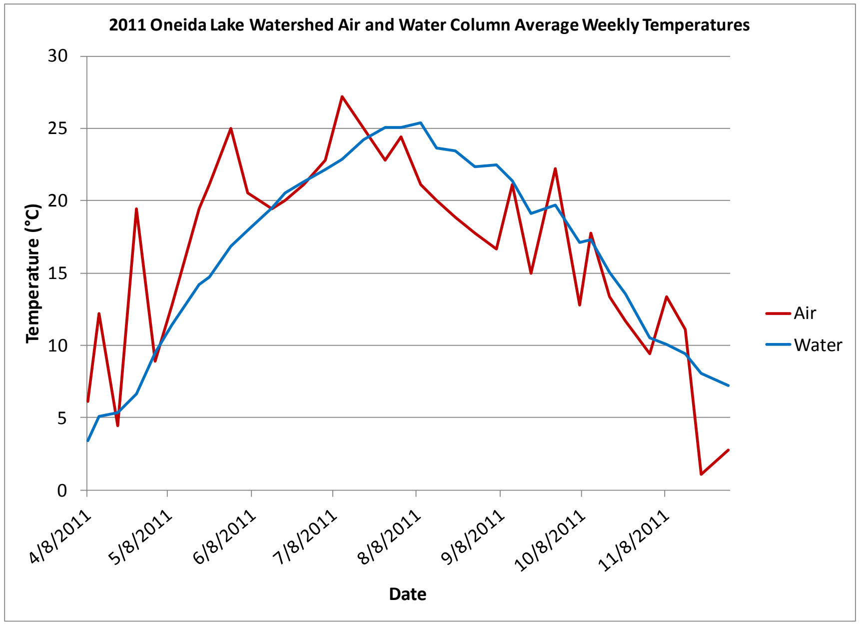


Figure 8. 2010 and 2011 Oneida Lake Watershed Average Weekly Air (Syracuse Airport) and Water Column Temperatures Across 5 Stations for 3/4/2010 to 11/29/2010 and 4/8/2011 to 12/1/2011. Average weekly air temperature calculated from average daily air temperature obtained for Syracuse Airport. Average weekly Oneida Lake water column temperatures calculated from weekly temperatures at 1 m intervals for Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

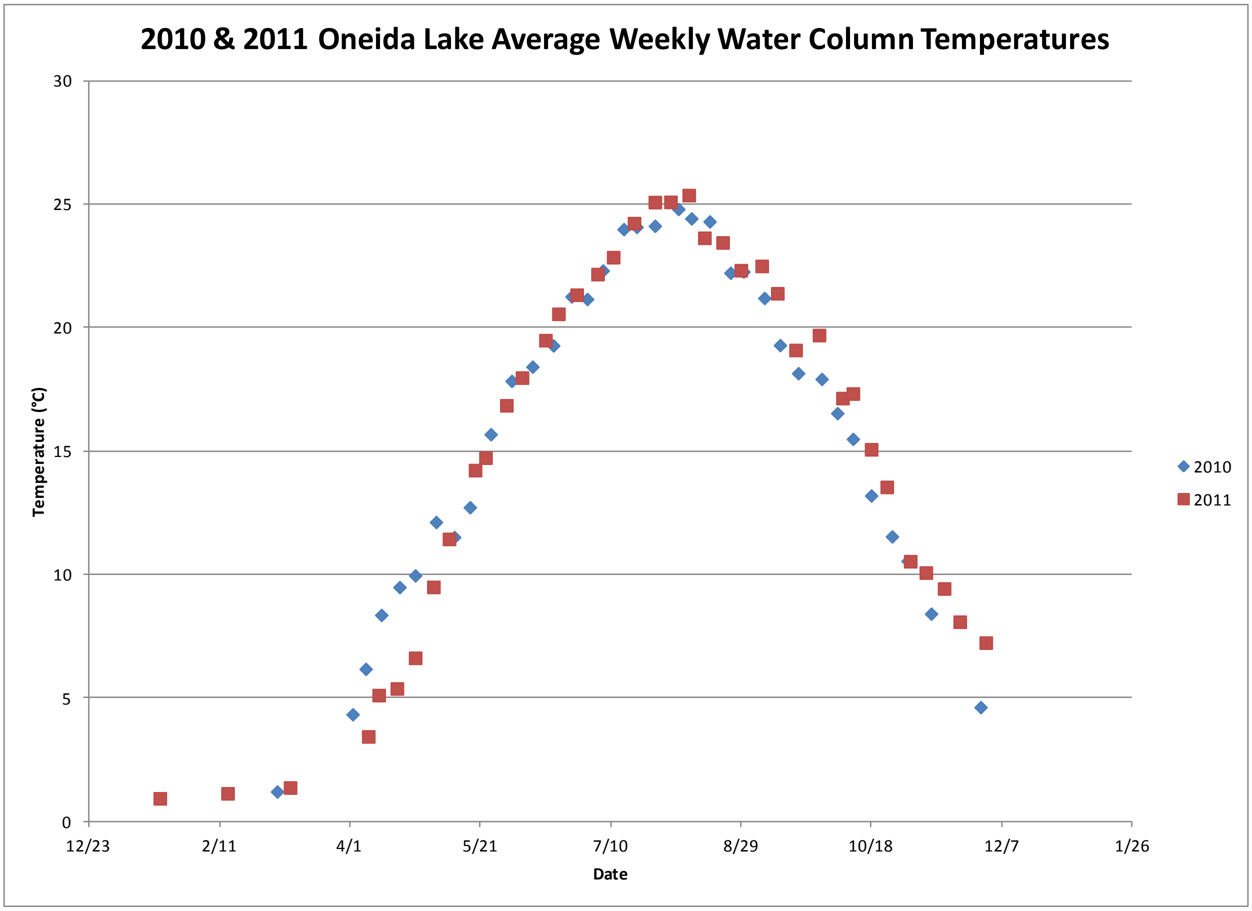


Figure 9. 2010 and 2011 Oneida Lake Average Weekly Water Column Temperatures Across 5 Stations for 3/4/2010 to 11/29/2010 and 1/19/2011 to 11/21/2011. Average weekly Oneida Lake water column temperatures calculated from weekly temperatures at 1 m intervals for Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

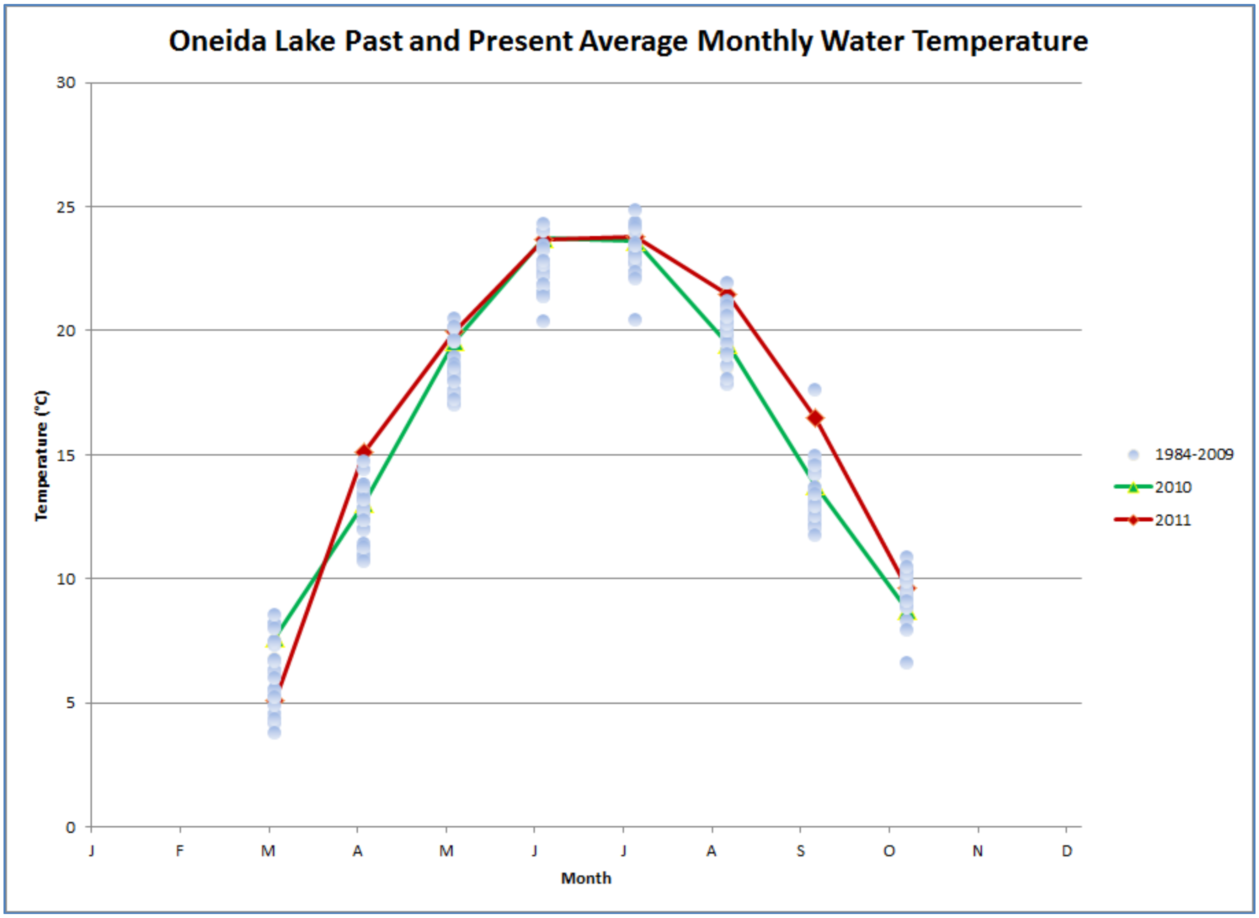
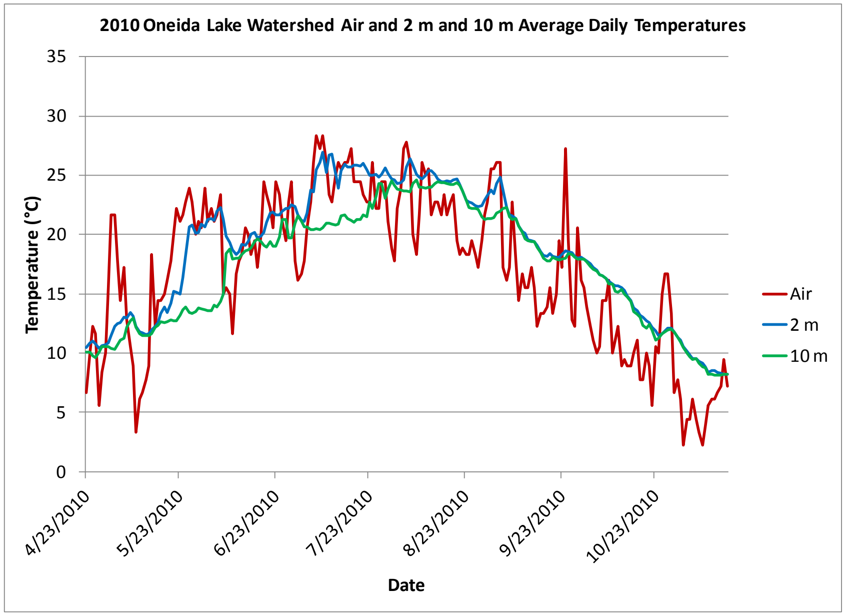


Figure 10. Oneida Lake Past (1984-2009) and Present (2010 and 2011) Average Monthly Water Temperatures Across 5 Stations from March to October. Average monthly Oneida Lake water column temperatures calculated from weekly temperatures at 1m intervals for Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.



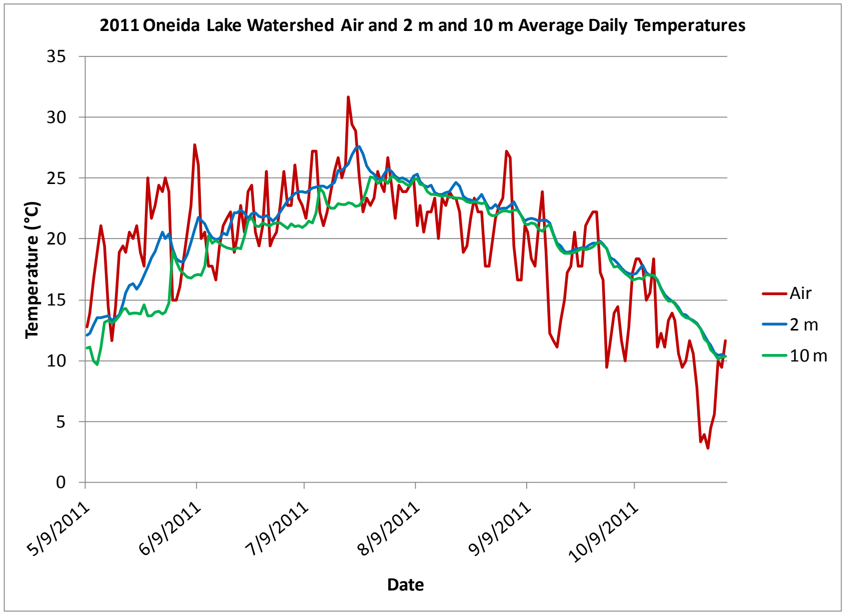
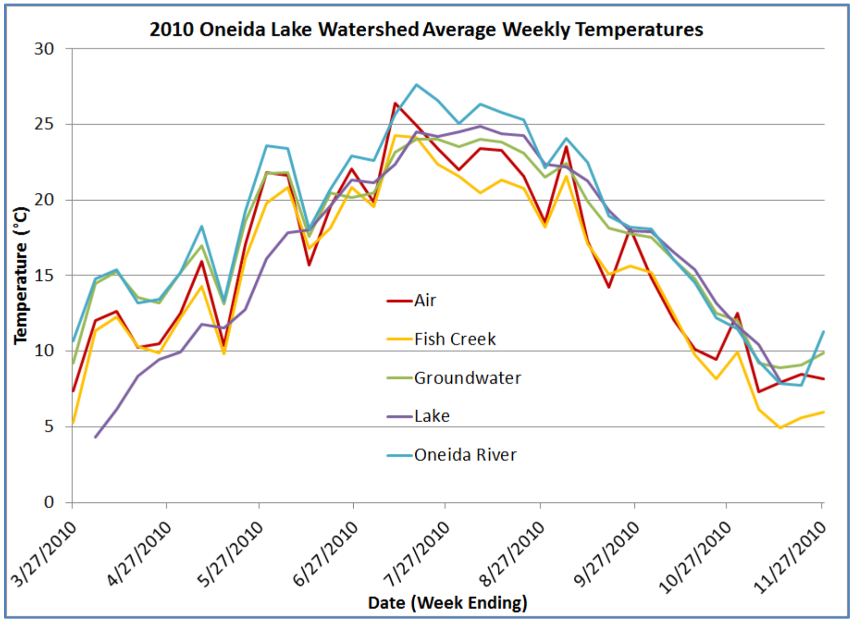


Figure 11. 2010 and 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and 2 m and 10 m Temperatures at Shackelton Point for 4/23/2010 to 11/15/2010 and 5/9/2011 to 11/3/2011. Average daily air temperature obtained for Syracuse Airport. Average daily 2 m and 10 m Oneida Lake temperatures calculated from water temperatures measured every 4 hours at Shackelton Point.

Watershed Temperatures

The average weekly inflow and outflow temperatures tracked with the average weekly air temperatures (Figure 12). In 2010 and 2011, the average weekly East Branch Fish Creek and groundwater temperatures were greater than the average weekly lake temperatures until early summer (Figure 12). The tributaries and groundwater contributed to the lake warming in the spring and early summer; however, the temperature of these inflows was less than the lake temperature in the late summer and fall potentially buffering the warm summer lake temperatures. The Oneida River average weekly temperatures were greater than the average weekly lake temperatures until fall in 2010 and 2011 (Figure 12). This was likely due to the placement of the datalogger in relatively shallow water in the Oneida River which was required due to boat traffic and the slow movement of water in the Oneida River.



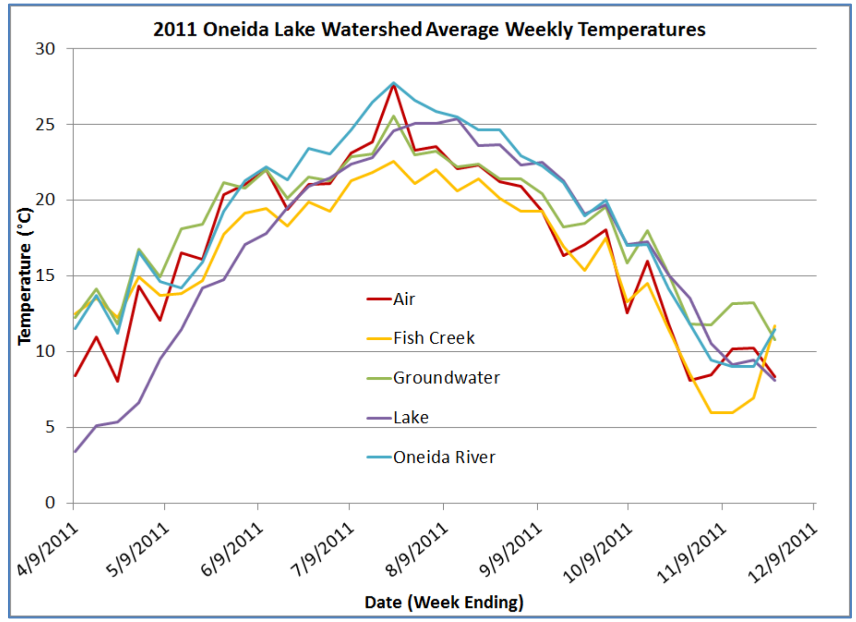


Figure 12. 2010 and 2011 Oneida Lake Watershed Average Weekly Air (Syracuse Airport), Inflow (East Branch Fish Creek – Measured 6/2/2010 to 11/21/2010 and 5/7/2011 to 11/19/2011 and 0.61 m or 2 ft Groundwater – Measured 6/20/2010 to 11/19/2010), Lake Across 5 Stations at 1 m Intervals Throughout Water Column, and Outflow (Oneida River – Measured 6/17/2010 to 11/20/2010 and 5/9/2011 to 11/18/2011) Temperatures. Average weekly air temperature obtained from average daily measurements for Syracuse Airport. Average weekly East Branch Fish Creek and Oneida River temperatures calculated from water temperatures measured every 4 hours at Taberg, NY and Euclid, NY, respectively. Average weekly 0.61 m (2 ft) groundwater temperatures in 2010 calculated from groundwater temperatures measured every 4 hours 8 m from the north and south shores of Oneida Lake. Average weekly 0.61 (2 ft) groundwater temperatures in 2011 derived from air/groundwater temperature comparison (Groundwater Temperature (°C)=0.670*Air Temperature (°C)+7.064, R^2=0.830, N=153). Average weekly Oneida Lake water column temperatures calculated from weekly temperatures at 1 m intervals for Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

Table 3. 2010 and 2011 Oneida Lake Watershed Temperatures. Average 2010 and 2011 air temperatures obtained from average daily measurements for Syracuse Airport. Average 2010 and 2011 stream inflow and outflow water temperatures calculated from stream temperatures measured every 4 hours for Chittenango Creek at Bridgeport, NY, East Branch Fish Creek at Taberg, NY, Oneida Creek at Sherrill, NY, Scriba Creek at Constantia, NY, and Oneida River at Euclid, NY. Average 2010 0.61 m (2 ft) groundwater temperatures calculated from groundwater temperatures measured every 4 hours 8 m from the north and south shores of Oneida Lake. Average 2011 0.61 (2 ft) groundwater temperatures calculated from average daily 0.61 (2 ft) groundwater temperatures derived from air/groundwater temperature comparison (Groundwater Temperature (°C)=0.670*Air Temperature (°C)+7.064, R^2=0.830, N=153). Average 2010 and 2011 Oneida Lake temperatures calculated from average weekly water column temperatures at 1 m intervals for Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

	Average Temperature (SE) (°C)		**Paired T-Test**	**Temperature Range (°C)**	
	2010	**2011**		**2010**	**2011**
Air (Syracuse Airport)	17.11 (0.52)	18.49 (0.43)	t=-2.02, df=345, p=0.04 (5/7 to 11/21)	2.22-28.33	2.78-31.67
Chittenango Creek	16.58 (0.44)	18.94 (0.22)	t=-4.82, df=225, p=2.64E-06** (5/7 to 11/20)	5.68-24.51	13.10-25.30
East Branch Fish Creek	16.31 (0.56)	16.73 (0.36)	t=-0.72, df=338, p=0.47 (5/7 to 11/21)	3.70-26.43	3.06-24.42
Oneida Creek	16.80 (0.46)	19.74 (0.27)	t=5.51, df=251, p=9.1E-08** (5/7 to 11/20)	4.94-26.14	12.30-26.49
Scriba Creek	16.82 (0.53)	20.05 (0.23)	t=-5.52, df=208, p=9.81E-08** (5/8 to 11/21)	4.21-27.29	13.23-27.00
Groundwater (0.61 m/2 ft)	18.51 (0.42)	14.61 (0.17)*	t=8.60, df=203, p=2.15E-15** (5/9 to 11/19)	8.44-25.81	8.89-17.62*
Oneida River	19.53 (0.51)	19.99 (0.40)	t=-0.69, df=316, p=0.49 (5/9 to 11/21)	6.81-28.30	7.28-29.63
Oneida Lake	16.40 (1.08)	16.34 (1.13)	t=0.04, df=67, p=0.97 (4/2 to 12/1)	4.33-24.80	3.43-25.37

*__Note:__ 2011 groundwater temperatures were only collected at 3.66 m (12 ft).
**Statistically significant with α=0.05.

Light Extinction Coefficients

The 2010 average light extinction coefficient of 0.52 (SE 0.02) was significantly less than the 2011 average light extinction coefficient of 0.66 (SE 0.04) (Paired T-Test; $t=-3.46$, $df=51$, $p=0.001$). In 2010 and 2011, the maximum average weekly light extinction coefficients occur in mid-August while the minimum average light extinction coefficients occur in the spring for 2010 and fall for 2011 (Figure 13). The maximum average weekly light extinction coefficients across 5 stations of 0.87 and 1.09 occur on August 17, 2010 and August 15, 2011, respectively; whereas, the minimum average weekly light extinction coefficients across 5 stations of 0.34 and 0.38 occur on May 13, 2010 and November 8, 2011.

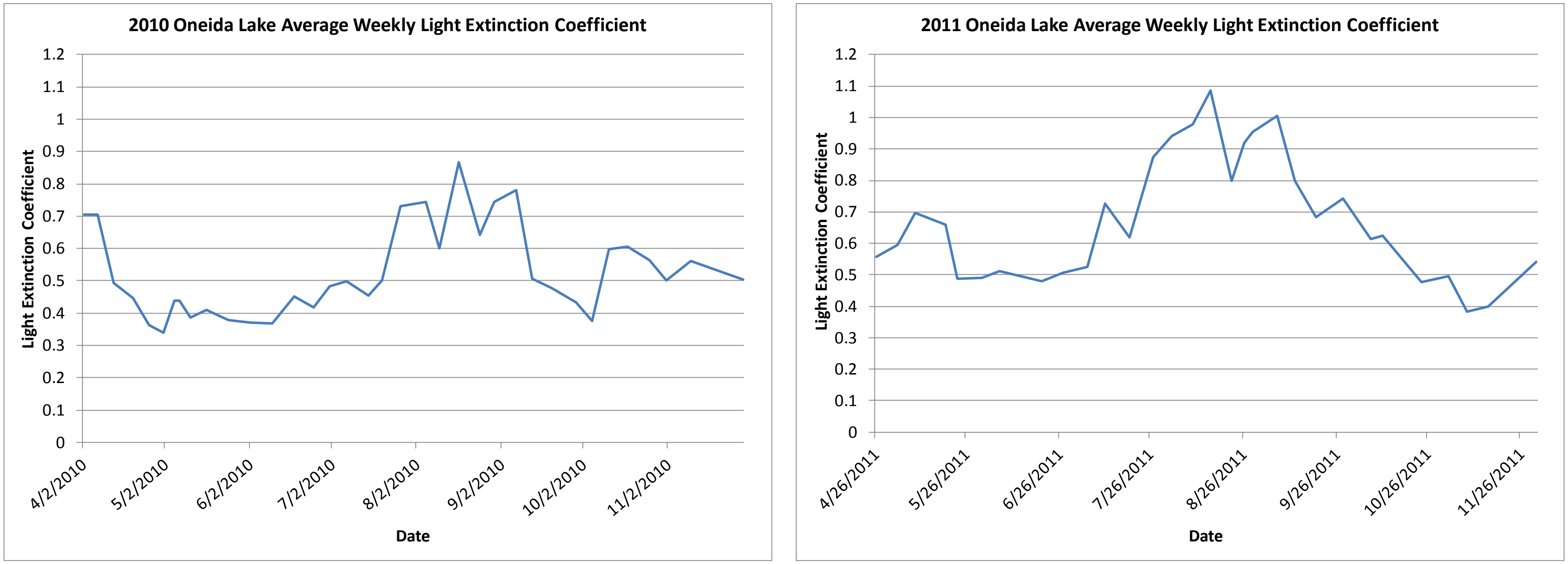


Figure 13. 2010 and 2011 Oneida Lake Average Weekly by Day of Year Light Extinction Coefficients Across 5 Stations for 4/2/2010 to 11/29/2010 and 4/26/2011 to 12/1/2011. Average weekly light extinction coefficients calculated from weekly water column irradiance at 0.5 m intervals for Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

Lake Surface Water Temperatures

Field data used for comparison or modeling are included in the Results section with additional data located in Appendices A-F. See Appendix C for Lake Surface Water Temperatures.

Air Temperatures

The average daily air temperatures at Shackelton Point and Syracuse Airport were similar (Figure 14) supporting the use of air temperatures from Syracuse Airport for DYRESM. In 2010, the average air temperature was 17.65°C (SE 0.62) and 16.91°C (SE 0.58) at Shackelton Point and Syracuse Airport, respectively. Likewise, the average air temperatures were similar between the locations in 2011. The average air temperatures were 17.32°C (SE 0.41) and 18.52°C (SE 0.43) at Shackelton Point and Syracuse Airport, respectively. There was not a significant difference in air temperature between Shackelton Point and Syracuse Airport in 2010 (Paired T-Test; $t=0.87$, $df=299$, $p=0.384$) and 2011 (Paired T-Test; $t=-2.00$, $df=389$, $p=0.05$). In 2010, the minimum air temperatures of 2.75°C and 2.22°C occurred on November 1st and November 7th at Shackelton Point and Syracuse Airport, respectively (Figure 14). In 2011, the minimum air temperatures of 1.45°C and 2.78°C occurred on November 18th and October 29th at Shackelton Point and Syracuse Airport, respectively (Figure 14). The maximum air temperatures were similar between the locations and occurred approximately on the same dates in 2010 and 2011 (Figure 14). In 2010, the maximum air temperatures of 31.35°C and 28.33°C occurred on July 8th and July 6th at Shackelton Point and Syracuse Airport, respectively (Figure 14). In 2011, the maximum air temperatures of 27.22°C occurred on July 22nd and 31.67°C on July 21st at Shackelton Point and Syracuse Airport, respectively (Figure 14).

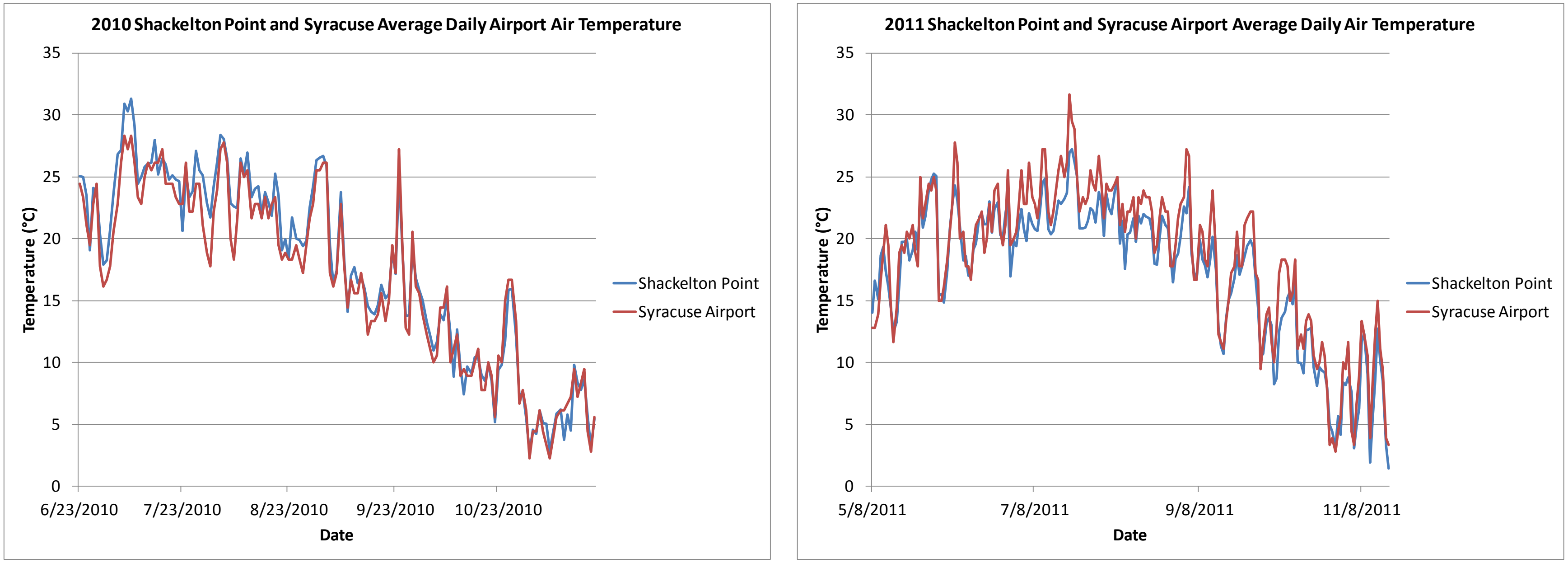


Figure 14. 2010 and 2011 Oneida Lake Watershed Shackelton Point and Syracuse Airport Average Daily Air Temperatures for 6/23/2010 to 11/20/2010 and 5/8/2011 to 11/18/2011. Average daily Shackelton Point air temperatures calculated from air temperatures measured every 4 hours on Oneida Lake. Average daily air temperature obtained for Syracuse Airport.

Light Intensity

Field data used for comparison or modeling are included in the Results section with additional data located in Appendices A-F. See Appendix D for Light Intensity.

Precipitation

Field data used for comparison or modeling are included in the Results section with additional data located in Appendices A-F. See Appendix E for Precipitation.

Evaporation

Field data used for comparison or modeling are included in the Results section with additional data located in Appendices A-F. See Appendix F for Evaporation.

Modeling

Inputs

Lake Morphometry

The morphometry of Oneida Lake (Table 4) was used as input to DYRESM. The maximum depth was 17 m at a surface lake level of 112 m above MSL. The corresponding lake surface area and lake volume were 207,100,000 m^2 and 1,561,860,000 m^3, respectively.

Table 4. Oneida Lake Morphometry. The lake surface during the summer is 112 m above mean sea level, total area is 207.1 km^2, and total volume is 156 x $10^7 m^3$.

Height from Lake Bottom (m)	Elevation Above MSL (m)	Area (m^2)	Volume (m^3)	% of Total Volume
0	95	0	0	0.0
1	96	60,000	1,020,000	0.1
2	97	460,000	7,420,000	0.5
3	98	2,330,000	35,470,000	2.3
4	99	6,060,000	87,690,000	5.6
5	100	18,930,000	255,000,000	16.3
6	101	42,710,000	540,360,000	34.6
7	102	60,470,000	735,720,000	47.1
8	103	77,930,000	910,320,000	58.3
9	104	92,900,000	1,045,050,000	66.9
10	105	104,410,000	1,137,130,000	72.8
11	106	117,140,000	1,226,240,000	78.5
12	107	134,480,000	1,330,280,000	85.2
13	108	152,550,000	1,420,630,000	91.0
14	109	168,750,000	1,485,430,000	95.1
15	110	181,690,000	1,524,250,000	97.6
16	111	193,890,000	1,548,650,000	99.2
17	112	207,100,000	1,561,860,000	100.0

Descriptive data for Oneida Lake also included the hypsographic curve (Figure 15) generated from the morphometry.

