Precipitation Shifts over Western North America as a Result of Declining Arctic Sea Ice Cover: The Coupled System Response

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ABSTRACT: Changes in Arctic sea ice cover have the potential to impact midlatitude climate. A previous sensitivity study utilizing the National Center for Atmospheric Research’s (NCAR) atmospheric general circulation model [AGCM; Community Climate Model, version 3 (CCM3)] to explore climate sensitivity to declining Arctic sea ice cover suggested that, as Arctic sea ice cover is reduced, precipitation patterns over western North America will shift toward dryer conditions in southwestern North America and wetter conditions in northwestern North America. Here, three complementary lines of research validate and explore the robustness of this possible climate change impact: 1) repetition of the previous sensitivity study (specified constant Arctic sea ice cover and atmospheric CO2) with an updated version of the NCAR AGCM [third Community Atmosphere Model (CAM3)], 2) investigation of the climate response to dynamically reduced Arctic sea ice cover (driven by a quadrupling of atmospheric CO2) in the coupled NCAR Community Climate System Model

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1. Introduction

The distribution of precipitation over western North America is highly dependent on storm tracks and exhibits substantial latitudinal and seasonal variation. During the dry season (May through October, henceforth referred to as summer), major storms are generally isolated along the coast in the Pacific Northwest, the Canadian Rockies, and Alaska, and the remainder of western North America receives little precipitation (Figure 1a). During the wet season (November through April, henceforth referred to as winter), storm tracks shift southward and provide increased precipitation to parts of Washington, Oregon, Idaho, California, Nevada, Utah, Arizona, Colorado, and New Mexico (Figure 1b). In much of this region, winter storm precipitation accounts for the majority of annual precipitation totals (Figures 1b,c). This spatial and temporal variability in storm tracks and consequent precipitation defines wet (the Pacific Northwest, the Canadian Rockies, and the Alaskan panhandle) and dry (parts of Washington, Oregon, Idaho, California, Nevada, Utah, Arizona, Colorado, and New Mexico) precipitation loci in western North America (Figure 1). Although there is some overlap between the wet and dry loci due to interannual variability and orographic influences, they are relatively persistent and clearly defined features of western North American precipitation.

Most of the western United States falls in the dry locus defined above, and water resources in this region are delicately balanced between variable and somewhat unpredictable supply and ever-increasing demand. From 1990 to 2000, population in the western United States increased by an average of 19.7% and the four fastest growing states were Nevada (66%), Arizona (40%), Colorado (31%), and Utah (30%) (Perry and Mackun 2001). This regional population growth, coupled with national growth of 13.2%, can be expected to increase recreational, residential, and agricultural demand for water in the west. While the growth in population and, consequently, demand for water resources is relatively easy to quantify, future changes in supply that may occur as a result of global climate change are not as straightforward.

In 2004, Sewall and Sloan presented general circulation modeling (GCM) results that suggested that annual precipitation in the western United States could be
Figure 1. Observed precipitation patterns over western North America from the CMAP project (cm). Regions and seasons are based on those areas that are relatively winter wet and summer dry and source precipitation primarily from Pacific storms. (a) Dry season average (May–October), (b) wet season average (November–April), and (c) annual average. The white dotted line encircles a region that is generally wet in all seasons and relatively wet annually (indicated by “W”; the wet locus). The solid white line encircles a region that is seasonally wet/dry and relatively dry annually (indicated by “D”; the dry locus).
negatively influenced by a decline in the ice cover of the Arctic Ocean. That study investigated the direct climate impact (all other aspects of the climate system, including atmospheric CO₂ concentrations, were held constant) of a reduction in Arctic sea ice cover of up to 50%. That study was similar to other work investigating the impact of prescribed changes in Arctic ice cover on climate in an atmospheric GCM (Rind et al. 1995; Alexander et al. 2004; Deser et al. 2004; Magnusdottir et al. 2004). However, unlike Deser et al. (Deser et al. 2004) and Magnusdottir et al. (Magnusdottir et al. 2004), Sewall and Sloan (Sewall and Sloan 2004) investigated the influence of changes in Arctic sea ice concentration, which Alexander et al. (Alexander et al. 2004) found to have a greater impact on climate than Arctic sea ice extent. In addition, much of that concurrent and subsequent work focused on changes in the North Atlantic region rather than impacts on western North America (Alexander et al. 2004; Deser et al. 2004; Magnusdottir et al. 2004; Sewall and Sloan 2004). While the sensitivity study of Sewall and Sloan (Sewall and Sloan 2004) provided a clear picture of linkages between changing Arctic surface conditions and precipitation patterns in western North America, it did not address the dynamic response of the fully interactive climate system to the driving forcing behind Arctic ice reduction (i.e., increased atmospheric greenhouse gas concentrations and the associated warming temperatures). In addition, there is the possibility that this potentially important result of Sewall and Sloan (Sewall and Sloan 2004) is either model or resolution dependent. In this study, I bolster the findings of Sewall and Sloan (Sewall and Sloan 2004) by 1) repeating the original Sewall and Sloan (Sewall and Sloan 2004) experiment in an updated version of the National Center for Atmospheric Research’s (NCAR) Community Atmosphere Model v.3 (CAM3) (Collins et al. 2005a) and 2) analyzing the results from multiple, fully coupled, Earth system models under increasing atmospheric CO₂ concentrations at the time of CO₂ quadrupling (4× CO₂).

