Forced Changes in the Arctic Freshwater Budget Emerge in the Early 21st Century

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Key Points:

- The observed increase in Arctic liquid freshwater (FW) storage is likely already driven by climate change
- A forced change in liquid FW flux through Nares Strait is likely to emerge within the next decade
- The already changing nature of many FW budget terms can delay detection of shift and emergence from observations

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Abstract

Arctic liquid freshwater (FW) storage has shown a large increase over the past decades, posing the question: Is the Arctic FW budget already showing clear signs of anthropogenic climate change, or are the observed changes the result of multi-decadal variability? We show that the observed change in liquid and solid Arctic FW storage is likely already driven by the changing climate, based on ensemble simulations from a state-of-the-art climate model. Generally, the emergence of forced changes in Arctic FW fluxes occurs earlier for oceanic fluxes than for atmospheric or land fluxes. Nares Strait liquid FW flux is the first to show emergence outside the range of background variability, with this change potentially already occurring. Other FW fluxes have likely started to shift but have not yet emerged into a completely different regime. Future emissions reductions have the potential to avoid the emergence of some FW fluxes beyond the background variability.

Plain Language Summary

The surface waters of the Arctic Ocean are fresher than the rest of the world oceans, due to the input of large amounts of river runoff. The very fresh surface ocean affects the ocean circulation and climate not just in the Arctic Ocean, but also at lower latitudes, especially in the North Atlantic. The last two decades have seen a freshening of the surface Arctic Ocean, for reasons that are currently unknown. Here we demonstrate that this freshening is likely already driven by climate change. Furthermore, we find that due to man-made climate change, Arctic freshwater fluxes to the North Atlantic are also likely to soon start showing signs of change beyond the range of the variability we have observed in the past. The information provided here about the expected timing of the emergence of climate change signals will allow us to monitor upcoming changes in real time, to better understand how changes in the Arctic Ocean can impact climate worldwide.

1 Introduction

Arctic Ocean liquid freshwater (FW) storage has shown a large increase from the 1990s until at least 2014 (e.g., Proshutinsky et al., 2009; Rabe et al., 2011, 2014; McPhee et al., 2009; Giles et al., 2012; Wang et al., 2019). Recent work suggests that this Arctic-wide increase is likely driven primarily by natural modes of variability rather than by anthropogenic climate change (Johnson et al., 2018). This contrasts with the observed reduction in the solid Arctic FW storage in sea ice over the same period, which has been shown to be at least partially driven by climate change (e.g., Notz & Marotzke, 2012; Wang et al., 2019; Schweiger et al., 2019). Furthermore, climate models predict a 21st century increase in the liquid FW storage and in many Arctic FW fluxes (e.g., Holland et al., 2006, 2007; Koenigk et al., 2007; Vavrus et al., 2012; Haine et al., 2015; Shu et al., 2018). While some Arctic FW fluxes have started to show changes in line with these predictions, others have not. In particular, as expected for a warmer climate, the Bering Strait FW influx (Woodgate, 2018), river runoff (Peterson et al., 2006), and net precipitation (Haine et al., 2015) have all increased, and solid FW storage has decreased (e.g., Haine et al., 2015; Wang et al., 2018). However, the liquid FW exports from the Arctic have not yet shown any clear changes or trends (de Steur et al., 2009; Curry et al., 2014; de Steur et al., 2018; Haine et al., 2015). This poses the question as to when the current monitoring of Arctic FW storage and fluxes will be able to detect an anthropogenic climate change signal.

Attributing observed change in the Arctic FW budget terms either to natural modes of variability or climate change is challenging due to the combination of the known influence of decadal to multi-decadal modes of variability on Arctic FW (e.g., Proshutinsky & Johnson, 1997; Proshutinsky et al., 2002; Polyakov et al., 2008; Johnson et al., 2018) and the short (25 years or less) continuous records available for many of the Arctic FW budget terms, in particular the liquid oceanic FW fluxes (e.g., de Steur et al., 2018; Münchow, 2016; Curry et al., 2014; Rabe et al., 2009, 2014). Here we show when we can expect to detect anthropologically-forced changes in the various Arctic freshwater budget terms, by determining the time of emergence outside the background variability using climate model simulations. Furthermore, we assess whether the detection of a forced change is dependent upon future emissions pathway choices. To separate the forced change from natural variability on multiple timescales and between emissions scenarios, we use ensemble simulations over the 20th and 21st centuries from a fully-coupled state-of-the-art earth system model under two different forcing scenarios (Kay et al., 2015; Sanderson et al., 2017). We find that the time of emergence of forced changes varies widely amongst Arctic FW budget terms. Some are already showing a climate-change signal or are likely to do so soon, in particular the FW storage terms and the Nares and Davis Strait liquid FW fluxes.

2 Methods

2.1 Model and Simulations

To assess the time of emergence of a climate change signal beyond natural internal variability in the Arctic FW budget, we use the Community Earth System Model (CESM) Large Ensemble (CESM LE; Kay et al., 2015) and a companion ensemble, the CESM Low Warming ensemble (CESM LW; Sanderson et al., 2017). Both ensembles use the CESM1.1, a fully-coupled, state-of-the-art global earth system model (Hurrell et al., 2013), and differ only in the applied forcing for the 21st century, allowing us to assess whether any of the results are sensitive to different future emissions choices. The historical CESM LE ensemble is created in 1920 through round-off level perturbations to the temperature field (Kay et al., 2015). After 2006, the CESM LE uses the high-emissions RCP8.5 scenario, leading to over 4 °C warming by 2100. The CESM LW is branched from the CESM LE ensemble members in 2006 and uses the RCP8.5 forcing until 2017, at which point it is then forced by a reduced emission scenario designed so that global warming stabilizes at 2 °C for several decades before the end of the 21^{st} century (Sanderson et al., 2017). The background variability is determined from the 1800 year long pre-industrial control simulation from the CESM LE project.

To consistently compare the CESM LE and LW, despite their different ensemble sizes (40 versus 11, respectively), all results shown are from the first 11 ensemble members of the CESM LE, referred to in the following as CESM LE. The effect of using the 40-member CESM LE was assessed and is discussed where applicable (with relevant figures in the supplementary), to provide insights into the impact of larger internal variability. None of the main conclusions are impacted by the use of the 11-member versus the 40-member CESM LE.

The CESM1.1 has already been used for a wide range of Arctic climate studies and generally performs well in the Arctic (e.g., Barnhart et al., 2015; Swart et al., 2015; DeRepentigny et al., 2016; Jahn et al., 2016; Jahn, 2018; Auclair & Tremblay, 2018; Morrison et al., 2019; England et al., 2019; Smith & Jahn, 2019). Nonetheless, as all models, the CESM1.1 has some biases. In terms of the simulated Arctic FW budget, which is calculated relative to the commonly used reference salinity of 34.8 (Aagaard & Carmack, 1989; Serreze et al., 2006; Haine et al., 2015), those biases are found primarily in the FW exports from the Arctic Ocean (see Fig. 1a for the ocean gateways used here). The liquid FW exports are underestimated by the model while the solid FW exports are overall too large, due to too much FW residing in the sea ice relative to the ocean over the observational period (see the Supplementary Material section S1 for details on the calculation of the FW budget and Table S1 for a comparison with observations). In particular, the Fram Strait and Barrow Strait liquid FW export are underestimated almost by a factor of three by the model for the late 20^{th} century, while the BSO liquid FW export is nearly 10 times as large as observed. However, the overall exchange of FW with the North Atlantic is within the observational uncertainty range. Furthermore, none of the biases found in the CESM1.1 Arctic FW budget are unique to the CESM1.1. Both fully-coupled CMIP3 (Holland et al., 2007) and CMIP5 models (Shu et al., 2018) as well as reanalysis-forced regional and global ocean-sea ice models (Jahn et al., 2012; Wang et al., 2016b, 2016a) exhibit biases in their simulated FW exports from the Arctic. So, while the results presented here have the caveat that they are derived from a single model, this study presents a first assessment of the changes in the Arctic FW budget in the context of internal variability, which is only possible when using an ensemble of simulations from one model. By enabling the separation of internal variability from the forced response, this study fills a clear gap in our understanding of the changing Arctic FW budget (as identified in Lique et al., 2016; Cornish et al., 2020).

