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Upland Sediment Production and Delivery in the Great Lakes Region Under Climate Change

Great Lakes-based bulk carrier freighter eases into the Poe Lock. January, 2012

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Executive Summary

The U.S. Army Corps of Engineers (USACE) has 139 harbors in the Great Lakes. Many of these harbors sit at the outlets of rivers that convey large amounts of sediment and create periodic dredging requirements. At the outset of this study, it was unknown how climate variability and future climate change might affect sedimentation rates, and therefore future dredging costs. This study examined the St. Joseph River and Maumee River watersheds to estimate the potential effects of climate change on sediment yield and resulting dredging requirements. The St. Joseph River is located in Michigan and Indiana and enters Lake Michigan through Detroit District's St. Joseph Harbor. The Maumee River flows through Indiana, Michigan, and Ohio before entering Lake Erie through Buffalo District's Toledo Harbor. A total of 346 climate change scenarios (112 Coupled Model Intercomparison Project Phase 3 [CMIP3] projections and 234 CMIP5 projections) were run through Soil and Water Assessment Tool (SWAT) sediment yield models of each watershed. A second model, the Landscape Hydrology Model (LHM), was run to look at the impact of model selection. Based on the average results of the SWAT simulations, small increases in dredging costs can be expected for the Maumee River and small decreases are likely on the St. Joseph River, but there is a significant range of variability in the results. In the most extreme cases, the change in dredging costs range from a decrease of more than $500,000 to an increase of $250,000 for the St. Joseph River and a decrease of $450,000 to an increase of $1,000,000 for the Maumee River. Other important findings of this study include identifying potential biases in the downscaled climate data and significant differences between the older CMIP3 scenarios and the newer CMIP5 scenarios. These two findings indicate that analyses performed using the older CMIP3 data may need to be revisited in light of more recent climate models. This study also found very different responses to climate change between the two adjacent watersheds using different modeling schemes. These results suggest that the findings on sediment and dredging should not be extrapolated to other watersheds except in a very general sense (e.g., the results exhibit differences in both magnitude and direction and a great deal of variability). Also, the difference in the results obtained from the two models show that multiple models should be considered to better understand the true range of potential variability.

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1. Background

The Great Lakes and Ohio River Division (LRD) of the U.S. Army Corps of Engineers (USACE) operates and maintains the U.S. portion of the Great Lakes Navigation System (GLNS), which consists of 139 projects (63 commercial and 76 shallow-draft), including 3 lock complexes, 104 miles of navigation structures, and over 600 miles of maintained navigation channels. The GLNS is a complex deepwater navigation system stretching 1,600 miles through all five Great Lakes and connecting channels from Duluth, Minnesota, to Ogdensburg, New York. In 2006, approximately 173 million tons of commodities were transported to and from U.S. ports located on the waterways of the GLNS. It is a non-linear system of interdependent locks, ports, harbors, navigational channels, dredged material disposal facilities, and navigation structures. The GLNS provides an estimated transportation rate savings benefit of $3.6 billion per year. Waterborne commerce is the most environmentally friendly and safest form of transportation of bulk commodities, producing lower emissions as well as lower damages to property and fewer fatal and non-fatal injuries when compared to transportation by truck or rail. A recent study concluded that pollution abatement savings resulting from the continued usage of the GLNS exceed $350 million annually. Many of these harbors sit at the outlets of rivers that convey large amounts of sediment and create periodic dredging requirements. At the outset of this study, it was unknown whether dredging costs might increase or decrease under future climate change.

This study specifically examines the St. Joseph River and Maumee River watersheds (Figure 1) to estimate the potential effects of climate change on dredging requirements. The St. Joseph River watershed covers 4,686 square miles in Michigan and Indiana. The river enters Lake Michigan through the Detroit District's St. Joseph Harbor. The Maumee River drains 6,570 square miles of Indiana, Michigan, and Ohio to Lake Erie through the Buffalo District's Toledo Harbor. These harbors were selected both because of their sizable dredging requirements and the existence of sediment yield models that could potentially be updated with new climate scenarios.

Figure 1: Location map of the St. Joseph River and Maumee River watersheds. The St. Joseph River watershed is to the left in the map and the Maumee is to the right.

Many climate change models predict both increased temperature and increased precipitation in the Great Lakes region (Pryor et al. 2014). The increased precipitation (and runoff), coupled with warmer temperatures, has the potential to significantly affect sediment production and transport in Great Lakes rivers, increasing the loadings to Federal harbors that already have a large dredging backlog. Additionally, a number of future climate scenarios predict lower water levels in the Great Lakes, which would further exacerbate the impacts on harbors. This project looked at two Federal harbors in the Great Lakes and their watersheds to examine potential impacts. The information gained from this work will help the USACE make qualitative comparisons between current and potential future dredging requirements at Federal harbors in the Great Lakes.

2. Purpose and Scope

The goal of this study was to assess how dredging cost requirements at Great Lakes harbors may vary in the future as changes in climate alter precipitation regimes and runoff characteristics. To approach this question, changes in watershed sediment yield and streamflow were modeled.

3. Methodology/Approach

Sediment for the two study areas was estimated using models created with the Soil and Water Assessment Tool (SWAT) (Arnold et al. 2012). SWAT is a lumped parameter hydrology model that was developed by the U.S. Department of Agriculture and is particularly well-suited for agricultural areas. At the start of the project, SWAT models of both the St. Joseph and Maumee Rivers were identified. Unfortunately, further investigation revealed that the existing models were created in older versions of SWAT and could not be easily updated. The existing data was used to create new models instead.

Both models were created using ArcSWAT 2012.10.0.7 and SWAT 2012, Rev. 622. Data used included 30m digital elevation models (DEM) from the National Elevation Dataset, 2006 land use/land cover data from the U.S. Geological Survey (USGS), and Soil Survey Geographic Database (SSURGO) soils data from the Natural Resources Conservation Service (NRCS). Observed precipitation and temperature data for 1950–2010 were obtained from the U.S. Department of Agriculture Agricultural Research Service (ARS) for stations in all counties covered by the study watersheds. This dataset is missing data for January 2002, so the entirety of year 2002 was excluded from all comparisons with the historical simulation. ArcSWAT then determined which gaging station to use for each subwatershed. All model outputs, including calibration and validation, were on a monthly basis. Each model run included a minimum of a 5-year warm-up period to avoid biases resulting from the initial states.