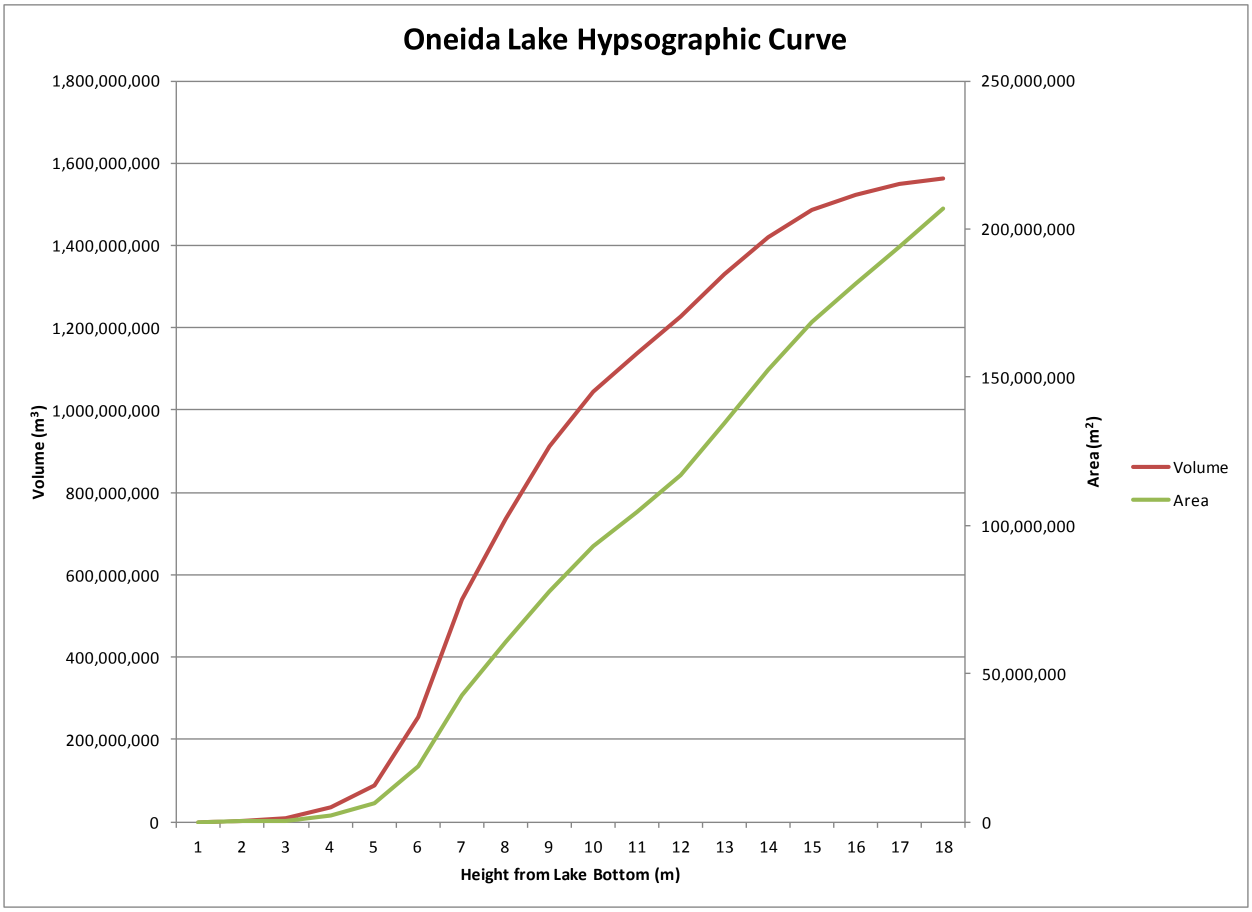


Figure 15. Oneida Lake Hypsographic Curve for DYRESM. The lake surface during the summer is 112 m above mean sea level, total area is 207.1 km^2, and total volume is 156 x $10^7 m^3$.

Initial Conditions

The initial temperature profiles at Shackelton Point in Bridgeport, NY for March 22, 2010 and April 8, 2011 were used as inputs to DYRESM. Measured values were recorded to 10 m depth in 2010 and 11 m in 2011 (Figure 16). The average temperatures for the initial profiles were significantly less in 2010 than 2011 with 1.60°C (SE 0.16) and 3.23°C (SE 0.08) for March 22, 2010 and April 8, 2011, respectively (Paired T-Test; t=-9.13, df=23, p=4.13E-09). The range of temperatures in the initial profile was greater in 2010 than 2011 with 0.2 – 2.1°C in 2010 and 2.9 – 3.6°C in 2011.

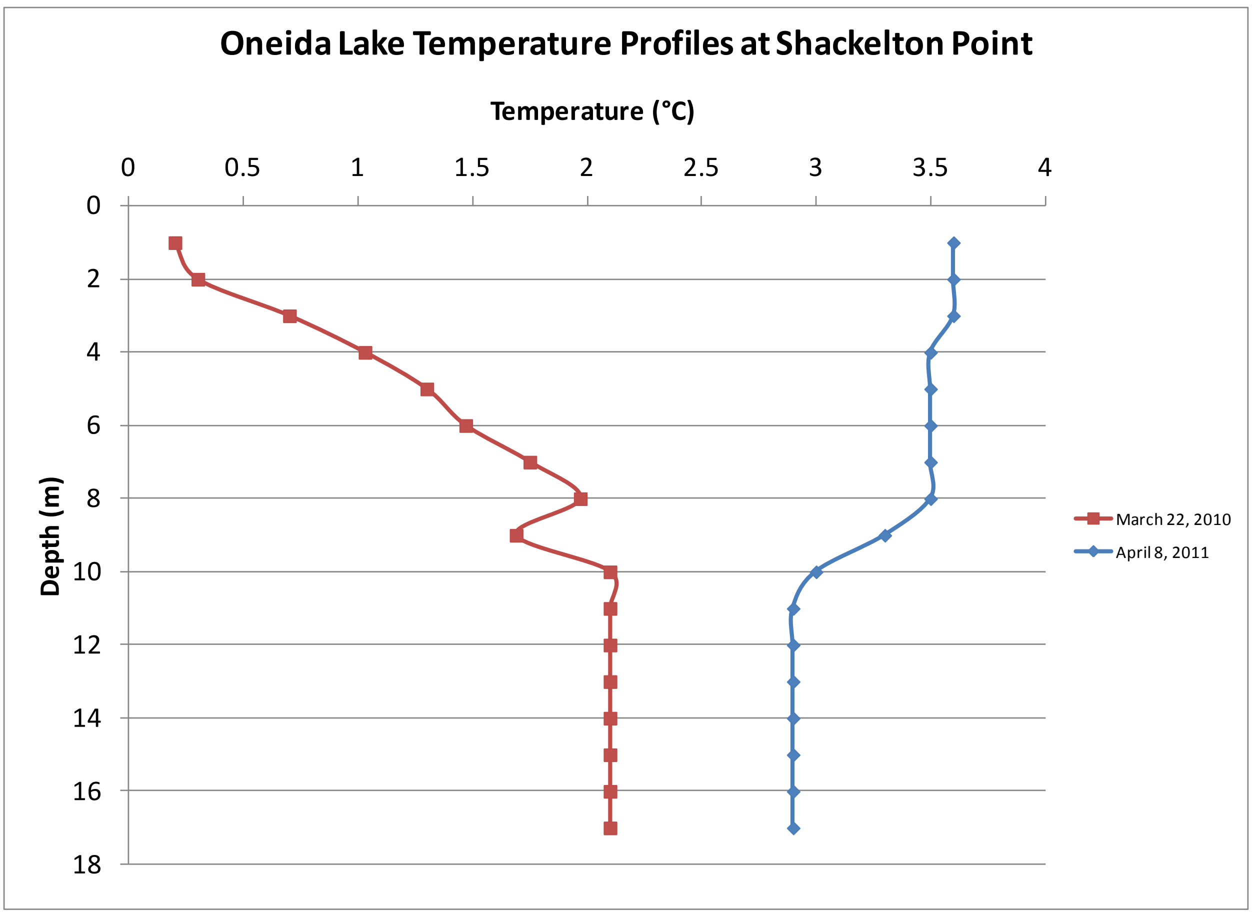


Figure 16. 2010 and 2011 Oneida Lake Shackelton Point Initial Temperature Profiles for DYRESM on 3/22/2010 and 4/8/2011. Water temperatures were measured for 1 m intervals to 11 m.

Meteorological Data

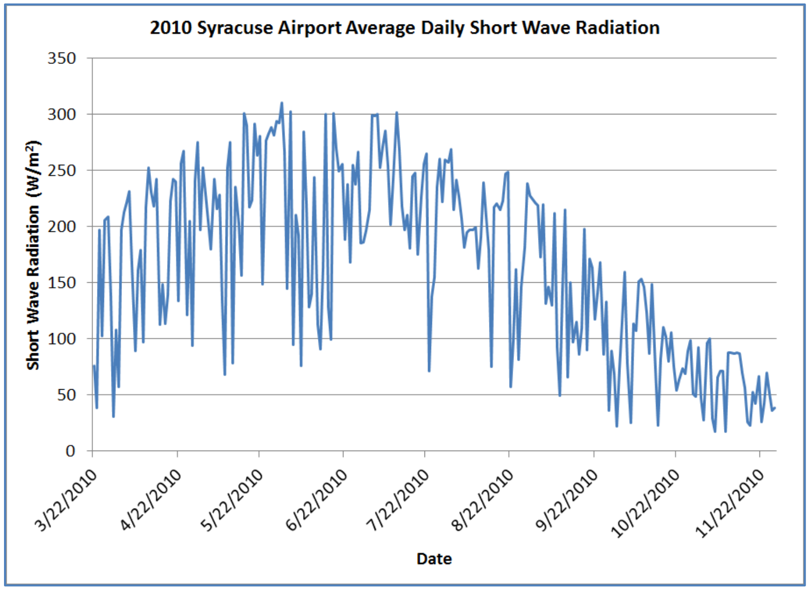
Hourly short wave radiation (W/m^2), cloud cover (%), air temperature (°C), vapor pressure (mb), wind velocity (m/s), and precipitation (m) from Syracuse Airport comprised the meteorological inputs to DYRESM (Table 5). The average hourly values and range for the meteorological inputs from Syracuse Airport were similar for 2010 and 2011.

Table 5. 2010 and 2011 Syracuse Airport Average Hourly Meteorological Inputs for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Hourly short wave radiation, cloud cover, air temperature, vapor pressure, wind velocity, and precipitation obtained for Syracuse Airport from the Northeast Regional Climate Center.

	Average (SD)		**Range**	
	2010	**2011**	**2010**	**2011**
Short Wave Radiation (W/m^2)	165.42 (237.15)	160.59 (232.45)	0–917.50	0–926.40
Cloud Cover (%)	72 (0.31)	74 (0.29)	0–100	0–100
Air Temperature (°C)	15.44 (8.00)	16.66 (7.59)	-7.80*–34.40	-4.40*–37.80
Vapor Pressure (mb)	13.14 (6.09)	13.81 (5.73)	1.53–29.79	3.09–29.88
Wind Velocity (m/s)	3.32 (2.40)	3.10 (2.32)	0–14.90	0–16.50
Precipitation (m)	0.00016 (0.001)	0.000173 (0.001)	0–0.02	0–0.03

*Minimum air temperature raised to 0.1°C to avoid errors in the UNESCO density function of water within DYRESM (Centre for Water Research, 2005).

Figure 17 – Figure 22 display the average daily meteorological inputs during the 2010 and 2011 simulation periods. Short wave radiation peaked on May 30, 2010 at 310 W/m^2 and 313 W/m^2 on July 2, 2011 (Figure 17). Cloud cover was variable with the hourly average for the day at 72% and 74% for the simulation periods in 2010 and 2011, respectively (Figure 18). The average daily air temperature was at a maximum of 28.58°C on July 8, 2010 and 31.79°C on July 21, 2011 (Figure 19). Average daily vapor pressure was variable throughout the 2010 and 2011 simulation periods (Figure 20). Likewise, average daily wind velocity varied for the 2010 and 2011 simulation periods; however, it was slightly less windy in the summer than the spring and fall (Figure 21). In 2010, there were 3 total precipitation peaks over 0.050 m/day occurring on July 23rd, August 22nd, and September 30th. Maximum total precipitation/day was 0.047 mm in 2011 (Figure 22). Total precipitation for the 2010 and 2011 simulation periods was 0.962 m and 0.991 m, respectively.



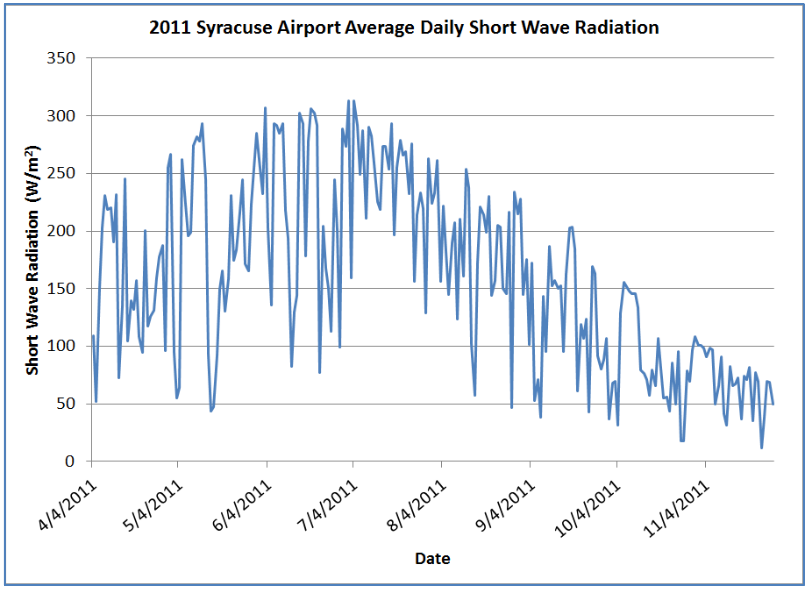


Figure 17. 2010 and 2011 Syracuse Airport Average Daily Short Wave Radiation for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Daily short wave radiation calculated from hourly short wave radiation obtained for Syracuse Airport from the Northeast Regional Climate Center.

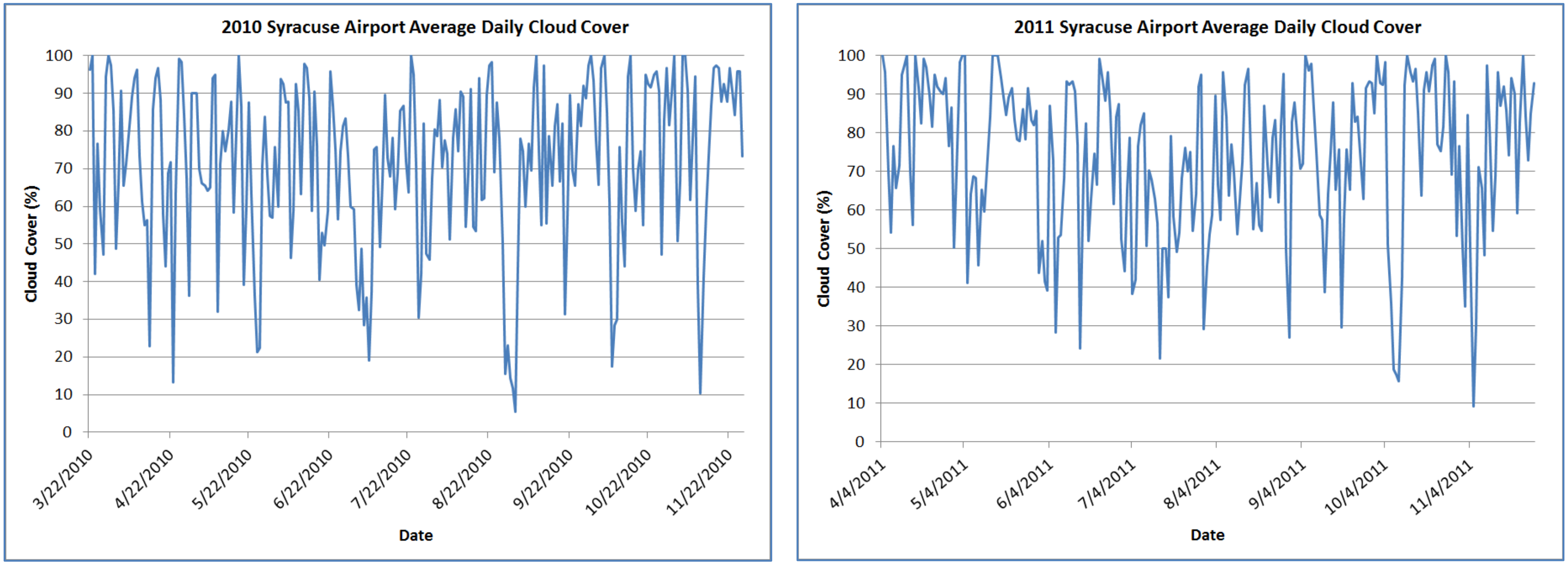


Figure 18. 2010 and 2011 Syracuse Airport Average Daily Cloud Cover for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Daily cloud cover calculated from hourly cloud cover obtained for Syracuse Airport from the Northeast Regional Climate Center.

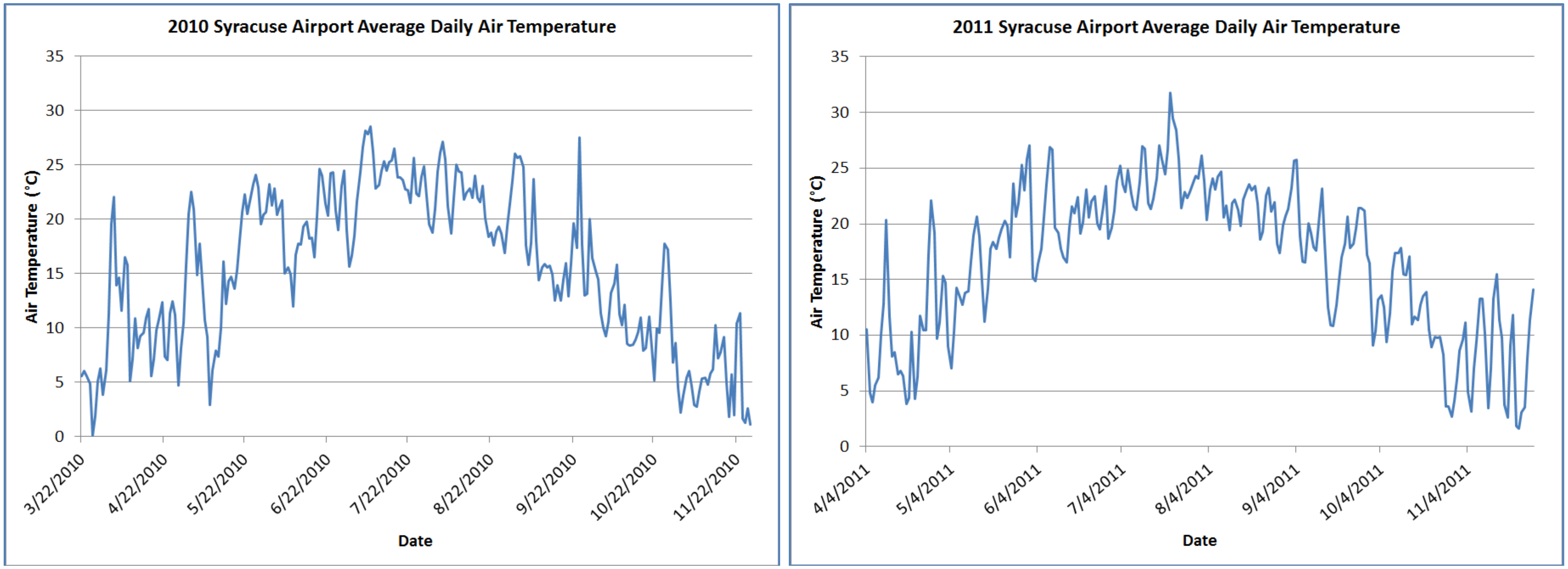


Figure 19. 2010 and 2011 Syracuse Airport Average Daily Air Temperatures for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Daily air temperature calculated from hourly air temperature obtained for Syracuse Airport from the Northeast Regional Climate Center.

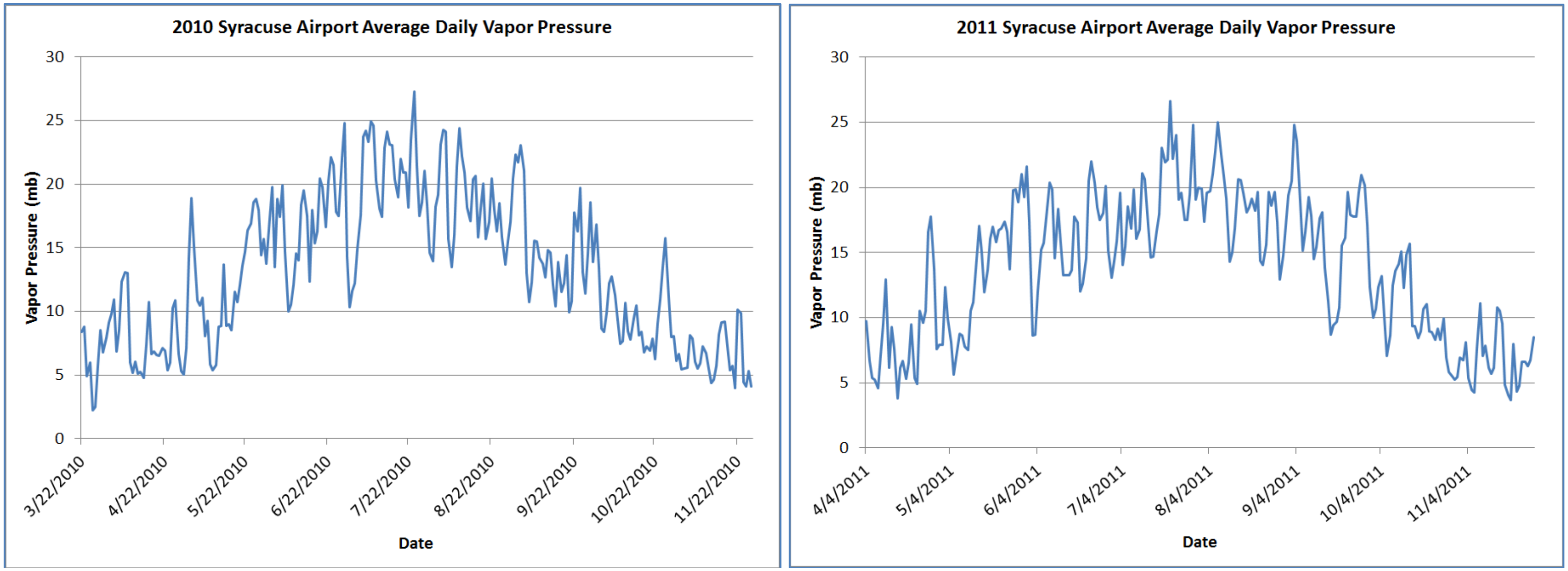


Figure 20. 2010 and 2011 Syracuse Airport Average Daily Vapor Pressure for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Daily vapor pressure calculated from hourly vapor pressure obtained for Syracuse Airport from the Northeast Regional Climate Center.

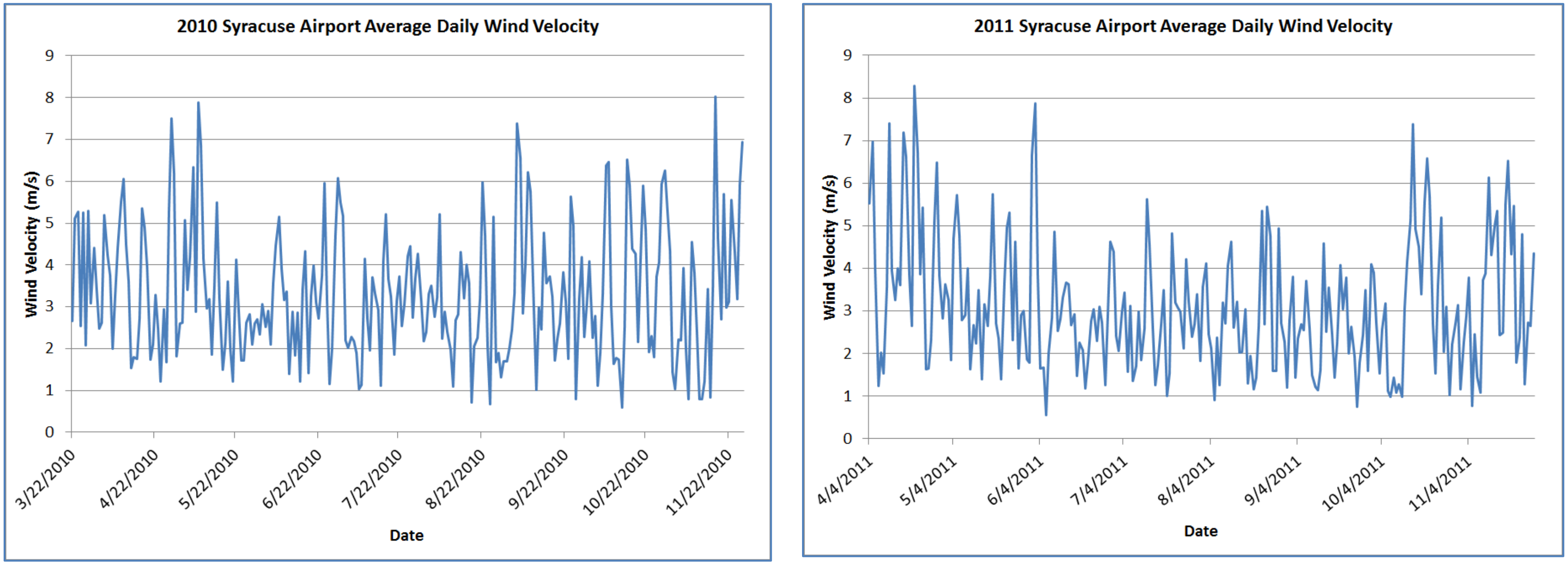


Figure 21. 2010 and 2011 Syracuse Airport Average Daily Wind Velocity for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Daily wind velocity calculated from hourly wind velocity obtained for Syracuse Airport from the Northeast Regional Climate Center.

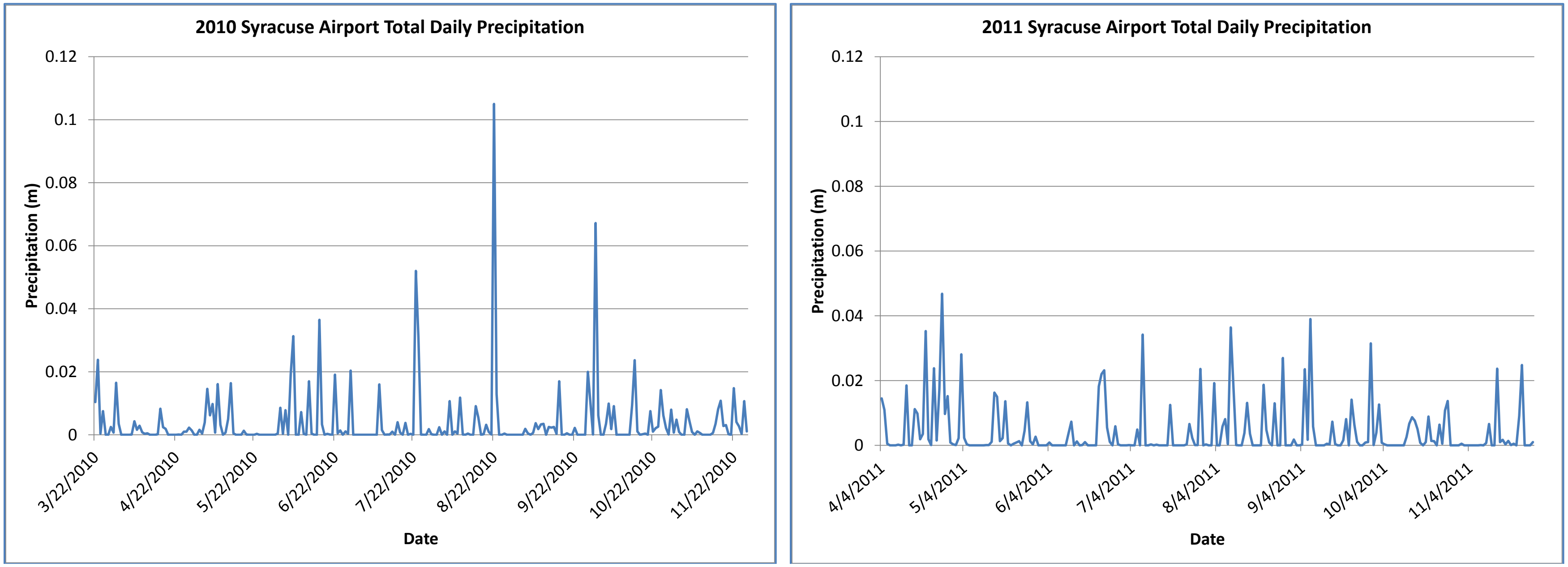
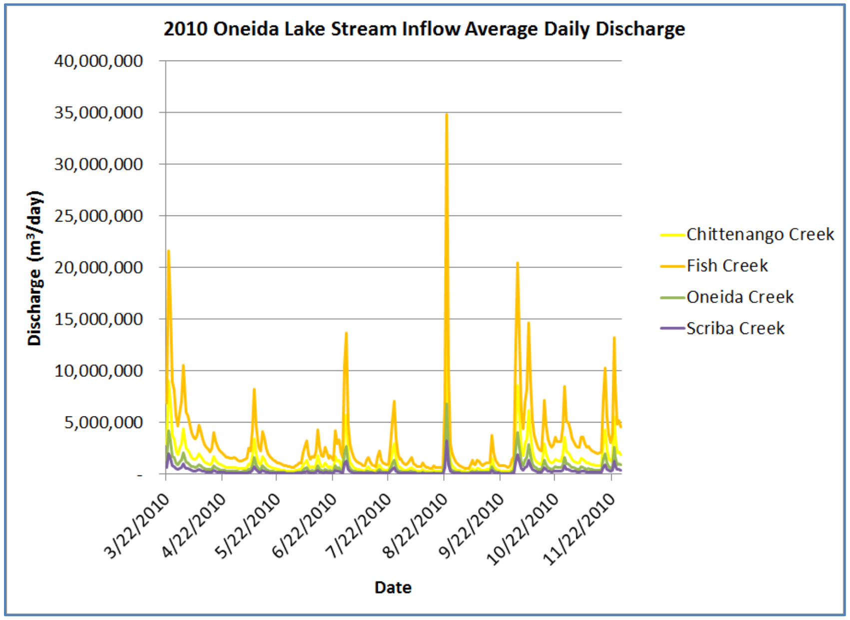


Figure 22. 2010 and 2011 Syracuse Airport Total Daily Precipitation for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Daily precipitation calculated from hourly precipitation obtained for Syracuse Airport from the Northeast Regional Climate Center.

Inflow Data

The volume contribution weightings for the four stream inflows were Scriba Creek (5.5%), Fish Creek (58.5%), Oneida Creek (11.5%), and Chittenango Creek (24.5%). The 2010 and 2011 calculated average daily discharges for the four stream inflows (Figure 23) were derived from the volume contribution weightings and the 2010 and 2011 Fish Creek and Oneida Creek USGS daily discharge data. In 2010, the maximum daily discharge occurred in late summer; whereas, there were higher discharges in the spring and early summer in 2011 with the peak in late spring.



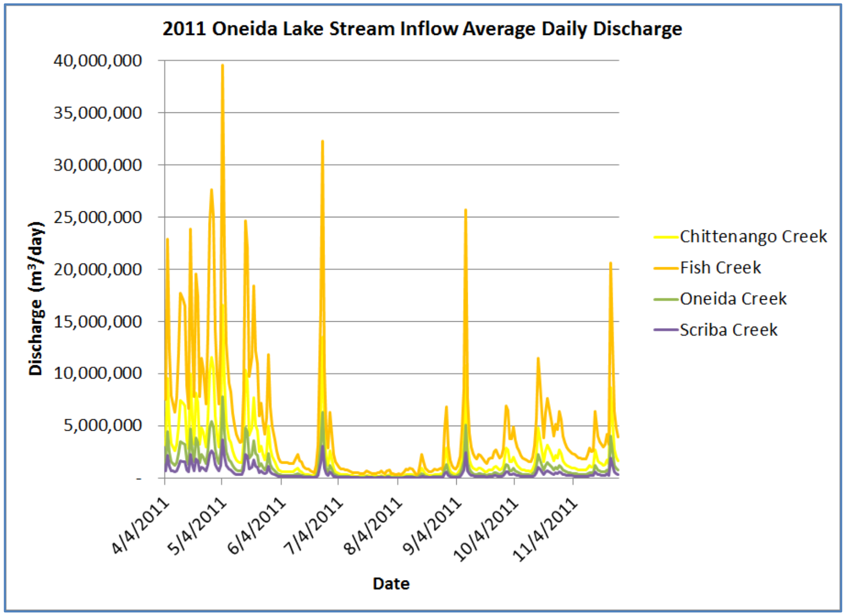


Figure 23. 2010 and 2011 Oneida Lake Watershed Average Daily Stream Inflow Discharge Derived from the Volume Contribution Weightings for the East Branch of Fish Creek and Oneida Creek USGS Measured Daily Discharge for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011).

The 2010 and 2011 average annual discharge for East Branch Fish Creek and Oneida Creek corresponded with the historical record beginning from 1931 (Figure 24). Also, the inflow and outflow average annual discharges corresponded over time (Figure 24). The similarity of the manual and USGS measured average daily discharges for the East Brach of Fish Creek validated the manually measured average daily discharges (Paired T-Test; t=-0.002, df=15, p=1.00) (Table 6). Additionally, the agreement of the measured and calculated average daily discharges (Greeson, 1971) for East Branch Fish Creek, Chittenango Creek, and Scriba Creek supported the calculations (Paired T-Test; t=-0.40, df=12, p=0.70) (Table 6).

