Exploring how global climate change will affect the water quality of the New York City Harbor Estuary: Linked watershed and estuary models

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SUMMARY OF THE RESEARCH

Introduction

The research proposed in 2015 included two main modelling components: 1) a watershed model to explore how future global climate change may affect the discharge of water, sediments, and nutrients from the Hudson River basin; and 2) an oceanographic model to investigate the response of the lower Hudson/NYC Estuary to potential changes in Hudson River discharge predicted from our watershed model, and a significant proportion of the work proposed involves adapting and using these tools to assess the response of the Estuary to regional climate change scenarios. These scenarios are themselves the realizations of multiple climate models being driven by emissions scenarios developed by the International Panel on Climate Change (IPCC). As noted in the proposal, a main focus was to assess the impact of change on summertime conditions, the most biologically active period of the Hudson River estuary, although we must model the watershed over all seasons to capture summer-time behavior (i.e., the influence of snowpack on groundwater recharge as it affects summer-time freshwater discharge in the Hudson River).

To drive the watershed model over future periods of projected climate change, it is also necessary to obtain estimates of regional climate change projections and process them into forms compatible with our watershed-scale model. Note that our ultimate goal is not to predict precise time-series trajectories associated with climate change: the climate model projections themselves are too imprecise on the regional scale to allow for such prediction. Rather, our primary goal was to explore the range of conditions which may be seen over many summers in the Hudson as the global temperature rises by 1.5˚ C (~15 years from now), 2.0˚ C (35 to 40 years from now), and more (Shindell et al. 2012; IPCC 2008, 2013, 2014) and to assess the corresponding range of change in residence time and corresponding estuarine processes relative to the current baseline. In some summers, discharge is likely to be higher than the mean over the past 50 years, but in others it may be substantially lower, and variation associated with increasingly extreme storm events is likely to increase. Our modeling permitted estimation of how much lower summertime discharge may be, how much larger streamflow variability may be, what the consequences could be for estuarine residence time and water quality in the Harbor estuary. The results are, of course, contingent on 1) the RCP scenarios driving the climate models, 2) the climate models considered, 3) the parameters and functional forms chosen to characterize land use and hydrology in the hydrologic model driven by climate data, and 4) the period of flow considered.

- **Regional climate projections**

For projections of future climate change in the Hudson basin, we are focusing on two scenarios from the IPCC (2008, 2013, 2014). We have obtained downscaled multimodel projections from the 5th IPCC climate projection archives, currently available at the http://gdo-dcp.ucllnl.org/ (Maurer et al. 2007). These model outputs, referred to as CMIP5, are available at 1/8-degree resolution (~12km x 12km grid) for the entire continental U.S. Daily estimates of precipitation and temperature are available, covering both the historic (1950-1999) and projected (to 2100) periods. We have downloaded these data for the grid cells intersecting with the Hudson River basin and have spatially-aggregated them for each of the 8-digit USGS hydrologic units comprising the Hudson/Mohawk watershed (Figure 1). These daily datasets (temperature and precipitation) have been stored as a series of files in a format compatible with our catchment model. Currently, climate projections from four representative concentration pathways are considered (RCPS, indicated by RCP2.6, RCP4.5, RCP6.0, and RCP8.5) which corresponds to IPCC fifth assessment report. To date, we have worked most with the RCP4.5 and RCP8.5 scenarios. The CMIP5 scenario RCP4.5 is similar to the earlier CMIP3 scenario B1 (emissions roughly corresponding to "business as usual" strategy), and RCP8.5 corresponds to relatively high emissions (Figure 2).

We used the ReNuMa model (described below), driven by multi-model realizations of daily climate trajectories corresponding to the RCP scenarios, to estimate hydrology, based primarily on the following two considerations: First, the hydrologic estimates from the macroscopic variable infiltration model (VIC; Liang et al., 1994), also available at the Climatic Archive, do not include groundwater components and processes (e.g., infiltration of rainfall and snowmelt to deep percolation and return flows to stream channel networks; Bureau of Reclamation, 2013) (This is especially relevant because we are focusing our analysis on summer periods when groundwater recharge is a relatively important term compared to other periods). Second, only monthly hydrologic estimates are available from the archive, whereas ReNuMa can produce daily streamflow, appropriate for linkage with the estuarine circulation model.

- **Watershed model**

As noted above, we are employing the hydrological component of the ReNuMa (regional nutrient management) model to estimate the response of local watershed hydrology to projected changes in climate (Hong and Swaney 2013). The model is run on a daily time step, and is driven by projected meteorological inputs, aggregated to the level of hydrologic units (Figure 1) as well as land-use in the watershed. We previously applied ReNuMa's predecessor, GWLF (Haith and Shoemaker, 1987; Haith et al 1996), to estimate fluxes of freshwater, sediment, and organic carbon from the Upper Hudson and Mohawk (Howarth et al. 1991; Swaney et al. 1996).

The model was run separately for each hydrologic unit to determine the streamflow originating in each region, and the resulting seasonal or annual flows are accumulated to determine the cumulative flow from the different components of the watershed. Thus, we could assess the responses of latitudinal variation of climatic variables from the northernmost subbasins, as well as the differential contributions of major tributaries, such as the Mohawk. To date, we have used v1 of the ReNuMa hydrology model, which has a relatively simple evaporative loss component based on the temperature-dependent Hamon equation, which has resulted in previous success in estimating annual and seasonal variation in the Upper Hudson and Mohawk basins.

We are currently assuming a fixed distribution of land uses within each hydrologic unit corresponding to 2010 values in order to assess the impact of the climate change projections without the added contribution of land-use change impacts.

- **Estuarine circulation model**

We employed the ROMS model (http://www.myroms.org), a state-of-the-art, open-sourced, three-dimensional ocean circulation model that can couple physical oceanographic drivers with ecological and water quality functions and responses, to estimate estuarine circulation in the Hudson Harbor Estuary. Versions 2 and 3 of ROMS have been previously applied to the Hudson River estuary by Warner et al. (2005) and Warner et al. (2010), respectively. In the version 2 application, the Hudson River estuary was represented by a curvilinear grid with 20 x 200 x 20 cells (along-channel x cross-channel x vertical dimension) covering areas from the Battery to Green Island (about 250 km long, Figure 3). In version 3 (Figure 4), the simulation grid was expanded to a composite grid with the following three grids connected to each other: (1) Hudson River grid similar to version 2 grid (20 x 248 x 20), (2) New York Harbor grid (111 x 100 x 20), and (3) East River grid (21 x 66 x 20).