2. Methods

Sewall and Sloan (Sewall and Sloan 2004) used the NCAR Community Climate Model version 3.6.6 [CCM3.6.6 (Boville et al. 2001)] driven by specified sea surface temperature (SST) and sea ice cover fields to investigate the climate impacts of reduced Arctic sea ice cover. They conducted a future climate scenario (FARC) where Arctic sea ice cover was reduced by up to 50% and a control scenario (MARC) with modern Arctic sea ice cover. Both FARC and MARC were integrated at T31 spectral resolution (~3.75° latitude × 3.75° longitude) with a vertical resolution of 18 levels. Greenhouse gas concentrations were specified at constant present values. Here, I repeat the FARC and MARC experiments of Sewall and Sloan (Sewall and Sloan 2004) with the updated NCAR CAM3. These new experiments are identical to FARC and MARC with two exceptions: 1) the use of CAM3 and 2) increased horizontal (T42; ~2.8° latitude × 2.8° longitude) and vertical (26 levels) resolution. I interpolated the driving sea ice cover and SST conditions used in FARC and MARC to the higher, T42 resolution and integrated the new experiments for 30 yr and averaged the final 20 yr for analysis [this updated sensitivity study is hereafter designated “reduced ice” (REDICE)].

While the REDICE sensitivity study tests the robustness of the climate response
to reduced Arctic sea ice cover under the updated physics and increased resolution of CAM3, REDICE continues to address only the climate sensitivity to reduced Arctic sea ice cover; it sheds no light on whether the modeled climate impacts will occur in a more realistic, coupled system where reduced Arctic sea ice cover is a consequence of other climatic forcing [most likely warming due to increasing greenhouse gas concentrations (Hassol 2004)]. To address that question, I analyzed output from seven fully coupled Earth system models driven by a quadrupling of atmospheric CO₂ concentrations (Table 1).

The seven models are all participants in the Intergovernmental Panel on Climate Change Fourth Assessment. As such, all models were run under conditions of CO₂ increases of 1% yr⁻¹ until atmospheric CO₂ concentrations reached quadrupling. [Actual CO₂ concentrations vary from quadrupling of preindustrial levels (∼1120 ppmv CO₂) to quadrupling of present values (∼1400 ppmv CO₂).] Once a quadrupled value was reached (at ∼year 140 of each simulation), the atmospheric CO₂ concentration was fixed and most models were run for another 150 yr. With two exceptions, the results I present here are comparisons between 50-yr averages at the time of CO₂ quadrupling (simulation year 140 ± 25 yr) and the final 50 yr of the twentieth century [1950–99; the average of this time period is hereafter indicated as (1950–99)]. In the case of the NCAR Community Climate System Model (NCAR_CCSMv3) and the IPSL_CM4, output was not available for more than 10 yr post-quadrupling of CO₂, and, consequently, the results presented represent 20-yr averages at the time of CO₂ quadrupling (simulation year 140 ± 10 yr).

In addition to comparisons between conditions at 4× CO₂ and the twentieth century, for the NCAR_CCSMv3, I also analyzed 20 yr at the time of CO₂ doubling (2× CO₂; ∼600 ppmv CO₂ at year 70 of the simulation) and compared these results to the final 50 yr of the twentieth century. Comparison of climate and ice cover changes in the NCAR_CCSMv3 at 2× CO₂ and 4× CO₂ gives an additional assessment of the climate impact of a progressively declining Arctic sea ice cover.

