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Rethinking Sea-Level Projections Using Families and Timing Differences

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Key Points:

- Sea-level projections can be sorted into families, based on similarities in methods and data
- Threshold analysis shows that for certain amounts of sea-level change it is a matter of *when*, not *if*
- Combining families and thresholds leads to three categories, each with recommendations for choices to be made, to assist decision makers

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract In the recent decade, many global and regional sea-level rise (SLR) projections have been published, which raises questions for users. Here, we present a series of strategies to help users to see the forest for the trees, by reducing the number of choices to be made. First, we use the similarities in the methodologies and contributing sources of the projections to group 82 projections from 29 publications into only 8 families. Second, we focus on the timing of reaching several global mean SLR thresholds, and the uncertainty therein, rather than the projected value in the year 2100. Finally, we combine the information on timing and families to define three categories which can support decision making. For global mean SLR up to 0.50 m the differences in timing are small, regardless of climate scenario or family, clearly indicating a timing window for adaptation decisions. For larger global mean SLR (0.75–1.00 m), the climate scenario becomes more important for the uncertainties in timing, but the SLR threshold will be crossed within a limited window of time, supporting adaptation decision making on the medium to long term. Beyond 1.00 m the differences between the families and climate scenario strongly determine the uncertainties in timing, and more information is needed, for instance using early warning signals, before decisions for adaptation can be made. We make recommendations on how each of these three categories, combined with the lead time and lifespan of adaptation options, can inform decisions on adaptation strategies using adaptation pathways planning.

Plain Language Summary Many global and regional sea-level rise projections have been published recently. As a consequence, it can be difficult to see the differences and to decide which projection to use, for instance for coastal planning. We therefore present a couple of strategies to help users see the forest for the trees in this large set of projections. First, we make a "family tree" of sea-level rise projections, based on the similarities and differences between projections. This reduces 82 projections to only 8 sea-level families. Next, we show when different sea-level thresholds (0.25 m, 0.5 m, etc.) will be crossed in each of the families. We then combine the information on the families and the timing to define three categories, where each category comes which a recommendation of the type of choices that need to be made for adaptation decision making.

1. Introduction

Sea-level rise (SLR) projections are required for long-term decision making in coastal zones. Many different global and regional sea-level projections for the 21st century have been published in the past years (Garner et al., 2018). Differences between sea-level projections result from (a) choices in modeling methodology (e.g., process-based, semi-empirical, reduced-complexity), (b) choices in the climate scenarios used to drive the models (e.g., Representative Concentration Pathways (RCP) (Moss et al., 2010), Shared Socio-economic Pathways (SSP) (O'Neill et al., 2017), or temperature pathways), or (c) choices in the data sources for the individual contributors to SLR (i.e., using different approaches to model thermosteric change, glaciers and ice sheets).

These choices are determined by several factors, such as the purpose of the projections; are they used for for example, information gathering or decision making on coastal protection or investments? Also, the availability of data and models or the required likelihood of the projections will affect the sea-level projections (e.g., the likely range or lower/upper/high end estimates). The wide variety in choices and combinations and new insights into SLR contributions have led to a large number of projections in the literature, with different amounts of projected SLR by 2100 and beyond. One of the largest sources of uncertainty in sea-level projections is caused by uncertainties in the magnitude, amount and timing of the Antarctic ice sheet contribution (Edwards et al., 2021; Fox-Kemper et al., 2021; Oppenheimer et al., 2019; Pattyn & Morlighem, 2020).

The large number of available projections poses difficulties for decision makers (Sriver et al., 2018) and raises questions such as: "Which projections should I use?"; "Why are these (new) projections different from others?"; "Does this difference matter?." If stakeholders select one particular projection they might run into the problem that the decisions may have to be adjusted later when new literature becomes available. To avoid the problem of having to select a particular projection, most national assessments build on an ensemble mean or consensus estimate from the Intergovernmental Panel on Climate Change (IPCC (Church et al., 2013; Fox-Kemper et al., 2021; Oppenheimer et al., 2019)), for instance in national assessments for Bangladesh (General Economics Division & Bangladesh Planning Commission, 2018) or Australia (Mcinnes et al., 2015). In some countries, the IPCC projections are tailored to the local situation (for instance in The Netherlands (KNMI'2014: Attema et al., 2014; KNMI, 2021) or Norway (Simpson et al., 2015)), or the IPCC projections are combined or extended with other projections (e.g., Finland (Johansson et al., 2014) or New Zealand (Lawrence et al., 2018)). As the IPCC projections are typically updated only every five to seven years, in some cases the IPCC AR5 projections have been adjusted for new information, in particular on accelerated ice sheet contributions, for instance in the UK (UKCP18, Palmer et al., 2018) or the US (New York City Panel on Climate Change, R. Horton et al., 2015). Alternatively, in some cases scenarios are based on (a set of) single planning values, for instance in the US (Sweet et al., 2017) or France (Le Cozannet et al., 2017).

The IPCC regularly provides an assessment of the latest research on sea-level change, and combines the existing methodologies and data into an assessed set of sea-level rise projections (Church et al., 2013; Fox-Kemper et al., 2021; Oppenheimer et al., 2019). Before IPCC AR6, these projections typically were central range projections, resulting from a combination of the necessity for scientific consensus and a lack of literature for projections outside the *likely* range. The lastest IPCC report, AR6 (Fox-Kemper et al., 2021), for the first time also provided projections for a low-probability, high-impact scenario, which includes *low confidence* processes of accelerated ice sheet mass loss in Greenland and Antarctica. As a result, the latest IPCC projections provide a larger range of possible futures and associated uncertainties in sea-level change.

In this manuscript, we discuss what the uncertainties in sea-level projections mean for different planning time horizons (mid-century, end-of-century and beyond). We also present a set of strategies which can provide guidance on how to use and interpret the available SLR projections. Our first step is to structure the large number of SLR projections by using the genealogy of SLR projections to define families by grouping projections that have a number of methods and/or SLR contribution approaches in common (Section 2), inspired by the work of Knutti et al., (2013) and Masson and Knutti (2011). Our second step is to rethink the information from the projections by reversing the information on the uncertainty and asking *when* a certain sea-level threshold will be crossed, in addition to *which* or *if* a certain sea level will be reached in 2100 (Section 3). Finally, we combine the information on the families and their timing into three categories, each of which require different types of decisions by adaptation decision makers (Section 4).

The notion that adaptation to SLR is a matter of *when* to adapt and not *if* has, for example, already been acknowledged for the U.S. Atlantic and Gulf coast (Hauer, 2017) where relocation may seem inevitable (Keeler et al., 2018). The importance of uncertainty in the timing of reaching different sea levels for coastal adaptation planning was acknowledged in the recent IPCC AR6 Working Group 1 report (Arias et al., 2021). Decision making and implementation of such drastic measures or large coastal defence structures requires a long lead time (SLR Box in Cooley et al., 2022; Haasnoot et al., 2020) and highlights the need to inform decision-makers early on about the projected timing of crossing a certain SLR threshold rather than a projected SLR magnitude at an arbitrary time.