The number of subwatersheds for each SWAT model was kept low to minimize computational time. The St. Joseph River was split into 33 subbasins and 338 Hydrologic Response Units (HRUs). The Maumee River was modeled using 24 subbasins and 307 HRUs.

Since dams can act as sediment sinks and affect the hydrology of a river, significant dams were included in the SWAT models. Five dams were included in the Maumee River model and 17 dams were modeled for the St. Joseph River watershed. Physical data for the dams was primarily obtained from the National Inventory of Dams. All dams were modeled in SWAT as uncontrolled spillways due to a lack of information on operation procedures.

The St. Joseph River SWAT model was calibrated to USGS flow data at Niles, Michigan (Gage 04101500). A sediment rating curve for this gage was obtained from a previous study (USACE 2007) and combined with the monthly flow data to generate monthly sediment data. SWAT parameters used for the hydrologic calibration were baseflow alpha factor (ALPHA_BF); deep aquifer percolation fraction (RCHRG_DP); groundwater delay (GW_DELAY); Soil Conservation Service (SCS) runoff curve number (CN2); and surface runoff lag time (SURLAG). Parameters used for sediment calibration were initial sediment concentration in reservoirs (RES_SED); median particle diameter of reservoir sediment (RES_D50); normal sediment concentration in reservoirs (RES_NSED); and number of days to reach target storage

from current reservoir storage (NDTARGR). Both calibration and validation Nash-Sutcliffe efficiencies for flow, seen in Table 1, are in the range characteristic of "good" or "very good" model fits, according to Moriasi et al. (2007). The percent bias of sediment for both calibration and validation is well within the "very good" range.

The Maumee River model was calibrated to USGS flow gages at both Waterville, Ohio (Gage 04193500), and Defiance, Ohio (Gage 04192500). Monthly sediment data for the USGS gage at Waterville was used to calibrate the sediment portion of the SWAT model. The model was calibrated for hydrology using the GW_DELAY, ALPHA_BF, and CN2 parameters in SWAT. Sediment calibration was accomplished using RES_SED, RES_D50, RES_NSED, and NDTARGR. Summary statistics for the calibration and validation of the model can be found in Table 1. The Nash-Sutcliffe efficiency for flow is "very good" for both the calibration and validation scenarios, as is the percent bias of the sediment delivery.

Table 1: Summary of Calibration and Validation Results for SWAT Models.

			Calibration	Validation
St. Joseph River at Niles, MI	Years		1990–1999	2000–2009
	Flow	R2	0.78	0.83
		N-S	0.78	0.71
	Sediment	R2	0.58	0.42
		N-S	0.51	0.21
		% Bias	4.6%	- 12.2%
Maumee River at Waterville OH	Years		1991–1999	2000–2001
	Flow	R2	0.86	0.87
		N-S	0.79	0.79
	Sediment	R2	0.53	0.55
		N-S	0.53	0.55
		% Bias	-3.8%	-2.5%
Maumee River at Defiance, OH	Flow	R2	0.84	0.85
		N-S	0.79	0.79

Downscaled climate projections developed using the Bias-Correction Spatial Disaggregation (BCSD) method (Reclamation 2013) were obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/). Projections from both the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset and the newer CMIP5 multi-model ensemble datasets were downloaded. These datasets have already been downscaled using BCSD methodology and the gridded temperature and precipitation data for 1950–1999 compiled by Maurer et al. (2002) and are more fully described in Reclamation (2013). The gridded monthly temperature and precipitation data were further downscaled to daily time steps for each of the gages utilized by the SWAT models. This was accomplished by creating MATLAB code to implement the BCSD technique described

in Maurer & Hidalgo (2008). A total of 112 CMIP3 projections and 234 CMIP5 projections, generated by different combinations of global circulation models (GCM) and emissions scenarios, were downscaled.

The downscaled climate data was input to the SWAT models and compared to the model results obtained with the historical temperature and precipitation observations. To gain a more refined understanding of the potential climates, three 20-year sequences were compared: 1989–2008 (historical); 2011–2030 (projected near future); and 2031–2050 (projected far future). Results for each of the future time periods are reported as a percentage change from the historical (1989–2008) simulation for that particular climate run.

The SWAT models produced an estimate of the sediment flowing out of each watershed, in metric tons per month, but not all of this sediment must be dredged. Some sediment moves through the harbor without settling out, and some locations within a harbor are not dredged due to either a lack of interest in maintaining the depths at that location or limited funding. Dredging costs were estimated by developing correlations between the simulations of the historical data and records of recent dredging operations. For St. Joseph Harbor, estimates were developed separately for both the inner and outer harbors. Dredging quantities were also calculated separately for the Maumee River Navigation Channel and Maumee Bay dredging sites and then added together. Dredging data from 1989–2009 was used for St. Joseph Harbor and data from 1990–2009 was used for both the Maumee River and Maumee Bay dredging sites. All costs were adjusted for inflation to 2009 dollars using Consumer Price Index data from the U.S. Bureau of Labor Statistics.

To investigate possible variability based on model selection, sediment yields were also calculated using the Landscape Hydrology Model (LHM). LHM is a fully distributed hydrologic model developed by Michigan State University for integrated surface and groundwater studies at the watershed to regional scale. For this study, the Modified Universal Soil Loss Equation (MUSLE), also used in SWAT, was selected to provide a comparison between similar methods. Since LHM takes much longer to run—approximately 12 days of computing time for a 70-year simulation—it was decided to run only a single scenario. The scenario presented here is an ensemble of the CMIP5 Representative Carbon Pathway (RCP) 6.0 inputs used for the rest of the study.