Findings to date

Our efforts to date have focused on climate projection data collection, synthesis and analysis, as well as simulations of hydrological responses for watershed subbasins (hydrologic units). We have reported some of these preliminary results at several meetings, as indicated in the "products" section below. We caution that these results are based on specific parameterizations and formulations of evaporation in the hydrology model, as well as being contingent on the climate projections and climate models used to estimate climate in the region, and are thus subject to revision.

We have also explored the ROMS model in the Hudson, and have made significant progress in using it to estimate estuarine residence time (i.e. water "age" distribution) and salinity levels. Progress was also made on configuring the model to estimate impacts suspended sediment and corresponding light regimes, which are critical in limiting phytoplankton growth rate in the estuary.

- **Climate data collection and synthesis**

Daily data (temperature and precipitation) from all RCPs generated by available models (Table 1) have been downloaded, processed and reformatted for use with ReNuMa. These climate projections are available for each of the Hudson/Mohawk hydrologic unit regions (Figure 1) through 2099. Both climate data and corresponding model results have been made available online (http://www.eeb.cornell.edu/howarth/web/HudsonRiverBasinProjects_home.html). Apart from their use to drive the hydrology model, these data are being analyzed to assess trends and patterns in derived metrics as needed for our research (e.g. estimated changes in mean values, percentiles, maxima, minima and other measures).

- **Modelling streamflow in response to RCP4.5 and RCP8.5**

To date, we have evaluated climate projections from RCP4.5 (emissions peaking in 2040) and RCP8.5 (emissions continuing to increase through this century) to assess annual and seasonal variations of temperature, precipitation and streamflow. Results from all available models (table 1) were evaluated, and model-median values were used in some cases. On the basis of a model comparison study by Najjar et al. (2009) we also examined results from a specific model ranked relatively highly for the Hudson basin. While the Najjar et al. study found that the Hadley climate center model performed the best of individual models studied, daily values of temperature and precipitation (required by ReNuMa) were not available for this model. Najjar et al also found that the model of Canadian Centre for Climate Modelling and Analysis (CANESM2) also performed well for the Hudson, and we chose this model because of the availability of its daily temperature and precipitation for the region.

In general, examining results of all-model-median results showed lower interannual variations and more modest deviations in future decadal means relative to 2000-2009 than the results of a specific model. This presumably results from the effect of averaging over a range of model realizations (some models provide multiple realizations) with significant intermodal variation in projections. Below, we describe the projections of CANESM2 (median of 5 realizations from the same model) and resulting streamflow estimates. (Streamflow estimates made by running ReNuMa (v.1) for each model realization and selecting the median of the model outcomes).

- **Annual projections**

RCP4.5 The climate model shows an approximate 2˚C increase in temp between the decade of 2000-09 and 2050-2059, which increases to ~ 3˚C by the decade of 2090-99. Temperature increases were more-or-less uniform across all subbasins in both periods (Figure 5a). For precipitation, between the first and middle decades, increases of 4% are seen in the northern end of the watershed, but decreasing to < 1% increases at the lower end (Figure 5b). The net effect of these changes on streamflow is a decrease in estimated annual flow of between 5-10% of 2000-09 estimates in various subbasins by the middle of the century, and modest increases or decreases beyond this by the end of the century (Figure 7a).

RCP8.5 Here, the climate model shows an approximate 3˚C increase in temp between the decade of 2000-09 and 2050-2059, which increases to ~ 5-6˚C by the decade of 2090-99 (Figure 6a). Precipitation increases modestly and uniformly (4-5%) by 2050-59, but by the decade of the 2090s, precipitation increases by over 8% in the north but only 3-4% in the southern end of the watershed (Figure 6b). The net effect of the large temperature change and north-south gradient of precipitation change means increases or modest declines in streamflow in the northernmost subbasins, but significant decreases in the Mohawk and lower Hudson subbasins (20-40% relative to 2000-2009) by the end of the century (Figure 7b).

- **Seasonal projections**

RCP4.5: changes in climate and discharge between 2000-09 and 2090-99. The largest temperature increases by the end of the century for all subbasins occurs during January, with major increases of ~4-6 ˚C across the watersheds (compare Figure 8a and 8b). A secondary peak occurs in summer-fall (increases of ~3-3.5˚C). The smallest temperature increase occurs in November (~2 ˚C). As with midcentury trends, winter and spring also show increases in precipitation (0%-40%); precipitation also increases in June by ~10-20%. Decreases in precipitation occur in the fall across all watersheds (0 to -20% relative to 2000-09). As in midcentury, resulting changes in streamflow are quite variable by subbasin. Notably, the upper (northern) subbasins show very significant increases in flow in January-February (80-100%) due in part to increased precipitation, but probably also due to the effect of increased temperature on the snowpack, which also explains the decrease in springtime flow. The lower subbasins show decreases during this period. All basins show relatively lower streamflow in the fall. In the summer, northern subbasins appear to show decreases in flow, but southern subbasins show little change or even increases in flow.

RCP8.5: changes in climate and discharge between 2000-09 and 2090-99. As with the midcentury projections, the largest temperature increases occur during winter (February, ~+6-8 ˚C) and late summer/early fall (September, +7-8 ˚C) across the watersheds (compare Figure 8c and 8d). The smallest temperature increase relative to 2000-09 occurs in December (~3 ˚C). Winter and spring also show increases in precipitation (~20%); precipitation also increases in August by ~20-30% relative to 2000-09. Decreases in precipitation occur in the fall across all watersheds (-10 to -20% relative to 2000-09) and also in June by ~-13 -18%. As in midcentury, resulting changes in streamflow are quite variable by subbasin. Again, the upper (northern) subbasins show very significant increases in flow in January-February (80-100%) and decreases in the spring; the Mohawk/Schoharie show intermediate increases/decreases over the same months, and the lower subbasins generally show decreases in flow, especially in the fall months. All basins show relatively lower streamflow in the fall. In the summer, northern subbasins (including Mohawk/Schoharie) again appear to show decreases in flow, but southern subbasins show little change or even increases in flow.