The overall aim of this work is to help decision makers 'see the forest for the trees' by providing insight into uncertainties on different time horizons and give tools on how to best deal with them in planning. The recommended starting point for decision makers is Section 4, where three categories of SLR thresholds are presented, with recommendations for different types of decisions that need to be taken in each category (Section 4.1). We then provide a flow chart with questions to assist decision makers in dealing with different bandwidths of the timing of SLR in relation to different types of lead times (Section 4.2).

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2. Data and Methods

The first step to restructure the large number of SLR projections (Section 2) is inspired by work done on the genealogy of climate models in the Climate Model Intercomparison Project (CMIP) database (Knutti et al., 2013; Masson & Knutti, 2011). Their aim was to determine how (in)dependent climate models in an ensemble are, as the models sometimes have components in common, for instance for the oceanic or atmospheric parts. Here, our aim is to use the genealogy of SLR projections to define families, by grouping projections that have a number of methods and/or SLR contribution approaches in common.

2.1. Selecting the Sea-Level Projections

All sea-level projections used here are from publications from 2013 onwards (when IPCC AR5 (Church et al., 2013) was published), use CMIP5 data and are based either on RCP scenarios or on temperature pathways. The only exception is most recent projection from IPCC AR6 which used SSP-RCP scenarios and CMIP6 information. We only use global mean sea-level projections from publications that provide information on the sources and methods of the individual contributions. This leads to a total of 82 projections from 29 publications: Bakker et al., 2017; Bamber et al., 2019; Le Bars et al., 2017; Bittermann et al., 2017; Buchanan et al., 2017; Carson et al., 2016; Church et al., 2013; Fox-Kemper et al., 2021; Goodwin et al., 2017; Grinsted et al., 2015; Jackson et al., 2018; Jackson & Jevrejeva, 2016; Jevrejeva et al., 2014, 2016, 2018; Kopp et al., 2014, 2016, 2017; Mengel et al., 2016; Nauels, Meinshausen, et al., 2017; Nauels, Rogelj, et al., 2017; Oppenheimer et al., 2019; Palmer et al., 2020; Perrette et al., 2013; Rasmussen et al., 2018; Schleussner et al., 2016; Slangen et al., 2014; De Winter et al., 2017; Wong et al., 2017.

The projections are distributed over five climate scenarios of RCP and global warming levels: RCP2.6 (16); RCP4.5 (19); RCP8.5 (29); 1.5° (7); 2° (8). For the analysis, the 1.5° scenario is combined with RCP2.6 and SSP1-2.6, the 2.0° scenario with RCP4.5 and SSP2-4.5, and RCP8.5 with SSP5-8.5 (Collins et al., 2013; Fox-Kemper et al., 2021).

In some publications, multiple projections are presented with different methods/sources: Bakker et al., 2017 (2), De Winter et al., 2017 (2), Fox-Kemper et al., 2021 (2), Goodwin et al., 2017 (3), Jackson & Jevrejeva, 2016 (2), Jevrejeva et al., 2018 (2), Jackson et al., 2018 (2) and Le Bars et al., 2017 (3). On the other hand, the projections presented in Slangen et al., 2014 and Carson et al., 2016 are the same, and the projections in Kopp et al., 2014 and Buchanan et al., 2017 are the same; each projection is therefore only included once.

For the comparison of all projections in 2100 (Section 3.1), we primarily use SLR projections from Garner et al., 2018 (their Table S1 in Supporting Information S1), who applied a linear approach to compute the SLR over 100 years (SLR_{100}) for all projections [$SLR_{100} = SLR_{pub}*(100/(y_{end}–y_{beg}))$], using the SLR from the original publication (SLR_{pub}) and the published begin year (y_{beg}) and end year (y_{end}). For more recent publications, the SLR is taken from the original publications following the same approach to compute the change over a 100 year period (Data Set S1). Missing 5th and 95th percentiles were calculated using the standard deviation of the dataset and assuming a normal distribution. This assumption may lead to an underestimation of the 95th percentile for the two publications which only provided 17th and 83rd percentiles and are non-Gaussian: SROCC, 2019 (Oppenheimer et al., 2019) (in Sections 3.1 and 3.2) and Perrette et al., 2013 (in Section 3.1).

For the SLR threshold analysis which assesses the timing at which a particular SLR threshold is exceeded (Section 3.2), we use a subset of publications which provide time series rather than only the difference over the 21st century (Data Set S2). We use one time series to represent a family if all family members are alike, or multiple time series to encompass all family members if required. Only five of these time series extend beyond 2100 and are used for threshold analysis up to the year 2200.

2.2. Sorting the Sea-Level Projections Into Families

For all available publications, we first analyze the treatment of four major contributors to SLR: the Greenland ice sheet, the Antarctic ice sheet, glaciers and ocean warming (thermosteric change). Each of these are modeled using a variety of methods across the literature, as explained in Text S1 and Figure S1 in Supporting Information S1. There is less variety in the treatment of the terrestrial water storage change contribution in the available

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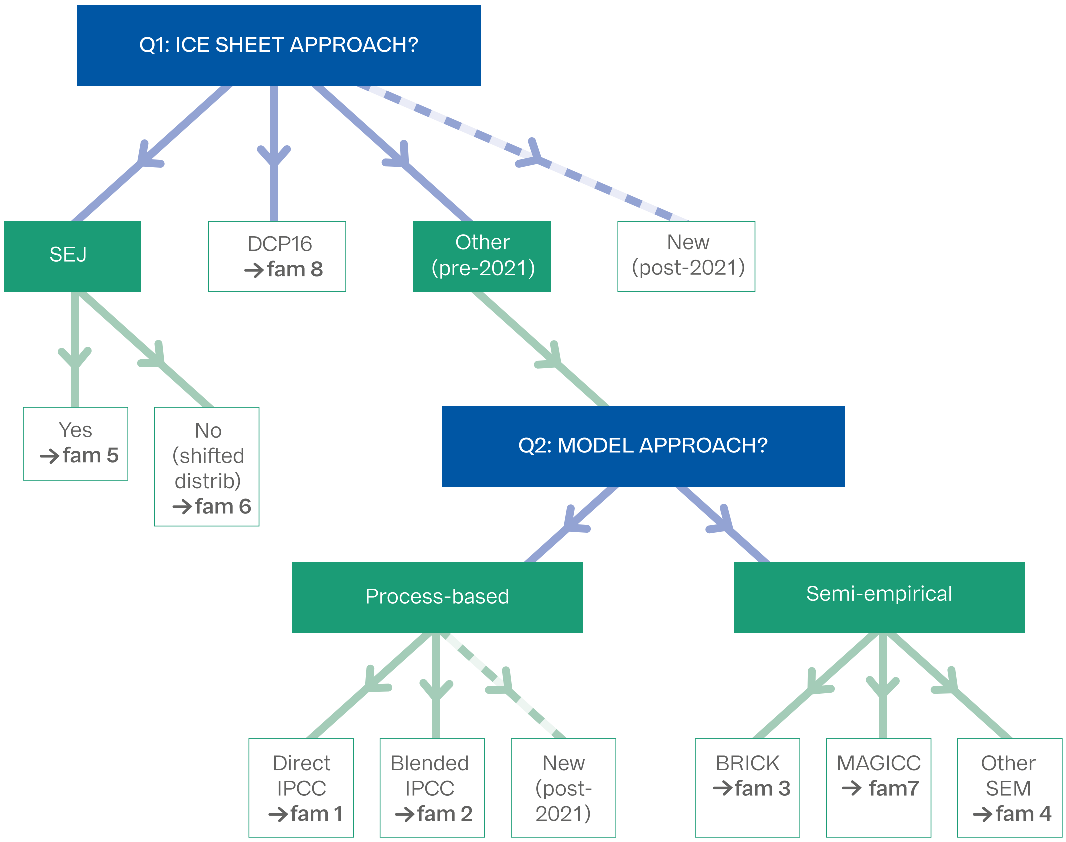