2.2 Definition of Shift and Emergence

In order to detect a climate change driven signal in the Arctic FW budget, we determine when annual-mean Arctic FW budget terms first depart from the pre-industrial natural internal variability range (*"shift years"*) and when they enter a completely different regime, with no overlap with the pre-industrial state (*"emergence years"*). While individual shift years can occur due to an unlikely extreme event (i.e., natural variability) or due to a forced change (i.e., climate change), emergence occurs only due to forced change.

To detect shift and emergence for each budget term, we use an Internal Variability Threshold (IVT) of ±3.5 standard deviations around the mean of the 1800 year long pre-industrial control simulation. For normally-distributed processes, as most of the investigated FW fluxes are in the pre-industrial simulation, ±3.5 standard deviations captures 99.95% of the unforced internal variability. This threshold of ±3.5 standard deviations lies between what is known as "evidence" (±3 standard deviations) and "discovery" (±5 standard deviations). Smaller/larger thresholds than 3.5 standard deviations as well as non-Gaussian methods to define the IVT lead to qualitatively similar results, with some changes in the specific shifts and emergence years (see the Supplementary Material, section S2 and Fig. S3).

The *shift year* is defined as the first year in which a simulated FW term crosses the pre-industrial IVT, independent of whether it subsequently crosses the IVT back into the background variability. The *emergence year* is the first year when the FW term consistently stays outside the pre-industrial IVT range until the end of the simulations in 2100. This means that for any shift that starts before 2005, the CESM LE and CESM LW shift years are the same, as they are based on the same 11 historical simulations. Emergence, however, can differ between the CESM LE and LW even before 2005, as emergence depends on the future behavior of the fluxes until 2100. *Shift and emergence periods* are defined as the period between the time when the first and last ensemble member satisfy these criteria. Hence, the shorter the shift and emergence period, the more strongly forced the simulated change is.

3 Results

3.1 21st Century Changes in the Arctic FW Budget

Arctic FW budget terms show a large spread in how much they are projected to change over the 21st century (Fig. 1b), as well as show clear differences between the low and high warming scenarios by the end of the 21st century (referred to as "scenario impact" in the following). The largest scenario impact is seen for those FW budget terms that change the most in magnitude over the 21st century, namely Arctic liquid and solid FW storage, Fram Strait liquid and solid FW fluxes, the Nares Strait and Davis Strait liquid FW flux, and river runoff (Fig. 1b). These changes simulated by the CESM are generally consistent with those previously reported over the 21st century for different individual models (Holland et al., 2006; Vavrus et al., 2012; Koenigk et al., 2007) as well as for CMIP3 (Holland et al., 2007) and CMIP5 (Shu et al., 2018) models. Note that we will focus on the larger FW budget terms, which means that except in Fig. 1b), we do not show or discuss the small FW fluxes (net observed fluxes smaller than 300 km^3/yr). For completeness, plots for these fluxes are included in the Supplementary Material (Fig. S1–S3).

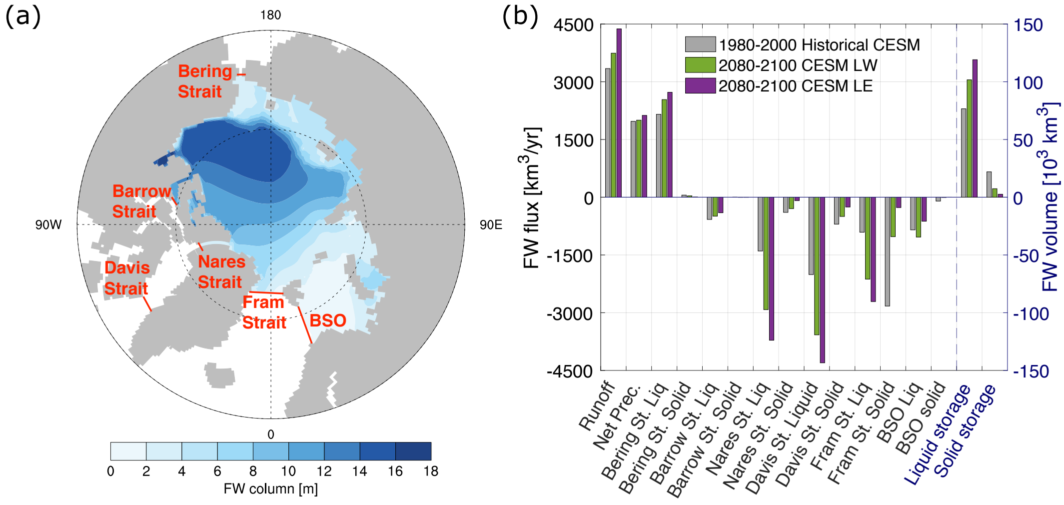

Figure 1. Arctic domain and Climatological FW budget. (a) Ocean gateways (labeled in red) and the Arctic Ocean domain used here (shaded; showing the simulated liquid FW column [in m] over 1980–2000). BSO stands for Barents Sea Opening. (b) Climatological ensemble-mean Arctic FW budget terms for the late 20th century (1980–2000) and the late 21st century (2080-2100), with the late 21st century shown under both low warming (CESM LW; green) and high warming (CESM LE; purple). The values of the flux terms are shown on the left y-axis, the values of the FW storage terms on the right y-axis. Note that Davis Strait is shown here for reference, as it has been used in several other studies of the Arctic FW budget (e.g., Haine et al., 2015; Wang et al., 2016b, 2016a; Shu et al., 2018), but is not part of the Arctic FW budget/domain used here.

In addition to changes in the mean, we also see an increase in the variability of many oceanic liquid FW fluxes over the late 20th and 21st centuries, while the variability of the solid FW fluxes decreases as the Arctic sea ice volume/solid FW storage decreases (Fig. 2 and Fig. S2). The FW budget terms that show the largest scenario impact in the mean also show the largest scenario impact on their range of internal variability (Fig. 2 and Fig. S2).