RCP8.5: changes in hydrological components between 2000-09 and 2090-99. Figure 9 shows the impact of climate change on snowfall and snowmelt, as well as evapotranspiration, drive seasonal and latitudinal subbasin-scale variation within the watershed. In the first decade of the 21st century, seasonal variation of net input to watershed soils (rainfall+snowmelt-evapotranspiration) is positive throughout most of the year, peaking in the spring due to the combined effects of snowmelt and spring rains; in a few summer months, evapotranspiration exceeds precipitation, resulting in a negative water balance in summer (Figure 9a). By the end of the century (Figure 9b), the springtime peak is no longer evident (due to loss of snowmelt and seasonal shifts in precipitation), and the summertime trough has deepened and widened (due to increased evapotranspiration due to temperature increases). The model also indicates that in the decade 2000-09, up to 80% of spring runoff was derived from snowmelt in the upper Hudson, but by the end of the century, this will have dropped considerably, with peak contribution occurring earlier in the year. Further south in the watershed, the contribution to flow from snowmelt nearly disappears by the end of the century (Figure 9c, d). Qualitatively similar, but smaller, responses are seen in RCP4.5 projections, and intermediate responses are seen for mid-century estimates.

- **Exploration of impacts of flow on estuarine circulation, water quality and primary production**

The primary aim of the estuarine modelling component of the project was to evaluate climatically-driven changes in flow and their impact on estuarine residence time and the ultimate effects on phytoplankton growth. The amount of time that phytoplankton species remain in a favorable environment (i.e. within an optimal range of salinity, temperature and light level, without nutrient limitations) is directly related to their rate of growth, with implications for eutrophication, harmful algal blooms, etc. Reductions in summertime riverine flow can potentially increase this residence time, suggesting the potential for environmental problems, so we aimed at evaluating circulation under alternative low-flow scenarios.

Toward this end, John Wilkin adapted the grid-cell representation of the lower Hudson that has been used in previous work (e.g. Warner et al. 2010), modifying the grid by reducing its resolution by a factor of 3, thereby reducing the number of grid cells required in the calculation by a factor of 9, and allowing the ROMS model time step to increase from 5 to 30 seconds. The overall result is that simulations are now ~ 50 times faster than with the original formulation.

Sam Nadell, a graduate student on the project (and Polgar fellow), worked closely with John Wilkin to explore the behavior of ROMS (salinity distribution and water residence time, or age) corresponding to different rates of flow at the upriver boundary. Historical annual average flow has been about 500 m^3s^{-1}, and ReNuMa suggests the possibility of lower annual flows of 200 m^3s^{-1}. We were particularly interested in summertime flow projections estimated by ReNuMa to be in the range of 50-200 m^3s^{-1}, and initially had some difficulty evaluating the impact of these low flows on estuarine circulation using the ROMS model, though ultimately low-flow condition simulation results were obtained to permit estimation of freshwater age and salinity distributions under different flow levels (see Nadell, S. 2018, attached). We could also observe empirical relationships between light availability and suspended sediment concentration, based on shared datasets provided by Stu Findlay at the Cary Institute; these showed no significant seasonal variation. These in-situ light attenuation and suspended matter data from Haverstraw Bay in the estuary were pooled and used to create a simple linear equation, used to predict light attenuation coefficients based on suspended sediment concentration (Figure 10), which in turn could be used with the ROMS model.

The model indicates that at neap tide conditions, weak bloom activity (as indicated by chl-a concentration) can occur north of Manhattan at typical summertime flows (Figure 11a) and stronger activity can occur along a somewhat extended range during the lower flows projected for later in this century (Figure 11b). Higher chl-a concentrations are also observed below the estuary. Spring tide conditions show some weaker chl-a concentration peaks in the same areas (not shown). However, model results also indicate that while phytoplankton growth increased as discharge rate decreased, extensive phytoplankton blooms were unlikely to occur under any realistic river conditions, as increased mixing and diminishing water column stratification associated with slower discharge rates appeared to counteract the favorability of increased residence times. Incorporating these relationships into new models could provide the capability of assessing not only the impact of changes in flow on residence time and corresponding phytoplankton growth, but the impact of flow on the light regime, mediated by changes in suspended sediment capacity. This could dramatically alter our view of the response of the estuary to climate-driven changes in the flow regime.

Ongoing and future work

Our ongoing work with respect to the watershed hydrology component involves completing sensitivity analysis of the watershed model, and comparing the impact of the current functional relationship for evapotranspiration used in the model (the Hamon equation formulation, which depends on daily mean temperature) with an alternative formulation (e.g. the Hargreaves-Samani equation, which additionally incorporates daily temperature range in the formula for evapotranspiration). A manuscript on the impacts of regional climate projection on Hudson/Mohawk hydrology is in preparation.

Future work will necessitate incorporation of newer IPCC climate projections as they come online (i.e., CMIP6), as well as incorporating projections of future land use and corresponding parameters.

The estuarine circulation work based on the ROMS modelling efforts of John Wilkin and Sam Nadell may provide the basis for a publication as well, beyond Nadell's master's thesis (appended). Copies of publications derived from the project will be provided to HRF upon their publication.

Products

- **Master's thesis**

Nadell, Sam. Modeling Water Parcel Age and Phytoplankton Growth in the Hudson River Estuary Under Climate-Influenced Discharge Conditions. Defended May 8, 2017. (See appended document).

- **Presentations**

Invited Oral Presentation: "The Role of the Mohawk in Hudson River Nutrient Dynamics". Swaney, D.P., B. Hong, and R. W. Howarth. 2016 Hudson River Symposium: "Watershed Influences in a Changed World", Hudson River Environmental Society, May 4th, 2016, SUNY New Paltz, New Paltz, NY.

Poster Presentation: "Projected impacts of climatic change on Hudson River hydrology". Swaney, D.P, B. Hong, and R. W. Howarth. ASLO 2016 Summer Meeting. 5–10 June, 2016. Santa Fe, NM.

Invited Oral Presentation: “Climate change and the sensitivity of the Hudson River Estuary to nutrient pollution,” R. W. Howarth. Hudson River Foundation Edward A. Ames Seminar. November 4, 2016. New York, NY.

Poster Presentation: Hydrological Impacts of IPCC-Projected Climatic Change on the Hudson River and its Estuary. Swaney, D.P, R.W. Howarth. ASLO 2017 Aquatic Sciences Meeting. 26 Feb–3 Mar, 2017. Honolulu, HI.

Poster Presentation: “Projected impacts of climatic change on seasonal variation of hydrology in the Hudson River.” Swaney, D.P, R.W. Howarth. 24th Biennial Conference of the Coastal and Estuarine Research Federation. 4-8 Nov, 2017. Providence, RI.