In the case of the CAM3 sensitivity study (REDICE), I analyzed the variables and seasons presented in Sewall and Sloan (Sewall and Sloan 2004) for the sake of continuity. Because of the limited number of output variables available for the fully coupled CO₂ forcing experiments, I analyzed only sea ice cover and precipitation. In the case of the fully coupled models I expanded my analyses to cover the entire wet (winter) season (November–April) rather than just December, January, and February as presented for REDICE; the November–April period encompasses not only the entire period when dry locus precipitation is most intense in western North America but also the entire winter ice season when Arctic ice anomalies are likely to have the greatest climatic impact (Rind et al. 1995).

### 3. Results and analyses

In all models, the actual (versus differenced) precipitation patterns over western North America (not shown) resemble those in observations (Figure 1) with a dry locus over central and southern California, the Great Basin, northern Mexico, the American Southwest, and the Intermountain West and a wet locus along the coast...
Table 1. Reference information for models and experiments and summary of results. In the summary of results, “wet locus precipitation” and “dry locus precipitation” refer to those regions outlined in white in Figure 1. Changes in precipitation and ice cover are calculated as the difference between modeled quantities at 4x CO₂ and the average for the period 1950–99 in each model’s control run.

<table>
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<th>Designator</th>
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<th>Model</th>
<th>Reference</th>
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<th>Max dry locus winter precipitation decrease</th>
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in the Pacific Northwest, the Canadian Rockies, and Alaska. This general precipitation pattern is visible in all control and reduced Arctic sea ice cover/increased CO₂ experiments. The boundaries of the loci are, however, slightly variable between models. In addition, in all reduced Arctic sea ice cover/increased CO₂ experiments, this pattern is enhanced (although magnitudes vary) with a wetter and expanded wet locus and a dryer and more expansive dry locus. In addition to these wet/dry changes in western North America, the increased CO₂ cases show other significant precipitation anomalies; however, given the scope of this work, all of the precipitation results I document below occur in either the wet or dry loci outlined above and are statistically significant at the 95% confidence interval by Student’s t test (Chervin and Schneider 1976). A summary of the results is presented in Table 1.

3.1. Sensitivity to an imposed reduction in Arctic sea ice in the NCAR CAM3

The results of REDICE corroborate the findings of Sewall and Sloan (Sewall and Sloan 2004). December–February (DJF) averaged precipitation decreases by 5 to 15 cm (up to 50%) over parts of the far western United States (the central, West Coast, and Great Basin) when Arctic sea ice cover decreases (Figure 2a). Mean annual precipitation (MAP) decreases by comparable absolute magnitudes but only over northern California and the percentage change is lower (~25%; Figure 2b). While the western United States experiences a pronounced drying (annual averaged evaporation – precipitation increases by up to 40%; not shown), reducing Arctic sea ice cover makes the Canadian Rockies wetter. DJF average precipitation increases by 10 to 15 cm (up to 20%; Figure 2a), although this winter increase does not have a significant impact on MAP (Figure 2b).

This combination of dryer conditions in the western United States and wetter conditions in the Canadian Rockies compares well in both pattern and magnitude to the results of Sewall and Sloan (Sewall and Sloan 2004) and supports the original findings in that the climate response to an imposed reduction in Arctic sea ice cover has been reproduced in a model with updated physics and at a higher resolution. Not only is the ultimate response to reduced Arctic sea ice cover reproduced in REDICE, the causal chain of events leading to the precipitation shift over western North America is also duplicated.

The decrease in Arctic sea ice cover, particularly in DJF, perturbs the planetary wave pattern and is associated with an increase in 500-mb geopotential height of up to 70 m off the west coast of North America (Figure 3a). Increased 500-mb geopotential height in this region serves to divert winter storms northward away from the western United States and into western Canada and southern Alaska. This shift in storm activity can be seen as a slight decrease in eddy kinetic energy (10 m² s⁻²; Figure 3b) off the west coast of the United States and an increase into Alaska (up to 10 m² s⁻²; Figure 3b). The storm-track shift is also obvious in meridional heat transport, which decreases up to 5 K m s⁻¹ × 100 (Figure 3c) off the West Coast of the United States and increases to the north. The migration of winter storms away from the western United States results in the up to 50% (25%) decrease in DJF precipitation (MAP) that this region experiences when Arctic sea
Figure 2. Precipitation differences over western North America (cm) due to an imposed reduction in Arctic sea ice cover in the NCAR CAM3 (REDICE). Shaded values are statistically significant at the 95% confidence level; the remainder of the field is shown as colored contours. (a) DJF average precipitation decreases by up to 50% in the dry locus and increases by up to 20% in the wet locus; (b) annual average precipitation decreases by up to 25% in the dry locus. These precipitation responses are similar to those seen in a previous version of the NCAR atmospheric model (Sewall and Sloan 2004).
Figure 3. Differences in DJF averaged atmospheric quantities due to an imposed reduction in Arctic sea ice cover in the NCAR CAM3 (REDICE). Shaded values are statistically significant at the 95% confidence level, and the remainder of the field is shown as colored contours. (a) The 500-mb geopotential height (m) increases by up to 70 m off the west coast of North America. Increased geopotential height deflects storms away from the dry locus and north into the wet locus. Shifts in storm activity are represented by changes in (b) 850-mb eddy kinetic energy (m$^2$ s$^{-2}$) and (c) 850-mb meridional heat transport (K m s$^{-1}$ x 100). These changes are similar to those seen in a previous version of the NCAR atmospheric model (Sewall and Sloan 2004).
ice cover is reduced and is also responsible for the up to 20% increase in DJF precipitation in the Canadian Rockies.

