Grant agreement no. 776479

COACCH

CO-designing the Assessment of Climate CHange costs

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D3.3 Climate tipping point analysis

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Contributors:	Gabriel Bachner (UNI GRAZ), Francesco Bosello (CMCC), Elisa Delpiazzo (CMCC), Nina Knittel (UNI GRAZ), Daniel Lincke (GCF), Jochen Hinkel (GCF), Ramiro Parrado (CMCC), Gabriele Standardi (CMCC), Karl Steininger (UNI GRAZ)……

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
CI	Classified, as referred to in Commission Decision 2001/844/EC	

Disclaimer

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Table of contents

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Version log

Version	Date	Released by	Nature of Change
0.1	10/December/18	Francesco Bosello (CMCC)	First draft
0.2	24/October/18	All partners	Request for input
03	18/July/2020	All partners	Second draft
04	31/July/2020	CMCC	Final version revised by the coordinator

Summary

This deliverable assesses the economic implications of the climatic tipping points identified in D3.2 (Scoccimarro et al. 2020). These are: global extreme sea- level rise, Alpine glaciers disappearance, disappearance of Arctic Summer sea ice and the slowdown of thermoaline circulation.

In what follows, only the first three tipping points are assessed economically, as the fourth, collapse of Thermoaline circulation, is very unlikely to occur within the century. Furthermore, the far reaching and potentially catastrophic nature of the associated consequences offer a very difficult if not unsuitable context for the application of economic assessments. A qualitative description of consequences of that tipping point is anyway reported in Soccimarro et al. (2020).

The study on sea-level rise analizes with the COIN-INT and the ICES computable general equilibrium models, respectively by Graz University and CMCC, the consequences of a 1.7 m sea-level rise that responds to the “tipping point nature” of ice sheet instability leading to concluding that “… it is about as likely as not that high end – more than 1.0 m- sea-level rise (SLR) will occur until 2100” (Lincke et al. 2018).

If SLR trend, even though intensifying, remains smooth, severe economic impacts are expected after 2050. However some EU areas like Latvia, Malta, Italy and in particular its Veneto region, can be affected with GDP losses larger than the 5% already in 2050. Higher losses at the sectoral level can be also experienced: for instance according to COIN-INT, agricultural production losses can be larger than the 6% in Germany, France, UK, Belgium, and other Northern European countries.

In 2070, the sub national assessment conducted with the ICES model shows that 50 EU regions over a total of 269 can experience GDP losses larger than the 5%. At the sectoral level, industrial production seems particularly affected with 47 regions, showing a loss larger than the 10%, peaking to the 23% in Malta and 20% in the Hamburg area.

The regional analysis also emphasizes how losses can be transmitted across regions. It is particularly interesting to note that those areas that in the different countries are particularly interconnected economically, not only with coastal areas, but also with the overall economic trade flows, which often coincides with regions where country capital

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cities are located, show losses of comparable magnitude. The cases of Piedmont and Lombardy in Italy, of the Ile de France in France, Madrid in Spain and of central Germany is emblematic.

Both modelling exercises confirm the huge benefit to cost ratio of coastal protection.

The deliverable then evaluates glaciers as a source of economic value along three different threads. The first is the relevance for tourism, both for skiing and other sports and as attraction. The analysis shows that roughly 4 billion EUR across the Alps is directly concerned by glaciers disappearance. The analysis then develops the case-study of the Pasterze glacier in the Austrian Alps. This glacier is a significant tourist attraction in the country with almost 1 million visits per year. A "preventive" cost analysis estimates that the costs associated with the necessary artificial snow production to prevent glacier vanishing is roughly 100 million EUR/year, which would by far exceed the estimated economic benefit generated by tourists.

The second line of investigation covers the support of glaciers to hydropower production. The starting point is the output of a global glacier model based on 14 GCMs under several RCPs to assess the absolute and relative glacier contribution to summer discharge for selected power plants in the Alps. The economic impact of reduced water availability is significant. In the case of Austrian hydropower electricity production, for instance, revenue lost can be € 163 mio. in the 2046-2075 period and € 184 mio. in the 2071-2100 period under the moderate warming RCP2.6 scenario. With a complete glacier retreat the cost can peak to € 215 mio. per year.

The impact of glacier meltwater dynamics on inland water transport highlights that a total glacier disappearance would increase the number of non-navigable days in the Kaub at the Rhine rivers from the current 7 days per year on average in the period 1986-2015, to potentially 12. Under current economic conditions the latter would imply for instance a potential loss of 0.4% or German industrial production, corresponding to a loss of German GDP at about € 35 billion, on average per year.

The transformation of the artic summer into an "Antarctic like" season would affect the regional economic and social structures. Defining the overall sign of these impacts is challenging. While some of them are widely considered positive, such as the opening of the Northern Sea Route, the Northwestern and Northeastern Passages, effects on ecosystem services are not clear. Thus, it is uncertain to assess the overall economic impact of reducing Artic ice. For the transport sector, the economic effect is slightly positive but highly uncertain in the future, mainly because of the inability to define when routes would be completely ice- free and to have a consistent framework of rules. Moreover, the development and exploitation of the new routes are strictly correlated to other local bottlenecks such as poor infrastructures and the lack of legislative regulations. Similar problems would arise for the cruise sector that could sustain local communities' incomes but at the same time it could increase black carbon pollution and, as a loop, amplify the ice melting process. Its negative effect on ecosystem services and habitat loss could counterbalance and possibly outweigh the positive sectoral economic benefits. Similarly, oil extraction has high environmental costs associated with oil leaks from pipes, oil spills and the required infrastructure

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development besides the increased carbon emissions resulting from oil use; mining for minerals and metals has very high environmental costs too. The necessity for a body of laws and the international cooperation among Artic countries appear as a keystone to maximize potential economic gains that are uncertain in the future.

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1. Introduction

This deliverable operationalizes the second part of COACCH task 3.2: “climate tipping point”. It assesses the economic implications of the climatic tipping points identified and “probabilised” in D3.2 (Scoccimarro et al. 2020).

These are: global extreme sea- level rise, Alpine glaciers disappearance, disappearance of Arctic Summer sea ice and the slowdown of thermoaline circulation.

In what follows, only the first three tipping points are assessed economically, as the fourth, collapse of Thermoaline circulation, is very unlikely to occur within the century. Furthermore, the far reaching and potentially catastrophic nature of the associated consequences offer a very difficult if not unsuitable context for the application of economic assessments. A qualitative diescription of consequences of that tipping point is anyway reported in Soccimarro et al. (2020).

Methodologically, the analysis of extreme sea-level rise starts from the direct impact assessment of a 1.7 m sea level rise qquantified with the DIVA model in COACCH D2.3 (Hinkel et al. 2018) whose output are used as input information for the two COACCH macroeconomic computable general equilibrium models: COIN-INT by Graz University and ICES by CMCC. The models offer slightly different perspectives for the assessment of sea level rise impact on economic performances of EU countries, sectors and regions within countries. Namely, although input information is the same, the models partially differ in baseline calibration, in the value of behavioural parameters, in the geographical detail. The two separate macroeconomic assessments are thus followed by a model comparison exercise that highlights robust findings and emphasizes which model drivers are more relevant in determining the results.

The analysis of the economic consequences of Alpine glacier melting considers three relevant activities related to glaciers: tourism, hydropower production, and riverine transportation. The tourism assessment is conducted developing an in depth case study on the Pasterze glacier in Austria, in addition to tourism flows, also the costs of artificial snowmaking needed to keep the glacier attractiveness at today’s level are evaluated. The economic assessment of impact on hydropower and transportation are developed in direct costing exercises.

Finally, the potential economic consequences, mostly related to changes and shifts in maritime routing through the Northern Sea Route (NSR) or North Western Passage (NWP) due to the disappearance of Arctic Summer sea ice are discussed by a literature review.

The organization of the deliverable is the following: section 2 briefly recalls major findings from Scoccimarro et al. (2020) on climatic tipping points. Section 3 is dedicated to the analysis of global “extreme” sea-level rise, section, 4 relates to the disappearance of Alpine glaciers, section 5 presents the survey on potential costs associated to disappearance of Arctic Summer sea ice.

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2. Climate tipping points within the XXI century

COACCH D3.2 (Scoccimarro et al., 2020) identifies and analyzes four different climate tipping points and the associated probability of occurrence within the XXI century: global extreme sea- level rise, Alpine glaciers disappearance, disappearance of Arctic Summer Ice and the slowdown of thermoaline circulation.

Main conclusions from the analysis are the following:

- Regarding *Global Sea Level Rise*, (CT1) the tiping point can originate from the melting of the polar ice sheets. Despite the uncertainty in ice-sheet response, it can be stated that in RCP2.6 and RCP4.5 high end SLR of more than 1.0 m is extremely unlikely within the current century, same as for RCP8.5 until 2050. However, it is about as likely as not that high end – more than 1.0 m will occur until 2100.
- Regarding *Alpine glaciers disappearing*,(CT2) considering 10% of the current cover as a threshold to define the Alpine glacier disappearing, only few ensemble members suggest that this could be reached within 2100. Nonetheless, average reductions in the order of 80% / 60% are expected for the end of the century already in the RCP4.5 / RCP2.6 scenario.
- Regarding *Arctic Summer sea-ice disappearance*, (CT3), associated abrupt changes in atmospheric circulation are not exected within the century. Relevant ice melting, however can be expect within the current century, at least under RCP8.5. Therefore, more regions in the Arctic will become less dangerous for navigation.
- Regarding the *slowdown of the thermohaline circulation* in the Atlantic basin (CT4), it results that the chance of abrupt transition or collapse in the 21st century for the scenarios considered is very unlikely.

In the light of these outcomes the following analysis focuses just on the first three climate tipping points. Qualitative discussion of CT4 is reported in Scoccimarro et al. (2020)

3 CT1 - Global Sea Level Rise

In Deliverable 3.2 (Scocciamrro et al. 2020) we have shown that uncertainty in sea-level rise stemming from the melting of glaciers and ice caps and from thermal expansion of the ocean water can be quantified reasonably well and has no tipping point characteristics. Estimates of the contribution to sea-level rise from the melting of the polar ice sheets, however, vary widely reflecting a "tipping point potential" of ice-sheet collapse. In particular, the review of recent studies showed that, for RCP8.5 it is about as likely as not that SLR of "more than 1.0m will occur until 2100". Accordingly, we extended the COACCH scenario matrix with a high-end sea-level rise scenario that

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models a global coastal mean-sea-level rise of 1.7m until 2100 (Lincke et al., 2018). While the tipping point of the unstoppable and permanent loss of the global ice-sheets does not necessarily imply such a scenario, a rapid melting of one or more global ice-sheets is a necessary condition for such a scenario. Indeed, steric sea-level rise and glacier melting alone are not sufficient to reach these high sea-level rise values. In this section we recall and expand the analysis of the direct impacts of this high-end sea-level rise developed initially in D2.3 and extend the assessment including the examination of its macroeconomic consequences. To do this, we apply two general equilibrium models: the COIN model by Graz University and the ICES model by the CMCC. The use of two models is important to test the robustness of our macro-economic conclusions. Furthermore, it highlights what model assumptions contribute to influence the results and in which direction.

3.1 Direct impact assessment

The direct impacts of the high end scenario have been explored in COACCH Deliverable D2.3 (Lincke et al., 2018) and are summarized in **Figure 1**.

The direct costs of sea-level rise are defined as the sum of sea flood cost, protection cost, migration cost and land loss cost in relation to GDP. These costs include the damages to capital assets that are flooded, the investment cost for constructing coastal protection infrastructure and the maintenance cost to maintain it, the cost of people permanently moving out of the coastal zone, and the value of land lost by permanent inundation.

It emerges that, for instance, in the EU28, sea flood cost in the 2080s are roughly three times higher than those of the RCP8.5 scenario assuming medium ice sheet contribution and no further adaptation taken. If adaptation is allowed, protection costs under the high end scenario in the 2080s are roughly twice those of the RCP8.5 scenario with medium ice sheet contribution.

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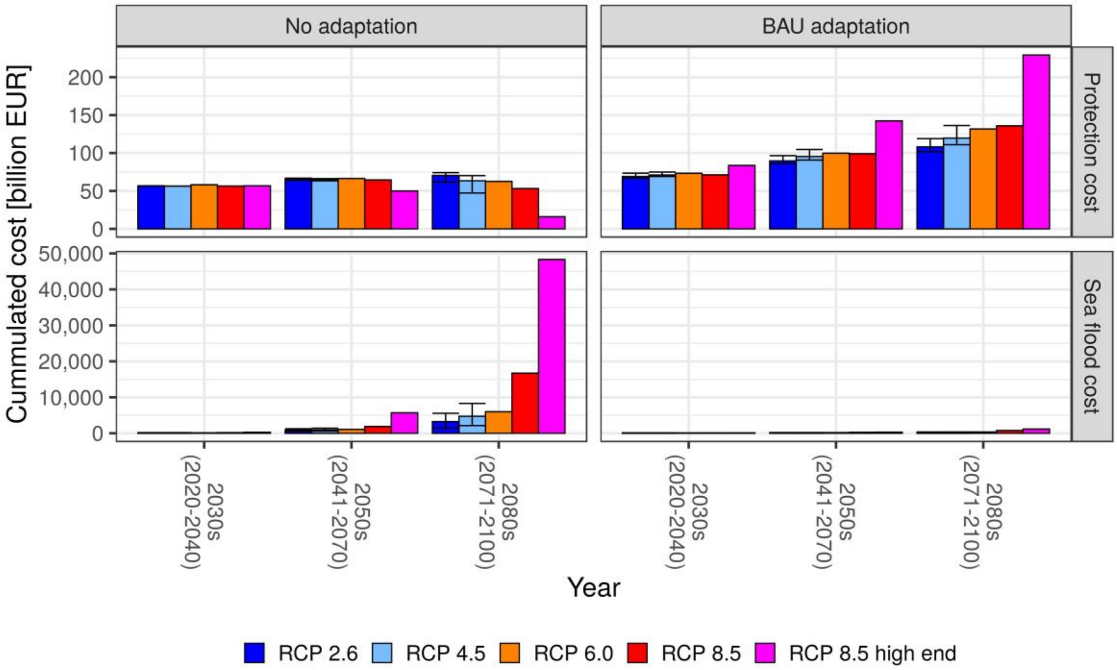

Figure 1: Accumulated EU28 sea flood and protection cost over different time periods of the 21st century. Error bars for RCP 2.6 and RCP 4.5 show the uncertainty range over all runs done for these RCPs. Source: Lincke et al., (2018)

As shown in **Figure 2**, these costs can be as high as 170% of country GDP if neither adaptation nor migration actions are taken. Most affected countries are small island nations as Marshall Islands (MHL), Maldive (MDV), Tokelau (TKL), Tuvalu (TUV) and Kiribati (KIR). But in total, 24 countries experience total cost of SLR exceeding 20% of their GDP. Note however that coastal protection and/or migration from areas at risk can reduce these costs significantly.

This applies to the EU 28 as well (**Figure 3**). For instance, in 2080, the largest losses (50% of GDP) are experienced by Aaland, a small island area with mainly low-lying inhabited areas. However, adaptation policies combining protection and retreat can reduce cost below 1% of GDP.

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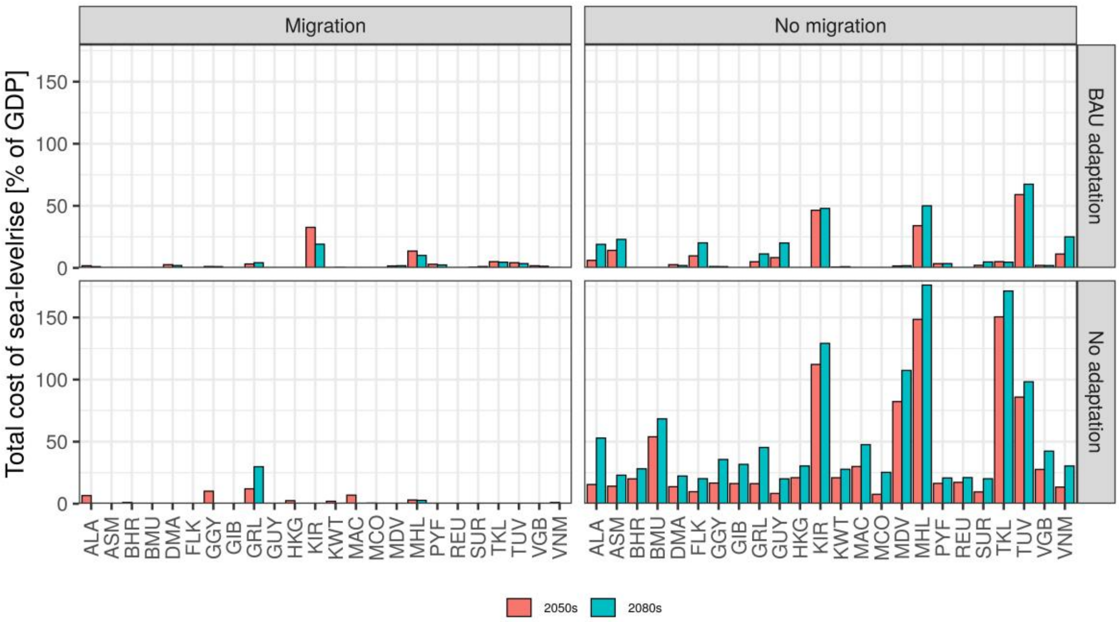

Figure 2: The relative cost of sea-level rise for the most affected countries under the RCP 8.5 high end SLR scenario. All countries with relative sea-level rise cost of at least 20% in the no further adaptation/no migration scenario are shown**.**

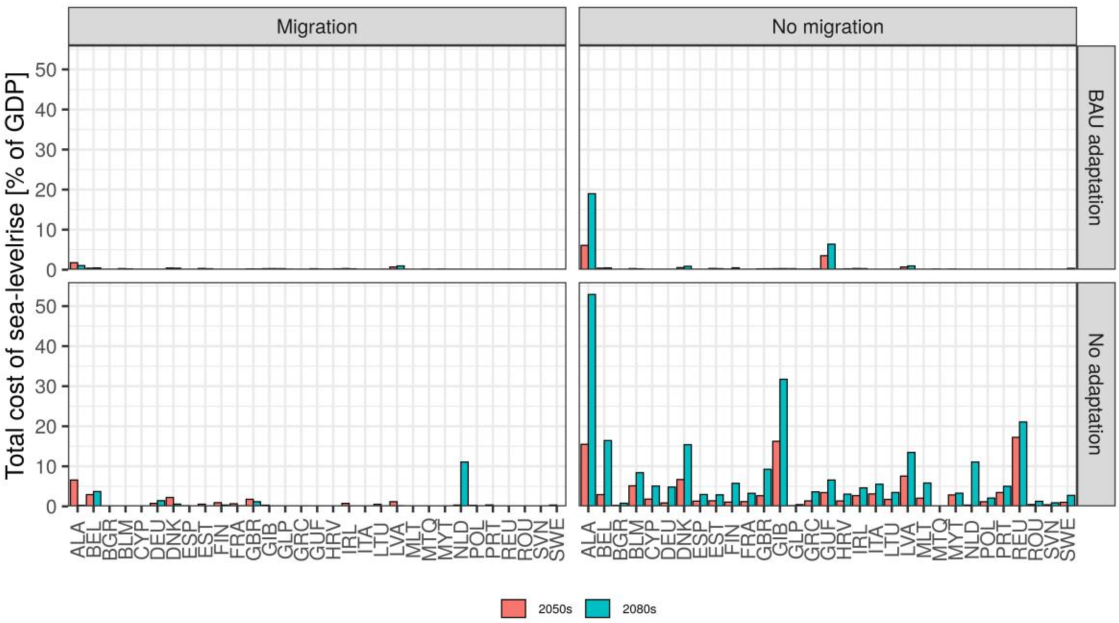

Figure 3: The relative cost of sea-level rise for the coastal EU28 countries under the RCP 8.5 high end SLR scenario.

Note that the evaluation performed so far is "direct". Costs are computed multiplying a "price" (e.g. value of assets) time a "quantity" (e.g. assets lost). Even though this is eventually reported in percent of GDP, this does not really reflect how GDP is finally affected. To do this, it is necessary to be endowed with tools that represent explicitly how sector and country economic performances are affected by the impacts. This is done in the next sections.

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3.2 Macro-economic assessment

The macro-economic assessment consists in evaluating the same physical impacts driving the direct cost assessment in section 3.1 with two computable general equilibrium models, the COIN-INT model by Graz University and the ICES model from CMCC.
Impacts are assumed to occur in a world characterized by the socioeconomic drivers of SSP5 and the climatic drivers of RCP8.5 “high-end ice melting”. To highlight the role of the ice melting assumption, we also include results from a medium ice melting case.
We also consider two adaptation scenarios: i) No additional adaptation (NoAd), a hypothetical scenario where adaptation measures are kept at their current level and ii) Business as usual adaptation (BauAd), where, more realistically, coastal protection is increased with increasing sea level.
Input information derives from the DIVA model and refers to:

a) Annual land loss due to submergence (km^2/year)
b) Expected annual damages to assets by sea floods (million US$/year)
c) Total capital stock (million US$/year)
d) Expected annual number of people flooded per year (thousands/year)
e) Protection costs (million US$/year).

For a consistent flow of information across each CGE model and DIVA, all values from DIVA, expressed in US$ PPP (Purchasing Power Parity) are converted to US$ MER (Market Exchange Rates), the CGE models’ reference, using the conversion factors from the World Development Indicators (World Bank, 2017).

The physical and economic data of the spatially resolved DIVA model are aggregated to match both the COIN-INT and ICES spatial resolution.

3.2.1 COIN-INT – Impact modelling

The impacts of sea level rise are implemented in COIN-INT via five channels: First, sea flood damages reduce the physical capital stock (capital costs). Second, we assume that each person that is flooded within a year, is not able to provide labour to the labour market for 2 out of 48 working weeks a year (labour costs). Third, the annual land area that is lost due to SLR is translated into lower cropland availability for agricultural crop production (land loss). Fourth, investment costs for renewing sea dikes or for upgrading them (in the case of adaptation) is modelled as forced investment activity of the government agent (investment cost fraction of DIVA’s protection costs). Fifth, maintenance costs for sea dikes are implemented as forced government consumption for construction activities (maintenance cost fraction of DIVA’s protection costs). The Appendix reports a more detailed description of the implementation of impacts.

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3.2.2 COIN-INT – Results

The five impact channels of sea level rise translate into GDP effects as shown in Figure 4.[1] In the NoAd cases and for high ice melting, GDP effects in the European regions are strongest in Italy (ITA) and Northern Europe (NEU), reaching losses of up to -4.5% in 2050 (lower GDP as compared to the Baseline). For Non-European regions effects are much stronger, reaching GDP losses of up to -11% in Asia's emerging economies (ECA). Due to comparative advantages we see slight positive GDP effects in landlocked regions, such as Austria (AUT) and Central Europe (CEU).

GDP losses are much lower, when planned adaptation in the form of dike heightening is implemented. The associated adaptation costs are accounted for as additional forced investment by the government. This is assumed to not increase the productive capital stock, but is only stimulating GDP in the short run. For EU regions we see that even with planned adaptation in place, GDP losses reach up to -1% (NEU, ITA) and up to -2.5% in non-European regions (all in 2050). To visualize the macroeconomic benefit of adaptation, we show in Figure 5 the %- point difference of changes in real GDP between NoAd and BauAd in 2050.

By comparing these results with a medium ice melting scenario we see that impacts on GDP are much higher, in the former case (Figure 6)[2]. For instance, in the NoAd scenario, GDP losses for ITA and NEU would be more than two to three times larger under high end ice melting. For non-European regions GDP differences are even larger topping to a four-fold increase in ECA. Under BauAd the differences get smaller, but are still notable.

GDP is often criticized as not being a fully informative welfare indicator in general and in particular for climate change impacts and adaptation assessment. One reason is that some negative impacts might in fact stimulate GDP (at least in the short term), another one is that GDP also includes relative price effects which might increase a regions GDP, but does not take into account the changes in purchasing power of people when prices change. To address particularly this last shortcoming we also measure the climate change impact on the Hicks'ian Equivalent Variation. This macroeconomic indicator, often considered a better proxy for welfare, measures the change in economy-wide consumption possibilities accounting for household consumption preferences. We find (Figure 7) that welfare effects in the BauAd scenario are often stronger than GDP effects, since protection costs (investment and maintenance) are forced expenditures which crowd out (government) consumption, leaving less budget for welfare enhancing consumption.[3]

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[1] The regions abbreviations are as follows: DEU: Germany; AUT: Austria; ITA: Italy; UKD: United Kingdom; FRA: France; BLU: Belgium and Luxemburg; NLD: Netherlands; CEU: Central Europe; NEU: Northern Europe; MEU: Mediterranean and Southeastern Europe; NAM: North America; AUZ: Australia and New Zealand; ERA: Eurasian countries; ECA: Emerging economies-Asia; TUR: Turkey and Israel; CHN: China; IND: India; SEA: South-East Asia; LAM: Latin America; OIE: Oil exporting countries; AFR: Africa.

[2] See Figure 15 in the Appendix for GDP changes relative to the baseline in the medium ice melting case.

