# River to ocean models interpolation

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**Abstract**

In CNRM-CM6-1 (Voldoire et al., 2019), the method used to interpolate river discharges simulated by the river routing CTRIP model to the NEMO ocean model is not conservative locally. This document explains the reasons of non-local conservation and proposes a new interpolation method that ensures local conservation. The consequences of this new interpolation are assessed in long term piControl type simulations in which forcing are fixed to preindustrial levels. In these simulations, we observe a strong impact on sea-ice extent and volume in both hemispheres. This in turn impacts the large-scale ocean mass transport (AMOC and ACC). Nevertheless, the resulting Arctic sea-ice extent is unrealistically large and it raises the need to tune the model ones the new interpolation method is included. More investigations would require such a tuning to be done.

The new interpolation method can be applied to any other models given that the models ocean and river grids are dealt with in the OASIS coupler. This interpolation method could also be used for other quantities: biogenic fluxes, calving, etc. To this aim, it will be made available directly in OASIS future versions.

## 1 Root Causes of non local conservation

In CNRM-CM6-1 (Voldoire et al., 2019) and in its derived versions CNRM-ESM2-1 (Séférian et al., 2019) and CNRM-CM6-HR, the interpolation method used to interpolate river discharge from the river routing model TRIIP to the ocean model NEMO has been chosen among the available methods in OASIS (Craig et al., 2017). There was not any interpolation method very appropriate for this type of remapping, so we used the simple method of distance-weighted interpolation. The conservative remapping was not appropriate since river discharge does not span the entire NEMO ocean grid points. The distance weighted interpolation method was thought to be less erroneous since outflow were distributed to ocean grid point closed to the river bank and since it takes into account the distance between source and target grid points.

### 1.1 Respective model areas of grid points are not taken into account

However, the area of TRIP (0.5° resolution) and NEMO (ORCA1 grid, 1° resolution) grid points are one order magnitude different (Fig. 1). Given that distance-weighted does not take into account the area of source-target grid points, this remapping method does not conserve the amount of water exchanged that are provided by TRIP in $kg/m^2$. The integral of this quantity should be conserved (ie flux∗area).

The total area of river discharge grid points in TRIP is 7 106 $km^2$, whereas it is spread over 64 $106km^2$ on the NEMO grid. There is a large mismatch in between these quantities. We could reduce the mismatch by increasing the number of masqued grid points on the ocean NEMO grid. The mismatch would also been reduced if the resolution of the two grids were closer. Such methods would reduce the local non conservation but would not ensure a perfect conservation.

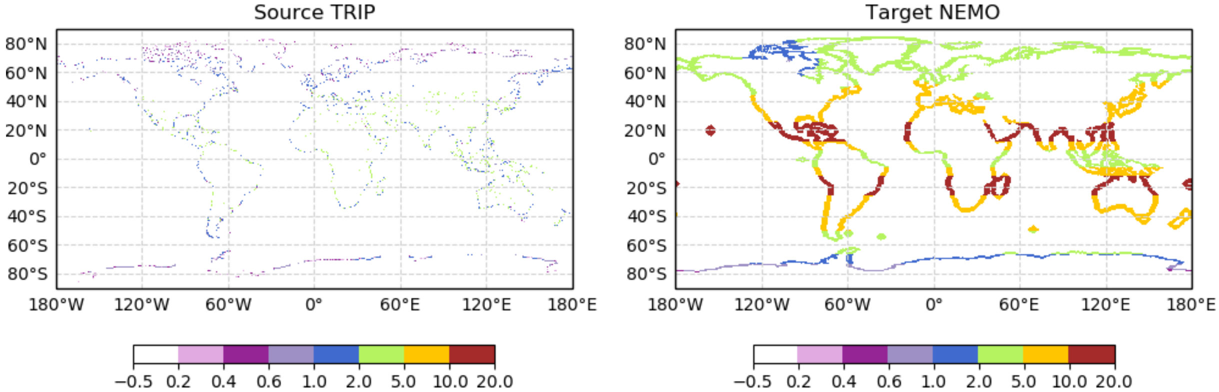


Figure 1: Area of non masqued points for the river model TRIP grid (left) and for the NEMO ocean model grid (right) in $10^3 km^2$

## 1.2 Non coastal river bank

In the TRIP grid, there are river bank that are not closed to the sea. For instance, there are many river bank over central Eurasia. These river discharges correspond to river discharges to small lakes. The water mass budget of these lakes is not dealt with in the current version of CNRM-CM6-1. In the OASIS distance-weighted interpolation algorithm, these grid points does not have an identified neighbour in the target ocean grid (Fig. 2), even if 10 neighbours are searched for (Fig 2b). This problem would also appear for bilinear or conservative interpolations. Thwater mass should be taken into account in the CNRM-CM6-1 system to properly close the water budget.

Therefore, in CNRM-CM6-1, there are 2 steps for the interpolation:

- remapping following a distance-weighted interpolation (DISTWGT OASIS) with only one neighbour
- global conservation procedure to ensure a global conservation of the water mass coming from the TRIP river model.

As we only take one neighbour in the first step, the number of river discharge point not taken into account during the first step is large (Fig. 2a). Note that even if we had taken 10 neighbours, the number of unused grid points would remain important.

## 1.3 Effects on local conservation

The TRIP simulated mean river outflow over the Amazon region (Fig. 3a, green bars) is systematically larger than the river outflow received by the ocean model (blue bars), whatever month considered. This is reversed over the south Greenland region (Fig. 3b). If we consider the globe (Fig. 3c), the amount of water received by the ocean model corresponds to the amount of water sent by the TRIP river model. However, due to the difference in mean area, the amount of water on the ocean grid after the first step, ie, the distance-weighted interpolation is dramatically overestimated. This is partly compensated by the non coastal river outflow not taken into account during this first step. This means that the error would have probably been larger if all river discharge grid points were taken into account. The ratio applied to conserve the global mean is thus large and the resulting regional outflow is severely modified. This ratio

