Hydrological modelling of climate change impacts on river
flows in Siberia’s Lena River Basin and implications for the
Atlantic Meridional Overturning Circulation
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ABSTRACT

A hydrological model of Siberia’s Lena River Basin is calibrated and validated against observed river
discharge at five stations. Implications of the Representative Concentration Pathway 4.5 scenario for
river discharge are assessed using projections from 41 Coupled Model Intercomparison Project Phase
5 General Circulation Models grouped into 12 genealogical-based groups as well as a group ensemble
mean. Annual precipitation increases in all scenarios (1.7–47.4%). Increases in annual PET are of a
similar range (6.0–45.5%). PET peaks in June compared to July for the baseline. All temperature
changes exceed 1.5°C (range: 2.2°C–6.2°C). The largest absolute increases are in winter (maximum
+7°C). Changes in mean annual discharge range from +8.5 to +69.9%. Ten GCM groups and the group
ensemble mean project increases. Earlier snowmelt is dominant so the annual
flood peaks in May
compared with June for the baseline. Increased discharge of the Lena and other Eurasian rivers to the
Arctic Ocean has the potential to impact Atlantic Meridional Overturning Circulation (AMOC).
Enhanced fluxes for four groups are capable of weakening the AMOC. Changes for other groups may
contribute to weakening when combined with other sources of freshwater and warmer temperatures.

Key words | Atlantic Meridional Overturning Circulation (AMOC), climate change, Coupled Model
Intercomparison Project Phase 5 (CMIP5), Lena, RCP4.5

INTRODUCTION

Climate change will intensify the global hydrological cycle. Modified precipitation patterns coupled with changes in
temperature and evapotranspiration will have important implications for river discharge (Vihma et al. 2016). The
most severe hydrometeorological impacts of rising temperatures are being observed in, and are projected for, the
Arctic, with mean annual air temperatures between 2001
and 2012 being 1.5°C warmer than during 1971–2000
(Overland et al. 2013). Precipitation is increasing and is pro-
tected to be >50% higher by 2100. Winter warming is
projected to be four times greater than summer warming,
modifying snowmelt, evapotranspiration and ultimately
river discharge (Ye et al. 2004).

Reported increases in Arctic river flows have raised con-
cerns about the integrity of Atlantic Meridional Overturning
Circulation (AMOC; Shu et al. 2017). AMOC comprises
northward flows of warm saline water, the formation of
North Atlantic Deep Water (NADW) through sinking due
to buoyancy loss and southward return flows of cold deep-
water (Buckley & Marshall 2016). Palaeoclimate proxy
records (e.g. Broecker et al. 1985; Clark et al. 2002) suggest
that the AMOC has collapsed in the past pointing to the
potential for it having stable ‘on’ and ‘off’ states. Simulations
from simple numerical models (e.g. Manabe & Stouffer 1988;
Hawkins et al. 2011) support the presence of this bi-stable be-


doi: 10.2166/nh.2019.151
of saltwater further reducing water density and, therefore, convection. However, studies using coupled general circulation models (GCMs) to assess AMOC alterations have not identified this instability, and the most recent consensus of the Intergovernmental Panel on Climate Change is that AMOC slowdown is more likely than complete collapse during the 21st century (Kirtman et al. 2013).

The implications of a weakening or collapse of AMOC would be widespread due to global-scale teleconnections (Vellinga & Wood 2008). Climatic implications may include North Atlantic cooling, an equatorward shift of the Inter-Tropical Convergence Zone and weakened monsoons (Buckley & Marshall 2016). AMOC collapse may also increase water resources stress in Europe and southern Asia due to altered precipitation patterns (Gosling 2013). Additionally, reductions in the extent of boreal and temperate forests are projected, with implications for carbon storage in these latitudes (Köhler et al. 2005). Fisheries and crop yields could be negatively impacted due to changes in ocean circulation with the potential for major societal implications (Keller et al. 2000; Kuhlbrodt et al. 2009). Given the significance of changes in AMOC, this study investigates the potential impacts of climate change upon river flows within Siberia’s Lena River Basin, a major contributor of freshwater to the Arctic. Results are scaled up to assess the potential implications for the AMOC of changes in Eurasian runoff to the Arctic Ocean.

**STUDY AREA: THE LENA RIVER BASIN**

The Lena River (Figure 1), which enters the Arctic Ocean via the Laptev Sea, is located in northern Asia and...
originates in the Baikal mountains (maximum altitude: 1,640 m). It is the eleventh longest river in the world (4,400 km) with the ninth largest basin (32,000 km²) (Gelfan et al. 2017). As the second largest Eurasian river in terms of discharge, following the Yenisei and preceding the Ob, the Lena provides around 15% of the total mean annual runoff to the Arctic Ocean (mean annual discharge: 524 km³; Shiklomanov et al. 2000; Ye et al. 2004) although it varies from year to year.