4. Results

Results from the models run using each of the downscaled climates were initially compared to the model results using the available observed data for the same time period (1988–2001, 2003–2008) to look for potential biases in the GCMs. These results can be seen in Figure 2, where the left-hand box plots are for the St. Joseph River and those on the right are for the Maumee River. Similar graphics for sediment yield (Figure 3) and sediment outflow (Figure 4) are also presented below. The average and standard deviations of the biases are also presented in Table 2 and Table 3. On average, the CMIP3 scenarios underpredict outflow during the historical period, while the CMIP5 scenarios tend to overpredict outflow. The set of CMIP5 scenarios tend to overpredict both sediment yield and delivery in the St. Joseph but underpredict sediment delivery in the Maumee during the historical period. Caution should be used when comparing the standard deviations computed for CMIP3 and CMIP5 because there are roughly twice as many CMIP5 scenarios as CMIP3 scenarios.

To avoid the biases in the climate data, all results in the remainder of this report will be presented as changes relative to the 1989–2008 time period of the respective climate change scenario.

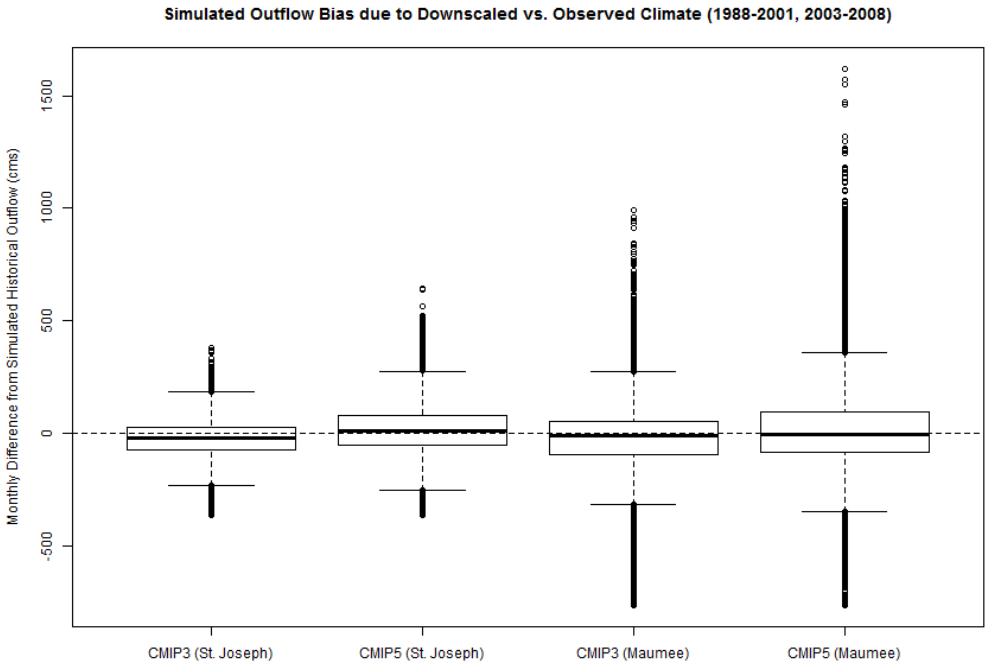

Figure 2: Bias in simulated outflow (climate change scenarios minus gaged precipitation and temperature inputs).

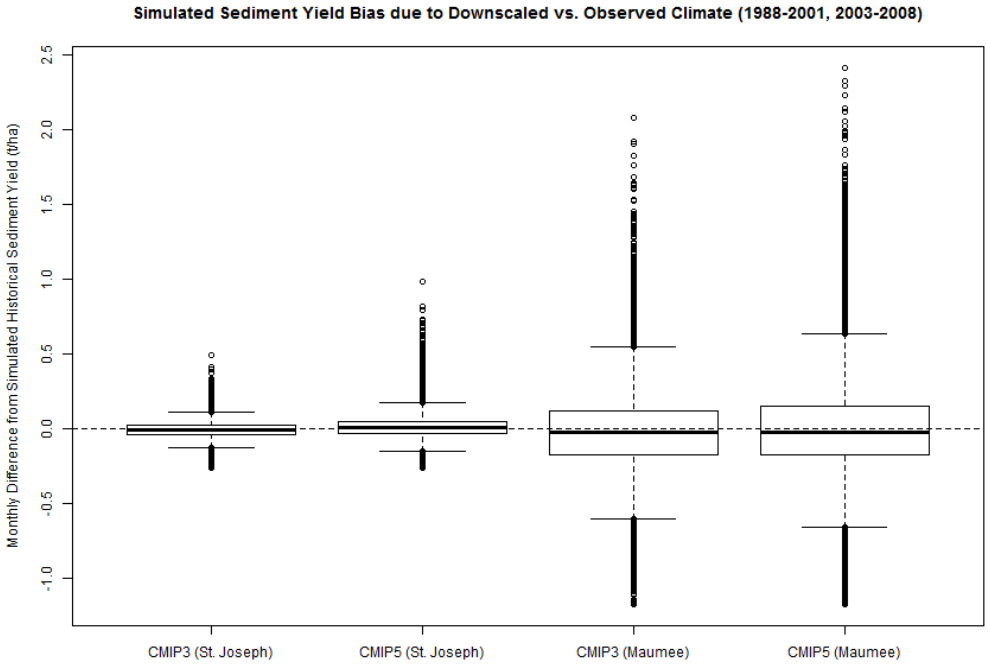

Figure 3: Bias in simulated sediment yield (climate change scenarios minus gaged precipitation and temperature inputs).