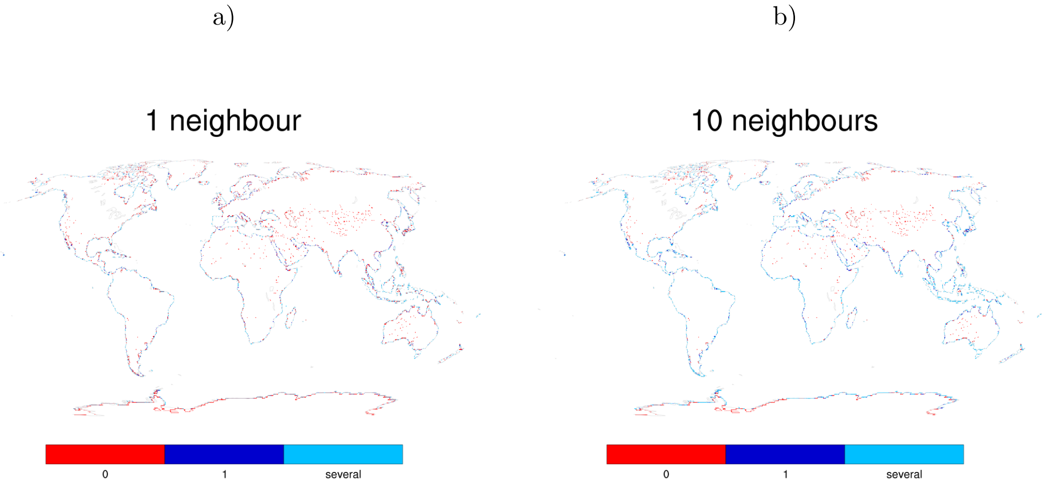


Figure 2: Number of neighbours in the NEMO ocean grid for each river bank grid point. In blue, the TRIP grid point has a neighbour in the target ocean grid, in red, no neighbour is found. a) Left panel is when interpolation is based on only one neighbour, b) right panel is based on 10 neighboors interpolation.

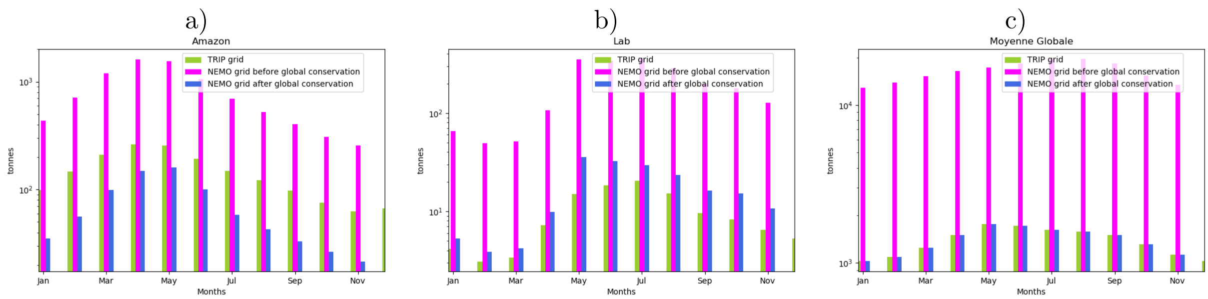


Figure 3: Mean annual cycle of water outflow (in tons) integrated over the a) Amazon region ([70W-30W, 3S-3N]), b) south of Greenland [60W-30W, 50N-70N]) and c) globally on the TRIP river grid (green), after distance-weighted interpolation (magenta) and received on the ocean grid after global conservation step (blue). Note that the vertical axis has a logarithmic scale.

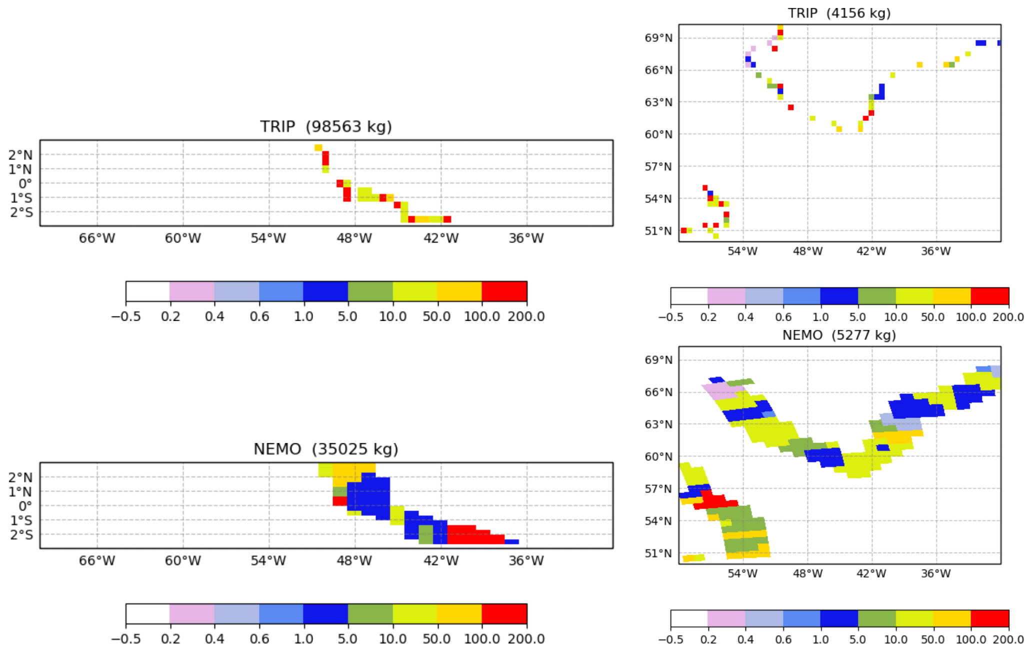


Figure 4: Water mass flux sent at each TRIP river discharge grid points (top) and water mass received by the ocean NEMO model (bottom) over the Amazon region (left) and the south Greenland region (right). The title of each plot indicates the total water mass (in kg) integrated over the region considered.

is indeed the same for all regions but depending on the error made during the first step of interpolation, this results in regions of underestimation and regions of overestimation of the river discharge.

OASIS interpolate these water masses as fluxes, ie the local values are relatively consistent between the two grids (figure 4). However, the total water mass is very different depending on the grid : 98 tons are simulated by TRIP over the Amazon and only 35 tons are received on the NEMO grid over the same region.

# 2 New method proposed

## 2.1 Description of the interpolation method

The interpolation should consider the water mass integrated over each grid points rather than the water mass flux and there is the need to take into account properly the "inland" river outflow. In general, interpolations in OASIS are written so as to provide a value on each unmasked target grid points. The idea is that the target model needs a value on each unmasked grid points. Here, to be appropriate, the new interpolation method should consider all input grid points and we do not need absolutely to get a value on each unmasked target grid points. The question is thus reversed: we take the interpolation links from a reverse interpolation distance-weighted from the ocean grid to the river grid. This allows to know for each river discharge grid points one (or several neighbours) in the ocean grid and there is no river discharge grid points unused. Note that this means that there can be several ocean grid points associated to one river grid point, the resulting water mass flux to the nemo grid points can be written :

$$F_{nemo} = \sum_i F_{trip}(i) * area_{trip}(i)/area_{nemo} \tag{1}$$

and the new weights are calculated following :

$$ww(i) = aire(i)/aire_{nemo} \tag{2}$$

In the case of using a n-neighbours distance weighted interpolation, then the effective area should take into account the number of neighbours effectively used for each river grid points :

$$area^{eff}_{trip}(i) = area_{trip}(i)/nneighbours^{eff} \tag{3}$$

## 2.2 Offline application to CNRM-CM6-1 outputs

Here, the new interpolation method is applied to TRIP outputs taken from a piControl CMIP6 simulation, and provides a new field on the NEMO ocean grid. As expected, the total mass of water over the domain is conserved. Over the amazon region, the results is close to 98 tons (figure 5). The small differences obtained arise from the fact that the domains considered are not "closed", ie there are river banks close to the northern border of the domain (Orinoco river) that partly spread over ocean grid points of the region. This also explains that the mismatch is larger when more neighbours are taken into account which means that more neighbours of the Orinoco river are in the region considered and thus more water from this river ends in the local domain. By looking at a closed domain like the Island coast, we have assessed that the local conservation is obtained (not shown). Figure 6 confirms the local conservation over the annual cycle for both regions.