The Lena Basin lies in a zone of continental moderate and sub-arctic climate (Liu & Yang 2011). Precipitation is highest during April–October (total precipitation at Yakutsk = 152 mm), peaking in July and subsequently decreasing during November–March (total precipitation at Yakutsk = 78 mm). Mean annual precipitation (based on CRU TS4.01) varies from 402 mm over the Tabaga sub-catchment to 280 mm over Stolb. This downstream decline is repeated for temperature with the mean annual temperature (CRU TS4.01) decreasing from –4°C over Tabaga to –17°C over Stolb. Temperature and evapotranspiration peak in July, after which snow accumulation commences, reaching a maximum extent in November, before snowmelt begins in March (Ye et al. 2003).

The lowest and highest river flows occur during winter and summer, respectively. Snowmelt during May causes rapid increases in discharge, which on average peaks in June (Gelfan et al. 2017). Permafrost underlays 95% of the basin and directs precipitation and snowmelt to rivers. It contributes to low sub-surface storage capacity, causing large differences between winter and summer flows (Ye et al. 2004). The Lena Basin has three main tributaries, the Aldan, Upper Lena and Vilui (Figure 1). The Aldan experiences peak flows that are approximately 60 times the lowest flows in April. Relatively higher high- and low-flows are experienced in the Upper Lena so that the ratio of the highest to lowest flows is 26 (Ye et al. 2003). The Vilui contributes a relatively small amount to annual runoff (9% of discharge). The reservoir on this tributary (completed in 1967) has a capacity equivalent to 7% of annual runoff. Whilst it increases winter flows above natural levels (Ye et al. 2003), these account for just 10% of annual discharge, and the higher summer flows are relatively unaffected (Holmes et al. 2012).

The basin is sparsely populated and vegetation is largely natural comprising forests (84%), shrublands (9%), grasslands (3%), croplands (2%) and wetlands (1%) (Liu & Yang 2011). Forests dominate the southwest and tundra dominates the north. Whilst the basin’s water resources are utilised for domestic purposes, hydropower and irrigation, the total use comprises a very low percentage of the mean annual runoff (Berezovskaya et al. 2005). The impacts of climate change can, therefore, be more easily identified and are likely to dominate future changes as opposed to anthropogenic activities.

Temperature and precipitation have increased across the basin, especially during the cold season (November–April; Dzhamalov et al. 2012). Changes in river discharge include earlier seasonal peaks and larger flows in spring, summer and winter in contrast to autumn declines. A significant upward trend (up to 90%) at the basin outlet (Stolb) during low-flow periods has been recorded, whilst slight increases (5–10%) in high-flows have been observed (Ye et al. 2005). Recognition that climate change may have already impacted the discharge of the Lena River, combined with the important role these flows and those from the other Eurasian rivers play in the global climate system, provides the impetus for assessing potential future changes within the current study.

METHODS

Model development, calibration and validation

This study employs a coupled hydrological/hydraulic model of the Lena River Basin developed using the MIKE SHE/MIKE 11 modelling system. MIKE SHE is commonly described as a deterministic, fully distributed and physically based hydrological modelling system, although it includes a range of process descriptions, some of which are more conceptual and semi-distributed in nature (Refsgaard et al. 2010). MIKE SHE is dynamically coupled to MIKE 11, a 1D hydraulic model that represents the channel flow (e.g. Thompson et al. 2004). Model development for the Lena Basin followed approaches used in other large river systems (e.g. Andersen et al. 2001; Thompson et al. 2013). Table 1 summarises the model set-up and the data it employs. Basin extent was determined using the USGS GTOPO-30 DEM with the lowest point defined as Stolb. A cell size of
10 km \times 10 \text{ km} (\text{total cells: 24,680}) was employed with GTOPO-30 being used to define the elevation of each grid cell. The saturated zone was represented using linear reservoirs, a conceptual, semi-distributed approach, particularly applicable to large river systems where the focus is river flow simulation (Andersen et al. 2001). The Lena Basin was divided into five sub-catchments (defining the extent of a series of saturated zone linear reservoirs – see Figure 1) based on the GTOPO-30 DEM and the location of gauging stations used for model calibration and validation. Stations were selected based on the length and completeness of discharge records within the Regional Arctic Hydrographic Network (R-ArcticNET) dataset. Each sub-catchment was further sub-divided according to elevation into zones of approximately equal size (14 in total) representing the highest, intermediate and lowest zones. These were specified as interflow reservoirs, whilst two baseflow reservoirs representing faster and slower baseflow storage were specified.