3.2 Shift and Emergence in Arctic FW Budget Terms

The solid and liquid Arctic FW storage terms show the earliest complete shift and emergence transition of all FW terms assessed, with emergence complete in all members under both scenarios by the early 2020s (Fig. 3). The very rapid emergence across all ensemble members, lasting less than two decades, indicates a strongly forced change into a new regime. For the liquid FW storage, the shift period is as short as the emergence period for the CESM LE, again indicating a strongly forced change despite large internal variability. However, the occurrence of a rare internal variability event outside the IVT has the potential to extend the shift period. This is the case for the early 20th century start of the solid FW storage shift period: One ensemble member shows an increase

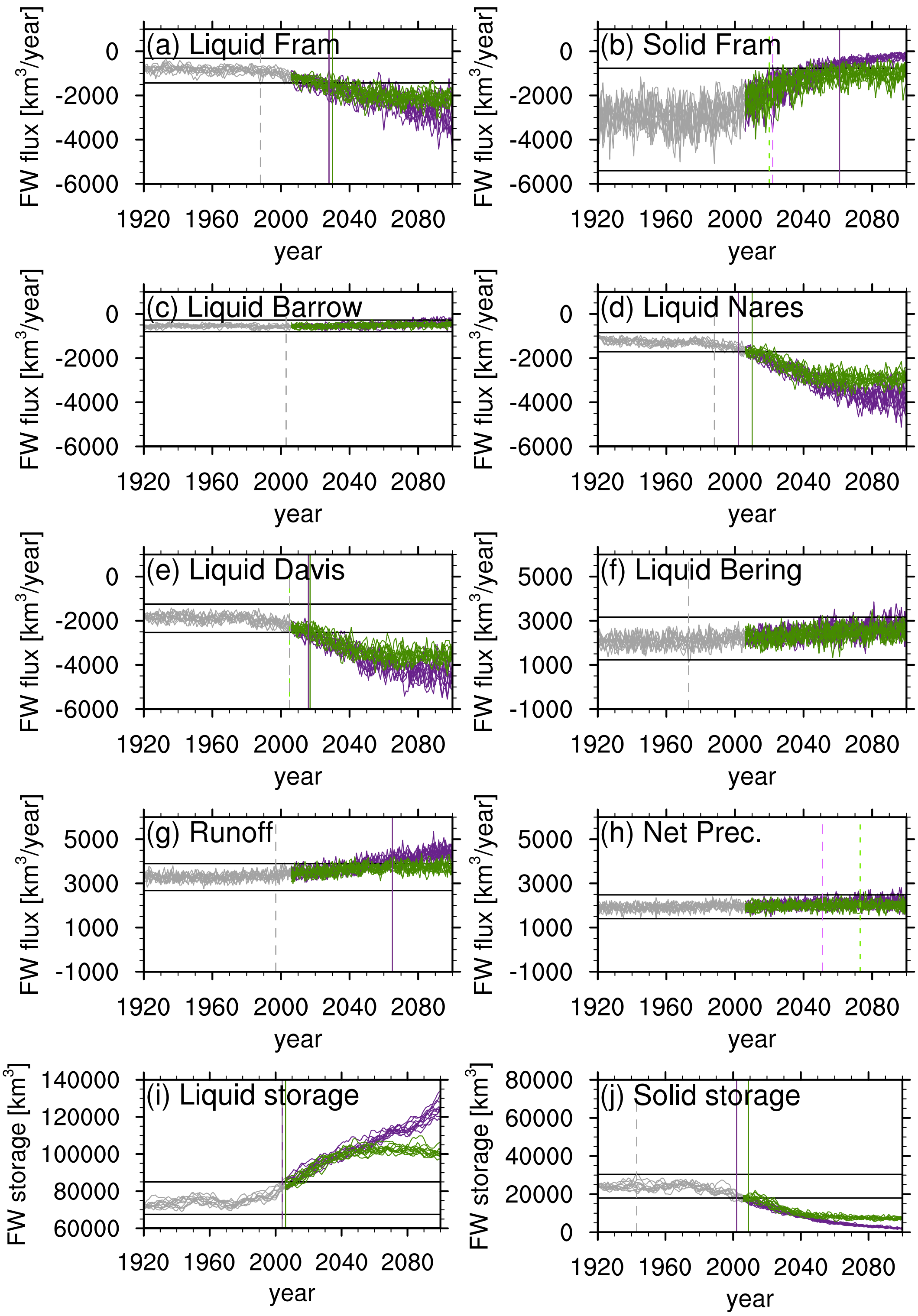

Figure 2. FW budget terms over time. Annual mean FW fluxes (a-h) and storage (i, j) over time for the different scenarios (CESM LE in purple, CESM LW in green, historical CESM in grey). The fluxes are labeled in the panels, with their respective ±3.5 standard deviations IVT lines (black). The earliest shift and emergence years for each scenario are shown as vertical lines, with the shift shown as dashed light purple/green for the CESM LE/LW and emergence shown as solid dark purple/green lines for the CESM LE/LW. If the shift occurs during the historical simulation, the shift is shown as grey dashed line. Only the fluxes with observed net fluxes above 300 km^3 are shown here, the smaller fluxes are shown in Fig. S2.

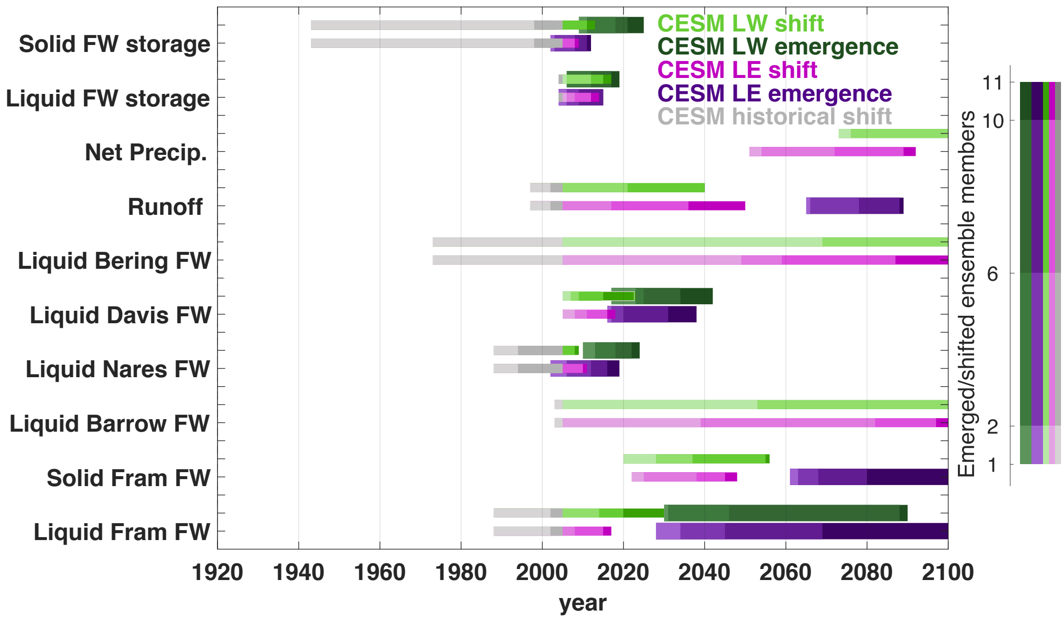

Figure 3. Shift and Emergence Periods. Shift (thinner bars and lighter colors) and emergence (thick bars and darker colors) periods for the simulated annual mean Arctic FW variables under the historical forcing (grey), the low warming scenario CESM LW (green colors), and the high warming scenario CESM LE (purple colors). The color gradient within each bar denotes the number of members that have shifted/emerged, as indicated in the colorbar, with a focus on the edges and middle of the distribution. Note that the grey bars are by definition the same for both scenarios, as they are from the same 11 historical simulations. The impact of sampling a larger range of internal variability in the 40-member CESM LE is illustrated in Fig. S3c. It shows that while the general sequence of shift and emergence stays the same, generally longer shift periods and some longer emergence periods are found. Fig. S3c also shows the shift and emergence for the small terms of the FW budget not shown here.

in solid FW storage above the IVT in 1943, but the forced change is towards lower solid FW storage and the lower bound of the IVT is not crossed until 1998 by the first ensemble member (Fig. 2j). As this early start of the shift period is due to internal variability, it disappears when a slightly larger IVT is used (Fig. S3). A similar early shift event occurs for the liquid FW storage when the full 40-member CESM LE is considered (Fig. S3), and is also due to a single crossing of the IVT in the opposite direction than the forced signal emerging in the 21st century.