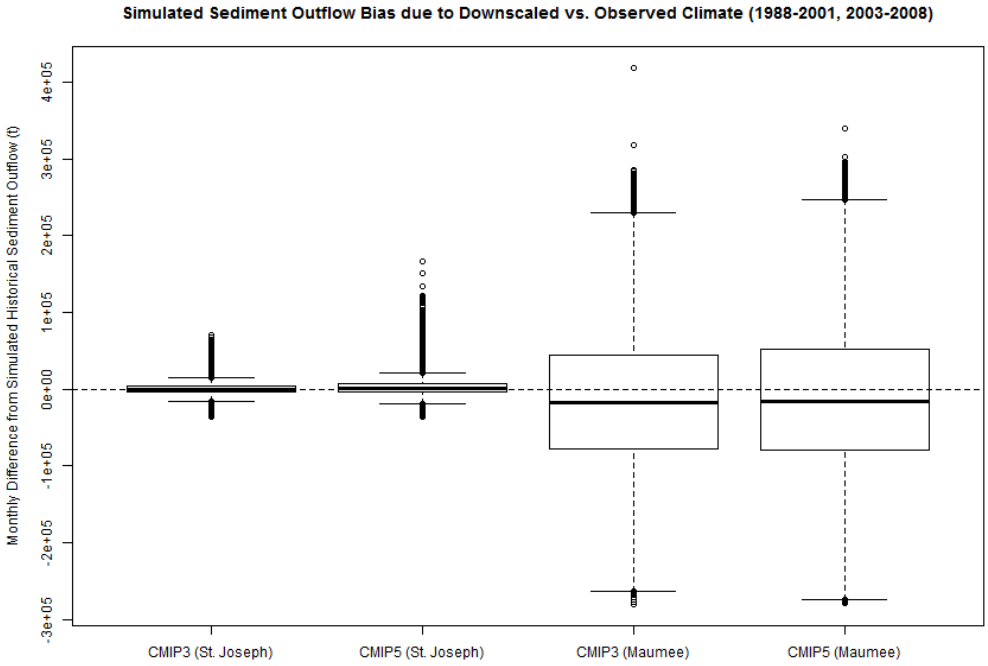

Figure 4: Bias in simulated sediment delivery to harbors (climate change scenarios minus gaged precipitation and temperature inputs).

Table 2: Modeled Climate Scenario Flow Bias for 1989–2008 (Calculated as the Average Difference from the Historical Simulation Divided by the Average of the Historical Simulation).

Flow				
	CMIP3		CMIP5	
	Avg.	St. Dev	Avg.	St. Dev.
St. Joseph	-15.4%	5.6%	+8.6%	8.4%
Maumee	-15.2%	7.0%	+8.0%	9.7%

Table 3: Modeled Climate Scenario Sediment Bias for 1989–2008 (Calculated as the Average Difference from the Historical Simulation Divided by the Average of the Historical Simulation).

	Sediment Yield				Sediment Delivered to Outlet			
	CMIP3		CMIP5		CMIP3		CMIP5	
	Avg.	St. Dev.	Avg.	St. Dev	Avg.	St. Dev.	Avg.	St. Dev.
St. Joseph	-7.3%	7.0%	+29.4%	12.1%	-2.0%	8.9%	38.5%	14.2%
Maumee	-9.8%	6.4%	+0.7%	7.5%	-13.6%	5.5%	-11.2%	5.0%

The distribution of relative flow changes for the near future scenarios (2011–2030 of the climate input data) are shown in Figure 5; the far future (2031–2050) results can be seen in Figure 6. In both figures, the histogram on the left is the St. Joseph River and the one on the right is the Maumee River. The boxplots show the difference in monthly values from the historical simulation period, aggregated by model category (CMIP3 vs. CMIP5) and watershed. Summary statistics are presented in Table 4. Generally, the median of the CMIP3 scenarios shows small increases in average flow for both basins. The median of the CMIP5 scenarios has flows very similar to current conditions, except for the far future simulations of the Maumee, which show small increases. For both CMIP3 and CMIP5 models, there is significant spread in modeled flows around the ensemble means.

Table 4: Modeled Flows Relative to 1989–2008.

			St. Joseph		Maumee	
		Years	2011–2030	2031–2050	2011–2030	2031–2050
Flow	CMIP3	Min.	-24.0%	-23.1%	-28.3%	-24.1%
		Avg.	+4.0%	+3.3%	+6.0%	+8.0%
		Max.	+28.7%	+37.3%	+44.4%	+53.7%
	CMIP5	Min.	-18.2%	-33.0%	-23.9%	-24.3%
		Avg.	+0.6%	+0.1%	+1.1%	+4.8%
		Max.	+41.5%	+28.7%	+46.9%	+57.6%

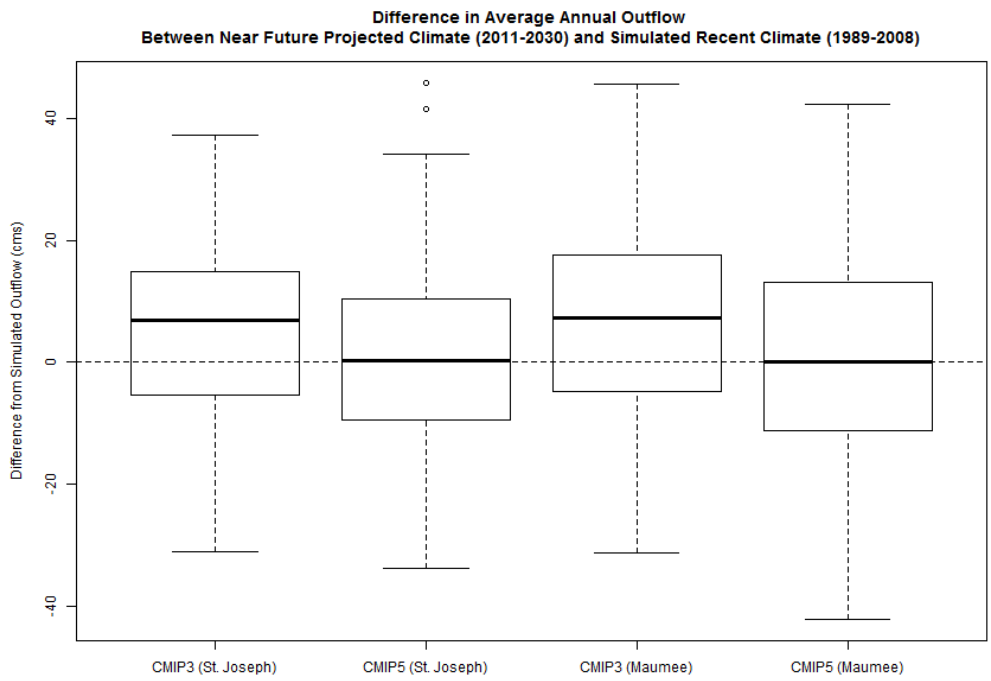

Figure 5: Modeled change in flow between present (1989–2008) and near future (2011–2030).