Table 1 | Data used in the MIKE SHE/MIKE 11 model of the Lena River Basin

| Component within model | Data source and derivation | Use within the MIKE SHE/MIKE 11 model |
|------------------------|---------------------------|-------------------------------------|
| Basin area             | Obtained using the USGS GTOPO30 DEM | Defined the model domain within MIKE SHE and specified as a shapefile. |
| Topography             | Values extracted from the USGS GTOPO-30 DEM | Defined the topography within MIKE SHE. Specified as a grid file. |
| Sub-catchments         | The USGS GTOPO-30 DEM, R-ArcticNET\(^b\) gauging station locations and major tributaries. | Defined five main sub-catchments within MIKE SHE. Specified as a shapefile. Also defined the linear reservoir sub-catchments and baseflow sub-catchments. A grid file defined the locations of the smaller 19 meteorological sub-catchments, which allowed the spatial distribution of climatic variables. Within these areas, parameters were adjusted during model calibration. |
| Land use               | USGS 1 km Global Land Cover Characterisation data\(^c\) | Defined the spatial distribution of land use within the Lena River Basin. Twenty-nine original classes were re-classified into nine classes. Specified as a grid file. |
| Vegetation properties: RD and LAI | Values from the literature (Arnell 2005) | Root depth was defined for each land-cover class. This value describes the depth of the zone from evapotranspiration can occur. These were constant for each land-cover classes. LAI describes the ratio of the leaf area to the ground area. |
| River network          | Using the USGS GTOPO-30, the river network was identified using ArcMap Hydrology Tools. | A shapefile was specified in MIKE 11. It was then manually digitised to define the river network. |
| Cross-sections         | Identified and measured using Google Earth Pro. Elevations were extracted from the basin DEM. | Defined channel cross-sections within MIKE 11. Each channel width was assigned a stream order. Elevations were assigned to each cross-section. |
| Overland Flow: Manning Number | Values from the literature using the approach of Thompson et al. (2013). | This was spatially distributed throughout the catchment based on the overlying vegetation. Specified as a grid file. Defined the rate at which overland flow is routed to channels. |
| Unsaturated Zone: Soil properties | FAO Digital Soil Map of the World\(^d\) Using ArcMap, the basin was separated into three main soil classes. Values from the literature (Atwell et al. 1999). | Defined for the water content at saturation, water content at field capacity, water content at the wilting point and saturated hydraulic conductivity within each soil class. |

\(^a\)ita.cr.usgs.gov/GTOPO30.
\(^b\)www.r-arcticnet.sr.unh.edu/v4.0/index.html.
\(^c\)ita.cr.usgs.gov/GLCC.
\(^d\)www.fao.org/soils-portal/soil-survey/soil-maps-and-databases.
beneath each sub-catchment. The two time constants (interflow and percolation) for each interflow reservoir and the baseflow time constant for each baseflow reservoir, which control exchanges between reservoirs and the MIKE 11 hydraulic model, were varied during calibration.

The unsaturated zone was simulated using the two-layer water balance method. Spatial distribution of soil types was based on the FAO Digital Soil Map of the World (v3.6, 2003) with groups aggregated into three textural classes: ‘fine’, ‘medium/fine’ and ‘coarse’. Hydraulic parameters were taken from Atwell et al. (1999). Land cover was based on the USGS Global Land Cover Characterisation dataset (GLCC). The dominant classes, including deciduous needle-leaf forest, bare rock and tundra, were retained. The remaining classes were aggregated into groups of similar characteristics, including water, croplands and grasslands, broadleaf forest, needle-leaf evergreen shrubs and bogs. For each, root depth (RD) and Leaf Area Index (LAI) were obtained from Arnell (2005). Permafrost was not included in the model as this is not a feature of MIKE SHE. This is common to a number of other hydrological models that have been used to assess the impacts of climate on river flows including within high latitude basins such as the Lena Basin (e.g. Gosling et al. 2017; Veldkamp et al. 2018).

To account for variations in climate, the areas defining the extent of the five saturated zone linear reservoirs were further divided into a total of 19 smaller areas herein referred to as meteorological sub-catchments. The discretisation of these areas was based on their ranges in latitude, longitude and elevation, as well as the major tributaries within each saturated zone linear reservoir sub-catchment (Figure 1). Time-series of mean monthly precipitation and monthly maximum and minimum temperatures were derived for each meteorological sub-catchment from the CRU TS4.01 dataset (Harris et al. 2014). Since R-ArcticNET data used in model calibration and validation comprised a mean monthly discharge necessitating the aggregation of simulated mean daily discharge for comparison, precipitation was distributed evenly and temperatures assumed constant on a daily basis through each month. Whilst this is acknowledged to be a simple approach, it follows earlier work undertaken using MIKE SHE and other hydrological models in similarly large river basins that demonstrated insensitivity to alternative temporal disaggregation of meteorological data when simulation results are aggregated to mean monthly discharges (e.g. Kingston et al. 2011; Thompson et al. 2013). Following approaches in other mountainous settings, varying precipitation lapse rates were applied over these sub-catchments (Ji & Luo 2013) and were subject to calibration but kept within the bounds used elsewhere (Immerzeel et al. 2011; Thompson et al. 2014). CRU TS4.01 temperatures for each meteorological sub-catchment were used to calculate the Hargreaves potential evapotranspiration (PET; Hargreaves & Samani 1985). MIKE SHE then calculates actual evapotranspiration using the evaporative demand (PET), crop coefficients and the available soil moisture. PET, as for precipitation, was evenly distributed through each month on a daily basis. This PET method is recommended as an alternative to Penman–Monteith in cases of limited data availability (Allen et al. 1998) and has been used in similar studies (e.g. Ho et al. 2016; Thompson et al. 2017a). Snowmelt was simulated using a degree-day method and meteorological sub-catchment averaged CRU TS4.01 temperature. As for precipitation, temperature lapse rates were specified within each meteorological sub-catchment.