[3] See Figure 16 in the Appendix)

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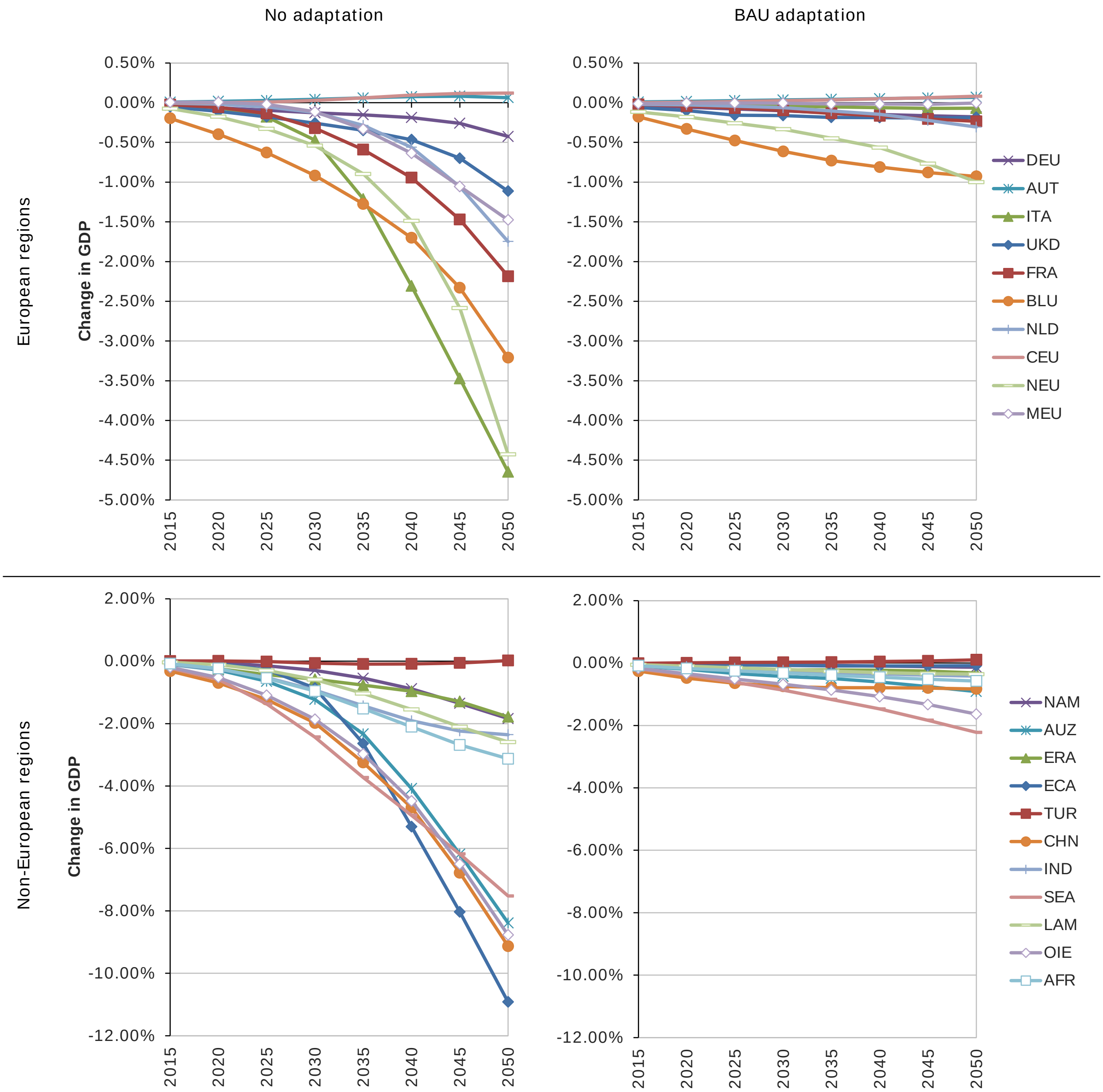

Figure 4: Change in real GDP in 2050 relative to Baseline scenario (SSP5-RCP8.5) for high end ice melting. Left: No Adaptation, right: BAU Adaptation, top: European regions, bottom: regions of the rest of the world. [Results from COIN-INT CGE model]

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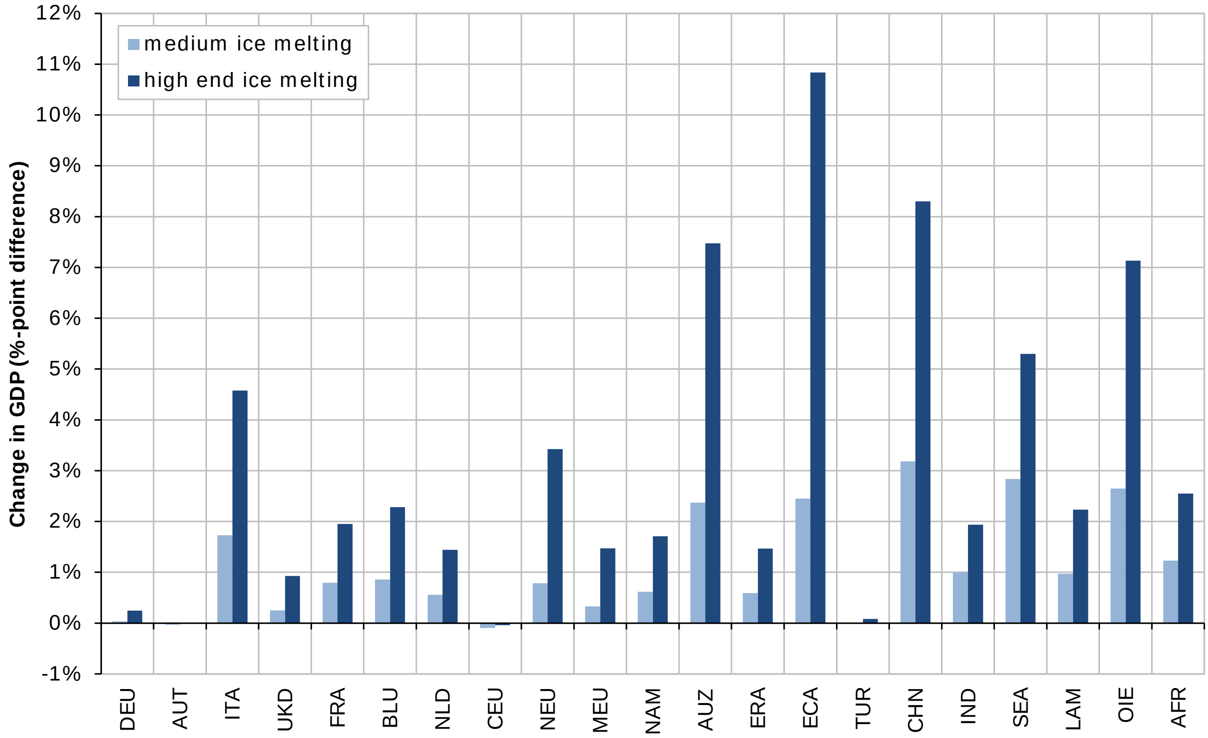

Figure 5: The benefits of adaptation in 2050 as percentage point difference of changes in real GDP (SSP5-RCP8.5) between No Adaptation and BAU Adaptation. [Results from COIN-INT CGE model]

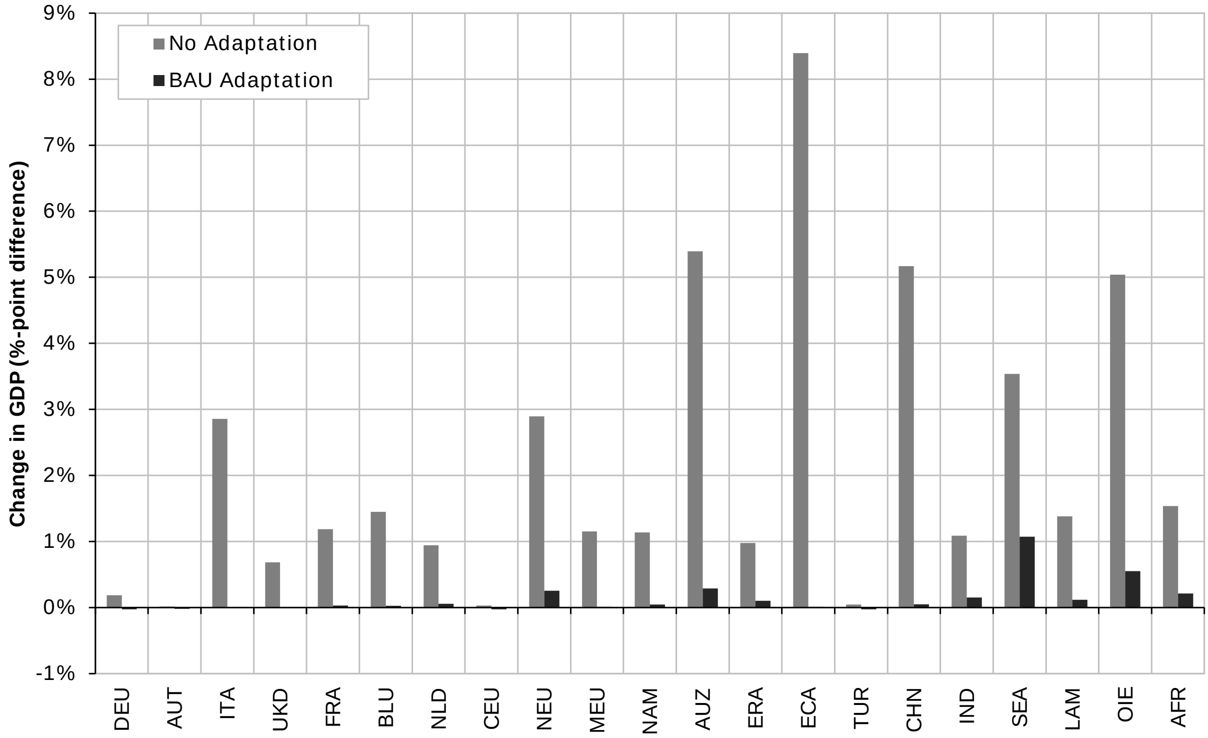

Figure 6: Percentage point difference of changes in real GDP in 2050 (SSP5-RCP8.5) between medium ice melting and high end ice melting [Results from COIN-INT CGE model]

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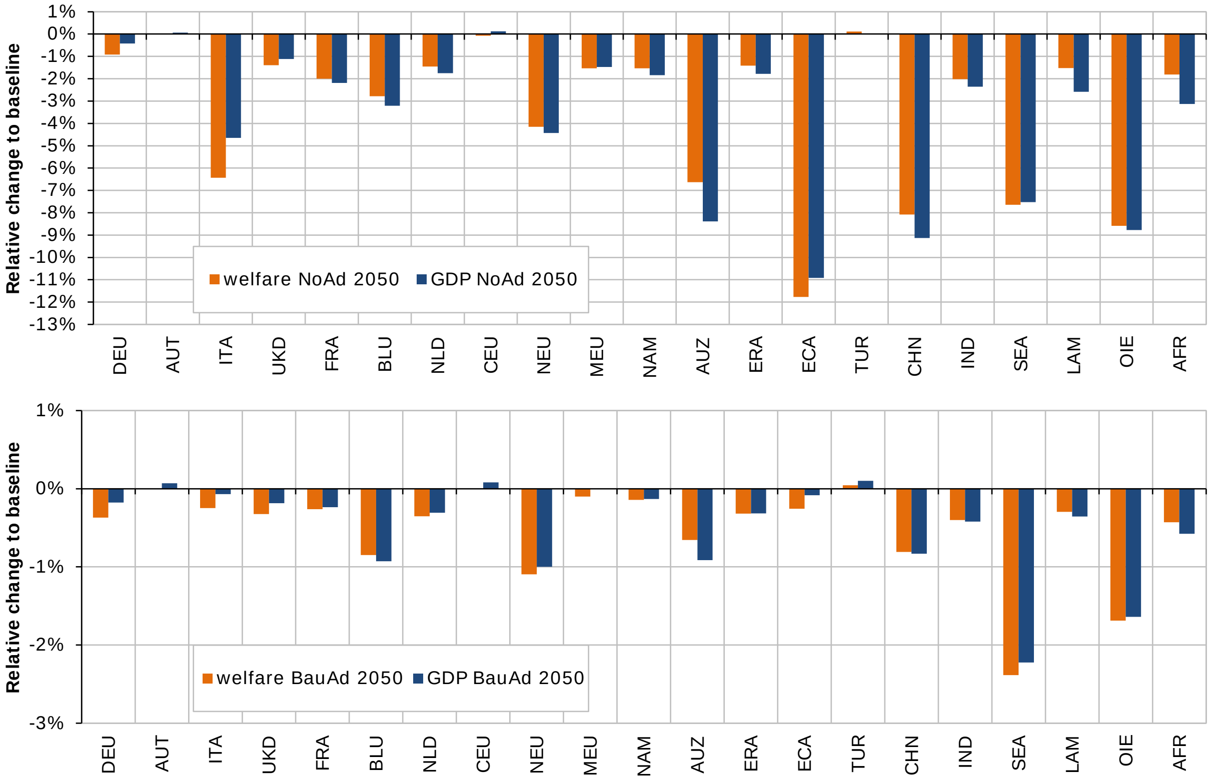

Figure 7: Comparison of welfare (Hicks'ian Equivalent Variation) and GDP effects for No Adaptation (top) and BAU Adaptation (bottom) in 2050 with SSP5-RCP8.5 high end ice melting.

Turning to impacts at the sectoral level, we aggregate the total of 21 COIN-INT sectors to four macro-categories: Primary (sector, i.e. agriculture), Energy, Industry, Services (see Table 1 in the Appendix for details). Figure 8 shows for the European regions and for non-European regions, how sectoral output (quantities) change under the high end ice melting scenario, relative to the baseline.

Sectoral impacts are much stronger under the NoAd scenario, the patterns between NoAd and BauAd are similar, though.

Impacts on the primary sector, are largely negative. This is explained by the sea level rise-induced agricultural land losses, combined with lower demand due to lower general economic activity. Note, that foreign trade effects also play an important role. For example, Austria is a net-exporter of primary products and thus suffers from decreased demand abroad. One exception here is Italy, where we see positive effects in the primary sector, indicating specialization of Italy and that Italy gains from a comparative advantage effect with respect to the rest of the world.

When looking at the energy sector we see that in most regions sectoral activity increases. This can be explained by substitution effects. Since capital is getting scarcer, capital rents (or "capital prices") are higher. Thus, production processes in the long term tend to be less capital intensive, and partially more energy intensive. This effect

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is in some cases outweighed, by contraction in overall economic activity like in the case of Italy or other strongly affected non-European regions. Interestingly, the overall net effect on emission is a quite substantial increase (Figure 9).[4]

Regional effects on the industrial sector are highly differentiated. In general they are more negative in non-European than in the European regions. Gains in Industry output occur in least SLR -affected regions, which can take advantage of their highly competitive industries; i.e. Germany (DEU), Austria (AUT), Netherlands (NLD) and to some extent Central Europe (CEU; including Switzerland) and United Kingdom (UKD).

For the Service sector we see negative effects throughout all regions, which can be explained by lower income and thus lower demand for services. Since services are typically region specific, we do not see trade-related differences across regions.

[4] Note that in COIN-INT different electricity generation technologies are modelled explicitly; i.e. there are a set of renewables and a set of fossil fuel-based technologies available, which can be substituted for each other.

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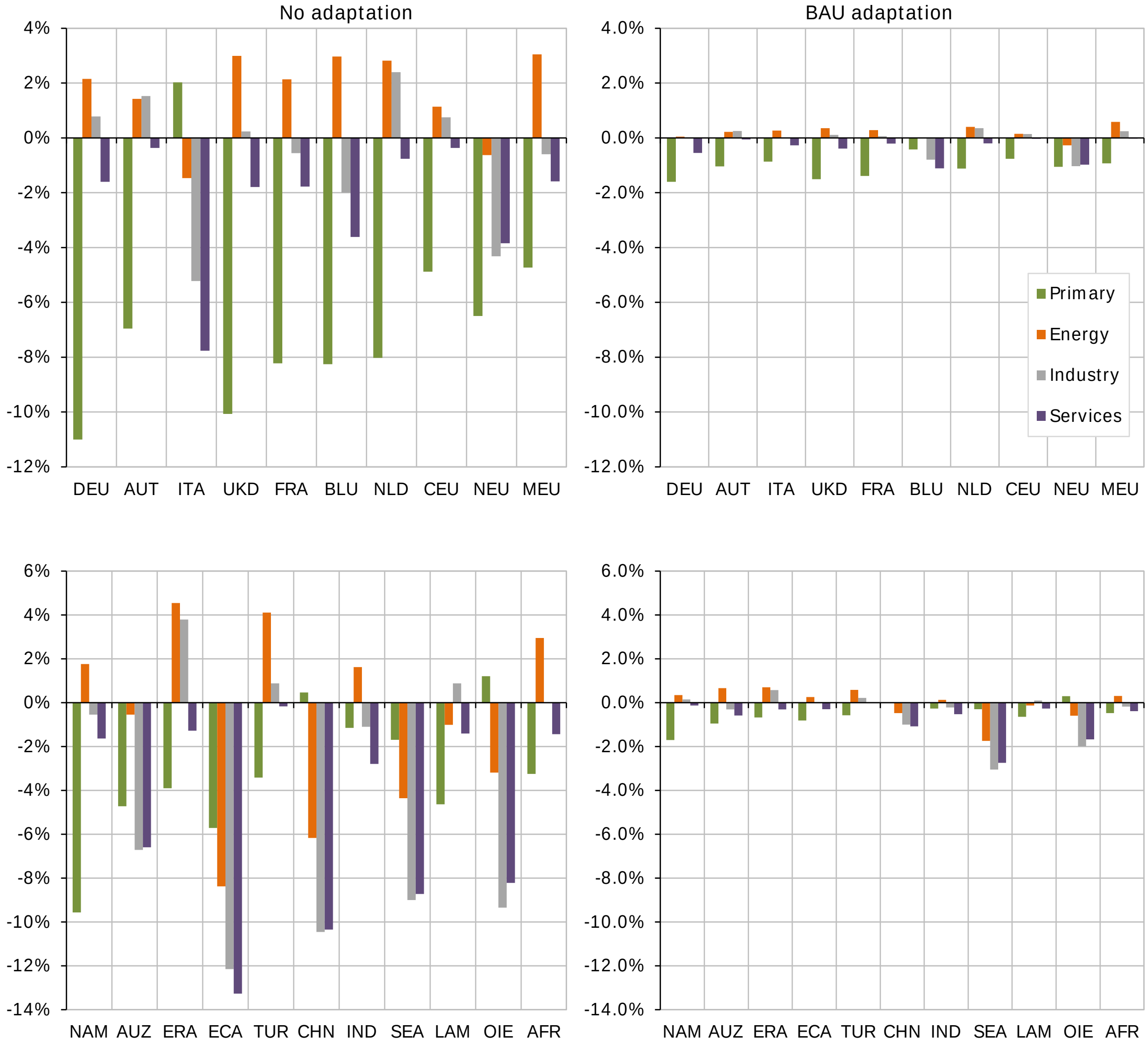

Figure 8: Change in sectoral activity relative to Baseline scenario in 2050 (SSP5-RCP8.5) for high end ice melting. Left: No Adaptation, right: BAU Adaptation , top: European regions, bottom: regions of the rest of the world. [Results from COIN-INT CGE model]

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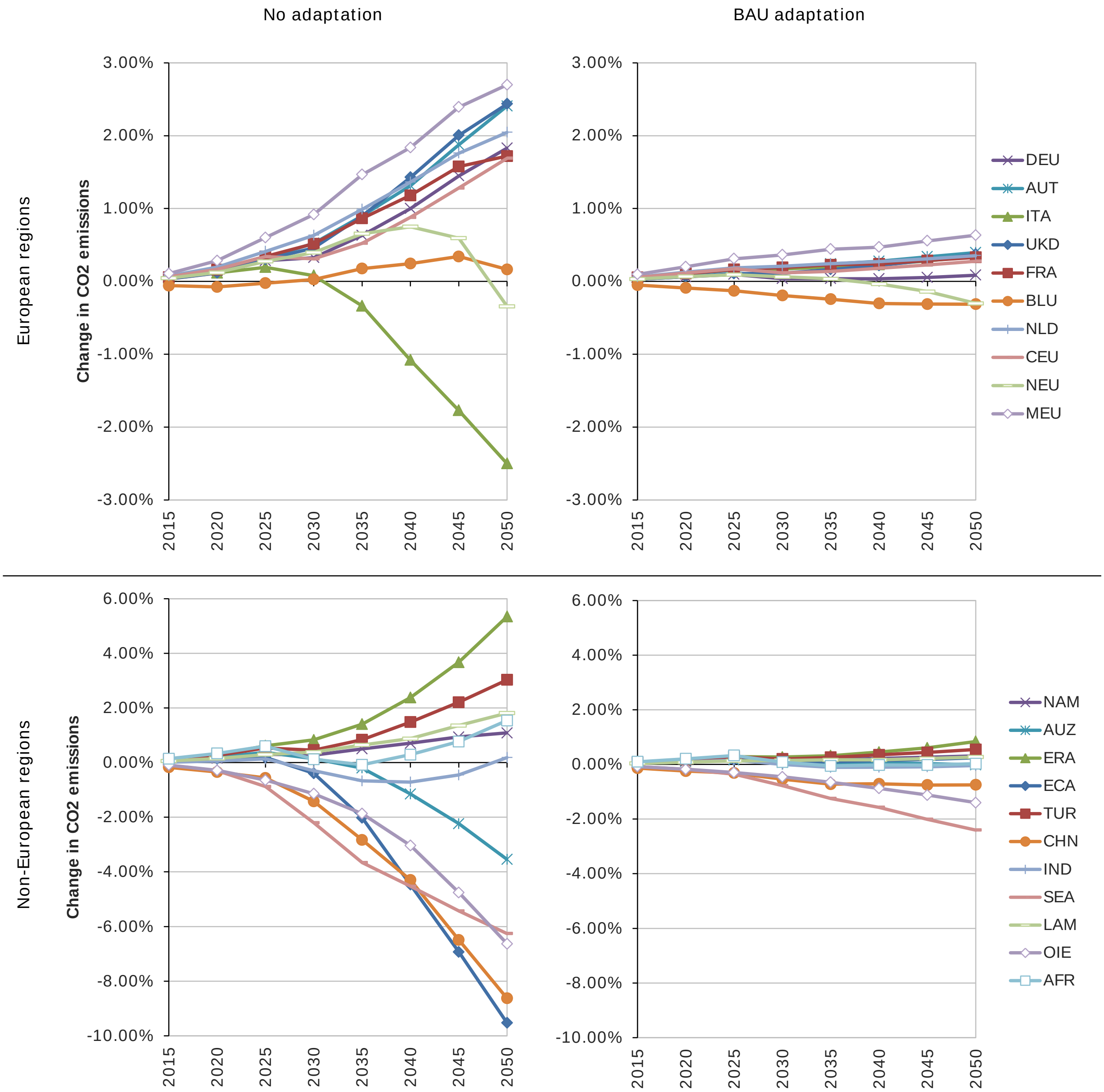

Figure 9: Change in CO_2 emissions relative to Baseline scenario in 2050 (SSP5-RCP8.5) for high end ice melting. Left: No Adaptation, right: BAU Adaptation , top: European regions, bottom: regions of the rest of the world. [Results from COIN-INT CGE model]

3.2.3 ICES – Impact modelling

Sea-level rise impacts are implemented in the ICES model exactly the same way they are in the COIN-INT model. In particular:

a) land loss is modelled decreasing the stock of productive land available to agriculture assuming this coincides with submerged land,

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b) labour productivity loss is modelled assuming that people flooded are not able to work for 2 working weeks per year.[5]

c) asset losses are modeled decreasing capital stock according to the ratio of expected annual damages to assets by sea floods over total capital stock using the DIVA model data.

For a more detailed description of the impact implementation in ICES we address the interested reader to COACCH Deliverable 2.7 (Bosello et al., 2020).

Some differences across modeling exercises relate to the implementation of adaptation (coastal protection) activity. In the ICES model this is simulated as a reduction in capital stock that translates into a lower investment and thus capital services, but also in a lower environmental damage.

A major difference with the COIN-INT model and exercise is that ICES disaggregates the EU at the sub national level (NUTS 2 and 1). It is thus possible to identify impacts at a finer resolution.

[5] This value is rather arbitrary and derives from assumptions made in Bosello et al (2012b) on the period of time that people will not be able to work after being affected by river floods.

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3.2.4 ICES – Results

Figure 10 and Figure 11 report the results in term of regional-country GDP losses. Among non-European countries, Japan and East Asia, with respectively 20% and 15% of GDP loss in 2070, are the more adversely affected. In the Mediterranean, Malta is the largest loser with a loss of roughly 15% of GDP in 2070. In the EU, also the Italian coastal regions, Ireland, the Baltic area are more adversely affected. In 2070, losses range from roughly 12% of regional GDP in Veneto to 7.5% in Ireland, Lithuania and Latvia. Southern Spanish and German coastal regions, but also Flanders and London, follow with losses at around 5% of GDP. A rapid inspection of Figure 13 also highlights the added value of the regional analysis. For instance, in 2050 Italy would highlight a country GDP loss of the 4%. This however hides a 6% regional loss in Veneto and a 2% regional loss in Sicily. In summary, in 2070 50 EU NUTS2 regions over the total 269 demonstrate a GDP loss larger than 5%. The exercise also confirms that: losses start to be relevant after 2050, even though in that year 3 EU NUTS areas highlight already a loss larger than 5%, the high ice-melting case produces losses considerably larger than the medium ice melting case; and finally that coastal protection has a very high benefit to cost ratio. Indeed, also accounting for the cost of adaptation, final GDP losses at the regional level are much smaller than in the no adaptation scenario. On average for the EU28, an incremental (BaU) adaptation following the increasing sea-level rise threat, produces costs that are 89% lower than in the no (i.e. constant) adaptation case in terms of GDP loss. This result is particularly important as it confirms also in a general equilibrium context what already found performing a direct cost assessment (Lincke et al. 2018), and stresses the high return of coastal protection expenditure.

The regional assessment also highlights spillover effects on land locked regions. Even though, as expected, regions on the coast, directly exposed to sea-level rise, tend to show higher economic impacts, regions that in the different countries are particularly interconnected economically, not only with coastal areas, but also with the overall economic trade flows, show losses of comparable magnitude. The cases of Piedmont and Lombardy in Italy, of the Ile de France in France, Madrid in Spain and of central Germany is emblematic.