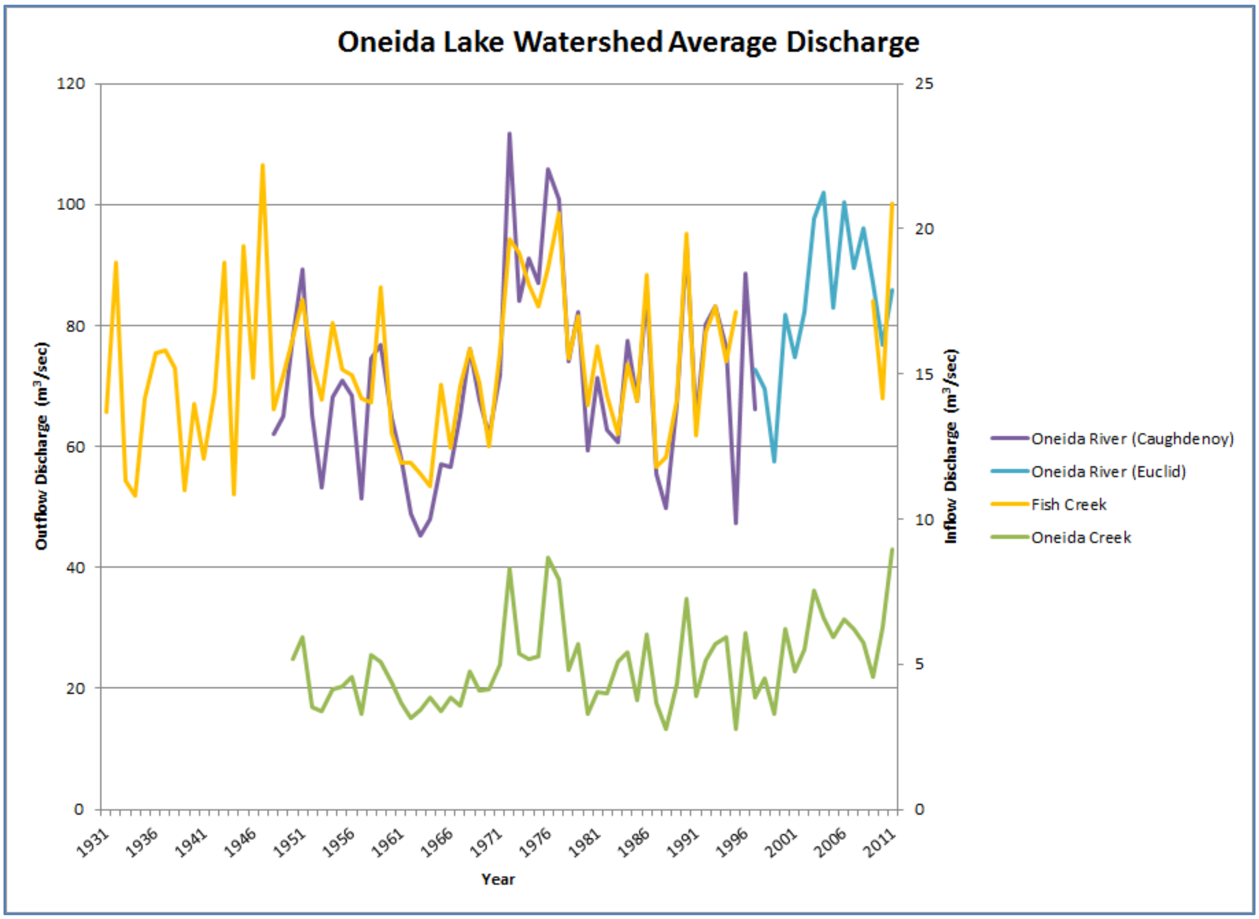


Figure 24. 1931-2011 Oneida Lake Watershed Average Annual Inflow from East Branch Fish Creek at Taberg, NY and Oneida Creek at Oneida, NY and Outflow from Oneida River Discharge at Caughdenoy, NY and Euclid, NY (USGS). Average annual inflow and outflow calculated from daily USGS measured discharge.

Table 6. 2010 Oneida Lake Watershed East Branch Fish Creek at Taberg, NY, Chittenango Creek at Bridgeport, NY, and Scriba Creek at Constantia, NY Measured, USGS, and Calculated Discharges. Measured discharge was calculated by measuring stream cross-sectional area and velocity for East Branch Fish Creek, Chittenango Creek, and Scriba Creek. USGS discharge was obtained for East Branch Fish Creek. Calculated discharge for the East Branch Fish Creek, Chittenango Creek, and Scriba Creek were derived from the volume contribution weightings for the East Branch of Fish Creek and Oneida Creek USGS measured daily discharge.

	Date	**Measured Discharge (m^3/s)**	**USGS Discharge (m^3/s)**	**Calculated Discharge (m^3/s)**
East Branch Fish Creek	07/13/2010	3.55	4.08	4.26
	07/21/2010	3.20	3.99	4.12
	07/27/2010	9.76	9.29	9.14
	08/03/2010	6.78	6.60	6.14
	08/10/2010	5.65	5.18	5.21
	08/28/2010	6.69	4.25	5.47
	09/09/2010	10.04	6.43	6.06
	10/16/2010	20.18	22.77	32.59
	11/06/2010	10.68	13.99	16.22
Chittenango Creek	07/08/2010	5.10	-	3.13
	07/20/2010	3.97	-	3.60
	07/26/2010	12.87	-	12.50
	08/02/2010	4.97	-	3.81
	08/09/2010	4.20	-	2.80
	08/28/2010	10.45	-	4.28
	09/12/2010	5.40	-	3.06
	10/16/2010	32.67	-	25.50
	11/07/2010	18.68	-	10.53
Scriba Creek	07/08/2010	0.38	-	0.69
	07/22/2010	1.00	-	0.77
	07/27/2010	3.40	-	1.59
	08/03/2010	0.79	-	1.07
	08/10/2010	0.69	-	0.91
	08/28/2010	1.70	-	0.95
	09/09/2010	1.03	-	1.05
	10/17/2010	3.82	-	3.69
	11/07/2010	2.75	-	2.82

The 2010 and 2011 average discharge and volumetric contributions for the year were compared with historical values from 1931-1960 (Table 7). The 2010 and 1931-1960 average annual discharges were similar at 5,842,2987 and 5,496,801 m^3/day, respectively; however, the 2011 average annual discharge was 8,798,043 m^3/day. This increase in average discharge was reflected in the volumetric contributions.

Table 7. 1931-1960 (Annual), 2010 (3/22/2010 to 11/27/2010), and 2011 (4/4/2011 to 11/27/2011) Oneida Lake Tributaries Average Discharge. 2010 and 2011 daily stream inflow discharge derived from the volume contribution weightings for the East Branch of Fish Creek and Oneida Creek USGS measured daily discharge.

Tributary	**Greeson (1931-1960)**		**Hetherington (2010)**	**Hetherington (2011)**
	Percentage Total Inflow (%)	**Average Discharge (m^3/day)**	**Average Discharge (m^3/day)**	**Average Discharge (m^3/day)**
Scriba	4.0	233,719	219,872	351,922
Fish	50.0	2,921,494	2,748,401	4,399,022
Oneida	7.0	409,009	384,776	615,863
Canaseraga	1.0	58,430	54,968	87,980
Cowaselon	4.0	233,719	219,872	351,922
Chittenango	18.0	1,051,738	989,424	1,583,648
Ungauged	16.0	934,878	879,488	1,407,687
TOTAL Inflow		5,842,987	5,496,802	8,798,043

Figure 25 – Figure 28 summarize the 2010 and 2011 air and water temperatures for the four tributaries used in DYRESM. The maximum air temperature occurred on July 8th in 2010 and July 21st in 2011. In both years, water temperatures tracked closely with air temperatures. The water temperature was warmer than the air temperature in spring/late fall more so in 2011 than 2010.

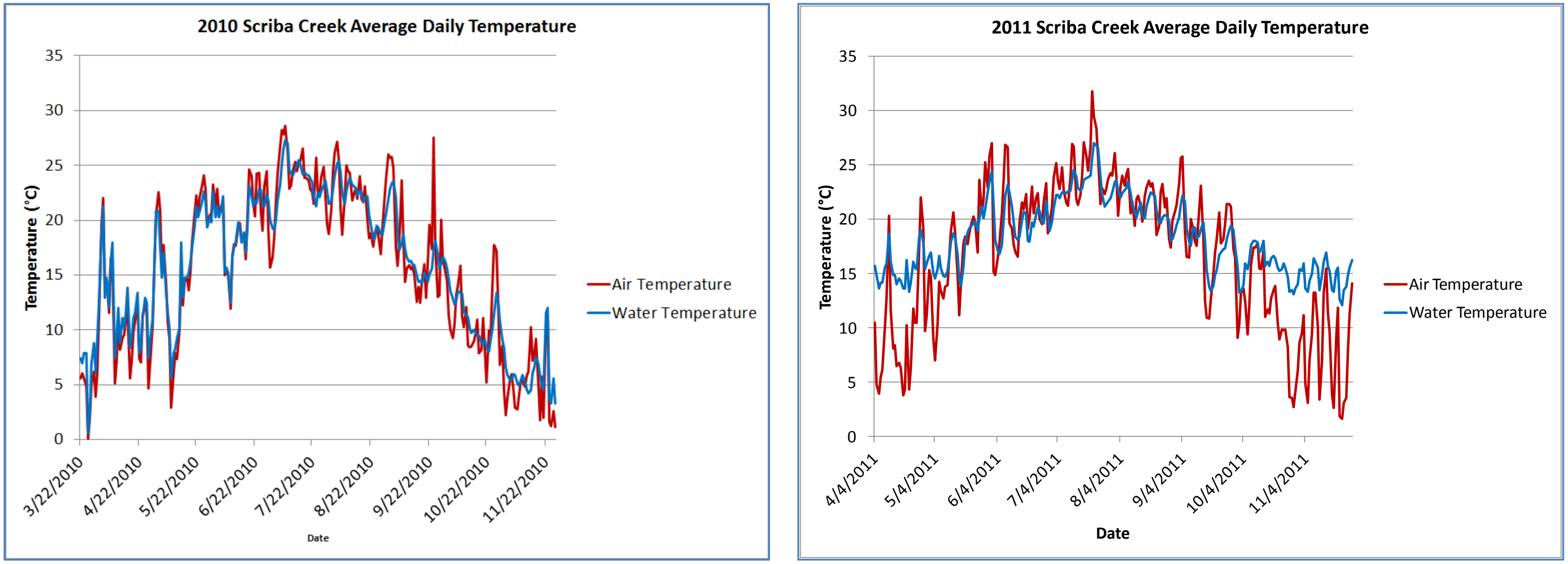


Figure 25. 2010 and 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and Scriba Creek Temperatures for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Average daily air temperature obtained for Syracuse Airport. Average daily water temperatures calculated from water temperatures measured every 4 hours for Scriba Creek at Constantia, NY for 6/22/2010 to 11/21/2010 and 5/8/2011 to 10/4/2011. Calculated average daily water temperatures for 3/22/2010 to 6/21/2010 and 11/22/2010 to 11/27/2010 and 4/4/2011 to 5/7/2011 and 10/5/2011 to 11/27/2011 obtained from air/water temperature comparisons (Scriba Creek Temperature (°C)=0.83*Air Temperature (°C)+2.84, R^2=0.882, N=206).

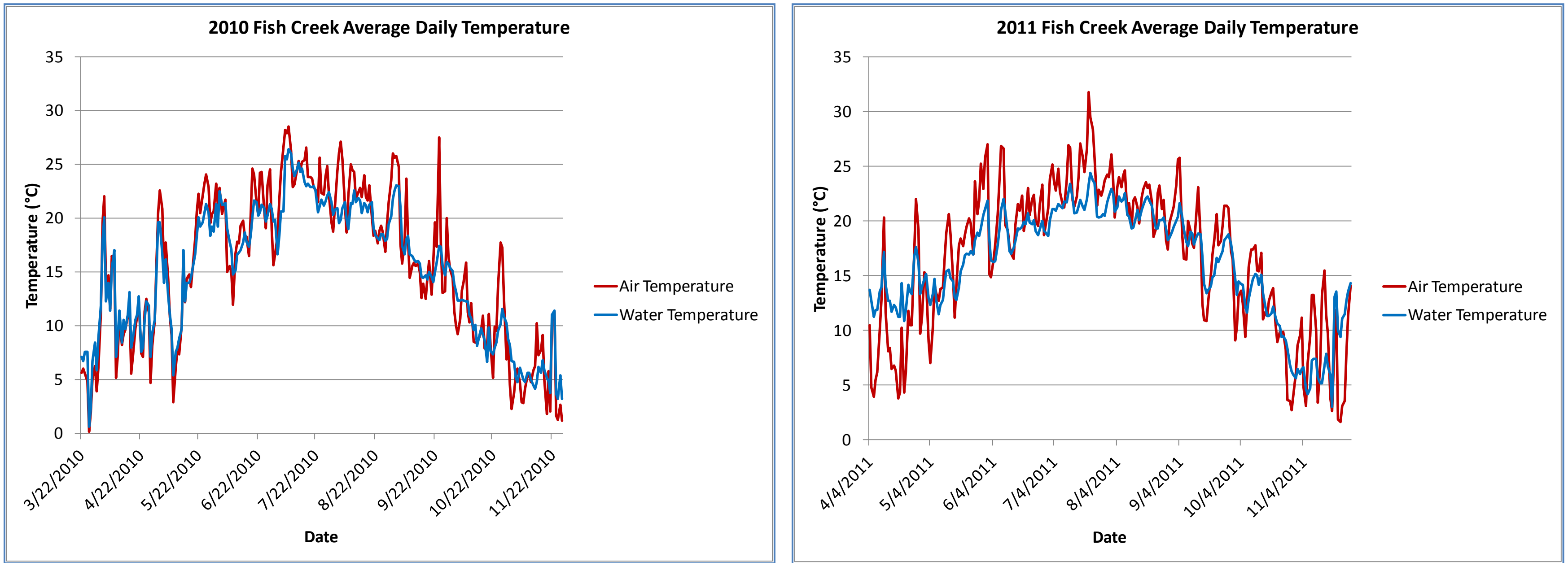


Figure 26. 2010 and 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and Fish Creek Temperature for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Average daily air temperature obtained for Syracuse Airport. Average daily water temperatures calculated from water temperatures measured every 4 hours for Fish Creek at Taberg, NY for 6/2/2010 to 11/21/2010 and 5/7/2011 to 11/19/2011. Calculated average daily water temperatures for 3/22/2010 to 6/1/2010 and 11/22/2010 to 11/27/2010 and 4/4/2011 to 5/6/2011 and 11/20/2011 to 11/27/2011 obtained from air/water temperature comparisons (Fish Creek Temperature (°C)=0.77*Air Temperature (°C)+3.05, R^2=0.857, N=313).

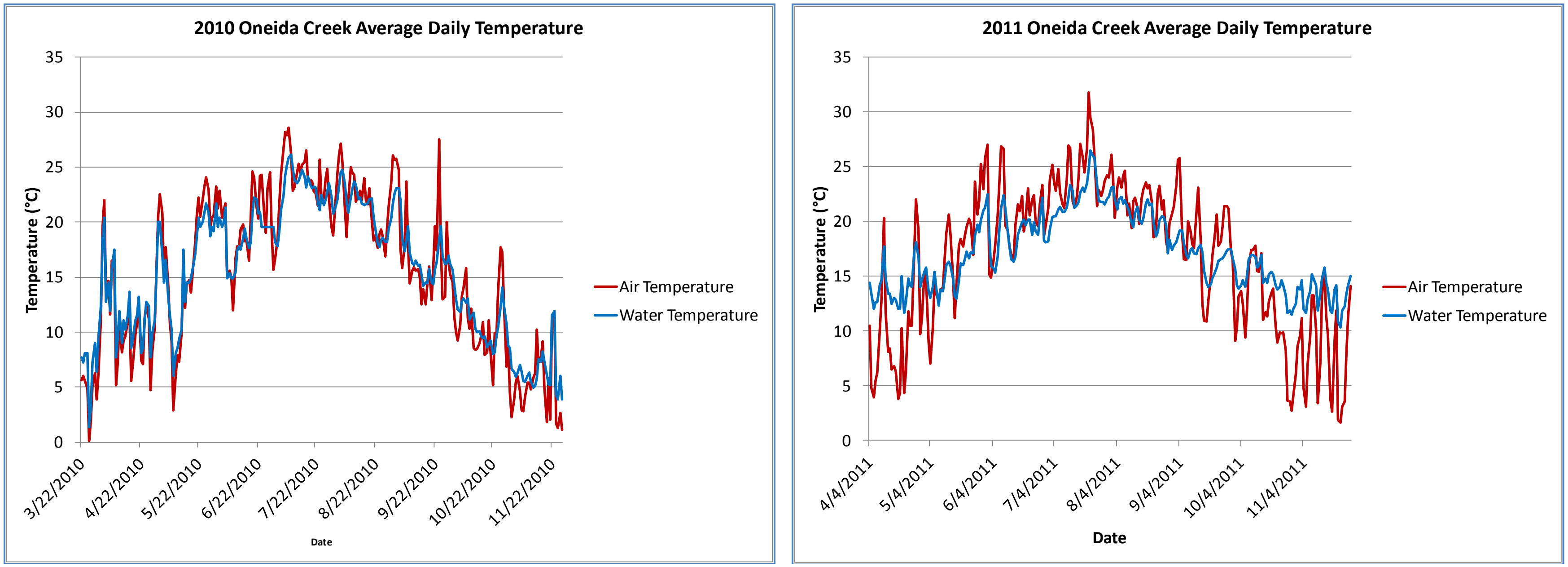


Figure 27. 2010 and 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and Oneida Creek Temperatures for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Average daily air temperature obtained for Syracuse Airport. Average daily water temperatures calculated from water temperatures measured every 4 hours for Oneida Creek at Sherrill, NY for 6/9/2010 to 11/20/2010 and 5/7/2011 to 8/28/2011. Calculated average daily water temperatures for 3/22/2010 to 6/8/2010 and 11/21/2010 to 11/27/2010 and 4/4/2011 to 5/6/2011 and 8/29/2011 to 11/27/2011 obtained from air/water temperature comparisons (Oneida Creek Temperature (°C)=0.75*Air Temperature (°C)+3.73, R^2=0.850, N=305).

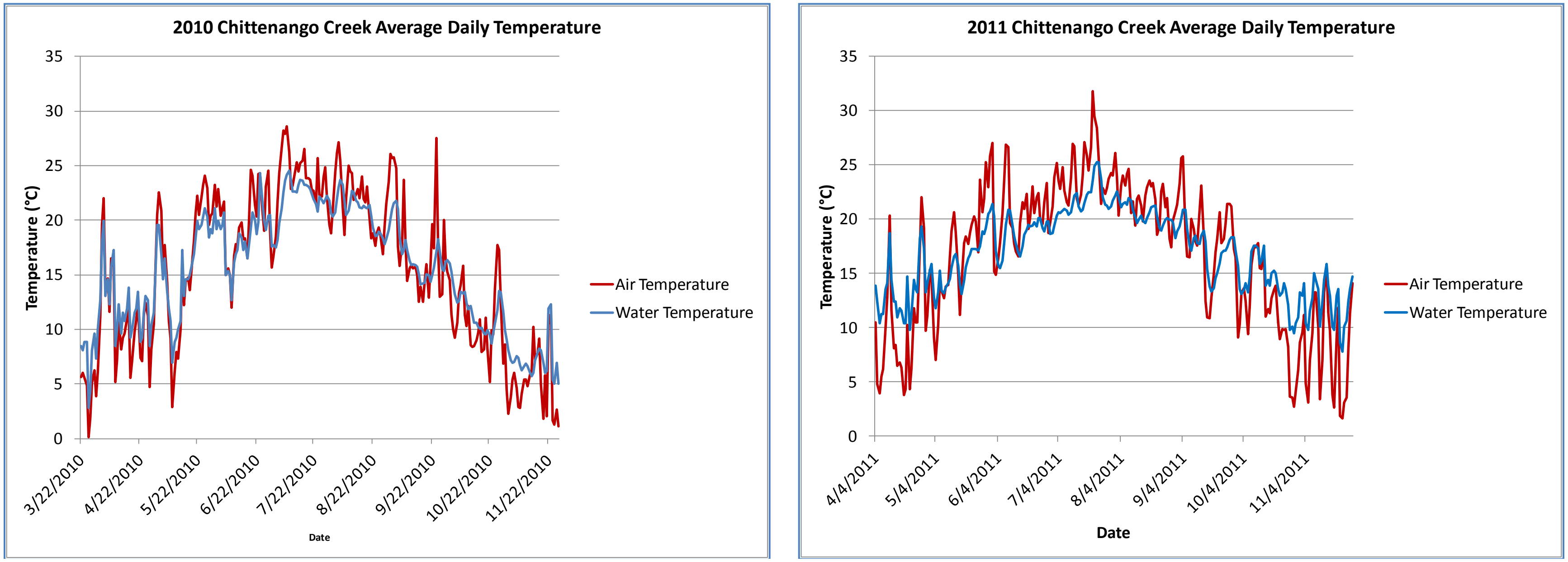


Figure 28. 2010 and 2011 Oneida Lake Watershed Average Daily Air (Syracuse Airport) and Chittenango Creek Temperatures for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Average daily air temperature obtained for Syracuse Airport. Average daily water temperatures calculated from water temperatures measured every 4 hours for Chittenango Creek at Bridgeport, NY for 6/18/2010 to 11/20/2010 and 5/7/2011 to 10/4/2011. Calculated average daily water temperatures for 3/22/2010 to 6/17/2010 and 11/21/2010 to 11/27/2010 and 4/4/2011 to 5/6/2011 and 10/5/2011 to 11/27/2011 obtained from air/water temperature comparisons (Chittenango Creek Temperature (°C)=0.68*Air Temperature (°C)+4.94, R^2=0.830, N=296).

Inflow water temperature regression equations based on air temperature were developed for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek to estimate water temperatures in the early spring and late fall for 2010 and 2011 (Table 8). There was excellent agreement and differences were consistently explained by more extreme daily air temperatures, both cooler and warmer, than the corresponding water temperatures.

Table 8. 2010 and 2011 Oneida Lake Watershed Inflow Water Temperature (T_{inf}) Regression Equations Based on Air Temperature (T_{air}) for June – November 2010 and 2011.

Inflow	Equation	r^2	N
Scriba Creek	$T_{inf} = 0.83T_{air}+2.84$	0.882	260
Fish Creek	$T_{inf} = 0.77T_{air}+3.05$	0.857	313
Oneida Creek	$T_{inf} = 0.75T_{air}+3.73$	0.850	305
Chittenango Creek	$T_{inf} = 0.68T_{air}+4.94$	0.830	296

Withdrawal Data

Oneida Lake is drained by a single outlet, Oneida River. The 2011 average daily discharge was greater than the 2010 discharge (Figure 29) which corresponded with the inflow (Figure 23). Likewise, the peaks in 2010 average daily discharge for the Oneida River related to increases in inflow.

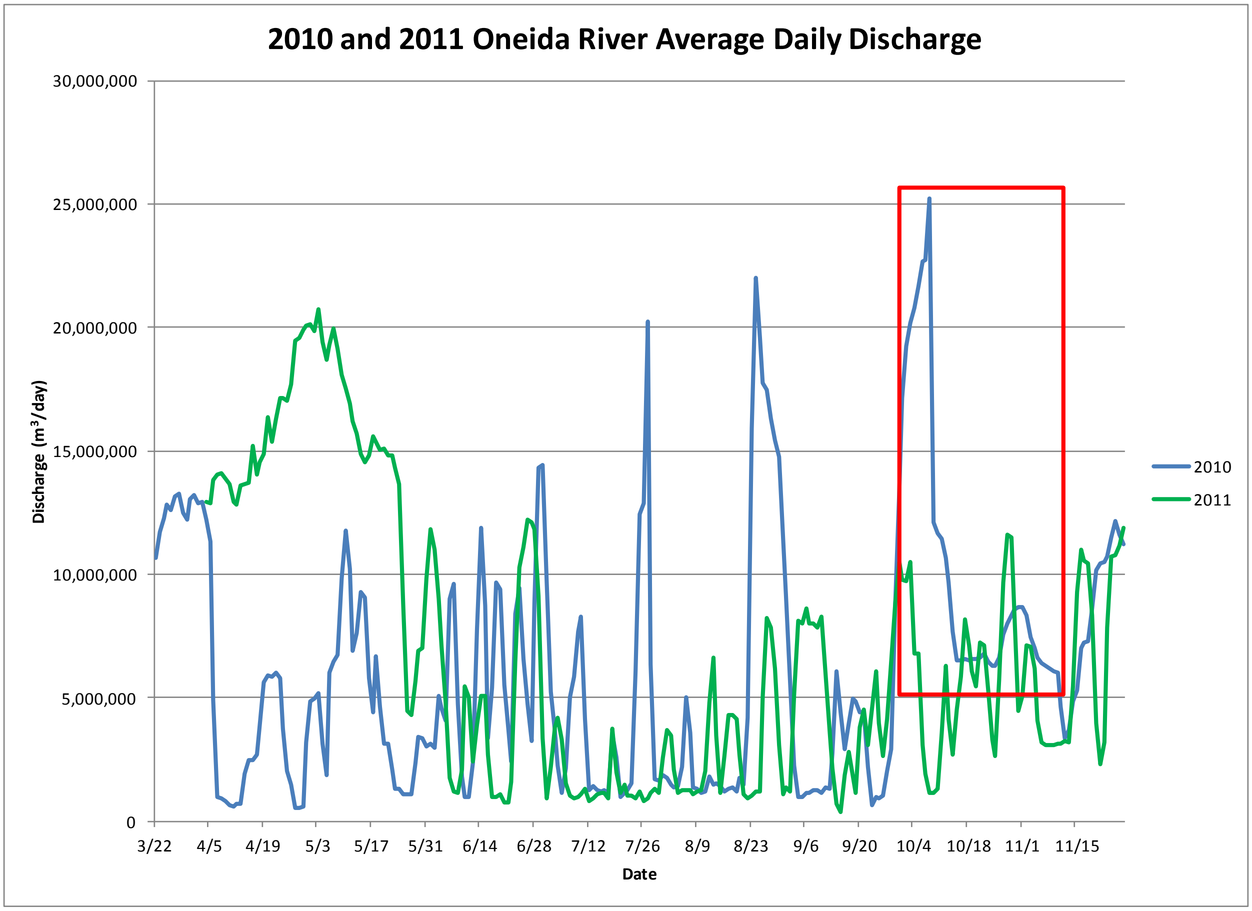


Figure 29. 2010 and 2011 Oneida Lake Watershed Average Daily Oneida River Discharge (USGS) for DYRESM (3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011). Red box indicates calculated average daily discharge measurements for 10/1/2010 to 11/10/2010 (Oneida River Discharge (m^3/day)=0.430*East Branch Fish Creek Discharge (m^3/day)+3.00E6, R^2=0.477, N=319).

Forty-one days of missing average daily discharge measurements from October 1, 2010 – November 10, 2010 (Figure 29) were resolved using a regression relationship between East Branch Fish Creek and the Oneida River where y=0.430x + 3.00E6; R^2 = 0.477; N = 319 (Figure 30).

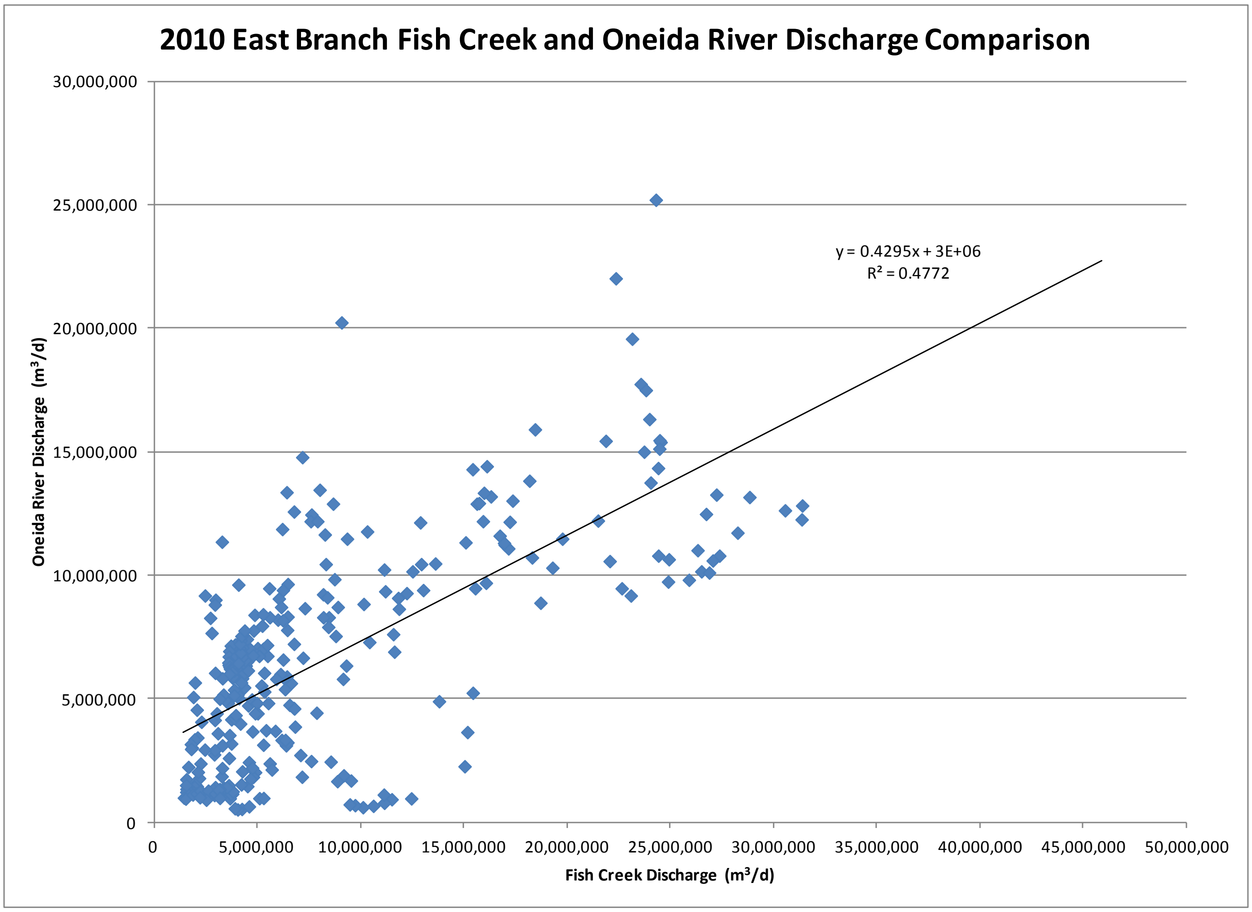


Figure 30. 2010 Oneida Lake Watershed East Branch Fish Creek and Oneida River Discharge Comparison for 1/7/2010 to 12/31/2010 (Oneida River Discharge (m^3/day)=0.430*East Branch Fish Creek Discharge (m^3/day)+3.00E6, R^2=0.477, N=319).

The Oneida River average daily discharge historical record is comprised of data from Caughdenoy for 1948 – 1997 and Euclid from 1997 – 2011 (Figure 24). The historical record of the outlet was somewhat variable with an average of 6,378,360 m^3/day (SD 1,355,926) and range of 3,919,964 - 9,657,770 m^3/day for the 1948-2011 period. The 2010 and 2011 Oneida River average discharge data were within this range.

Water Budget

Table 9 summarizes the original and revised water budgets for 2010 and 2011. The revised water budgets balanced the water inflow and outflow on a daily basis accounting for changes in lake level. In 2010, output exceeded input by an average of 402,045 m^3/day or approximately 6% of total input. After balancing the water budget, input was greater than output by an average of 190,035 m^3/day or 3% of total input. For 2011, input exceeded output by an average of 2,416,885 m^3/day or 33% of total output and 26,510 m^3/day or less than 1% of total output before and after balancing the water budget, respectively.

Table 9. 2010 and 2011 Oneida Lake Average Initial and Balanced Water Budgets for 3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011. Average daily stream inflow includes daily discharge for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek derived from the volume contribution weightings for the East Branch of Fish Creek and Oneida Creek USGS measured daily discharges. Average daily precipitation obtained for Syracuse Airport. Average daily Oneida River outflow from USGS measured daily discharge at Euclid, NY. Average daily evaporation calculated from wind speed, relative humidity, and air temperature for Syracuse Airport and Oneida Lake surface water temperature at Shackelton Point. Average daily Oneida Lake storage calculated from daily difference in 5 day moving average of lake level. 2010 and 2011 balanced water budgets reflect increases in inflow and outflow, respectively.