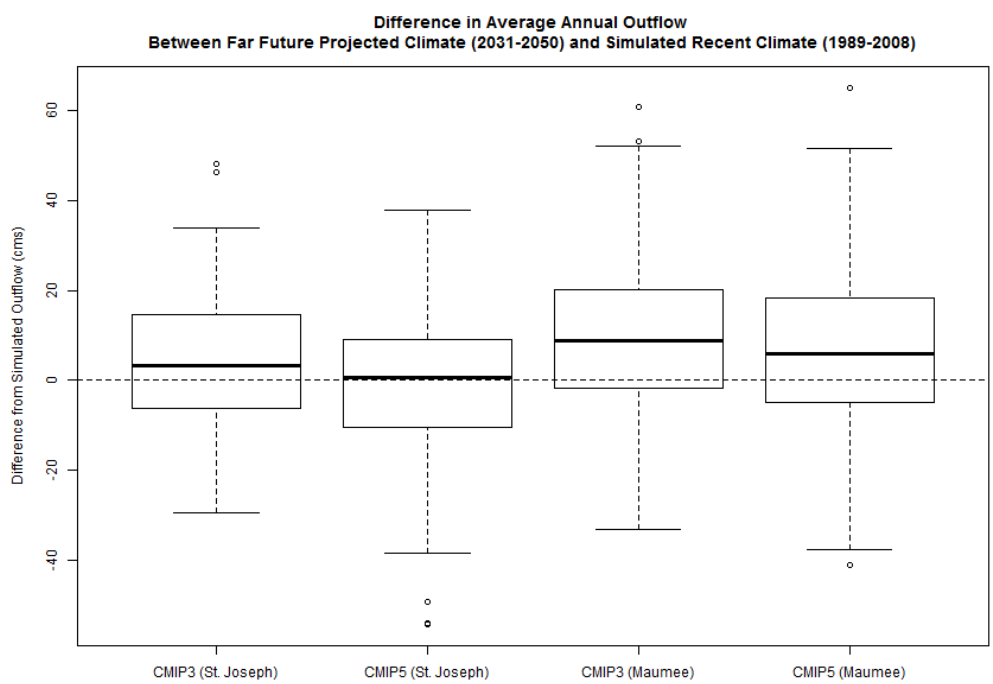

Figure 6: Modeled change in flow between present (1989–2008) and far future (2031–2050).

Modeled changes in 20-year sediment yield for the near future climate scenarios are shown in Figure 7. Figure 8 shows the far future change in 20-year sediment yields. These graphics, along with the summary statistics in Table 5: Modeled Sediment Yield Results Relative to 1989–2008, show that the difference in the effects of the CMIP3 and CMIP5 input data on sediment yield are significant. The CMIP3 scenarios produce an increase in sediment yield that increases over time. The CMIP5 scenarios for the St. Joseph River watershed, however, result in a decreased sediment yield. In the near term, the CMIP5 scenarios result in very little change to sediment yield in the Maumee but a small increase for the later time period.

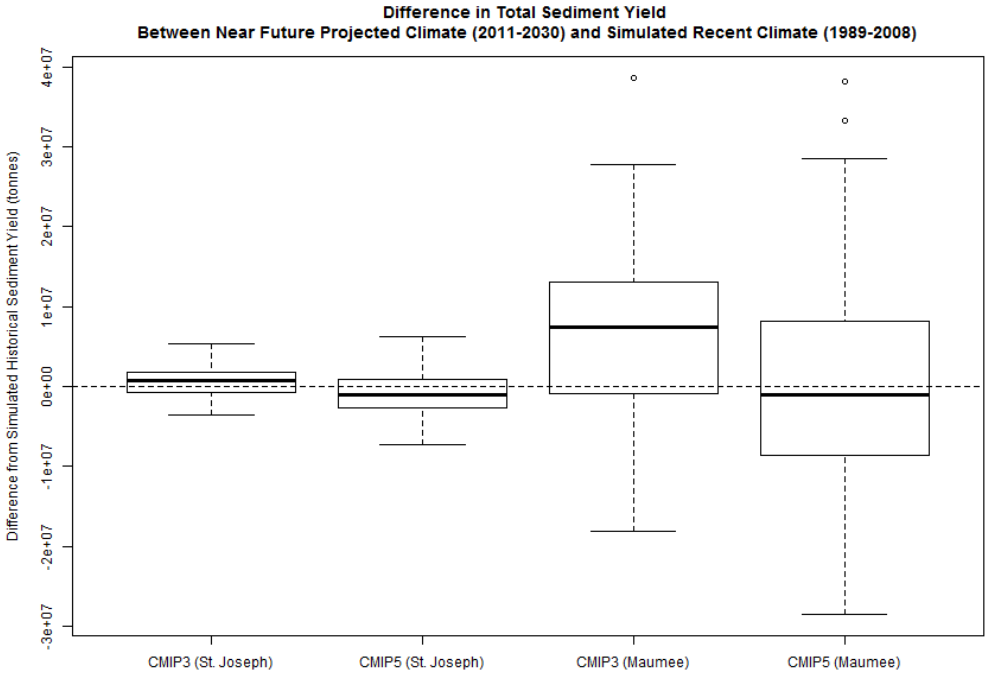

Figure 7: Modeled change in 20-year sediment yield between present (1989–2008) and near future (2011–2030).

Table 5: Modeled Sediment Yield Results Relative to 1989–2008.