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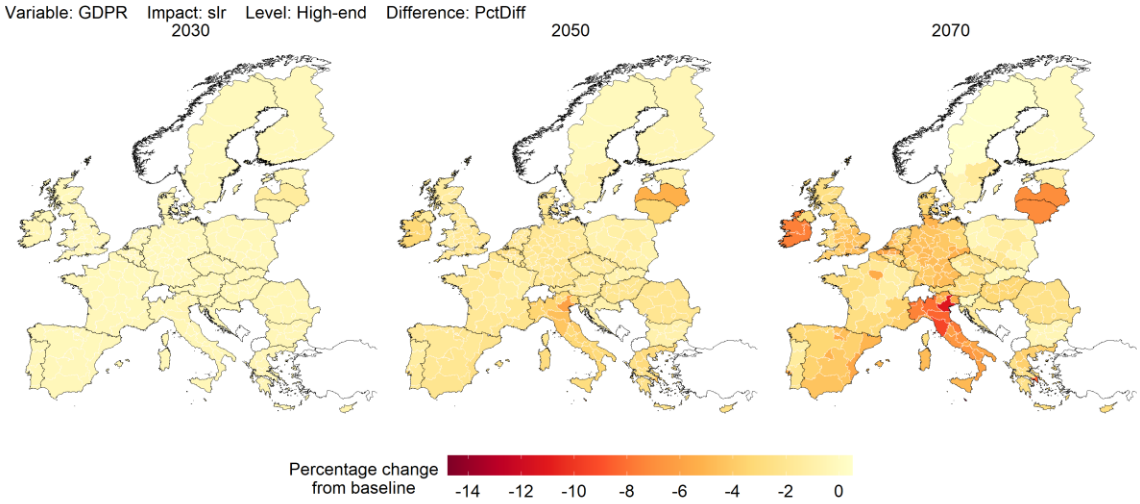

Figure 10: GDP losses by NUTS region in the EU No additional adaptation scenario in 2030, 2050 and 2070 (SSP5 RCP8.5 high end sea-level rise scenario). % differences wrt baseline

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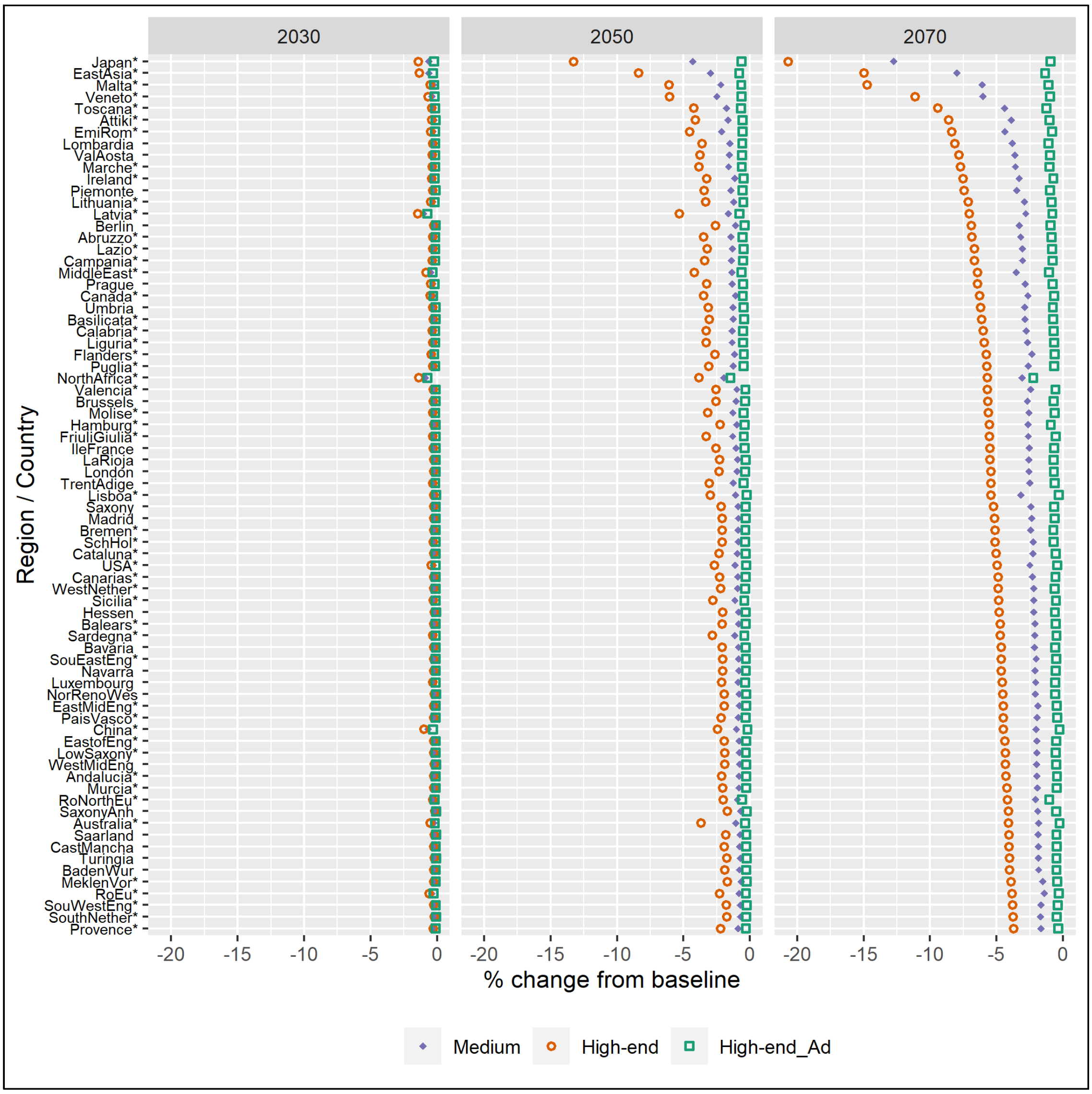

Figure 11: Top 75 GDP losing regions. (*) denotes countries/regions on the coast

Figure 12 reports macro-sectoral costs expressed in terms of production contractions. Results are prevalently negative across all sectors. The prevailing ranking, although with some country differences, depicts the industrial sector as the largest loser, followed by the energy - service sectors, and finally by the agricultural sector.

Sea-level rise impacts are mostly driven by effects on capital, that, also in terms of direct economic losses, are much larger than land and labour productivity impacts. Accordingly, more capital intensive sectors in the different regions, tend to lose more. The top loser in 2070 is the Hamburg area, featuring a potential 20% contraction of industrial production, but industrial output losses above 10% are common affecting 47 EU NUTS regions. Among these, there are many Italian regions, but Central and Norther EU areas like the Netherlands, or Latvia as well as other Southern European regions like Attica, are represented. Energy and services production contracts less, roughly the 3 – 8%, with a negative peak of the 20% and 14% respectively in Latvia. Note also the huge decrease in energy production in the Trentino Alto Adige land

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locked region in Italy. The region is a large producer of hydropower in Italy, therefore, its regional supply is hit particularly by the overall contraction of the economic activity in the whole country. Agricultural production decreases, but much less, although some non-negligible negative peaks, like for instance the -8% in the Italian Veneto region, can be observed. Moreover, in several EU regions, agricultural production increases slightly. This is a response to increased agricultural commodity demand that is sustained either by domestic consumers that shift from capital intensive to land intensive goods, or by international-regional consumers that can find some regional products more competitive.

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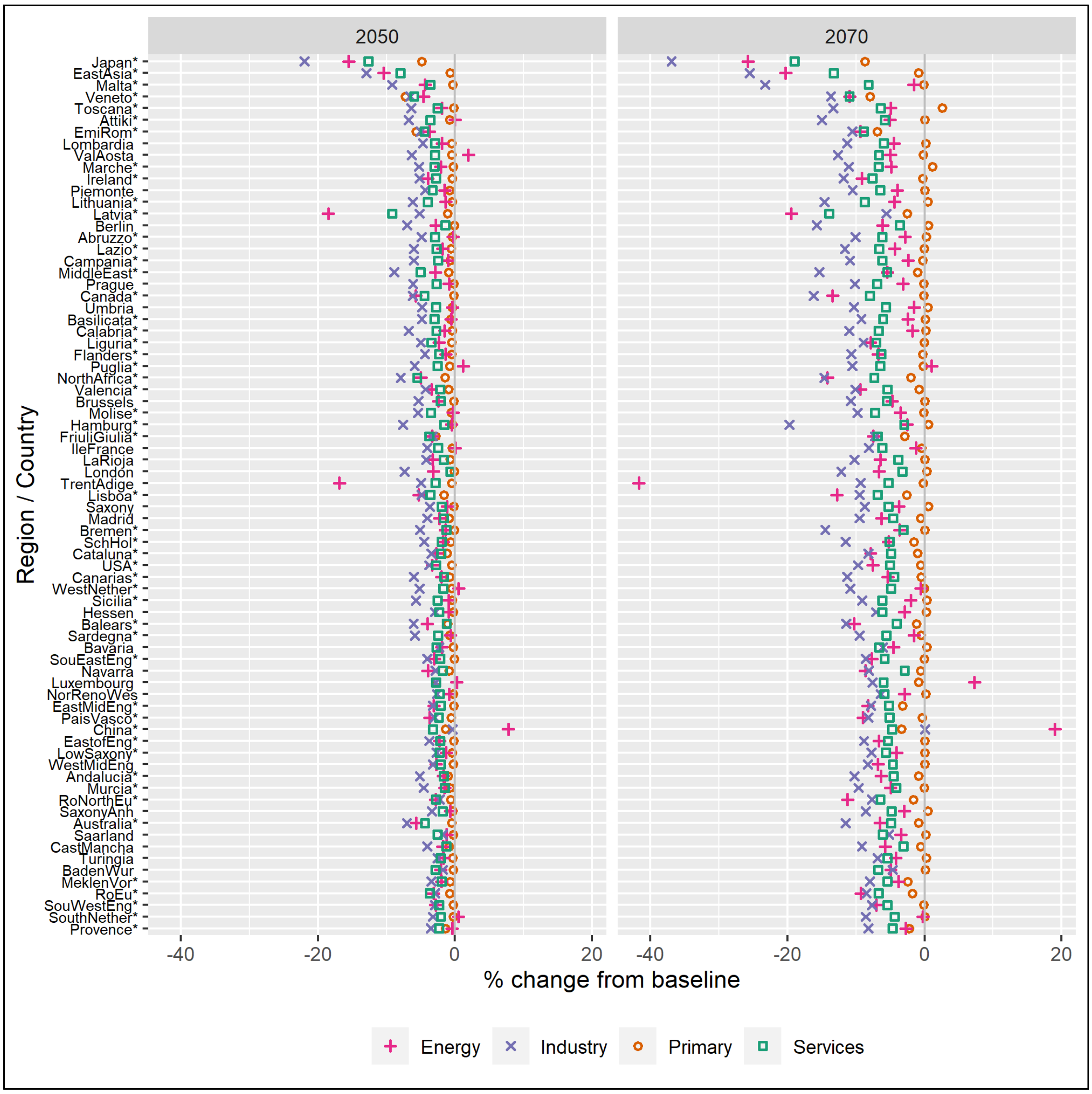

Figure 12: Changes in sectoral production (% change from baseline) in the top 75 GDP loosing regions. (*) denotes countries/regions on the coast

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3.2.5 Model Result Comparison

In this section we examine the robustness of our findings proposing first a comparison across direct and indirect economic assessments and then focussing on the two macro-economic models used.

Figure 10 compares selected GDP results across COIN-INT and ICES where ICES regional results have been aggregated to match the scale of COIN-INT. Models behave very similarly in the adaptation case. This is partly expected as, due to the working of adaptation, physical impacts and therefore effects spreading on the overall economic activity are small. Some difference across models however, is already appreciable when land locked countries, like Austria, are concerned. Differences across model results are magnified in the No-Adaptation case, where inputted impacts are larger and trigger stronger economic reactions. In this case, the match across models remains good in France, Italy, the Netherlands while the order of magnitude in results is definitely comparable in the UK. Considering the different parameterization of the models (including the different base years to which the models are calibrated), the not exact matching of the sectors, the differences in the baselines that cannot be perfectly harmonized, especially in the macro-sectoral composition of value added, and the regional detail difference, this is a good robustness check for our results. Interestingly, larger differences across models are visible in landlocked or “almost” landlocked countries like for instance Austria, or Germany, where the exposed coast is definitely small compared to the total country borders. In these two countries GDP impacts are triggered mostly by indirect “trade” and factor (in the case of ICES capital) mobility effects. In ICES these effects are stronger and, eventually, losses spill over more acutely. In particular, the ICES model features international capital mobility which is triggered by the equalization of countries return to capital, “corrected” with a GDP growth factor. Countries losing capital (because of sea-level rise) experience increases in capital rental rates and returns. They thus become more attractive for capital that “migrates” from other countries. This effect partly compensate losses is sea-level rise exposed countries and transmit losses to land locked countries.

In COIN-INT the mechanism is different as regions are connected only via trade of goods and services, but production factors – including capital – are immobile across regions. Thus, there is no such effect of capital outflow in landlocked regions as it is the case in ICES. Hence, landlocked countries do not loose productive capacities and at the same time can fully benefit from comparative advantage effects.

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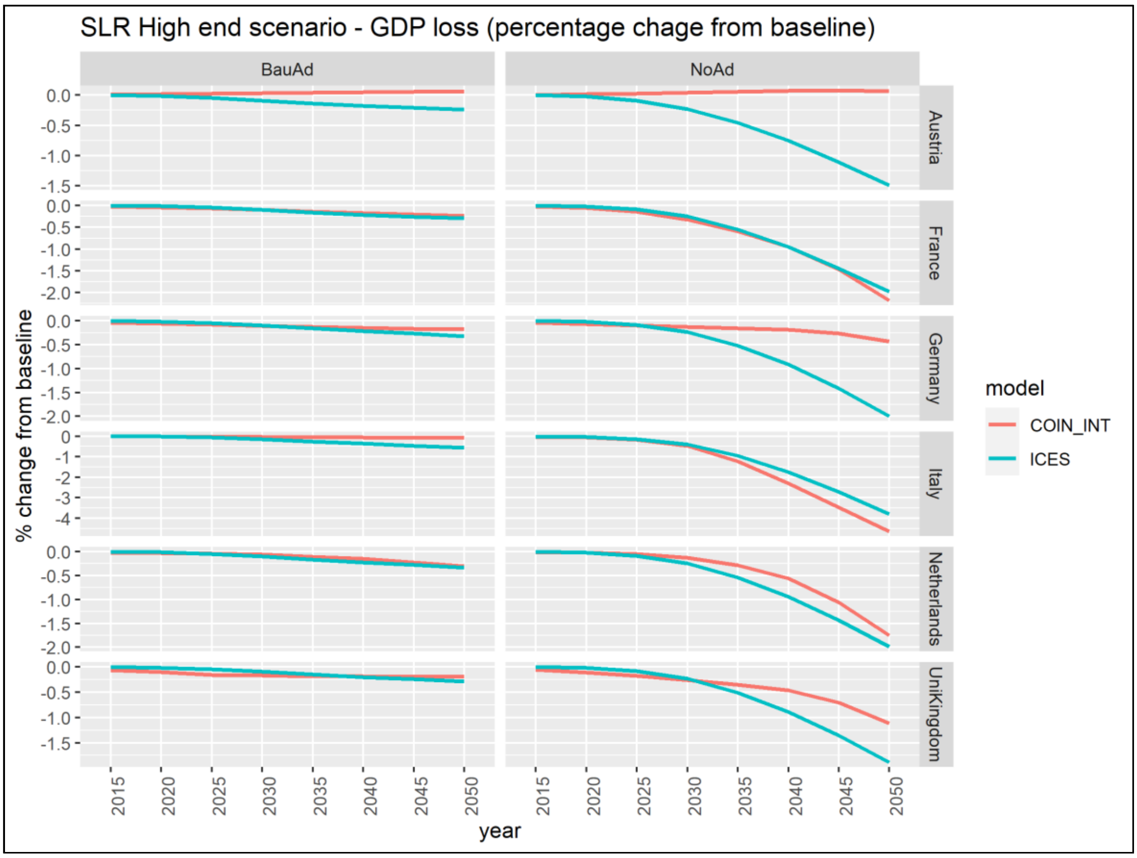

Figure 13: CGE model comparison for GDP loss in selected EU countries (in % change from baseline)

The difference across models becomes more evident turning to sectoral effects (Figure 14). Trends in the service sector remain robust across models and qualitative similarities can be found in the agricultural sector, even though losses in COIN-INT are considerably larger compared to ICES. Looking at Figure 8 and Figure 12 this appears a generalized trend characterizing all economies. In this case, the different nesting of the production function and substitution elasticity between land and other production factors explain the difference. Apparently, ICES favours relatively more than COIN-INT the substitution from capital intensive toward land-labour intensive activities.

On the contrary, COIN-INT shows a definitely stronger substitutability between capital and energy input than ICES. Energy production in the former increases, while in the latter an income effect prevails leading to a decrease.

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Figure 14: CGE model comparison for sectoral output loss in selected EU countries (in % change from baseline in 2050)

3.3. Conclusions

Extreme SLR, that in the present study refers to an increase of 1.7 m by the end of the century, can induce relevant GDP losses in the EU and outside. If SLR trend, even though intensifying, remains smooth, severe economic impacts are expected after 2050. This statement however needs some qualification. Italy as a country and in particular its Veneto regions can be severely affected with GDP losses larger than the 5% already in 2050. Similar losses are experienced by Latvia and Malta. Northern EU regions feature GDP losses between the 2% and the 5%. These results are robust across the modelling exercises. At the sectoral level, impacts magnify. There is agreement across the models on the negative impact on service and agricultural production. According to COIN-INT this last can be larger than the 6% in Germany, France, UK, Belgium, and other Northern European countries. The results for industry and energy production are more mixed depending upon models and regions. In particular, especially when sea-level rise impacts are still moderate, both models highlights that some countries in Europe might benefit due to trade comparative advantages. The models however diverge on which sectors can benefit. COIN-INT emphasizes potential gains especially in energy and in industry production in Germany, Austria, the Netherlands and other Central European Countries. These gains are however moderate reaching the maximum of 2.5% in the Netherlands. The ICES

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model, on the contrary, emphasizes the possibility of slight gains in agricultural production. However, as shown, according to both models these potential gains are moderate and do not reverse the net macroeconomic (GDP and welfare) effects that remain negative.

In 2070, the sub national assessment conducted with the ICES model shows that 50 EU regions over a total of 269 can experience GDP losses larger than the 5%. At the sectoral level, industrial production seems particularly affected with 47 regions, showing a loss larger than the 10%, peaking to the 23% in Malta and 20% in the Hamburg area.

The regional analysis also emphasizes how losses can be transmitted across regions. It is particularly interesting to note that those areas that in the different countries are particularly interconnected economically, not only with coastal areas, but also with the overall economic trade flows, which often coincides with regions where country capital cities are located, show losses of comparable magnitude. The cases of Piedmont and Lombardy in Italy, of the Ile de France in France, Madrid in Spain and of central Germany is emblematic.

Both modelling exercises confirm the huge benefit to cost ratio of coastal protection. This is particularly interesting as it shows that findings obtained with partial equilibrium analyses holds also under a macro-economic point of view.

It is finally worth to stress that the economic model comparison performed, turned particularly useful not only to test the robustness of findings, but also to better investigate the economic mechanisms behind these findings. We thus encourage more macroeconomic modelling comparison exercise. Most important sensitivities with respect to macroeconomic modeling seem to be (i) assumptions on capital mobility, (ii) the structure of sectoral production functions (nestings) as well as (iii) elasticities of substitution.

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Appendix

Implementation of sea level rise impacts in COIN-INT

The impacts of SLR are implemented in COIN-INT via five channels:

1. **Capital costs due to sea flood damages**: Sea flood damages are implemented via a reduced capital stock that leads to lower capital availability for production (i.e. a lower capital endowment in the economy). This leads to lower economic activity (as productive capacities are getting smaller), to lower income and in turn to lower consumption and savings (subject to a fixed savings rate.). Lower savings lead in turn to lower investment and thus to lower capital accumulation over time. The sea flood costs to capital stock-ratio from DIVA is calculated and then applied to the capital stock accumulation equation in COIN-INT.
2. **Labour costs**: DIVA calculates the number of people that are flooded in each year. We assume that each person that is flooded within a year, is not able to provide labour to the labour market for 2 out of 48 working weeks a year. We use the annual labour income per capita in each region, apply the ratio of 2/48 to it and multiply it with the number of people that are flooded to obtain the total labour costs.
3. **Land loss**: DIVA calculates the annual land area that is lost due to SLR in each year. We cumulate this effect over time and calculate the change in land availability in each year (relative to the land area that is available in COIN-INT). The relative land loss is then implemented in COIN-INT as lower cropland availability for agricultural crop production. As the effect of land loss happens gradually, we can assume that the type of land that is close to the shore and that it not protected is land of lowest value, i.e. agricultural land.
4. **Sea dike investment costs**: Investment costs for renewing sea dikes or for upgrading them (in the case of adaptation) is modelled as forced investment activity of the government agent in each model region and year. This forced investment is assumed to crowd out government consumption. Further, we assume that this investment is only effective in the short term, i.e. it has a positive effect on GDP in the year of investing (at the cost of government consumption, though), but it does not build up the productive capital stock as sea dikes cannot be regarded as a production factor that earns a rent (as opposed to other capital such as machinery or buildings). Higher sea dike investment thus lead to lower capital accumulation over time.
5. **Sea dike maintenance costs**: Maintenance costs for sea dikes are implemented as forced government consumption for construction activities, which crowds out generic government consumption.

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Additional results from COIN-INT

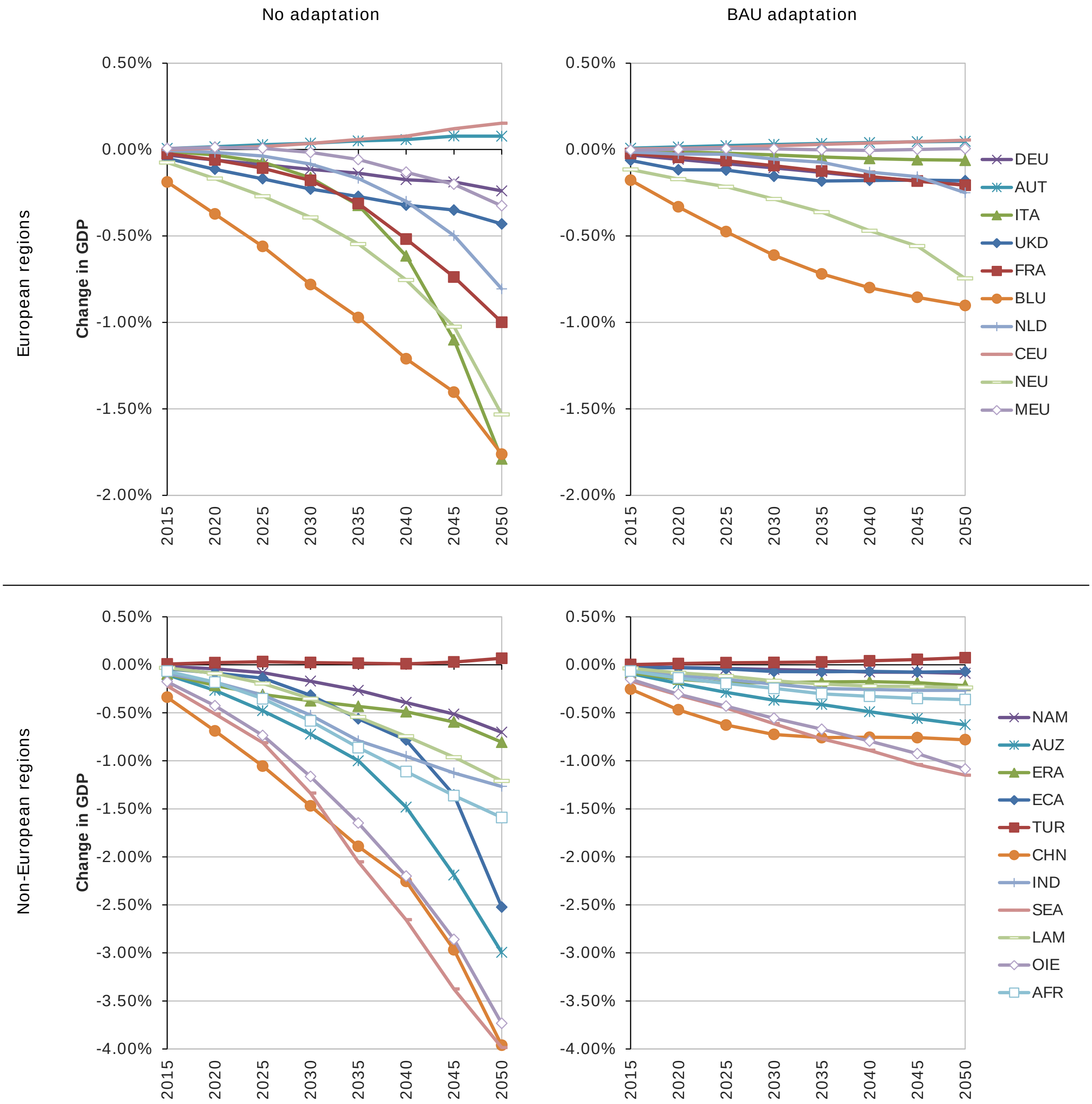

Figure 15: Change in real GDP relative to Baseline scenario (SSP5-RCP8.5) for medium ice melting. Left: No Adaptation, right: BAU Adaptation , top: European regions, bottom: regions of the rest of the world. [Results from COIN-INT CGE model]

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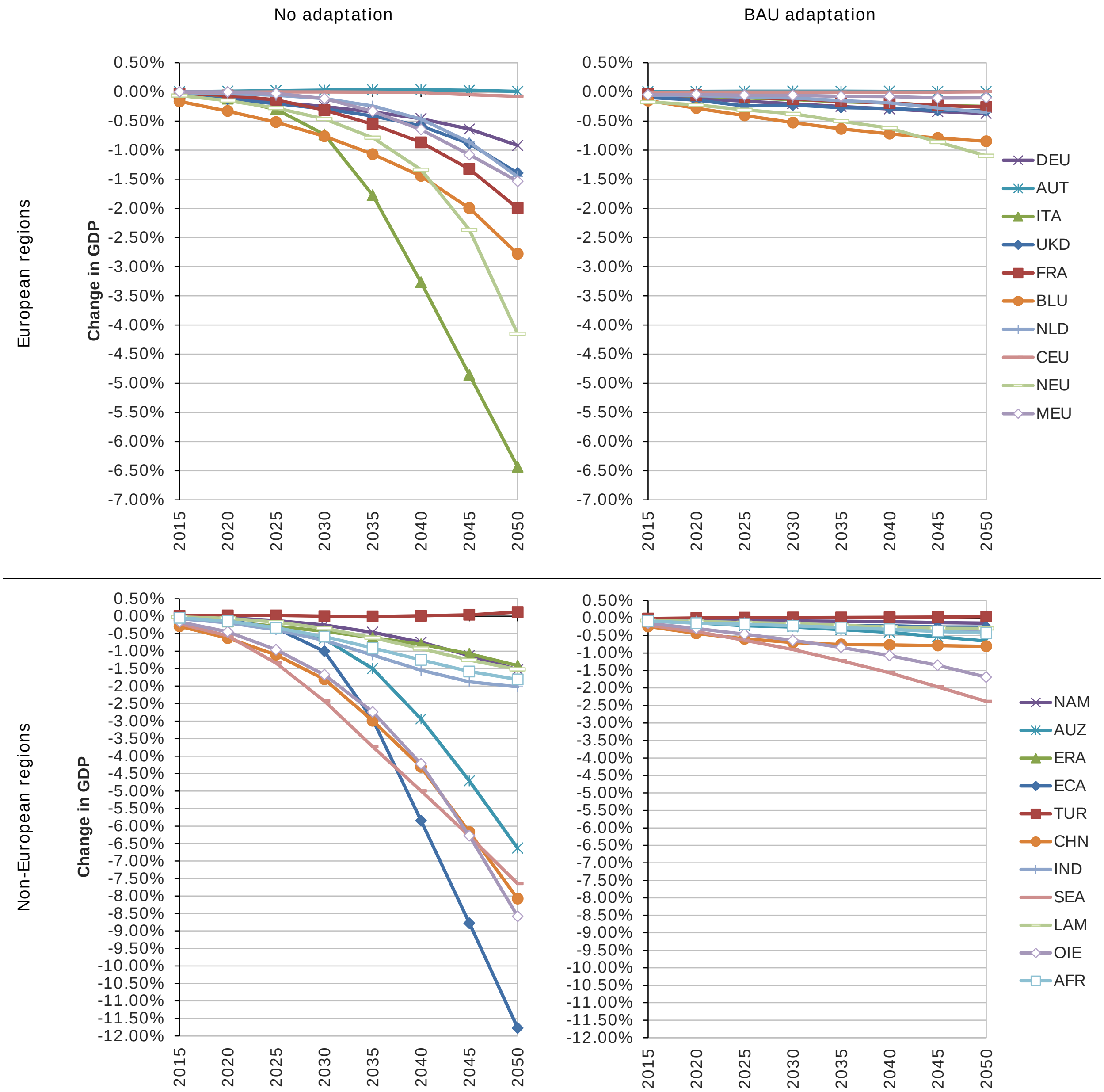

Figure 16: Change in Welfare (Hicks'ian Equivalent Variation) relative to Baseline scenario (SSP5-RCP8.5) for high end ice melting. Left: No Adaptation, right: BAU Adaptation , top: European regions, bottom: regions of the rest of the world. [Results from COIN-INT CGE model]

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Table 1: COIN-INT and ICES sectoral attribution to macro-categories

COIN-INT	ICES	Macro-category
AGC Agricultural products -crops AGL Agricultural products -livestock FOF Forestry and Fishery	Oth_Crops Veg_Fruits Livestock Timber Fishery	**Primary**
COA Coal OIL Crude Oil GAS Natural Gas P_C Refined oil products ELY Electricity: Transmission and Distribution Baseload Nuclear Coal Gas Wind Hydro Oil Other Peakload Gas Hydro Oil Solar	Coal Oil Gas Oil_Pcts TnD Nuclear FossilsEly Wind Hydro OthersEly Solar	**Energy**
OMN Other mining CON Construction FBT Food, beverages and tobacco products TWO Textile industry and other manufacturing OME Machinery etc CRP Chemical industry MIS Manufacture of other non-metallic mineral products etc	Heavy_ind Construction Light_ind	**Industry**
LAT Transport – Land WAT Transport –Water AIT Transport –Air OSG Public services SER Other services and utilities PIN Private insurance	Trp_Road Trp_Water Trp_Air PubServ Services	**Services**

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Section references

Lincke, D., Hinkel, H., van Ginkel, K., Jeuken, A., Botzen, W., Tesselaar, M., Scoccimarro, E., Ignjacevic, P. (2018). D2.3 Impacts on infrastructure, built environment, and transport Deliverable of the H2020 COACCH project.