The choice of the number of neighbours remains subjective, more neighbours are taken, more the flux is spread over the ocean and less there is a risk of numerical explosion in the ocean model in case of strong outflow.

## 2.3 Inland river discharge management

The new interpolation method remains problematic for inland river outflows. For these points, the closer ocean grid point can be very far from the river outflow and it would be unrealistic to discharge this water mass on such localised places. In the TRIP river atlas, the river outflow grid points are provided following two categories, the second one corresponds to these inland outflows. To limit the problem, we can thus apply a different treatment to these outflow regions. Figure 7 is an updated version of figure 2 in which inland outflow grid points which do not have any neighbours are coloured green. In this new figure, the number of red grid points, ie coastal river outflow according to TRIP but no neighbour using the old method, is drastically reduced and most of them are closed to the ocean so we can rely on the new interpolation method to deal with them correctly. Note however, that there are still few inland grid points (over east Africa for instance). This means that we may not avoid totally some spurious effects where these inland outflow will be spread on ocean coastal grid points.

Concerning inland river discharge, as the objective is mainly to close the water budget of the coupled system and not to spread this amount of water in spurious regions, we can spread the total amount of water provided by these grid points over the whole ocean, as is already done for the lake water budget. Spread over the ocean, this represent a very small water flux locally that should have a negligible effect. This allows to close the water budget without introducing a spurious spatialisation.

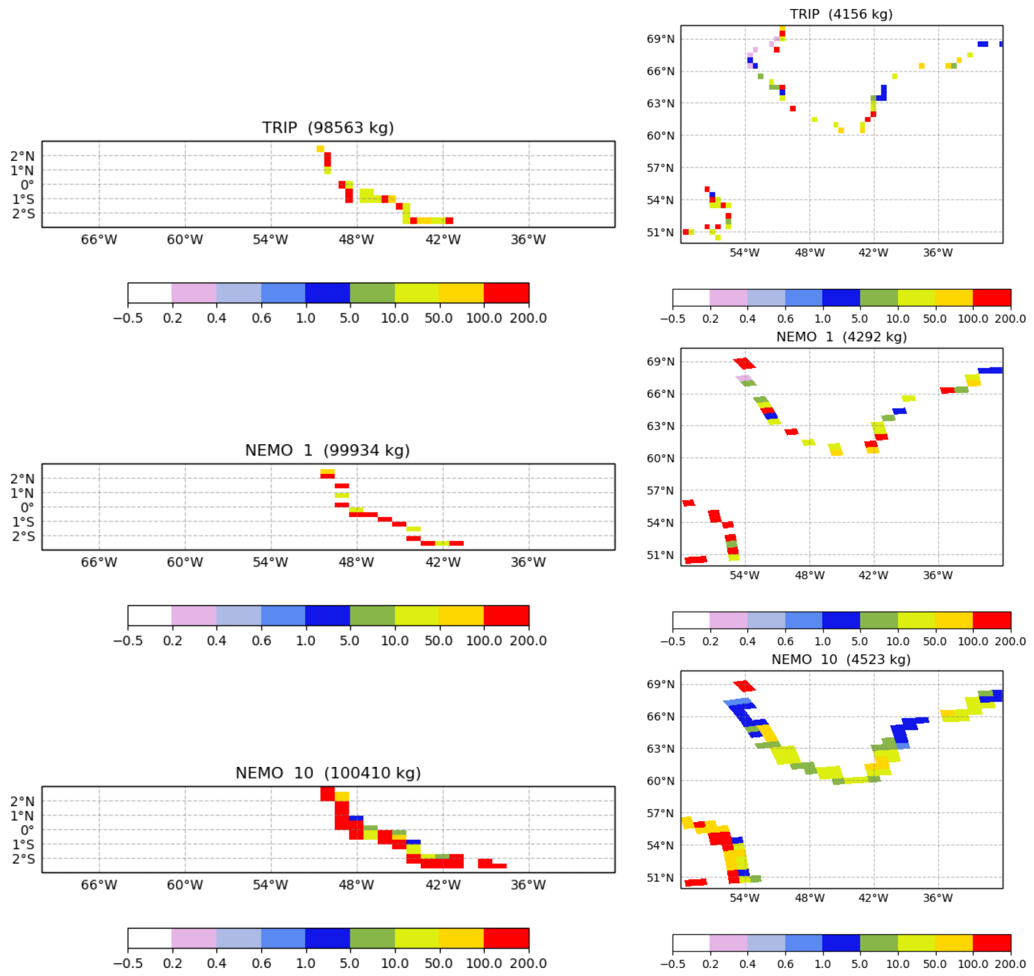


Figure 5: Water mass flux sent at each TRIP river discharge grid points (top) and water mass received by the ocean NEMO model using the new interpolation method with one neighbour (middle) and 10 neighbours (bottom) over the Amazon region (left) and the south Greenland region (right). The title of each plot indicates the total water mass (in kg) integrated over the region considered
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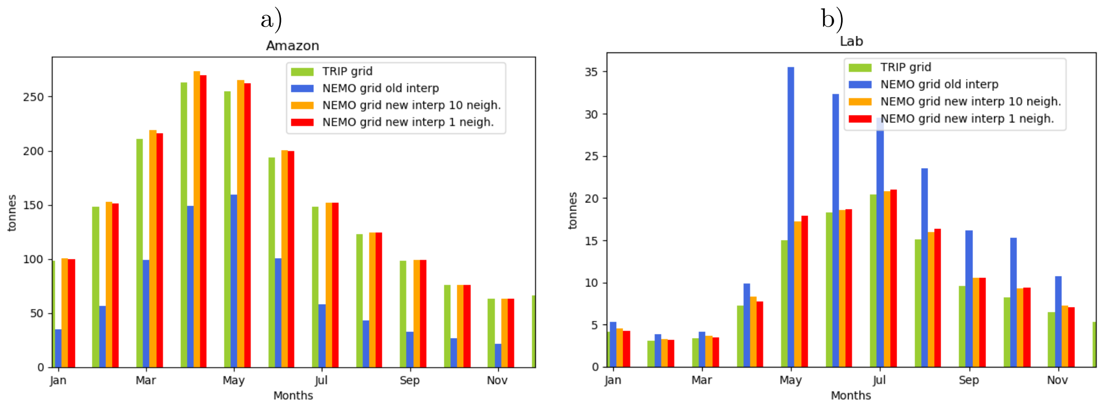



Figure 6: Mean annual cycle of river discharge (in tons) averaged over the period 2350-2359 of the piControl CMIP6 simulation done with CNRM-CM6-1 integrated over the a) Amazon region ([70W-30W, 3S-3N]) and b) south of Greenland [60W-30W, 50N-70N]) calculated on the TRIP river model grid (green), on the NEMO model grid (after applying global conservation) using the distance-weighted interpolation used in CNRM-CM6-1 (blue) and with the new method with 10 neighbours (orange) and one neighbours (red).