	2010	2010 Balanced	2011	2011 Balanced
Average Stream Inflow (m^3/day)	5,496,802	6,088,882	8,798,043	8,798,043
Average Precipitation (m^3/day)	793,033	793,033	861,920	861,920
AVERAGE INPUT (m^3/day)	6,289,835	6,881,915	9,659,963	9,659,963
Average Oneida River Outflow (m^3/day)	6,287,366	6,287,366	7,000,126	9,390,500
Average Evaporation (m^3/day)	404,514	404,514	242,953	242,953
AVERAGE OUTPUT (m^3/day)	6,691,880	6,691,880	7,243,079	9,633,453
Average Oneida Lake Storage (m^3/day)	190,035	190,035	26,510	26,510
AVERAGE OUTPUT - INPUT (m^3/day)	402,045	(190,035)	(2,416,885)	(26,510)

In 2010 and 2011, the Oneida Lake average daily output corresponded with the input as expected in this managed lake (Figure 31). In 2010, average daily output exceeded input in late summer and early fall (Figure 31). In contrast, average daily input exceeded output in 2011 with this occurring primarily in the spring (Figure 31). Average input and output increased from 2010 to 2011 (Figure 31) with the average daily input of 6,881,915 m^3/day in 2010 and 9,659,963 m^3/day in 2011 and average daily output of 6,691,880 m^3/day in 2010 and 9,633,453 m^3/day in 2011 (Table 9). The increase in average input was due to an increase in average stream inflow and precipitation (Table 9 and Figure 32). The increase in average stream inflow could be due to snowpack in early 2011 or groundwater recharge to the lake from late 2010.

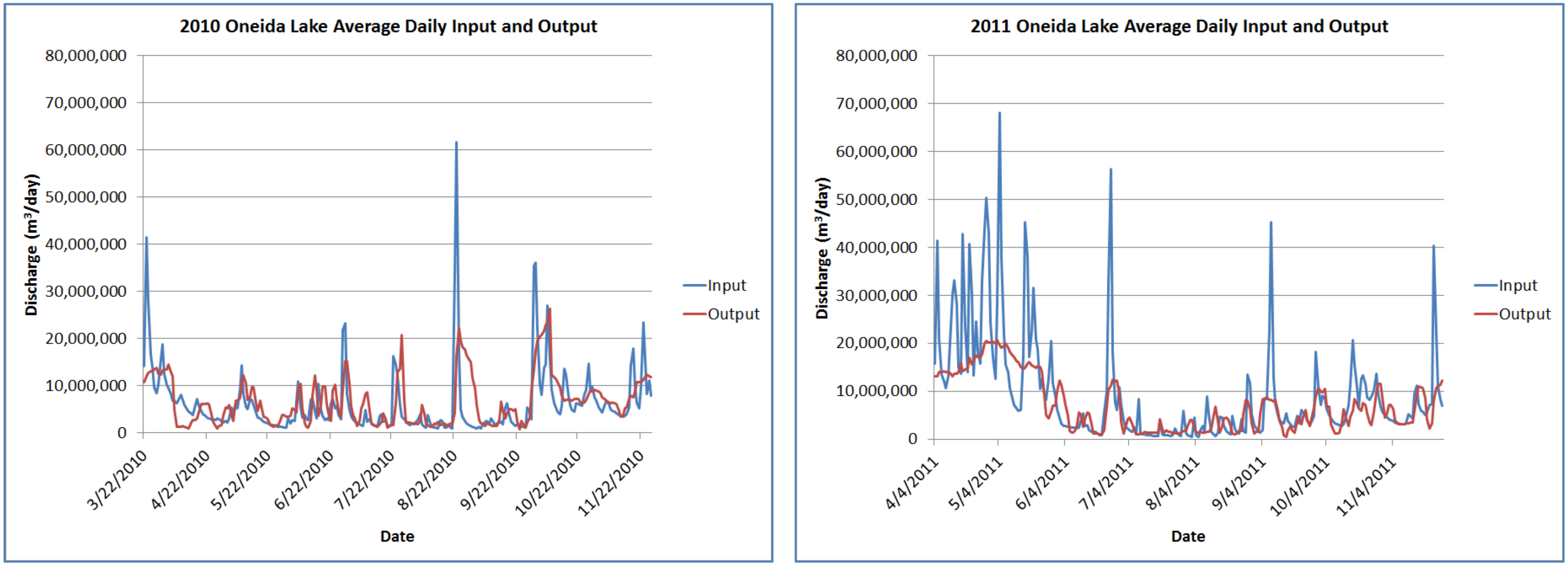


Figure 31. 2010 and 2011 Oneida Lake Initial Average Daily Input (Stream Inflows and Precipitation) and Output (Outflow and Evaporation) for 3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011. Average daily stream inflow includes daily discharge for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek derived from the volume contribution weightings for the East Branch of Fish Creek and Oneida Creek USGS measured daily discharges. Average daily precipitation obtained for Syracuse Airport. Average daily Oneida River outflow from USGS measured daily discharge at Euclid, NY. Average daily evaporation calculated from wind speed, relative humidity, and air temperature for Syracuse Airport and Oneida Lake surface water temperature at Shackelton Point.

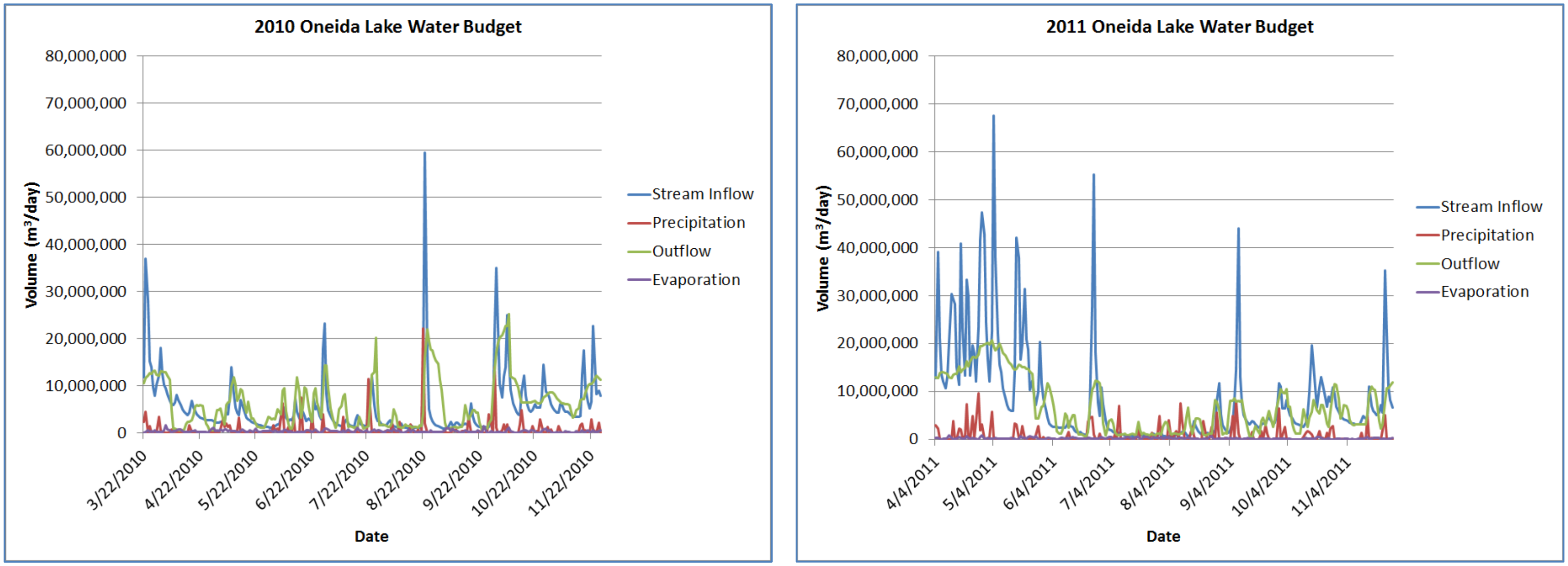


Figure 32. 2010 and 2011 Oneida Lake Initial Average Daily Water Budget for 3/22/2010 to 11/27/2010 and 4/4/2011 to 11/27/2011. Average daily stream inflow includes daily discharge for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek derived from the volume contribution weightings for the East Branch of Fish Creek and Oneida Creek USGS measured daily discharges. Average daily precipitation obtained for Syracuse Airport. Average daily Oneida River outflow from USGS measured daily discharge at Euclid, NY. Average daily evaporation calculated from wind speed, relative humidity, and air temperature for Syracuse Airport and Oneida Lake surface water temperature at Shackelton Point.

Further comparison of the 2010 and 2011 water budgets with the historical record (Greeson, 1971) indicated the 2010 and 2011 average inputs and outputs were greater than the 1931-1960 average inputs and outputs; however, the 2010 measurements were closely aligned with the historical record (Table 10). While the 2011 average input exceeded the 1931-1960 and 2010 average input, the 2011 average output corresponded with the increased average input even though the evaporation decreased (Table 10).

Table 10. 1931 – 1960 (Annual), 2010 (3/22/2010 to 11/27/2010), and 2011 (4/4/2011 to 11/27/2011) Oneida Lake Balanced Water Budgets. Average daily stream inflow includes daily discharge for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek derived from the volume contribution weightings for the East Branch of Fish Creek and Oneida Creek USGS measured daily discharges. Average daily precipitation obtained for Syracuse Airport. Average daily Oneida River outflow from USGS measured daily discharge at Euclid, NY. Average daily evaporation calculated from wind speed, relative humidity, and air temperature for Syracuse Airport and Oneida Lake surface water temperature at Shackelton Point. 2010 and 2011 balanced water budgets reflect increases in inflow and outflow, respectively.

	Greeson (1931-1960)	Hetherington (2010)	Hetherington (2011)
Average Stream Inflow (m^3/day)	5,842,987	6,088,882	8,798,043
Average Precipitation (m^3/day)	505,559	793,033	861,920
AVERAGE INPUT (m^3/day)	6,348,546	6,881,915	9,659,963
Average Oneida River Outflow (m^3/day)	5,847,718	6,287,366	9,390,500
Average Evaporation (m^3/day)	500,827	404,514	242,953
AVERAGE OUTPUT (m^3/day)	6,348,545	6,691,880	9,633,453

Light Extinction Coefficients

DYRESM requires the average light extinction coefficients for the simulation period. The average light extinction coefficients for Oneida Lake in 2010 and 2011 were 0.52 and 0.66, respectively.

Baseline Simulation

Comparison of the 2010 baseline daily simulated and weekly observed Oneida Lake temperatures indicated the modeled temperatures were generally less than the observed temperatures throughout the water column (Figure 33). In Spring 2010, there were periods when the modeled temperatures were greater than the observed temperatures in the water column (Figure 33). The greatest differences, approximately 4°C – 6°C, between the observed and modeled temperatures occurred in the late spring and early summer of 2010 (Figure 33).

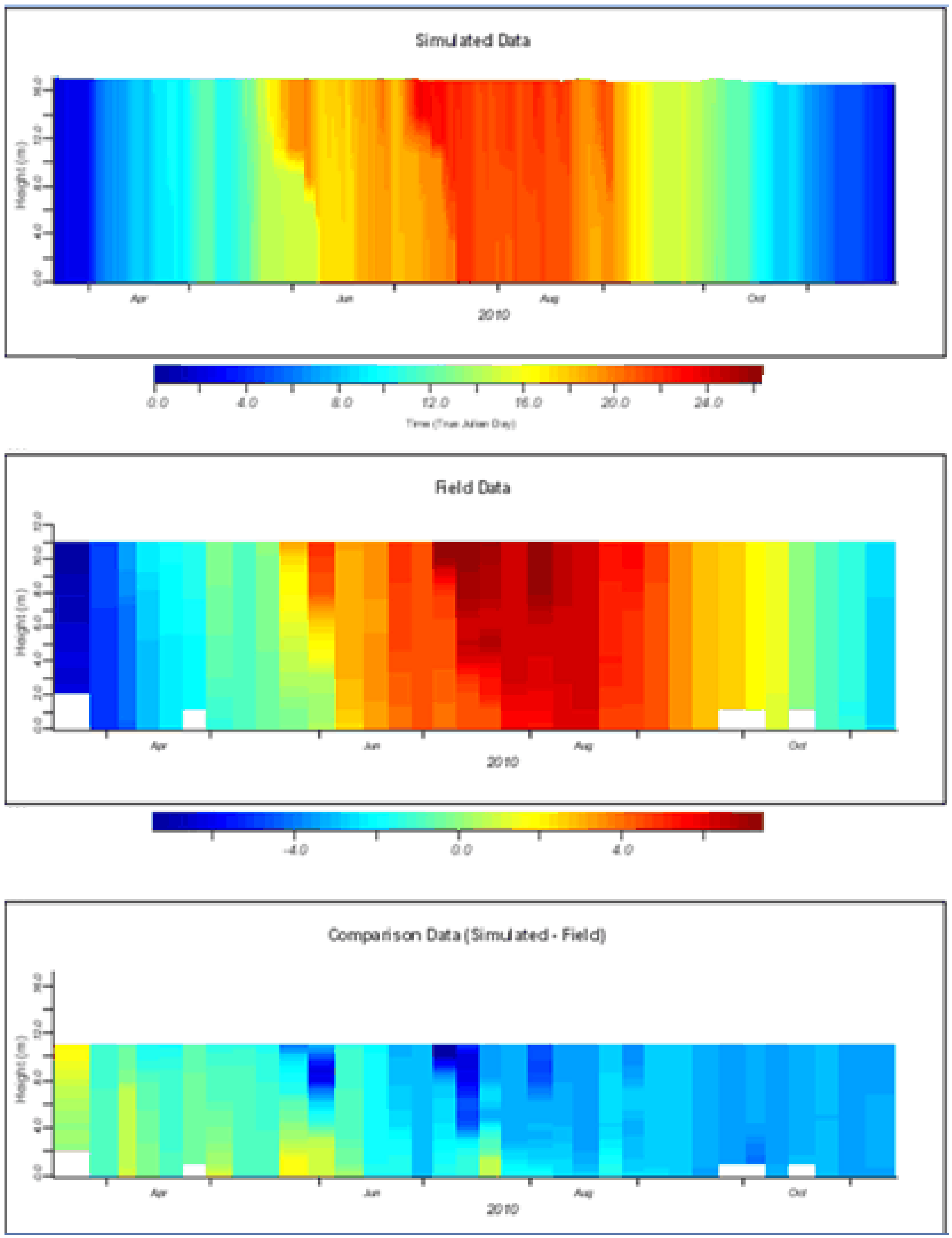


Figure 33. 2010 Oneida Lake Baseline Simulated, Observed (Weekly), and Simulated - Observed Time Series Plots for 3/22/2010 to 11/27/2010. Baseline simulation used 2010 field monitoring inputs from Oneida Lake and its watershed and default parameters. Weekly observed water temperatures consisted of average weekly water temperatures at 1 m intervals throughout the water column at Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

For the simulation period from March 22nd to November 27th, the 2010 baseline daily average simulated temperatures at 2 m and 10 m in Oneida Lake tracked the daily observed temperatures with r^2 = 0.97 and r^2 = 0.93, respectively. The simulated temperatures at 2 m (Figure 34) and 10 m (Figure 35) were generally less than the observed temperatures; however, at 10 m, there were periods from spring to mid-summer where the daily average modeled temperatures were greater than the observed temperatures (Figure 35). The average deviation (observed – modeled) at 2m was 2.84°C (SD 0.94) and 2.03°C (SD 1.46) at 10 m. The average absolute difference between modeled and observed temperatures at 2 m was 2.84°C (SD 0.94) and the root mean square error was 2.99°C. At 10 m, the average absolute difference between modeled and observed temperatures and the root mean square error were 2.26°C (SD 1.09) and 2.50, respectively.

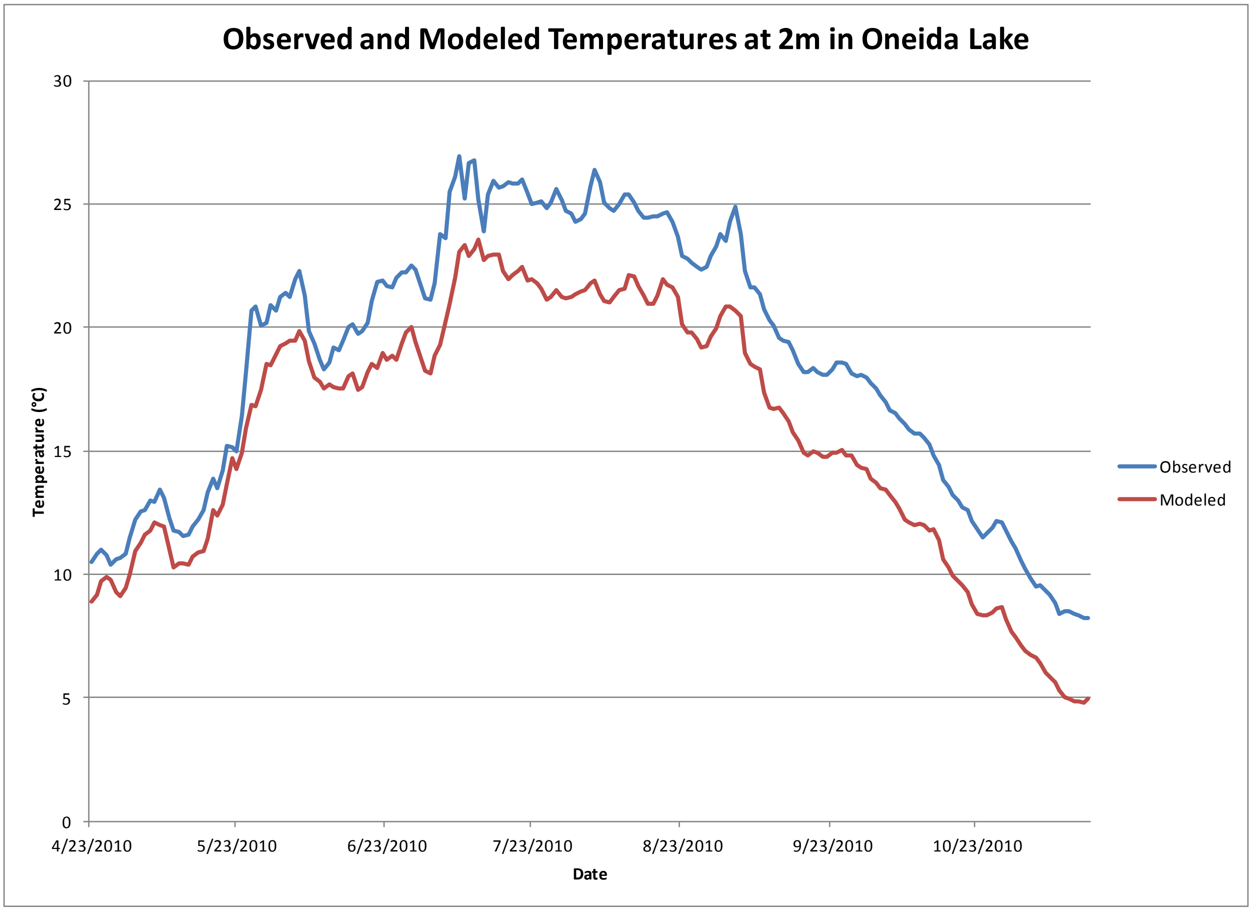


Figure 34. 2010 Oneida Lake Baseline Average Daily Simulated and Observed 2 m Temperatures for 4/23/2010 to 11/15/2010. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Average daily observed 2 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

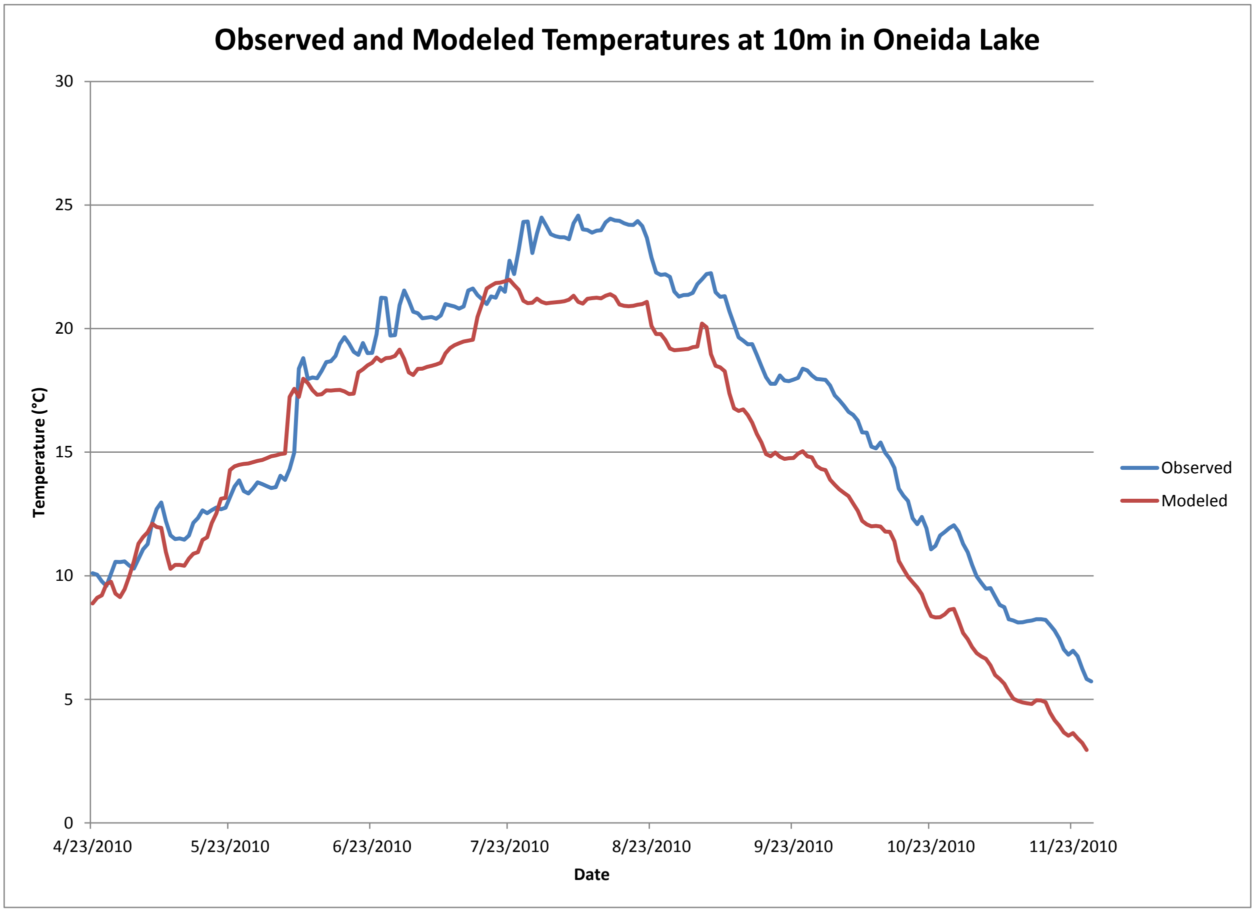


Figure 35. 2010 Oneida Lake Baseline Average Daily Simulated and Observed 10 m Temperatures for 4/23/2010 to 11/26/2010. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Average daily observed 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

The difference between 2 m and 10 m temperatures is an indicator of stratification within the water column. In 2010, the greatest observed differences between 2 m and 10 m temperatures or stratification occurred from late spring to mid-summer (Figure 36). The modeled differences tracked with the observed differences between 2 m and 10 m temperatures; however, the simulated strength of stratification was less than the observed (Figure 36).

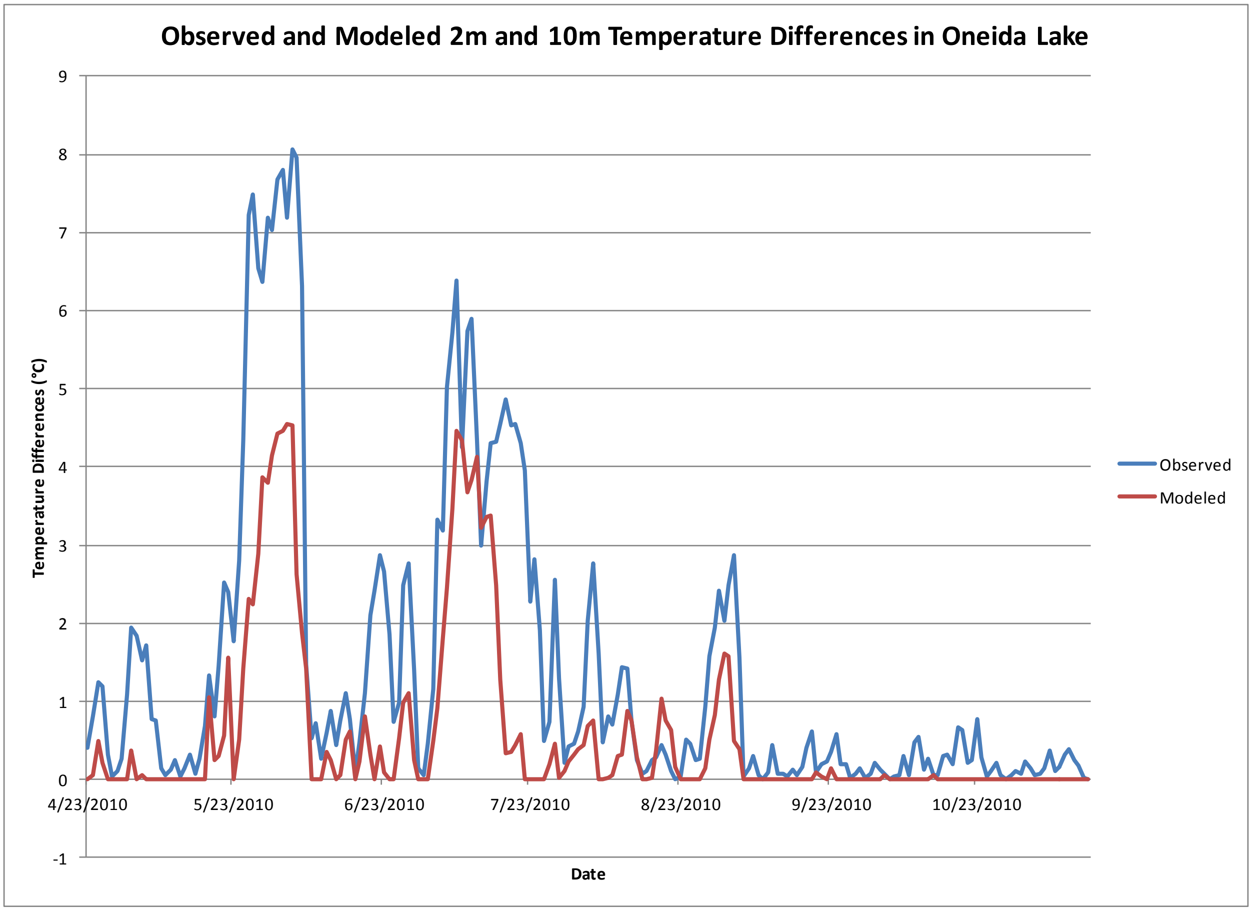


Figure 36. 2010 Oneida Lake Baseline Simulated and Observed 2 m and 10 m Temperature Differences for 4/23/2010 to 11/2/2010. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Average daily observed 2 m and 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

Sensitivity Analysis

The effective surface area coefficient, mean albedo, minimum layer thickness, and critical wind speed were the parameters tested for the sensitivity analysis (Table 11 and Table 12). The selected values for the effective surface area coefficient and critical wind speed parameters were the default values as changing these parameters did not affect model performance (Table 11). The default value for the mean albedo was 0.08; however, the selected value was 0.01. The average deviation between the simulated and observed temperatures decreased from 2.84°C (SD

0.94) for the default to 2.24°C (SD 1.03) for the selected mean albedo at 2 m and from 2.03°C (SD 1.46) for the default to 1.44°C (SD 1.60) for selected parameter at 10 m (Table 11). The minimum layer thickness default value was 1.5, but the selected value was 0.5. At 2 m, the average deviation between the simulated and observed temperatures was 2.84°C (SD 0.94) for the default and selected parameters, respectively. However, at 10 m, the average deviation between the simulated and observed temperatures decreased from 2.03°C (SD 1.46) to 1.97°C (SD 1.46) for the default and selected parameters, respectively (Table 11).

In addition to parameters, forcing variables, including solar radiation, wind speed, and groundwater, were tested for the sensitivity analysis (Table 12). By increasing the solar radiation by 30%, the average deviation between the simulated and observed temperatures decreased from 2.84°C (SD 0.94) and 2.03°C (SD 1.46) for the baseline to 0.56°C (SD 1.40) and 0.20°C (SD 1.70) for the simulation with the altered forcing variable at 2 m and 10 m, respectively. Furthermore, the performance of decreasing the wind speed was tested for the sensitivity analysis (Table 12). By decreasing the wind speed by 40%, the average deviation between the simulated and observed temperatures at 2 m decreased from 2.84°C (SD 0.94) for the baseline to -0.57°C (SD 0.92) for the simulation with wind speed decreased by 40%. At 10 m, the average deviation between the simulated and observed temperatures decreased from 2.03°C (SD 1.46) for the baseline to 0.05°C (SD 1.17) for the -40% wind speed simulation. Lastly, the performance of 0.61 m (2 ft) and 3.66 m (12 ft) well groundwater temperatures was tested for the sensitivity analysis (Table 12). The 0.61 m (2 ft) performed better than the 3.66 m (12 ft) well groundwater temperatures as compared to the baseline at 2m and 10 m for all metrics. The average deviation between the simulated and observed temperatures at 2 m decreased from 2.84°C (SD 0.94) for the baseline to 2.80°C (SD 0.94) for the simulation with 0.61 m (2 ft) groundwater well temperatures; however, the average deviation between the simulated and observed temperatures at 2 m increased from 2.84°C (SD 0.94) for the baseline to 2.88°C (SD 0.94) for the simulation with 3.66 m (12 ft) groundwater well temperatures. At 10 m, the average deviation between the simulated and observed temperatures decreased from 2.03°C (SD 1.46) for the baseline to 1.92°C (SD 1.47) for the 0.61 m (2 ft) groundwater well simulation. The average deviation increased to 2.12°C (SD 1.30) at 10 m for the 3.66 m (12 ft) well temperatures.

Table 11. 2010 Oneida Lake Parameter Sensitivity Analysis Performance Results at 2 m and 10 m. Simulations were performed using the 2010 input data for forcing variables and default input parameters while varying one of the tested parameters at a time and comparing the daily temperature output at 2 m and 10 m with the baseline simulation.

		2m				10m			
Parameter	**Value**	**r^2**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**	**r^2**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**
Effective Surface Area Coefficient	1.00E+0.6	0.97	2.84(0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	0.5E+07	0.97	2.84 (0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	1.00E+0.7[*ǂ]	0.97	2.84 (0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	0.5E+08	0.97	2.84 (0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	1.00E+0.8	0.97	2.84 (0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
Mean Albedo	0.08[*]	0.97	2.84 (0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	0.07	0.97	2.75 (0.98)	2.75 (0.97)	2.92	0.91	1.79 (1.68)	2.19 (1.13)	2.46
	0.05	0.97	2.58 (0.98)	2.58 (0.98)	2.76	0.90	1.65 (1.72)	2.26 (1.09)	2.38
	0.03	0.97	2.39 (1.00)	2.39 (0.99)	2.59	0.93	1.47 (1.78)	2.07 (1.03)	2.31
	0.01[ǂ]	0.96	2.24 (1.03)	2.24 (1.02)	2.46	0.92	1.44 (1.60)	1.91 (1.00)	2.15
Minimum Layer Thickness	1.5 m[*]	0.97	2.84 (0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	1.0 m	0.97	2.84 (0.96)	2.84 (0.96)	3.00	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	0.5 m[ǂ]	0.97	2.84 (0.96)	2.84 (0.96)	3.00	0.93	1.97 (1.46)	2.18 (1.13)	2.45
	0.2 m	0.97	2.88 (0.95)	2.88 (0.95)	3.03	0.93	1.99 (1.45)	2.20 (1.11)	2.46
Critical Wind Speed	2.00 m/s	0.97	2.86 (0.99)	2.86 (0.98)	3.03	0.94	2.15 (1.34)	2.29 (1.09)	2.53
	3.00 m/s[*ǂ]	0.97	2.84 (0.94)	2.84 (0.94)	2.99	0.93	2.03 (1.46)	2.26 (1.09)	2.50
	4.00 m/s	0.97	2.88 (0.95)	2.88 (0.94)	3.03	0.89	1.80 (1.85)	2.31 (1.17)	2.58
	5.00 m/s	0.97	2.90 (0.96)	2.91 (0.95)	3.06	0.91	1.86 (1.69)	2.25 (1.12)	2.51
	6.00 m/s	0.97	2.86 (0.94)	2.87 (0.93)	3.01	0.90	1.89 (1.69)	2.28 (1.13)	2.53

[*]Default Value
[ǂ]Selected Value

Table 12. 2010 Oneida Lake Variable Sensitivity Analysis Performance Results at 2 m and 10 m. Simulations were performed using the 2010 input data for forcing variables and default input parameters while varying one of the tested variables at a time and comparing the daily temperature output at 2 m and 10 m with the baseline simulation.