Schleypen, J.R., Dasgupta, S., Borsky, S., Jury, M., Ščasný, M., Bezhanishvili, L. (2019). D2.4 Impacts on Industry, Energy, Services, and Trade. Deliverable of the H2020 COACCH project.

Scoccimarro, E., Steininger, K.W., Watkiss, P.. Boere, E., Hunt, A., Linke, D., Grossmann, W., Tesselaar, M., Williges, K., Ignjacevic, P., Jeuken, A., van Ginkel, K., Costa, A.L., Groen, F., Peano, P., Fogli, G., Ruggieri, P., Chaves Montero, MdM., (2020). D3.2. Tipping point likelihood in the SSP/RCP space. Deliverable of the H2020 COACCH project.

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4. CT2 - Alpine glaciers disappearance (CMCC, VU)

Glaciers play an important role in mountains and downstream drainage areas regarding several aspects and they bear an economic value on strikingly different sectors. Inherently, they are an attraction as a unique landscape feature that hosts some archaic and iconic value and is hence very relevant for tourism. Glaciers store water in its aggregate state "ice" and under a changing climate there is potential to change this storage. This can – for some transition period – add additional water volume to downstream water usage. However, once they have disappeared (and this becomes relevant already when their volume has reduced significantly), this excess water volume may be missing. Most importantly the glacier storage modulates seasonal streamflow by providing water during otherwise very dry periods, where the excess meltwater can buffer low-water situations, occurring for instance at riverine waterways with implications for shipping and hydropower.

We attempt to assess the above mentioned and arguably very different aspects of glaciers as an economic factor – in order to evaluate the economic implications of their loss – along three different major threads: We start with the glaciers´ relevance for tourism, both for skiing, other sports tourism and as a touristic attraction. Even though the relevance of glacier skiing has declined over the last three decades, skiing areas with glaciers still contribute about 8% of overnight stays in the Alps. The tipping point of full glacier retreat will however not imply all of this tourism to vanish, as high altitude and north orientation of those areas may grant many of them favourable conditions for natural or artificial snow cover. It is the locally specific surface conditions underneath the current ice cover that will determine the respective predisposition as also future ski areas. Under a changed climate with other skiing destinations lost, their relative importance may grow, yet in a world in which the overall (social) relevance of skiing will most likely have declined. Glaciers as a touristic attraction are more directly linked to the very existence of the glaciers. For this type of touristic relevance we analyse the case-study of Pasterze glacier in the Austrian Alps. This glacier is a significant tourist attraction, as a road was already built in 1935 to access a viewpoint. With the glacier retreat of the recent decades, it is a place where tourists witness climate change and almost 1 million people visit it annually. Beyond estimating the economic value added lost when the glacier would vanish, we add a preventive cost analysis: what would be the resource need to keep the glacier in existence, then remaining a touristic attraction? Our experiment is based on measured data and a state-of-the-art surface mass and energy balance model to estimate the amount of artificial snow production needed, in order to keep Pasterze glacier in its current shape. We then convert this snow production and hence water need into an estimate of the economic costs and find that while water availability would suffice for preserving the glacier (around 20% of the annual basin precipitation would need to be converted into snow), the costs associated with the necessary snow production (in the order of 100 million EUR/year) to date exceed by far the estimated touristic economic benefit generated.

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The second line of thought covers the impact of glaciers as a resource in the context of hydropower production. We evaluate both the implications of a complete retreat of glaciers but also the impacts along the timeline of this retreat under different RCPs. We apply the model output of a global glacier model based on 14 GCMs under several RCPs and assess the absolute and relative glacier contribution to summer discharge for selected power plants in the Alps. Evidently, power plants closer to the glacier show larger values of relative glacier contribution than the ones further downstream. Converting the water volume derived from glaciers to power production shows that depending on the site, the glacier contribution to production will likely decrease by an order of magnitude for several sites during the 21st century. We estimate the economic impact of this reduced water availability and for Austrian hydropower electricity production we assess already under RCP 2.6 a lower boundary for revenue lost at € 163 mio. (2046-2075) to € 184 mio. (2071-2100), for complete glacier retreat the lower boundary is at € 215 mio. per year.

Finally, we exemplarily investigate the impact of glacier meltwater on low-flow conditions for inland water transport. The same global glacier model as above is applied, together with measured gauge data and available threshold values for shipping, in order to quantify the number of days when shipping is impossible and when it only will be possible with a surcharge. In Kaub at the Rhine river for instance, we found on average 7 days per year, when shipping has been impossible in the period 1986-2015, with the glacier cover present at the end of the 20th century. If we applied the reduced streamflow we expect for the future, this value will, depending on the scenario, increase on average to 10-11 days per year (applying glacier contributions modelled for the end of the 21st century) or to 12 days with entirely vanished glaciers. Under current economic conditions the latter would imply an additional loss of 0.4% or German industrial production, corresponding to a loss of German GDP at about € 35 billion, on average per year.

4.1 Direct impact and assessment methodologies

4.1.1 Alpine glaciers and tourism

Glaciers are relevant attractions for tourism in winter as well as in summer. The tourism activities in winter can be mainly attributed to winter sports tourism, in particular ski tourism (Frank et al., 1993), while tourism in summer is more diverse. While summer skiing plays only a now small and (relative to the 1970s and 1980s) diminishing role for tourism on glaciers (Mayer (2012); Mayer and Abegg (2020b)), many glacier areas serve as attraction points of sight-seeing, starting points for hikes and high alpine tours and hence attract hikers as well as climbers, where about half is mainly interested in the view and attractive landscapes, to which glacial formations make a significant contribution (Pröbstl-Haider et al., 2016).

Any evaluation of the impact of a complete retreat of Alpine glaciers on tourism needs to be based on two core elements: current relevance of glaciers for tourism, and the potential role of then glacier-free areas for tourism in a world under a different climate. Unfortunately, data availability on the first issue, current relevance, can be

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characterised to be very scarce at best, with only very few papers, and no review or assessment available, neither at the international level nor at the national level (Mayer and Abegg, 2020a). The second issue is quite speculative in assumptions on long-term (socioeconomic) development, but we discuss a few elements relevant for such development below, that can at least shed some light on the possible directions.

On the relevance of glaciers for ski tourism we report from a data base of (Mayer and Abegg, 2020b): in the Alpine region across history there were a total of 60 glacier ski areas (yet not simultaneously), located on 77 glaciers in the Alps. As of 2019 there were still 38 in operation (with a peak of 49 in 1987). Only fifteen still offer summer skiing (applying the definition of at least one day of operation between June 1st and September 22nd), in the mid 1980s there were 37 (Mayer and Abegg, 2020a).

The tourist significance of these (former) glacier skiing areas varies considerably: from just 5000 visitors in one season (Lobbia Alta/Adamello) up to more than 1 million first entries, e.g. Stubai Glacier or Kitzsteinhorn (Mayer et al., 2018).

On the basis of Mayer et al. (2011), the share of overnight stays in all glacier ski destinations in the Alps for 2011 is estimated to be about 8 percent (around 25.9 million out of a total of 330 million).[6] While this number is a very rough estimate, as (by far) not every overnight stay there is due to skiing on the glaciers and day trippers are missing in this number, it does indicate that glacier ski destinations in the Alps are of considerable importance.

Zooming into the region of Tyrol, in 2012 10.8% of arrivals (total year) were in communities with glacier ski areas (Neustift, Tux, Kaunertal, St. Leonhard/Pitztal, Sölden), in absolute figures 1.074 of 9.943 million. In terms of overnight stays the share was 11.9% (5.265 million of 44.397 million) (Land Tirol, 2013). This share is seasonally very diverse, for November it was even 38.1%, for October 15.1%, for April 21.0%. Again, not every visitor in these communities is a glacier skier, but it is evident that these destinations are very important from a regional/local and seasonal perspective.

The second core element is even more difficult to answer, what will the future relevance of these resorts be for tourism, once the glaciers have fully retreated?[1]

If the glaciers have melted, this does not directly imply that all tourists will have gone. The very high natural snow reliability in winter and spring remains, as well as the good snowmaking possibilities already relatively early in autumn. What is much more decisive is what kind of underground will be opening up under the ice masses and how much effort will be needed to convert it into a terrain suitable for skiing. If the latter is easily possible, chances are high that the glacier ski areas will be among the last ski areas to be closed due to lack of snow, simply because of their altitude (also often northern exposure). It is true, however, that the autumn season will be increasingly problematic and the start of the season is likely to be delayed. However, experience from the last few years shows that even without a glacier base it is possible to prepare slopes on the basis of depot snow only. However, it is also to be expected that there

[6] M. Mayer, Univ. Innsbruck, pers. comm., July 2020.

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will be qualitative losses (slope quality, width, etc.) if there is no longer any ice base. A main question then will be, whether these losses in quality will not be much stronger at lower altitudes. This means there will be no linear relationship between glacier condition and visitor frequency. The overall socioeconomic development will probably be even of larger relevance for the number of visitors, particularly the issue of what fraction of the population still will be skiing at all under such climatic conditions, also given ongoing demographic change in core markets (Steiger, 2012).

In the summer season, glaciers are mainly used as sight-seeing destinations with the (presumed) main motive of a snow experience in summer or a snow and ice experience at all (guests from overseas). If the glaciers were to disappear completely, this demand could actually be declining, especially since it is less easy to substitute. At least until the early summer, residual snow in the high alpine areas will probably continue to exist, even without glaciers.[1]

In COACCH we thus on the one hand estimate the overall tourist potential that is affected, even though it may not be fully lost, and analyse a particular case study for destination attraction, the Pasterze glacier, given that this type of tourism appears to be in more direct and immediate correlation with the existence of the glacier.

The Pasterze glacier case study

For glacier attraction tourism we assess the impact of changing glaciers analysing a specific example. Pasterze glacier is among the largest glaciers in Austria (Fischer et al., 2015) with a size of about 17 km² and a drainage area of 33.7 km² (Geilhausen et al., 2012). It has undergone a strong retreat over the last decades, which is well quantified and bears several geomorphologic consequences (Avian et al., 2018; Kellerer-Pirklbauer and Kulmer, 2019). The reduction in volume is in line with recent glacier changes throughout the Alps (Sommer et al., 2020). Pasterze glacier has long been a magnet for tourism. Factual events such as the visit by emperor Kaiser Franz Joseph with his wife in 1856 may have played an important role for giving Pasterze glacier an iconic status, while the trigger for mass tourism likely lies in the construction of a pass road that got completed in 1935 after 5 years of construction (Lieb and Slupetzky, 2004). Tourists access the glacier typically using a car, motorbike or by bus following a toll road towards Kaiser-Franz-Josefs-Höhe (2369 m a.s.l.). From there they descend with a short cable car or walk towards the glacier. The main attraction from Kaiser-Franz-Josefs-Höhe is the view towards Pasterze and there especially the glacier's tongue. A visit these days is striking as it lets the visitor experience with her own eyes how dramatic recent changes are.

Today, about a million of visitors per year (SN, 2020) from all over the world access the viewpoint of Pasterze, of which many also walk their way towards the glacier tongue. Besides other points of interest there is also an instructive glacier trail where glacial processes, glacier stages as well as the relationship of the glaciers with the climate are explained.

Pasterze has some unique characteristics of topography. The large accumulation area builds a reservoir of snow and ice which is then transported over a steep cliff zone (Hufeisenbruch) towards the lower-lying glacier part. With some generalization,

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Pasterze glacier's accumulation area lies above the Hufeisenbruch whereas the area below Hufeisenbruch is the ablation area. However, in years of extreme glacier melt even large parts above Hufeisenbruch are ablation zone. Kellerer-Pirklbauer and Kulmer (2019) recently presented a reduction of Pasterze glacier velocity in the ablation zone by about 50% during the first decade of the 21st century. This slow-down acts as a feedback process enhancing glacier ablation because of lower ice flux towards the ablation zone. In a way, Pasterze glacier already passed a tipping point in relation to the current climate, as the melted ice below Hufeisenbruch is not replaced by mass flux from above.

The role of Pasterze glacier as an icon of climate change in Austria motivates our following experiment, where we use a state-of-the-art glacier model that is calibrated with recent climate data and hence is able to simulate the surface mass and energy balance. In our experiment we then use the same climate but alter snow fall in order to achieve a balanced glacier. Since snow cover impacts the surface energy balance in several ways, such as the albedo or the surface roughness, we can quantify energy fluxes under the assumption of different rates of artificially accumulated snow. We iteratively solve the energy balance in a way that the annual balance becomes zero. This is done for each elevation band individually for the current glacier's area below Hufeisenbruch which covers approx. $2.3x10^6$ m^2. Doing so, we can answer the question: 'How much snow would be needed under today's climate in order to preserve Pasterze glacier's tongue?' In section **Errore. L'origine riferimento non è stata trovata.** an attempt is made to assess the approximate costs of such a hypothetical endeavor. We thus answer the question of the economic costs of one possible path to counter glacier retreat under current climate in order to keep the tourism potential unchanged. This economic figure can serve as a lower bound for a similar effort under future climate scenarios.

Studies of artificial snow production (ASP) and related impact on the surface energy balance have been done before for different sites and purposes, using different methods. Olefs et al. (2010) studied the boundary conditions and recent trends of artificial snow production in the Austrian Alps, while Olefs and Fischer (2008) review also other methods in order to sustain a snow-pack artificially. Hanzer et al. (2014) established regressions between snow production potential of snow using a physically-based snow model for a ski resort in the Eastern Alps, where they include information on realistic snowmaking infrastructure. Oerlemans et al. (2017) focused on the future evolution of a mountain glacier und artificial snow production regime. They conclude that over this century, glacier length reduction can be decreased by 400-500 m by producing summer snow in the ablation zone over an area in the order of 1 km². Their perspective is slightly different to ours, since they attempt to quantify the impact of ASP on glacier evolution rather than prescribing an unchanged surface geometry and deducing the necessary ASP from that. Also, the temporal scale of their study differs considerably from ours.

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Figure 17: upper panel: Pasterze Glacier in 2016 seen from the glacier trail; Figure from ***(Robson et al., 2016)****; lower panel: map of the area including the road towards Franz-Josefs-Höhe;* ***(AMAP, 2020)****.*

In the following we detail the steps that are involved in order to achieve the quantitative results presented thereafter. In general, we follow a physically based surface energy balance approach as it is utilized in several studies with minor variations (e.g., van As, 2011; van den Broeke et al., 2011; Abermann et al., 2019). The surface energy balance of a snow or ice surface can be written in the following form:

$$S\downarrow (1-\alpha) + L\downarrow + L\uparrow + QS + QL + QC + QPS = F$$

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where $S\downarrow$ is the incoming shortwave radiation, α is the surface albedo, $L\downarrow$ and $L\uparrow$ are the incoming and outgoing longwave radiation fluxes, QS and QL are the turbulent fluxes of sensible and latent heat, respectively, QC is the conductive heat flux in the subsurface, and QPS the energy flux from penetrating shortwave radiation in the subsurface. The sum of these fluxes yields a resulting flux F which represents the latent energy for melting if glacier surface temperature reaches the melting point. All the fluxes are determined or driven by the energy provided from the atmosphere or from the ice underneath. Required input data are the radiative fluxes $S\downarrow$, $S\uparrow$, $L\downarrow$, and $L\uparrow$, air temperature, humidity, pressure and wind speed as well changes in surface height for validation.

An automated weather station (AWS) was set up in 2012 by ZAMG[7] in 2200 m a.s.l. that records the relevant atmospheric variables. We performed a thorough analysis, calibration and error assessment of the period 2017-2019 in (Theurl, 2019). While the calculation of the radiation balance is straightforward since it has been measured directly with a four-component radiometer, the quantification of turbulent fluxes deserves some additional explanation. We apply the bulk-method that requires minimal data input and proofs to provide reasonable results (e.g., Mölg and Hardy, 2004; van As et al., 2005; Conway and Cullen, 2016). Roughness parameters differ depending on the surface type (snow: 0.001 m or ice: 0.003 m), which we infer from the measured surface elevation changes and albedo.

Based on the calibrated mass balance at the location of the AWS, we can start our 'glacier experiment' and assess the amount of snow that is required in order to preserve glacier mass for each season individually. That way, we get a useful overview on the interannual variability of the snow quantity required. We stress that this approach is different from simply calculating measured ablation and converting this into water equivalent (w.e.), as the varying surface energy balance allows for adaptation of artificially changed surface conditions. Doing so, the artificial snow added to the surface for instance changes surface albedo from low value bare-ice in summer to a fresh snow-albedo, which results in drastically changed energy available for melt at the surface. While we artificially alter α and adapt the roughness parameter for the turbulent fluxes, we keep the remainder of the input variables to the measured, realistic values. The amount of snow that is necessary to add is a tuning parameter which we approach as follows: We assume that ASP can only be done when air temperature is at or below 0°C[8]. We then assume a constant rate of snowfall under the conditions where ASP is possible and change this iteratively until we reach a neutral balance at the end of the balance year. An example of the build-up and

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[7] The authors thank the 'Zentralanstalt für Meteorologie und Geodynamik' and especially B. Hynek and A. Neureiter for providing data and their expertise on the glaciological work on Pasterze glacier.

[8] Other studies use the Wet Bulb Temperature of -2°C as a threshold for efficient snowmaking (e.g., (Olefs et al., 2010; Hartl et al., 2018)). Sensitivity tests of the simplified 0°C air temperature used in this study show that the deviations are not negligible but do not change the conclusions.

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removal of the artificial and natural snow cover at the AWS is given in Figure 18 for the year 2012/2013.[9]

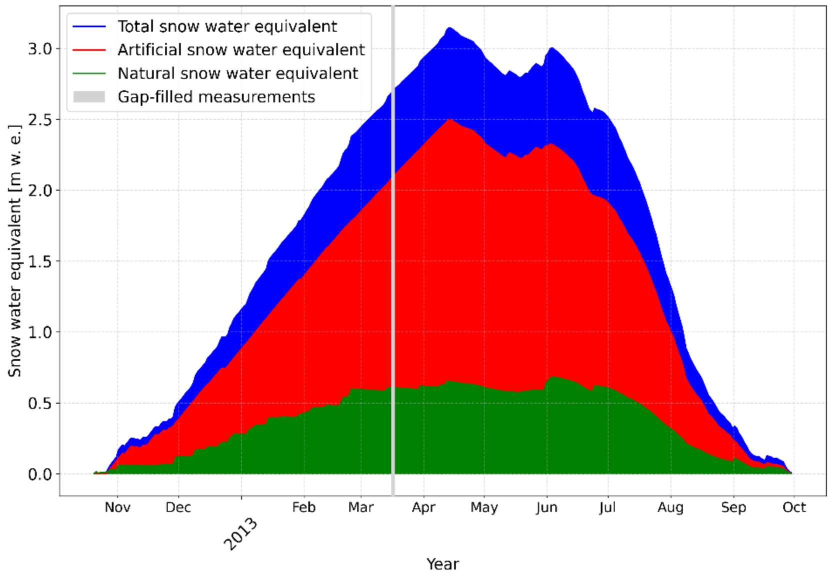

Figure 18: Natural, artificial and total snow water equivalent exemplarily for the year 2013 and the position of the AWS. The ASP rate is chosen in a way that neutral balance is reached at the end of the season.

Once the point-wise energy balance is adjusted for our approach, we expand it to spatial distribution. For that, it is necessary to apply site-specific and/or elevation-dependent modifications of the individual input variables measured at the AWS. Air temperature and air pressure follow a clear vertical dependency (we use the standard atmospheric lapse rate of 0.0065 K/m for air temperature and 0.12 hPa/m for air pressure) that we apply according to elevations from the 2012 digital elevation model with 1m resolution. We assume constant long-wave radiation fluxes for the lower part of Pasterze glacier and adapt the shortwave incoming radiation scaling the measured values at the AWS with the potential incoming shortwave irradiance at a resolution of 30 m and on a daily basis. That way, topographically induced spatial variabilities due to shading are accounted for. Once this is done, we alter albedo according to the surface conditions, which is snow throughout the year as a precondition for a neutral balance, that disappears at the end of the hydrological year. We imply an ageing-dependent decrease of albedo following the simple parameterization introduced by Oerlemans and Knap (1998). As before in the point-wise approach, we also need to alter snow amounts spatially and we do this introducing a vertical dependence of precipitation

[9]Other measures of glacier protection could be discussed here as well, such as coverage of the surface with reflective textiles that do help to reduce, ablation, too, as it was shown earlier by e.g., Olefs and Fischer (2008). Likewise, 'artificial feeding' of the accumulation zone could be an approach, thus initiating a positive mass imbalance that leads to increased mass transport via Hufeisenbruch and hence triggering an artificial glacier advance. Given the large accumulation area of Pasterze that is needed to be supplied and other logistical constraints, this approach appears less feasible and a detailed investigation of these options is beyond the scope and resource-constraints of this case-study.

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based on measurements in the nearby Sonnblick region as quantified by Leidinger (2013). A linear increase of precipitation with elevation is introduced therein that amounts to approx. 11%/100 m of elevation. We solve the spatial approach in 25 m elevation bands and set the precondition to meet neutral balance for each average elevation band.

4.1.2 Alpine glaciers and streamflow: hydropower and transportation

Glaciers are an important, sometimes essential, water resource in mountain catchments. Given the importance of water as a production factor in many economic activities, not to mention its life supporting service, glaciers, as “water providers”, can be considered as well as economic inputs in the production processes. Among the many activities where glaciers play a role, we focus on two relevant aspects (I) how glaciers impact hydropower production now and in the future and (II) how the reduced glacier contribution to discharge will impact the frequency of low-water conditions that impede shipping along riverine waterways.[10]

Glaciers are moderating downstream streamflow dynamics as the runoff stemming from the glacier covered part correlates negatively with the runoff from the ice-free part of a catchment (van Tiel et al., 2020). For instance, in a dry, warm summer, we expect a below-average discharge from the ice-free part that is in parts compensated with above average ice melt. This so-called ‘glacier compensation effect’ (GCE) is relevant when assessing economic implications of glacier-fed catchments. There is a general connection between relative glacier cover of a catchment and the strength of the GCE (Chen and Ohmura, 1990), however, this relation is all but linear and is valid for large differences in relative glacier cover but less reliable for smaller differences (Koboltschnig and Schöner, 2011; van Tiel et al., 2020). Along a given river, this means that there is generally a higher GCE closer to the glaciers, i.e. in the upper parts of any given river, while this diminishes strongly with distance to the glaciers (Kaser et al., 2010; Huss and Hock, 2015, 2018).

Huss (2011) quantifies the contribution of glacier storage change to runoff for various macro-scale catchments in Europe and finds that on a monthly basis, the fractional glacier cover can be much lower than the percentage of the contribution of the glaciers downstream and this difference is particularly large in hot summer months and decreases in future with decreasing glacier cover. (Huss and Hock, 2015) calculate the contribution from glaciers for 14 Global Circulation Models (GCMs) forced by three scenarios (RCP2.6, RCP 4.5 and RCP 8.5) for a state-of-the-art mass balance model (GloGEM) on a monthly basis and for individual glaciers. Their output is available to the authors of this chapter and embedded in the COACCH scenarios it builds the basis for the quantification of the glacier contribution.

[10] There are several other hydrogeological risks potentially occurring during the glacier melting phase that we do not analyse in this study focusing on the economic implications of the tipping point having occurred. These include changes in the sediment yields or episodic glacier-related extreme events, posing risks in general, but also to transport infrastructure in particular.

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As the relative fraction of glacier runoff to total discharge at a given gauge changes with climate change due to changing melt conditions (leading to an increase in melt per unit area) but also glacier volume reduction (leading to a decrease in total melt volume), it is a worthwhile question to assess, how such an intricate and complex set of factors interacts and what the economic consequences of such an interaction could be.

Hydropower

Hydropower provides around 16% of the world's total electricity production (Gernaat et al., 2017). In the EU, around 19% of the gross energy consumption stems from renewable sources (Eurostats, 2020), of which roughly a third is hydropower. When we consider the impact of glaciers on hydropower, both timing and total discharge volumes play a role. In addition, the type of hydropower plant will impact the potential for adaptation. Schaefli et al. (2019) assessed the role of glacier retreat for Swiss hydropower production and found that under current conditions only 3%-4% of the country-scale hydropower production was directly provided by the net glacier mass loss. They state, that this share will likely reduce in the future as a result of reduced glacier volume and stress the transition from glacio-nival to nival runoff regime types that will be a consequence of this and impact different hydropower types in a different manner. Wagner et al. (2017) studied the impact of climate change on streamflow and hydropower generation in the Alps applying four different climate simulations and found that the shift of runoff towards winter leads to an overall positive effect on the hydropower sector since also energy consumption is higher during winter. They do not solve the impact of glaciers on hydropower generation explicitly. Farinotti et al. (2016) assess the potential of mitigating the negative economic effects of a future change in seasonal runoff distribution. They find that there is a large volume in areas becoming deglacierized in future that could technically be dammed and through the water stored within those dams a seasonal shift of the runoff curve could be compensated for. However, the authors stress, that on an Alpine scale, an overall ice volume component of 0.73±0.67 km^3/year could be missing by 2070-2099.