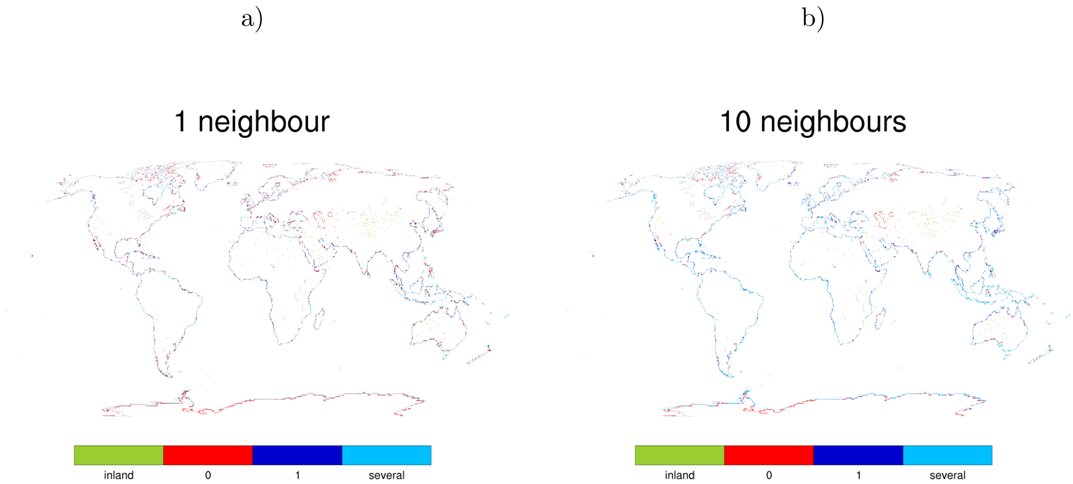



Figure 7: Same as Figure 2 where grid points without any neighbour which are considered as inland river outflow in TRIP are mouved to green color. Remaining red grid points thus represents coastal grid points according to TRIP which have no neighbours using the old interpolation method with a) one neighbour and b) 10 neighbours.

# 3 Impact of the new method

## 3.1 Experiments performed

3 sensitivity experiments have been performed based on the CMIP6 piControl simulation with CNRM-CM6-1 to assess the impact of the new treatment of the coupling between rivers and ocean:

- interp_n10: new interpolation method using 10 neighbours (each river grid points has 10 neighbours in the ocean)
- interp_n1: new interpolation method using 1 neighbour
- all_changes: apply a different treatment for river discharge depending on its location (inland or coastal) and interpolation with the new method with one neighbour for the coastal discharge. In this simulation, there is also a new land-sea mask introduced in the atmospheric-surface model to better match the ocean model land-sea mask and avoid mismatches. This feature has been developped for CMIP6 but was not valided anough to be activated in CNRM-CM6-1, it is only activated in CNRM-CM6-HR.

For all these experiments, the reference simulation is the piControl CNRM-CM6-1 simulations published for CMIP6 in which there is no local conservation (old interpolation method). All simulations use constant greenhouse gases and aerosol forcings representative of the preindustrial era as provided for CMIP6 and all share the same equilibrated initial state.

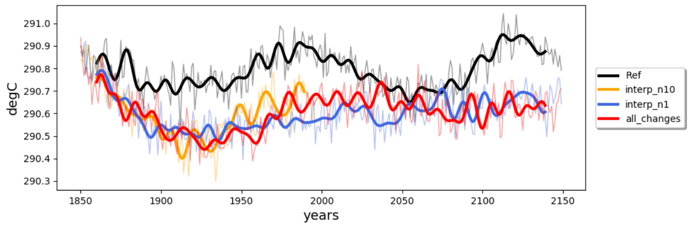
Simulation interp_n10 was the first test done and has allowed to validate the interpolation method ensuring no numerical explosion would happen. Using one neighbour appeared less questionable scientifically. As there was not any numerical problem using only one neighbour, it has been decided to extend only interp_n1. Finally, interp_n10 has been run over 150 years, whereas interp_n1 and all_changes experiments are 300 years long.

## 3.2 Results

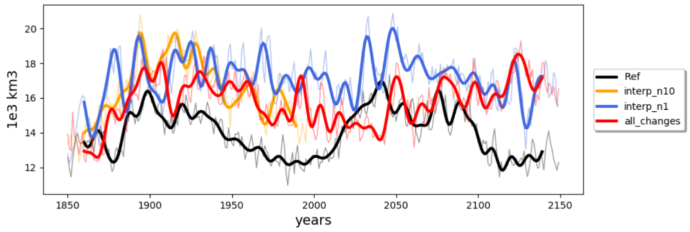
### 3.2.1 Impact on the global mean climate

Figure 8 shows the time series of several key quantities summarising the global mean climate of these simulations. The impact of the change in river-ocean coupling on global mean temperature (Fig. 11a) is similar in all three sensitivity experiments. There is a decrease of temperature over the first 50 years then a weak warming tendency is observed but the mean temperature remains colder than in the reference simulation even after 300 years for interp_n1 et all_changes. interp_n10 is shorter but its evolution is similar to the others. The Arctic sea-ice volume is larger in all three sensitivity experiments (Fig. 11b). On the contrary, the impact on the Antarctic sea-ice volume is negligible in interp_n1 and interp_n10 whereas there is a net increase in all_changes. The origin of this difference are further explained in section 3.2.3. The impacts on the large-scale ocean circulation are consistent with the sea-ice changes. In all three sensitivity experiments, we observe a strong weakening of the mean Atlantic Meridional Overturning Circulation (AMOC, Fig. 11d) that stabilizes after 70 years of simulation to 11.5 Sv. The large AMOC low-frequency variability observed in the reference experiment nearly disappears. The AMOC seems less stable in all_changes, but a longer simulation would be necessary to confirm this feature. The impact on the Antarctic Circumpolar Circulation (ACC, Fig. 11e) differs in between the sensitivity experiments. Consistently with the southern hemisphere sea-ice volume changes, there is a large increase of the ACC only in all_changes where it reaches 117Sv on average over the last 50 years whereas it is 110Sv in the other experiments and in the reference experiment. In the following, we focus on the all_changes experiment in which there are impacts on the sea-ice volume in both hemispheres.