The Nares Strait liquid FW export from the Arctic is the next FW budget term, and the first FW flux, that shifts and then emerges from the pre-industrial background variability in all ensemble members (Fig. 3). In particular, we find that emergence already starts in the early 2000s in some ensemble members, and is complete in the early 2020s when accounting for all ensemble members of both scenarios. As for the FW storage terms, the low warming scenario does not prevent the emergence of the forced signal in the Nares Strait liquid FW export, as the forcings only begin to diverge in 2017. However, by the end of the 21st century, the magnitude of the Nares Strait liquid FW export increase is very different based on the two scenarios, with a much larger increase under the high warming scenario compared to the low warming scenario (Fig. 1b and 2). Downstream of Nares Strait, Davis Strait exhibits similar variability as well as similar shift and emergence periods compared to Nares Strait in CESM LE and LW, but slightly later than what is seen for Nares Strait (Fig. 2 and 3).

The Fram Strait liquid FW export also shows shift and a potential to begin to emerge over the next decade (Fig. 3). Shift begins in the late 1980s, but only due to one event, with the second crossing of the IVT towards larger liquid FW export not occurring until the early 2000s (Fig. 2a and Fig. 3). This indicates that the early shift event is due to an anomalous, unforced event rather than climate change, similar to the observed large FW export events leading to Great Salinity Anomalies in the North Atlantic (e.g., Dickson et al., 1988; Belkin et al., 1998). Emergence for the Fram Strait liquid FW export begins as early as the mid-2020s. However, due to the large and increasing variability of the liquid Fram Strait FW export compared to the forced change (Fig. 2), the emergence period extends to 2090 (CESM LW) and beyond 2100 (CESM LE). This means that full emergence outside the pre-industrial background variability may occur anytime between the mid 2020s and the late 21st century (Fig. 3). The shorter emergence period in the low warming scenario compared to that in the high warming scenario is the result of the enhanced internal variability of the liquid Fram Strait FW export in a warmer climate (Fig. 2), so that the internal variability is larger for the CESM LE than the CESM LW.

The solid Fram Strait FW export stands out as the Arctic FW flux with the largest variability over the historical and pre-industrial period (Fig. 2 and Fig. S1). As a result, the shift period only begins in the early 2020s (Fig. 3), despite a much earlier clearly visible decrease of this FW flux within the IVT range (Fig. 2).

Both the solid Fram Strait FW export and the river runoff show a clear scenario impact on the emergence of a forced climate change signal, with emergence only occurring in the high emission scenario, but shift occurring for both the high and low warming scenarios (Fig. 3). In particular, runoff shows full emergence in the CESM LE by 2089 (and in all but one of the 40 ensemble members of the full CESM LE before 2100, see

Fig. S3c). Similarly, the solid Fram Strait FW export shows emergence in all but one ensemble member of the CESM LE by 2100 (Fig. 3). Reaching shift but not emergence under the low warming scenario means that these two FW fluxes show clear changes over time, but the fluxes do not consistently lie outside the pre-industrial IVT range by 2100 (Fig. 2).

Bering Strait and Barrow Strait liquid FW fluxes both show very long shift periods under both scenarios, but no emergence (Fig. 3). Bering Strait liquid FW fluxes begin to shift earlier (in the 1970s) than Barrow Strait liquid fluxes (in the 2000s). However, while over 90% of the ensemble members shift before 2100 under the high warming scenario for both fluxes, less than 50% of the low warming scenario members shift before 2100 (Fig. 3), reflecting a scenario impact that is also clearly detectable in the late 21st century means (Fig. 1b). A gradual increase in the liquid FW inflow through Bering Strait over the last decades is consistent with the observed increase (Woodgate, 2018).

Net precipitation also shows a clear scenario impact on the shift (Fig. 3). Net precipitation shows complete shift for the CESM LE between the mid 21st century and the 2090s (and for 90% of the full 40 member CESM LE over a longer period, see Fig. S3c), but only for 18% of the low warming scenario. So while net precipitation over the Arctic is clearly slowly increasing under both scenarios (Fig. 2), in agreement with observations (Peterson et al., 2006; Haine et al., 2015), the changes are small compared to the background variability, at least in the CESM1.1 simulations.

4 Discussion

We assessed when a clearly forced change in the Arctic FW budget terms can be detected and found very short emergence periods across all ensemble members in both scenarios in the CESM for the liquid and solid Arctic FW storage. These short emergence periods suggest a strongly forced change in the Arctic FW storage terms. Hence, based on these CESM results, the large changes in the Arctic FW storage that have been observed over the last three decades are likely to be the beginning of an anthropogenic forced change towards larger liquid FW storage and smaller solid FW storage. In agreement with another recent study (Wang et al., 2019), we find that the increase in the liquid FW storage is not exclusively driven by the concurrent decrease in the solid FW storage: The contribution from the decrease in solid FW storage to the increase in the liquid FW storage varies between 35%–89% for the different ensemble members over the period over which we see shift and emergence in the two storage terms (1996–2015). The remaining freshening is due to a change in the sum of the FW fluxes, as previously suggested (e.g., Rabe et al., 2014; Carmack et al., 2016). Physically, the storage terms showing emergence prior to the exports means that the changes in the FW exports are an adjustment to the expanded reservoir state.

The finding that the solid FW storage is already showing a forced change agrees with the previous interpretation of the solid FW storage decrease as at least partially driven by climate change due to the loss of sea ice (e.g., Haine et al., 2015; Wang et al., 2019; Schweiger et al., 2019). The interpretation of the increased liquid FW storage since the 1990s as a climate change signal is also generally consistent with other climate model studies that show a robust increase of liquid FW storage in the Arctic over the 21st century (e.g., Holland et al., 2006, 2007; Koenigk et al., 2007; Vavrus et al., 2012; Haine et al., 2015; Shu et al., 2018). In particular, the CMIP5 multi-model mean shows an increase in the liquid Arctic FW content since the 1990s, at about 50% of the observed magnitude, suggesting a forced contribution to that change (Shu et al., 2018). However, our results seem to disagree with the interpretation that liquid FW storage changes "observed to date appear to have resulted from natural atmospheric variability" in Johnson et al. (2018). But the two studies may not be in as much in conflict as it appears at first glance. The fact that the reconstructed FW storage timeseries from of Johnson et al. (2018) matches the observed change between the early 1990s and 2012 very well does not preclude the existence of a forced signal in that timeseries, as the FW storage reconstruction is based on the sea level pressure variations from reanalysis, which may contain a climate change signal. This possibility is also alluded to in the recent study of Cornish et al. (2020). Furthermore, Cornish et al. (2020) find that the strength of the relationship between sea level pressure and liquid FW storage variability varies greatly between different CMIP5 models and is weaker than in the model used in Johnson et al. (2018), leaving room for other contributions to the liquid FW content change beside those driven by changes in sea level pressure. Our analysis also does not in any way preclude a contribution from internal variability on top of a forced change. In fact, a contribution from internal variability is likely, and has been shown to exist for the solid FW storage decrease (Notz & Marotzke, 2012; Wang et al., 2019; Schweiger et al., 2019). The strong link between the liquid FW storage changes and the sea-level pressure variability identified in Johnson et al. (2018)

may well be part of the physical mechanism that imprints the climate change forcing onto the liquid Arctic FW storage.