			St. Joseph		Maumee	
		Years	2011–2030	2031–2050	2011–2030	2031–2050
Sediment Yield	CMIP3	Min.	-22.1%	-23.1%	-19.4%	-14.7%
		Avg.	+4.4%	+9.0%	+6.9%	+15.4%
		Max.	+38.8%	+41.5%	+44.5%	+57.4%
	CMIP5	Min.	-27.5%	-38.7%	-22.8%	-24.6%
		Avg.	-3.3%	-5.4%	+0.3%	+2.8%
		Max.	+48.7%	+43.2%	+49.1%	+82.9%

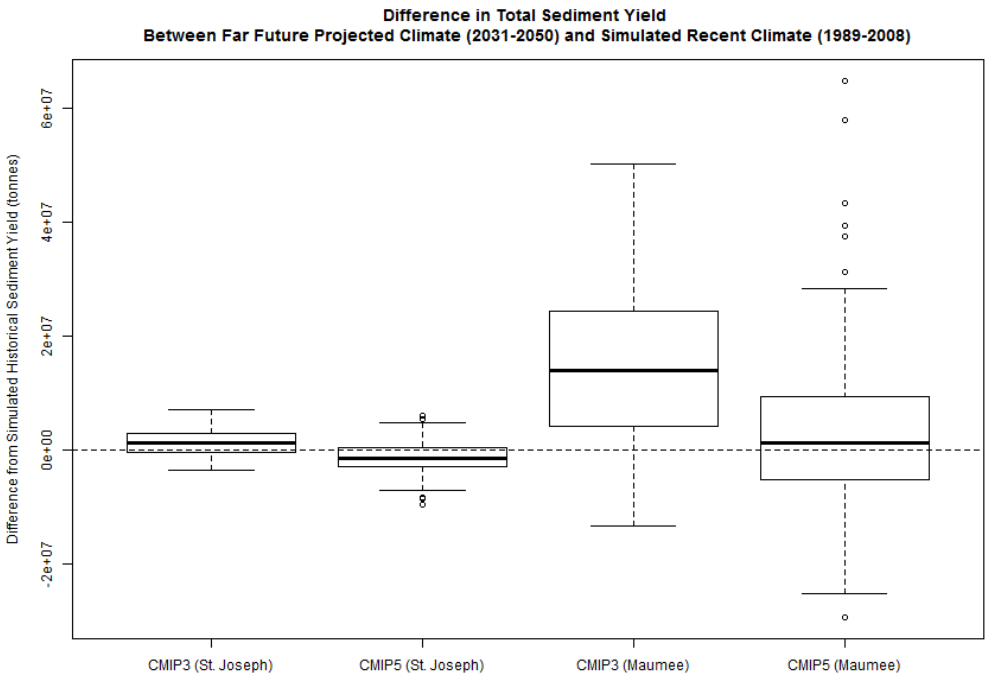

Figure 8: Modeled change in 20-year sediment yield between present (1989–2008) and far future (2031–2050).

The sediment delivered to the harbor at the watershed outlet drives dredging needs. Figure 9 and Figure 10 show boxplots of the average sediment volume delivered to the watershed outlet, while Table 6 summarizes these same results. Similar to the sediment yield results, the CMIP3 scenarios indicate small increases in the amount of sediment arriving at the harbor, which grow in the far time period. The CMIP5 scenarios, however, project a decreasing trend for the St. Joseph River. Toledo Harbor, at the outlet of the Maumee, could see very similar amounts of sediment coming from upstream in the near term but increasing amounts later in time, according to the CMIP5 scenarios.

Table 6: Modeled Sediment Delivery to the Watershed Outlet Relative to 1989–2008.

			St. Joseph		Maumee	
		Years	2011–2030	2031–2050	2011–2030	2031–2050
Sediment Delivered to Outlet	CMIP3	Min.	-24.8%	-23.9%	-24.3%	-16.7%
		Avg.	+8.5%	+14.2%	+1.5%	+6.0%
		Max.	+50.1%	+54.3%	+23.7%	+36.2%
	CMIP5	Min.	-29.0%	-44.0%	-17.9%	-18.0%
		Avg.	-3.4%	-6.1%	+0.3%	+4.9%
		Max.	+58.2%	+41.3%	+26.6%	+37.0%

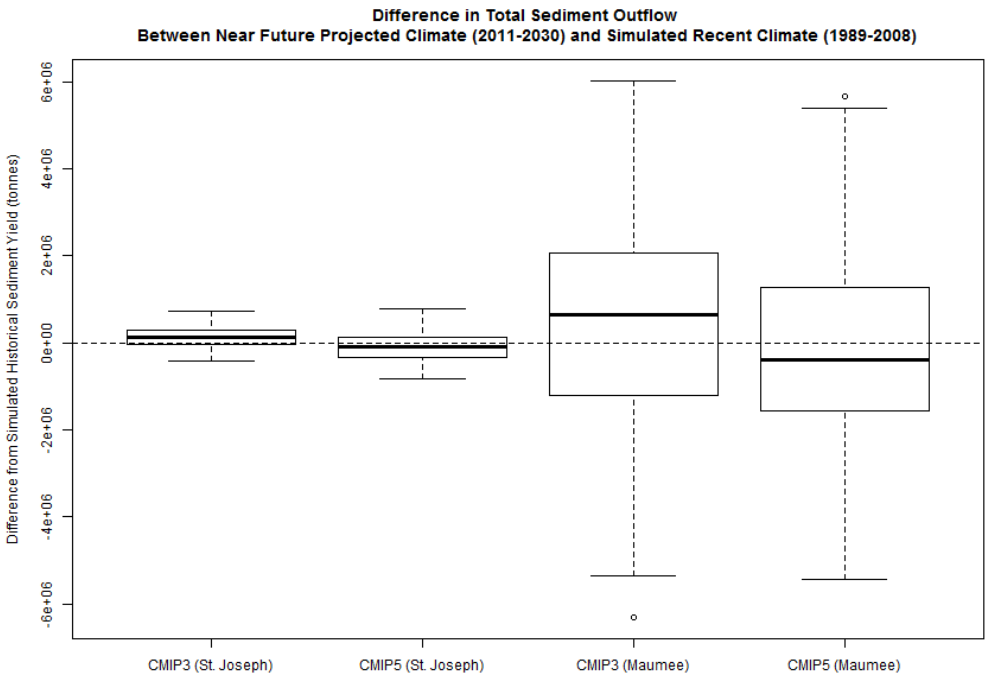

Figure 9: Modeled change in sediment delivery to the harbors between present (1989–2008) and near future (2011–2030).