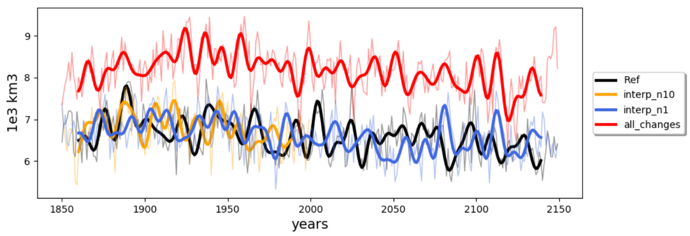
a)



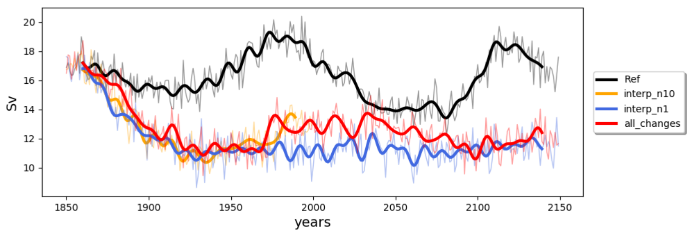

b)




c)




d)




e)

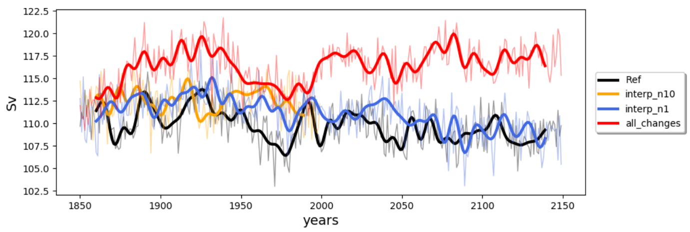



Figure 8: Evolution of the annual mean a) global temperature, b) Arctic sea-ice volume, c) Antarctic sea-ice volume d) Atlantic Meridional Overturning Circulation (AMOC) at 26°N and e) Antarctic Circumpolar Circulation (ACC) for the reference piControl CMIP6 experiment (black) and sensitivity experiments interp_n10 (orange), interp_n1 (blue) and all_changes (red). The bold line represents the low-pass filtered time series with 10 years cut-off.

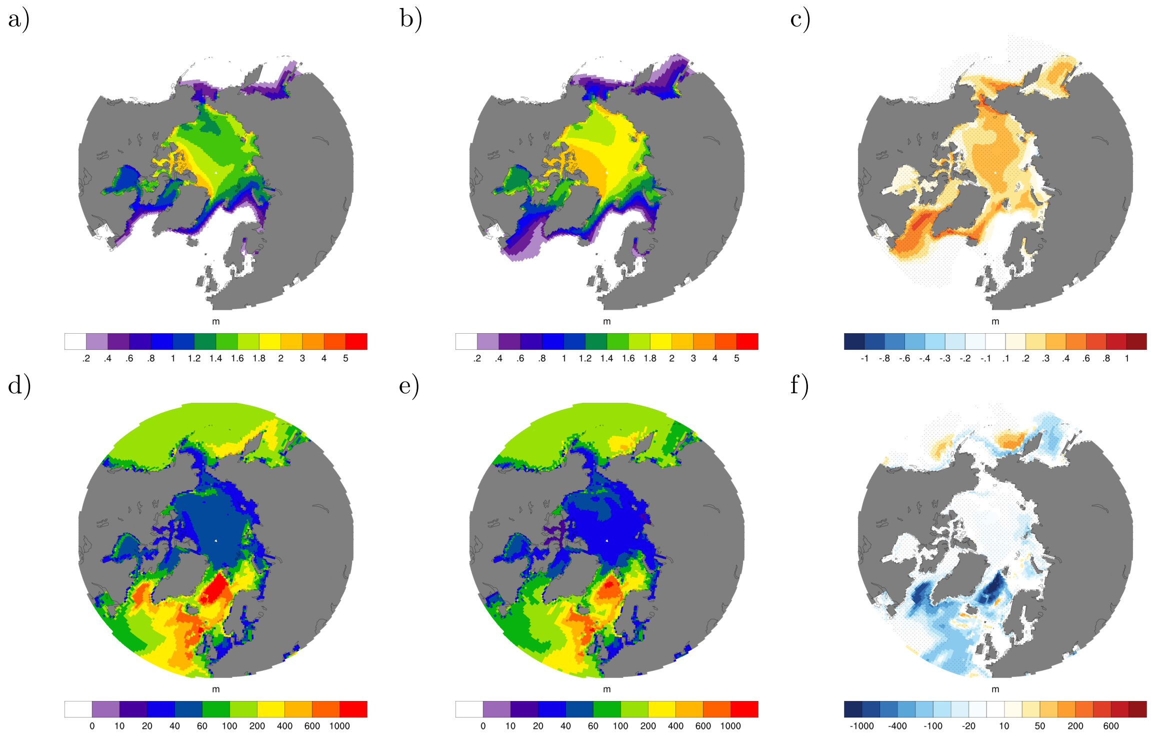



Figure 9: Arctic sea-ice volume in march (in m, top) and annual maximum mixed layer depth (in m, bottom) averaged over the last 50 years of each experiments (2100-2149) a) and d) for the reference experiment, b) and e) for the all_changes experiment and c) and f)for the difference all_changes - piControl. Dots indicate significant changes at the 95% significance level.

### 3.2.2 Impacts on the Arctic region

Figure 9 shows the sea-ice volume in the Arctic in march (the month of maximum extension). The sea-ice cover is now over-estimated over northern Atlantic and Pacific. Such an extension limits the deep water formation in these regions. The change is even drastic in the Labrador Sea (Fig. 9d-e) where in the all_changes experiment, the annual maximum mixed layer depth is reduced from more than 500 m to 100 m. The change in sea-ice and mixed layer depth are very similar in interp_n1. Thus, this reduction in deep water formation in the region probably explains the large AMOC weakening obtained in the sensivity experiments. As seen on figure 6b, the impact of the new interpolation method on the local river discharge is large particularly in winter. This probably explains a larger sea-ice extent. As the Arctic sea-ice extension obtained is unrealistic, this points out that sea-ice tuning made for the reference experiment to reach a realistic sea-ice extent is not appropriate in the sensitivity experiment. A new tuning would be necessary to better match with the observed sea-ice extent.