Similarly to the Arctic FW storage, the short emergence period for the liquid Nares Strait FW flux across all ensemble members and both scenarios suggest that any observed shifts in the 2000s to 2020s towards larger liquid FW fluxes through Nares Strait may already include a climate change driven signal. Hence, it is possible that climate change may have contributed at least partially to the observed larger FW fluxes through Nares Strait between 2003–2006 and 2007–2009 (Münchow, 2016). In fact, Münchow (2016) attributed 69% of this increase in the Nares Strait liquid FW export to the effects of a climate-change driven sea ice decline on the ocean, through the freshening of the surface waters from ice melt and more efficient momentum transfer from the atmosphere to the ocean under a more mobile ice cover.

Since the results presented here are only from one model, which has biases in its representation of the Arctic FW budget, a general agreement with ensembles of CMIP3 and CMIP5 models is promising. Different models will, however, likely show differences in the specific years of emergence and shift than those shown here. However, the focus here is not the precise predictions of the shift and emergence years, which fully-coupled models can not provide due to the large impact of internal variability (Deser et al., 2012). Instead, the main take-away should be the overall likelihood of the emergence of forced signals for different budget terms in the presence of large internal variability, and the general timing of the possible emergence of different fluxes within the 21^{st} century.

Detecting emergence of a climate change signal from the observational timeseries will be more challenging than from model simulations, since even the longer observed FW timeseries only go back to the 1990s (e.g., de Steur et al., 2009; Rabe et al., 2009, 2014). Furthermore, rather than a system in steady-state, as in the control simulation, the observations capture a system that is already responding to climate change, in particular from the 2000s on (e.g., Kwok, 2018). Comparing the influence of these two complications present in observed timeseries, we find that it is the changing nature of the FW budget terms during the base period, rather than the much shorter base period itself, that complicates the diagnosis of emergence and shift from observations that, at best, extend to the mid or late 1990s (see section S3 and Fig. S4 for details).

Despite this difficulty with detecting emergence and shift from observations, the current lack of trends in observed liquid FW exports through the Arctic gateways (de Steur et al., 2009; Curry et al., 2014; de Steur et al., 2018; Haine et al., 2015) are consistent with the CESM results: Full emergence into a new climate state, which would allow a clear trend detection in the presence of increased variability, only occurs for Nares Strait by 2020, and only in some ensemble members but not in others. However, in Nares Strait all ensemble members show emergence before 2030 in the CESM, and by 2042 in Davis Strait. Hence, based on the CESM, we should see sustained increased FW exports in Nares and Davis Strait relatively soon, leading to positive trends eventually. Based on the CESM, we could also soon start to see sustained increased exports and positive trends in Fram Strait, but it could also still take a few decades, depending on the details of the natural modes of variability we will experience. This means that continued monitoring of the oceanic fluxes through these gateways and the downstream convective regions over the next decades is crucial to record this expected regime shift and assess its impact on the ocean circulation in the North Atlantic.

5 Conclusions

We showed that different Arctic FW budget terms shift toward and emerge into a new climate regime outside their pre-industrial variability at different times. Climate change forced shift and emergence occur first for the Arctic FW storage (both liquid and solid). The simulated emergence period of a climate change signal in both liquid and solid FW storage in the CESM overlaps with the observed increase in Arctic liquid FW storage between the early 1990s and 2014 and decrease of the solid FW storage since the 1990s (with no Arctic-wide liquid FW data available since 2014). This suggests that the observed increase in the liquid and solid FW storage is at least partially driven by climate change, rather than the result of unforced internal variability.

Generally, oceanic FW fluxes show much earlier emergence than FW fluxes from the atmosphere and land. The first FW flux to emerge is the Nares Strait liquid FW export, which emerges by the end of the 2020s for all members and both scenarios. Emergence in Davis Strait liquid FW export follows Nares Strait, with emergence between the late 2010s and early 2040s. Detecting shift and emergence from shorter timeseries that overlap with the observational period is possible, but the changing nature of many of the FW budget terms, in particular since 2000, can lead to a delayed detection of shift and emergence. This means that even if so far there is no trend detected at Nares or Davis Strait in observations, a clearly detectable shift towards positive trends in FW exports is potentially imminent. For Fram Strait the CESM suggests that we are currently in the shift period towards higher liquid FW exports, with the potential for full emergence starting in the mid 2020s. Reduced future emissions may be able to prevent the emergence into a completely different regime in the late 21st century for some FW fluxes such as runoff and the solid Fram Strait FW export, reducing but not avoiding changes in those Arctic FW fluxes. The possibility of ongoing and imminent changes in the oceanic liquid FW exports highlights the importance of continued observational programs at the Arctic gateways and in the Arctic Ocean, in order to detect these changes in the real world as they occur.

Acknowledgments

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Supplementary Material

Section S1. Climatological Arctic FW Budget in the CESM1.1

The Arctic FW budget is calculated from the CESM1.1 model simulations, relative to a reference salinity of 34.8. The surface fluxes (net precipitation and runoff) and the FW storage terms are calculated over the shaded region shown in Fig. 1a, which is delineated by Bering Strait, Barrow Strait, Nares Strait, Fram Strait, and the BSO (shown in Fig. 1a). The liquid FW fluxes through those gateways are given as net FW fluxes over the full depth of the gateways, and for solid FW combine the FW contained in sea ice and in snow on sea ice. The liquid FW storage shown throughout the paper is calculated down to the 34.8 isohaline, following previous conventions (Serreze et al., 2006; Haine et al., 2015). Davis Strait is shown for reference as an additional strait that is often used in Arctic freshwater studies (e.g., Haine et al., 2015; Wang et al., 2016b, 2016a; Shu et al., 2018), but is not part of the Arctic domain over which the FW budget is calculated.

Compared to the observational Arctic FW fluxes for the late 20$^{\text{th}}$ century, we find that the largest biases in the CESM1.1 FW budget compared to observations are found in the liquid FW exports from the Arctic Ocean. In particular the Fram Strait liquid FW export is much smaller than observed, while the net BSO FW flux is too large. The total solid FW exports on the other hand are slightly too large compared to the observations, except in Barrow Strait, where they are too small. However, the net simulated FW export from the Arctic (7066 km^3/yr) is within the observational uncertainty of the observed net FW export from the Arctic ($8324 \pm 1263 km^3/yr$), so the biases in the fluxes represent a combination of a bias in FW export routes (e.g., more FW export through the BSO, at the expense of the Fram Strait) and a bias between solid and liquid FW export (i.e., more solid FW export than observed, at the expense of the liquid FW export), rather than an overall too small FW exchange between the Arctic and North Atlantic. The bias in the liquid versus solid FW fluxes goes along with a larger than observed solid FW storage in the CESM1.1 (see Table S1), indicating that in the late 20$^{\text{th}}$ century more FW is stored in the solid versus liquid component in the CESM1.1 compared to observations. Note that while this means there is more solid FW stored in the CESM1.1 over 1980–2000 than observed, the simulated decrease in the solid FW storage over the first decade of the 21$^{\text{st}}$ century is not too large and agrees well with estimates based on PIOMAS: Haine et al. (2015) found a decrease of 6,900 km^3 in the solid FW storage based on PIMOAS between 1980–2000 and 2011, compared to 6,387 km^3 in the ensemble mean from the CESM1.1 if calculated over the same period and domain as used in Haine et al. (2015) (using Davis Strait rather than Nares and Barrow Straits as boundary west of Greenland; for the smaller Arctic domain used here the simulated decrease over this period is slightly less, at 5,869 km^3). Hence, the liquid FW storage increase in the CESM1.1 over the early 21^{st} century that leads to the simulated emergence is not unduly driven by a concurrent too large decline in the solid FW storage over the early 21^{st} century period. Eventually, however, the bias in the solid FW storage over the historical period will lead to a too large contribution from sea ice melt, compared to the real world.