In the following we will address the question of the role of glaciers in hydropower production by assessing a state-of-the-art model output on the glacier scale that delivers monthly runoff amounts for 14 GCMs and three different climate scenarios of the COACCH set. We will briefly describe the datasets and methodologies used and summarize the results below. As a first step we quantify the computed mean monthly glacier runoff for the macro-scale catchments Rhine, Rhone, Danube and Po, and with that the contribution of the glaciers to the overall runoff for the period 1980 to 2100. The data is derived from Huss and Hock (2018). The runoff was calculated for every glacier in the catchment separately and then summed up over the entire macro-scale catchment. There are two definitions of 'Glacier runoff' in the original dataset – one refers to precipitation and ice melt minus refreezing over the glacierized area in 1980 as taken from the Randolph Glacier Inventory version 4.0 (Pfeffer et al., 2014); the other one accounts for a diminishing glacier volume and explicitly quantifies the ice volume contribution separately. Unless otherwise stated, we show the results for the second definition. Figure 19 shows an example of the contribution of glaciers to total

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discharge of four Alpine macro-scale catchments for the summer seasonal averages (June, July and August) for RCP 2.6. It can be interpreted as the runoff volume that stems from all glaciers in the given catchment at the point where the last glacier-fed tributary meets the main river. It is evident, that Rhone delivers more than twice the melt water than the other three macro-scale catchments. The year 2003 sticks out as an extraordinary melt year across the Alpine region and glacier contribution will be decreasing throughout the 21st century. At the end of the 20th century only Rhone will carry significant melt water stemming from glaciers. The year of peak water has passed for all macro-scale catchments in the recent decades.

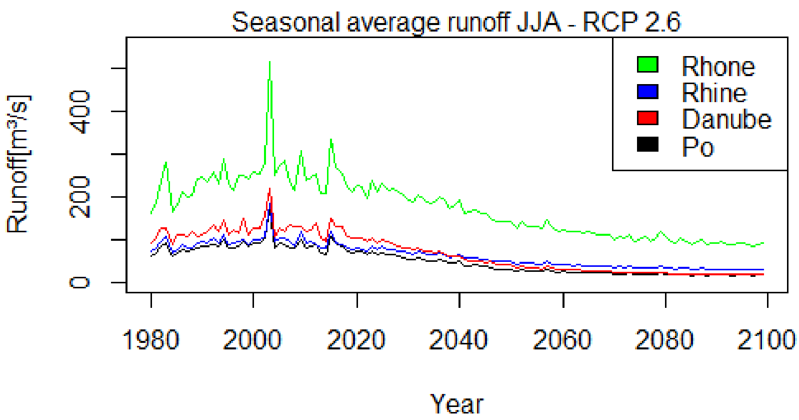

Figure 19: Average summer runoff contribution for the four macro-scale catchments that stems from glacier sources. Calculations are based on the RCP2.6 scenario and are based on the output of 12 GCMs (data source: Huss and Hock 2018).

In order to assess the variation according to the differing RCPs, we show exemplarily the results for the Rhone catchment (Figure 20). The differences among the RCPs first becomes really discernible towards the second half of the 21st century.

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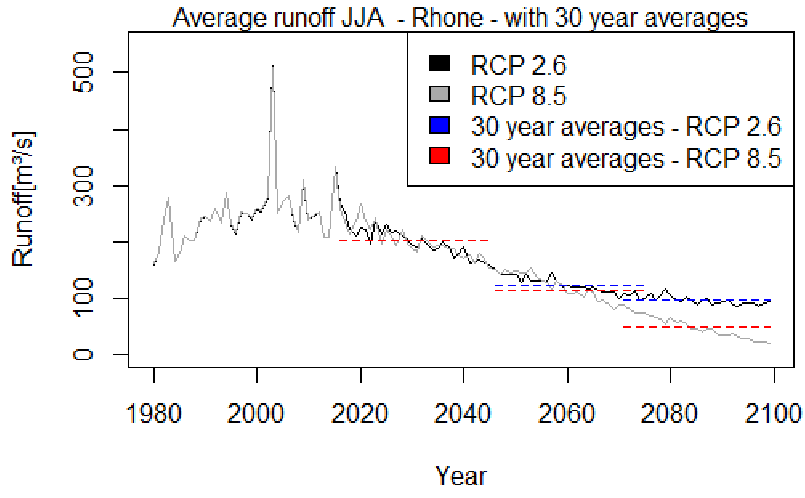

Figure 20: Average summer runoff contribution that stems from glacier sources for the macro-scale catchments Rhone. Calculations are based on the RCP2.6 and RCP8.5 scenarios. 30 year averages are shown in dashed lines for the respective periods (data source: Huss and Hock 2018).

Transport on Inland Waterways

Commercial Shipping along riverine waterways depends on water availability and particularly on low-flow conditions. In Europe, riverine transportation and constraints related to low-flow conditions play a major role on river Rhine, while this is much less the case for the other macro-scale catchments. Before we turn to the thus detailed analysis of Rhine we shortly cover these other catchments.

While the glacier melt water contribution, as established in Figure 4, is largest for the Rhone, it is of little importance for its navigation. Upstream from Lyon, where the glacier contribution would be the most significant, the Rhone is only partly navigable for small vessels up to 400 tons (CEMT[11] Class I). Only below its confluence with the Saone at Lyon the Rhone is classified as a Class V waterway (passable for ships up to 3000 tons) and therefore of relevance for inland navigation (Jonkeren, 2009). Due to the distance from the glaciers and the fact that 310km of the subsequent 325km passage of the rivers are controlled through dams and locks the impacts of variations in melt water runoff are likely to be minor downstream from Lyon (French Waterways, 2010). Moreover, the overall economic relevance of inland waterways for freight transportation in France is with 2.7 percent of all ton kilometers well below the European average of a 5.9 percent share (European Commission, 2019). The relevance of the Rhone for water transports is further diminished by the fact that large parts of

[11] Within Europe waterways are categorized into capacity levels ranging from I to V within the CEMT division. Class I allows for vessels up to 400 tonnes, class V waterways allow for the passage of inland ships up to 3000 tonnes. (ECMT Resolution 92/2, 1992)

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the French inland waterway transports are to be accounted to navigation on the Seine hence leading to the implication that the economic impact of low water on the Rhone due to variations in glacier melt water are of minor relevance.

Although the Danube is considerably longer than the Rhine, the importance of the Rhine for the economy and the transport sector is significantly larger as with its four main tributaries it is more branched than the Danube and hence less journeys by road or rail following or preceding the waterway transportation are needed. This contributes to Germany having a larger share of waterway transportation in the modal split (8.5 percent of all tonne kilometres are transported via waterways) than for example Austria (2.6 percent of all tonne kilometres are transported via waterways) (European Commission, 2019; REWWAY, 2020).

An extensive analysis of the influence of glaciers on low-flow conditions on River Rhine throughout the 20th century is available (Stahl et al., 2017).

At selected sites, where limits of water depth for shipping exist, we assess the probability of water levels below those threshold values in the past years. Such thresholds can entail that shipping is still possible, but a surcharge will be asked for (we name the days when this occurs SCSD: ‘Surcharge Shipping Days’) or it can be a limit under which shipping is not possible at all (we name the days when this occurs NSD: ‘Non-Shipping Days’).[12]

A methodological constraint is that for assessing the shipping limits we are dependent on daily values of discharge as pointed out through the analysis of monthly average vs. daily glacier contributions by Stahl et al. (2017). The dataset we use from Huss and Hock (2018) gives future glacier runoff on a monthly basis. To overcome this, we apply the same distribution as measured in a very glacierized catchment (Obersulzbach, Austria) during the extraordinarily dry summer 2003 and scale the monthly future glacier runoff contributions from Huss and Hock (2018) with the same distribution and use the derived daily distributions for the further analysis. With this, we can assess the impact of changing glacier discharge on low-flow conditions theoretically, by assessing the current average number of NSD based on 1986-2015 and calculate how this number increases when we hypothetically remove the glacier contribution from 1986-2015. We do so one on hand for complete glacier contribution removal to indicate a situation when glaciers will have fully retreated. To also show the timeline of this increase we assess low-flow conditions based on measured runoff data for the past and include the changing future glacier contributions under RCP2.6 and RCP8.5 (30-year average annual contribution under respective scenario).

[12] While we are able to assess the impact of changing glacier-derived runoff on discharge, other factors such as precipitation, landcover and evapotranspiration can decrease water level in future critically, too.

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4.2. Economic impacts and assessment methodologies

4.2.1 Alpine glaciers and tourism: the Pasterze glacier case study

Glacier tourism attractiveness

To provide an example of the importance of glaciers for tourism activities we here focus on the Pasterze case study emphasizing both visits and the cost of artificial snow making that would be necessary to keep "intact" the Pasterze tourism attractiveness.

Data regarding visitor numbers is only available for the Grossglockner high alpine road, leading up to the Kaiser-Franz-Josefs-Höhe, where the GROHAG (Grossglockner Hochalpenstraße AG) has conducted frequency assessments starting in 1935, counting and classifying the vehicles at the Grossglockner high alpine road (see **Errore. L'origine riferimento non è stata trovata.**). The number of vehicles is then translated into visitor numbers using a distribution key for the average vehicle passengers (**Errore. L'origine riferimento non è stata trovata.**). The number of visitors peaked with an estimated 1,314,533 visitors in 1962 and varied within a range of 1 million yearly visitors experiencing a peak up to 1.2 million visitors in the early 1970s where the highest numbers of cars (340,648 in 1971) as well as trucks and buses (12,916 in 1972) were observed. There was another peak to around 1.2 million yearly visitors following the opening up of Eastern Europe in the late 1980's. Since then a declining trend in visitor numbers down to 800,000 visitors per year, can be observed (807,333 visitors in 2019).

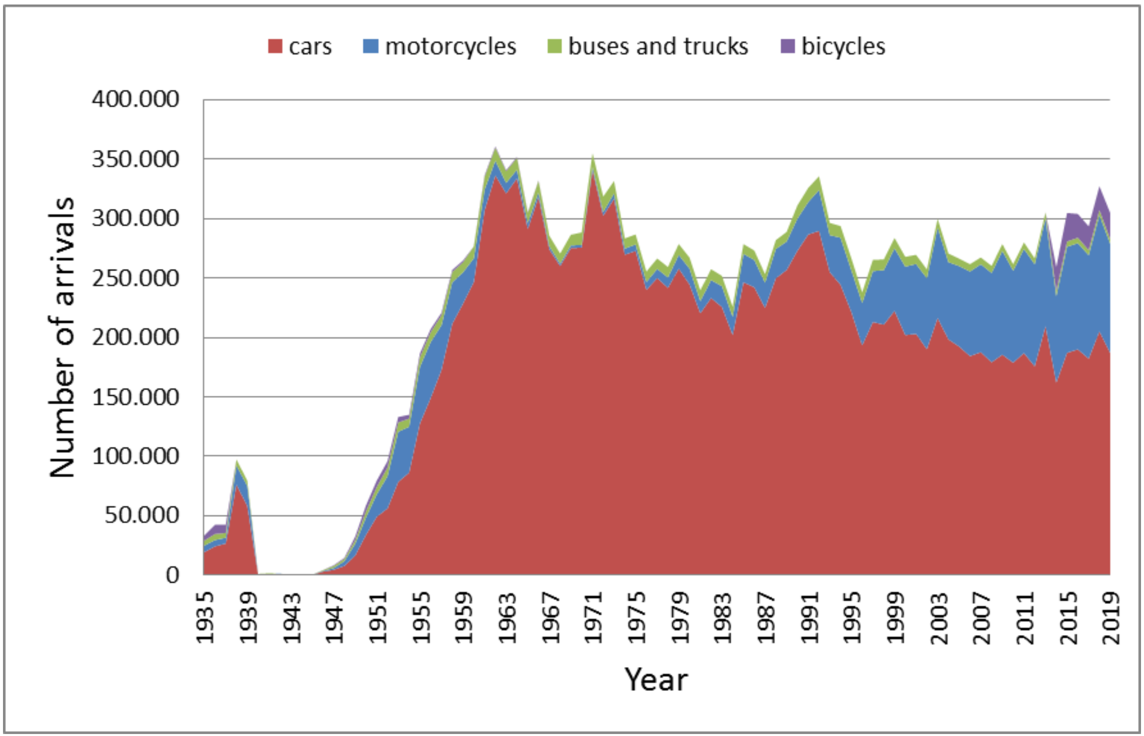

Figure 21: Frequency analysis of vehicles at the Grossglockner high alpine road (source: Schöndorfer (2020)).

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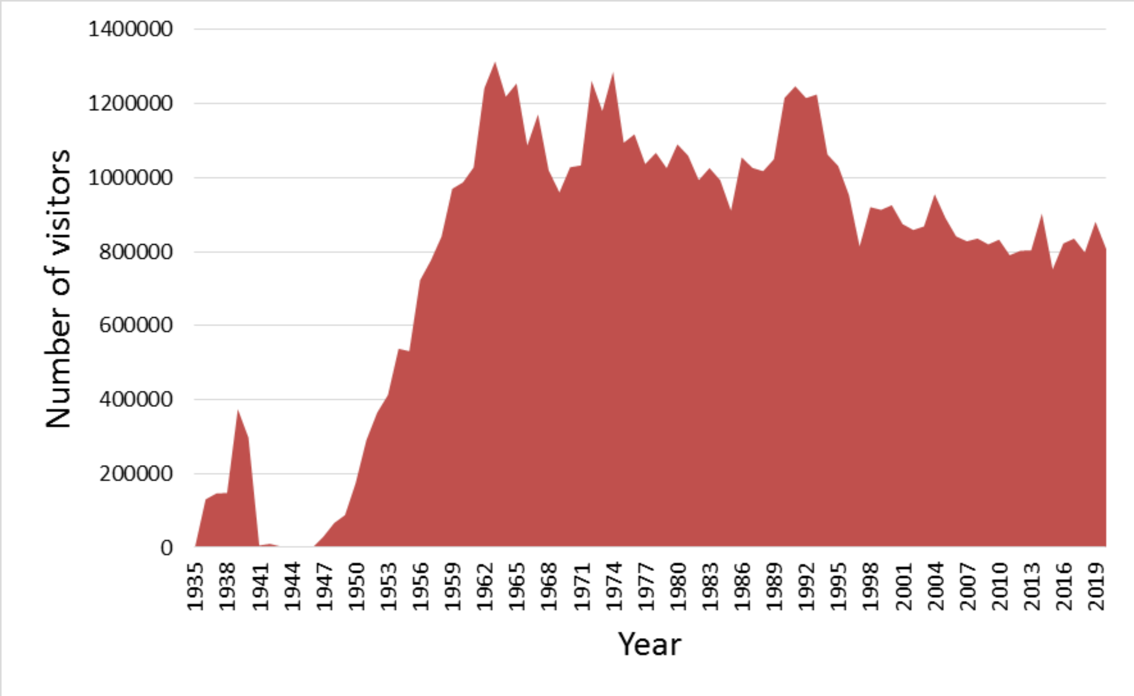

Figure 22: Number of visitors at Grossglockner high alpine road (derived from vehicle frequency, using a distribution key for the average number of vehicle passengers) (source: Schöndorfer (2020))

However, not all visitors can be attributed to the Pasterze as there are multiple reasons to travel the high alpine road. Unger (1989) conducted a survey among 150 visitors at the Kaiser-Franz-Josefs-Höhe in 1985 and identified the results shown in **Errore. L'origine riferimento non è stata trovata.** as the main motives for the trip.

Table 2: Motivations for a trip to the Kaiser-Franz-Josefs-Höhe (data source: Unger (1989)**)**

Motivations for a trip to the Kaiser-Franz-Josefs-Höhe						
	very important		not important		Neutral	
	absolute	%	absolute	%	Absolute	%
see the highest mountain of Austria up close	106	70,7	21	14	23	15,3
drive a panorama road in the high mountains	119	79,3	18	12	13	8,7
be in the middle of the mountains	103	68,7	20	13,3	27	18
view the glacier up close	112	74,7	20	13,3	18	12

While the motivation of viewing the glacier in this survey ranks second, the results of another survey question conducted among the same visitors shows that only 19.33 percent of those surveyed viewed the Pasterze as the main point of attraction (see

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Errore. L'origine riferimento non è stata trovata.). This significantly lower percentage implies that while the Pasterze contributes to a combination of reasons to visit the Kaiser-Franz-Josefs-Höhe (accumulated reasons for decision), the share of visitors frequenting the Kaiser-Franz-Josefs-Höhe due to the Pasterze alone, is much lower than the 74.7 percent identified in **Errore. L'origine riferimento non è stata trovata.**.

Table 3: The fascination of various features at the Kaiser-Franz-Josefs-Höhe (data source: Unger (1989)).

The fascination of various features at the Kaiser-Franz-Josefs-Höhe		
	absolute	%
many high mountains	70	46,67
many visitors	4	2,67
street and building	4	2,67
Grossglockner	30	20
Pasterze	29	19,33
Sublimity	8	5,33
Other	5	3,33

If we are interested in the fraction of visitors that visits solely because of the Pasterze, the conclusion, that the share of visitors frequenting the Kaiser-Franz-Josefs-Höhe to see the glacier is around – or more likely below – the 19.33 percent result rather than being close to the 74.7 percent share estimated in **Errore. L'origine riferimento non è stata trovata.**, is consistent with the information provided by the manager of the Grossglockner cableway company, that approximately 3 percent of all visitors to the Kaiser-Franz-Josefs-Höhe ride the cableway down to the glacier. The percentage share proved quite stable and only a small declining trend is observable due to the increased difficulty of marketing the product due to the continuing retreat of the glacier from the valley station. A large part of the effects of the receding glacier could be mitigated through a change in the marketing strategy from offering the cableway down to the glacier, to offering a 'time travel experience to the glacier' starting at the Kaiser-Franz-Josefs-Höhe (position of the glacier snout in 1930), to the valley station of the cableway 144 meters below (position of the glacier snout in 1960) and then following the path of the glacier along an adventure trail up to the current beginnings of the glacier approximately a 30 minute walking distance away[13]. It is likely, that the travels of those riding the cableway are motivated solely by the Pasterze. The numbers would therefore decline with a further retreat of the glacier and be lost completely when the glacier disappears. Considering current visitor numbers at the Kaiser-Franz-Josefs-Höhe, a 3 percent share would account for approximately 25,000 visitors per year that would be lost. This estimate, however, clearly represents a lower bound. Under the presumption that not all visitors who visit the Kaiser-Franz-Josefs-Höhe motivated by seeing the Pasterze also ride the cableway, as quite some hike down to the glacier or

[13] P. Schmiedl, Grossglockner Bergbahnen Touristik GmbH, pers. comm., 06.07.2020.

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are content with seeing it from afar, the visitors lost following a further glacier retreat may well be much higher.

For truck and bus arrivals there is only a single category covered in arrival statistics (see also **Errore. L'origine riferimento non è stata trovata.**). Assuming the number of truck arrivals at the Kaiser-Franz-Josefs-Höhe to be constant, as they are assumed to arrive at the Kaiser-Franz-Josefs-Höhe only to deliver supplies which are further assumed to be constant over time, we observe a sharp decline in bus arrivals (arrivals are steadily declining starting from approximately 10,000 buses and trucks arriving in the mid 90's to below 4,000 buses and trucks counted in 2019)[14]. The reason could be the same challenge of increased difficulty in marketing the Pasterze as a tourist destination.

The measured frequency in arrivals of cars at the Kaiser-Franz-Josefs-Höhe follows a declining trend since the peak in visitor numbers after the opening up of Eastern Europe in the late eighties (from 272,894 car arrivals in 1990 down to 186,931 car arrivals in 2019) while arrivals of motorcycles are increasing (from 27,051 arrivals in 1990 to 91,831 motorcycles measured in 2019). This is consistent with the assumption that the motivation of traveling to the Kaiser-Franz-Josefs-Höhe to see the glacier is higher amongst car drivers than amongst motorcyclists who are estimated to be mainly motivated by the driving experience along the Grossglockner high alpine road. This suggests that the number of car arrivals at the Kaiser-Franz-Josefs-Höhe is more affected by the retreat of the glacier, while the frequency measured in motorcycles is not dependent on the developments of the glacier. It is not known, however, how much of the decline in car arrivals can actually be attributed to the glacier retreat.

Cost for artificial snow production

The estimation of the cost for the necessary artificial snow production is based on Damm et al. (2014). These authors take as their starting point the amount of snow required per year, the possible snow making hours and the corresponding water consumption for given snowmaking technologies that are assumed to be constant over time. The snowmaking is therefore only limited by meteorological conditions, the number of snow guns and the maximum water consumption. Damm et al. (2014) found electricity cost for artificial snow production to be around 0.38 EUR, and 0.4 m^3 of water to be required to produce 1 m^3 of snow. Calculations based on Rogstam and Dahlberg, 2011 who tested different snow gun and snow lance models regarding their capacity, energy usage and water consumption, leads to similar results. Water consumption for three chosen models varies between 0.453 m^3 (Areco Supersnow) and 0.494 m^3 (Snowtech T60). Energy usage varies on a greater scale with results ranging from 0.649KWh (Bachler NESSy) to 1.802KWh (Snowtech T60). Using an average energy price for 2017 of 0,197 EUR per kWh (Statistik Austria, 2019) this results in slightly lower energy costs of 0,36 EUR per m^3 of snow for the model Snowtech T60, and a significantly lower energy cost of 0.128 EUR per m^3 of snow for

[14]D. Schöndorfer, GROHAG Grossglockner Hochalpenstraße AG, pers. comm., 07.07.2020

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the snow lance model Bachler NESSy. The considerably lower energy cost for Bachler NESSy is due to the model being extremely energy efficient, the higher value for Snowtech T60 is however more representative for a wider spectrum of modern technologies. Adding costs for labour and material as well as investment costs derived from the depreciation value of investments Damm et al. (2014) conclude on a total cost per m^3 of artificial snow of 1.5 EUR. This cost estimate for artificial snow represents a lower bound for the snow production costs that are to be expected on the Pasterze, as Damm et al. (2014) assume the infrastructure concerning the type and number of snow guns used to be preexistent and stable and hence only reinvestment to be necessary. In the case of the Pasterze an initial investment for snow guns including the associated infrastructure and water reservoirs, capable of supplying the water needed in production, as well as additional investments to the general infrastructure would be necessary. It is therefore likely that the cost of snow production on the Pasterze are higher and more in line with or above a cost of 3,3 EUR per m^3 of snow as suggested in Cognard et al. (2015).

4.2.2 Alpine glaciers and streamflow: hydropower and transportation

Hydropower

Glacier run-off contributes to hydropower production, particularly so in the summer months. The loss in production can be evaluated at the level of value added connected to the respective amount of electricity produced (or not produced for that matter). We use gross electricity prices, as these cover the total of all components contributing to value added, i.e. production costs and taxes (in particular energy and value added tax). We use a mean price of private households and industry. This can serve as a lower bound. In D3.4 (section 3.9) we apply a different approach, linking electricity supplied to the value added produced by its use, which would imply a multiple value of one unit of electricity. However, as long as electricity not generated in hydropower plants due to lower glacier run-off can be substituted by other electricity production, the approach used below is adequate. Only if loss of electricity production cannot be accommodated for by different plants or imports, actual loss of electricity supply would occur, potentially even causing a black-out, which then would turn the approach as used in D3.4 the relevant one. D3.4 treats black-out situations.

Transport on Inland Waterways

In navigation there are no official closures of waterways at low water. The available fairway depth determines the draught of a vessel and hence the possible loading quantity (Viadonau, 2020). Economic costs in low water are incurred due to the reduced cargo capacity. Moreover, the decreasing under keel clearance at low water levels leads to increasing hull forces in longitudinal and transverse direction, causing the resistance and hence the power needed to increase. That results in longer travel times, higher fuel consumption and decreasing turning capabilities (De Boer, 2019). Low water levels also increase the risk of accidents and grounding, further increasing the freight costs (Schreuder, 2019).

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The arising additional costs differ across various barge models and freight types. They tend to be higher for freight with high specific densities since the restrictions to the maximum cargo capacity are more likely to be binding for weight critical goods as opposed to freight transports where volume is the critical factor[15].

Along the Rhine some inland waterway companies have issued low water surcharges to cover the additional costs. For example, inland navigation companies that operate as service providers for Ocean Network Express (ONE) calculate surcharges on the basis of the gauging stations in Kaub and Duisburg Ruhrort. If water levels at Kaub are below 150cm a surcharge of 35 Euro per 20-foot container and 45 Euro per 40-foot container is calculated. At the gauging station Duisburg Ruhrort a surcharge of 30 Euro per 20-foot container and 40 Euro per 40-foot container is issued at water levels below 270cm. The surcharges rise with decreasing water levels (DVZ, 2019).

In the following the focus here is on navigation on the German Rhine. As the free flowing middle sections of the Rhine are especially prone to low water, there is a good database on the economic impacts of low water levels. The Rhine is also considered the most important waterway in Germany and Western Europe. Roughly 80 percent of inland waterway freight transportation of Germany takes place on the Rhine (BDB, 2019), it is further estimated, that about two thirds of the goods transported on European waterways pass the Rhine (REWWAY, 2020).

The majority of goods transported on German inland waterways have high specific densities and are therefore particularly affected by restrictions in cargo space capacities as a result of low water levels[12]. About 25 percent of the goods transported on German waterways are ores, stones or earths, followed by coking plant and petroleum products accounting for a share of 17 percent and coal, crude oil and natural gas products with a share of 14 percent. Chemical products account for about 11 percent of the goods transported via navigation. Although the overall share of navigation in the total volume of transportation in Germany is only around 7 percent, inland waterway transportation is of high significance for industrial goods (BDB, 2019). Roughly 30 percent of the total transported volume of coal, crude oil and natural gas and about 20 percent of the transported volume of coking plant and petroleum products are shipped on inland waterways (Ademmer et al., 2020).

Ademmer et al. (2020) analyse the relation between low water levels on the Rhine, navigation and German industrial production. In this paper, for low water levels on the Rhine the water level at Kaub, a gauging station in the shallowest part of the middle section of the river, is used as an indicator. A low water day is defined by a gauge level below the official reference low water level of 78 cm. At this level the maximum barge capacity can only be utilised to about 25 percent, meaning that four ships are needed to transport the freight that is carried by one at a 'normal' gauge level of 250 cm (Contargo, 2017). The effects of low water levels on the inland waterway freight transport are calculated by regressing the changes in transportation volume on the change in the number of days with low water. Results indicate, that an additional day of low water causes a fall in freight transport by 0.9 percent. A full month (30 days)

[15] A. Herkel, viadonau, pers. comm., 18.06.2020.

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would then imply a decline in inland water transportation by 25 percent compared to normal water levels. Econometric regression results also indicate that in the following period a lagged effect of about half the size further decreases the freight volume. Isolating the effect that low water has via changes in transportation volume on industrial production, Ademmer et al. (2020) find that an additional day of low water causes a decline of 0.034 percent in industrial production, resulting ceteris paribus in a 1 percent decrease in industrial production for a full month (30 days) of low water levels. Analysing the 2018 low water period (a period including the full month of November had low water), this period was found to have caused the level of industrial production 1.5 percent below the counterfactual level without low water effects. With industrial production accounting for approximately 25 percent of the German GDP, that corresponds to a 0.4 percent decline in the German GDP, which in 2018 would account for a cost of approximately 135 billion Euros that can be attributed to the November 2018 low water period on the Rhine (Statistisches Bundesamt, 2019). As the majority of goods transported via waterways are industrial goods that are often at the beginning of production chains, it is likely, that the overall economic impact is much higher. This may be due to delivery bottlenecks and other spillover effects from the industry to the service sector.