Figure 1. Decision tree for sea-level families. Blue boxes indicate main questions (Q1 and Q2), green boxes indicate follow-up questions, white boxes indicate families. To show that this is not meant as a static framework, two example boxes for new families are indicated by the dashed arrows, but new families can be added in other places as well. See Text S1 and Figure S1 in Supporting Information S1 for additional details.

projections, and this is therefore not taken as a distinguishing factor for the sorting. Using the information on the four main contributors, we set up a decision tree (Figure 1), which allows us to sort the projections into families. Based on the analysis of the methods and data used in the projections, we identify eight different families, as detailed below.

The first question in the decision tree relates to the treatment of the ice sheet contributions. We identify two families relying on structured expert judgement (SEJ) studies: family 5 (SEJ) which uses the SEJ results directly and family 6 (shifted SEJ) which uses the SEJ to inform the shape of the ice sheet probability distribution. All publications which use the Antarctic estimates of Deconto and Pollard (2016) are in family 8 (DCP16).

The second question in the decision tree relates to the modeling approach: process-based or semi-empirical. We identify two IPCC-related families relying primarily on process-based modeling, where the difference is that family 1 uses a combination of multiple ice sheet and glacier estimates (direct IPCC), while family 2 uses individual glacier or ice sheet estimates (blended IPCC). There are three different families using semi-empirical (SEM) type approaches: family 3 (BRICK), family 4 (SEM), and family 7 (MAGICC/SEM) which uses SEM methodology in combination with the reduced-complexity model MAGICC (Meinshausen et al., 2011).

The families can be used for different purposes. For instance, families 1 and 2 are primarily based on IPCC and therefore represent a consensus-based estimate. Families 5, 6 and 8 all feature skewed probability distributions for the Antarctic ice sheet contribution, and may be used by decision makers that are particularly interested in low-probability/high-risk SLR. If one would like to use the outcomes of fully coupled climate models primarily, families 1 and 2 might be most suitable, whereas if one would like to be able to use and reproduce the SLR projections, reduced-complexity models in families 3, 4 and 7 might be the best choice. Families 5 and 6 may inform uncertainties in SLR as a result of processes potentially still missing from models.

The decision tree presented here reflects current knowledge, but we stress that it is not meant to be a static framework: new families may be added when new data, methods or models become available (indicated by a few example "new" boxes in Figure 1), while other families may become obsolete when there are no more new developments in a family. An example of a start of a potential new family are the IPCC AR6 projections, which are currently added to family 1. These are based on CMIP6 models rather than CMIP5 models, and when more publications with CMIP6 data become available they might branch off into their own family.

3. Rethinking the Sea-Level Projections

With the sea-level projections sorted into families, the second step in our approach is to rethink the information that can be derived from the projection families. In addition to knowing *which* sea level will be reached in 2100, as is often the focus in SLR publications, it might be helpful to reverse the information about the uncertainty, and assess *when* a certain sea level threshold will be exceeded. The timing of a particular magnitude of SLR in the SLR projection families may demonstrate that the question is not *if* to adapt but *when* to adapt. Thus, in addition to presenting uncertainty as a range in the magnitude of SLR at a certain point in time (*which/if*, Section 3.1), we also present uncertainty as a range in the timing (a period) for crossing a particular SLR threshold (*when,* Section 3.2).

3.1. Sea-Level Family Projections for the Year 2100

The projected SLR in the year 2100 (Figure 2) shows an overall good agreement within families for all three scenarios. For the RCP2.6 scenario (Figure 2a) the differences between the families are the smallest of all three scenarios. There is only one projection outside the overall 5%–95% probability range (the black dashed lines): in family 7 (MAGICC/SEM) Perrette et al., (2013) presents a large SLR projection, due to relatively large contributions from the Greenland and Antarctic ice sheets (0.22 and 0.23 m, respectively), which is about three times larger than the ice sheet contributions in the other family 7 projections. The reason for this is that in Perrette et al. (2013) the ice sheets are taken as the residual of the total sea-level change computed with a semi-empirical model, minus the steric and glacier contribution. In the other family 7 projections the ice sheet contribution is explicitly parameterized, leading to smaller ice sheet contributions.

The differences between and within the families increase for the RCP4.5 scenario, but the overall agreement is still high (Figure 2b). Families 3 (BRICK) and 8 (DCP16) project a larger amount of SLR compared to the other families, illustrating the uncertainty in SLR projections as a result of the Antarctic ice sheet contribution. Within family 8 (DCP16), Kopp et al. (2017) directly used the DCP16 estimates leading to the higher SLR projection, whereas Nauels, Rogelj, et al. (2017) used the DCP16 estimate to calibrate their SEM and arrived at a slightly lower SLR projection.

For the RCP8.5 scenario, the differences between and within the families are the largest, and mainly families 3 (BRICK) and 8 (DCP16) stand out (Figure 2c). For family 8, the projected Antarctic contribution used from DCP16 is either 0.64 m ± 0.49 (Bakker et al., 2017; Kopp et al., 2017; Nauels, Rogelj, et al., 2017) or 1.05 ± 0.30 m in 2100 (Le Bars et al., 2017), due to differences in the ice model configuration, which leads to SLR projections that are generally larger than the SLR projections in the other families.

When considering the families over all three scenarios, the medians of families 4 (SEM), 5 (SEJ), 6 (SEJ-shifted) and 7 (MAGICC/SEM) are close to the ensemble-mean for all scenarios. Families 3 (BRICK) and 8 (DCP16) are always above the overall ensemble-mean, in particular for RCP8.5, and the upper 95% probability is larger due to a skewed distribution of higher projected contributions from the Antarctic ice sheet.