While there are clear biases in the CESM1.1, it is important to note that limited observations make it challenging to even know what some of the details of the Arctic FW budget should be (as also discussed by Haine et al., 2015; Lique et al., 2016). In particular, the liquid FW export west of Greenland has in the past been assumed to be strongly dominated by Barrow Strait/Lancaster Sound, based on the available data at the time (Jahn et al., 2012). However, more recent data from Nares Strait has raised the expected contribution from Nares Strait liquid and solid FW export, due to the inclusion of the surface layer, as well as revealed large, previously unknown interannual variability (Münchow, 2016). This new data suggests that the two main channels west of Greenland may in fact be exporting approximately equal amounts of FW from the Arctic (Table S1). Similarly, there is a wide range of estimated solid FW storage (Haine et al., 2015), due to uncertain Arctic wide sea ice thickness data, in particular prior to the 2000s.

Section S2. IVT Sensitivity to Different Threshold Choices

We here chose an IVT of ±3.5 standard deviations, as for normally distributed processes the range between the upper and lower IVT captures 99.95% of values due to unforced internal variability. For most of the FW budget terms, this means that all values in the 1800 year long control simulation fall within this ±3.5 standard deviation range. However, for a few terms (Fram Strait liquid FW flux, runoff, liquid FW storage, and solid BSO), the IVT threshold is crossed a few times during the 1800 years of the control simulation (Fig. S1). Such isolated occurrences outside the ±3.5 standard deviation over 1800 years are consistent with the fact that individual very rare (<0.05% probability) events can potentially lead to departures outside the IVT range, even for an IVT range of ±3.5 standard deviations. For the BSO solid term, it is also a reflection that this flux is not normally distributed (as it is close to but does not cross the zero line), so different probabilities apply; however, this term is small and it is only included for completeness as part of the Arctic FW budget. All results presented also generally hold if we do not assume normally distributed processes but instead use the maximum and minimum values of each FW budget terms during the 1800 year long control simulation plus an extra margin of 10% of the flux to exclude any unsampled rare natural variability-driven events (Fig. S3).

As we are using at least 11 ensemble members for the 20^{th} and 21^{st} centuries, it would be extremely unlikely to see rare events with a probability of <0.05% occurring for all ensemble members over the 181 years of the 20^{th} and 21^{st} centuries simulation. This means that the detection of spurious complete shifts is highly unlikely. Spurious emergence is not statistically possible, as emergence requires sustained changes outside the pre-industrial IVT range. Hence, this methodology and IVT choice is able to detect truly forced changes in the Arctic FW budget terms. Smaller/larger thresholds than 3.5 standard deviations and a non-gaussian approach lead to qualitatively similar results, but some changes in the specific shifts and emergence years due to the change of the probability of events outside the chosen range (see Fig. S3).

Note that our methodology to determine time of emergence differs from several other "time of emergence" methods (e.g., Hawkins & Sutton, 2012; Mora et al., 2013; Lehner et al., 2017). In particular, we look at annual mean values outside the IVT range rather than considering when the ensemble mean first exceeds the background variability by a certain factor (a typical signal/noise ratio definition of emergence). This approach is most similar to the determination of shift and emergence of Arctic open water days in Barnhart et al. (2015), who demonstrated that there can be substantial differences between the emergence time of a variable's ensemble mean versus its unsmoothed trajectory. As we want to be able to assess when we can expect to observe fluxes and storage that are fully outside the background state, we prefer this time of emergence methodology of using the unsmoothed variables, as that is what we will be able to observe in the real world.

Section S3: Effect of a shorter base period and of sampling a non-steady state system

To provide insights into how shift and emergence detection would look different for observations of the Arctic FW budget, we have repeated our emergence analysis for 20-year periods from the control as well as from the historical simulation (Fig. S4). This allows us to assess how the results presented here are affected by using a shorter base period as well as a base period that covers a period where forced changes are starting to affect some of the budget terms. We find that the shorter base period by itself does not affect the main results on emergence, but does change the start and end years by a few years (see Fig. S4b and c versus Fig. S4a). Shift periods on the other hand are more strongly affected by a shorter base period, with some changes of several decades in either direction. This behavior is expected, as emergence detects a sustained, forced change while shift is triggered by an individual event, so a small change in the IVT will affect shift more strongly than emergence. Sampling a non-steady state system for 20 years, however, has a big effect on detecting emergence. Emergence patterns similar to the ones based on the full length of the control simulation are found primarily for a 20 year period from the historical simulation that ends before 2000 (see Fig. S4a, d, g). Once the base period extends past 2000, emergence is reached later, in particular for the terms that show early emergence (Fig. S4e, f, h, i). Nonetheless, the general order of emergence of FW budget terms remains the same even for base periods that extend to 2009. For base periods that extend past 2009, however, even the order of emergence changes, as the base period from 2000-2019 now samples the already very different FW storage terms, leading to a much later emergence of these terms compared to their already very different base state. Hence, it is the changing nature of the FW budget terms during the base period, rather than the much shorter base period itself, that complicates the diagnosis of emergence and shift from observations that, at best, extend to the mid or late 1990s.

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Table S1. Climatological Arctic Ocean freshwater (FW) budget (1980–2000). Observational values are partially taken from the compilation by Serreze et al. (2006) (indicated by * in the table). Terms that are not from Serreze et al. (2006) are: Bering Strait solid FW fluxes (Woodgate & Aagaard, 2005), BSO solid FW fluxes (Kwok et al., 2005), Nares Strait liquid and solid FW fluxes (Münchow, 2016), Barrow Strait solid and liquid fluxes (Prinsenberg & Hamilton, 2005), and Davis Strait solid and liquid FW fluxes (Haine et al., 2015). The solid FW storage in the Arctic is shown as range, based on the values given in Serreze et al. (2006) and Haine et al. (2015). These two estimates differ in the assumed mean ice thickness (thinner ice assumed in Serreze et al. (2006) than Haine et al. (2015)) as well as in their Arctic domain, with the Arctic domain in Serreze et al. (2006) smaller than our domain (entirely excluding the CAA) and the domain in Haine et al. (2015) larger than our domain (including Baffin Bay down to Davis Strait). In the CESM1.1, the impact of these domain differences compared to the Arctic domain used here is an additional solid FW storage of 1,868 km3 for the domain of Haine et al. (2015) and 2988 km^3 less solid FW storage for the domain of Serreze et al. (2006), which does not change the fact that the CESM1.1 has too much solid FW storage. However, note that the solid FW flux and storage includes FW from the snow on sea ice as well as from the ice itself while the observational estimates typically only include the FW in the sea ice, which leads to a difference of about 10%. Further note that the Nares and Barrow Strait values are from the early 2000s, rather than the late 20^{th} century, as no earlier data exists. If available, error estimates for the observations are included. Model values show the ensemble mean values, and the ± indicates the standard deviation of the 40-member CESM LE in the 21-yr averages. All FW fluxes are quoted in km^3/year, and the FW storage is quoted in km^3. All values are annual mean net fluxes, for oceanic fluxes over the full depth of each channel, combining negative and positive fluxes through a strait, where applicable. Positive values indicate FW sources and negative values indicate FW sinks for the Arctic Ocean. Note that Davis Strait is included here for reference only, with the surface fluxes and storage calculated over the Arctic Ocean domain delineated by Nares Strait and Barrow Strait west of Greenland (see Fig. 1a).