4.3 Results

4.3.1 Alpine glaciers and tourism

A reduction or complete loss of glaciers would determine relevant economic losses due to visual landscape changes, as glacial formations are lost, and increased risk to the mountain’s infrastructure as the frequency of soil erosion is higher in areas of glacial retreat and therefore endangering buildings, footpaths and roads as well as cableways (Patek, 2007; Pröbstl and Damm, 2009). Some of these implications are analysed in the context of the Pasterze case study example below.

The current size of glacier induced skiing tourism might be in the range of 8% of total overnight stays (26 million out of 330 million) across the Alps (see section 4.1.1). If we apply an average daily expense per tourist from one of the relevant countries, Austria, available for the tourism year 2013/14 of 152 EUR in winter (WKO, 2018), we can conclude that a yearly economic value of roughly 4 billion EUR across the Alps is directly concerned. We know that by no means this implies that all of that directly concerned economic value would be lost if the glaciers retreat, as skiing might still be possible under newly arranged conditions. However, it is dependent on locally specific factors whether this is possible and at what costs, but also whether arising risks of soil erosion or increased steepness may be preventive.

With rising temperatures snow lines will rise causing a shift in tourist flows to glacier ski areas, therefore increasing their economic relevance and possibly the loss that can be associated with their disappearance. Glacier ski areas in Switzerland and France might benefit from the shifts of tourist flows at first, as on average they are at higher altitudes and hence could benefit from Austrian glaciers located at somewhat lower altitude and thus possibly melting earlier, if local conditions do not allow their continuation as a ski resort under natural or artificial snow. In the long run however,

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also they will suffer severe economic losses comparable to those established above (ZAMG; Astelbauer-Unger et al., 2011).

The Pasterze glacier case study

Table 4 and Figure 23 show the total annual artificial snow production (ASP) in m^3 that would have been necessary to keep the tongue of Pasterze in balance in the hydrological years 2012/2013-2017/2018. The artificial snow density is assumed to be 450 km/m³ (Rogstam and Dahlberg, 2011) and natural fresh snow to be 250 kg/m³ (Cuffey and Paterson, 2010).

Table 4: Overall artificial snow production (ASP) volume and cumulative specific ASP required in order to obtain neutral balance at Pasterze glacier's tongue (2.3 km²) for each hydrological year. Note, that the numbers do refer to cumulative fresh ASP with a density of 450 kg/m³ and the cumulative specific ASP should not be interpreted as snow height but as cumulative values of ASP averaged over the entire tongue.

hydrological year	cumulative ASP volume [m³]	cumulative specific ASP [m]
2012/2013	28297941	12.3
2013/2014	23753177	10.3
2014/2015	37950917	16.5
2016/2017	31287367	13.6
2017/2018	36319366	15.8
2018/2019	33035654	14.3

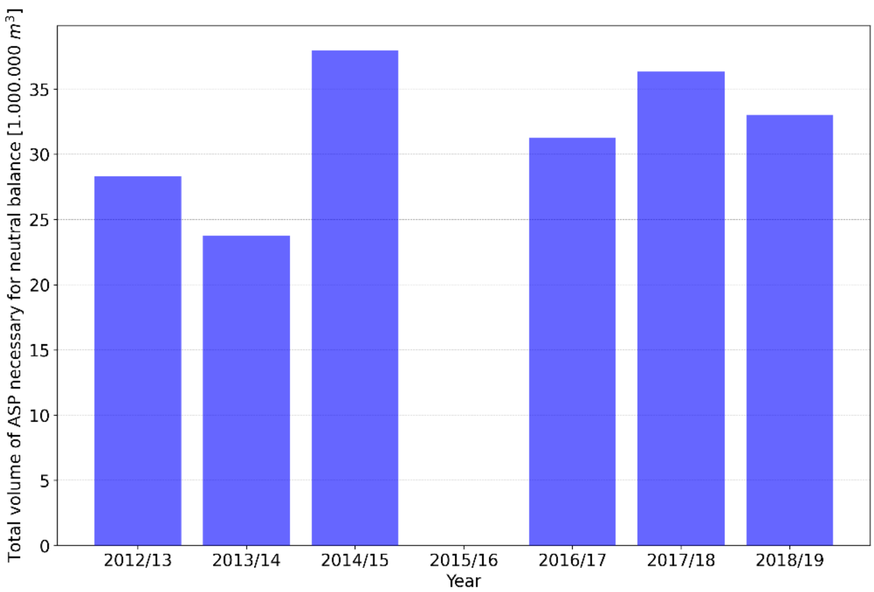

Figure 23: Total artificial snow production volume necessary to obtain neutral balance for each hydrological year. Note, that 2015 is missing due to a data gap of several months from the automated weather station (AWS) at Pasterze.

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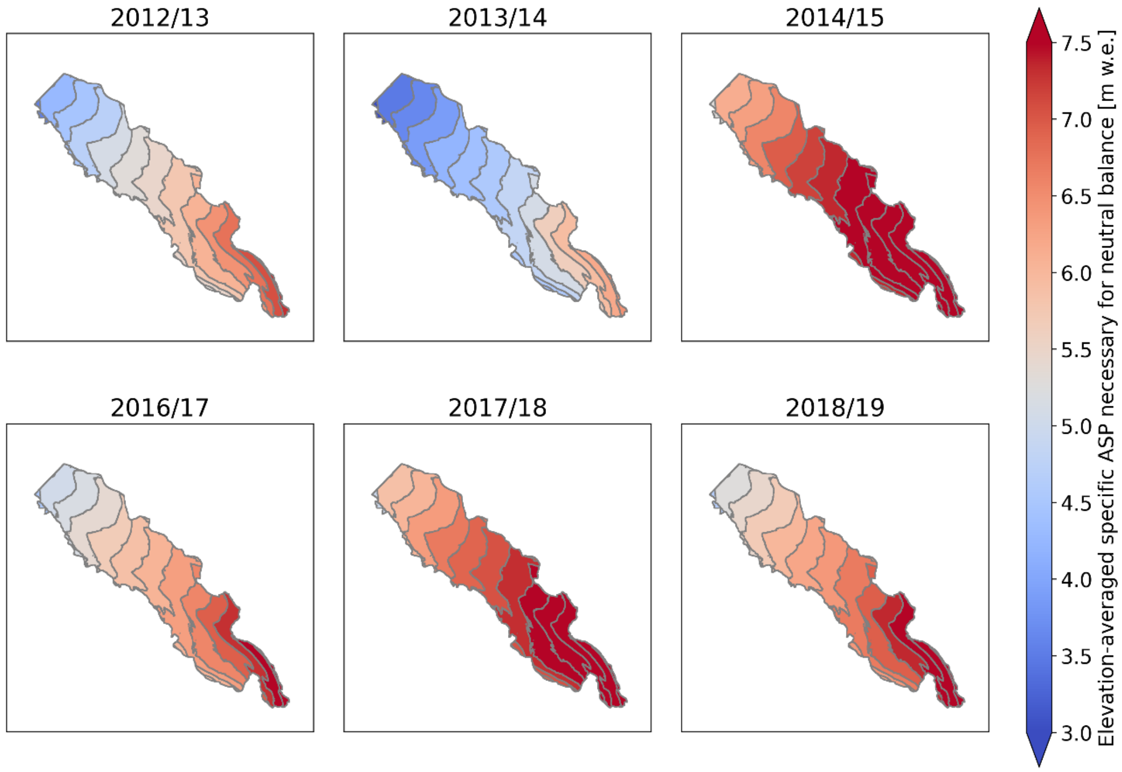

Figure 24 shows the spatial patterns of ASP necessary at Pasterze glacier's tongue in order to achieve a neutral balance in each elevation band for the years 2012-2018.

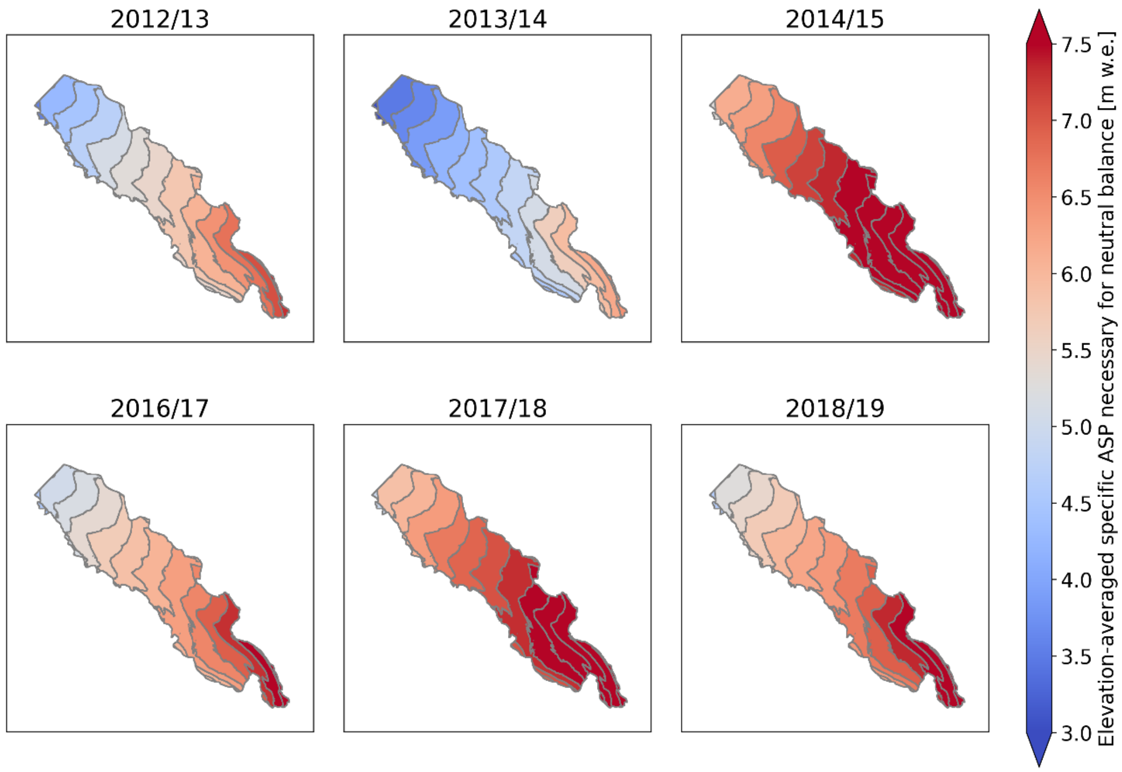

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Figure 24: Spatial distribution of specific ASP necessary to obtain neutral balance for the years 2012-2018. Note, that 2015 is missing due to a data gap of several months from the AWS.

The spatial distribution of ASP is rather similar each year at a relative scale, while absolute values vary strongly, depending on how far the glacier balance (without ASP) deviates from equilibrium conditions. Comparing for instance the year 2012/2013 (a year with favourable conditions for the glacier) with 2013/2014 shows that ASP can differ by 2-3 m w.e..

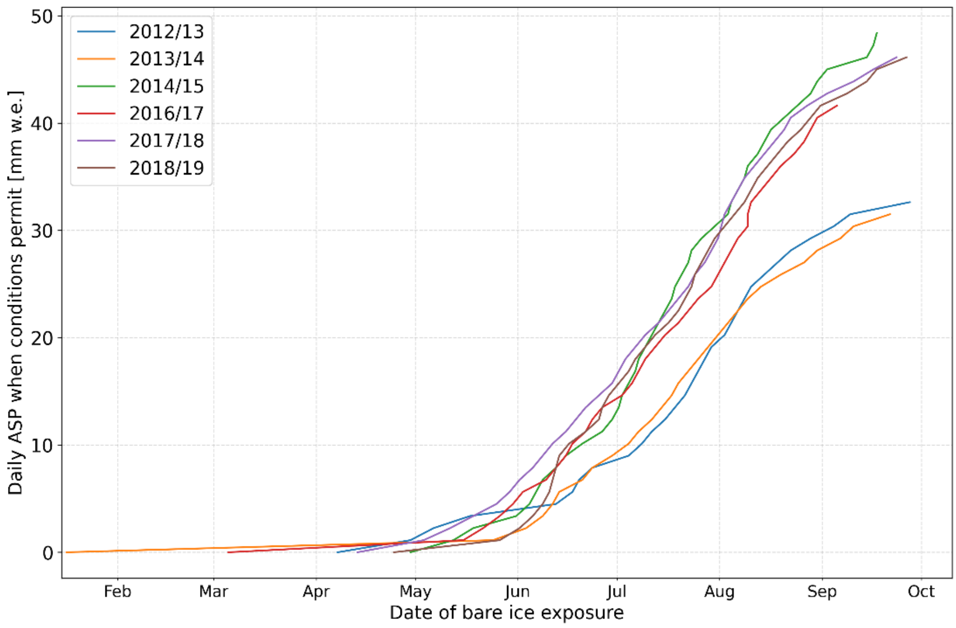

Figure 25: Date on which mass balance becomes 0 (bare-ice exposure) at the location of the automated weather station (AWS) as a function of daily artificial snow production (ASP) amount (Each line represents a different hydrological year).

The results can also be used in order to quantify the efficiency of ASP in shifting the date of bare-ice exposure. This is shown in Figure 25, where the date of bare-ice exposure (b = 0) is presented as a function of ASP rates for each hydrological year. Exemplarily, an ASP of 10 mm w.e./day using all days with air temperature >0°C, will shift bare-ice exposure at the ASW to early July in the year 2012/2013, while the same ASP amount in 2017/2018 will result in bear-ice exposure in early June. The general shape of the curves indicates that a strong increase of ASP rates is needed to avoid bare-ice exposure during core summer, while comparably little extra snow is needed to efficiently protect the glacier from ice melt early and late in the ablation season, when radiation availability is lower. Additionally, this seasonal difference is stronger in years with a less negative natural mass balance anomaly (e.g., 2012/2013) and weaker for strongly negative years (e.g., 2014/2015).

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An important constraint of the results to discuss, is that in principle, glacier dynamics modify surface conditions in addition, namely by the moving ice (emergence or submergence). In the ablation zone upward ice flux (emergence) is able to compensate height changes of the glacier surface due to ablation to some extent. However, the simplifying approach to neglect ice flux is useful, particularly over the short study period of 8 years, since dynamic decoupling of the ablation zone from the accumulation zone has largely happened at Hufeisenbruch. Rather small numbers of observed emergence velocities in the order of below 0.5 m/year as found by Hynek et al. (2018) support the simplified approach as they are much smaller than the natural ablation values. On a multi-decadal to centennial scale however, ice flux would again become a relevant forcing, particularly during positive mass balance years (Abermann et al., 2007).

Another simplification of our model approach lies in the fact that we do not consider differential ablation over debris-covered regions of the glacier. While this influences ablation in reality strongly (Hynek et al., 2019) it does not impact the results of our experiment as we assume neutral balance at the end of the balance year as a precondition and hence both debris-covered and debris-free areas of the glacier remain snow-covered.

On the feasibility of keeping a neutral balance of the glacier tongue let us take a look at both the water demand and the economic cost. The water amount that is necessary in order to obtain neutral balance is very high (see Table 4). We attempt a very rough estimate of the fraction of the catchment's precipitation that would represent the water volume necessary. If we assume an average annual precipitation of 2000 mm/year (a typical value for 2500 m a.s.l. in the nearby Sonnblick area stemming from homogenized measured data; Leidinger, 2013) and a total catchment area of Pasterze Glacier of 33.7 km² (Leidinger, 2013) we would obtain 6.7×10^{7} m³ of water which corresponds to 6.7×10^{10} kg of water. The average ASP volume necessary to achieve neutral balance would be 3.1×10^{7} m³ (Table 4) which corresponds to 1.4×10^{10} kg of water. This simplistic back-of-the-envelope calculation would mean that about 20% of the annual precipitation in the entire catchment would need to be converted into ASP in order to achieve neutral balance. While parts of the catchment do not change from solid to liquid state under current climate conditions, this result means that from a water availability perspective this would likely be principally doable.

The snow volumes required per year (Table 4) translate to yearly economic costs shown in Table 5 when evaluated with the cost of ASP (as established in section 4.2.1 to be ranging between 1.5 EUR per m^3 and 3.3 EUR per m^3).

Table 5: Cost of the artificial snow production (ASP) required in order to obtain neutral balance at Pasterze glacier's tongue (2.3 km²) for each hydrological year in Million EUR for 1.5 EUR/m^3 and 3.3 EUR/m^3 respectively

hydrological year	1.5 EUR/m^3	3.3 EUR/m^3
2012/2013	42.446	93.383

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2013/2014	35.630	78.385
2014/2015	56.926	125.238
2016/2017	46.931	103.248
2017/2018	54.479	119.854
2018/2019	49.553	109.018

As mentioned above in section 4.2.1, the cost of 1.5 EUR per m^3 of snow does not include initial investments, which however, due to the lack of snow making infrastructure on the Pasterze, would likely be significant. Hence assuming a cost per m^3 of snow closer to 3.3 EUR appears to be a better approximation of the economic cost arising in order to keep the Pasterze in the shape it is.

In order to relate the more realistic annual cost of artificial snow production to keep the glacier‘s balance neutral (109 Mio EUR in the most recent winter season) the value added that can be attributed to tourism around the Pasterze can be assessed. In section 4.2.1 we established a share of 3 to 20 percent of the arrivals that are attracted by the Pasterze (overall 807,333 arrivals in 2019). If we take the Pasterze to attract its visitors to stay for an extra day, we can account for an average value added of approximately 150 EUR per visitor[16] (covering both the average daily expenses per tourist and the toll for the High Alpine road). Lost value added due to glacier loss would then range between 3.6 Mio. EUR (for 3 percent share of overall visitors attracted by Pasterze) and 24.2 Mio. EUR (for 20 percent). Additional losses are probable to occur when the glacier retreats further or disappears completely due to diminishing numbers of hikers and climbers in the region as a result of a decline in landscape beauty and attraction (WANG and ZHOU, 2019) as well as due to increasing risks including increased risk of rockfall and increasing steepness of hiking trails as well as prolonged hiking times due to the melting of the glacier tongue (Pröbstl-Haider et al., 2016).

When assessing the maintenance of the Pasterze in its current shape from a solely economic viewpoint the costs of artificial snow production (109 Mio. EUR) can be interpreted as preventive costs to mitigate the negative impacts of climat echange in order to preserve tourism. If we relate this cost to the 20 percent of current annual tourist arrivals that were identified as rather the upper bound of being attracted by the Pasterze, the preventive costs amount to approximately 680 EUR per tourist arrival. If the attraction potential is closer to the share of tourists also using the cable care (3 percent), the preventive cost per tourist would be respectively higher, up to a multiple of that number. Evidently in a future scenario where most Alpine glaciers will have disappeared the attractiveness of the few (or possibly single one) remaining glaciers will increase, lowering the (preventive) cost ratio per tourist. Yet, further warming will also increase the demands on snow production, and thus related costs.

[16] On tourist expenditure we use the average daily expenses per tourist for the tourism year 2013/14, building on an average of 152 EUR in winter and 125 EUR in summer (WKO, 2018), for our purpose weighing the summer value at 80 percent, as the High Alpine road is closed for much of the winter. For the toll for the High Alpine road, which accounts for 37 EUR for cars (Grossglockner Hochalpenstraße AG, 2020)), we assume an occupancy rate of 2 passengers per car.

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Thus, only if it would be an (almost) single and very favoured attraction could the cost allocation per tourist decline, but given its current level of at least 680 EUR per tourist (and possibly a multiple of that) this still might not be an attractive option considering the average value added per tourist to be around 150 EUR as established above.

While it could be argued that the preservation of the Pasterze has to be valued higher due to symbolic as well as intergenerational reasons, from an economic standpoint the conclusion is obvious, that, even though water availability is not a binding constraint, the tipping point of feasibility of keeping the Pasterze in its current shape has already been passed under an economic cost perspective.

Only for a society also considering the case that demand for a – possibly also symbolic and – then single glacier might rise dramaticly in the future, we add: in comparison to theoretically building Pasterze glacier's tongue up again after it has entirely vanished, preservation will be more cost-efficient. For preservation, the energy balance and therein particularly the net-radiation exchange is less negative as long as snow and ice are present, and keeping the glacier balanced requires less water and energy than adding mass from zero.

4.3.2 Glaciers and streamflow as an economic factor

Hydropower

In order to assess the impact of glaciers on hydropower generation, we show an overview of available data on hydropower plants in the Alpine region. The database we use is also applied in COACCH D2.4 (Schleypen et al., 2019) and is the combination of Gotzens et al. (2019) and Copernicus Climate Change Service (C3S) (2017)

. In order to obtain relevant results for the connection between glaciers and hydropower we choose two selected power plants for each macro-scale catchment: one that is in the vicinity of the glaciers, where we expect more relative impact through glaciers and one that is further downstream and hence represents a site of lower impact. This can be understood as a best guess for end members concerning the direct impact of glaciers to runoff. Further downstream from the lower site, we can expect the absolute impact of glaciers to remain stable, while its relative importance reduces further until the mouth of the river.

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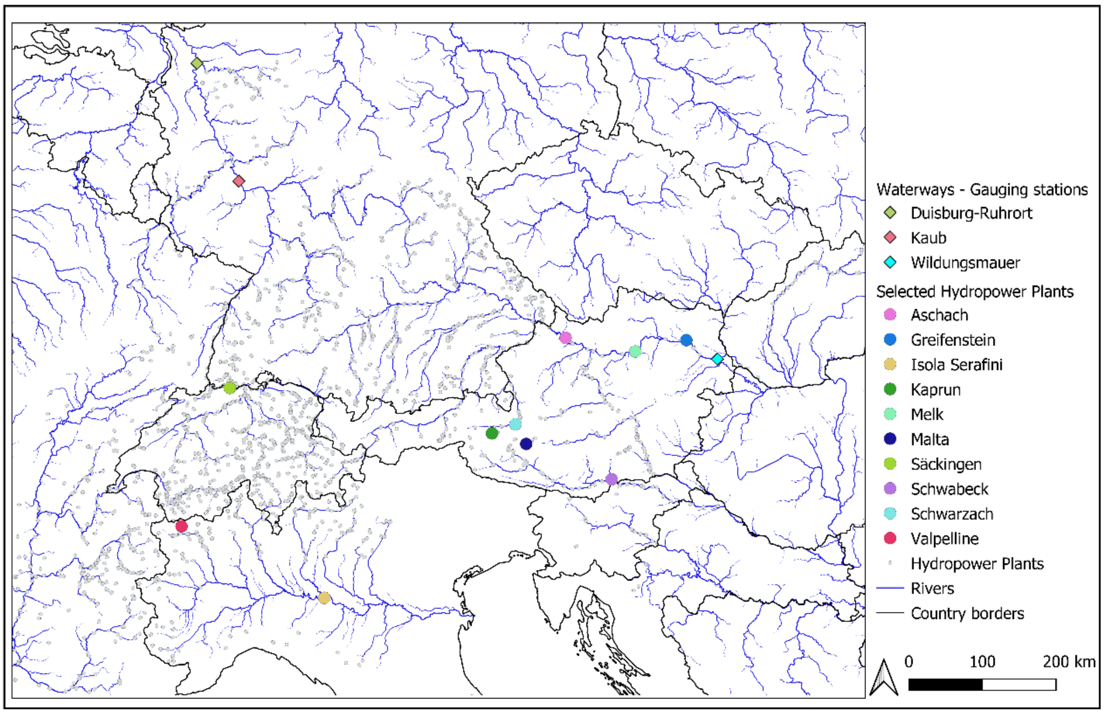

Figure 26: Power Plants in the Alpine region (grey), specific power plants for which we show individual results (coloured circles) and three selected gauges where we assess the impact of glacier discharge on shipping (coloured squares). Data source: Schleypen et al., (2019)

The next step is to quantify the relative importance of the glaciers at the selected stations' discharge. For that we obtained daily discharge data for selected stations from the Global Runoff Data Center (GRDC, 2020) and complement those with data from national agencies, (e.g., EHYD, 2020). We calculate an average of the selected stations for the summer months JJA where we expect the most significant contribution from glaciers and relate the modelled contribution for all glaciers in the respective drainage area to the overall runoff. For future assessments we use the fact that we have a period of measured total discharge at the selected gauges and modelled glacier runoff from all glaciers in the drainage area and hence determine the absolute contribution that does not come from glaciers in the climatological reference period. We then assume in a simplified approach that this part (the non-glacier-related quantity) does not change significantly in future and hence can deduce the fraction stemming from glaciers according to RCP scenario of COACCH in future. In Figure 27 we show exemplarily a time-series of relative glacier contribution to total summer runoff at four selected sites. While Bern and Innsbruck are rather close to the glacier sources, Andernach and Passau are significantly further downstream the respective river. While the absolute runoff increases as we move further downstream the river, the relative contribution of glaciers reduces strongly – for the case of macro-scale catchment Rhine from about 22% in Bern to around 5% in Andernach or from around 20% in Innsbruck to around 8% in Passau. Along with the decrease in relative contribution of glaciers, we observe an increase in variability of absolute runoff as we

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move downstream, which is due to the change in prevailing runoff regime from glacio-nival to pluvial.

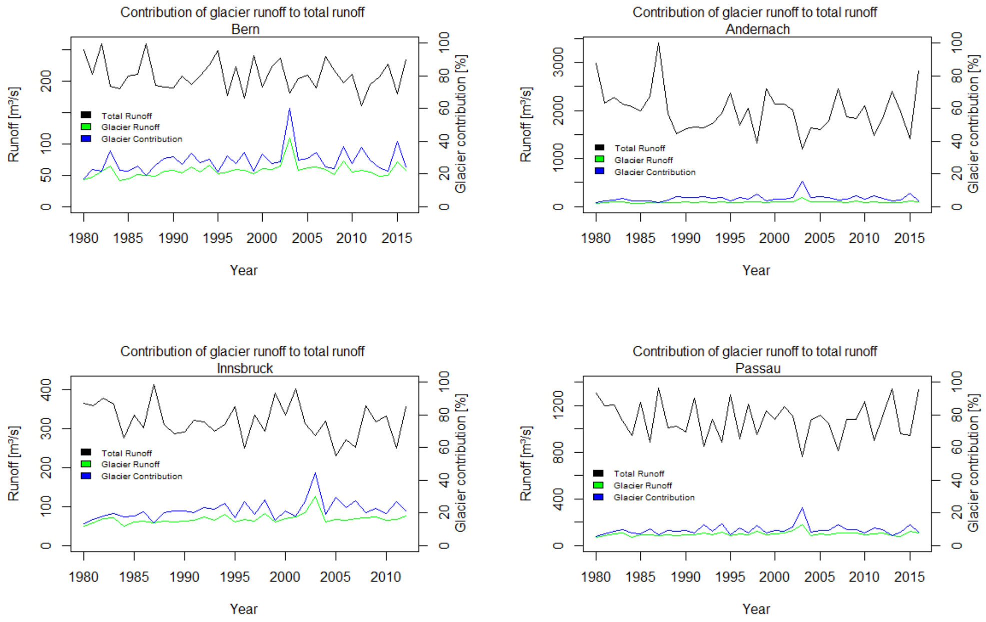

Figure 27: Total Runoff, absolute and relative glacier contribution for selected gauges along the macro-scale catchments Rhine and Danube for summer averages (JJA). Data source: Huss and Hock (2018).