- **Downscaled IPCC climate projection datasets**

(for all USGS hydrologic units in the Hudson watershed, daily data, area-weighted average values for each hydrologic unit)

- RCP2.6 (36 files)
  (http://www.eeb.cornell.edu/howarth/web/HudsonDataDwnlds/rcp26temp_and_precip/RCP26.htm)
- RCP4.5 (42 files)
  (http://www.eeb.cornell.edu/howarth/web/HudsonDataDwnlds/rcp45temp_and_precip/RCP45.htm)
- RCP6.0 (13 files)
  (http://www.eeb.cornell.edu/howarth/web/HudsonDataDwnlds/rcp60temp_and_precip/RCP60.htm)
- RCP 8.5 (40 files)
  (http://www.eeb.cornell.edu/howarth/web/HudsonDataDwnlds/rcp85temp_and_precip/RCP85.htm)

- **Publications in preparation**

Swaney, D.P., Howarth, R.W., Hong, B. Estimating projected impacts of climatic change on Hudson River hydrology using regional climate projections and the ReNuMa watershed model.

Acknowledgements

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 1) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Table 1. Modelling groups providing daily output for one or more RCPs. Each of the 20 models for which daily climate projections are run one or more times (which differ according to different initial conditions, etc) for each of the four RCPs analyzed. Parenthetical values indicate number of runs available for each RCP. Source: http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.docx

Modeling Center (or Group)	Institute ID	Model Name	Available RCPs
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0	4.5(1),8.5(1)
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1	All (1)
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2	2.6(5), 4.5(5), 8.5(5)
University of Miami - RSMAS	RSMAS	CCSM4(RSMAS)	
National Center for Atmospheric Research	NCAR	CCSM4	2.6(2), 4.5(2), 6.0(2), 8.5(2)
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC)	4.5(1),8.5(1)
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5	4.5(1),8.5(1)
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence EC-EARTH consortium	CSIRO-QCCCE EC-EARTH	CSIRO-Mk3.6.0	2.6(10), 4.5(10), 8.5(10)
NOAA Geophysical Fluid Dynamics Laboratory NASA Goddard Institute for Space Studies	NOAA GFDL NASA GISS	GFDL-CM3	2.6(1), 6.0(1), 8.5(1)
NOAA Geophysical Fluid Dynamics Laboratory NASA Goddard Institute for Space Studies Institute for Numerical Mathematics Institut Pierre-Simon Laplace	NOAA GFDL NASA GISS INM IPSL	GFDL-ESM2G	all(1)
		GFDL-ESM2M	all(1)
		INM-CM4	4.5(1),8.5(1)
Institute for Numerical Mathematics Institut Pierre-Simon Laplace Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	INM IPSL MIROC	IPSL-CM5A-LR	2.6(3), 4.5(4), 6.0(1), 8.5(4)
		IPSL-CM5A-MR	2.6(1), 4.5(1), 6.0(1), 8.5(1)
		MIROC-ESM	2.6(1), 4.5(1), 6.0(1), 8.5(1)
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC MIROC	MIROC-ESM-CHEM	2.6(1), 4.5(1), 6.0(1), 8.5(1)
		MIROC5	2.6(3), 4.5(3), 6.0(1), 8.5(3)
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-LR	2.6(3), 4.5(3), 8.5(3)
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) Meteorological Research Institute	MPI-M MRI	MPI-ESM-MR	2.6(1), 4.5(3), 8.5(3)
		MRI-CGCM3	2.6(1), 4.5(1), 6.0(1), 8.5(1)
Norwegian Climate Centre	NCC	NorESM1-M	2.6(1), 4.5(1),6.0(1), 8.5(1)

Figures

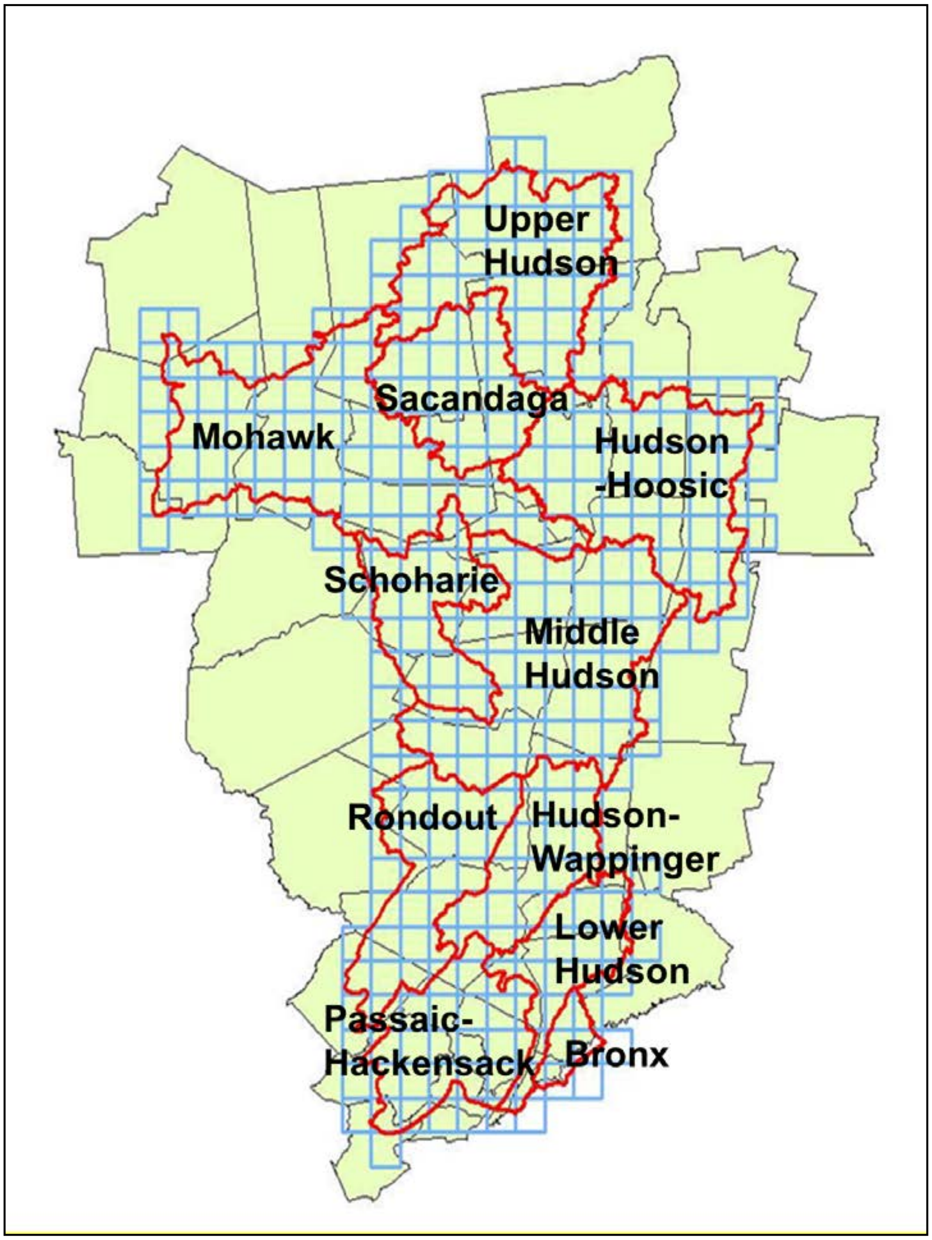

Figure 1. *Hudson/Mohawk basin, including USGS HUC8 hydrologic unit subbasins (red outline) and IPCC climate model grid cells (blue outline). Hudson basin region counties are outlined in black.*