FW fluxes	**Observations**	**CESM LE**
River runoff	3200 ±110*	3358±55
Net precipitation	2000 ±200*	1958±32
Bering Strait liquid FW	2400 ±300*	2159±66
Bering Strait solid FW	140 ±40	56±14
Barrow Strait liquid FW	−1510	−567±25
Barrow Strait solid FW	−76	2±1
Nares Strait liquid FW	−1356±236	−1439±69
Nares Strait solid FW	−252±63	−395±15
Davis Strait liquid FW	−3200±320	−2044±69
David Strait solid FW	−160	−701±24
Fram Strait liquid FW	−2700 ±530*	−948±68
Fram Strait solid FW	−2300 ±340*	−2776±174
BSO liquid FW	−90 ±94*	−852±50
BSO solid FW	−40	−91±41
Liquid FW storage	74,000 ±7400*	77,485±1562
Solid FW storage	10,000* – 17,800	21,931±1011

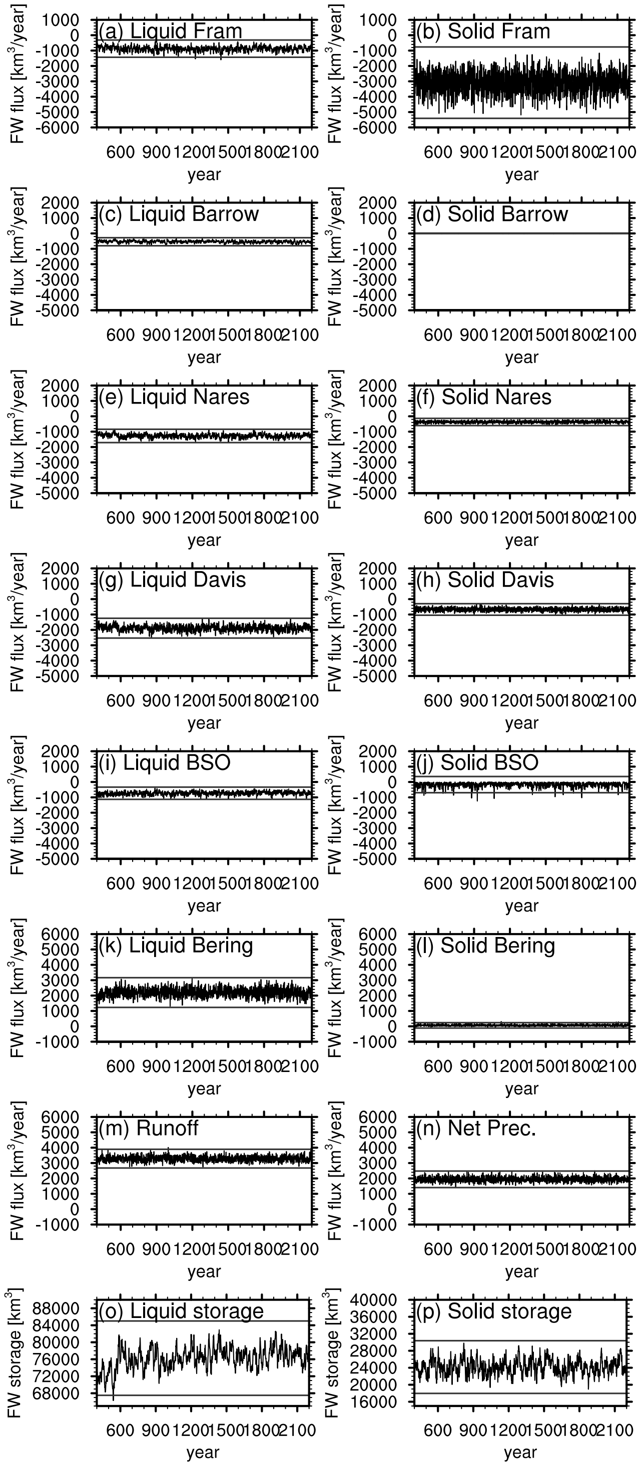

Figure S1. Variability in the control simulation. The ±3.5 standard deviation threshold for each variable (which is used to determine shift and emergence in the 20th and 21st centuries simulations) is shown as solid dark grey lines. Flux terms (a-n) and storage terms (o, p) are labeled in the panels. Note that all flux panels (a-n) and all storage panels (o-p) each have the same y-axis range, but that the axis are offset from each other.

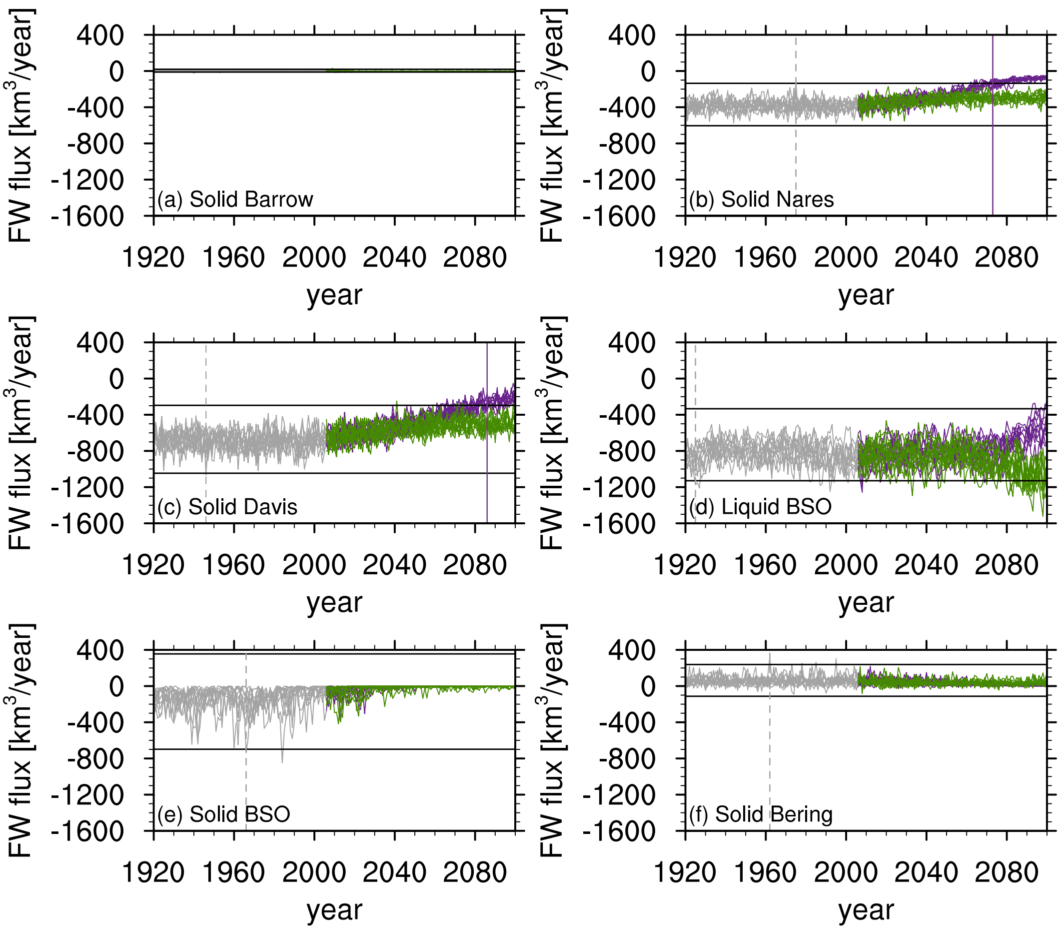

Figure S2. Small FW budget terms over time. As in Fig. 2, but for the small (less than 300 km^3/yr in the observed net fluxes) FW fluxes not shown in Fig. 2. Note that the y-axis is the same for all panels, but is different from Fig. 2 to allow a more meaningful depiction of these small fluxes.