Families 1 (Direct IPCC) and 2 (Blended IPCC) are generally below the median of all the projections, which is in line with previous analyses that the assessment methodology of IPCC tends to underestimate rather than overestimate the projected changes in the climate system (Brysse et al., 2013; Garner et al., 2018; Horton et al., 2020). The medians of the IPCC AR6 projections (Fox-Kemper et al., 2021) are close to previous IPCC estimates for all scenarios, although they are based on SSP scenarios and CMIP6 models rather than RCP scenarios and CMIP5 models (see also Hermans et al., 2021). The 95th percentile of the IPCC AR6 *low confidence* projections is an outlier in family 1, which can be explained by the fact that these are based on a combination of SEJ and DCP,

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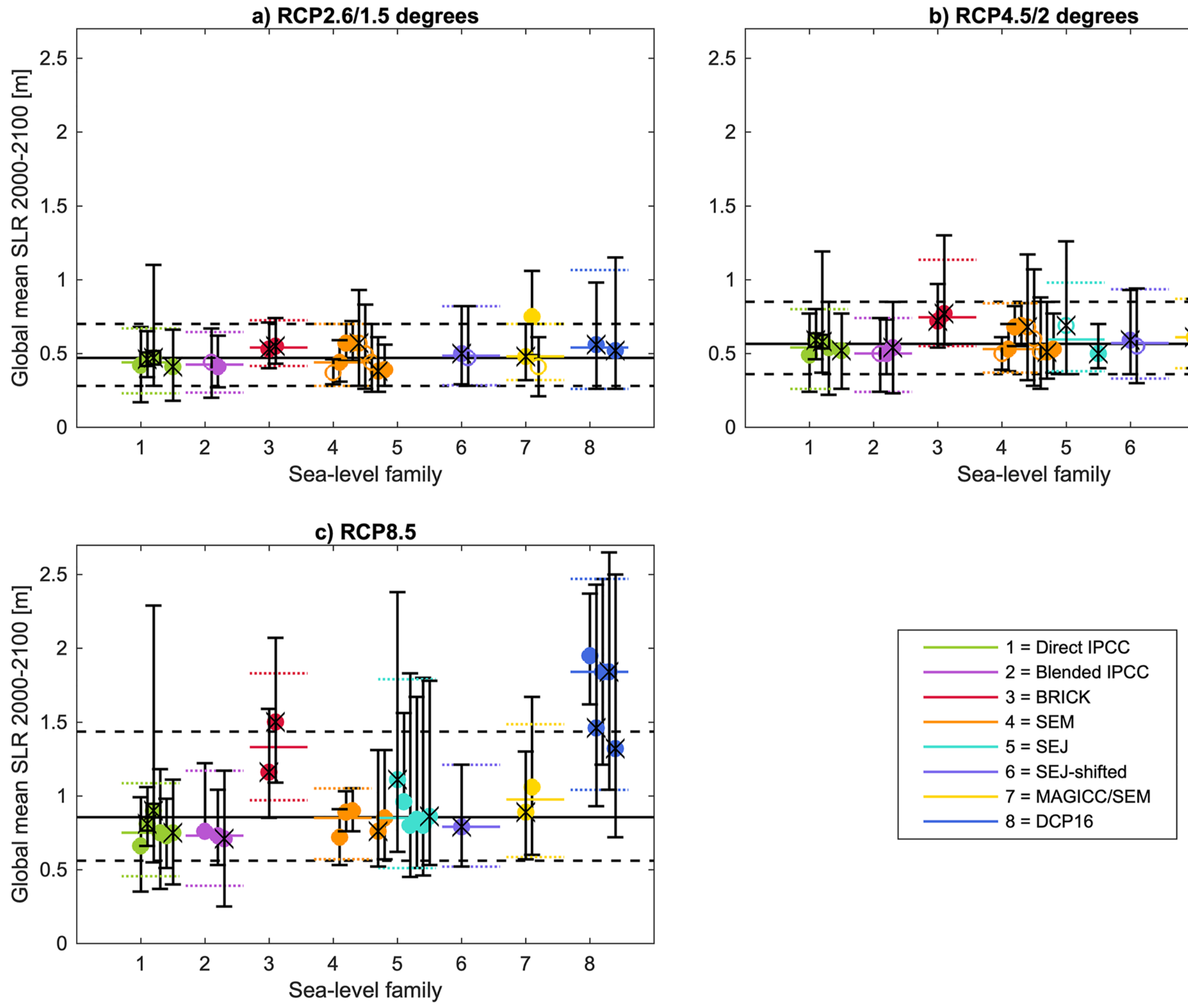

Figure 2. Global mean sea-level projections for 2000–2100 (m) for eight projection families and three scenarios: (a) RCP2.6/1.5°; (b) RCP4.5/2.0°; (c) RCP8.5. Circles indicate the medians, black error bars the 5%–95% range of each projection. Filled circles are RCP scenarios, open circles are temperature scenarios, black open circles are the IPCC AR6 SSP-RCP projections. The median of each family is indicated by the colored full line, the medians of 5%–95% probabilities per family by colored dashed lines. The median of all projections for each scenario is indicated by the horizontal black full line and the median of all 5%–95% probabilities by horizontal black dashed lines. Crosses (X) indicate the global mean projection time series used for threshold analysis.

and therefore are also related to families 5, 6 and 8, with a skewed distribution to higher contributions from Antarctica.

3.2. Timing in Reaching Thresholds in the Sea-Level Families

We use global mean SLR projection time series to compute the crossing of different SLR thresholds (Figure 3), with at least one time series representing each family (see Section 2.1). We find that the time when a SLR threshold of 0.25 m (with respect to the year 2000) is first reached differs little across the eight families and the three RCP scenarios. All eight families project the exceedance of 0.25 m with a 50% probability for the middle of the century (~2040–2060). With a 5% probability, 0.25 m is already reached before 2040 in more than half of the families, regardless of the scenario.

A SLR of 0.50 m is projected for the second half of the 21st century in all families for all scenarios (Figures 3a–3c), with at least a 5% probability across scenarios, and a 50% probability for all families in RCP4.5 (2066–2099) and RCP8.5 (2059–2081). For RCP2.6, the median exceedance of 0.50 m occurs late in the 21st or early in the 22nd century (Figure 3d). With a 5% probability, 0.50 m is exceeded before 2060 in four families (RCP2.6), in