A digitised channel network defined the MIKE 11 river branches comprising the main river channels. All branches were specified as coupled to MIKE SHE. Cross-sections were established using channel widths obtained from Google Earth and estimated maximum depths based on similar studies (Thompson et al. 2014). The Viliui reservoir was excluded from the section of the MIKE 11 model within this sub-catchment due to a lack of data and its small influence on the annual discharge (Holmes et al. 2012).

R-ArcticNET discharge data were separated into two periods, 1960–1979 and 1980–1999, for calibration and validation, respectively. In both cases, the previous year was used as a spin-up period. Calibration was undertaken from upstream to downstream by adjusting the parameters defined above (principally the saturated zone linear reservoir time constants and lapse rates). As previously indicated, simulated river discharges, which were stored at the maximum model time step of 24 hours, were aggregated to mean monthly discharge for comparison with the R-ArcticNET data. Model performance was assessed visually and statistically using the Nash–Sutcliffe efficiency coefficient.
(NSE), bias ($Dv$) and the Pearson correlation coefficient ($r$). Performance based on the values of these three statistics was further classified into one of five classes (ranging between ‘very poor’ and ‘excellent’) using the scheme of Ho et al. (2016), which was itself adapted from Henriksen et al. (2005).

Climate change scenarios

Precipitation and minimum and maximum temperatures were obtained for the 41 GCMs of Phase 5 of the Climate Model Intercomparison Project (CMIP5) and the Representative Concentration Pathway (RCP) 4.5 scenario as it represents the most likely increase in global temperatures (UNFCCC 2015). The use of an ensemble of climate models enables assessment of the magnitude of GCM-related uncertainty (Ho et al. 2016). Using the mean output from a range of GCMs to force a hydrological model is thought to provide a more reliable representation of future conditions than the output from a single GCM. However, this assumption only holds if the GCMs are independent of one another (Pirtle et al. 2010). This is not strictly the case for the CMIP5 ensemble since GCMs developed by different institutions share literature, parameter values and some model code, and the ensemble includes multiple versions of some GCMs or numerous GCMs from a single institution. The potential for biases due to this lack of model independence was addressed by grouping the 41 GCMs according to their genealogy using 12 groups (Ho et al. 2016; Table 2).

Mean monthly maximum, mean and minimum temperatures and precipitation were obtained for each meteorological sub-catchment for the baseline (1961–1990) and scenario (2071–2100) periods for all 41 GCMs. This 30-year scenario period was selected to represent conditions towards the end of the 21st century (e.g. Thompson et al. 2017b). The baseline is of identical length and incorporates most of the period used in model calibration/validation, but excludes the latter part of the 20th century during which changes in meteorological networks may impact model performance (discussed below). The mean values were then obtained from the GCMs in each of the 12 groups. Monthly differences (°C for temperature, % for precipitation) between baseline and scenario meteorological conditions were calculated for each GCM group for each of the meteorological sub-catchments. These differences, referred to as delta factors, were subsequently used to perturb the original CRU TS4.01 precipitation and temperature data, and then Hargreaves PET was re-calculated. The delta factor approach ensures that scenario time-series retain the baseline climate variability and are not affected by any biases inherent within an individual GCM (Anandhi et al. 2011). An additional group ensemble mean scenario was established using the same approach and employing the mean monthly baseline and scenario temperatures and precipitation from the 12 groups.

RESULTS

Model calibration and validation

Figure 2 demonstrates the generally good model performance. Timings of low- and high-flows are well represented, with slightly earlier increases in simulated discharges at Kusur and Stolb. Annual peaks are well reproduced upstream. Although the model is less successful at simulating low-flows at Vilui towards the end of the period (most likely due to the dam), the rising and recession limbs are well represented. This generally superior upstream performance is further demonstrated by the observed and simulated river regimes (mean monthly discharge) for each gauging station and the calibration, validation and baseline periods.

NSE for the calibration period is classified as ‘excellent’ at two stations and ‘very good’ at the remaining three stations (Table 3). Lower NSE values at Kusur and Stolb are related to the poorer representation of peak discharges. It was not possible to increase peaks without impacting the annual rise and recession, and ultimately increasing the overall bias. Since the focus of this study is the volume of water flowing into the Arctic Ocean, calibration was focussed on achieving a good match between the observed and simulated mean flows. The bias for one station (Tabaga) was classified as ‘excellent’, whilst for the remaining stations it was ‘very good’. The values of $r$ were varied, as calibration was a compromise between achieving higher $r$ values and smaller biases.