### 3.2.3 Impact on the Antarctic region

The impact on the Antarctic sea-ice volume is more realistic than the Arctic sea-ice change, as is the increase in ACC. However, in this region, the impact is not similar in all three sensitivity experiments.

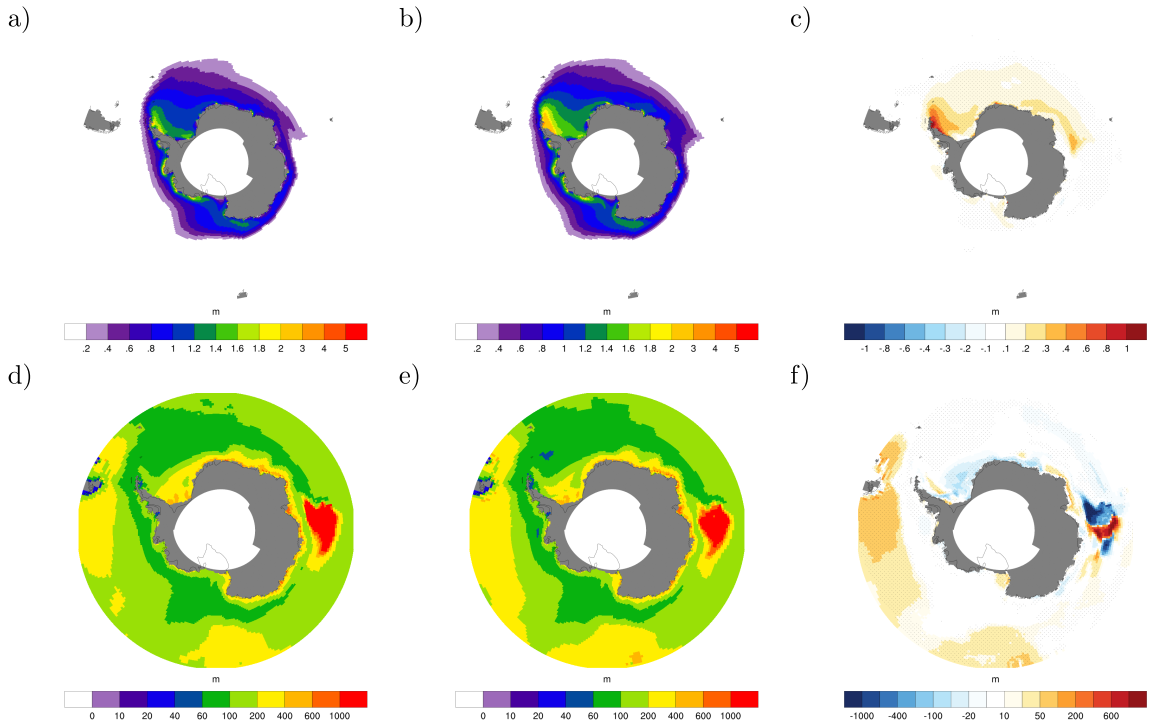



Figure 10: Same as Fig. 9 for the Antartic with sea-ice volume in september.

As there is no impact in interp_n1 and interp_n10, this indicates that it is not the interpolation method which is at play to explain the different sea-ice cover.

To better understand what happens in the austral ocean, Figure 11 shows the evolution of the water fluxes south of 60S. On coastal grid points, the river discharge simulated by TRIP is weaker in the all_changes experiment than in other experiments mainly due to a reduction of TRIP river runoff on Antarctica (Fig. 11a). On this figure, the dashed line indicates the amount of water that originates from inland river discharge (a uniform value applied all over the ocean that originates from all inland river discharge grid points). This flux is much weaker than the coastal discharge around Antarctica and does not greatly impacts the coastal runoff. Now, if we consider the budget over all ocean grid points south of 60S (Fig. 11b), the water flux from rivers is higher in the all_changes experiment than in the others. This is due to the integration of the global inland river discharge over this large domain which results in a large contribution relative to the regional coastal runoffs that are very weak aroud Antarctica. Indeed, in all other experiments, the river discharge flux is zero over non coastal grid points. Even if the value is very weak on all grdi points in the all_changes experiment ($7.5.10^{-3} kg.m^{-2}.d^{-1}$), integrated over the whole ocean surface, this flux is higher than the regional coastal river discharge. However, this remains a small contribution to the surface water budget over open ocean south of 60S since the iceberg flux represents $0.3 kg.m^{-2}.d^{-1}$ in the same region, this is one order of magnitude higher.

The net water flux received at the ocean surface (Fig. 11c) is not significantly changed over the region. This means that the difference comes from the geographical distribution of the river water fluxes. Figure (11d) shows the difference in annual mean river discharge between interp_n1 and all_changes experiments and picture the reduction in coastal water flux around Antarctica, without a clear regional pattern. To summarize, the difference between interp_n1 and all_changes comes from the way the inland river outflow are distributed over the ocean. In interp_n1, it is concentrated on coastal grid points whereas in all_changes it is spread out over a large region. This raises the sensitivity of the Antarctic sea-ice and ACC to fresh water fluxes treatment in the region.

It could be raised that the change in behavior is due to the land-sea mask change. The land-sea mask change could impact the all_changes simulation via an initial chock that would modify irreversibly the large-scale ocean circulation. In the all_changes experiment, the ocean is in equilibrium and a shock could only reflect a disequilibrium in the land surface water content. To check this possibility, an additional experiment has been run in which the initial land water (including snow) reservoirs are better initialised. In this experiment, the large-scale ocean circulation is similarly impacted as in the all_changes experiment, confirming the role of the design of the river-ocean coupling in explaining the difference in Antarctic sea-ice cover.

# 4 Conclusion

A new way to couple river discharges to ocean is proposed and rely on two new features:

- implementation of a new interpolation method from the TRIP river model grid to the NEMO ocean grid to ensure local conservation of water. This new method is independent of the models used so can be useful in other models and applied to other coupling fields (such as calving or geochemical fluxes). The method can be adapted to any model grid supported by the OASIS coupler. The OASIS development team will include this new interpolation method in a future version of OASIS. This feature is very easy to implement, there is only to change the interpolation weights file without model code change.
- separate treatment of coastal river discharges and inland river discharges from TRIP: use of the new interpolation method for coastal river discharges and uniform spreading over the ocean for inland river discharges. This second feature requires modification of TRIP and NEMO codes as well as the addition of a new coupling field to be indicated in the OASIS nameliste file.