		2 m				10 m			
Variable	**Value**	**r^2**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**	**r^2**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**
Solar Radiation	+10%	0.96	2.03 (1.07)	2.05 (1.02)	2.30	0.91	1.22 (1.69)	1.86 (0.94)	2.08
	+20%	0.95	1.29 (1.23)	1.57 (0.84)	1.78	0.91	0.68 (1.73)	1.66 (0.85)	1.86
	+30%	0.94	0.56 (1.40)	1.35 (0.68)	1.51	0.91	0.20 (1.70)	1.42 (0.96)	1.71
	+40%	0.93	-0.20 (1.60)	1.32 (0.91)	1.61	0.90	-0.45 (1.85)	1.48 (1.19)	1.90
	+50%	0.91	-0.94 (1.81)	1.60 (1.26)	2.04	0.89	-1.06 (1.95)	1.74 (1.38)	2.22
Wind Speed	-10%	0.97	2.21 (0.91)	2.22 (0.89)	2.39	0.94	1.53 (1.30)	1.79 (0.90)	2.01
	-20%	0.97	1.42 (0.87)	1.48 (0.78)	1.67	0.95	0.94 (1.19)	1.31 (0.77)	1.52
	-30%	0.97	0.42 (0.95)	0.87 (0.56)	1.03	0.94	0.06 (1.36)	0.93 (0.99)	1.36
	-40%	0.98	-0.57 (0.92)	0.80 (0.72)	1.08	0.95	0.05 (1.17)	0.93 (0.70)	1.17
	-50%	0.98	-1.88 (0.93)	1.88 (0.93)	2.09	0.97	-1.46 (1.11)	152 (1.03)	1.83
Groundwater	0.61 m (2 ft) Temps	0.97	2.80 (0.94)	2.80 (0.94)	2.95	0.93	1.92 (1.47)	2.17 (1.07)	2.42
	3.66 m (12 ft) Temps	0.97	2.88 (0.94)	2.88 (0.94)	3.93	0.94	2.12 (1.30)	2.24 (1.07)	2.48

Calibration

The calibrated or best fit model simulation included the selected parameter values from the sensitivity analysis, which include effective surface area coefficient of 1.00E+0.7, mean albedo of 0.01, minimum layer thickness of 0.5 m, and critical wind speed of 3.00 m/s, and reducing the forcing variable of wind speed by 25%. Due to modifying two parameters, mean albedo and minimum layer thickness, and a forcing variable, wind speed, in the same simulation, the wind speed was only reduced by 25% to obtain the best fit model simulation.

Comparison of the 2010 best fit daily simulated and weekly observed Oneida Lake temperatures indicated very good agreement between the simulated and observed temperatures throughout the water column with deviations within ±1°C (Figure 37). Throughout the simulation period, there were occurrences of differences between simulated and observed greater than ±1°C; however, these discrepancies were infrequent and tended to occur in the bottom waters (Figure 37). The largest deviation between simulated and observed temperatures of approximately 4°C occurred in late spring (Figure 37).

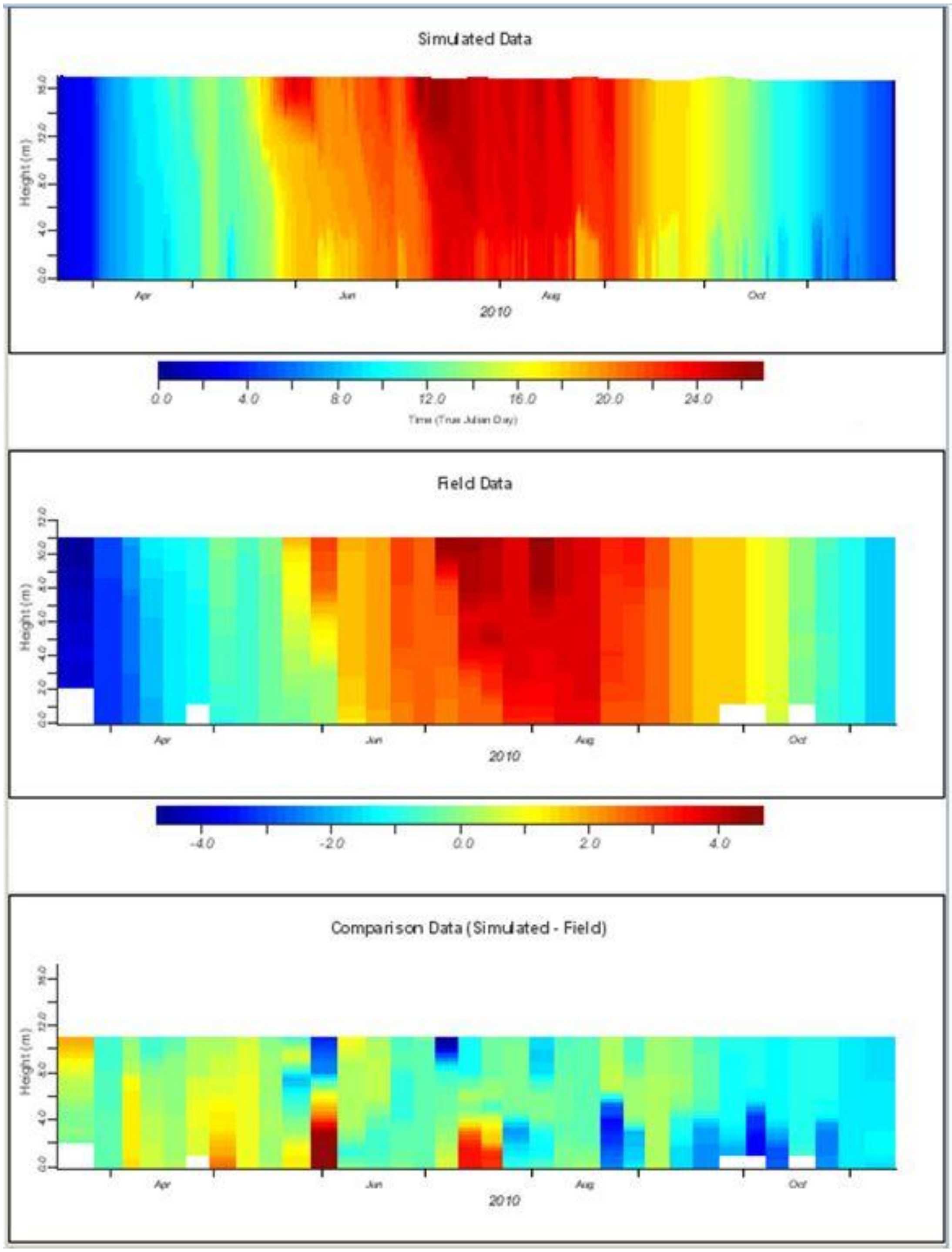


Figure 37. 2010 Oneida Lake Best Fit Simulated, Observed (Weekly), and Simulated - Observed Time Series Plots for 3/22/2010 to 11/27/2010. Best fit simulation used 2010 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Weekly observed water temperatures consisted of average weekly water temperatures at 1 m intervals throughout the water column at Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

For the simulation period from March 22nd to November 27th, the 2010 best fit daily average simulated temperatures at 2 m and 10 m in Oneida Lake tracked the daily observed temperatures with $r^2 = 0.97$ and $r^2 = 0.94$, respectively. The simulated temperatures at 2 m were in general agreement with the observed temperatures throughout the simulation period with exceptions in late spring and fall (Figure 38). The average deviation (observed – modeled) at 2 m was 0.13°C (±1.07). At 10 m, the simulated temperatures were generally less than the observed temperatures; however, there were periods from spring to mid-summer where the daily average modeled temperatures were greater than the observed temperatures (Figure 39). The average deviation (observed – modeled) at 10 m was -0.32°C (SD 1.53). The average absolute difference between modeled and observed temperatures at 2 m was 0.86°C (SD 0.65) and the root mean square error was 1.07°C. At 10 m, the average absolute difference between modeled and observed temperatures and the root mean square error were 1.12°C (SD 1.09) and 1.56°C, respectively. As expected, the best fit simulation tracked the observed temperatures at 2 m (Figure 38) and 10 m (Figure 39) in 2010 better than the baseline simulation.

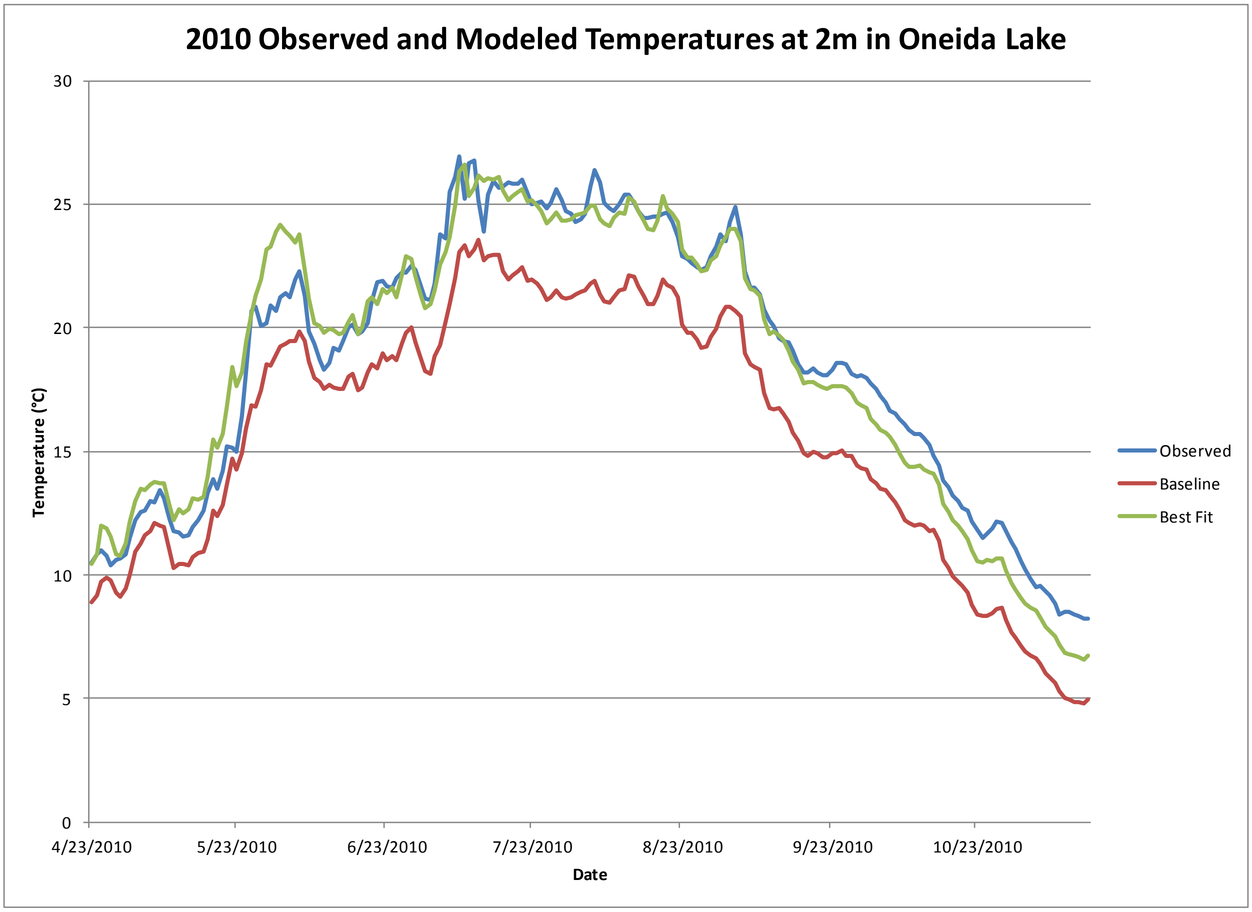


Figure 38. 2010 Oneida Lake Baseline, Best Fit, and Observed Average Daily Temperatures at 2 m for 4/23/2010 to 11/15/2010. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Best fit simulation used 2010 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Average daily observed 2 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

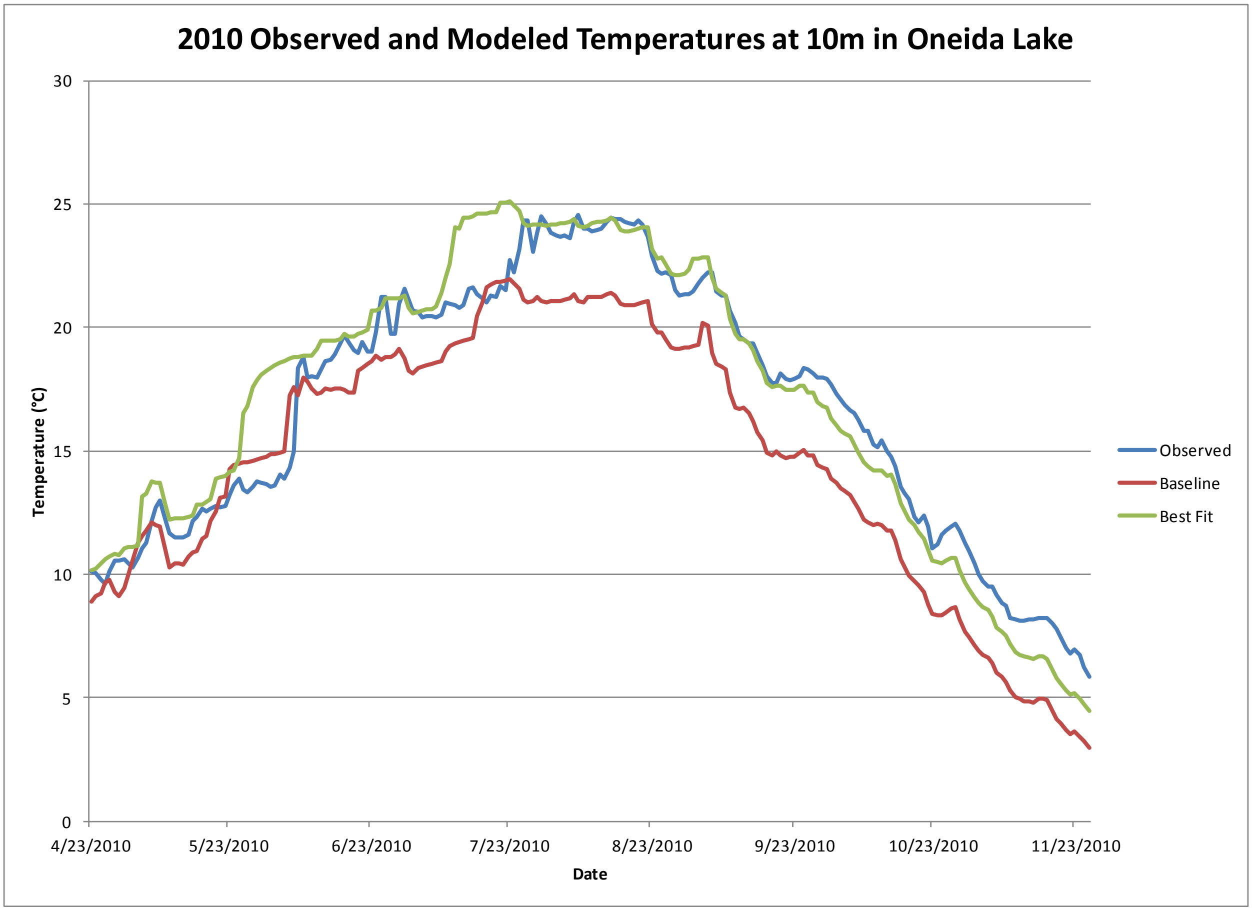


Figure 39. 2010 Oneida Lake Baseline, Best Fit, and Observed Average Daily Temperatures at 10 m for 4/23/2010 to 11/26/2010. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Best fit simulation used 2010 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Average daily observed 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

The difference between 2 m and 10 m temperatures was an indicator of stratification within the water column. In 2010, the greatest observed differences between 2 m and 10 m temperatures occurred from late spring to mid-summer (Figure 40). The modeled differences tracked with the observed differences between 2 m and 10 m temperatures; however, the simulated strength of stratification was generally less than the observed (Figure 40). As expected, the best fit simulation more closely represented the observed stratification in 2010 than the baseline simulation (Figure 40).

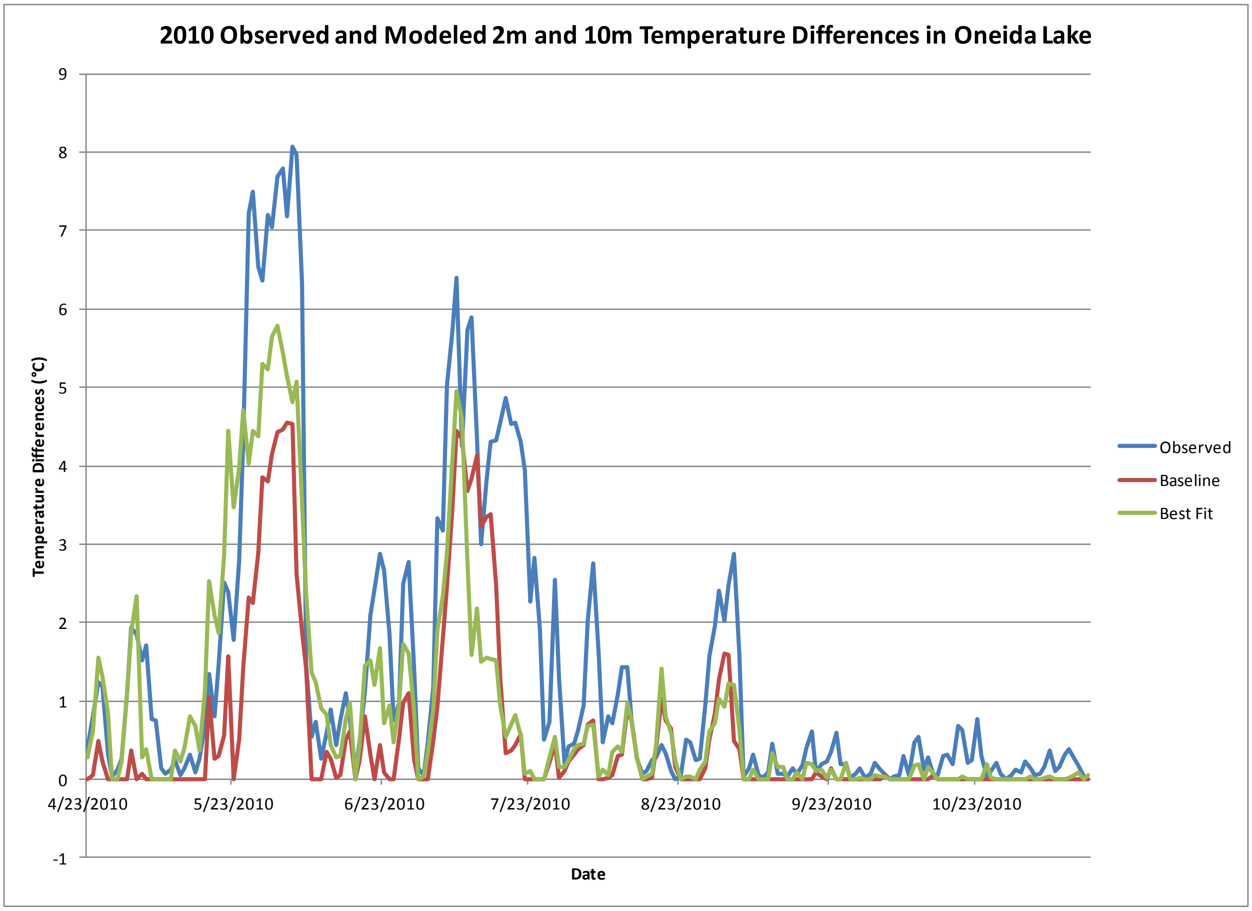


Figure 40. 2010 Oneida Lake Baseline, Best Fit, and Observed 2 m and 10 m Temperature Differences for 4/23/2010 to 11/15/2010. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Best fit simulation used 2010 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Average daily observed 2 m and 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

Validation

The calibrated or best fit model was tested with 2011 data to validate or confirm the model. Comparison of the 2011 best fit daily simulated and weekly observed Oneida Lake temperatures indicated generally very good agreement between the simulated and observed temperatures throughout the water column with deviations within ±1°C (Figure 41). Throughout the simulation period, there were occurrences of the difference between simulated and observed greater than ±1°C; however, these discrepancies tended to occur in the bottom waters (Figure 41). The largest deviation between simulated and observed temperatures of approximately 4°C was again observed in late spring (Figure 41).

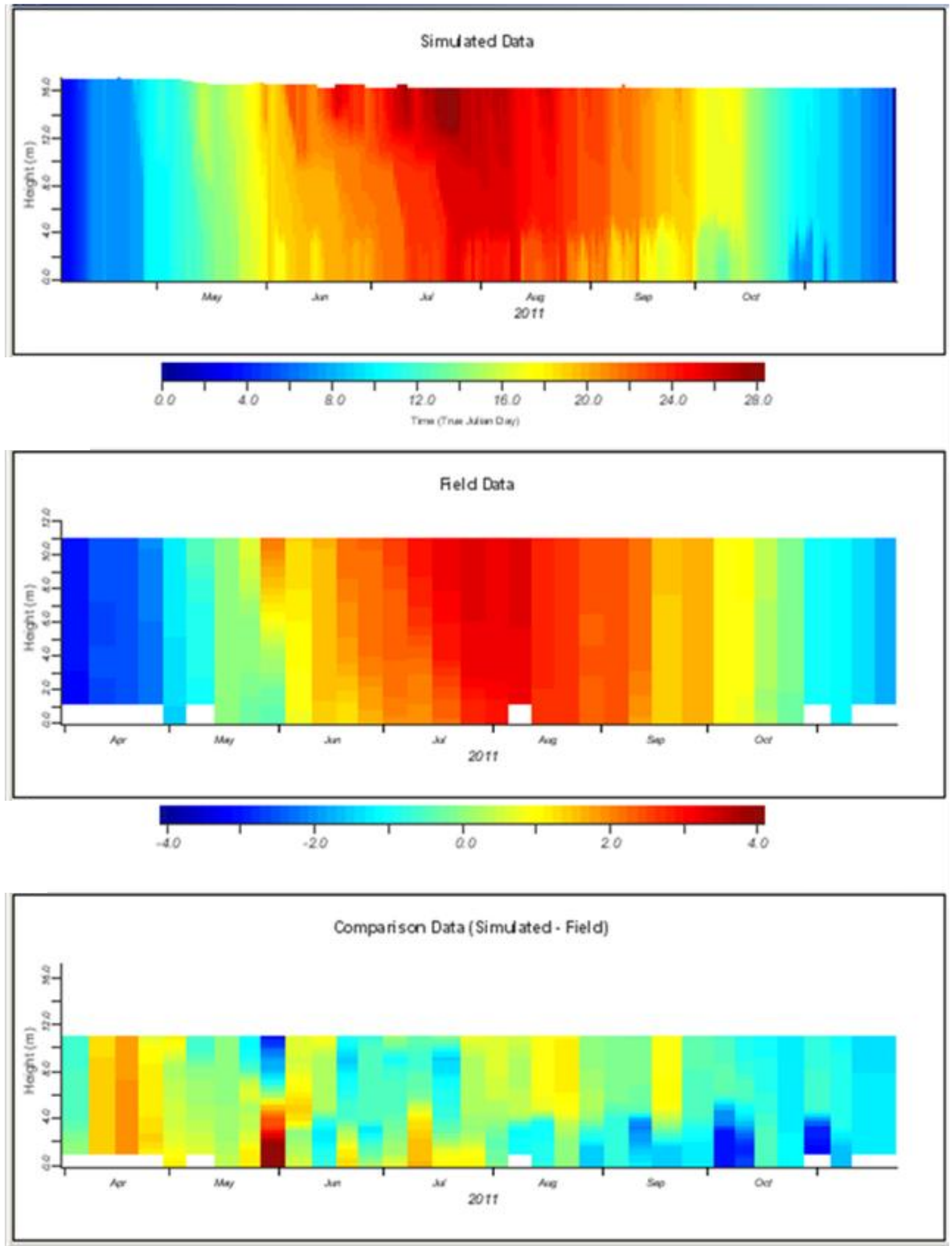


Figure 41. 2011 Oneida Lake Best Fit Simulated, Observed (Weekly), and Simulated - Observed Time Series Plots for 4/4/2011 to 11/27/2011. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Weekly observed water temperatures consisted of average weekly water temperatures at 1 m intervals throughout the water column at Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point.

Additionally, the 2011 best fit daily simulated data were compared with daily, as opposed to weekly, observed Oneida Lake temperatures (Figure 42). Model performance was basically the same when compared to weekly or daily observed data (Table 13). Again, the comparison indicated very good agreement between the simulated and observed temperatures throughout the water column with average absolute deviations within ±1°C (Figure 42). Average deviations (observed – modeled) at 2 m and 10 m were 0.96°C (SD 0.69) and -0.61°C (SD 1.00) when using weekly observed temperatures and -0.53°C (SD 1.06) and -0.60°C (SD 0.99) with daily observed temperatures, respectively.

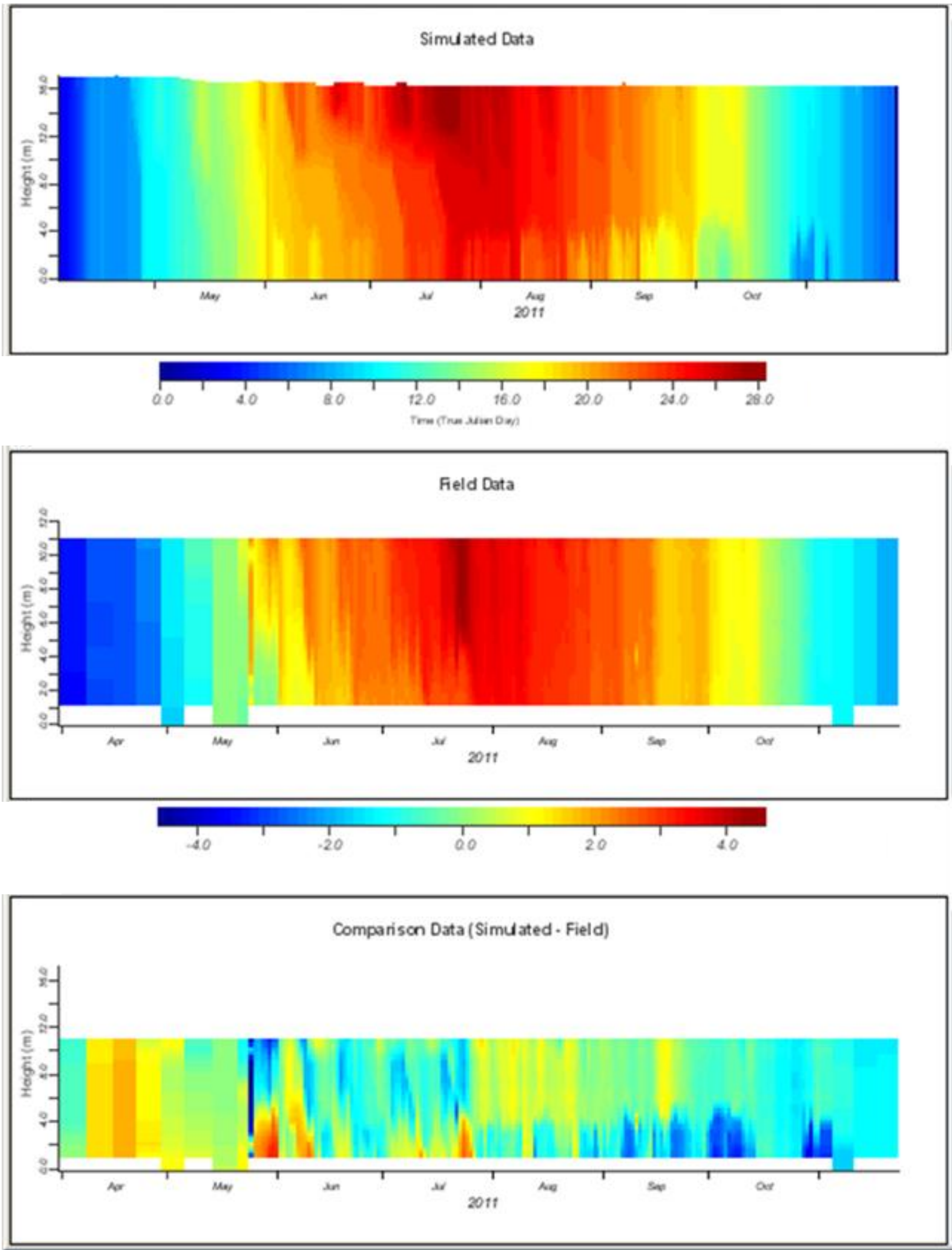


Figure 42. 2011 Oneida Lake Best Fit Simulated, Observed (Daily), and Simulated - Observed Time Series Plots for 4/4/2011 to 11/27/2011. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Daily observed water temperatures calculated from water temperatures measured at 1 m intervals every 4 hours for Oneida Lake at Shackelton Point.

Table 13. 2011 Oneida Lake Best Fit and Observed (Weekly & Daily) Performance Results at 2 m and 10 m for 4/4/2011 to 11/27/2011. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Weekly observed water temperatures consisted of average weekly water temperatures at 1 m intervals throughout the water column at Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point. Daily observed water temperatures calculated from water temperatures measured at 1 m intervals every 4 hours for Oneida Lake at Shackelton Point.

	2m				10m			
	r^2	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**	**r^2**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**
Observed (Weekly)	0.97	0.96 (0.69)	0.96 (0.69)	1.18	0.95	-0.61 (1.00)	0.88(0.77)	1.17
Observed (Daily)	0.97	-0.53 (1.06)	0.95 (0.70)	1.18	0.95	-0.60 (0.99)	0.87(0.77)	1.17

For the simulation period from April 4th to November 27th, the 2011 best fit daily average simulated temperatures at 2 m and 10 m in Oneida Lake tracked the daily observed temperatures with $r^2 = 0.97$ and $r^2 = 0.95$, respectively. The simulated temperatures at 2 m and 10 m were in general agreement with the observed temperatures throughout the simulation period; however, the simulated temperatures were often greater than the observed temperatures (Figure 43 and Figure 44). The average absolute difference between modeled and observed temperatures at 2 m was 0.96°C (SD 0.69) and the root mean square error was 1.18°C (Table 13). At 10 m, the average absolute difference between modeled and observed temperatures and the root mean square error were 0.88°C (SD 0.77) and 1.17, respectively (Table 13). The average deviations (observed – modeled) at 2 m and 10 were 0.96°C (SD 0.69) and -0.61°C (SD 1.00) (Table 13). The best fit simulation generally tracked the observed temperatures at 2 m (Figure 43) and 10 m (Figure 44) in 2010 better than the baseline simulation.