NSE values for the validation period are ‘excellent’ or ‘very good’ at all stations, except Vilui where winter flows
Table 2 | The CMIP5 GCMs and their grouping by genealogy

| No | GCM                | Institution                                                                 | GCM group |
|----|--------------------|------------------------------------------------------------------------------|-----------|
| 1  | ACCESS1.0          | Commonwealth Scientific and Industrial Research Organisation (CSIRO) and     | 10        |
|    |                    | Bureau of Meteorology (BOM), Australia                                       |           |
| 2  | ACCESS1.3          |                                                                               | 10        |
| 3  | BCC-CSM1.1         | Beijing Climate Center, China Meteorological Administration                 | 12        |
| 4  | BCC-CSM1.1(m)      |                                                                               | 12        |
| 5  | BNU-ESM            | College of Global Change and Earth System Science, Beijing Normal University | 12        |
| 6  | CanESM2            | Canadian Centre for Climate Modelling and Analysis                           | 1         |
| 7  | CCSM4              | National Center for Atmospheric Research                                    | 12        |
| 8  | CESM1(BGC)         | Community Earth System Model Contributors                                   | 12        |
| 9  | CESM1(CAM5)        |                                                                               | 12        |
| 10 | CMCC-CM            | Centro Euro-Mediterraneo per I Cambiamenti Climatici                         | 11        |
| 11 | CMCC-CMS           |                                                                               | 11        |
| 12 | CNRM-CM5           | Centre National de Recherches Météorologiques/Centre Européen de Recherche et | 11        |
|    |                    | Formation Avancée en Calcul Scientifique                                     |           |
| 13 | CSIRO-Mk3.6.0      | Commonwealth Scientific and Industrial Research Organisation in collaboration | 2         |
|    |                    | with the Queensland Climate Change Centre of Excellence                      |           |
| 14 | EC-EARTH           | EC-Earth consortium                                                          | 11        |
| 15 | FGOALS-g2          | LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences          | 3         |
| 16 | FIO-ESM            | The First Institute of Oceanography, SOA, China                              | 12        |
| 17 | GFDL-CM3           | NOAA Geophysical Fluid Dynamics Laboratory                                   | 6         |
| 18 | GFDL-ESM2G         |                                                                               | 6         |
| 19 | GFDL-ESM2M         |                                                                               | 6         |
| 20 | GISS-E2-H p1       | NASA Goddard Institute for Space Studies                                     | 7         |
| 21 | GISS-E2-H p2       |                                                                               | 7         |
| 22 | GISS-E2-H p3       |                                                                               | 7         |
| 23 | GISS-E2-H-CC       |                                                                               | 7         |
| 24 | GISS-E2-R p1       |                                                                               | 7         |
| 25 | GISS-E2-R p2       |                                                                               | 7         |
| 26 | GISS-E2-R p3       |                                                                               | 7         |
| 27 | GISS-E2-R-CC       |                                                                               | 7         |
| 28 | HadGEM2-AO         | Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by  | 10        |
|    |                    | Instituto Nacional de Pesquisas Espaciais                                   |           |
| 29 | HadGEM2-CC         |                                                                               | 10        |
| 30 | HadGEM2-ES         |                                                                               | 10        |
| 31 | INM-CM4            | Institute for Numerical Mathematics                                         | 4         |
| 32 | IPSL-CM5A-LR       | Institut Pierre-Simon Laplace                                                | 8         |
| 33 | IPSL-CM5A-MR       |                                                                               | 8         |
| 34 | IPSL-CM5B-LR       |                                                                               | 8         |
| 35 | MIROC5             | Atmosphere and Ocean Research Institute (the University of Tokyo), National    | 9         |
|    |                    | Institute for Environmental Studies, and Japan Agency for Marine-Earth Science|           |
|    |                    | and Technology                                                              |           |

(continued)
are underestimated. A shift from overestimation, or small underestimation, during the calibration period, to underestimation during the validation period is evident. $Dv$ values ranged from ‘good’ at Tabaga, Aldan and Stolb, to ‘poor’ at Kusur and Vilui. This poorer performance may be related to changes in meteorological networks and how well they represent Lena’s climate. These factors (discussed below) may have been particularly acute towards the end of the 20th century. If so, they are less likely to impact the baseline period against which climate change results are compared. NSE for this period is classified as ‘very good’ for three stations and ‘good’ for two stations (Table 3). $Dv$ is classified as ‘excellent’ at four stations and ‘very good’ at the remaining station. Figure 2 confirms the generally very good performance of the model for this period.

**Projected climate**

Mean annual precipitation, temperature and PET are projected to increase for all GCM groups across the Lena Basin (Figure 3). The magnitude of these changes varies between the groups and sub-catchments. Seasonal patterns of change are also variable, most prominently at higher latitudes; where some groups (2, 6, 8, 9, 10 and 11) project a second precipitation peak in October in addition to the July baseline peak. In general, but with the exception of Group 5, larger increases in precipitation are projected downstream. The largest increase in annual precipitation across all groups and sub-catchments is 47.4% (Group 9, sub-catchment $r$), whilst the smallest is 1.7% (Group 4, sub-catchment $d$). Group 10 is associated with the largest inter-sub-catchment range (11.9–45.1%) and Group 7 the smallest (12.5–20.7%). Changes for the group ensemble mean range between 15.0 and 27.5% (mean: 19.7%).