Using the new interpolation method, the local conservation of river discharges is assessed on long term control simulations. These changes have large impacts on the sea-ice volume and large-scale ocean circulation. The new interpolation method modifies significantly the extent of the Arctic sea-ice and the deep water formation in the northern Atlantic. The separate treatment of coastal and inland river discharges has a clear impact on the Antarctic sea-ice by limiting the amount of fresh water entering the ocean along the coast. These sensitivity experiments confirm that the treatment of river discharge is an important feature in climate models that has a large impact on the mean climate. This coupling should be implemented carefully. This new method will be implemented in future versions of CNRM-CM along with a new tuning of the sea-ice properties.

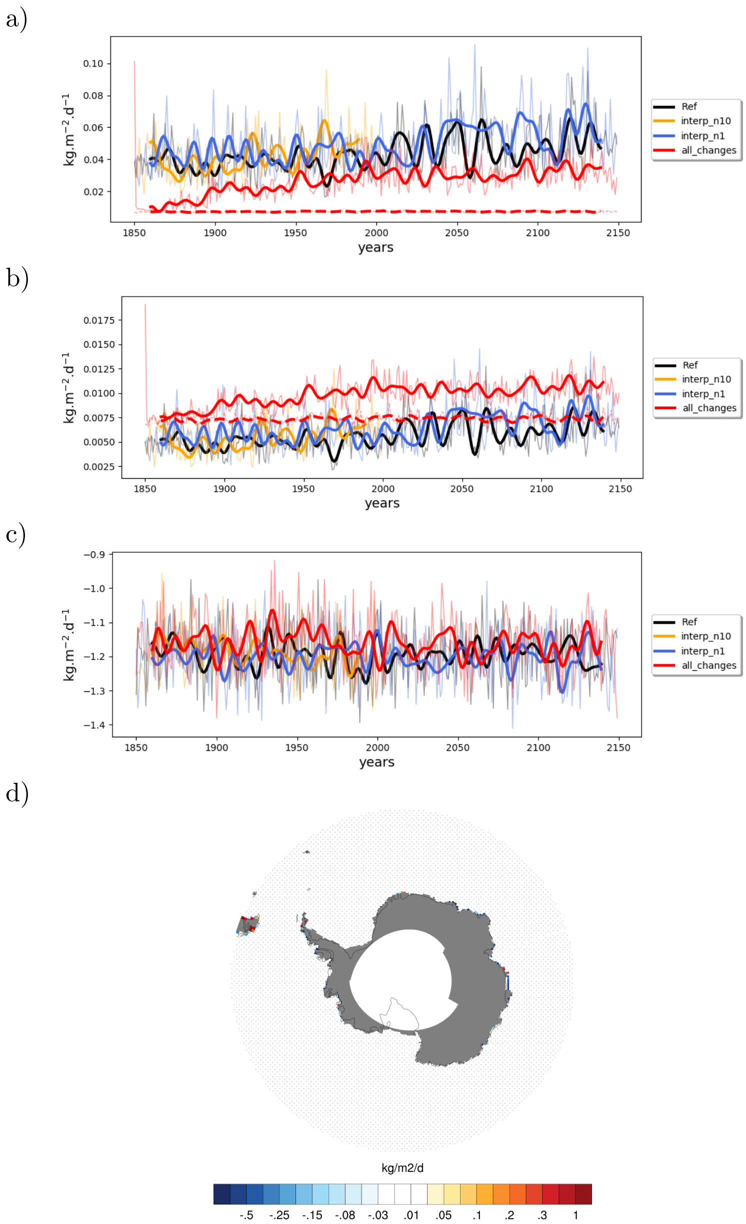



Figure 11: Evolution of a) the river discharge ($kg.m^{-2}.d^{-1}$) received on the NEMO ocean grid averaged along coastal points south of 60S b) the river discharge received on the NEMO grid averaged over all ocean grids points south of 60S, on a) and b) the dashed line indicates the flux received from non coastal grid points as a uniform value over the ocean surface for the all_changes experiment, c) net water flux received at the ocean surface averaged south of 60S for the reference piControl CMIP6 experiment (black) and sensitivity experiments interp_n10 (orange), interp_n1 (blue) and all_changes (red). The bold line represents the low-pass filtered time series with 10 years cut-off. d) Annual mean river discharge anomaly between simulations all_changes and interp_n1 averaged over 2100-2149 (the last 50 years of each simulation). Dots indicate significant changes at the 95% significance level.

## References

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# A Figures additionelles

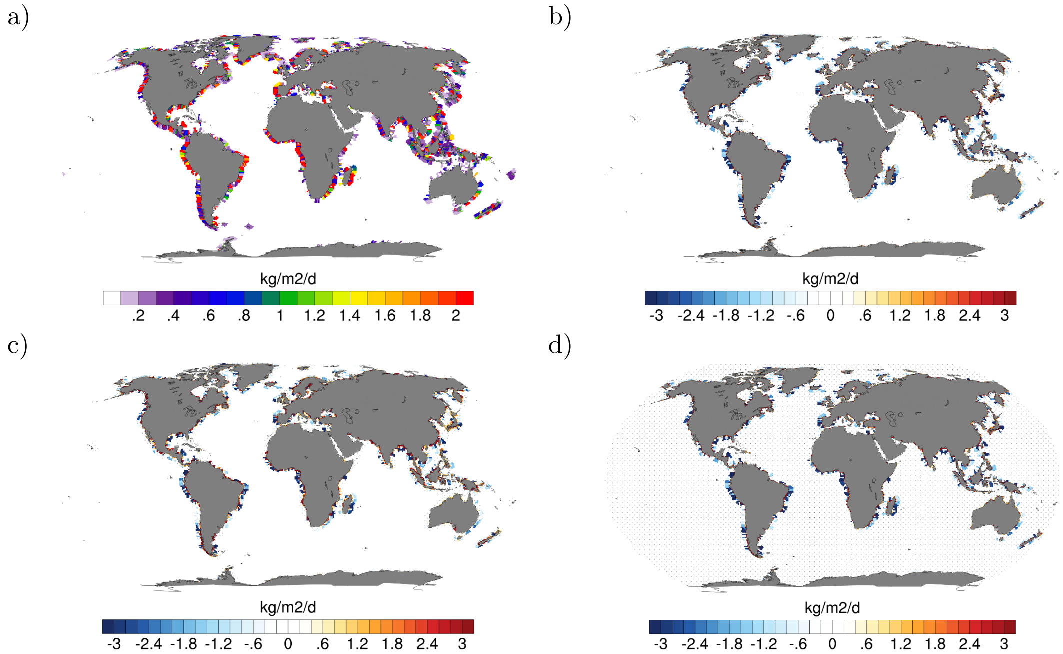


Figure 12: a) Annual mean river discharge to the ocean averaged over 50 years (2100-2149) for the reference piControl experiment, and anomaly to the reference experiment for b) interp_n1, c) interp_n10 et d) all_changes. Note that for the all_changes experiment the flux contains the inland discharges and explains the significant differences found all over the ocean.