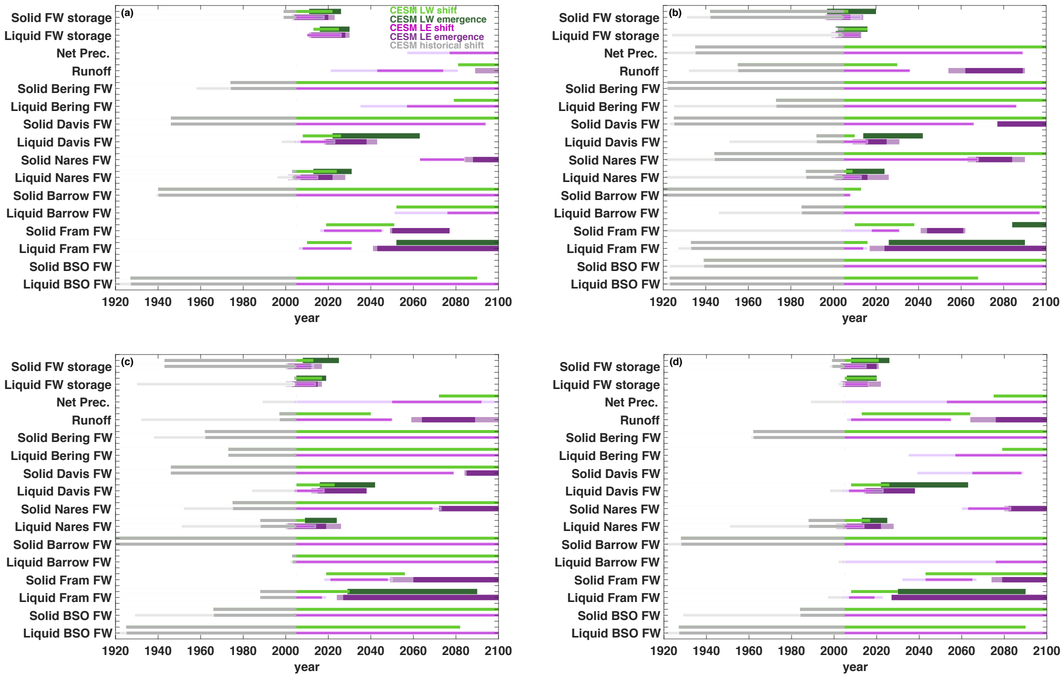

Figure S3. Sensitivity of results to different IVT choices. As Fig. 3, but for an IVT defined as (a) the maximum/minmum values in the control ±10% of the mean, (b) ±3 standard deviations, (c) ±3.5 standard deviations, and (d) ±4 standard deviations. This figure also includes the FW fluxes with a net observed flux of less than 300 km^3/yr, which were not shown in Fig. 3. These different IVT choices (a, b, d) show qualitatively similar results as for 3.5 standard deviations (c), with the largest changes primarily in the start dates of the shift periods, due to the smaller/larger IVT range. None of the main conclusions are affected by the choice of the IVT, as they mainly focus on the emergence of the forced signal.

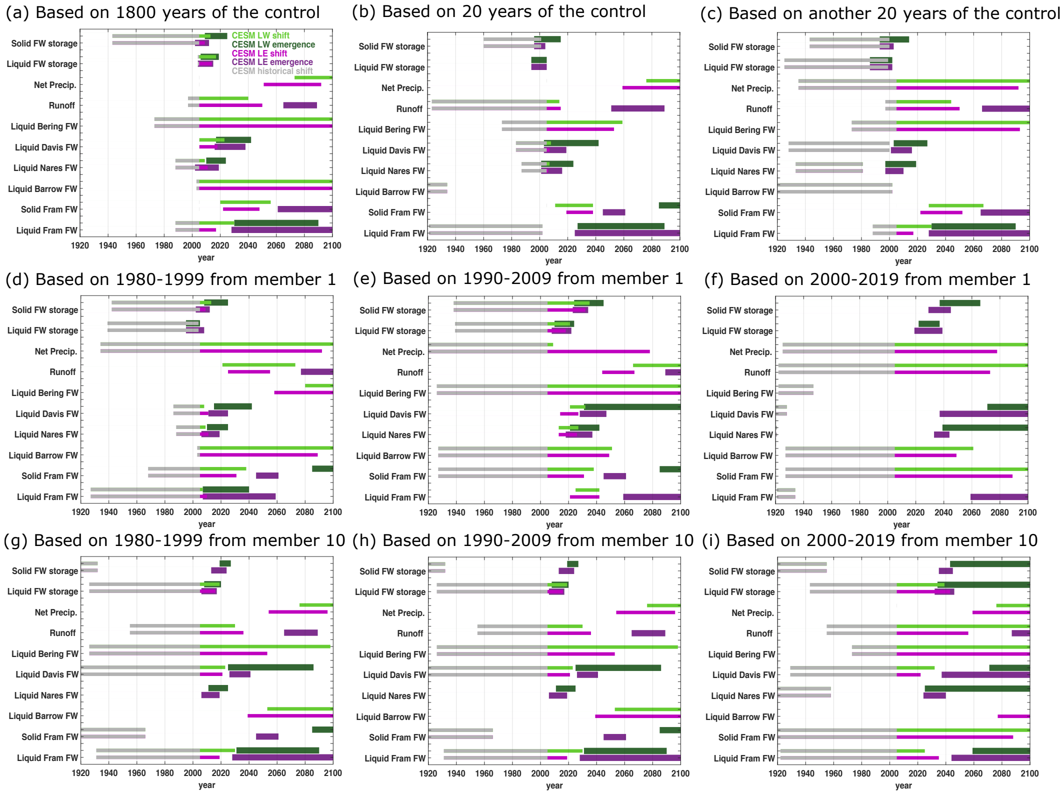

Figure S4. Influence of different base periods on shift and emergence. Shift and emergence, as shown in Fig. 3, but using different base periods in the different panels to determine the IVT, to assess the impact of a shorter base period, as would be available from observations. (a) Using the full 1800 years of the control simulation, same as Fig. 3, (b) using only 20 years of the control (here years 1000-1019), (c) using a different set of 20 years from the control (here years 400-419), (d/g) using years 1980-1999 from ensemble member 1/10 of the CESM LE, (e/h) using years 1990–2009 from ensemble member 1/10, (f/i) using years 2000-2019 from ensemble member 1/10. This shows that sampling of a system more and more affected by climate change if years after 2000 are included in the base period affects the results more than using a shorter base period, in particular for emergence (with shift sensitive to both). Results are similar for 30 year instead of 20 year periods. Members 1 and 10 are shown in panels d–f and g–i, respectively, to illustrate the effects of sampling different 20-yr periods under the same external forcing but with different internal variability. Other ensemble members show slightly different patterns, but changes are qualitatively similar to the difference between the two members shown here.