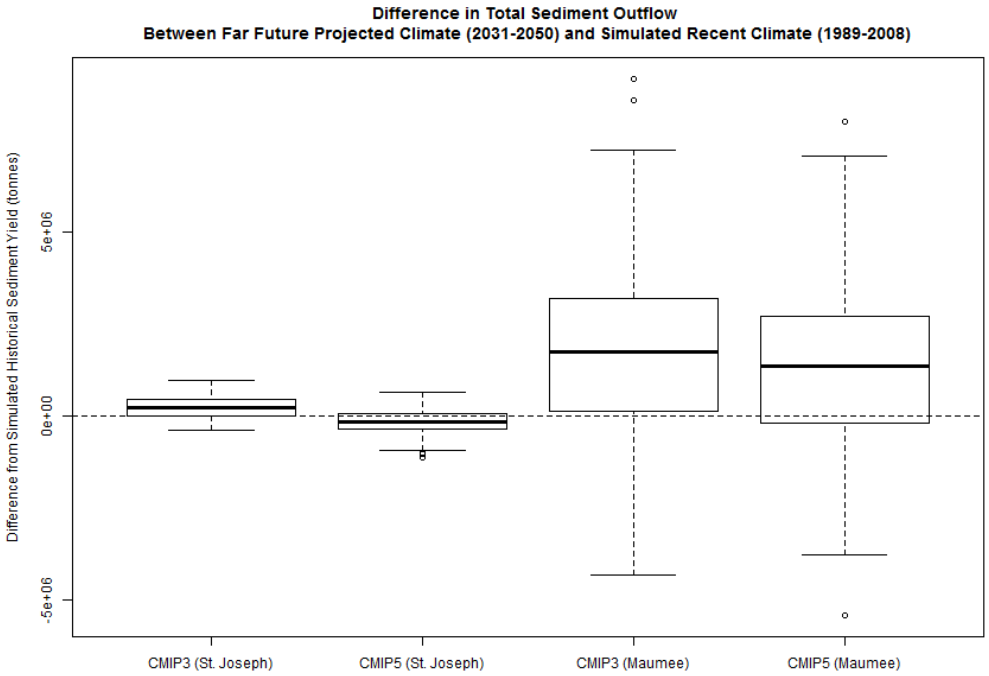

Figure 10: Modeled change in sediment delivery to the harbors between present (1989–2008) and far future (2031–2050).

The best fit linear regression for dredging costs at the St. Joseph inner and outer harbor dredging sites was a relationship to the moving average of sediment outflow for the last 2 water years (i.e., dredging costs for 2008 were most strongly correlated to sediment outflow in water years 2007 and 2008 [October 2006 to September 2007 and October 2007 to September 2008, respectively]). This relationship, shown in Equation 1, had an r^2 of 0.478.

Equation 1

$$Dredging\ Cost_{SJ} = -\$693{,}700 + \$14.30 * (Sediment\ Out_{WY} + Sediment\ Out_{WY-1})/2$$

Dredging costs for the Maumee were estimated separately for the Maumee River and Maumee Bay dredging sites and then added together. Dredging data for the Maumee Bay site correlated best with the previous calendar year's sediment outflow (r^2=0.301) and is shown as Equation 2. Dredging costs for the Maumee River site showed very poor correlation to all model outputs. The best correlation was with the sediment deposited in the downstream reach for the current water year (Equation 3), but this only had an r^2 of 0.147. Comparisons to the historical period of the climate change scenarios showed that these estimates all underpredicted the actual dredging quantities by $303,525 to $496,632 per year, relative to an actual annual average dredging cost of $2,718,783.

Equation 2

$$Dredging\ Cost_{MB} = -\$859{,}800 + \$1.26 * Sediment\ Out_{CY-1}$$

Equation 3

$$Dredging\ Cost_{MR} = \$3{,}159{,}000 - \$16.88 * Sediment\ Deposition_{WY}$$

In addition to incoming sediment, a number factors affect dredging of navigation channels. These include longshore transport of sediment, lake levels, navigational considerations, and funding availability. Due to the uncertainties associated with these factors and the relatively weak correlations between model outputs and dredging costs, Table 7 lists both the costs estimated from the developed relationships and those estimated based on a conservative estimate that assumes a one-to-one relationship between dredging costs and sediment outflow. Generally, the CMIP5 scenarios produce slight decreases in future dredging at St. Joseph, Michigan, but slight increases at Toledo, Ohio. The range of these estimates is significant, however, on the order of +/- $500,000 at St. Joseph and -$500,000 to +$1,000,000 at Toledo.

Table 7: Forecasted Change in Average Annual USACE Dredging Costs at St. Joseph, Michigan, Relative to 1989–2008.

St. Joseph						
			Regression (Equation 1)		1:1 Sediment Outflow (Based on 1989–2009)	
		Years	2011–2030	2031–2050	2011–2030	2031–2050
Forecast Change in Dredging Costs	CMIP3	Min.	-$320,591	-$247,983	-$128,317	-$123,660
		Avg.	+$86,474	+$146,319	+$43,980	+$73,473
		Max.	+$539,924	+$666,665	+$259,221	+$280,952
	CMIP5	Min.	-$581,792	-$815,794	-$150,048	-$227,659
		Avg.	-$64,892	-$131,701	-$17,592	-$31,562
		Max..	+$466,208	+$438,786	+$301,131	+213,689

Table 8: Forecasted Change in Average Annual USACE Dredging Costs at Toledo, Ohio, Relative to 1989–2008.

Maumee						
			Regression (Equation 2 + Equation 3)		1:1 Sediment Outflow (Based on 1990–2009)	
		Years	2011–2030	2031–2050	2011–2030	2031–2050
Forecast Change in Dredging Costs	CMIP3	Min.	-$84,047	-$52,972	-$660,664	-$454,037
		Avg.	+$11,812	+$29,179	+$40,782	+$163,127
		Max.	+$110,842	+$147,319	+$644,351	+$984,199
	CMIP5	Min.	-$91,587	-$64,317	-$486,662	-$489,381
		Avg.	+$12,235	+$23,127	+$8,156	+$133,220
		Max.	+$108,554	+$129,019	+$723,196	+$1,005,950

The effect of model choice can be seen in Figure 11, where the results from SWAT are compared to those from LHM. The results are not only different between the two models; the differences appear to vary spatially. There are a number of potential reasons for these differences, including the spatial resolution (lumped HRUs and subwatersheds vs. independent grid cells), the temporal resolution (daily vs. hourly computational time steps), and the physical processes used in the models (SCS curve numbers vs. excess precipitation calculation), in addition to geological differences between the watersheds.