All temperature increases exceed the 2015 Paris target of 1.5 °C (UNFCCC 2015) varying between 2.2 °C and 6.2 °C (mean: 2.7 °C). The greatest absolute increases are projected during winter (maximum 6.2 °C, Group 9, sub-catchment $r$). The duration of the period when temperatures are above freezing extends by, on average, 1 month, most prominently at higher latitudes. Group 9 is associated with the largest increases (mean: 5.4 °C), including earlier seasonal gains in temperature. Group 10 again has the largest inter-sub-catchment range of change (2.0 °C). In contrast, groups 4 and 5 project relatively small increases (2.2 °C–3.2 °C and 2.2 °C–3.5 °C, respectively). Increases in temperature for the group ensemble mean range between 3.2 °C and 4.4 °C (mean: 3.7 °C).
Figure 2 | Observed and simulated mean monthly discharge and river regimes at the five gauging stations within the Lena River Basin for the calibration (1960–1979), baseline (1961–1990) and validation (1980–1999) periods. Note different y-axis scales.
Increases in mean annual PET are of a similar range, albeit slightly smaller, to those of precipitation (6.0–45.5% across all GCM groups and sub-catchments). The smallest increases are predominantly projected by Group 5 (6.0–15.2%, mean: 10.9%), whilst Group 1 generally produces the largest increases (24.7 to 34.5%, mean: 27.8%). The range for the group ensemble mean is 15.5–24.2% (mean: 19.2%). All groups and the group ensemble mean project basin-wide peaks in June, 1 month earlier than for the baseline (although the largest absolute changes occur in May; Figure 3).

Projected river discharge

Changes in discharge are generally consistent with 10 of the 12 groups and the group ensemble mean projecting increases at all gauging stations. These increases are, however, of variable magnitude (Figure 4). Across the basin changes range between −8.5 and +36.8%. Groups 1, 3 and 5 project the largest basin-wide increases. Declines are limited to groups 4 and 12, which project declines at four (−8.5 to −1.0%) and five (−5.8 to −1.7%) stations, respectively. These groups are associated with relatively large increases in PET (8.0–19.0% and 18.1–26.2%, respectively) that exceed increases in precipitation (1.7–17.2% and 9.6–19.5%, respectively). The group ensemble mean projects increases in the mean discharge of between 5.6 and 18.6% (mean: 10.1%) with the increase of 9.2% for Stolb, indicative of Arctic Ocean inflow, contrasting with the range for the 12 groups of −5.3 to 21.7%. All but two groups (again 4 and 12) are associated with increases in these flows.

High (Q5) and low (Q95) flows also increase for most groups. Changes in Q5 across all groups and gauging stations range between −2.8 and +69.9%. Increases are, in percentage terms, larger than those for the mean annual discharge. Declines are again limited to groups 4 (three stations) and 12 (one station). However, they are small compared with most increases. The group ensemble mean projects increase in Q5 at all stations (range: 10.2–30.2%). Q95 increases in most cases with relatively small (≤6.7%) declines limited to just two stations for Group 4 and one for groups 2 and 12. The small (2.8%) decline for Tabaga

Table 3  Model performance statistics and classification for the calibration (Cal, 1960–1979), baseline (1961–1990) and validation (Val, 1980–1999) periods

| Station | Period | Dv   | NSE     | r        |
|---------|--------|------|---------|----------|
| Tabaga  | Cal    | −3.27| 0.90    | 0.95     |
|         | Baseline | −3.87| 0.83    | 0.95     |
|         | Val    | −10.00| 0.83    | 0.93     |
| Aldan   | Cal    | 8.14 | 0.88    | 0.95     |
|         | Baseline | 3.23 | 0.83    | 0.95     |
|         | Val    | −8.25 | 0.79    | 0.92     |
| Vilui   | Cal    | 5.33 | 0.82    | 0.90     |
|         | Baseline | −2.17| 0.66    | 0.87     |
|         | Val    | −16.47| 0.49    | 0.77     |
| Kusur   | Cal    | −5.05| 0.74    | 0.87     |
|         | Baseline | −7.87| 0.63    | 0.88     |
|         | Val    | −12.70| 0.76    | 0.92     |
| Stolb   | Cal    | 5.69 | 0.70    | 0.83     |
|         | Baseline | 2.44 | 0.61    | 0.76     |
|         | Val    | −5.22 | 0.80    | 0.92     |

Performance indicator

| Excellent | Very good | Fair | Poor | Very poor |
|-----------|-----------|------|------|-----------|
| /         |           | /    |     |           |

Note: Model performance classification is based on Ho et al. (2016) and adapted from Henriksen et al. (2003).
Figure 3 | Mean monthly precipitation, temperature and PET in six representative sub-catchments in the Lena River Basin for the baseline, each GCM group and the group ensemble mean (GM). Note different y-axis scales.
Figure 4 | Percentage changes in mean discharge, high (Q95) and low (Q95) discharges for each gauging station in the Lena River Basin. Note different y-axis scales.
projected by Group 2 is the only reduction in any discharge measure beyond groups 4 and 12. These two groups project the smallest increases in $Q_{95}$ (<8.2%), whilst groups 1, 3 and 5 project some of the largest (up to 41.7%, Group 3, Aldan). Increases in $Q_{95}$ of between 15.7 and 28.0% are projected by the group ensemble mean.