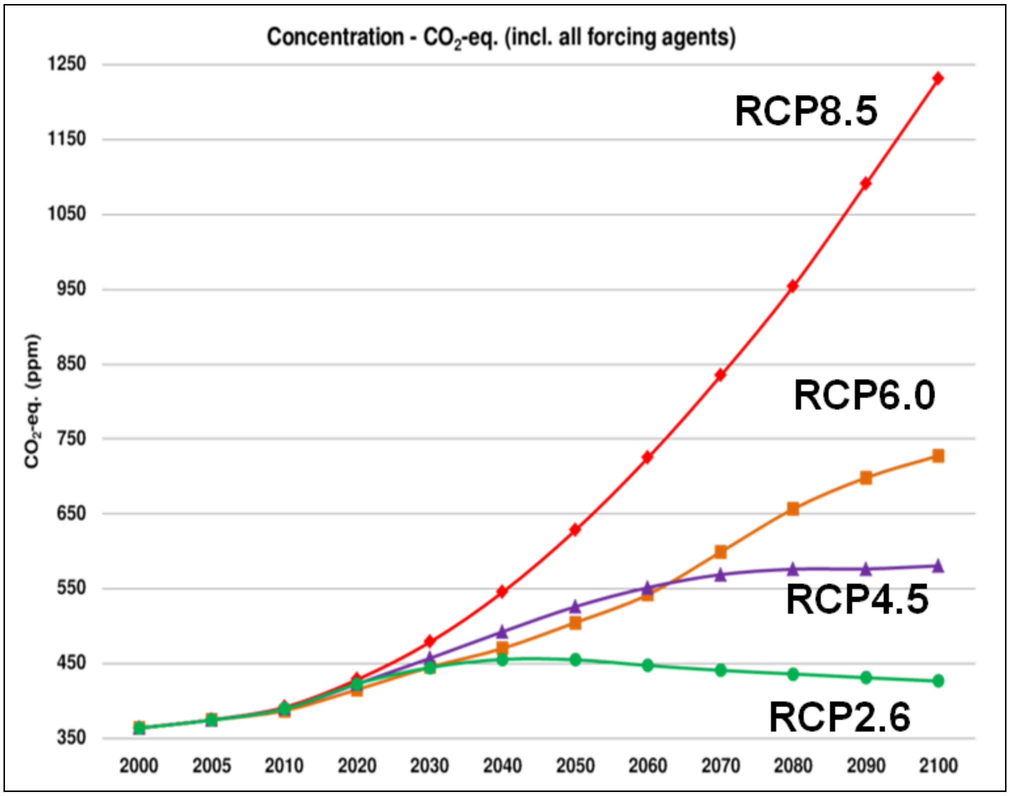

Figure 2*. Representative Concentration Pathways (RCPs) are four greenhouse gas concentration trajectories adopted by the International Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5) in 2014. They are named after their radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively). (https://en.wikipedia.org/wike/Representative_Concentration_Pathways)*

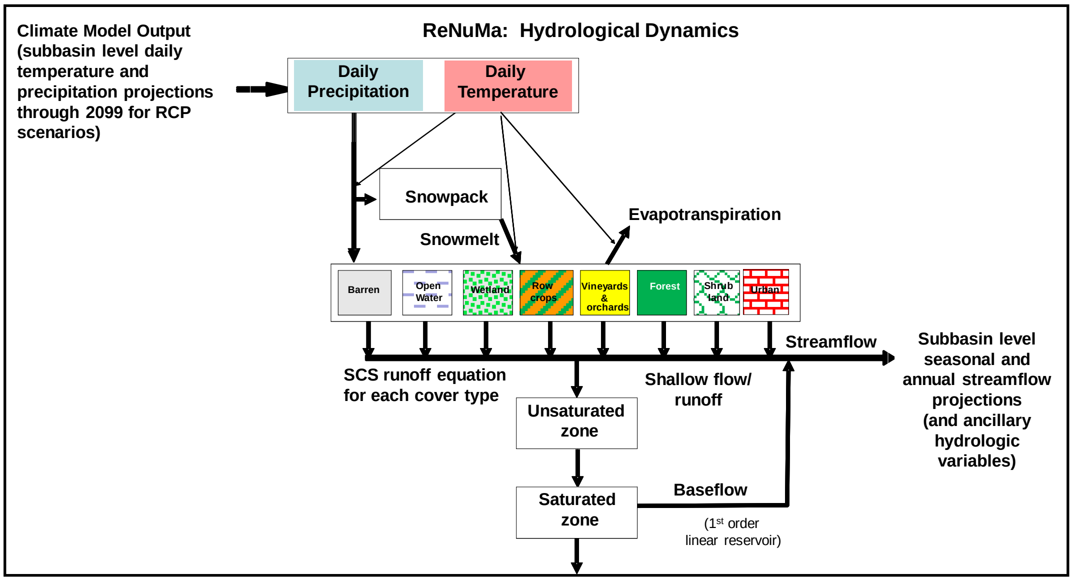

Figure 3. *Information flow through the hydrological component of the ReNuMa modelling platform. The model uses daily precipitation and temperature estimates to drive changes in snowmelt, evapotranspiration, as well as runoff and groundwater contributions to streamflow for each of the hydrologic units comprising the Hudson/Mohawk basin.*