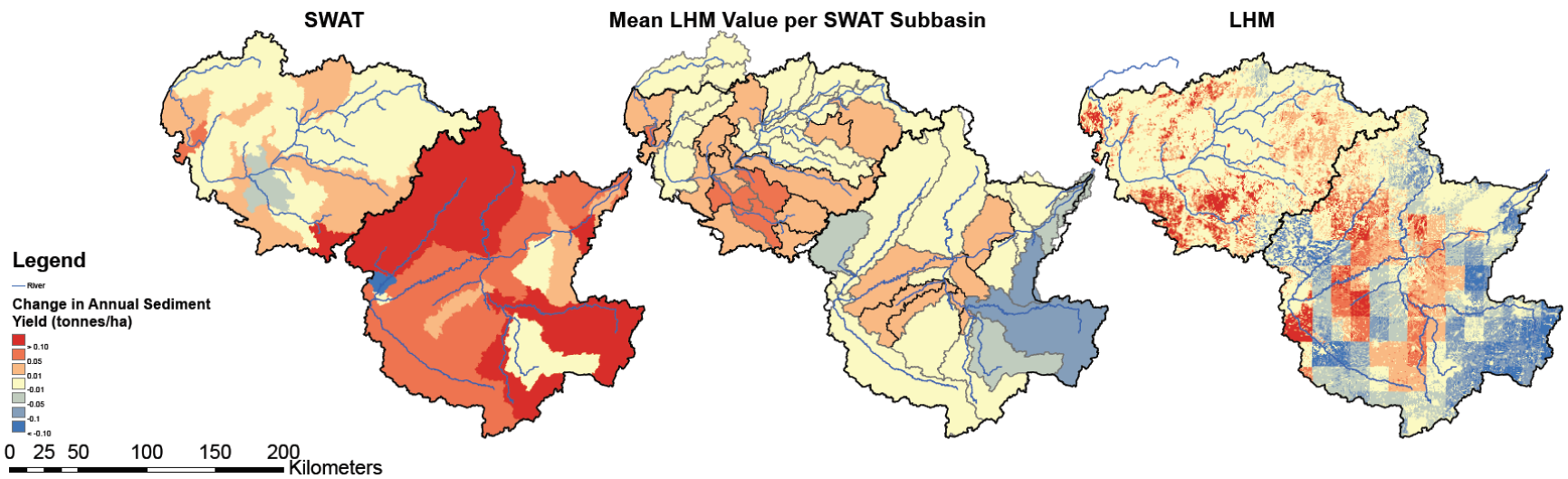

Figure 11: Comparison of spatial results for the CMIP5 RCP 6.0 ensemble run, displayed as the change in annual sediment yield (tonnes/ha) from the historical to the near future time period. The graphics show, from left to right, the SWAT output, the LHM outputs aggregated to the same subwatersheds as SWAT, and the spatially distributed LHM output. Note that the large rectangular blocks visible in the LHM output are an artifact of the North American Land Data Assimilation (NLDAS) grid used for downscaling of the input temperature and precipitation data.

This study did not address a number of additional ways that climate change may impact dredging requirements for Great Lakes harbors. The largest potential impact is a sustained or permanent change in Great Lakes water levels. A significant decrease in water levels not only would increase dredging requirements to maintain commercial navigation but also could cause headcuts to propagate upstream through river systems, releasing additional sediment. An increase in water levels could change the locations of deposition, with uncertain impacts on dredging. This study also did not examine potential changes to farming practices or land use patterns that may be driven by climate change, which in turn might affect the rate at which sediment is contributed to streams.

5. Lessons Learned

- Both CMIP3 and CMIP5 data may produce simulation results that are biased relative to the current climate for a given area.
- Despite examining adjacent watersheds of similar size, the modeling results differed between the St. Joseph and Maumee. This indicates that great caution should be exercised when extrapolating climate change results to other areas, even from nearby watersheds.
- There are large differences between the results based on the CMIP3 scenarios and those based on the newer CMIP5 scenarios, even when the climate model biases are accounted for by looking at relative changes. This implies that conclusions from earlier studies performed using CMIP3 should be revisited using the more recent data.
- Different models may result in qualitatively different outcomes, suggesting that multiple models should be considered to capture the range of plausible future conditions.

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Table 9: CMIP5 Modeling Centers and Associated Model Used in This Study.

Modeling Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0 ACCESS1.3
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2 CanCM4 CanAM4
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5) CESM1(CAM5.1,FV2) CESM1(FASTCHEM) CESM1(WACCM)
Center for Ocean-Land-Atmosphere Studies and National Centers for Environmental Prediction	COLA and NCEP	CFSv2-2011
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CESM CMCC-CM CMCC-CMS
Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5 CNRM-CM5-2
Commonwealth Scientific and Industrial Research Organization in Collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
EC-EARTH Consortium	EC-EARTH	EC-EARTH
LASG, Institute of Atmospheric Physics, Chinese Academy of	LASG-CESS	FGOALS-g2

Modeling Center (or Group)	Institute ID	Model Name
Sciences and CESS,Tsinghua University		
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP	FGOALS-gl FGOALS-s2
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM
NASA Global Modeling and Assimilation Office	NASA GMAO	GEOS-5
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM2.1 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GFDL-HIRAM-C180 GFDL-HIRAM-C360
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadCM3 HadGEM2-CC HadGEM2-ES HadGEM2-A
Institute for Numerical Mathematics	INM	INM-CM4
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC4h MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR MPI-ESM-LR MPI-ESM-P
Meteorological Research Institute	MRI	MRI-AGCM3.2H MRI-AGCM3.2S MRI-CGCM3 MRI-ESM1
Nonhydrostatic Icosahedral Atmospheric Model Group	NICAM	NICAM.09
Norwegian Climate Centre	NCC	NorESM1-M NorESM1-ME