Projected river regimes (Figure 5) show that in many cases the seasonal peak advances to May compared with June under baseline conditions. This is most pronounced for groups 9 and 10, both of which project large basin-wide increases in temperature, and Group 11 and the group ensemble mean at Vilui. Group 9 projects the most pronounced change at Stolb with the mean May discharge being 82% larger than the baseline. For many groups, the recession limb declines more rapidly so that discharges in September are lower than during baseline conditions. The largest reductions at Stolb (19.0%) are projected by Group 4.

### DISCUSSION

#### Model performance

This study expands research into the impacts of climate change on river discharge within the Arctic (e.g. Peterson et al. 2002; Arnell 2005), including, in comparison to other studies of the Lena Basin (Ye et al. 2003), extending the geographical range downstream to Stolb.

Model performance for the baseline period was classified as at least ‘very good’, and in some cases ‘excellent’. It was comparable to, and in some instances better than, other models of the Lena and similar basins (e.g. Gosling et al. 2017; Veldkamp et al. 2018). Model performance was relatively weaker at Vilui possibly due to a lack of information regarding the reservoir and thus its exclusion from the model. Similar issues have been experienced elsewhere (Ho et al. 2016). Whilst performance for the validation period based on NSE was, in most cases, at least ‘very good’, discharges were notably underestimated, especially downstream. As previously stated, it is possible that this relates to a decline in how well the data used to force the model represents the basin’s climate. Gridded CRU TS4.01 data are produced through interpolation of observations from meteorological stations (Harris et al. 2014). However, Arctic climatic observations are fraught with uncertainties due to sparse station networks, biases in measurements and changes in measurement methods (Rawlins et al. 2006). Within the Russian Arctic, both the instruments used to measure precipitation and the frequency of observations have changed over time. There is also potential for underestimation of precipitation due to difficulties in measuring snow, especially during windy winter conditions (Groisman et al. 1991). This could explain underestimated discharges at the most northern stations since unrealistically low winter snowfall will limit the volume of simulated spring meltwater. A mismatch between increasing Arctic discharge and declining or plateaued precipitation has been attributed to the closure of multiple meteorological stations in the late 20th century (Groisman et al. 1991). Many high elevation stations were lost and thus, interpolation is based on the stations at lower elevations with potentially less precipitation (Wang et al. 2016). Poor model performance for the latter validation period supports the argument that these problems were particularly acute towards the end of the last century.

#### Projected hydrometeorological changes within the Lena Basin

Results suggest relatively small inter-GCM variability in projected temperatures across the Lena Basin. Inter-GCM variability is larger for precipitation and PET with the range of change being slightly greater for precipitation, replicating results from other similar studies (Ho et al. 2016; Thompson et al. 2017a).

In general, model results suggest that discharge of the Lena River and its main tributaries will increase. This echoes findings of other studies that have highlighted increasing Arctic river flows (Peterson et al. 2002) and those that project future increases (Arnell 2005; Gosling et al. 2011; 2017; Hattermann et al. 2017). The shift towards earlier snowmelt floods has been reported in Siberia and throughout the Arctic (e.g. Overeem & Syvitski 2010; Vihma et al. 2016). Projected increases in winter precipitation, and hence deeper snow pack, will also contribute to higher spring discharges (Ye et al. 2004). The dominance of steeper recessions following the annual peak replicates results from Woo et al. (2008) that were attributed to increases in PET in excess of gains in precipitation.
Figure 5

Mean monthly discharges at each gauging station for each scenario. The baseline and group ensemble mean (GM) are shown in each figure to facilitate comparison. Note different y-axis scales for different stations.
Although increased discharges dominate scenario results, the changes vary considerably in magnitude. This uncertainty could be constrained using GCM weightings (e.g. Maxino et al. 2008) following the approach of Krysanova et al. (2018) who recommend assessing models based on their performance, then weighting or excluding them as appropriate. This could reduce the number of GCM groups, and therefore, the number of scenarios and subsequent uncertainty. Nonetheless, utilising this approach introduces questions regarding model exclusion, weight complexity and their derivation (Zaherpour et al. 2019), which potentially adds further uncertainty.

In common with similar studies (e.g. Arnell 2005; Thompson et al. 2013), potential changes in vegetation or anthropogenic interventions were not explicitly considered. Vegetation will shift northward with altered climate regimes (Vihma et al. 2016) with potential hydrological feedbacks (Arnell 2005). The omission of such features will have hydrological implications for processes such as PET, interception and infiltration. The incorporation of future land-use projections, such as those used within the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP2b; Frieler et al. 2017), which themselves are impacted by climatic and socio-economic drivers, would enable these impacts to be simulated. Permafrost melt, which as previously noted was not included in this and other models used to assess climate change impacts on the Lena and other similar basins (e.g. Gosling et al. 2017; Veldkamp et al. 2018), would also have hydrological implications including enhanced infiltration that may contribute to increasing groundwater contributions to river flow (Walvoord & Striegl 2007; Vihma et al. 2016). In contrast, continued melting may enhance vertical flow paths enough that increased infiltration reduces the volume of water reaching the river (Walvoord & Kurylyk 2016). These changes may be most significant in higher latitude sub-catchments due to the greater projected temperature increases (Gautier et al. 2018).