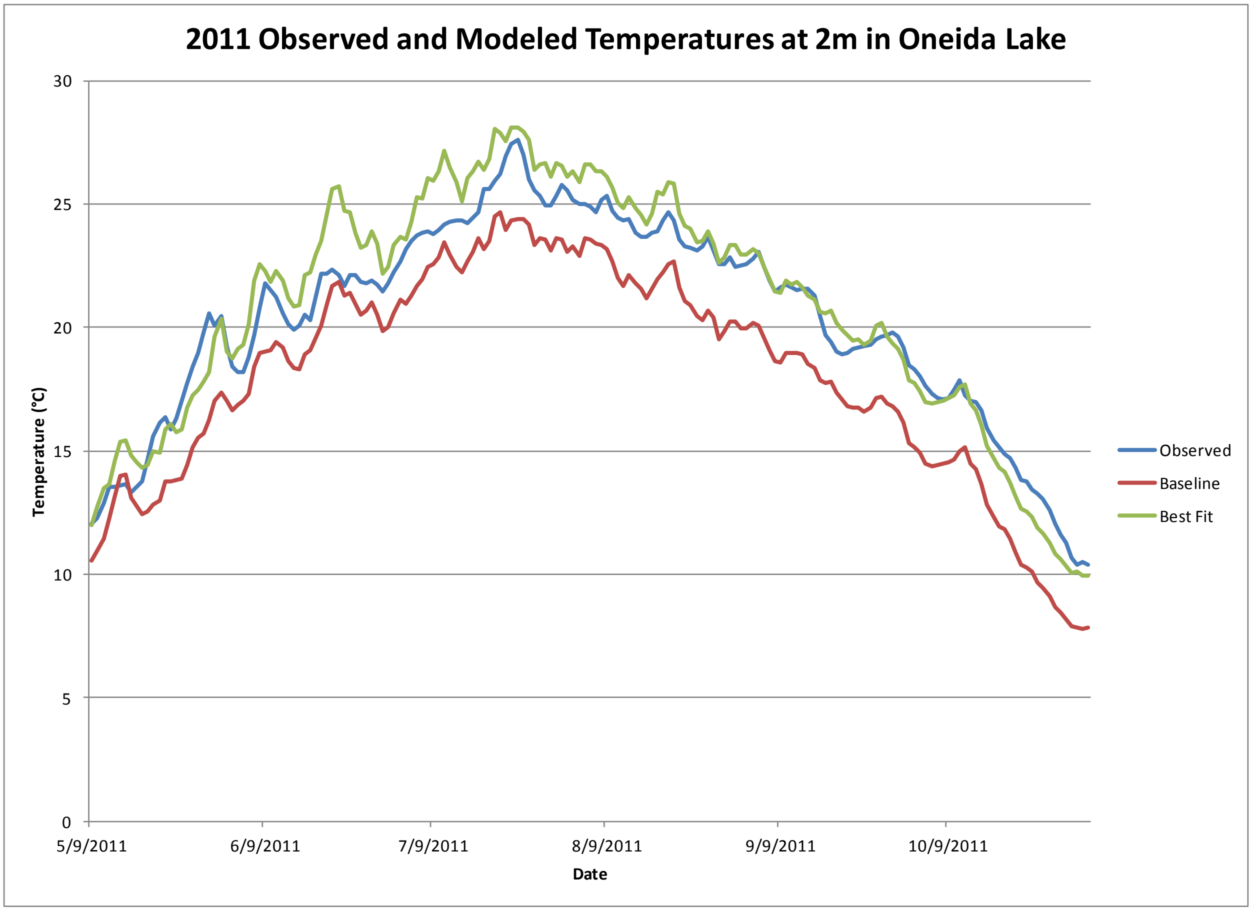


Figure 43. 2011 Oneida Lake Baseline, Best Fit, and Observed Average Daily Temperatures at 2 m for 5/9/2011 to 11/3/2011. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Average daily observed 2 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

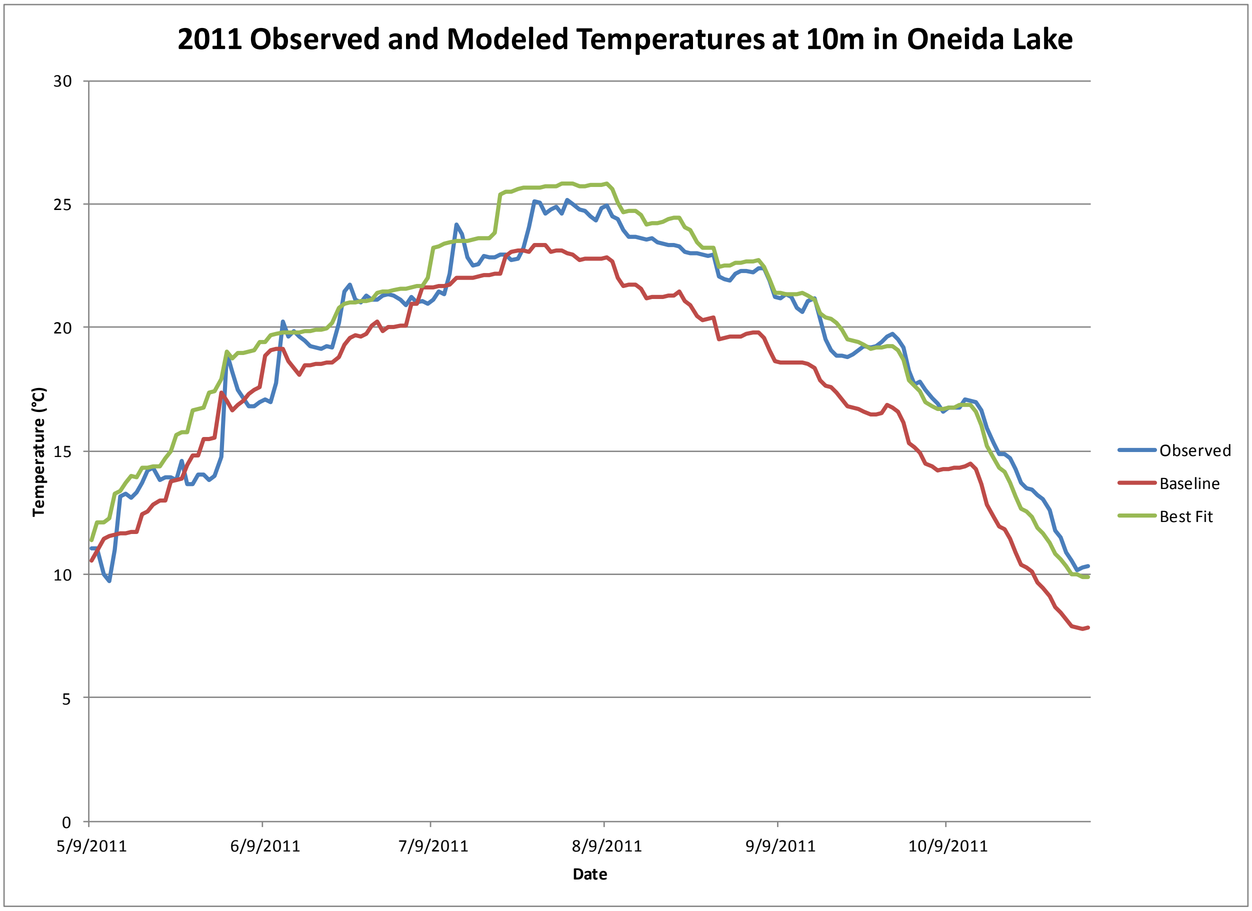


Figure 44. 2011 Oneida Lake Baseline, Best Fit, and Observed Average Daily Temperatures at 10 m for 5/9/2011 to 11/3/2011. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Average daily observed 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

The difference between 2 m and 10 m temperatures was an indicator of stratification within the water column. In 2011, the greatest observed differences between 2 m and 10 m temperatures or stratification occurred from late spring to mid-summer (Figure 45). The modeled differences tracked with the observed differences between 2 m and 10 m temperatures; however, the simulated strength of stratification was generally less than the observed (Figure 45). The best fit simulation more closely represented the observed stratification in 2011 than the baseline simulation (Figure 45).

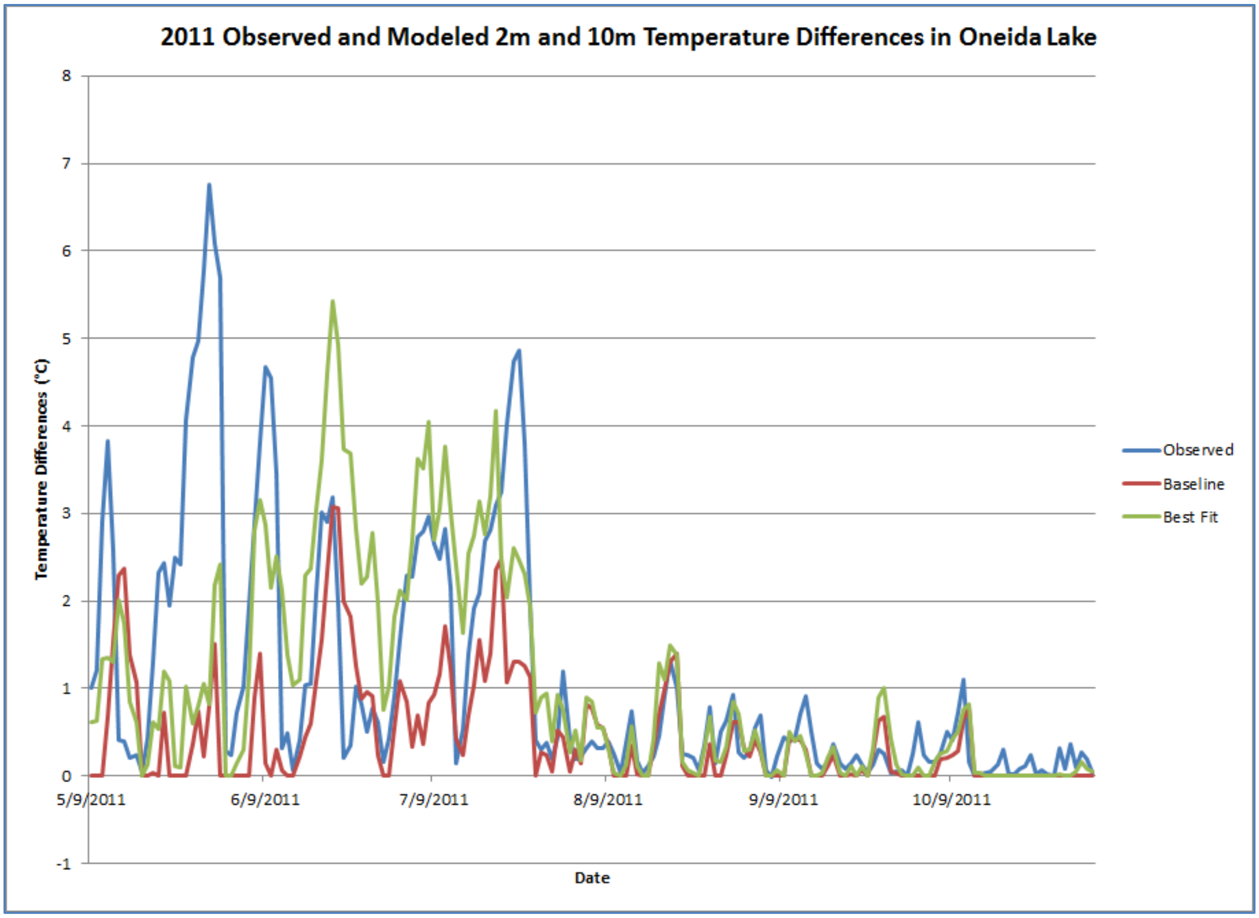


Figure 45. 2011 Oneida Lake Baseline, Best Fit, and Observed 2 m and 10 m Temperature Differences for 5/9/2011 to 11/3/2011. Baseline simulation used field monitoring inputs from Oneida Lake and its watershed and default parameters. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. Average daily observed 2 m and 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point.

Climate Scenarios

DYRESM simulations using daily high-resolution (5 km) regional temperature and precipitation 2050 and 2099 projections for Central New York under the A1fi (higher) and B1 (lower) emissions scenarios were performed to assess the potential impacts of climate change on the thermal structure of Oneida Lake. The 2099 A1fi climate scenario indicated the highest temperatures at 2 m and 10 m in Oneida Lake and deviated the most from the 2011 best fit model simulation for the April 4th to November 27th simulation period (Figure 46 and Figure 47). The average deviation between the 2099 A1fi and 2011 best fit temperatures at 2 m was 2.47°C (SD 1.08) and 2.01°C (SD 1.43) at 10 m (Table 14). For the 2099 B1, 2050 A1fi, and 2050 B1 climate scenarios, the temperatures at 2 m and 10 m were more closely aligned with the 2011 best fit simulation (Figure 46). Surprisingly, the average absolute difference and root mean square error deviation at 2 m and 10 m were lowest for the 2099 B1 (lower) simulation (Table 14) indicating the least deviation from current conditions. Further analysis indicated 2010 and 2011 average daily air and weekly water temperatures were at the higher end of the monthly range for 1984-2009 (Figure 48 and Figure 49). Additionally, the 2010 and 2011 average daily air and weekly water temperatures exceeded the 2050 A1 predicted average daily air and weekly water temperatures in the spring (Figure 48 and Figure 49). Furthermore, the 2011 average weekly water temperatures exceeded the 2050 A1 predicted average weekly water temperatures from mid-summer to late fall and aligned with the 2099 A1 predicted average weekly water temperatures in late fall (Figure 48 and Figure 49).

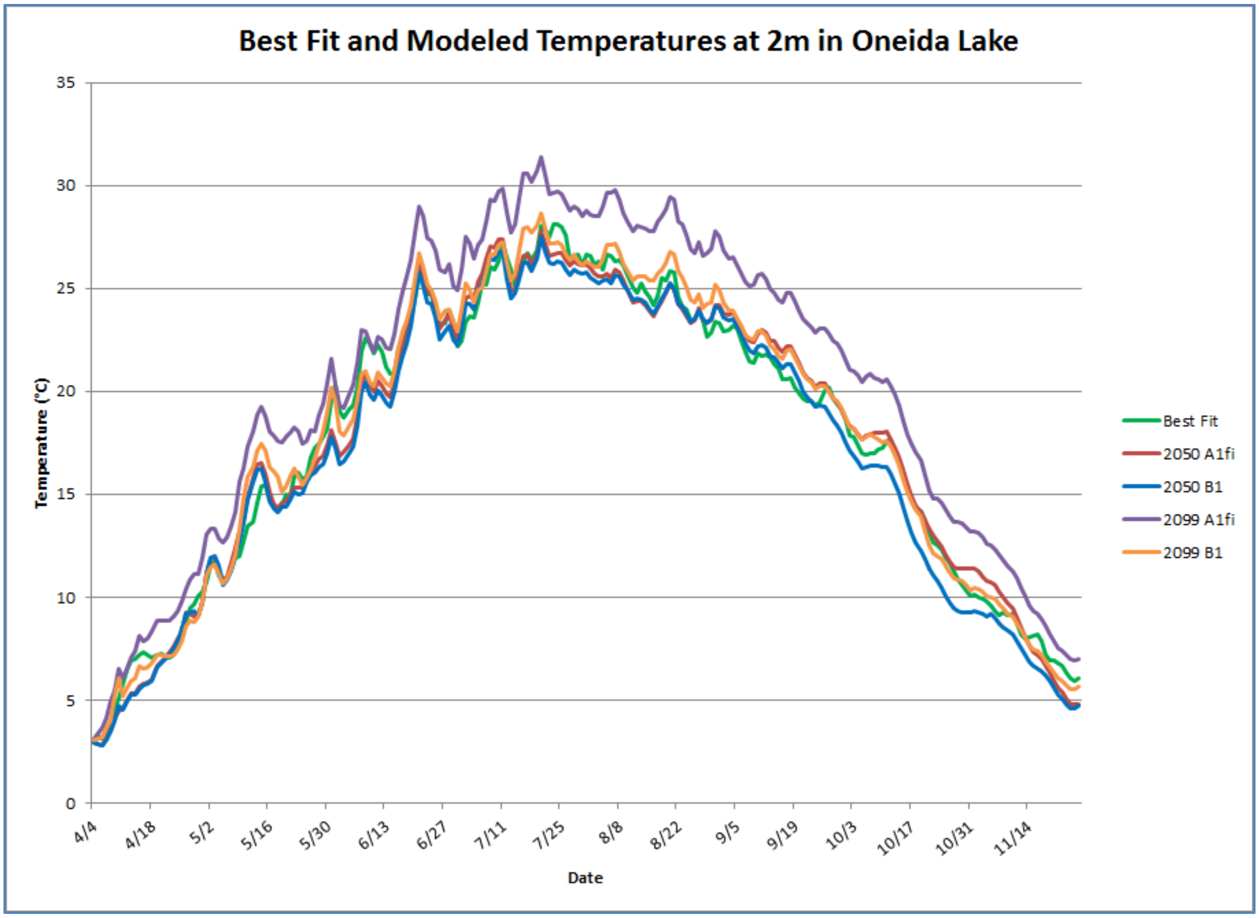


Figure 46. Oneida Lake 2011 Best Fit, 2050 A1fi and B1, and 2099 A1fi and B1 Average Daily Temperatures at 2 m for April 4th to November 27th. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi and B1 and 2099 A1fi and B1 simulations used 2011 best fit simulation with daily high resolution (5 km) regional temperature and precipitation projections for Central New York provided by the Northeast Regional Climate Center.

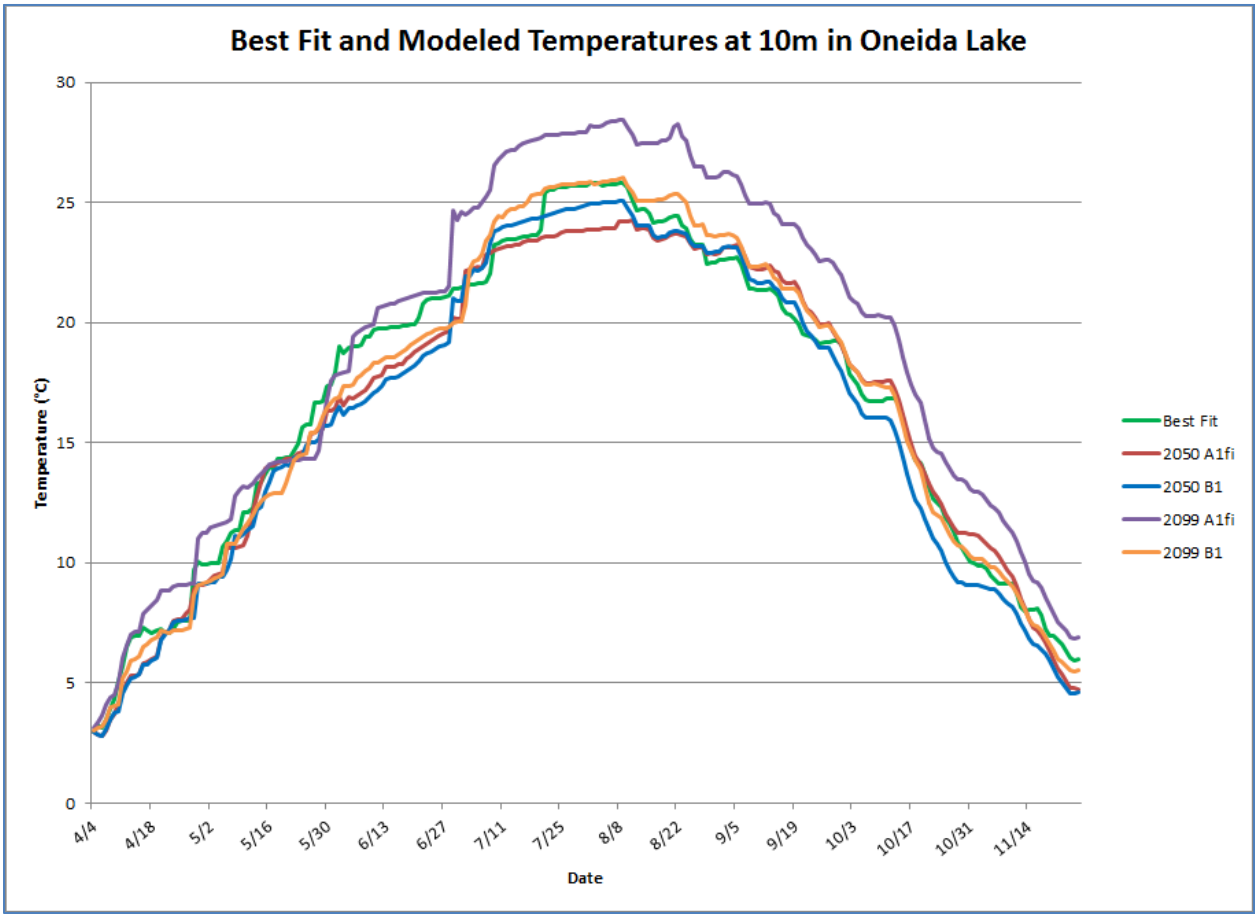


Figure 47. Oneida Lake 2011 Best Fit, 2050 A1fi and B1, and 2099 A1fi and B1 Average Daily Temperatures at 10 m for April 4th to November 27th. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi and B1 and 2099 A1fi and B1 simulations used 2011 best fit simulation with daily high resolution (5 km) regional temperature and precipitation projections for Central New York provided by the Northeast Regional Climate Center.

Table 14. Oneida Lake 2050 and 2099 A1fi and B1 Climate Scenario Responses at 2 m and 10 m for April 4th to November 27th. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi and B1 and 2099 A1fi and B1 simulations used 2011 best fit simulation with daily high resolution (5 km) regional temperature and precipitation projections for Central New York provided by the Northeast Regional Climate Center.

	2m				**10m**	
Scenario	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**
2050 A1fi	-0.05 (0.88)	0.71 (0.52)	0.88	-0.41(0.99)	0.89 (0.60)	1.07
2050 B1	-0.63 (0.84)	0.86 (0.61)	1.05	-0.78 (0.87)	0.97 (0.65)	1.17
2099 A1fi	2.47 (1.08)	2.47(1.08)	2.70	2.01 (1.43)	2.14 (1.24)	2.47
2099 B1	-0.27 (0.78)	0.65 (0.51)	0.83	-0.05 (0.84)	0.71(0.46)	0.84

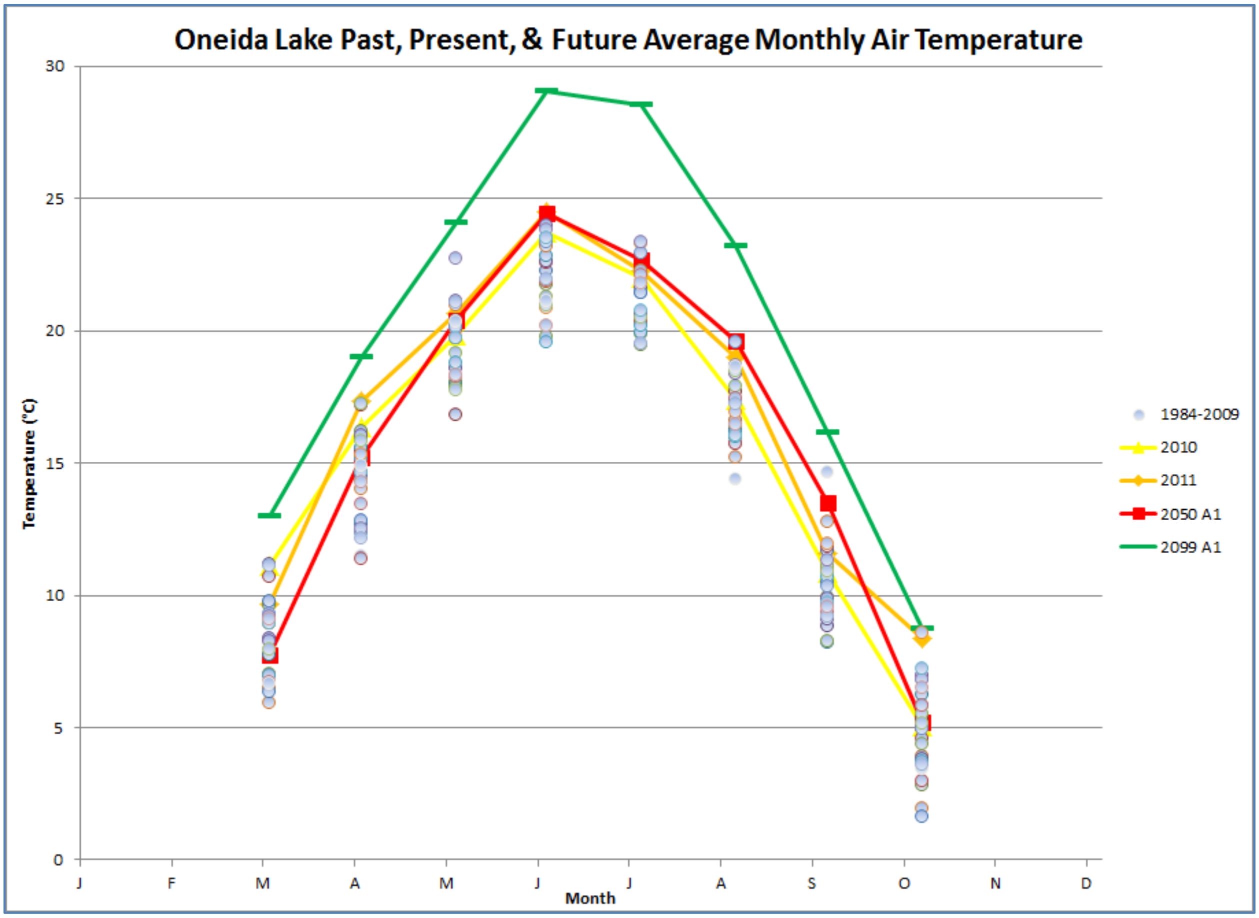


Figure 48. Oneida Lake Past (1984-2009), Present (2010 and 2011), and Future (2050 and 2099) Average Monthly Air Temperature at Syracuse Airport from March to October. Past and present average monthly air temperatures calculated from daily air temperatures obtained for Syracuse Airport. Future average monthly air temperatures calculated from daily high resolution (5 km) regional temperature projections for Central New York provided by the Northeast Regional Climate Center.

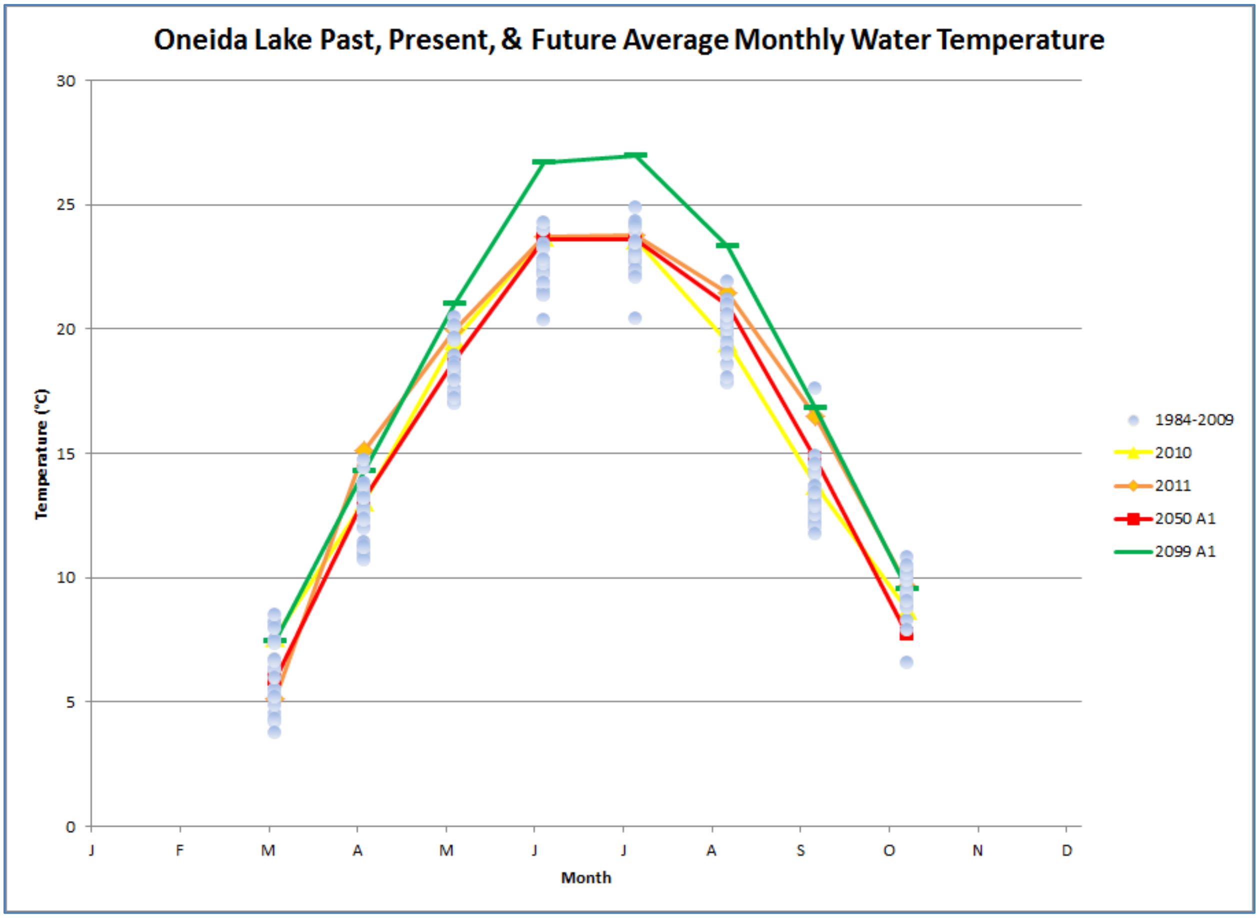


Figure 49. Oneida Lake Past (1984-2009), Present (2010 and 2011), and Future (2050 and 2099) Average Monthly Water Temperature Across 5 Stations from March to October. Past and present average monthly Oneida Lake water column temperatures calculated from weekly temperatures at 1m intervals for Buoy 109, Buoy 117, Buoy 125, Three Mile Bay, and Shackelton Point. Future average monthly water temperatures calculated from daily water temperature projections from simulations based on 2011 best fit simulation with daily high resolution (5 km) regional temperature and precipitation projections for Central New York provided by the Northeast Regional Climate Center.

The difference between 2 m and 10 m temperatures is an indicator of stratification within the water column. Generally, the 2 m and 10 m temperature differences in Oneida Lake for the climate scenarios exceeded those for the 2011 best fit simulation (Figure 50). This was supported by further analysis of the number of days and number of consecutive days with >1°C difference between 2 m and 10 m for the climate scenarios and 2011 best fit analysis. For May 9th – November 3rd, the A1fi scenarios indicated 78 and 75 days for 2050 and 2099 followed by the 2099 B1 scenario yielding 73 consecutive days of stratification as compared to 47 consecutive days of stratification in 2011 (Table 15). Additionally, the length of stratification decreased with increased strength of stratification and decreased from the A1 to the B1 emissions scenarios for a given stratification strength (Figure 51).

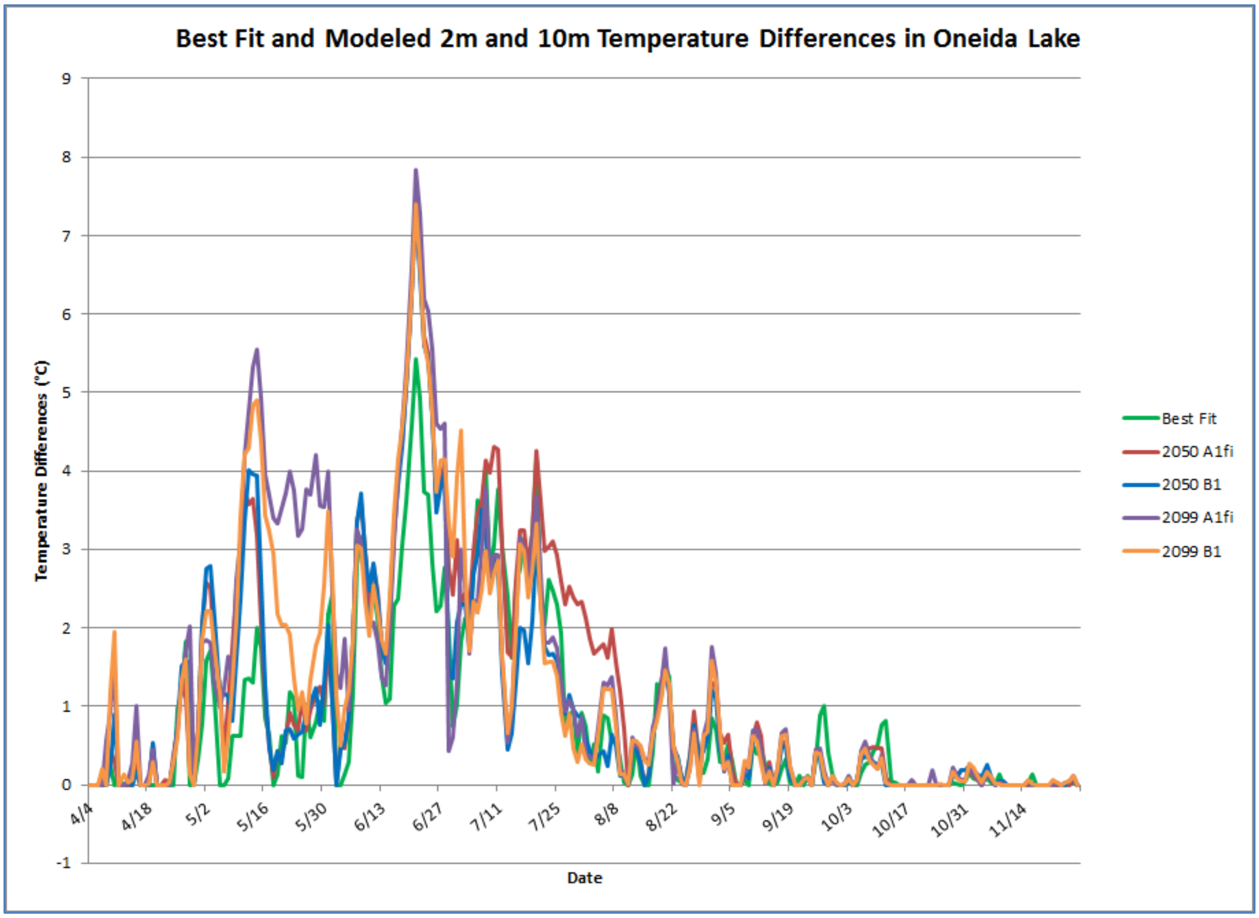


Figure 50. Oneida Lake 2011 Best Fit, 2050 A1fi and B1, and 2099 A1fi and B1 2 m and 10 m Temperature Differences for April 4th to November 27th. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi and B1 and 2099 A1fi and B1 simulations used 2011 best fit simulation with daily high resolution (5 km) regional temperature and precipitation projections for Central New York provided by the Northeast Regional Climate Center.

Table 15. Oneida Lake 2011 Observed, Best Fit, and 2050 and 2099 A1fi and B1 Climate Change Scenario Stratification Duration for May 9th to November 3rd. Stratification defined as the difference between 2 m and 10 m temperatures within the water column. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi and B1 and 2099 A1fi and B1 simulations used 2011 best fit simulation with daily high resolution (5 km) regional temperature and precipitation projections for Central New York provided by the Northeast Regional Climate Center.