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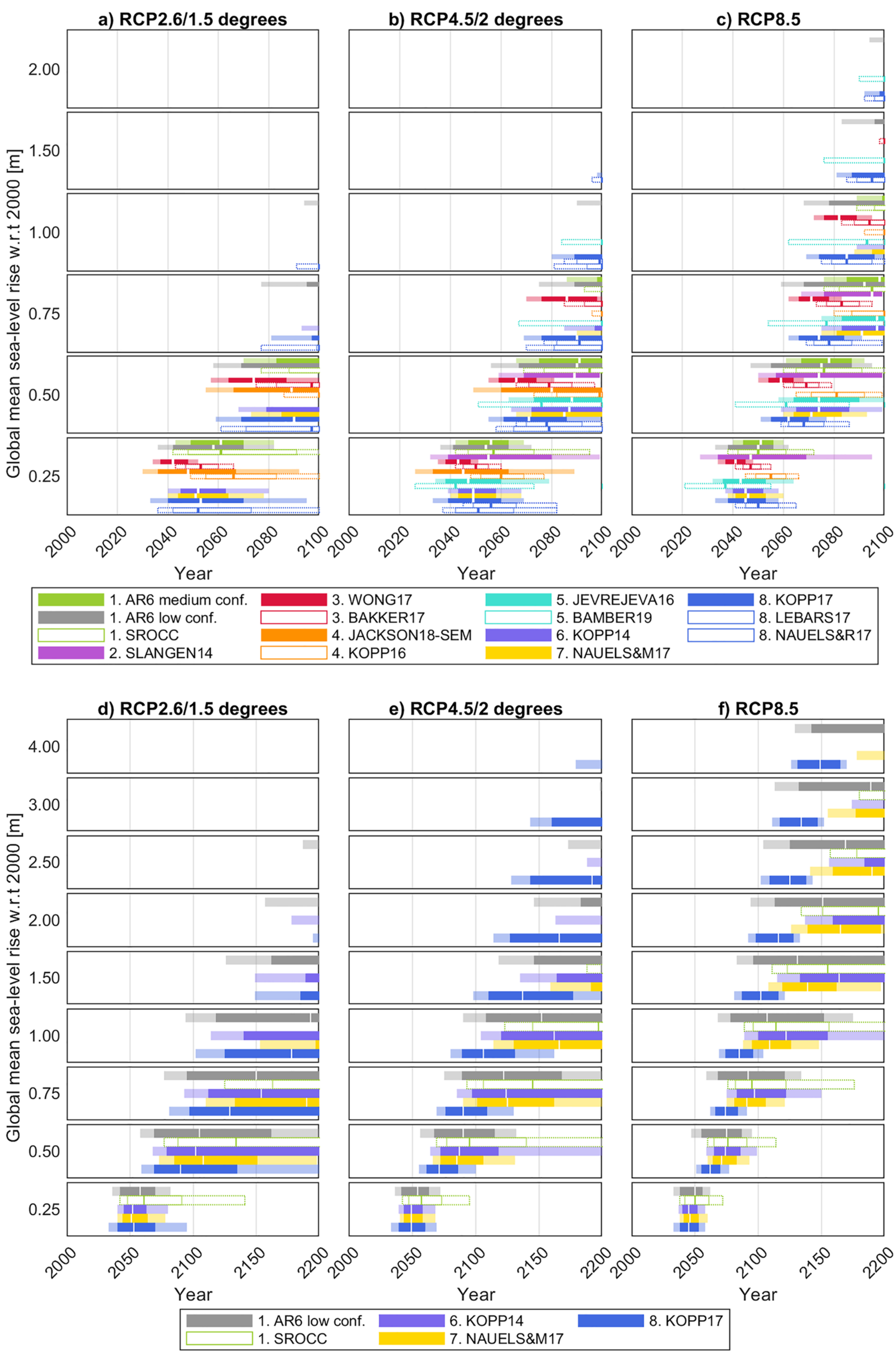

Figure 3. Timing in reaching global mean sea-level rise threshold values (m). The first year in which a projected total sea-level threshold (m) is reached with respect to the year 2000, for three RCP/temperature scenarios, and projection time series representing the eight families (colors as in Figure 2), (a–c) between 2000 and 2100, (d–f) between 2000 and 2200. Vertical bars represent the median, dark colors the 17%–83% range, light colors the 5%–95% range.

six families (RCP4.5) and in seven families (RCP8.5, the eighth by 2065), and can be crossed as early as 2041 for RCP8.5. This means that, regardless of the scenario, 0.50 m SLR will occur in the second half of this century according to most projections, with RCP2.6 and RCP4.5 mainly in the fourth quarter and RCP8.5 moving up to the third quarter of the century.

For SLR thresholds beyond 0.50 m there is an increasing dependency on the climate scenario. At the end of the 21st century, a SLR of 0.75 m (with at least 5% probability) is projected for RCP2.6 in three families, for RCP4.5 in seven families and in all families for RCP8.5. A SLR of 1.00 m is exceeded before 2100 in the median projections of RCP8.5 for families 3 (BRICK), 5 (SEJ) and 8 (DCP16), and in addition in the first half of the next century (Figures 3d and 3e) in families 1 (Direct IPCC), 6 (SEJ-shifted) and 7 (MAGICC/SEM). For RCP4.5, families 1, 6, and 7 reach 1.00 m in the second half of the 22nd century (50% probability), but 1.00 m can already occur as early as 2069 in family 8 (RCP8.5, 5% probability).

For thresholds over 1.00 m SLR the projections between families show increasing divergence, in particular for the RCP8.5 scenario (Figures 3c and 3f), where families 3 (BRICK), 5 (SEJ) and 8 (DCP16) tend to reach higher thresholds earlier than other families. For instance, SLR reaches 1.50 m around 2100 in family 8 for RCP8.5 (median), and this does not happen until several decades later in families 1, 6 and 7 (Figure 3f). This divergence between families continues for SLR thresholds above 2.00 m.

Overall, the likely (17%–83%) and very likely (5%–95%) time windows for SLR to exceed any of the defined thresholds are widest for RCP2.6 (Figures 3a and 3d) and narrowest for RCP8.5 (Figures 3c and 3f), as sea level rises faster for warmer climate scenarios. The narrowest time range for each threshold is projected in family 3 (BRICK) and the widest in family 2 (Blended IPCC). Up to 0.5 m of SLR, the timing in threshold exceedance is within a range of 20–30 years for the median values of the projections in all eight families.

For some purposes it may be more relevant to know the timing of reaching a certain SLR rate rather than a cumulative threshold, for instance when determining the feasibility of soft and nature-based adaptation measures. For example, beach nourishments are temporary adaptation measures and their lifespan can be compromised by higher SLR rates, which require larger or more frequent nourishments (Haasnoot et al., 2020). Coastal vegetation can trap and stabilize sediments (Nepf, 2012), but vegetation needs time to grow and keep up with SLR (Kirwan et al., 2016), which may not be possible for higher SLR rates. To illustrate the timing differences in SLR rates, Figures S2–S4 in Supporting Information S1 provide the timing of different SLR rates (mm/yr) for the 5th, 50th and 95th percentiles.

4. Connecting SLR Families and Timing Differences to Adaptation Decision Making

We now combine the information on SLR timing and uncertainty in the different families to define categories of SLR thresholds which each require different types of decisions (Section 4.1). We also discuss how the global framework presented in this study can be a starting point for local applications (Section 4.1). Finally, we provide a flow chart with questions to assist decision makers in dealing with the uncertainties in timing of SLR (Section 4.2).

4.1. Defining Categories of Sea-Level Thresholds

Based on the information from the analysis of the families and timing differences, we define three categories of SLR thresholds. Each category provides a recommendation for the type of choices required when it comes to selecting a sea-level projection family and scenario:

Category 1: a small bandwidth in timing, for low SLR thresholds (up to 0.50 m). There is little uncertainty that this threshold will be crossed within the foreseeable future, irrespective of the projection family chosen or the climate scenario followed. This means that, for decisions on adaptation measures to 0.50 m, decision makers do not need to worry about which SLR family or even which individual projection they choose, they can use whichever is accessible to them.