We propose two different ways to assess the economic impact of reduced glacier runoff on hydropower depending on data availability. For power plants where we have access to conversion factors between discharge [m³/s] and the obtainable capacity [MW] based on (Habersack et al., 2011) and a daily discharge time series from the past, we follow, what we label 'Method 1' in the results Table 7. After converting measured discharge to capacity we apply the methods sketched out above for summer months to derive the future capacity that will reduce due to the reduced discharge from glaciers. We then use these average summer capacities [MW] and multiply with the total summer hours (92 days x 24 hours→2208 hours) and obtain the energy production for the respective quantities. We provide the results for summer months (JJA), as during those, the fraction of glacier contribution is and will be highest.

Method 2 is applied for selected power plants where measured discharge as well as the future glacier projections for the respective catchments are available. However, since we do not have conversion factors between runoff and power yield for those, we follow a more simplified approach based on the power plants' total capacity that we know from an existing database used for D2.4 (Schleypen et al., 2019). Under the assumption that the respective power plant yields full capacity during entire summer, we can estimate what the loss in power yield is when glaciers reduce according to the given scenarios in the respective drainage basin. Since the assumption of full capacity is somewhat arbitrary and likely unrealistic now and, in the future, these numbers can

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be used as upper boundaries for the glaciers' influence on power reduction. We stress, that Method 1 likely gives more realistic values.

We perform both approaches for two different scenarios and average for different climatological periods in the future. Figure 28 shows for one power plant (Aschach, close to Linz at the Danube) the total summer month energy production since 1980 and the future evolution assuming that all other components influencing discharge and hence energy production remain the same and the contribution from glaciers reduces according to the modelled results. The blue curves show the quantity of production that is contributed by glaciers. While this contribution is around $3.2x10^4$ MWh on average for the summers 1986-2015 it drops to $5x10^3$ MW for RCP 2.6 and to 800 MWh by 2071-2100. Results of these approaches are summarized for selected power plants in Table 6 and Table 7.

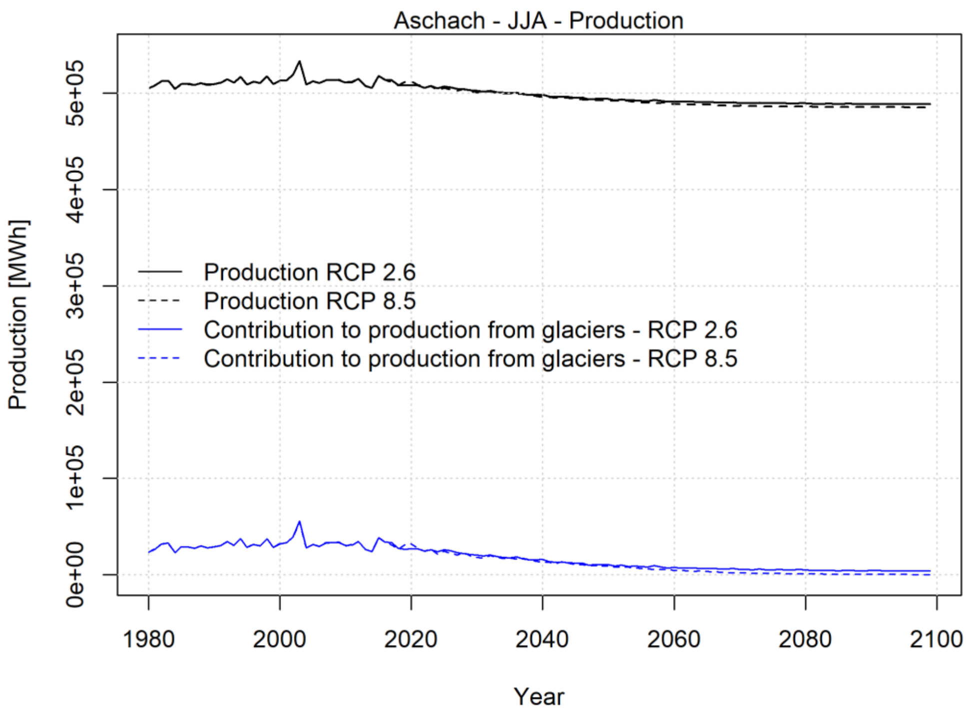

Figure 28: Summer (JJA) total energy production and the part that stems from glaciers based on measurements and future projections for two different scenarios for the power-plant Aschach at Danube near Linz in MWh. Data source: Huss and Hock (2018); Habersack et al. (2011); (EHYD, 2020).

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Table 6: Summer discharge and relative glacier contribution at selected hydropower locations for different time periods and the scenarios RCP2.6 and RCP8.5. Data source: Huss and Hock (2018); Habersack et al. (2011), Data source: Schleypen et al., (2019)

RCP2.6									
Hydropower Plant	average JJA discharge total	average JJA discharge glacier contribution				relative glacier contribution to JJA discharge			
	1986 - 2015	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100
	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[%]	[%]	[%]	[%]
Aschach	1685	106	68	25	15	6	4	2	1
Melk	2201	106	69	25	15	5	3	1	1
Greifenstein	2183	111	72	26	16	5	3	1	1
Kaprun	13	2	1	1	0	16	10	5	4
Malta	2	1	1	0	0	77	66	51	44
Säckingen	1327	99	71	42	33	7	5	3	3
Schwabeck	308	25	16	8	6	8	5	3	2
Schwarzach	149	17	10	4	3	11	7	3	2
Isola	951	58	38	19	16	6	4	2	2
Valpelline	151	4	3	1	1	3	2	1	0
RCP8.5									
Hydropower Plant	average JJA discharge total	average JJA discharge glacier contribution				relative glacier contribution to JJA discharge			
	1986 - 2015	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100
	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[%]	[%]	[%]	[%]
Aschach	1685	106	66	17	3	6	4	1	0
Melk	2201	106	67	17	3	5	3	1	0
Greifenstein	2183	111	70	17	3	5	3	1	0
Kaprun	13	2	1	0	0	16	10	4	1
Malta	2	1	1	0	0	77	66	44	34
Säckingen	1327	99	69	34	11	7	5	3	1
Schwabeck	308	25	16	7	3	8	5	2	1
Schwarzach	149	17	9	2	0	11	6	2	0
Isola	951	58	38	15	6	6	4	2	1
Valpelline	151	4	3	1	0	3	2	0	0

Table 7: Average (Method 1) or Maximum (Method 2) capacity [MW] or production [MWh] at selected hydropower locations for different time periods and the scenarios RCP2.6 and RCP8.5. Data source: Huss and Hock (2018); Habersack et al. (2011); Schleypen et al., (2019)

RCP2.6											
Hydropower Plant	mean/*max* JJA capacity total	mean/*max* JJA capacity glacier contribution				average JJA production total	average JJA yield glacier contribution to production				Method
	1986 - 2015	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100	1986 - 2015	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100	
	[MW]	[MW]	[MW]	[MW]	[MW]	[MWh]	[MWh]	[MWh]	[MWh]	[MWh]	
Aschach	232	15	9	3	2	512643	32145	20879	7647	4616	1
Melk	171	8	5	2	1	377514	18219	11860	4348	2625	1
Greifenstein	233	12	8	3	2	514399	26091	17038	6242	3765	1
Kaprun	*260*	*41*	*25*	*12*	*9*	*574080*	*90823*	*54951*	*26756*	*20178*	2
Malta	*120*	*93*	*47*	*21*	*16*	*264960*	*204290*	*104089*	*45988*	*34699*	2
Säckingen	*598*	*44*	*32*	*19*	*15*	*1320384*	*98202*	*70575*	*41587*	*32570*	2
Schwabeck	*158*	*13*	*8*	*4*	*3*	*348864*	*28226*	*18600*	*8942*	*7139*	2
Schwarzach	*120*	*13*	*8*	*3*	*2*	*264960*	*29650*	*17080*	*6428*	*4490*	2
Isola	*120*	*7*	*5*	*2*	*2*	*264960*	*16093*	*10673*	*5380*	*4481*	2
Valpelline	*130*	*4*	*2*	*1*	*1*	*287040*	*8172*	*5333*	*2023*	*1384*	2
RCP8.5											
Hydropower Plant	mean/*max* JJA capacity total	mean/*max* JJA capacity glacier contribution				average JJA production total	average JJA yield glacier contribution to production				Method
	1986 - 2015	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100	1986 - 2015	1986 - 2015	2016 - 2045	2046 - 2075	2071 - 2100	
	[MW]	[MW]	[MW]	[MW]	[MW]	[MWh]	[MWh]	[MWh]	[MWh]	[MWh]	
Aschach	232	15	9	2	0	512675	32185	20234	5060	819	1
Melk	171	8	5	1	0	377529	18241	11495	2881	466	1
Greifenstein	233	12	7	2	0	514421	26123	16502	4156	673	1
Kaprun	*260*	*41*	*24*	*8*	*2*	*574080*	*90890*	*53829*	*18698*	*4086*	*2*
Malta	*120*	*93*	*46*	*16*	*10*	*264960*	*204429*	*102013*	*34812*	*22251*	*2*
Säckingen	*598*	*45*	*31*	*15*	*5*	*1320384*	*98299*	*69087*	*33567*	*10840*	*2*
Schwabeck	*158*	*13*	*8*	*3*	*1*	*348864*	*28247*	*18178*	*7575*	*2893*	*2*
Schwarzach	*120*	*13*	*7*	*2*	*0*	*264960*	*29669*	*16340*	*4050*	*836*	*2*
Isola	*120*	*7*	*5*	*2*	*1*	*264960*	*16102*	*10467*	*4235*	*1770*	*2*
Valpelline	*130*	*4*	*2*	*1*	*0*	*287040*	*8175*	*5229*	*1284*	*189*	*2*

During the summer months, focusing first on hydropower plants where evaluation is possible with Method 1, the average annual production loss relative to 1986-2015

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even under RCP 2.6 for the period 2046-2075 (2071-2100) is identified for Aschach at 24,500 MWh (27,500 MWh), for Melk at 13,900 MWh (15,600 MWh) and for Greifenstein at 19,800 MWh (22,300 MWh). This amounts to 3.7% (Melk) to 4.8% (Aschach) of summer production in the period 2046-2075, or 4.1% (Melk) to 5.4% (Aschach) for 2071-2100. Under RCP 8.5 the losses amount to 4% (Melk) to 5.3% (Aschach) of summer production for the period 2046-2075, or 4.7% (Melk) to 6.1% (Aschach) for 2071-2100. After full glacier retreat the losses amount to 4.8% (Melk) to 6.8% (Aschach), relative to 1986-2015. Evaluated at a mean electricity price (private households and industry, at 144 €/MWh in 2018) at these three hydropower plants value added of 8.4 Mio. € (2046-2075), respectively 9.4 Mio € (2071-2100) would be lost annually during the summer months under RCP2.6, relative to production in 1986-2015. Under RCP 8.5 losses amount to 9.3 Mio € (2046-2075) and 10.7 Mio € (2071-2100) respectively per year. Assuming that losses at these three plants were representative for all Austrian run-of-river power plants the value added lost per year would amount to 163 Mio € (2046-2075), respectively 184 Mio. € (2071-2100) under RCP 2.6, to 181 Mio € (2046-2075), respectively 209 Mio. € (2071-2100) under RCP 8.5, and to 215 Mio € (after full glacier retreat). However, given that the basis for this rough estimate are rather down-stream hydropower plants, this represents a lower bound rather than a best estimate. For upstream power plants the fraction of glacier loss is higher, in our (overestimated) method 2 approach it rises to above 60% (Malta), around 12% (Kaprun) or around 10% (Schwarzach), rather than the 3-6% of summer production loss we found at the three Danube hydropower sites.

Transport on Inland Waterways

In Figure 29 we show how the annual number of NSD at Kaub changed throughout the past decades (black line). This can be understood as the number of days, where the critical level of 78 cm was not reached in a specific year. In this context it is interesting to compare the two largest values: while 2003 is known for the record warm and dry summer (Schär and Jendritzky, 2004), the low-flow in 2018 was caused by a drought in autumn (Sheppard and Chazan, 2018). It is evident, that glaciers were able to buffer some of the summer low-flow conditions, while this buffering cannot accommodate late autumn droughts, when glacier melt has ceased for the season. Hence, despite other potential causes, this reflects the importance of the seasonal timing of a drought for the respective buffering capacity of glaciers. In general, NSD based on measurements varies between 0 and >100 days per individual year (Figure 29) and has been 7 days on average for 1986-2015 (Table 8**Errore. L'origine riferimento non è stata trovata.**). The reduced glacier cover projected for the future would increase this value on average by 3-4 days depending on the climate scenario applying the hypothetical glacier volume from the end of the 21st century to the past decades' base-flow data. If we would assume no glacier contribution at all (i.e., same base-flow as measured but all glaciers have disappeared), NSD at Kaub would increase by additional 1-2 days and SCSD by additional 2-4 days, compared to the reduced glacier cover as of 2071-2100 under RCP2.6 and 8.5, respectively. Non-shipping days then will have increased to 12 days and surcharge shipping days to 44 days, on average per year.

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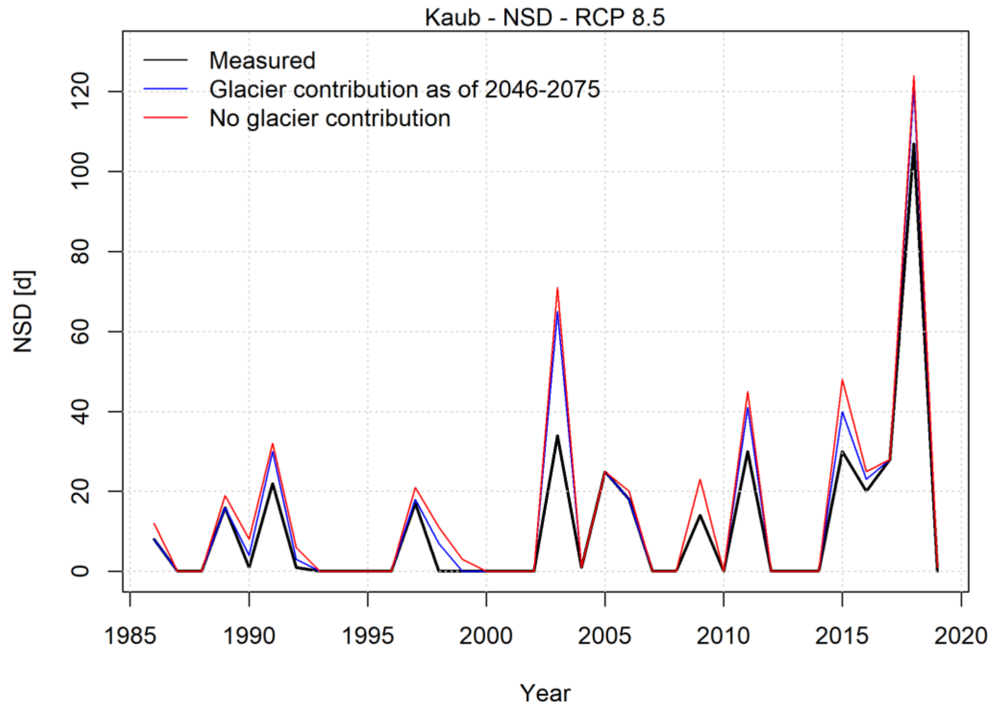

Figure 29: Annual NSD for Kaub at river Rhine based on measurements of the critical threshold (black) and on varying glacier contributions according to RCP8.5 for three periods in the 21st century if the non-glacial base-flow was kept the same as for 1986-2015 but the glacier contribution was altered according to the respective period (colors). Data source: Huss and Hock (2018) and Bundesanstalt für Gewässerkunde (2020)

Table 8: Average annual NSD and SCSD for Kaub and Duisburg-Ruhrort as measured (1986-2015) and with hypothetically altered glacier contributions for three climatic periods in the 21st century for selected RCP scenarios. Data source: Huss and Hock (2018) and Bundesanstalt für Gewässerkunde (2020)

Kaub	NSD				
Glacier contribution as of	1986 - 2015	2016-2045	2046 - 2075	2071 - 2100	no glacier
	[d/yr]	[d/yr]	[d/yr]	[d/yr]	[d/yr]
RCP2.6	7	9	10	10	12
RCP8.5	7	9	10	11	

Kaub	SCSD				
Glacier contribution as of	1986 - 2015	2016-2045	2046 - 2075	2071 - 2100	no glacier
	[d/yr]	[d/yr]	[d/yr]	[d/yr]	[d/yr]
RCP2.6	82	84	88	89	93
RCP8.5	82	84	89	91	

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Duisburg	SCSD				
Glacier contribution as of	1986 - 2015	2016-2045	2046 - 2075	2071 - 2100	no glacier
	[d/yr]	[d/yr]	[d/yr]	[d/yr]	[d/yr]
RCP2.6	37	39	41	42	44
RCP8.5	37	39	42	43	

SCSD was 82 days (37 days) on average for Kaub (Duisburg Ruhrort) during 1986-2015 and would have been around 90 (> 40) applying the reduced glacier cover from the end of the 21st century and another 2-4 days larger if no glacier contribution would occur.

Under current economic conditions (water transport intensity, dependence of industrial production, as Ademmer et al., 2020, analysed) 12 additional non-shipping days on river Rhine – on average, per year, as the situation will be once glaciers will have disappeared – imply a loss in overall German industrial production at 0.4%, or a loss of roughly € 35 billion in terms of German GDP.

Section references

Abermann, J., Lambrecht, A., and Schneider, H. (2007). Analysis of surface elevation changes on Kesselwand glacier – Comparison of different methods. *Zeitschrift für Gletscherkd. und Glazialgeol.* 41, 147–168.

Abermann, J., van As, D., Wacker, S., Langley, K., and Machguth, H. (2019). Strong contrast in mass and energy balance between a coastal mountain glacier and the Greenland ice sheet. *J. Glaciol.* 65, 263–269. doi:10.1017/jog.2019.4.

Ademmer, M., Jannsen, N., and Mösle, S. (2020). Extreme weather events and economic activity: The case of low water levels on the Rhine river. Kiel Available at: https://www.ifw-kiel.de/publications/kiel-working-papers/.

AMAP (2020). Austrian Maps. Available at: http://www.austrianmap.at/amap/index.php?SKN=1&XPX=637&YPX=492.

Astelbauer-Unger, K., Baumgartner, C., Hrbek, R., and Plattner, G. (2011). Alpiner Wintertourismus und Klimawandel. Vienna.

Avian, M., Kellerer-Pirklbauer, A., and Lieb, G. K. (2018). Geomorphic consequences of rapid deglaciation at Pasterze Glacier, Hohe Tauern Range, Austria, between 2010 and 2013 based on repeated terrestrial laser scanning data. *Geomorphology* 310, 1–14. doi:10.1016/j.geomorph.2018.02.003.

BDB - Bundesverband der Deutschen Binnenschifffahrt e.V. (2019). Daten und Fakten 2018/2019. Available at: https://www.binnenschiff.de/service/daten-fakten [Accessed July 5, 2020].

Bundesanstalt für Gewässerkunde (2020). Wasserstraßen- und Schifffahrtsverwaltung des Bundes (WSV). Available at:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

https://www.gdws.wsv.bund.de/DE/startseite/startseite_node.html.

Chen, J., and Ohmura, A. (1990). Estimation of Alpine glacier water resources and their change since the 1870s. *IAHS Publ.* 193, 127–136.

Cognard, J., François, H., Köberl, J., and Morin, S. (2015). Review of ski resort operating costs and market analysis. Available at: www.prosnow.org.

Contargo (2017). Low water. Available at: https://www.contargo.net/assets/pdf/Kleinwasser%7B%5C_%7DInfo-2017-EN.pdf [Accessed July 4, 2020].

Conway, J. P., and Cullen, N. J. (2016). Cloud effects on surface energy and mass balance in the ablation area of Brewster Glacier , New Zealand. *Cryosph.* 10, 313–328. doi:10.5194/tc-10-313-2016.

Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home

Cuffey, K. M., and Paterson, W. S. B. (2010). *The physics of glaciers*. 4th ed. Oxford: Butterworth-Heinemann.

Damm, A., Köberl, J., and Prettenthaler, F. (2014). Does artificial snow production pay under future climate conditions?-A case study for a vulnerable ski area in Austria. *Tour. Manag.* 43, 8–21. doi:10.1016/j.tourman.2014.01.009.

De Boer, W. (2019). Impact o flow water on sailing performance of ships: Design considerations. *ZKR-Workshop Low water Eff. Rhine Navig. (Bonn, 26.11.2019)*. Available at: https://www.ccr-zkr.org/13020151-de.html [Accessed July 5, 2020].

DVZ - Deutsche Verkehrs-Zeitung (2019). Rhein: Schifffahrt berechnet Kleinwasserzuschlag. Available at: https://www.dvz.de/rubriken/see/container/detail/news/rhein-schifffahrt-berechnet-kleinwasserzuschlag.html [Accessed July 5, 2020].

ECMT Resolution 92/2 (1992). Resolution No.92/2 on new classification of inland waterways. in (Athens).

EHYD (2020). EHYD. Available at: https://ehyd.gv.at/.

European Commission (2019). Transport in the European Union - Current Trends and Issues. Brussels.

Eurostats (2020). Eurostats. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics.

Farinotti, D., Pistocchi, A., and Huss, M. (2016). From dwindling ice to headwater lakes: Could dams replace glaciers in the European Alps? *Environ. Res. Lett.* 11. doi:10.1088/1748-9326/11/5/054022.

Fischer, A., Seiser, B., Stocker Waldhuber, M., Mitterer, C., and Abermann, J. (2015). Tracing glacier changes in Austria from the Little Ice Age to the present using a lidar-based high-resolution glacier inventory in Austria. *Cryosph.* 9, 753–766.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

doi:10.5194/tc-9-753-2015.

Frank, E., Herlicska, H., Hojetsky, H., Lorbeer, G., Moche, W., Peschek, R., et al. (1993). Gletschergebiete Österreichs: Bestandsaufnahme und chemisch-analytische Untersuchungen. Vienna.

French Waterways (2010). French Waterways in Detail: Rhone.

Geilhausen, M., Otto, J.-C., and Schrott, L. (2012). Spatial distribution of sediment storage types in two glacier landsystems ({Pasterze} \& {Obersulzbachkees}, {Hohe} {Tauern}, {Austria}). *J. Maps* 8, 242–259. doi:10.1080/17445647.2012.708540.

Gernaat, D. E. H. J., Bogaart, P. W., Vuuren, D. P. V., Biemans, H., and Niessink, R. (2017). High-resolution assessment of global technical and economic hydropower potential. *Nat. Energy* 2, 821–828. doi:10.1038/s41560-017-0006-y.

F. Gotzens, H. Heinrichs, J. Hörsch, and F. Hofmann, Performing energy modelling exercises in a transparent way - The issue of data quality in power plant databases, Energy Strategy Reviews, vol. 23, pp. 1–12, Jan. 2019.

GRDC (2020). Global Runoff Data Center, Koblenz. Available at: https://www.bafg.de/GRDC/EN/Home/homepage_node.html.

Grossglockner Hochalpenstraße AG (2020). Preise und Öffnungszeiten.

Habersack, H., Wagner, B., Hauer, C., Jäger, E., Krapesch, G., Strahlhofer, L., et al. (2011). Entwicklung eines Decision Support Systems zur Beurteilung der Wechselwirkungen zwischen Klimawandel, Energie aus Wasserkraft und Ökologie. Vienna.

Hanzer, F., Marke, T., and Strasser, U. (2014). Distributed, explicit modeling of technical snow production for a ski area in the Schladming region (Austrian Alps). *Cold Reg. Sci. Technol.* 108, 113–124. doi:10.1016/j.coldregions.2014.08.003.

Hartl, L., Fischer, A., and Olefs, M. (2018). Analysis of past changes in wet bulb temperature in relation to snow making conditions based on long term observations Austria and Germany. *Glob. Planet. Change* 167, 123–136. doi:10.1016/j.gloplacha.2018.05.011.

Huss, M. (2011). Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. *Water Resour. Res.* 47, 1–14. doi:10.1029/2010WR010299.

Huss, M., and Hock, R. (2015). A new model for global glacier change and sea-level rise. *Front. Earth Sci.* 3, 1–22. doi:10.3389/feart.2015.00054.

Huss, M., and Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Chang.* 8. doi:10.1038/s41558-017-0049-x.

Hynek, B., Neureiter, A., Binder, D., Felbauer, L., and Greilinger, M. (2018). Global Cryosphere Watch - GCW-S _ G Sonnblick Gletscher- und Schneedeckenmonitoring. Vienna, Austria.

Hynek, B., Neureiter, A., Binder, D., Greilinger, M., and Weyss, G. (2019). Global

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Cryosphere Watch - GCW-S _ G Sonnblick Gletscher- und Schneedeckenmonitoring.

Jonkeren, O. E. (2009). *Adoption to Climate Change in Inland Waterway Transport*.

Kaser, G., Großhauser, M., and Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *PNAS* 2010. doi:10.1073/pnas.1008162107.

Kellerer-Pirklbauer, A., and Kulmer, B. (2019). The evolution of brittle and ductile structures at the surface of a partly debris-covered, rapidly thinning and slowly moving glacier in 1998–2012 (Pasterze Glacier, Austria). *Earth Surf. Process. Landforms* 44, 1034–1049. doi:10.1002/esp.4552.

Koboltschnig, G. R., and Schöner, W. (2011). The relevance of glacier melt in the water cycle of the Alps: The example of Austria. *Hydrol. Earth Syst. Sci.* 15, 2039–2048. doi:10.5194/hess-15-2039-2011.

Land Tirol (2013), Ankünfte und Nächtigungen nach Gemeinden, Amt der Tiroler Landesregierung Abteilung Raumordnung und Statistik, Innsbruck.

Leidinger, D. (2013). Analyse der zeitlichen und räumlichen Variabilität des Niederschlags im Gebiet des Hohen Sonnblicks. *Diplomarbeit*.

Lieb, G., and Slupetzky, H. (2004). *Gletscherweg Pasterze*. 2nd ed. Innsbruck: Österreichischer Alpenverein.

Mayer, M. (2012). "Summer ski areas in the Alps: first victims of climate change?," in *Transforming and Managing Destinations: Tourism and Leisure in a Time of Global Change and Risks*, eds. A. Kagermeier and J. Saarinen (Mannheim), 27–35.

Mayer, M., and Abegg, B. (2020a). Glacier ski areas in the Alps: a literature review. *prep*.

Mayer, M., and Abegg, B. (2020b). The evolution of glacier ski areas in the Alps. *in prep.*

Mayer, M., Demiroglu, O. C., and Ozcelebi, O. (2018). Microclimatic volatility and elasticity of glacier skiing demand. *Sustainability* 10, 1–14. doi:10.3390/su10103536.