Scenario	# of Days >1°C Difference Between 2m and 10m	# of Consecutive Days >1°C Difference Between 2m and 10m
Observed	57	47
2011 Best Fit	66	60
2050 A1fi	84	78
2099 A1fi	83	75
2050 B1	68	60
2099 B1	81	73

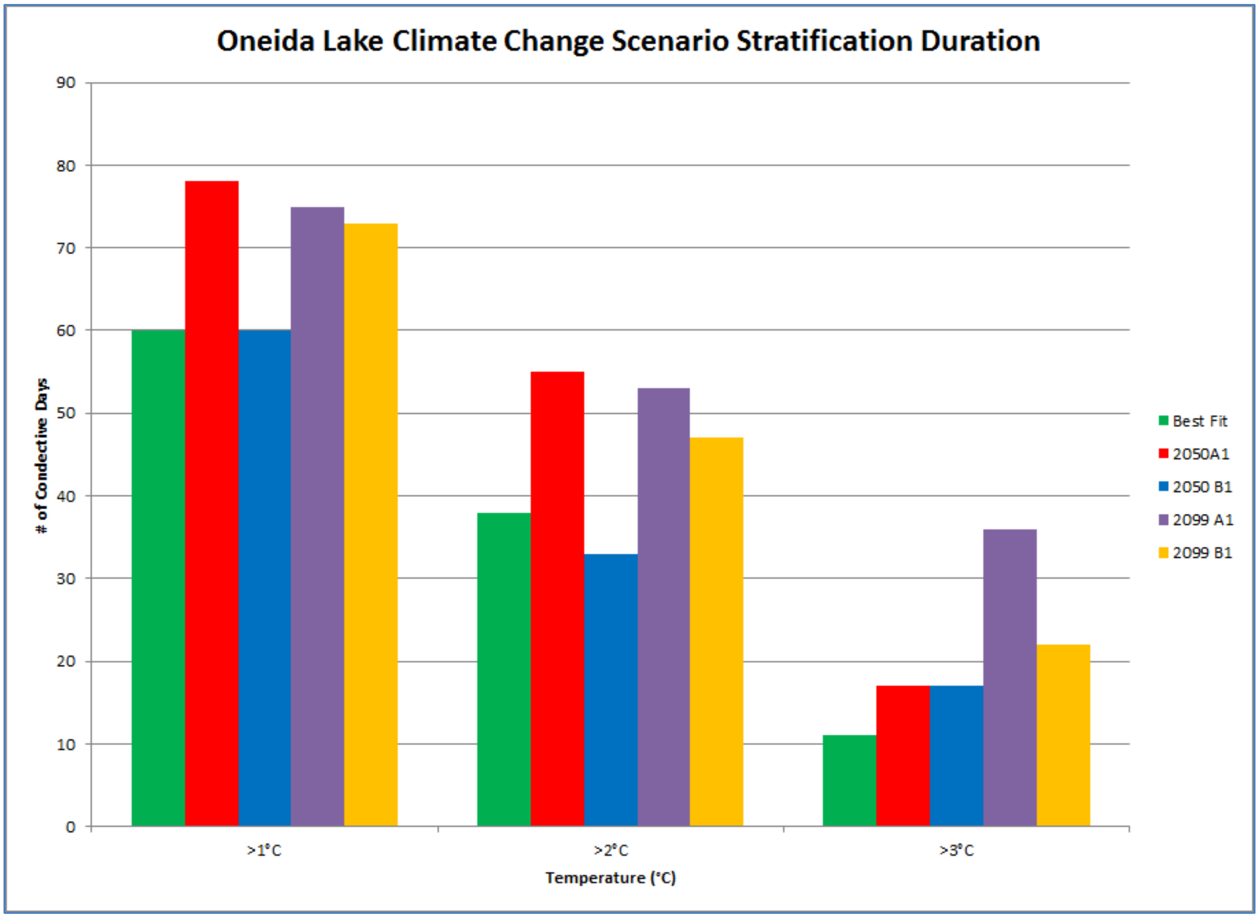


Figure 51. Oneida Lake Climate Change Scenario Stratification Duration for May 9th to November 3rd. Stratification defined as the difference between 2 m and 10 m temperatures within the water column. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi and B1 and 2099 A1fi and B1 simulations used 2011 best fit simulation with daily high resolution (5 km) regional temperature and precipitation projections for Central New York provided by the Northeast Regional Climate Center.

As a complement to the DYRESM simulations performed with altered air temperature and precipitation for 2050 and 2099 under the A1fi (higher) and B1 (lower) emissions scenarios, additional scenarios were executed altering the air temperature, precipitation, water temperature, and inflow volume forcing variables to their maximum predicted values for the higher emissions scenario (A1fi) in 2050 and 2099 (Table 16). Regression relationships between air and water temperatures were calculated for each of the four inflow streams (Table 8) and used to predict the water temperatures in 2050 and 2099. Air temperature was the driving variable in the A1fi climate scenarios. For the 2050 A1fi scenario, the average absolute difference and root mean square error deviation were 3.56°C (SD 0.79) and 3.65°C at 2m and 3.27°C (SD 0.79) and 3.36°C at 10 m (Table 16). Furthermore, the average absolute difference and root mean square error deviation were 5.69°C (SD 1.22) and 5.82°C at 2 m and 4.67°C (SD 1.57) and 4.93°C at 10 m for the 2099 A1fi scenario (Table 16).

Table 16. Oneida Lake 2050 and 2099 A1fi Max Forcing Variable Responses for April 4th to November 27th. Daily air temperature and precipitation data for 2011 were modified based on the average annual projections under the A1fi emissions scenario for 2040-2069 and 2070-2099 (Union of Concerned Scientists, 2006) with the 2011 daily air temperature and precipitation increased by 5.8°C and 5% for 2050 and 9.5°C and 10% for 2099, respectively. Predicted water temperatures for the inflowing streams were estimated from air/water temperature regression relationships for each of the four inflow streams using the predicted air temperatures for 2050 and 2099. 2011 daily inflows were increased by 5% for 2050 and 10% for 2099.

			2 m			**10 m**		
Variable	**Scenario**	**Modification**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**
Air Temperature	2050 A1fi Max	+5.8°C	3.56 (0.79)	3.56 (0.79)	3.65	3.27 (0.79)	3.27 (0.79)	3.36
	2099 A1fi Max	+9.5°C	5.69 (1.22)	5.69 (1.22)	5.82	4.67 (1.57)	4.67 (1.57)	4.93
Precipitation	2050 A1fi Max	+5%	0.01 (0.13)	0.07 (0.11)	0.15	0.00 (0.20)	0.10 (0.18)	0.23
	2099 A1fi Max	+10%	0.00 (0.10)	0.06 (0.09)	0.10	-0.09 (0.39)	0.17 (0.36)	0.40
Water Temperature	2050 A1fi Max	Based on Air Temp +5.8°C	-0.23 (0.23)	0.25 (0.22)	0.33	-0.39 (0.41)	0.39 (0.41)	0.57
	2099 A1fi Max	Based on Air Temp +9.5°C	-0.54 (0.34)	0.55 (0.33)	0.64	-0.7 (0.62)	0.77 (0.62)	0.98
Inflow Volume	2050 A1fi Max	+5%	0.02 (0.12)	0.07 (0.10)	0.12	-0.06 (0.33)	0.16 (0.29)	0.33
	2099 A1fi Max	+10%	0.00 (0.19)	0.13 (0.14)	0.19	-0.19 (0.58)	0.33 (0.51)	0.61

The forcing variable modifications were combined to represent the likely outlook for 2050 and 2099 under the A1fi climate scenario. For 2050, this included 2011 best fit air temperature +5.8°C, precipitation +5%, water temperature based on air temperature +5.8°C, and inflow volume +5%. Withdrawal was increased by 5% to account for the increased inflow volume. For 2099, the scenario consisted of 2011 best fit air temperature +9.5°C, precipitation +10%, water temperature based on air temperature +9.5°C, and inflow volume +10% with corresponding withdrawal +10%. As expected, the 2099 and 2050 A1fi climate scenarios predicted higher water temperatures at 2 m (Figure 52) and 10 m (Figure 53). The average absolute difference between the simulated 2050 A1fi climate scenario and 2011 best fit simulation and the root mean square error were 3.73°C (SD 0.82) and 3.82°C at 2 m and 3.67°C (SD 0.83) and 3.76°C at 10 m (Table 17). For the 2099 climate scenario simulation, the average absolute difference between the simulated 2099 A1fi climate scenario and the 2011 best fit simulation and the root mean square error were 6.06°C (SD 1.21) and 6.18°C at 2 m and 5.94°C (SD 1.26) and 6.07°C at 10 m (Table 17). Likewise, the stratification strength increased (Figure 54).

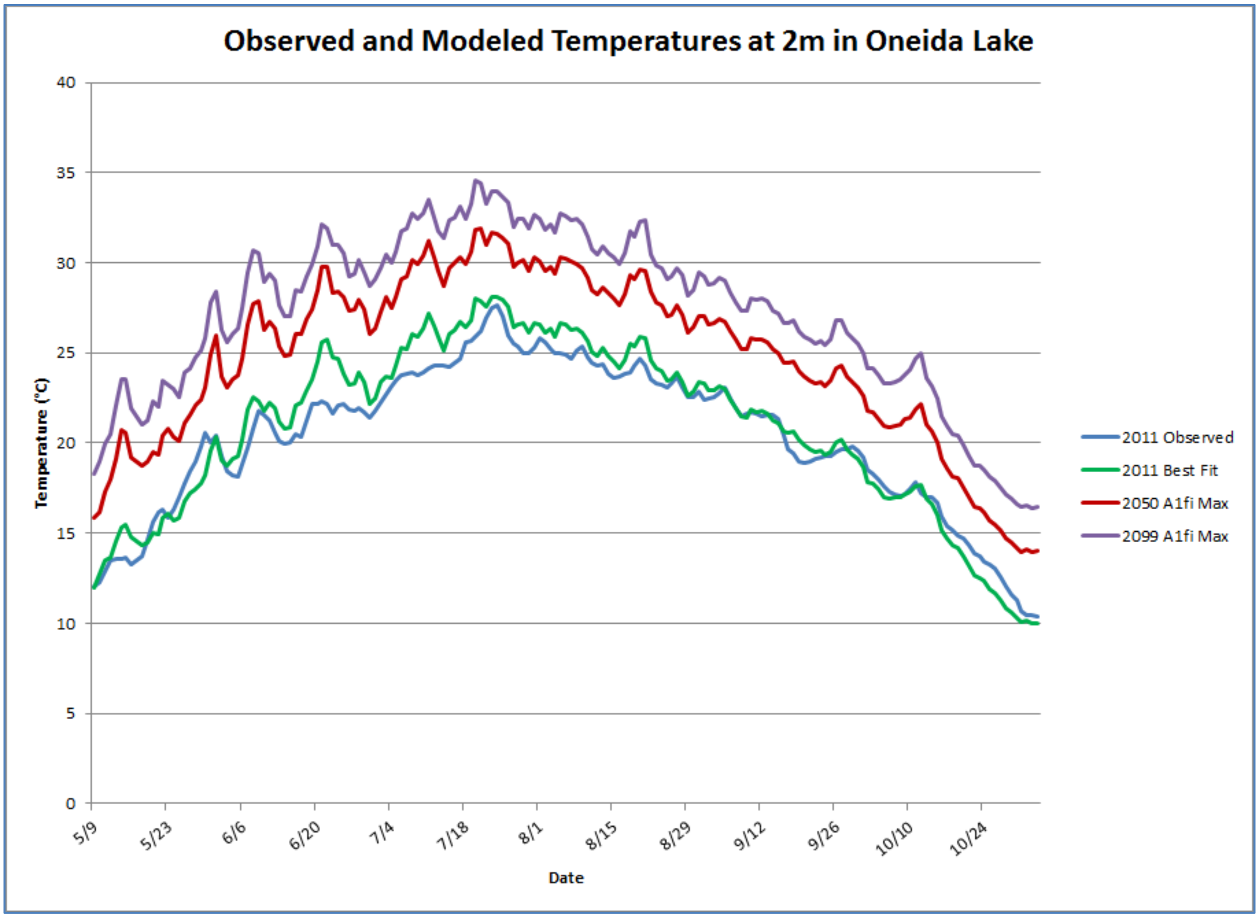


Figure 52. Oneida Lake 2011 Observed, Best Fit, and 2050 and 2099 A1fi Max Climate Scenario Temperatures at 2 m for May 9th to November 3rd. 2011 average daily observed 2 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi Max simulation based on 2011 best fit air temperature +5.8°C, precipitation +5%, water temperature based on air temperature +5.8°C, and inflow volume +5%. 2099 A1fi Max simulation based on 2011 best fit air temperature +9.5°C, precipitation +10%, water temperature based on air temperature +9.5°C, and inflow volume +10% with corresponding withdrawal +10%.

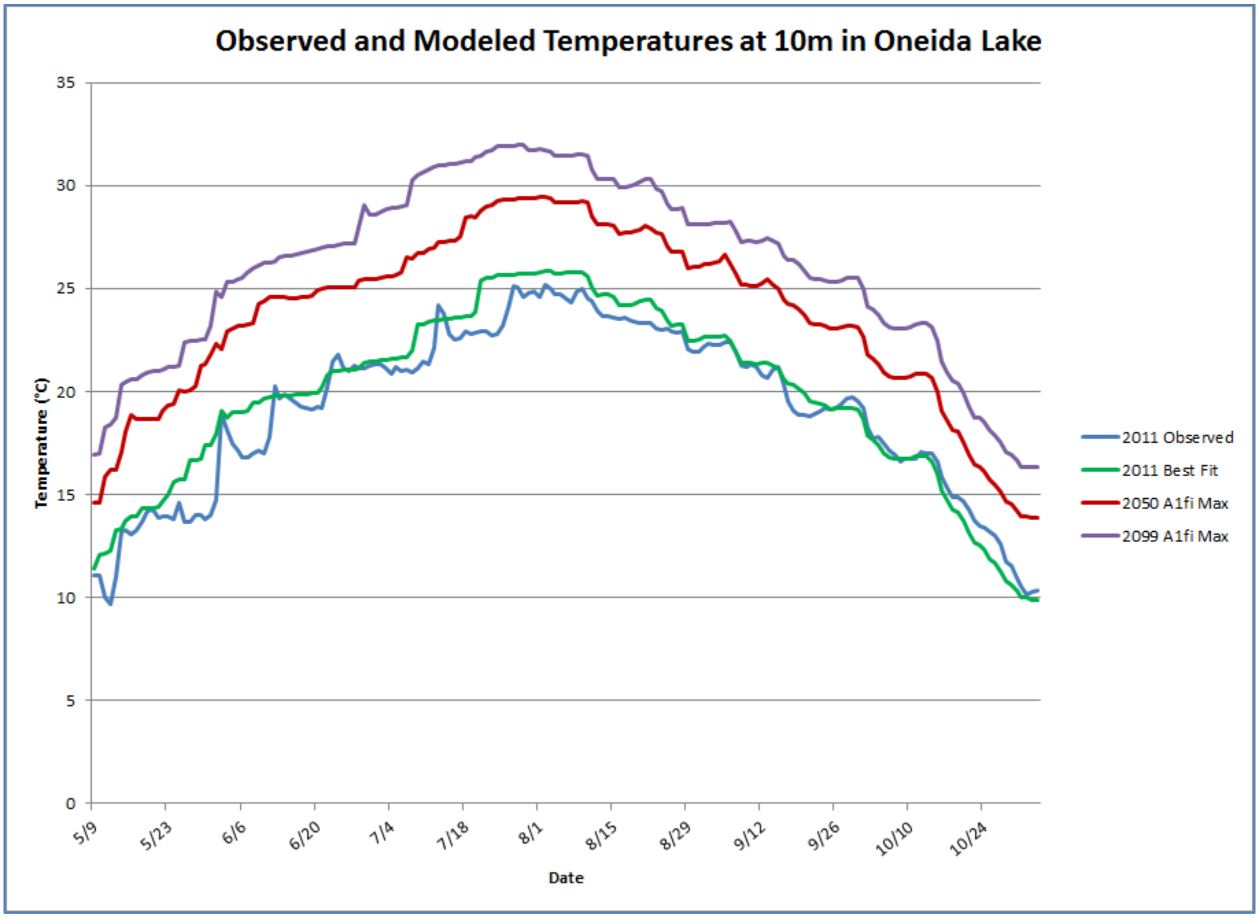


Figure 53. Oneida Lake 2011 Best Fit and 2050 and 2099 A1fi Max Climate Scenario Temperatures at 10 m for May 9th to November 3rd. 2011 average daily observed 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi Max simulation based on 2011 best fit air temperature +5.8°C, precipitation +5%, water temperature based on air temperature +5.8°C, and inflow volume +5%. 2099 A1fi Max simulation based on 2011 best fit air temperature +9.5°C, precipitation +10%, water temperature based on air temperature +9.5°C, and inflow volume +10% with corresponding withdrawal +10%.

Table 17. Oneida Lake 2050 and 2099 A1fi Max Climate Scenario Responses for May 9th to November 3rd. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi Max simulation based on 2011 best fit air temperature +5.8°C, precipitation +5%, water temperature based on air temperature +5.8°C, and inflow volume +5%. 2099 A1fi Max simulation based on 2011 best fit air temperature +9.5°C, precipitation +10%, water temperature based on air temperature +9.5°C, and inflow volume +10% with corresponding withdrawal +10%.

	2 m			**10 m**		
Scenario	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**
2050 A1fi Max	3.73 (0.82)	3.73 (0.82)	3.82	3.67 (0.83)	3.67 (0.83)	3.76
2099 A1fi Max	6.06 (1.21)	6.06 (1.21)	6.18	5.94 (1.26)	5.94 (1.26)	6.07

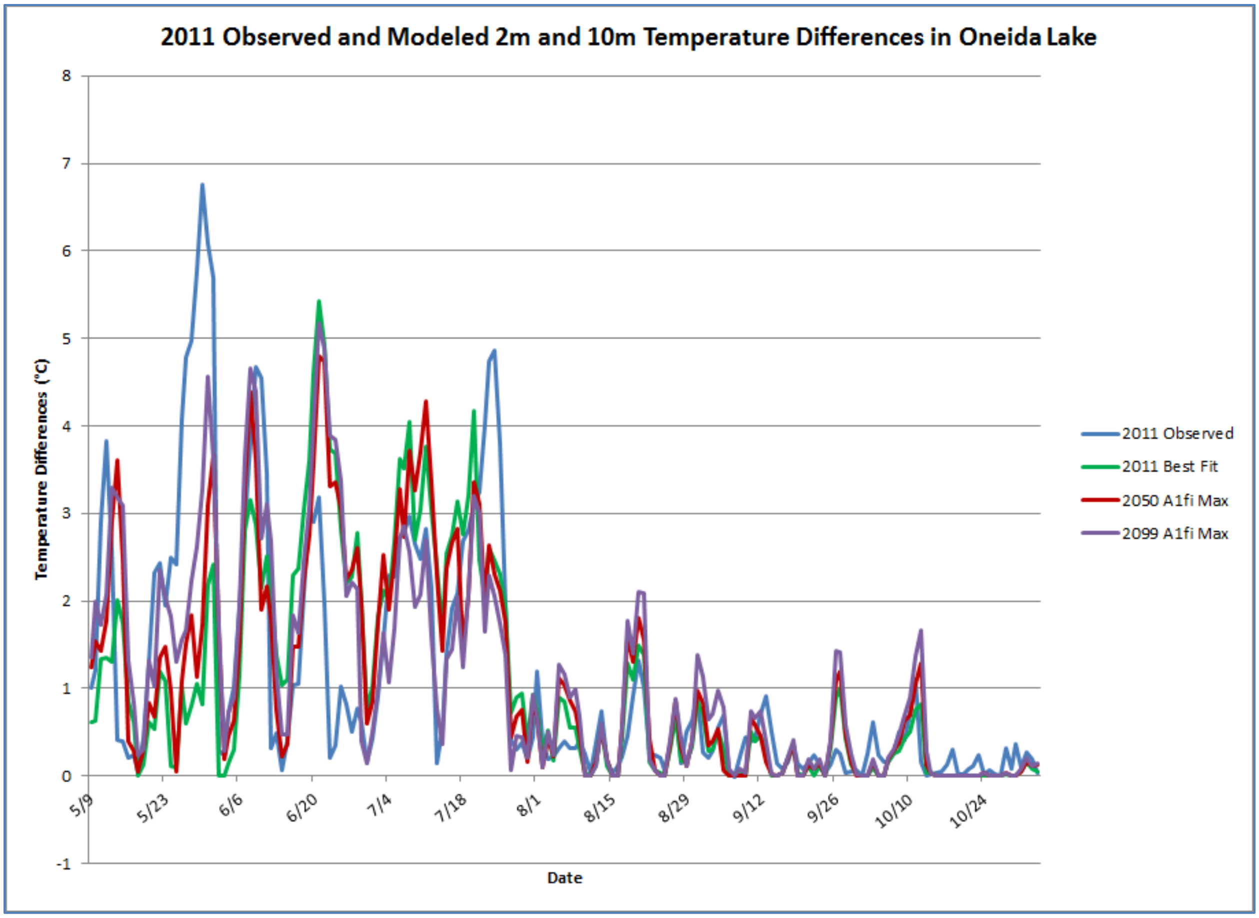


Figure 54. Oneida Lake 2011 Best Fit and 2050 and 2099 A1fi Max Climate Scenario 2 m and 10 m Temperature Differences for May 9th to November 3rd. 2011 average daily observed 2 m and 10 m temperatures calculated from water temperatures measured every 4 hours for Oneida Lake at Shackelton Point. Best fit simulation used 2011 field monitoring inputs from Oneida Lake and its watershed and default parameters with wind speed decreased by 25% each day, mean albedo decreased to 0.01 and minimum layer thickness decreased to 0.5 m. 2050 A1fi Max simulation based on 2011 best fit air temperature +5.8°C, precipitation +5%, water temperature based on air temperature +5.8°C, and inflow volume +5%. 2099 A1fi Max simulation based on 2011 best fit air temperature +9.5°C, precipitation +10%, water temperature based on air temperature +9.5°C, and inflow volume +10% with corresponding withdrawal +10%.

Different methodologies were used to calculate the 2050 and 2099 A1fi climate change scenario responses. Comparison of the methodologies indicated the average absolute difference and root mean square error were highest at 2 m and 10 m from altering the air temperature, precipitation, water temperature, and inflow volume variables to their maximum predicted values for 2050 and 2099 as opposed to altering the air temperature and precipitation according to regional downscaling of the GCMs for 2050 and 2099 (Table 18).

Table 18. Oneida Lake 2050 and 2099 A1fi Climate Scenario Responses (2050 and 2099 maximum air temperatures based on 2011 air temperatures +5.8°C and +9.5°C, 2050 and 2099 maximum precipitation based on 2011 precipitation +5% and 10%, 2050 and 2099 water temperatures estimated from predicted air temperatures, 2050 and 2099 maximum inflows based on predicted precipitation).

		2 m			10 m		
Scenario	**Modification(s)**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**	**Average Deviation (SD) (°C)**	**Average Absolute Difference (SD) (°C)**	**RMSE (°C)**
2050 A1fi	2050 Air Temperature 2050 Precipitation	-0.05 (0.88)	0.71 (0.52)	0.88	-0.41 (0.99)	0.89 (0.60)	1.07
2099 A1fi	2099 Air Temperature 2099 Precipitation	2.47 (1.08)	2.47(1.08)	2.70	2.01 (1.43)	2.14 (1.24)	2.47
2050 A1fi Max	2050 Air Temperature 2050 Precipitation	3.58 (0.78)	3.58 (0.78)	3.66	3.35 (0.87)	3.35 (0.87)	3.46
2099 A1fi Max	2099 Air Temperature 2099 Precipitation	5.82 (1.24)	5.82 (1.24)	5.95	5.38 (1.27)	5.38 (1.27)	5.53
2050 A1fi Max	2050 Max Air Temperature 2050 Max Precipitation 2050 Max Water Temperature 2050 Max Inflow	3.73 (0.82)	3.73 (0.82)	3.82	3.67 (0.83)	3.67 (0.83)	3.76
2099 A1fi Max	2099 Max Air Temperature 2099 Max Precipitation 2099 Max Water Temperature 2099 Max Inflow	6.06 (1.21)	6.06 (1.21)	6.18	5.94 (1.26)	5.94 (1.26)	6.07

DISCUSSION

Through comprehensive field monitoring and modeling, this study provided an understanding of the forcing inputs and thermal structure of Oneida Lake and the impacts of predicted climate change on lake temperature profiles and stratification. A deterministic, one-dimensional model, DYRESM, was calibrated and validated using lake morphometry, an initial thermal profile, and inflow, meteorological, and withdrawal data to simulate daily water temperature profiles for Oneida Lake. A sensitivity analysis improved the model's performance and confirmed the importance of meteorological variables, including solar radiation and wind speed, as drivers of the thermal regime of the lake. The Oneida Lake simulations successfully captured the dynamics of temperature in both the surface and bottom waters for both the 2010 calibration and 2011 validation periods with deviations throughout the water column generally within ±1°C. Additionally, the model captured the onset and duration of the alternation of weak mixing and stratification events for 2010 and 2011. Furthermore, climate change analyses indicated Oneida Lake 2 m and 10 m temperatures and length of stratification will increase from between 2.5°C to 6.2°C and 13 to 15 days by the end of the century depending on the emissions scenario. These physical changes due to climate change in Oneida Lake and other freshwater systems may induce chemical and biological responses with abrupt shifts as thresholds are crossed.

Field Monitoring

Field monitoring of Oneida Lake watershed air, inflow, and lake temperatures provided useful insights into the drivers and dynamics of the thermal structure in Oneida Lake. Water temperatures were largely influenced by air temperature as stream and groundwater inflow and lake temperatures paralleled air temperatures throughout the study period. In examining a period of 15 days in July 2010 where the difference between the maximum and minimum average daily air temperatures was 11.7°C, the lag time in stream inflow's response to air temperature changes was generally 1 day with a maximum of 2 days. Surprisingly, Fish Creek, a large inflow from the north contributed warmer water in July 2010 than a south shore inflow, Chittenango Creek, and a small north shore inflow, Scriba Creek, with the opposite occurring in October 2010. This was likely due to the placement of the Fish Creek temperature datalogger closer to the shore than in other streams. Over the two years, it was consistently observed that the streams provided warmer water in the spring relative to lake temperatures, but then provided cooler water in the summer with air temperature having an important effect on the lake temperature due to its large area. Air temperatures were greater than lake temperatures for several weeks in the spring, but then were less than lake temperatures in the fall.

In late Spring 2010 and 2011, the importance of inflows was demonstrated by brief periods of lake stratification likely caused by spring snowmelt and/or storm events, which contributed high volumes of cooler water to the lake. The timing and temperature of these storm runoff events may also have influenced the thermal structure of Oneida Lake in early summer. In 2010 and 2011, the difference in average 2 m and 10 m water temperatures indicated periods of stratification punctuated by mixing events. In 2010, there were 10 stratification events with 2 or more consecutive days of >1°C difference between 2 m and 10 m and 6 stratification events in 2011. The average length of the stratification events was 23 and 10 days in 2010 and 2011, respectively. Summer stratification events were likely due to meteorological drivers, such as solar radiation and air temperatures based on Oneida Lake's large surface areas and shallow depth. Alternatively, decreased wind velocity could have created stratification events. In Fall

2010, the average daily 2 m and 10 m water temperatures were similar; however, this trend began approximately one month earlier in 2011.

In addition to stream inflows providing cooler water to the lake, groundwater is prevalent (Schneider et al., 2004). Studies suggest groundwater flux throughout much of the lake bed or approximately 80,000,000 m^3/year is contributing to lake wide hydrologic budgets (Schneider et al., In Press; Schneider et al., 2004). This was only equivalent to 3.5% and 2.4% of total inflow in 2010 and 2011, respectively. Stream inflows are often cooler than shallow groundwater and provide more volume to the total inflow; therefore, this groundwater inflow was unlikely to impact lake temperatures. Further investigations into Oneida Lake groundwater discharge and temperature need to be conducted to accurately determine its role in the water budget and thermal regime of the lake.

Modeling

This work advanced previous Oneida Lake DYRESM studies (DeStasio et al., In Press; Joice, 2002) by performing a sensitivity analysis to understand the importance of model input variables and parameters obtained through field monitoring and improve model performance. All studies concluded that Oneida Lake is polymictic and exhibits mild summer thermal stratification for brief periods not longer than 2 to 3 weeks (DeStasio et al., In Press; Joice, 2002). As with other DYRESM studies that include sensitivity analyses (Tanentzap et al., 2008; Tanentzap et al., 2007; Gal et al., 2003), the Oneida Lake sensitivity analysis confirms the role of meteorological variables, such as wind and solar radiation, as drivers of lake thermal regimes. Additionally, these studies highlighted the importance of customized DYRESM input parameters implicated in thermal processes for their influence on heating and mixing of individual lakes. For Oneida Lake, adjustment of variables and parameters improved model reproduction of the measured thermal structure. In this study, wind speed was reduced by 25% and mean albedo and minimum layer thickness were reduced from 0.08 to 0.01 and 1.5 m to 0.5 m, respectively, to sufficiently increase heat within the modeled lake as compared to 2010 observed temperatures. Simulated Oneida Lake temperatures and strength of stratification for 2010 were generally within ±1°C of actual values. The adjustment of the wind speed variable in this study was greater than the adjustment by Joice (2002) who decreased the wind speed by 15% and increased the wind stirring efficiency and shear production efficiency from 0.40 to 0.80 and 0.06 to 0.08, respectively. In this study, adjustments to wind stirring efficiency and shear production efficiency had little effect. Additionally, the sensitivity analysis revealed that increasing solar radiation improved the alignment of modeled and observed temperatures in 2010 and 2011. The selected modifications yielded a very good representation for Oneida Lake. Adjustment of wind speed, mean albedo, and minimum layer thickness decreased average absolute deviations between modeled and observed temperatures at 2 m from 2.84°C to 0.86°C and 2.26°C to 1.12°C at 10 m. Furthermore, the adjustments were successful in 2011 with average absolute deviations between modeled and observed temperatures at 2 m and 10 m of 0.96°C and 0.88°C, respectively.

A well calibrated and validated model for Oneida Lake, in conjunction with downscaled climate data from three general circulation models and two emissions scenarios and maximum projections, provided the ability to predict the impacts of climate change on Oneida Lake by the end of the century. Under the most extreme climate scenario, this study determined Oneida Lake temperatures will increase by as much as 6°C at 2 m and 10 m with 15 additional consecutive stratification days (April – November) by the end of the century. Furthermore, climate change analyses indicated increases in average and maximum air and water temperatures and length of time above 25°C at 2 m and 10 m under the higher emissions scenario by the end of the century. The length of time above 25°C at 2 m will almost double from 44 to 86 days and almost triple from 22 to 65 days at 10 m. Interestingly, the 2011 maximum air temperature, average water temperature, maximum water temperature, and length of time above 25°C at 2 m and 10 m are already greater than the higher emissions scenario for mid-century which suggests that the 2099 predictions could be conservative. In another analyses of Oneida Lake, using altered meteorological data from the HadCM3 GCM, DeStasio et al. (In Press) concluded that potential changes in meteorology from an altered climate will result in increased summer water temperatures of almost 5°C by 2096 likely prolonging stratification.

These changes in lake thermal regimes will likely impact the chemical and biological characteristics of Oneida Lake. Lake temperature increases result in increases in water column stability (Sahoo and Schladow, 2008) prolonging summer stratification (Trolle et al., 2011). Longer periods of summer stratification cause increased hypolimnetic anoxia, or at least lower oxygen concentrations (Magnuson et al., 1997), which enhances the nutrient release from the sediment (Pettersson et al., 2003). Increased water temperatures alone may increase phosphate release from the sediments (Jensen and Andersen, 1992), decrease the grazing potential of zooplankton on phytoplankton (Jeppesen et al., 2007, 2009) and favor the dominance of cyanobacteria (George and Harris, 1985; George et al., 1990; Hyenstrand et al., 1998; Paerl and Huisman, 2008; Wagner and Adrian, 2009), thereby further enhancing the effects of eutrophication (Trolle et al., 2011). Oneida Lake is expected to become eutrophic with more cyanobacteria blooms.

Coldwater fish species have already started to decline in Oneida Lake (Jackson et al., 2008) and water temperature increases would likely present an additional stress on these fish species, particularly if thermal refugia at depth were reduced or eliminated (Hostetler and Small, 1999). Bioenergetics models suggest that water temperatures greater than 21°C result in weight loss in burbot, and the average duration of this period of high summer stress increased to almost 2 months in 2005 (Jackson et al., 2008). In 2011, the length of time greater than or equal to 21°C at 10 m in Oneida Lake was 83 days or almost 3 months and predicted to increase to 106 days by 2099. Furthermore, by the end of the century, the length of time greater than or equal to 27°C, the lethal limit for burbot (*Lota lota*) (Pääkkönen et al., 2003), at 10 m in Oneida Lake is predicted to be 44 days. Therefore; burbot will likely be extirpated from Oneida Lake by 2099.

Conversely, many warmwater fish species will benefit from temperature increases favoring growth, decreasing winterkill, and allowing occupation of previously less favorable areas with expansion of range northward and to higher elevations (Kaufman and Allen, 2008). A study of Oneida Lake gizzard shad (*Dorosoma cepedianum*), a warmwater fish species with a northern range already extended beyond its historical boundary, concluded warmer lake temperatures will lead to age-0 gizzard shad entering winter at larger sizes and provide greater temperature refuges during the winter leading to increased gizzard shad recruitment to age 1 and a greater role of gizzard shad in the Oneida Lake food web (Fetzer et al., 2011).