Category 2: a moderate bandwidth in timing, for SLR thresholds between 0.50 and 1.00 m. Here, the uncertainty in timing mainly results from different climate scenarios. In this case it is important to realise that if the timing of crossing the threshold is within the envisioned lifespan of a measure or the time horizon of the decision analysis, it is a matter of *when* and not *if* this SLR threshold will be crossed. For adaptation measures within this bandwidth, this means that the main uncertainty is in the choice of the climate scenario, and less in the choice of the SLR projection family.

Category 3: a large bandwidth in timing, for SLR thresholds beyond 1.00 m, with uncertainty in timing both resulting from different climate scenarios and from projection families. In this situation, gathering more information on the likelihood of each of the climate scenarios could reduce the uncertainty in the timing. If the timing is beyond the lifespan of a measure or the time horizon of the decision analysis, this SLR amount is likely not relevant for this particular measure. For decision makers, it now becomes relevant to choose a particular family and climate scenarios, for instance based on their risk aversion, as the choice impacts the timing in crossing SLR thresholds. However, as the timing is further into the future, there may still be time to adjust the adaptation decision when more information about climate scenarios and uncertainties in SLR contributions becomes available.

We use a conceptual example to show how the timing bandwidths of SLR thresholds (Figures 4a and 4b) can be used to assess when signals may be detected that can inform adaptation and for how long present and future investments and measures can perform acceptably (i.e., contain risk) as sea levels rise. The latter is sometimes referred to as an adaptation threshold or tipping point (Barnett et al., 2014; Haasnoot et al., 2013; Kwadijk et al., 2010). The period over which such an adaptation tipping point is reached can be considered as the functional lifespan of a measure. Beyond an adaptation tipping point, additional or new measures may be needed. Alternative sequences of measures, or adaptation pathways, can be visualized into a route map or adaptation map (Haasnoot et al., 2013) (Figure 4c). The lead time needed for planning and implementation of follow-up measures can inform decision makers about when decisions need to be made at the latest (Figure 4d). By comparing the timing of SLR threshold exceedance (in families or individual projections) to the lead time and functional lifespan of adaptation options, decision makers can assess whether it is justified to make the adaptation investment.

Although the analyses here are based on global mean SLR projections, it is important to note that adaptation decision making often relies on local information. For local applications, the global time series in Figure 4a should therefore be replaced by local sea-level projections, which can then be combined with local information on adaptation options to inform a local adaptation pathway analysis. As an example, Figure S5 in Supporting Information S1 shows the local timing of SLR threshold exceedance at four locations compared to the global timing in Figure 3. This shows that indeed there are regional differences compared to the global mean, for instance at the east coast of the US, where an above-average projected SLR leads to earlier crossing of thresholds (compared to the global mean) by about 5–10 years. However, it also shows that the global analysis gives a first order assessment of the timing of SLR threshold exceedance and that the three categories defined above can serve as a starting point for local decisions. We do note that not all of the projections included in the current analysis provide sufficient regional or local information that would allow a similar analysis for all families. For instance, semi-enclosed basins are often poorly represented in climate models and would therefore require an additional downscaling step to allow for a local analysis (e.g., Hermans et al., 2020). There are also publications which only provide global mean projections, for instance many of the semi-empirical projections in Family 3, which would require a regionalization step in order to be used in regional analyses.

4.2. Using SLR Families and Timing to Inform Adaptation Decision Making

When it comes to adaptation decision making, the timing of SLR thresholds in the different families can be compared against the potential functional lifespan of present and future measures under multiple futures. To assist with the types of questions to ask and decisions to take, we present a flowchart (Figure 5). We identify three main uses of the sea-level families and their timing in threshold exceedance.

The first use of our analysis is to assess whether or not it is a matter of time (*when* instead of *if*). The timing bandwidth of threshold exceedance corresponds with the shortest to longest functional lifespan and thus also indicates if the uncertainty about the functional lifetime is (relatively) small or large (first question in Figure 5). For example, a coastal defense structure designed for 0.50 m of SLR could be sufficient for the next 40–75 years

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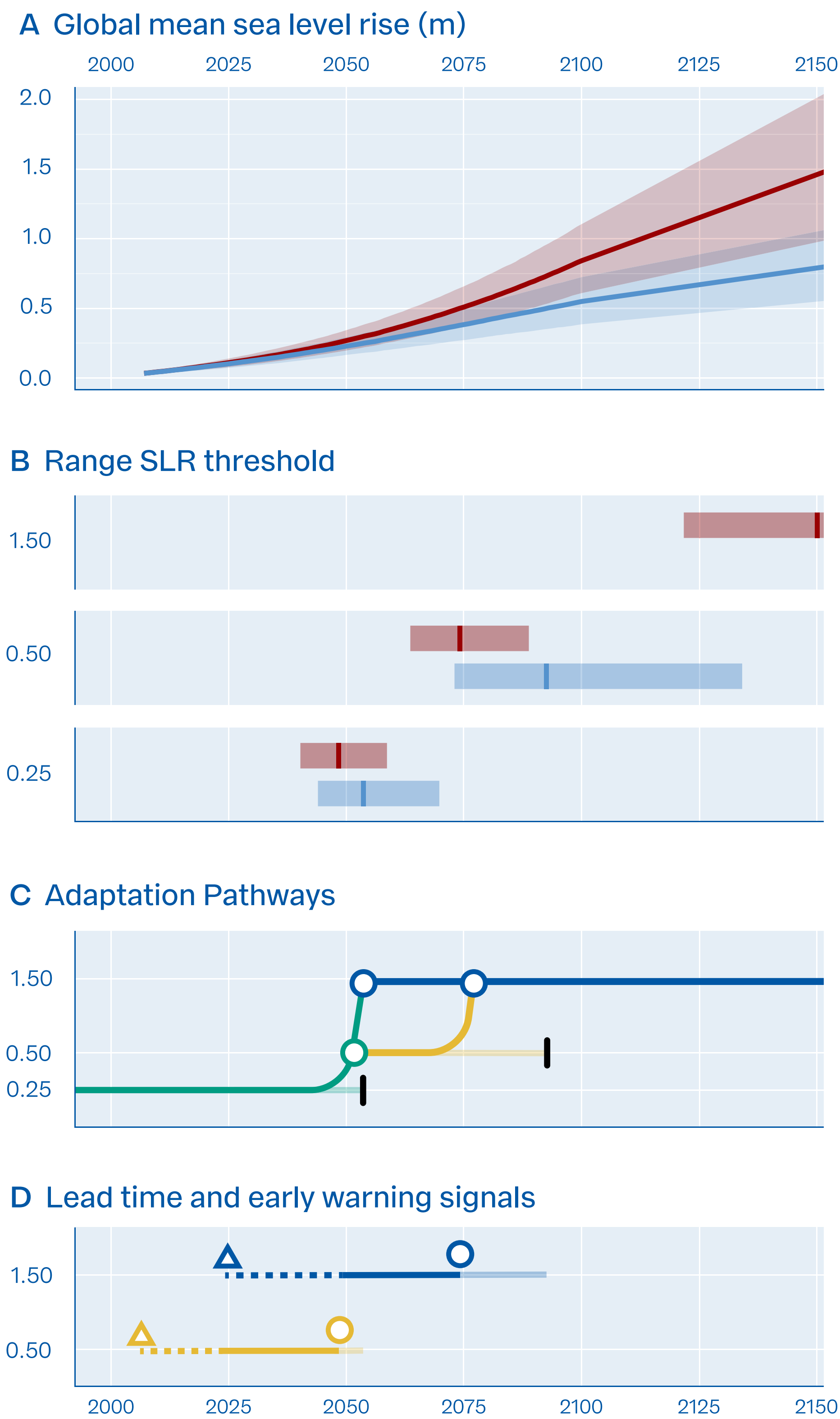

Figure 4.

