# Coupling a global climate scenario, general circulation models, and lake models to partition uncertainty in the projected thermal budget of a northern oligotrophic lake

## Abstract

Using the representative concentration pathway (RCP) 8.5 scenario coupled with four general circulation models (GCMs), an ensemble modelling approach using 5 general lake models will be applied to the northern oligotrophic Lake Sunapee. The output of the ensemble model will include temperature profiles and ice coverage from 1986 to 2099. Using these projections, insights regarding the thermal budget of Sunapee will be discussed such as stratification strength and depth, mixing, and water column temperature. Ice coverage projections will be presented and discussed as well. The outputs of the ensemble models will include sufficient information to carry out uncertainty propagation in relation to climate model uncertainty, parameter uncertainty, ecosystem model process uncertainty, and climate scenario uncertainty. The results of this study will be relevant to both stakeholders of Lake Sunapee as well as climate modelers and researchers.

## Introduction

Due to human activities, freshwater ecosystems around the globe are increasingly changing. Clear water, or oligotrophic, lakes provide critical ecosystem services such as drinking water yet are experiencing relatively abrupt and severe water quality problems attributed to climate change and land development. Because of this, new tools to predict future water quality are vital to improving the management of oligotrophic lakes and combat water quality degradation. In this project, the focus of this research will be Lake Sunapee, an oligotrophic lake in New Hampshire and important drinking water source. Lake Sunapee is an exemplary case study for understanding how currently high-water quality lakes are being rapidly degraded due to human activities.

Thermal stratification in lakes is a known regulator of physical, chemical and biological processes in lakes and reservoirs, contributing to primary production depth1, quality of fisheries habitats2, deep-water oxygen levels34 and atmospheric gas exhange56.7 The effects of climate change on stratification is less known, however the effects on temperate lakes appears to be a slow but steady regime shift from multiple mixing annually (polymictic and dimictic) to a single mixing event (monomictic).8 This could be potentially devastating for the ecosystems residing within Lake Sunapee, which are acclimated to multiple mixing for a relatively static duration every year. Processes such as primary production, fish habitation and atmospheric gas exchange could shift dramatically from the status quo.

The study uses the representative concentration pathway (RCP) 8.5 scenario, which combines assumptions about multiple ecological and sociological factors, including high population, slow income growth, and modest technological change and energy intensity improvements.9 Under these assumptions, the greenhouse gas emissions continually increase over time, leading to a radiative forcing of 8.5 W/m2 at the end of the century.9 The RCP 8.5 scenario will be used in conference with four general circulation models (GCMs), all of which model Earth’s atmosphere using the radiative and thermodynamic properties of the atmosphere as well as the frictional dissipation and dynamics of kinetic energy on multiple scales.10

The LakeEnsemblR R package is used to project lake temperature and ice cover in this study. The package includes the following lake models: FLake (Freshwater Lake model) which simulates lake systems using a two-layer parametric representation focusing on heat budget, GLM (General Lake Model) which applies a lagrangian structure to replicate mixing dynamics, GOTM (the General Ocean Turbulence Model) which is a vertical 1D hydrodynamic water column model, MyLake (Multi-year Lake simulation model) which simulates daily vertical profiles of water temperature, seasonal ice and snow cover as well as others, and Simstrat, which is a vertical 1D hydrodynamic model combining a buoyancy-extended k-epsilon model with seiche parameterization.11

Uncertainty partitioning is a novel aspect of this study. It is important in ecological forecasting for scientists to understand the “weak points” in the materials and methods. This allows researchers to focus resources on constraining the largest uncertainties in a study.12 For example, Raiho et al. found that process uncertainty greatly outweighed parameter uncertainty, even though parameter uncertainty has been the focus of the ecological modeling community.12 Gaining insight into the predictability of ecology makes ecology more relevant to policy, management and decision making. It also impacts the data collected, how models are structured, and the statistical tools linking models to data.13 The following study will require propagating the contributions of model parameters, ecosystem model processes and climate model projections.14

The following study is overall a novel approach to a climate change impact study, including four general circulation models coupled with a high intensity representative concentration pathway modeled by five lake models in LakeEnsemblR. Studies of this nature that partition uncertainty are few and far between, and virtually nonexistent concerning individual lakes and their future projected outcomes. Because of this, a major goal of this study is to make the workflow usable to others so that they may do similar studies on one or more lakes of their choosing.