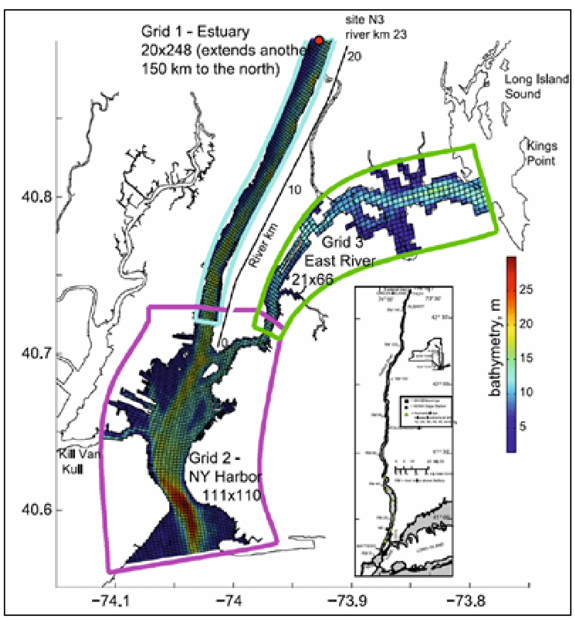

Figure 4. *ROMS model multi-grid used in Warner et al. (2010). A similar grid system is being adopted for this project, focusing on the Hudson above river km 0. (From Warner et al. 2010)*

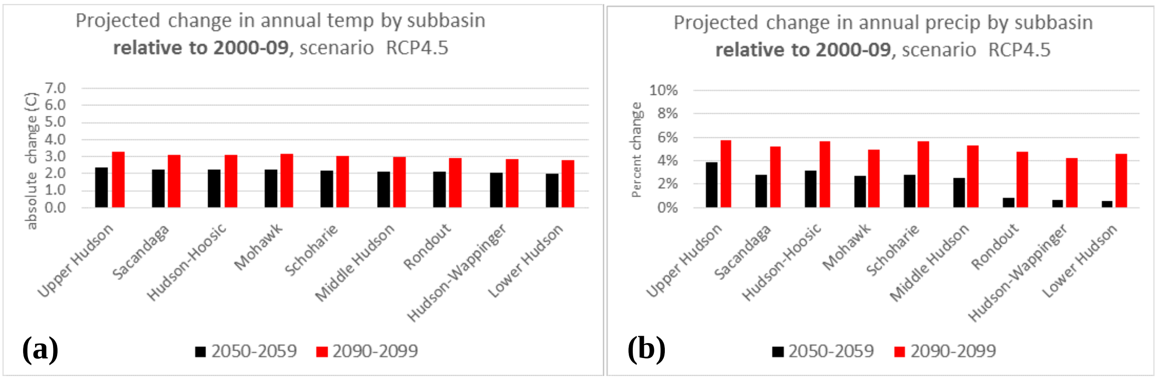

Figure 5. *Projected decadal-mean annual changes in temperature (a) and precipitation (b) for subbasins of the Hudson/Mohawk watershed for the periods 2050-59 and 2090-2099 compared to the first decade of the century, 2000-2009 under RCP4.5 using the CANESM2 model. Temperatures increase 2-3°C; precipitation initially shows a north-south gradient, but eventually a uniform increase of 4-6%.*

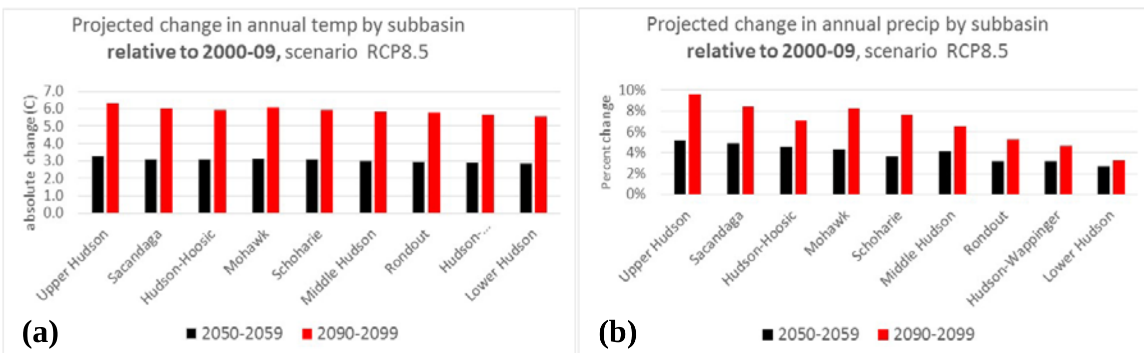

Figure 6. *Corresponding changes in temperature (a) and precipitation (b) for the same periods compared to the first decade of the century, under RCP8.5 using the CANESM2 model. Temperature increases are higher than for RCP4.5 and uniform across the region; Precipitation initially increases uniformly, but shows a latitudinal gradient by end of century.*

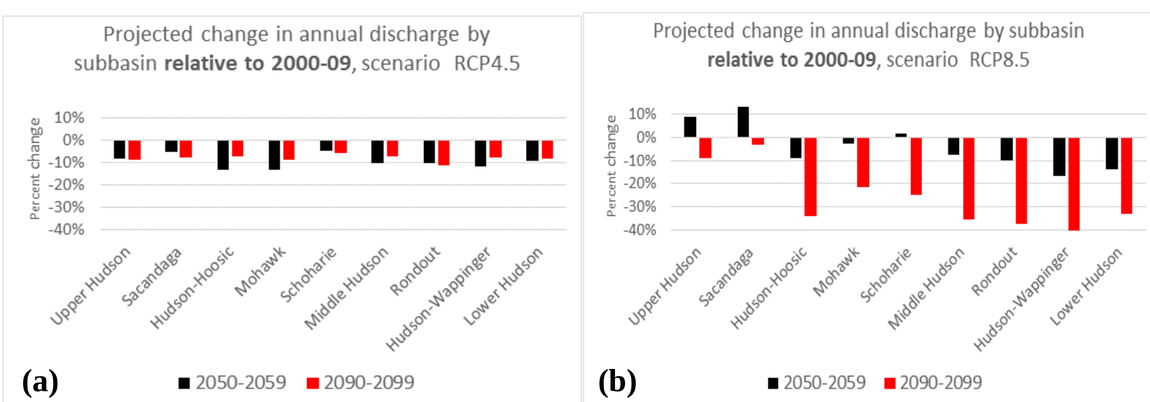

Figure 7. *Corresponding changes in annual discharge for the same periods under a) RCP4.5 and B) RCP8.5 using the CANESM2 model. Under RCP4.5, Increased temperatures cause increased evaporation which outweigh precipitation increases, resulting in an annual decrease of streamflow of ~ 5-10% across the region. Under RCP8.5, streamflow increases in the north, shows modest changes in the north-central, and declines in the southern part of the watershed.*