(median values), but might already reach the end of its functional lifetime within 25 years (2045) under RCP8.5 in some families. Comparing this range in timing with the envisioned lifespan helps to evaluate the consequences and whether or not to invest in a particular measure. For instance, a small uncertainty in timing (middle blue box, Figure 5) that occurs within the envisioned lifespan of a measure will reduce the functional lifespan (right blue box, Figure 5). With a moderate to large uncertainty in timing that is inside the envisioned lifespan of a measure, it is a matter of time. If the threshold exceedance occurs partly outside the envisioned lifespan of an investment (middle light green box, Figure 5), more information about for instance climate mitigation and the relevance of particular climate scenarios (e.g., through learning over time) could reduce uncertainty. If this is only occurring for some climate scenarios, climate mitigation could, to some extent, still avoid lifespan reduction. The above is not only relevant for a particular measure, but also for an adaptation plan and its lifespan and thus the time horizon of a decision analysis.

The second use of our analysis lies in assessing which measures to take. Building upon the notion that the functional lifespan of an investment is determined by exceeding a certain amount or rate of SLR, the timing in SLR families can help to assess which adaptation measure would be needed given the preferred lifetime of an investment or the preferred frequency of adaptation. Large coastal defense structures such as the Dutch Delta works have a long lifespan (typically 50–200 years (Haasnoot et al., 2020; Hallegatte, 2009)), but also other adaptation strategies, such as floodproofing of buildings, are intended to be effective for several decades or more. The associated SLR thresholds tend to fall into category 3, which means there is a stronger dependency on the choice of SLR family and climate scenario. If the functional lifespan is considered too short because of the required economic or societal investments or impacts, this could indicate that it would be necessary to adapt to higher amounts of SLR, which would be increasingly needed under accelerating SLR (Haasnoot et al., 2020). Not only investments for coastal adaptation, but also the functioning of other investments, such as buildings or power plants, may become unacceptably affected as sea levels rise. The timing of SLR could indicate whether and when this could happen and thus affect the investments' lifespan.

In addition the functional lifespan of measures, one needs to account for the lead time of potential follow-up measures to assess whether and when to start preparing for them. Decision makers with a very low risk tolerance (Hinkel et al., 2019; Oppenheimer et al., 2019) may want to focus on the earliest moment of threshold exceedance in SLR family 8 (red boxes in Figure 5). The lead time needed for planning and implementation of coastal defense measures can take years to decades (Haasnoot et al., 2020) and time may also be needed for research, experiments and technological developments, especially when hard limits are exceeded and step-changes are needed. In practice, the preparation time will also depend on the political, societal and institutional context. Overlap in bandwidth of the timing of relevant thresholds for adaptation could complicate adaptation, as preparation for a measure may need to start when its predecessor is still being implemented. This becomes an increasingly relevant problem under accelerating SLR (Haasnoot et al., 2020).

The third use of our analysis is to indicate whether the timing of SLR thresholds in the different families can be used to evaluate SLR indicators on their potential to serve as early warning signals and inform decision-making (Haasnoot et al., 2018; Stephens et al., 2018). Ideally, signals on changing conditions would leave enough time for planning and implementation of coastal defense measures and would thus be detected reliably before a decision point (Haasnoot et al., 2018). For example, in Figure 4 the projected timing of a threshold exceedance of 0.25 m might not provide enough time to implement a follow-up measure of the yellow measure under RCP8.5. A risk-averse decision-maker could decide to adjust the plan (e.g., replace the measure protecting against 0.50 m by a measure protecting against 0.75 m) or to make preparations to reduce the lead time (e.g., regulations or spatial planning). The concept of *learning scenarios,* as introduced by (Hinkel et al., 2019) could be used to describe the effect of the timing of new information becoming available on reducing the time range for the threshold

Figure 4. Conceptual example of threshold exceedance and decision making. (a) Example sea-level rise projections (blue and red, median and 5%–95%), (b) the timing of reaching 0.25, 0.50 and 1.50 m SLR thresholds in the projections in panel (a). Time series can be replaced by a global or regional SLR time series from any family, depending on the required application. Threshold timing determines the functional lifespan of a measure in (c) the adaptation pathways map (the length of the colored line). The measure designed for 0.25 m SLR (category 1, green) reaches an adaptation tipping point ~2045–2055 (based on the median values) and could be followed by a measure for 0.50 m of SLR (category 2, yellow) which reaches an adaptation tipping point ~2070–2090. Alternatively, a switch to a measure for 1.50 m of SLR is possible (category 3, dark blue), which only reaches an adaptation tipping point in RCP8.5 in the next 130 years. (d) The adaptation tipping points (circles) combined with the lead times indicate when a decision for a measure associated with the yellow and blue pathways needs to be taken (triangles) in order to have enough time for planning and implementation of a measure and contain the risk of SLR (lead time can be adjusted for specific measures). Confronting the timing of the SLR thresholds from (b) with the lead time helps to assess if a particular threshold exceedance can be used as an early warning signal for adaptation.