The model demonstrated good agreement between simulated and observed temperatures throughout the water column, captured seasonal variability in thermal profiles, and reproduced the timing of the onset of stratification. It had a tendency to underestimate heat and the degree of stratification for both the calibration and validation periods which were possibly due to the limitations of DYRESM and the accuracy of forcing and validation data. DYRESM is a one-dimensional numerical model for the prediction of temperature in small to medium lakes (Imberger and Patterson, 1981) and may have problems in larger lakes. Oneida Lake is a large, broad, shallow lake and some modifications to variables and parameters were required to accurately model the lake's thermal regime (Table 11). However, the direction of modifications, decreasing wind speed and increasing solar radiation, was somewhat counterintuitive. DYRESM does not account for orientation or fetch; therefore, it was expected the model would underestimate the effect of wind speed. On the contrary, the modeled temperatures were less than the observed temperatures suggesting DYRESM overestimates the effect of wind speed. Additionally, DYRESM required inputs to calculate the surface area to volume ratio which would highlight the importance of solar radiation for Oneida Lake; however, the model likely underestimated the effect of solar radiation. Further insight into the model's underlying principles and assumptions would be useful.

An alternate explanation as to the model's required variable and parameter modifications was meteorological data error. Meteorological data for this study were collected at Syracuse Airport located on average 21 km from Oneida Lake. Onsite meteorological data would potentially decrease discrepancies in representation of water temperatures and mixing regimes; however, comparison of Oneida Lake and Syracuse Airport wind speed data for 2006-2009 was inconclusive. Given the relative proximity of the airport to the lake, meteorological data from the airport were used as input to the model with few adjustments. Additionally, despite its importance, solar radiation remains among the least measured climatological variables (DeGaetano et al., 1993). The Northeast Regional Climate Center has adapted and implemented the Meyers and Dale (1983) model to provide daily solar radiation estimates for sites in the northeastern United States. The Meyers and Dale model uses standard meteorological observations as input and accounts for the attenuating effects of Rayleigh scattering, absorption by water vapor and permanent atmospheric gases, absorption and scattering due to aerosols, and absorption, scattering, and reflection from clouds (DeGaetano et al., 1993). Comparisons of the radiation estimates provided by the modified model and observations at northeastern sites show mean absolute error of less than 13% and a mean error very close to zero (DeGaetano et al., 1993). Errors were also calculated seasonally and tended to be largest in summer and smallest during winter (DeGaetano et al., 1993). Based on the simulation periods for this study, which included spring, summer, and fall, this error could be higher. The sensitivity analysis indicated the least deviation between simulated and observed temperatures at 2 m and 10 m when increasing the solar radiation by 30%.

Since the late 1960's, the hydrology of the Oneida Lake watershed has not been extensively studied. A review of the basic hydrology in the Oneida Lake basin was done to develop a daily water balance model. In 2010 and 2011, the daily water budget was calculated for the simulation periods in this study using Greeson's (1971) volumetric contribution weightings for Scriba Creek, Fish Creek, Oneida Creek, and Chittenango Creek combined with the 2010 and 2011 Fish Creek and Oneida Creek daily discharge data from USGS to determine daily relative inflow volumes for the four stream inflows. There is likely some error in the USGS discharge data for Fish Creek and Oneida Creek. Additionally, there is error in the estimation of the Scriba Creek and Chittenango Creek stream volumes. This methodology assumes there is consistency in discharge across the watershed based on the Fish Creek and Oneida Creek discharge measurements. Additional stream inflow gauging is needed to better understand the hydrology of the Oneida Lake watershed.

Although the model simulations in this study generally reproduced the physical dynamics of Oneida Lake, the accuracy of the future predictions of the model depends on the reliability of the predicted data for the meteorological forcing variables and scenarios. Compared to other meteorological forcing variables, air temperature has the most significant effect on lake temperature variability (Henderson-Sellers, 1988; Hondzo and Stefan 1992, 1993) and the predictions are considered relatively reliable (Mooij et al., 2005). Reliable projections of other meteorological variables, such as solar radiation, cloud cover, and wind speed, influencing the heat budget and thermal structure of lakes are unavailable both globally and regionally making it difficult or impossible to make concrete predictions of the future development of lake thermal structure. For example, cloud cover affects long wave and short wave radiation; relative humidity influences the exchange of latent heat; wind speed influences mixing and the exchange of both latent and sensible heat at the water surface (Livingstone, 2003). Additionally, changes in meteorological variables, including air temperature, will not only influence the thermal dynamics of lakes and the balance of evaporation and rainfall at the water surface, but also catchment scale runoff (Trolle et al., 2011). It is highly uncertain which effects global change will have at the catchment scale, where increasing temperatures, change in land use and frequency of extreme events will lead to changing nutrient fluxes into surface waters (Mooij et al., 2005). Attempts were made to account for the effects of climate change within the watershed by increasing the inflow by 5% and 10% in the 2050 and 2099 maximum scenarios. It was determined that this variable has little effect on lake temperatures on its own. Further study is needed to refine these predictions. Even if definitive predictions cannot be made, the use of DYRESM to predict lake temperatures based on future air temperatures contributes to our understanding of lake thermal structure in a warmer world.

By applying DYRESM to a polymictic lake, this study has provided a starting point for broad-scale predictions of the effects of climate change on the thermal structure of the majority of global freshwater lakes. Shallow lakes are more numerous worldwide than deep lakes and are of great importance especially in densely populated areas providing many services to humankind (Dokulil and Teubner, 2003). Dynamic models, such as DYRESM, validated through historical databases and combined with regional climate models could project future changes to the thermal structure of lakes in different world regions; however, integration of DYRESM across the landscape could provide a powerful tool to predict the response of many of these lakes to climate change. The responses of lake ecosystems to climate change variability and change can vary considerably due to geographical position, lake morphology, lake history, and biotic/abiotic interactions, and catchment characteristics (Magnuson et al., 1990; Blenckner, 2005). These components should be considered in conjunction with dynamic modeling results to develop a general framework for the predicted effects of climate change on the thermal structure of lakes worldwide.

APPENDIX A: STREAM DISCHARGE

Rating curves were developed from 2010 stage and discharge data for Scriba Creek (Figure 55), East Branch of Fish Creek (Figure 56), and Chittenango Creek (Figure 57). There was good agreement between stage and discharge for all three creeks with r^2 values from 0.82 to 0.98 (Figure 55 - Figure 57).

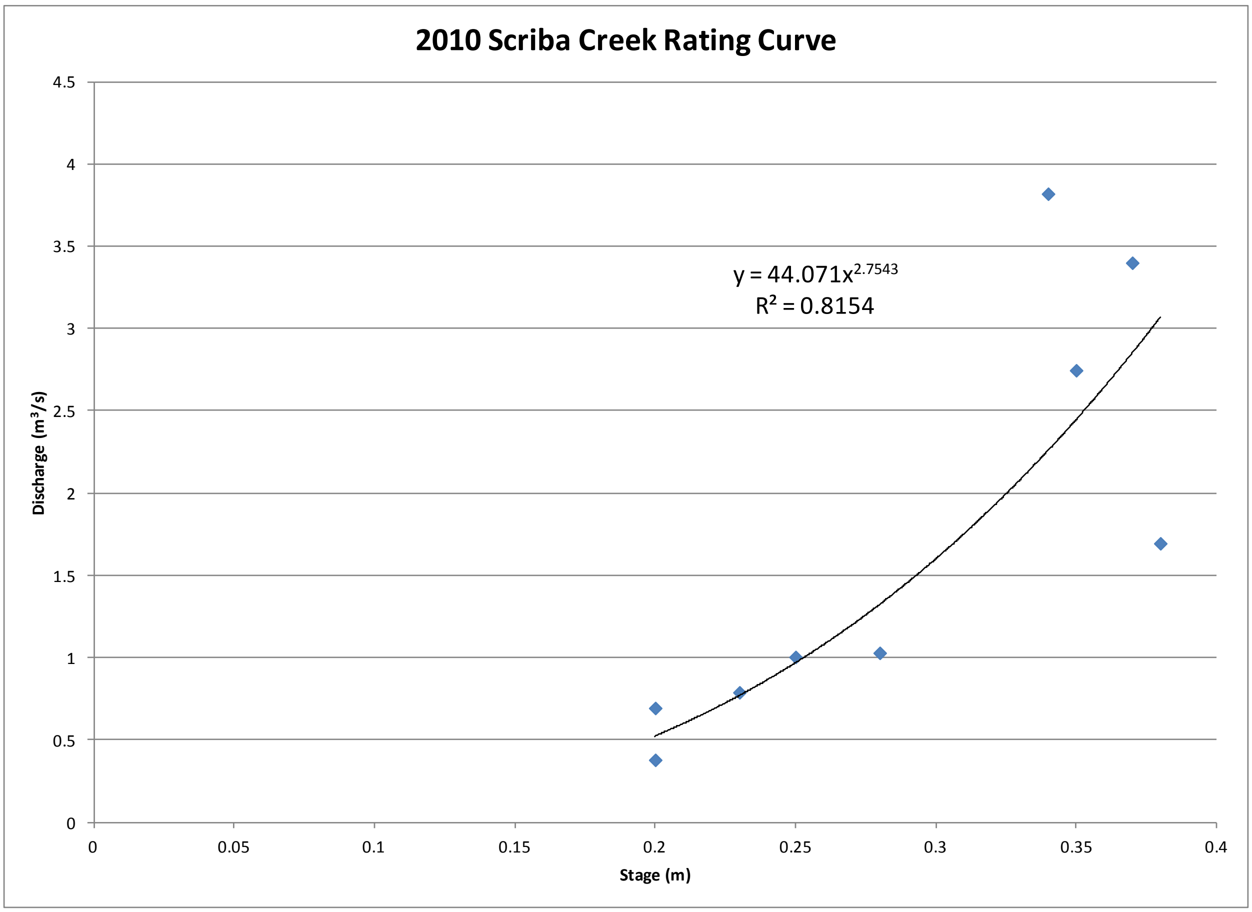


Figure 55. 2010 Oneida Lake Watershed Scriba Creek at Oneida Lake Fish Cultural Station (Constantia, NY) Rating Curve for 7/8/2010 to 11/7/2010. Stage calculated from average depth measurements at 1 m intervals for the width of Scriba Creek. Discharge calculated from stream cross-sectional area and velocity at 1 m intervals for width of Scriba Creek.

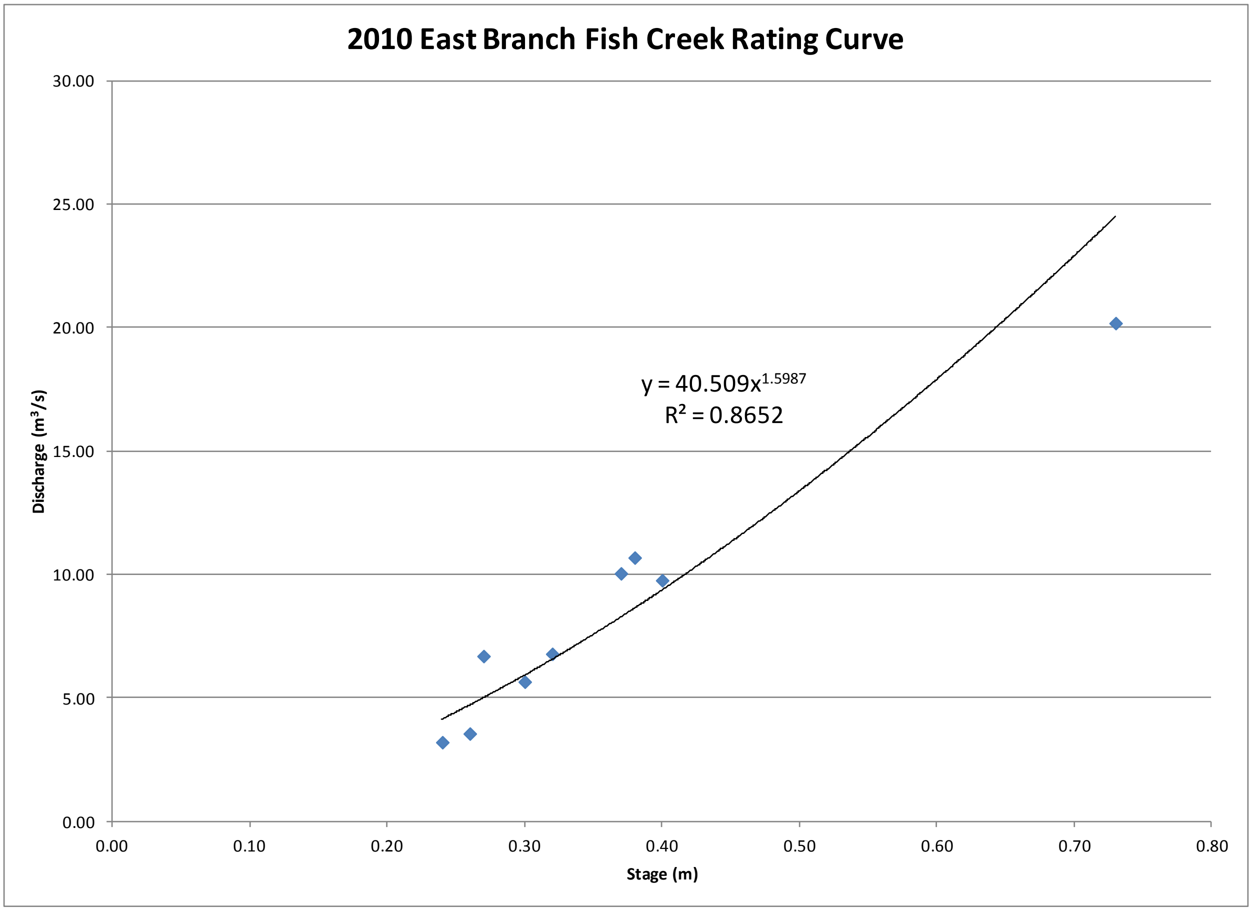


Figure 56. 2010 Oneida Lake Watershed East Branch Fish Creek at Main Street Bridge (Taberg, NY) Rating Curve for 7/13/2010 to 11/6/2010. Stage calculated from average depth measurements at 1 m intervals for the width of East Branch of Fish Creek. Discharge calculated from stream cross-sectional area and velocity at 1 m intervals for width of East Branch of Creek.

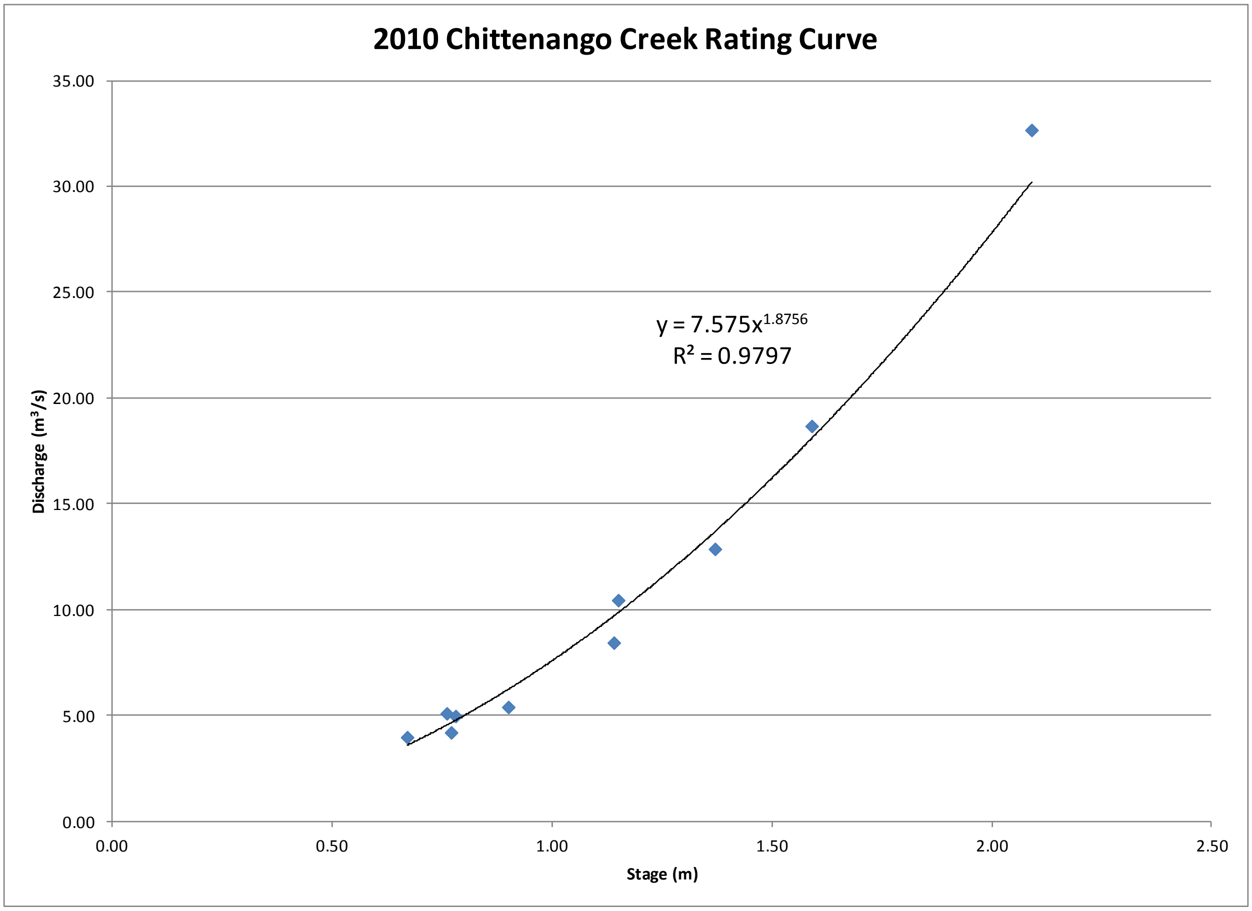


Figure 57. 2010 Oneida Lake Watershed Chittenango Creek at Lake Road Bridge (Bridgeport, NY) Rating Curve for 7/8/2010 to 11/7/2010. Stage calculated from average depth measurements at 1 m intervals for the width of Chittenango Creek. Discharge calculated from stream cross-sectional area and velocity at 1 m intervals for width of Chittenango Creek.

APPENDIX B: GROUNDWATER DISCHARGE

Discharge was calculated using Darcy's Law as follows:

$$Q = -K \frac{dh}{dl} A$$

where
Q = Discharge (m^3/s)
K = Hydraulic Conductivity (m/s)
A = Area (m^2)
dh/dl = Hydraulic Gradient (Freeze and Cherry, 1979).

Hydraulic conductivity was estimated to be 0.01 m/s at Cleveland and 0.0001 at Shackelton Point based on geological materials (Freeze and Cherry, 1979). Discharge was calculated based on an area of 1 m^2. Manual hydraulic head gradients were collected from June 18th to September 9th, 2010 at Cleveland and June 23rd to August 9th, 2010 at Shackelton Point for these 0.61 m (2 ft) wells.

Average hydraulic head gradient was higher on the southern shore at Shackelton Point than on the northern shore of Oneida Lake at Cleveland; however, the average discharge was greater at Cleveland than Shackelton Point due to different geological materials and associated hydraulic conductivity values (Table 19). Average hydraulic head gradient and discharge were 0.05 (SD 0.03) and 0.45 m^3/d (SD 0.23) at Shackelton Point and 0.03 (SD 0.01) and 22.67 m^3/d (SD 9.25) at Cleveland (Table 19). The hydraulic head gradients ranged from 0 – 0.09 and 0.01 – 0.04 at Shackelton Point and Cleveland, respectively (Table 19). The discharges ranged from 0.04 – 0.80 m^3/d and 6.84 – 32.07 m^3/d at Shackelton Point and Cleveland, respectively (Table 19).

Table 19. 2010 Oneida Lake Watershed Groundwater Hydraulic Head Gradients and Discharge at Cleveland (6/18/2010 – 9/9/2010, N=10) and Shackelton Point (6/23/2010 – 8/9/2010, N=8). Hydraulic head gradients were calculated from manual measurements of the difference of water height inside and outside groundwater wells 8 m from the north and south shores of Oneida Lake and the lake depth at Cleveland and Shackelton Point. Hydraulic conductivity was estimated to be 0.01 m/s at Cleveland and 0.0001 at Shackelton Point based on geological materials (Freeze and Cherry, 1979). Discharge calculated according to Darcy's Law for a 1 m^2 area.

	Hydraulic Head Gradient		**Discharge (m^3/day)**	
	Cleveland	**Shackelton Point**	**Cleveland**	**Shackelton Point**
Average (SD)	0.03 (0.01)	0.05 (0.03)	22.67 (9.25)	0.45 (0.23)
Range	0.01 – 0.04	0 – 0.09	6.84 – 32.07	0.04 – 0.80

APPENDIX C: LAKE SURFACE WATER TEMPERATURES

The average daily Shackelton Point surface water temperatures at 0.25 m corresponded with the average daily air temperatures (Figure 58). The average daily surface water temperatures were similar with 19.23°C (SD 6.71) from June 22, 2010 to November 20, 2010 and 19.34°C (SD 5.52) from May 8, 2011 to November 18, 2011. The minimum average daily surface water temperatures were 6.86°C on November 19, 2010 and 6.45°C on November 18, 2011. The maximum average surface water temperatures were in July for 2010 and 2011 with 30.48°C on July 8, 2010 and 29.00°C on July 23, 2011.

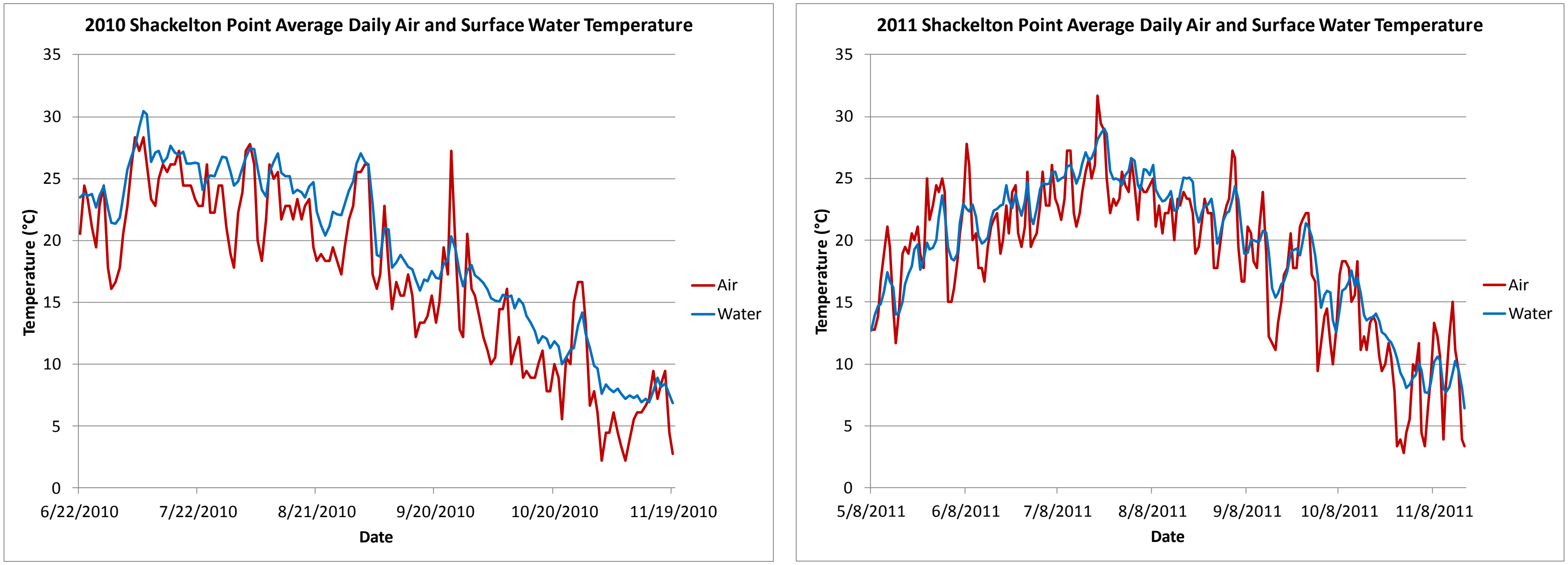


Figure 58. 2010 and 2011 Oneida Lake Watershed Shackelton Point Average Daily Air (Syracuse Airport) and Surface Water (0.25 m) Temperatures for 6/22/2010 to 11/19/2010 and 5/8/2011 to 11/18/2011. Average daily air temperature obtained for Syracuse Airport. Average daily surface water temperature calculated from water temperatures measured every 4 hours at 0.25 m in Oneida Lake at Shackelton Point.

APPENDIX D: LIGHT INTENSITY

Light Intensity

In 2010, the average daily light intensity on land was greater than the average daily light intensity on the raft within Oneida Lake at Shackelton Point (Figure 59). This decreased light intensity on the water was likely due to shade from trees on the shoreline for a portion of the day or disruption from ducks. The average light intensities on land for 2010 and 2011 were similar (Figure 59).

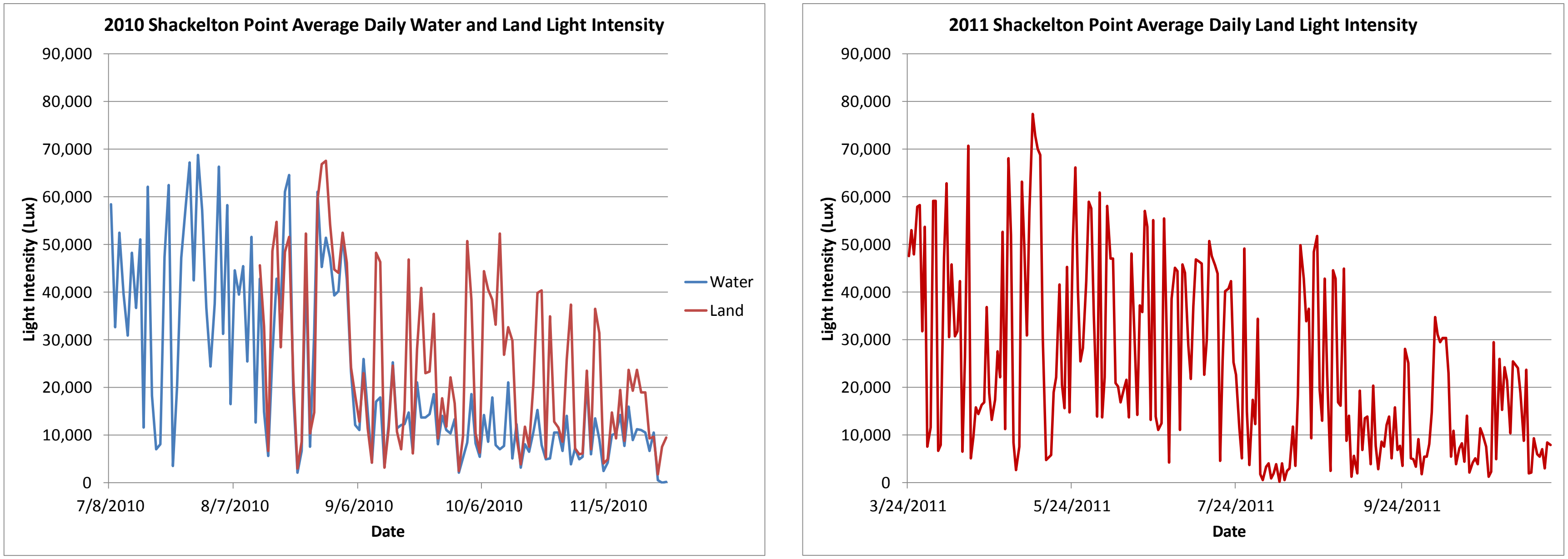


Figure 59. 2010 and 2011 Oneida Lake Watershed Shackelton Point Average Daily Water and Land Light Intensity for 7/8/2010 to 11/19/2010 and 3/24/2011 to 11/18/2011. Average daily light intensity on water and land were calculated from light intensity measured every 4 hours mounted on a raft anchored in a shallow bay and in an open meadow 18 m from shore at Shackelton Point.

APPENDIX E: PRECIPITATION

For July 9 – August 6, 2010, the average daily precipitation patterns for Shackelton Point and Syracuse airport varied (Figure 60). The total precipitation at Shackelton Point was 133.03 mm; whereas, the total precipitation at Syracuse Airport was 95.52 mm. Additional precipitation data for Shackelton Point are needed for further comparison.

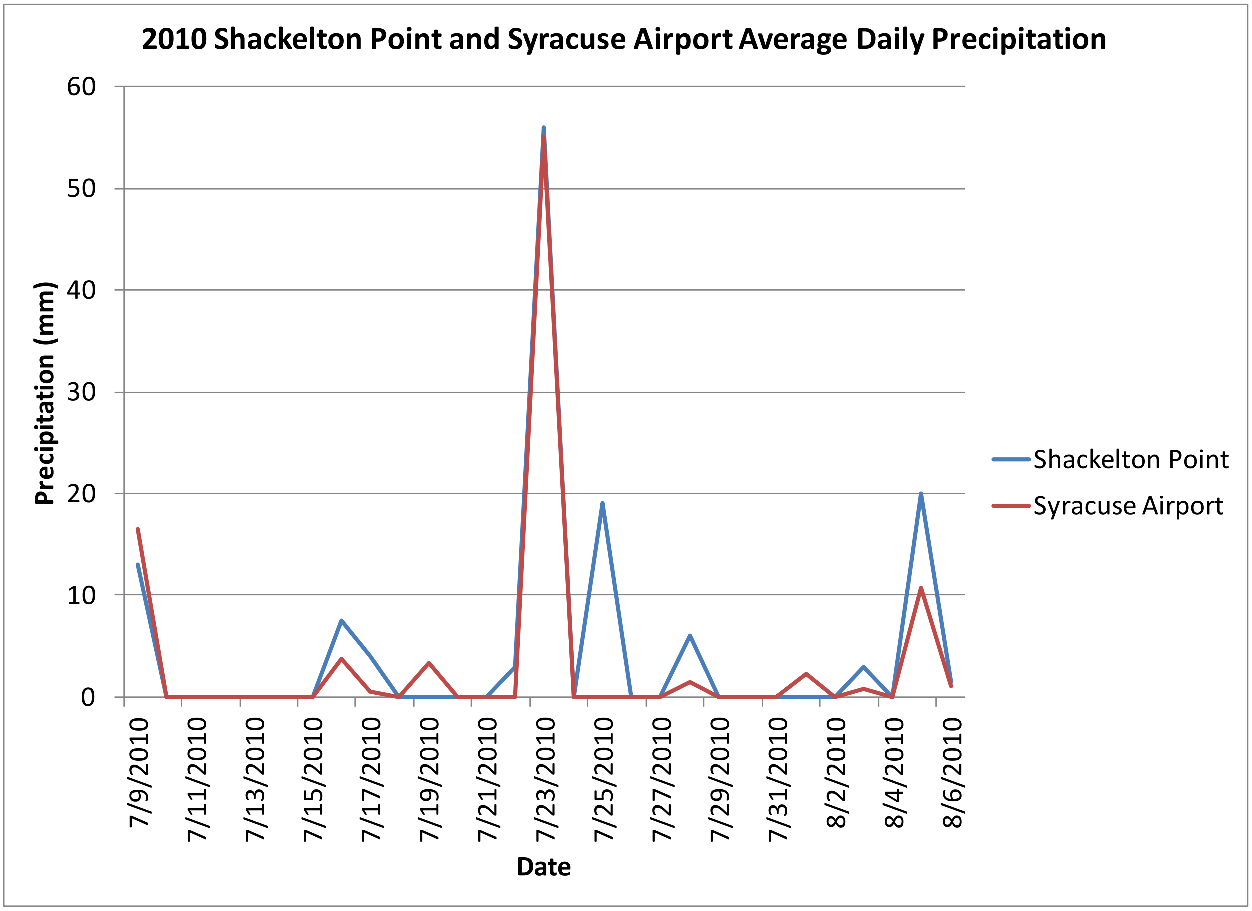


Figure 60. 2010 Oneida Lake Watershed Shackelton Point and Syracuse Airport Average Daily Precipitation for 7/9/2010 to 8/6/2010. Average daily precipitation measured from a Tru-Check® rain gauge mounted on a raft anchored in a shallow bay at Shackelton Point. Average daily precipitation obtained for Syracuse Airport.

APPENDIX F: EVAPORATION

For July 6 – July 8, 2010 and July 11 – 13, 2010, the evaporation at Shackelton Point was 0.005 m (Table 20). The average daily air temperature at Shackelton Point exceeded 30°C for July 6 – July 8, 2010; whereas, the average daily air temperature at Shackelton Point ranged from 25.01°C to 26.07°C for July 11 – 13, 2010 (Table 20). Although the air temperature decreased, the wind speed increased from July 6 – 8, 2010 to July 11 – 13, 2010 (Table 20).

Table 20. 2010 Oneida Lake Shackelton Point Evaporation and Average Daily Temperature and Syracuse Airport Wind Speed for 7/6/2010 to 7/13/2010. Average daily evaporation was measured from a 38 cm diameter stainless steel pan containing 4 L of water mounted on a raft with a submerged bottom in a shallow bay at Shackelton Point. Average daily air temperature calculated from air temperature measured every 4 hours mounted on a raft anchored in a shallow bay 18 m from shore at Shackelton Point. Average daily wind speed obtained for Syracuse Airport.

Date	Shackelton Point Evaporation (m)	Shackelton Point Average Temperature (°C)	Syracuse Airport Wind Speed (m/s)
7/6/2010	0.005	30.9	1.92
7/7/2010	0.005	30.27	1.07
7/8/2010	0.005	31.35	1.25
7/11/2010	0.005	25.01	2.01
7/12/2010	0.005	25.83	3.76
7/13/2010	0.005	26.07	3.18

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