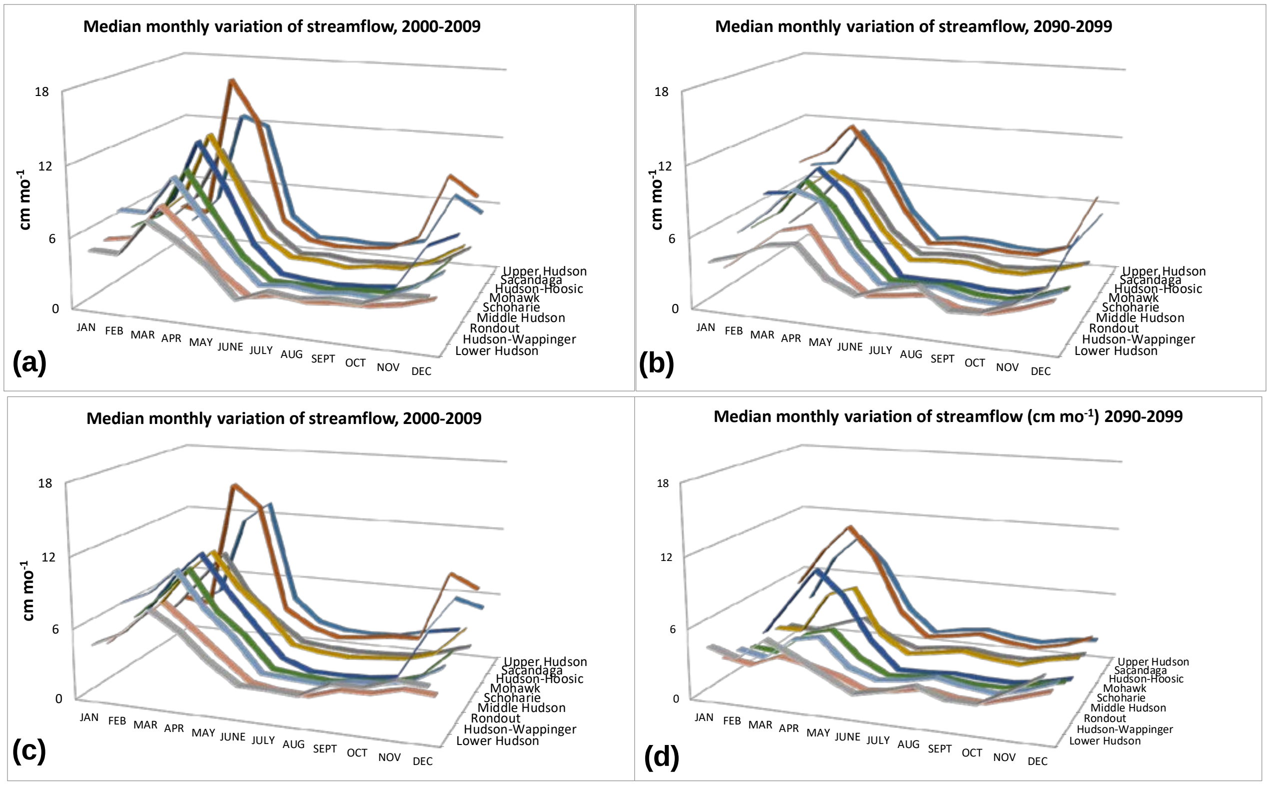

Figure 8. *Projected decadal-median monthly streamflow (median of 5 realizations of the CANESM2 model). Results for RCP4.5 are shown in fig a,b and for RCP8.5 in fig c,d. Estimates for the decade 2000-2009 used climate model projections rather than historical data for consistency between periods. Future winter streamflow shows increases in the north, modest changes in the north-central, and declines in the southern part of the watershed. Future spring and summer flows are reduced across all subbasins, especially for RCP8.5*

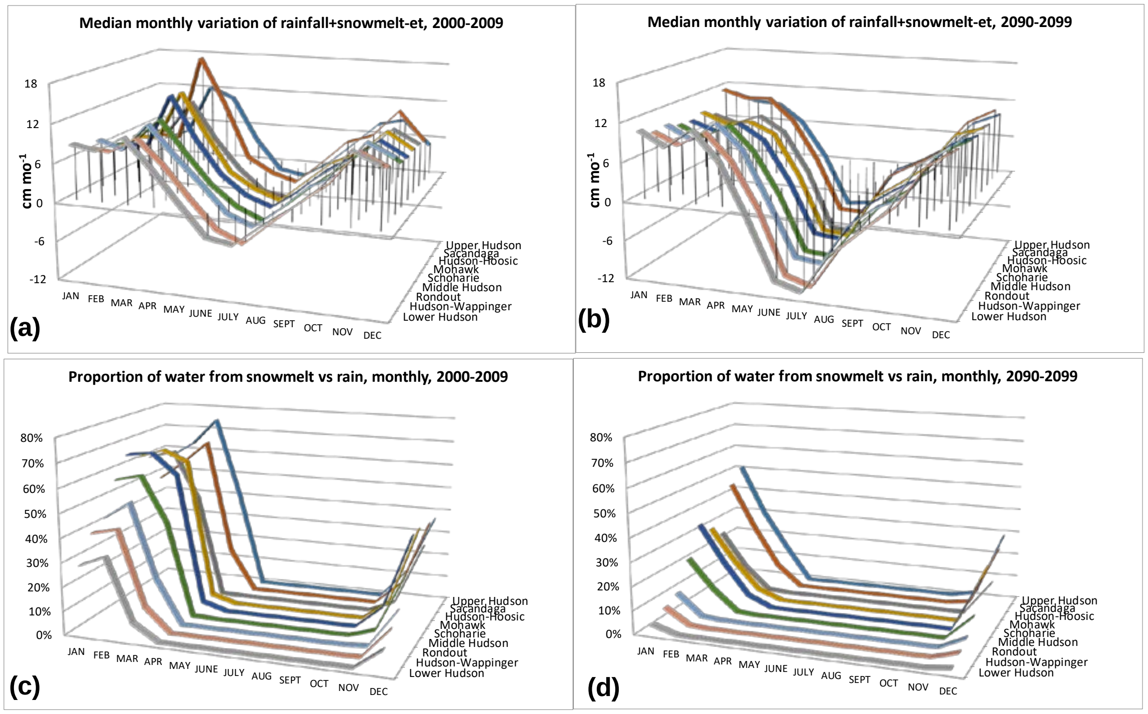

Figure 9. *Response of watershed hydrological components to RCP8.5 climate projections. Projected decadal median rainfall+snowmelt excess above evapotranspiration (a, b), and proportion of water resulting from snowmelt (vs rainfall) (c,d) by month and subbasin as in Fig 8.*