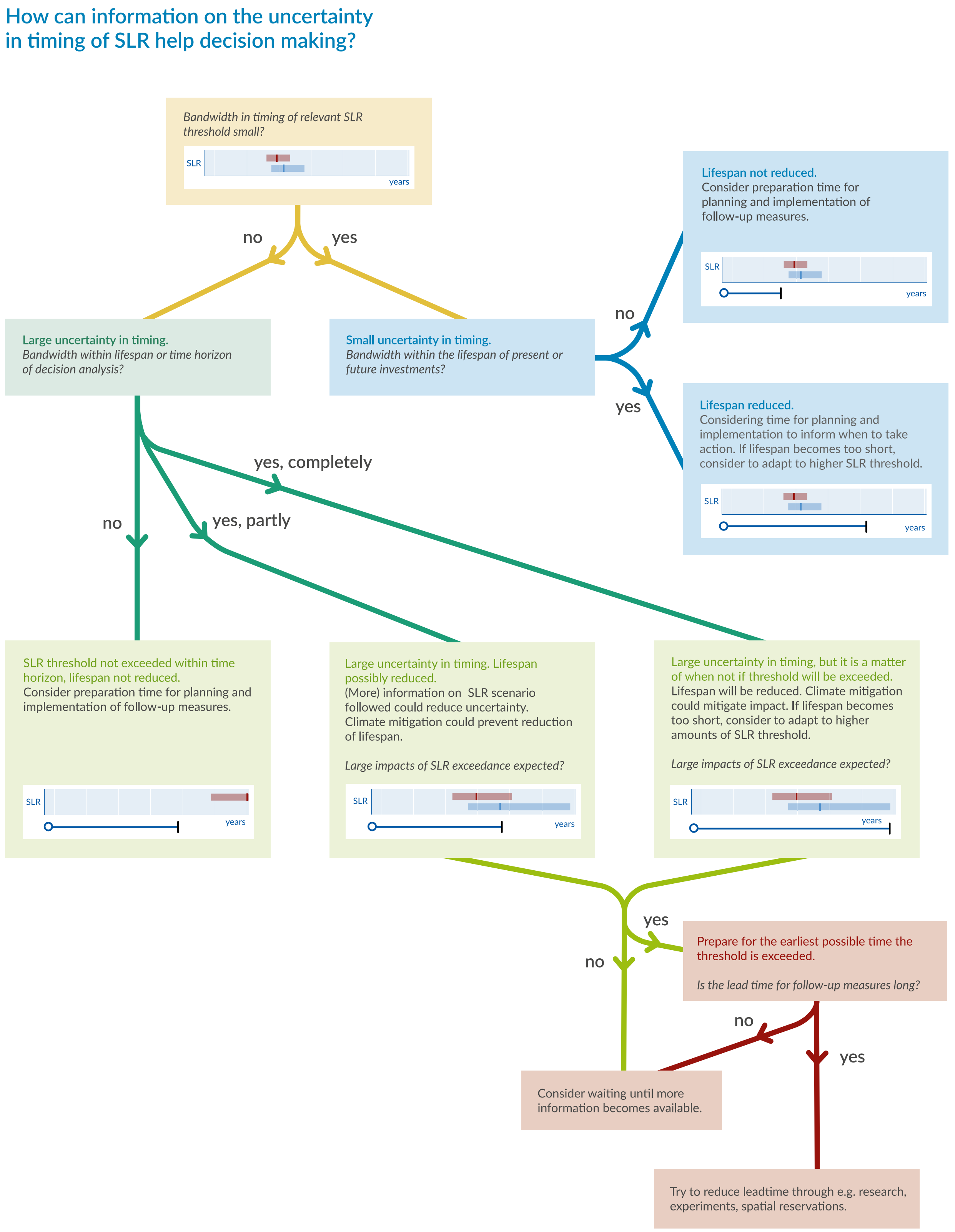

Figure 5. Flow chart illustrating how the bandwidth in timing of threshold exceedance can be used for decision making while considering the envisioned lifespan of investments, the lead time for planning and implementation as well as the risk tolerance of decision makers.

exceedance. Particularly for categories 2 or 3, the observed SLR may also indicate which of the projection families is being followed, when climate scenarios start to diverge, or if an adaptation tipping point is approaching.

5. Conclusions

In this paper, we have proposed a series of strategies to rethink the growing set of sea-level projections and help decision makers "see the forest for the trees". First, we restructured the large number of projections by grouping 82 projections of 29 publications into 8 families, based on similarities in the choice of methodology and contributing sources. Second, we analyzed the timing of reaching certain SLR threshold levels, and found that there is a remarkable agreement in the timing of when a certain threshold will be first reached in each of the temperature and RCP scenarios.

Finally, we combined the analysis of SLR families and their threshold exceedance times to define three categories, where each category requires different choices to be made by decision makers. Category 1 includes the smaller SLR thresholds (up to 0.50 m), where the small differences in timing show that adaptation to these levels will have to happen in the foreseeable future anyway, regardless of the projection family used or the climate scenario realised. Category 2 includes the moderate SLR thresholds (0.75–1.00 m), where the climate scenario becomes more important, but the divergence between the families is still limited. SLR thresholds beyond 1.00 m fall into category 3, where the differences between the families, in combination with the climate scenario realised, critically determine the uncertainties in timing of reaching a certain threshold. For decisions with a longer lifespan or for long-term planning, SLR in category 3 may still be within their lifespan and it can therefore still be a matter of *when* and not *if* adaptation is needed. For each SLR threshold, a decision maker may choose and compare different SLR families with different characteristics, based on their level of risk-aversion, on their measures' desired lifespan or on the lead time required, but we have shown that this choice becomes more relevant for the higher SLR thresholds. The timing of threshold exceedance can also be used to assess for how much SLR to adapt or invest (and thus also how to adapt), depending on the envisioned lifetime of an investment, and to assess if a SLR threshold exceedance can serve as a early warning signal to inform adaptation decision making.

The families can aid decision makers in identifying the type of sea-level projections that best match their risk tolerance level. Whereas some decision makers may prefer consensus estimates from the IPCC family, decision makers with a very low risk tolerance may want to use families that include significantly larger contributions from the Antarctic ice sheet, such as family 8. In addition, we have shown how the timing of SLR threshold exceedance in the SLR families can be used as a basis for the dynamic adaptive policy pathways approach (Haasnoot et al., 2013), which feeds into an adaptive plan consisting of short-term actions and long-term options that can be implemented as sea levels rise.

We do note that there are many more elements to sea-level change that play a role on various spatial and temporal scales (e.g., Slangen, Meyssignac, et al., 2017) and are important for local decision-making and adaptation to SLR. For one, sea-level change is not uniform across the world: large spatial differences exist as a result of differences in ocean density, mass-induced gravitational effects and vertical land movement (glacial isostatic adjustment, tectonics, subsidence) (Church et al., 2013; Fox-Kemper et al., 2021; Slangen et al., 2014, 2012; Slangen, Adloff, et al., 2017). Second, sea-level change varies on different timescales. Uncertainties related to interannual to decadal variability, for instance the El Nino Southern Oscillation, the Pacific Decadal Oscillation or the North Atlantic Oscillation (e.g., Roberts et al., 2016), are partially accounted for by using multi-model ensembles for the sea-level projections. While these responses tend to be dampened in the global mean, they will have a larger impact on sea-level change on local scales. On shorter time scales, sea-level changes locally from season to season (Hermans et al., 2022) and on even shorter time scales as a result of storms, tides and waves (sea-level extremes (e.g., Haigh et al., 2019; Wahl et al., 2017)). When considering adaptation to SLR, the knowledge on local (changing) extremes therefore needs to be taken into account, by using the framework presented here in combination with more tailored information on changing local sea-level extremes or existing coastal protection measures to complete the analysis.

We recognize that the strategies presented still require the user to take some decisions, which is inevitable as science keeps on progressing and the future is never completely certain. However, we are convinced that this framework, which rethinks the sea-level projections by using families and threshold timing, can serve as an easier starting point for SLR projection users across the board.

Data Availability Statement

The data used in this study (original time series and processed data for figures) are available as Data Sets S1 and S2, and on Zenodo under doi:10.5281/zenodo.6340076.

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