This study focussed on GCM-related uncertainty in future hydrometeorological conditions within the Lena Basin and did not consider hydrological model-related uncertainty. This could be investigated by simulating the same climate change scenarios with a number of hydrological models of the Lena using alternative model codes to MIKE SHE, the different process descriptions available within MIKE SHE or alternative parameterisations and spatial distributions of model input data (e.g. Thompson et al. 2013, 2014; Robinson 2018). Whilst the overall fraction of uncertainty within hydrological impact studies of climate change that is attributable to different hydrological models has been shown to be smaller than that due to different GCMs (e.g. Krysanova et al. 2017), choice of hydrological model may not be insignificant where processes are implemented uniquely in different models (Hattermann et al. 2018). Snowmelt schemes, for example, include degree-day methods as used here or more complex energy balance approaches (Pohl et al. 2005; Corripio & López-Moreno 2017). Given the significance of snow accumulation and melt within the Lena, these different methods could simulate variable responses to the same climate change scenario.

Implications for the AMOC

Increases in mean discharge at Stolb dominate scenario results (10 of 12 GCM groups). Projections range between −5.3% (840 m³ s⁻¹) and +21.7% (3,440 m³ s⁻¹) with the group ensemble mean projecting an increase of 9.2% (1,458 m³ s⁻¹). These results can be used to provide estimates of potential changes in Eurasian runoff to the Arctic Ocean. The Lena, Yenisei and Ob contribute approximately 45% (~46,700 m³ s⁻¹) of the mean annual runoff to the Arctic (Ye et al. 2004). Changes in these inflows can be established if percentage changes for Stolb are applied to the downstream gauging station of each river (Igarka and Salekhard for Yenisei and Ob, respectively; R-Arctic.Net). These estimates assume regionally homogeneous climatic changes, the same hydrological responses to these changes within the Yenisei and Ob basins, and exclude future anthropogenic impacts. Whilst it is recognised that this is a simplification, the approach does enable an initial assessment of climate change driven modifications to Eurasian runoff to the Arctic for each of the 12 GCM groups. Increases of between 1,729 m³ s⁻¹ and 10,146 m³ s⁻¹ (1.7–10.1 mSv) (1 Sv = 1,000 mSv = 10⁶ m³ s⁻¹) are projected for 10 groups (declines of 0.8–2.5 mSv for two) and the group ensemble mean (Figure 6).
Peterson et al. (2002) suggested that an additional freshwater flux of between 60 mSv and 150 mSv would inhibit NADW formation. The changes summarised in Figure 6 are far below these values. However, sustained enhanced fluxes of 5–100 mSv could weaken convection (Schulz et al. 2007; Yang et al. 2016). Four of the GCM groups (1, 3, 5 and 9) project fluxes that cross the minimum threshold with projections for Group 10 coming close (Figure 6). Climate-induced changes in Eurasian river discharge under RCP4.5 may, therefore, produce freshwater fluxes capable of weakening AMOC. This extends the analysis of Shu et al. (2017), who found that enhanced runoff from all Arctic rivers under RCP8.5 could weaken AMOC, by suggesting that such a weakening may occur under a broader range of future climate conditions. Additionally, as Lena discharge shows increases with temperature (Gosling et al. 2017), it is likely that under the higher temperatures projected by RCP6.0 and RCP8.5, discharge may increase further, thus causing a more substantial weakening of AMOC. Therefore, whilst AMOC collapse may be improbable during the 21st century, it may be more likely in the future. Furthermore, the increases projected herein will be coupled with warmer temperatures (Thornalley et al. 2013), likely increased North American Arctic discharges (e.g. Arnell 2005; Shu et al. 2017), greater precipitation, and meltwater from the Greenland ice sheet (Vihma et al. 2016), which will all also act to reduce convection. These changes will increase the potential for a weakening of the AMOC that will have important implications for global climate.

CONCLUSION

A MIKE SHE/MIKE 11 model was used to investigate climate change impacts on discharge within the Lena River Basin for 12 genealogical-based GCM groups and the RCP4.5 scenario in 2071–2100. All groups projected basin-wide increases in precipitation, temperature and PET. However, the magnitudes of changes varied. Increases in mean annual discharge dominate with declines restricted to two groups. Seasonal shifts in the timing of snowmelt were simulated due to increases in temperature and precipitation during winter and spring. The application of projected changes to the three major Eurasian rivers suggests that AMOC weakening could potentially occur if enhanced freshwater inputs are sustained. When augmented by increases in other freshwater sources, and combined with higher temperature more groups may cross the threshold, increasing the likelihood of AMOC weakening by the end of the 21st century. Eurasian rivers alone could, therefore, play a significant role in altering this component of the Earth’s climate system.

ACKNOWLEDGEMENTS

We thank two anonymous reviewers for their valuable comments and suggestions on earlier drafts of the manuscript.
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First received 29 November 2018; accepted in revised form 9 July 2019. Available online 2 August 2019