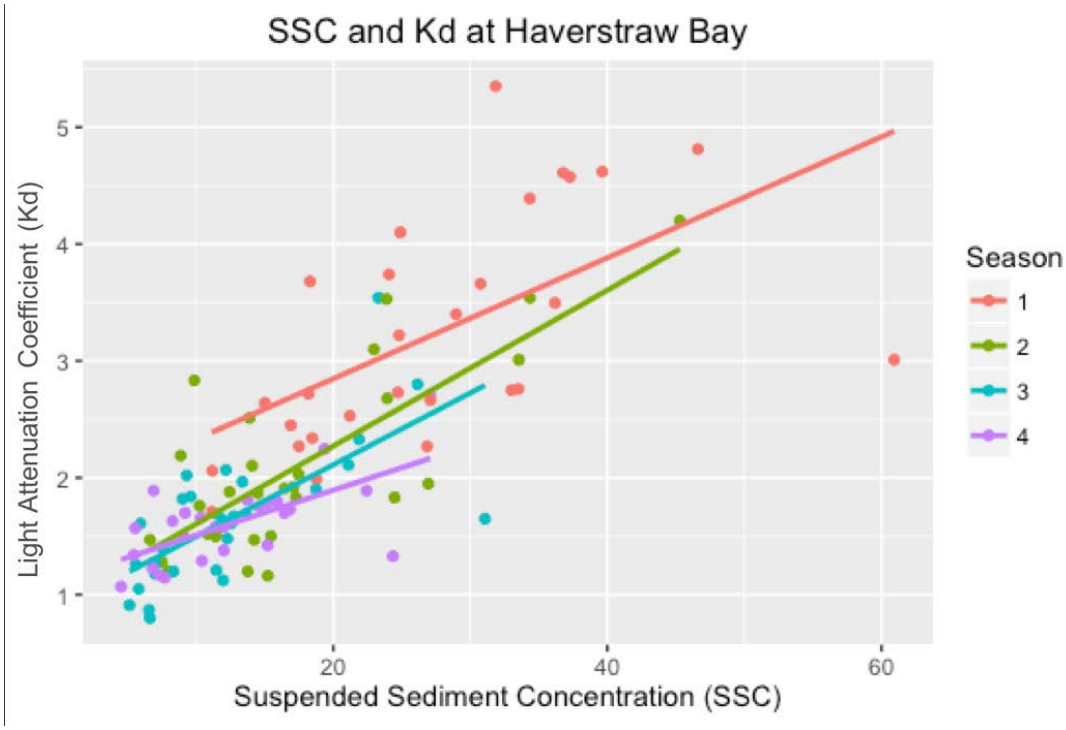

Figure 10. *Empirical relationships between light attenuation and suspended sediments. (Nadell, S. 2018). Data provided by the Cary Institute for Ecosystems Studies.*

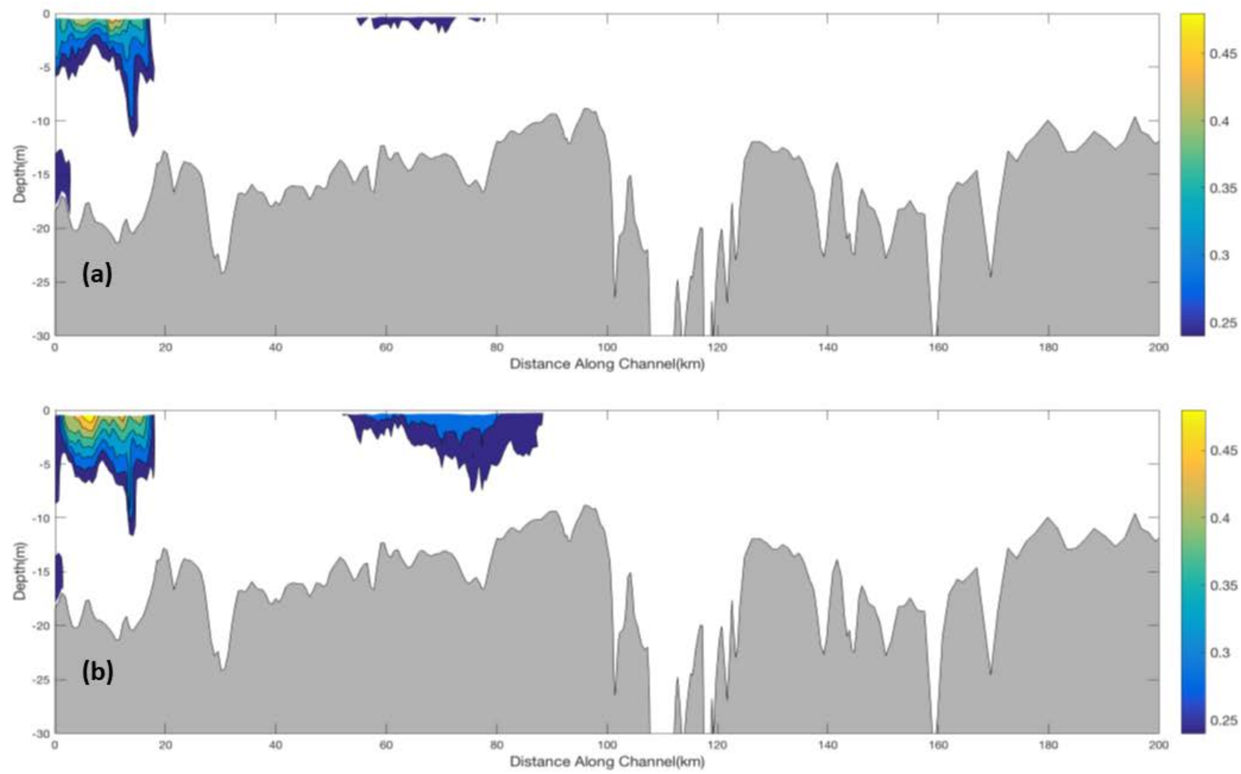

Figure 11. *Cross-sectional chlorophyll-a concentration (mg $m^{-3)}$ along the thalweg of the model domain during a neap tide, from 0 km to 200 km up-river, corresponding to two river discharge conditions: (a) 200 m^3 s^{-1} and (b) 50 m^3 s^{-1}. The flow conditions correspond to (a) typical summer seasonal averages and (b) low-end projections of summer to late summer flow conditions by end of century, using current model estimates. Areas of white do not indicate that there is no chlorophyll present, but where chlorophyll did not exceed the initial chlorophyll concentration. The southern extent of the Hudson River Estuary can be considered to be located at the 42 km marker. The elevated chlorophyll levels seen in panel (b) between km 50 and 90 are located geographically north of Manhattan and south of Haverstraw bay, i.e. Yonkers and Tarrytown. (Nadell, S. 2018).*

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