## Materials and Methods

In order to better understand the impacts of the future climate change scenario representative concentration pathway (RCP 8.5), four general circulation models (GCM) will be used to model lake temperature with the five lake models within LakeEnsemblR. Using a 30+ year historical dataset, parameters will be calibrated, and baselines will be created for each GCM. GCM climate data will then be forced through the calibrated LER and the anomalies between GCM’s will be compared using a 30-year intervals up to 2099. Metrics of interest from this LER output will include thermocline depth, length of stratification, thermocline strength, and ice coverage. An array of compiled outputs including parameter distributions, water column output, and anomaly values can subsequently be used to partition uncertainty across the climate models, parameters, lake models, total forecast and climate scenario.

1. Download the following EWEMBI corrected general circulation models: MIROC5, IPSL-CM5A-LR, GFDL-ESM2M, HADGEM2-ES under RCP 8.5 conditions.
2. Download forcing data for Sunapee needed to drive LER. This includes historical observations of discharge, outflow, hypsography, and initial conditions, as well as EWEMBI data in place of the on-site meteorology data. EWEMBI data will be used in order to maintain consistency when transferring from historical datasets to GCM datasets within LakeEnsemblR.
3. Ensure that all models run on LER using base parameters. Once all models run, calibrate parameters for LER using a specific set of years in the historical dataset. First choice of calibration method is MCMC utilizing priors from a LHC simulation so that there are understandable distributions to work with.
4. When parameters are calibrated, RMSE should be within ~2C for water temperature, stratification should be captured, and Schmidt Stability should be replicated. We will determine this by looking at observed vs modeled water temperature aggregated for the whole water column.
5. Calculate the historical anomaly for water temperature over the 30-year historical dataset. This is what we will use to compare the projections to the historical baseline.
6. Force the GCM model output for meteorology (and possibly inflow/outflow) into LER and produce results for all LER models up to 2099.
7. Once results are produced, analyze projected LER water temperature over 30-year time periods from present up until 2099. 30-year time periods signify a complete climate cycle – an analysis using 30-year intervals leads to a more complete and broad annual picture than shorter or longer intervals, and will remove interannual noise. There are many metrics of interest that can be calculated from LER temperature simulations, including the length of stratification, thermocline depth, and thermocline strength, among others.
8. Once metrics of interest have been calculated for each model over 30-year time periods, a comparative analysis between all LER and GCM model combinations, and the historical baseline should be carried out.
9. The comparative analysis will revolve around the spread and difference of values between the LER models.

Possibilities:

* Mean stratification duration by year with 95% confidence intervals for each LER model up to 2099. Track the average change from year to year for each model.
* Difference between surface and bottom temperature up to 2099 for each LER model. Would give more insight into the magnitude of the stratification according to each model. Unsure of how uncertainty could be quantified in this case.
* Compare water temperature per meter (0-33m), averaged yearly with a 95% confidence interval. Would give a better insight into differences in modeling the entire water column for the LER models. Maybe some models are better at upper column, middle column, lower column?

1. Move on to uncertainty partitioning.

**Uncertainty Partitioning**

1. Climate model uncertainty: Use median parameter values; Do not propagate process uncertainty; Uncertainty is defined as the width of the 95% CI of percent change in stratification duration from 2021 (ish) up to 2099.
2. Parameter uncertainty: Sample from the posterior distributions of the parameter sets; Generate separate ensembles for each climate model and calculate uncertainty by taking the width of the 95% CI of ensembles averaged across the climate models.
3. Ecosystem Model process uncertainty: Comparing different outputs using sampled parameters and using an ensemble approach; Take the width of the 95% CI averaged across models.
4. Total forecast uncertainty: propagate from previous three.
5. Climate scenario uncertainty: Difference in percent change of temperature from different climate model scenarios (RCP 4.5, RCP 8.5) using the anomaly values produced by combining LER and ISIMIP models.

## Results

This project will be multifaceted in its outcomes: first, the outputs of the LakeEnsemblR models will give insight into the future of Lake Sunapee given certain climate conditions. This will provide desired insights to managers and homeowners residing at Lake Sunapee, who are greatly interested in mitigating the impacts of climate change on their lake in order to maintain its community-wide and personal values. Second, this project will lead to novel insights revolving around the modelling itself. Because all models have inherent uncertainty, whether that be revolving around future temperature projections, global circulation methods, or water column properties, it is important for researchers to understand how much uncertainty is present and where that model uncertainty is coming from (e.g., model parameters, driver data). Because this project contains multiple models for both climate projections and lake water quality response, the ability to compare an ensemble of predictions is possible and extremely useful. These insights will be relevant to researchers and modelers carrying out similar climate change impact studies in order to mitigate future negative impacts on lake water quality.

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