Mayer, M., Kraus, F., and Job, H. (2011). Tourismus - Treiber des Wandels oder Bewahrer alpiner Kultur und Landschaft? *Mitteilungen der Österreichischen Geogr. Gesellschaft* 153, 31–74. doi:10.1553/moegg153s31st.

Mölg, T., and Hardy, D. R. (2004). Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. *J. Geophys. Res.* 109, 1–13.

Oerlemans, J., Haag, M., and Keller, F. (2017). Slowing down the retreat of the Morteratsch glacier, Switzerland, by artificially produced summer snow: a feasibility study. *Clim. Change* 145, 189–203. doi:10.1007/s10584-017-2102-1.

Oerlemans, J., and Knap, W. H. (1998). A 1 year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland. *J. Glaciol.* 44, 231–238.

Olefs, M., and Fischer, A. (2008). Comparative study of technical measures to reduce

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

snow and ice ablation in Alpine glacier ski resorts. *Cold Reg. Sci. Technol.* 52, 371–384. Available at: http://www.sciencedirect.com/science/article/B6V86-4NRT36H-1/2/7a920ad26cb1607ec9f1f826b7183337.

Olefs, M., Fischer, A., and Lang, J. (2010). Boundary Conditions for Artificial Snow Production in the Austrian Alps. *J. Appl. Meteorol. Climatol.* 49, 1096–1113. doi:10.1175/2010JAMC2251.1.

Patek, M. (2007). Klimawandel und Naturgefahren. *Online-Fachzeitschrift des Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft*.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., et al. (2014). The Randolph Glacier Inventory : a globally complete inventory of glaciers. 60, 537–552. doi:10.3189/2014JoG13J176.

Pröbstl-Haider, U., Dabrowska, K., and Haider, W. (2016). Risk perception and preferences of mountain tourists in light of glacial retreat and permafrost degradation in the Austrian Alps. *J. Outdoor Recreat. Tour.* doi:10.1016/j.jort.2016.02.002.

Pröbstl, U., and Damm, B. (2009). Wahrnehmung und Bewertung von Naturgefahren als Folge von Gletscherschwund und Permafrostdegradation in Tourismus-Destinationen am Beispiel des Tuxer Tals (Zillertaler Alpen/Österreich). Vienna.

REWWAY - Research and Education in Inland Waterway Logistics (2020). Reader - Internationale Binnenwasserstraßen. Available at: https://www.rewway.at/de/lehrmittel/reader-internationale-wasserstraßen/ [Accessed July 5, 2020].

Robson, B. A., Hölbling, D., Nuth, C., Strozzi, T., and Dahl, S. O. (2016). Decadal scale changes in Glacier area in the Hohe Tauern national park (Austria) determined by object-based image analysis. *Remote Sens.* 8. doi:10.3390/rs8010067.

Rogstam, J., and Dahlberg, M. (2011). Energy usage for snowmaking: A review of the energy use of mobile snowmaking at Swedish ski resorts. Älvsjö Available at: https://www.bachler.ch/media/archive1/produkte/NESSy%7B%5C_%7DEnergy%7B%5C_%7Dusage%7B%5C_%7Dfor%7B%5C_%7Dsnowmaking%7B%5C_%7DEN.pdf.

Schaefli, B., Manso, P., Fischer, M., Huss, M., and Farinotti, D. (2019). The role of glacier retreat for Swiss hydropower production. *Renew. Energy* 132, 615–627. doi:10.1016/j.renene.2018.07.104.

Schär, C., and Jendritzky, G. (2004). Hot news from summer 2003. *Nature* 432, 559–560. doi:10.1038/432559a.

Schleypen, J.R., Dasgupta, S., Borsky, S., Jury, M., Ščasný, M., Bezhanishvili, L. (2019). D2.4 Impacts on Industry, Energy, Services, and Trade. Deliverable of the H2020 COACCH project

Schreuder, M. (2019). Digital tools to optimize sailing at low water levels. *ZKR-Workshop Low water Eff. Rhine Navig. (Bonn, 26.11.2019)*. Available at: https://www.ccr-zkr.org/13020151-de.html [Accessed July 5, 2020].

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Sheppard, D., and Chazan, G. (2018). Rhine drought leaves Europe's industry high and dry. Available at: https://www.ft.com/content/6356471c-d6c7-11e8-a854-33d6f82e62f8.

SN (2020). SN. Available at: https://www.sn.at/wiki/Großglockner_Hochalpenstraße_Besucherzahlen.

Sommer, C., Malz, P., Seehaus, T. C., Lippl, S., Zemp, M., and Braun, M. H. (2020). Rapid glacier retreat and downwasting throughout the European Alps in the early 21st century. *Nat. Commun.* 11. doi:10.1038/s41467-020-16818-0.

Stahl, K., Weiler, M., Freudiger, D., Kohn, I., Seibert, J., Vis, M., et al. (2017). The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change. Final report to the International Commission for the Hydrology of the Rhine (CHR). Available at: www.chr-khr.org/en/publications.

Statistik Austria (2019). Jahresdurchschnittspreise- und Steuern 2017 für die eichtigsten Energieträger. Available at: https://www.statistik.at/web%7B%5C_%7Dde/statistiken/wirtschaft/preise/energiepreise/index.html [Accessed July 7, 2020].

Statistisches Bundesamt (2019). Bruttoinladsprodukt 2018 für Deutschland. in (Berlin). Available at: https://www.destatis.de/DE/Presse/Pressekonferenzen/2019/BIP2018/pressebroschuere-bip.html%7B%5C%25%7D0D.

Steiger, R. (2012). Scenarios for skiing tourism in Austria: integrating demographics with an analysis of climate change. *J. Sustain. Tour.* 20, 867–882. doi:10.1080/09669582.2012.680464.

Theurl, M. (2019). Energiebilanz im Ablationsgebiet der Pasterze.

Unger, C. (1989). Der Massentourismus im Bereich Großglockner-Pasterze.

van As, D. (2011). Warming, glacier melt and surface energy budget from weather station observations in the Melville Bay region of northwest Greenland. *J. Glaciol.* 57, 208–220. doi:10.3189/002214311796405898.

van As, D., van den Broeke, M., Reijmer, C., and van de Wal, R. (2005). The summer surface energy balance of the high Antarctic plateau. *Boundary-Layer Meteorol.* 115, 289–317. doi:10.1007/s10546-004-4631-1.

van den Broeke, M. R., Fettweis, X., and Mölg, T. (2011). "Surface energy balance," in *Encyclopedia of Snow, Ice and Glaciers*, eds. V. P. Singh, P. Singh, and U. K. Haritashya (Berlin: Springer), 1112–1122.

van Tiel, M., Kohn, I., Van Loon, A. F., and Stahl, K. (2020). The compensating effect of glaciers: Characterizing the relation between interannual streamflow variability and glacier cover. *Hydrol. Process.* 34, 553–568. doi:10.1002/hyp.13603.

Viadonau (2020). Abladetiefenberechnung. Available at: http://www.viadonau.org/wirtschaft/online-services/abladetiefenberechnung [Accessed July 5, 2020].

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Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., and Birk, S. (2017). Impacts of climate change on stream flow and hydro power generation in the Alpine region. *Environ. Earth Sci.* 76. doi:10.1007/s12665-016-6318-6.

WANG, S. J., and ZHOU, L. Y. (2019). Integrated impacts of climate change on glacier tourism. *Adv. Clim. Chang. Res.* 10, 71–79. doi:10.1016/j.accre.2019.06.006.

WKO (2018). Tourismus und Freizeitwirtschaft in Zahlen: Österreichische und internationale Tourismus- und Wirtschaftsdaten. Wien.

ZAMG (Zentralanstalt für Meteorologie und Geodynamik) Extremereignisse.

5. CT3 – Disappearance of Arctic Summer Ice

Arctic ice caps have been melting as a result of global warming and there is broad agreement on continued ice reductions through this century. This implies that, in the near future the extent of the Arctic ice caps will be greatly reduced and even completely ice-free during the summer season. This will have socio economic effects at the global scale trough the possibility of new available routes for trade. The opening of the Northern Sea Route (NSR) or North Western Passage (NWP) would lead to a reduction in the average shipping distances and days of transportation connecting East Asian major exporters (i.e. China, South Korea, Japan) and Northwestern European ports directly avoiding the currently used Suez Canal (or Southern Sea Route, SSR). Although these reductions translate into fuel savings and overall transport costs transforming supply chains in industries between East Asia and Europe, they also imply high shipping volumes through the Arctic, likely adding to underlying shocks to the ecosystem.

The NSR is already open during summer and several ships have already used this route. The past few decades showed a dramatic decline of the Arctic sea ice level, with a record minimum ice extent in 2011. Although there is still controversy about the feasibility of the commercial use of the NSR, there is a broadened consensus in favor of its likely commercial use in the near future. A growing number of papers find that this shipping route could be fully operational for several months or all-year round at different points in the future according to different assumptions and estimates regarding the pace of the ice caps melting, and developments in the shipping industry. In recent years literature has focused on estimating the economic effects of the exploitation of these new routes. These papers can be mainly categorized into two strands. A more recent approach focuses on defining at the global level the implication of the opening of the Artic routes according to different assumptions on economic development and climate evolution. Bekkers et al. (2016), ESRI (2014), Yumashev et al. (2017), Benassi et al. (2016) and Melia et al. (2016) are examples of this strand in recent years. A second line of research includes analysis focusing on defining the profitability of Artic routes for specific shipping segments through defining overall

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transport costs. From the seminal paper by Wergeland et al. (1991), recent literature includes Verny and Grigentin (2009), Lasserre (2014), Hansen et al. (2016).

5.1. Global trade implications of summer arctic ice disappearance

Bekkers et al. (2016) estimate that under RCP8.5 travel distances between Asia and Europe would be shorter up to 40% and consequently, around 5% of the world's trade could be shipped through the NSR. Applying a multi-sector Computable General Equilibrium model, they quantify that after the NSR will be completely free of ice the actual shipping cost reduction, considered both fuel savings and other transport costs would be 20/30 percent lower, while iceberg trade costs, e.g. transport time savings that can effectively create new supply chains in certain industries could reach 3% of the value of traded goods. It is also estimated that, in a "current development scenario", i.e. the SSP2, trade between East Asia and Northwestern Europe would increase by around 6%, and globally, 4.7% of the share of World trade could be re-routed through the NSR.

However, this estimation has some limits. Firstly, the analysis is static and considers that the new route will be available in one single step after 2030, to overcome uncertainties about the exact time of this process. Although the economic adjustment for the new route will be gradual, the analysis provides a one- shot cumulated economic value. It also assumes the route will be free of ice for all the year- round. It is thus particularly "optimistic" assuming the NSR becomes a perfect substitute of the SSR.

Some of these complexities are considered by ESRI (2014): using a gravity model, the study estimates that a 1% distance reduction in using the NSR would increase trade by 0.82%. Major benefiting countries include Asian countries (Japan, Korea, North Korea, China, Taiwan the Philippines and Hong Kong) Northern European countries and few Southern European countries, such as France, Spain, and Portugal.

However the process is slow: assuming it takes 150 years to reach clear shipping conditions and 50 years to allow for ice free shipping during half the year, it would take 30 years (2042) to reach 16.1% of Arctic ice free trade potential.

A richer analysis than Bekkers et al. (2016) is performed by Yumashev et al. (2017) that include estimates for the navigability windows, ice water distances, uptake-dependent trends in icebreaker waiting times and differentiation between ship types. They consider a larger set of assumptions in the framework of a business model based on Hansen et al. (2016). General conclusions suggest that travel distances would be shorter (nearly 40%) between Asia and Europe involving around 5% of the world's trade under alternative RCPs in the "middle of the road" SSP2 scenario. Specifically, the total GDP gains amount to $6.5 trillion in RCP8.5, and $1.8 trillion in RCP4.5. Nearly two thirds of these gains are set to occur in China, while the EU could account for around one fourth, leaving the remaining gains to Japan and South Korea.

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The study also considers some negative environmental implications of the NSR opening. In particular the larger economic activity could increase global mean temperature the 0.05% and 0.04% in 2100 under RCP8.5 and RCP4.5, respectively. The study then translates these temperature increases into damages and extends the analysis to 2200. The net present value (NPV) of additional impacts of climate change adds other $2.15 trillion and $0.44 trillion under RCP8.5 and RCP4.5, respectively. This means that climatic losses offset 33% of the total economic gains from NSR under RCP8.5 and 24.7% under RCP4.5, with the biggest losses set to occur in Africa and India. This leads to a net economic gain from NSR until 2200 of $4.36 trillion in RCP8.5 and $1.34 trillion in RCP4.5.

Benassi et al. (2016) uses a simpler trade model without sector-level details and macroeconomic feedbacks. In this case, they suggest a 7% increase in exports between EU and Asia based on CMIP5 climate models' predictions assuming that NSR will be navigable for 6 months per year on average by the end of the twenty-first century under RCP8.5. Note that these gains refer to a period of one century implying a corresponding annual growth rate of export of only the 0.072%. The increase is even smaller (0.051%) under RCP4.5. Moreover, Benassi et al. analysis emphasizes that the difficulty in being able to predict the start and the end dates of summer ice conditions in the Arctic, combined with the lack of infrastructure in the hinterland could prevent the route from becoming popular with liner services. On the contrary, for bulk dry carriers and wet carriers, the route may become an alternative to more traditional shipping routes in the near future.

As a step further respect Benassi et al., Melia et al. (2016) extend the analysis in term of navigability of the Arctic including other routes such as the one through the North Pole, although they are not used for a fully economic assessment. Indeed, the paper presents its outcomes in terms of shorter travelling times to connect major ports in Asia, Europe and North America. European routes to Asia would become 10 days faster via the Arctic than alternatives by midcentury, and 13 days faster by late century, while North American routes become 4 days faster. The shipping season would reach 4–8 months in RCP8.5, doubling that of RCP2.6 until the end of the century. Moderately, ice strengthened vessels would have a longer shipping period reaching for 10–12 months by late century.

5.2 Profitability of Arctic routes

The trade implications discussed in the previous section are obviously subjected to the possibility to use the Arctic routes in an economically viable way, and, most importantly, at competitive costs compared to alternatives. Many studies try to compare the profitability of NSR against alternatives, often represented by the transit through the Suez Canal. Most of this literature identifies efficiency gains either in terms of saved navigation days and fuel consumption, with some side benefits on emissions. However these conclusions are based on many assumptions which are difficult to verify in practice. Studies considering, more realistically, operational and logistic issues find that gains, when present, are lower and further in time.

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Verny and Grigentin (2009) consider an example of voyage between Shangai (representative port in Asia) and Hamburg (representative port in Europe) comparing the transportation cost of one container using six alternative routes: Royal Route (via Suez), Trans-Siberian Railway, NSR, sea and air (via Dubai), and Air (direct)) in the period 2015-2025. It turns out that the cost of shipping a container along the NSR is about twice that through the Royal Route, the cheapest option. However, it is considerably lower than most of the alternatives. For example, using sea and air routes via Dubai could be 15 times more costly than the Royal Road, while a direct air connection is 50 times higher. Only the Trans-Siberian Railway option is cheaper (just 30% of the costs of the Royal Route). Thus, the NSR appears as a valid alternative, as well as the Trans-Siberian Railway, and most of the uncertainty in its exploitation is related to the uncertainty in climate evolution along the century.

Faury and Cariou (2016) quantify the potential costs and transit time savings for oil tankers in 2013 using the NSR instead of the Suez Canal. Assuming a higher bound in ice thickness, the NSR is more competitive in terms of cost and transit time savings in the months from August to November. Sailing in September gives the opportunity to save $753,086, while October is the best option with regards to transit time (17 transit days saved). Assuming a lower bound in ice thickness for 2013, the NSR is more competitive in terms of cost and transit time savings in all months from July. In terms of cost savings, September is the best option ($754,447) and in terms of transit time, October is the most favourable option (18 days).

Hua et al. (2011) estimate that the annual saving in fuel cost for a container fleet using the seasonal NSR alternative compared to the Suez Canal ranges between 3% and 5%. Then, assuming the total cost of a fleet with eight mono-engine 10 000 TEU container ships, the saving reaches more than $2.61–$8.14 million, based on two fuel price levels (i.e. 350 $/ton and 500 $/ton). According to Zhao and Hu (2016) the navigation time is more than 9 days shorter than that of the Suez Canal. The shorter voyage time leads to lower fuel consumption, lower emission and saves $0.236 million in fuel cost.

Liu and Kronbak (2009) analyse the profits for containers along the Asia-Europe route under a scenario combination of NSR navigable days (i.e. three, six and nine months) and ice-breaking fees (current, 50%, 85%, and 100% reduction) against the Suez Canal route. In principle, the NSR generates higher revenues in all scenarios because of the distance savings but annual profit are lower due to the current high fee for ice-breaking. With a fee reduction of 50% the NSR will be profitable when it opens for 3 and 6 months, still it remains more costly than the Suez Canal route independently on the navigation days. A fee reduction of the 85% and navigability of at least 3 months are necessary for NSR to be cheaper than the Suez Canal route. If the usage of the NSR is free of charge, then it is preferable to the Suez Canal route in all scenarios. In this case, a navigability of 3 months would bring 16% more profit than the Suez Canal (at low bunker price). When the route is navigable for 6 or 9 months, one can expect a 48% or even 83% higher annual profits.

Schøyen and Bråthen (2011) assess the time savings and increased energy efficiency using NSR route instead of the Suez Canal (SCR) or the Cape of Good Hope (CGH). The study distinguishes between minor bulk trade (e.g. nitrogen fertilizer) and major bulk

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trade (e.g. iron ore). Regarding minor bulk shipping the NSR route is about twice as energy efficient as the one via SCR and four to five times as energy efficient as the one via CGH. Considering major bulk, the increase in energy efficiency reaches 78%. Moreover, cost difference for minor bulk reaches 1.5% and 15% compared with SCR and the CGH, respectively; major bulk cost difference instead is close to 30% compared with SCR. Finally, the paper assesses the CO_2 emissions saving for the two bulk classes; for minor bulks it is 1433 Mton compared to SCR and 3021 Mton compared to CGH, while for major bulks it is 3270 Mton compared to SCR.

The problem in analyzing the issue lies exactly in the difficulties of defining reliable values for the many parameters influencing the profitability of Arctic shipping. This is shown by Lasserre (2014) that reviews twenty-six models, published between 1991 and 2013 on the topic. There are three key variables that need to be considered. Firstly, the tariff level for NSR. Its uncertainty is a crucial aspect that determines the profitability of the route. Secondly, the transit speed. It is much more relevant than fuel costs for the success of these new routes. Consequently, a lower transit speed, which is very uncertain, than that assumed in any paper may, radically change the picture; similarly occurs with operational aspects, that are important factors.

Partially rielaborating Verny and Grigentin (2009) and accounting for Lasserre (2014) points, Hansen et al. (2016) assess the ship owner's profitability of investing in ice resilience to re-route to the NSR. They conclude that, under current sea ice conditions and realistic near-term climate projections, shipping firms would not profit from investments in ice-strengthened container ships operating along NSR at least until 2030s. The main bottlenecks include limited navigability windows, low average utilization of capacity, waiting times to form an icebreaker convoy, icebreaker fees, insurance costs and other economic factors associated with Arctic operations. For medium-size container there are additional operational restrictions and therefore they may not be re-routed until the 2050s. This business point introduces a realism that is missing in the majority of papers and only partially addressed by Yumashev et al. (2017).

5.3 Other environmental, socio-economic consequences

As discussed, the increase in navigability of the NSR appears as the most investigated economic issue related to the Artic summer ice melting. Probably, its importance is emphasized by its geopolitical implications. With a generalized expected decline in the shipping transit through the Indian Ocean and the Suez Canal as well as an increased political interest in the Arctic from neighboring countries, the opening of the NSR may potentially have global repercussions. It would be a possibility in the future but in recent years some effects have been already shown. For instance, China has already revealed political interests in the Arctic by signing a free trade agreement (FTA) with Iceland in 2013, and in the same year, together with Japan and South Korea, it gained observer status on the Arctic Council.

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However, there are other important consequences of the disappearance of Arctic ice due to its peculiar ecosystem services that we briefly mention. Arctic ecosystem provides subsistence food, fisheries, existence values, climate regulation, minerals and oil. The economic effects of altering the Artic ecosystem may have local and global consequence as well as positive and negative economic impacts on communities.

Preliminary estimations from O'Garra (2017) suggest that the Arctic ecosystems currently provides about 2016 US$ 281 billion per year, but assuming ice-free summer by 2037 most of ecosystem services may be lost. As example, Durner et al. (2009) suggest that the decline in polar bear population will reach 30%. Although there is no direct economic value generated for polar bears, there is a unanimous consensus of the economic value obtained from tourism and polar bears are considered attractions as other species, such as beluga or whales. O'Garra evaluate this annual loss in $ 96 per capita. Similar reasoning apply to other species dependent on sea ice such as bearded seals whose mortality rate would increase due to the disappearing habitat.

On the contrary, as sea-ice retreats, fishing grounds that were previously not accessible will open up, benefiting some existing commercial fish species.

The US Geological Survey states that the Arctic holds 30% of undiscovered gas and 13% of undiscovered oil. Accessibility improved dramatically in recent years with the reduction in sea-ice extent, and the expectation for the future will continue to encourage exploration. Increased access has made exploration possible where it once was not considered. In addition, reduced sea ice potentially provides better access to markets using the NSR. Greater accessibility and lower risks indicate greater profit margins for the oil and mining industry.

Calzadilla et al. (2014) quantify gains from additional gas production as a GDP growth of 1.3- 1.4% in 2040 and modest spillovers on other sectors when natural gas is produced off the coasts of Greenland. Lower macroeconomic impacts are envisaged for Russia and Norway. Respect to the exploitation of oil, GDP increases significantly in producing countries, especially in Norway and Greenland/Denmark (up to 1.7%), and the Artic production seriously damages traditional competing oil exporters, such as Middle East countries, North and Sub-Saharan Africa and the states of the Former Soviet Union.

Moreover, summer ice melting enhances tourism in some Arctic locations, resulting in short- to medium-term benefits to local communities. According to the Association of Arctic Expedition Cruise Operators (AECO), the number of cruise passengers around Svalbard increased from nearly 39,000 in 2008 to over 63,000 in 2017 (Alvarez et al. (2019)). In the same decade, the number of passengers in Greenland increased at a slower pace, ranging between 20,000 and 30,000 per year. In the rest of the Arctic region, only few cruises occur, although the absolute number of passengers moved from 124 passengers in 2008 to 1199 in 2017. Overall, the growth rate of cruise passengers is about 57% from 67,752 in 2008 to 98,238 in 2017.

As an example of likely benefits for local communities, in Alaska, commercial passengers' vessels revenues shared with local municipalities, cities or districts

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increased from US$ 744,580 in 2007 to US$ 15,750,925 in 2016 (an annual growth rate of 20%).

5.4 Conclusions

The transformation of the artic summer into an "Antarctic like" season would affect the regional economic and social structures. Defining the overall sign of these impacts is challenging. While some of them are widely considered positive, such as the opening of the Northern Sea Route, the Northwestern and Northeastern Passages, effects on ecosystem services are not clear. Thus, it is uncertain to assess the overall economic impact of reducing Artic ice. For the transport sector, the economic effect is slightly positive but highly uncertain in the future, mainly because of the inability to define when routes would be completely ice- free and to have a consistent framework of rules. Moreover, the development and exploitation of the new routes are strictly correlated to other local bottlenecks such as poor infrastructures and the lack of legislative regulations. Similar problems would arise for the cruise sector that could sustain local communities' incomes but at the same time it could increase black carbon pollution and, as a loop, amplify the ice melting process. Its negative effect on ecosystem services and habitat loss could counterbalance and possibly outweigh the positive sectoral economic benefits. Similarly, oil extraction has high environmental costs associated with oil leaks from pipes, oil spills and the required infrastructure development besides the increased carbon emissions resulting from oil use; mining for minerals and metals has very high environmental costs too (van Leeuven, 2017). The necessity for a body of laws and the international cooperation among Artic countries appear as a keystone to maximize potential economic gains that are uncertain in the future.

Section references

Alvarez J Yumashev D Whiteman G (2020). A framework for assessing the economic impacts of Arctic change. Ambio 49: 407-418

Bekkers E, Francois JF, Rojas-Romagosa H (2016) Melting ice caps and the economic impact of opening the Northern Sea Route. Econ J: 1468–0297.

Bensassi S, Stroeve JC et al (2016) Melting ice, growing trade? Elem Sci Anth 4: 000107.

Calzadilla A Growitsch C Panke T Petrick S Rehdanz K Schwind H (2014). The economy-wide impact of Arctic energy supply. Deliverable 4-11 of ACCESS project

DeWeaver E Serreze M C (2009). Predicting 21st-century polar bear habitat distribution from global climate models. Ecol. Monogr. 79 (1), 25–58.

Durner, G.M., Douglas, D.C., Nielson, R.M., Amstrup, S.C., McDonald, T.L., Stirling, I., Mauritzen, M., Born, E.W., Wiig, Ø., DeWeaver, E., Serreze, M.C., 2009. Predicting 21st-century polar bear habitat distribution from global climate models. Ecol. Monogr. 79 (1), 25–58.

ESRI (2014) Socio-economic costs and benefits of Arctic transport. D2.61 report for the ACCESS project

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Faury O, Cariou P (2016) The Northern Sea Route competitiveness for oil tankers. Transp Res Part A 94: 416- 469

Hansen CO, Gronstedt P et al (2016) Arctic shipping—commercial opportunities and challenges. CBS Maritime, Copenhagen ISBN: 978-87-93262-03-4

Hua X Zhifang Y Dashan J Fengjun J Hua O (2011) The potential seasonal alternative of Asia–Europe container service via Northern sea route under the Arctic sea ice retreat. Marit Pol and Manag, 38(5): 541-560,

Lasserre F (2014) Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector. Transp Res Part A Policy Pract 66: 144–161

Liu M Kronbak J (2009) The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. J of Transp Geogr 18: 434- 444

Melia N, Haines K, Hawkins E (2016) Sea ice decline and 21st century trans-Arctic shipping routes. Geophys Res Lett 43: 9720–9728

O'Garra T (2017). Economic value of ecosystem services, minerals and oil in a melting Arctic: A preliminary assessment. Ecosystem Services 24: 180-186

Schøyen H, Bråthen S (2011) The Northern Sea Route versus the Suez Canal: cases from bulk shipping. J of Transp Geogr 19: 977- 983

Van Leeuven J W S (2017). Comments on: Kvanefjeld Project. Environmental Impact Assessment.

Verny J, Grigentin C (2009) Container shipping on the northern sea route. Int J Prod Econ 122: 107–117

Yumashev D, van Hussen K, Gille J, Whiteman G (2017) Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route. Climatic Change: 143–155

Zhao H Hu H (2016) Study on Economic Evaluation of the Northern Sea Route- Taking the Voyage of Yong Sheng as an Example. Transportation Research Record: Journal of the Transportation Research Board. Transportation Research Board, Washington, D.C., 2016, 2549: 78–85.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***