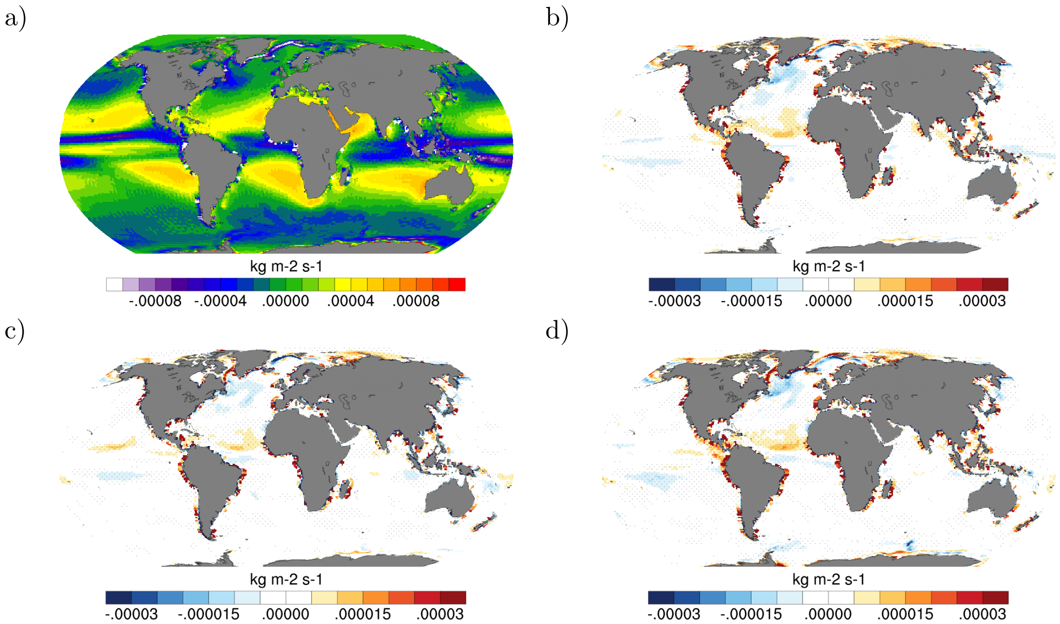


Figure 13: Same as Fig. 12 for the net outgoing water flux at the ocean surface. Dots indicate significant changes at the 95% confidence level.

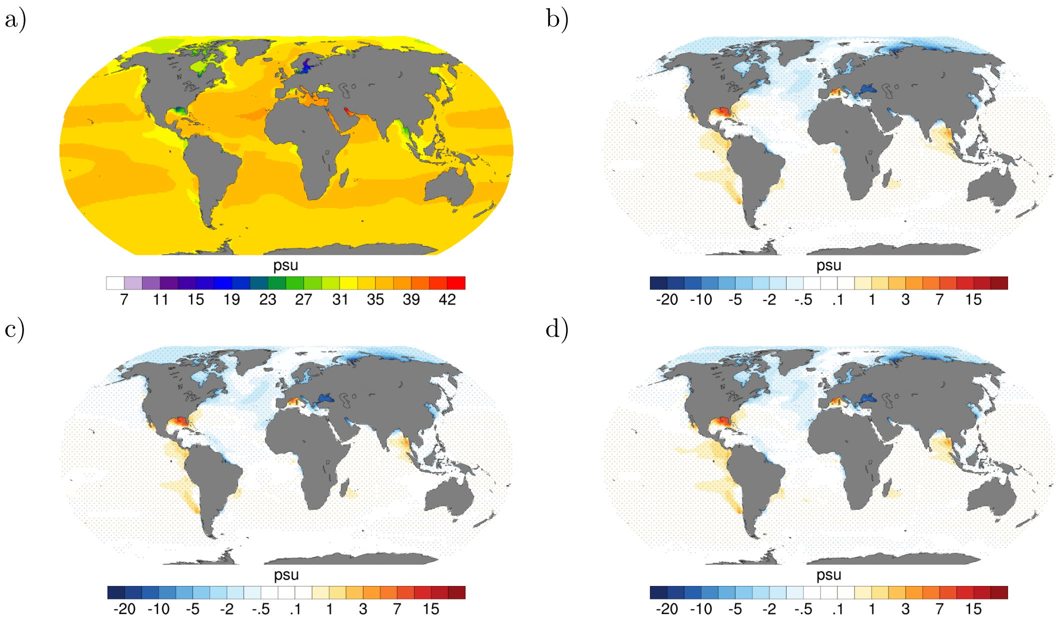


Figure 14: Same as Fig. 13 for the sea surface salinity.

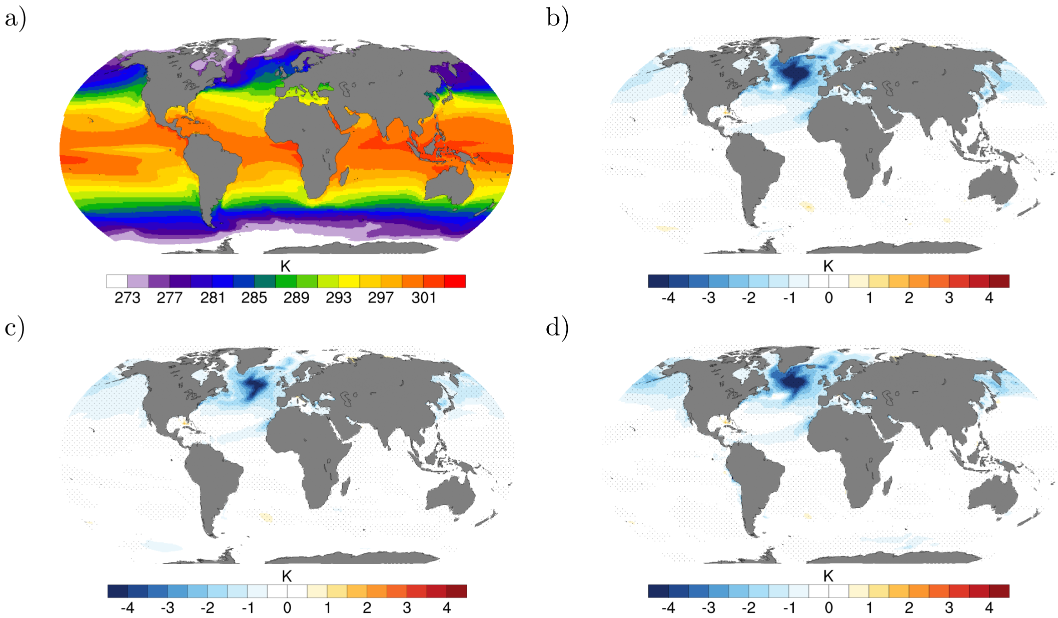


Figure 15: Same as Fig. 13 for the sea surface temperature.