While the reproduction of the Sewall and Sloan (Sewall and Sloan 2004) result in an updated and higher-resolution version of the NCAR atmospheric GCM serves to corroborate the climate response to an imposed reduction in Arctic sea ice cover, it continues to beg the question of whether this precipitation shift is a robust feature of the dynamic climate system. To address that question, I turn now to results from the fully coupled NCAR_CCSMv3.

3.2. The coupled response to dynamically reduced Arctic sea ice in the NCAR_CCSMv3

In the coupled NCAR_CCSMv3, winter Arctic sea ice cover is substantially reduced [50%–90% less than (1950–99) over most of the central Arctic; Figure 4a] at the time of CO$_2$ quadrupling. Correspondingly, winter precipitation decreases by 5 to 20 cm (up to 50%) over southern and central California, Arizona, and parts of Nevada, Utah, Colorado, and New Mexico, and increases by 10 to 35 cm (up to 42%) in the Canadian Rockies and the Alaskan panhandle (Figure 5a). As seen in the sensitivity studies, the changes in winter precipitation translate into changes in MAP. At 4× CO$_2$, MAP in the NCAR_CCSMv3 decreases by 5 to 20 cm (up to 20%) over California, Nevada, Utah, and Arizona when compared to (1950–99) (Figure 5b). MAP at 4× CO$_2$ increases by 15 to 50 cm (44%) over the Canadian Rockies and the Alaskan panhandle (Figure 5b).

The pattern and magnitude of these precipitation responses are similar to those seen in the sensitivity studies and are associated with a notable reduction in Arctic sea ice cover. Therefore, it seems reasonable to conclude that, while increased CO$_2$ concentrations are the ultimate driver (by warming climate and reducing Arctic sea ice cover), the precipitation responses over western North America are a direct result of the reduction in Arctic sea ice cover. A further line of evidence supports this conclusion; at the time of CO$_2$ doubling, winter Arctic sea ice cover in the NCAR_CCSMv3 is reduced by 90% in only a very small region and over most of the Arctic basin is very similar to the Arctic sea ice cover of (1950–99) (Figure 4b). Corresponding to this minor reduction in Arctic sea ice cover at 2× CO$_2$, winter precipitation over western North America shows a much smaller difference from that of (1950–99) than at the time of CO$_2$ quadrupling, and the MAP changes are both weaker and less geographically extensive than those seen at the time of CO$_2$ quadrupling (Figures 5c,d).

These two lines of evidence (first, the similarity between the precipitation anomalies at 4× CO$_2$ and those in REDICE and their association with a substantial decline in winter Arctic sea ice cover and, second, the lack of significant precipitation anomalies at the time of CO$_2$ doubling and their correlation to a minimal change in winter Arctic sea ice cover) support the findings of both Sewall and Sloan (Sewall and Sloan 2004) and REDICE—reducing Arctic sea ice cover shifts precipitation patterns over western North America. Furthermore, the reproduction of this result in a fully coupled climate model at still higher resolution (T85, ~1.4° latitude × 1.4° longitude) under CO$_2$ forcing indicates that this is a reasonably robust climate response and not unique to highly controlled sensitivity experiments.
Figure 4. Winter (November–April) average Arctic sea ice concentration differences (%) due to increasing atmospheric CO₂ concentrations in the NCAR CCSMv3. Differences are between 20-yr averages at (a) 4x CO₂ and (b) 2x CO₂, and (1950–99) Arctic sea ice cover at 2x CO₂ is very similar to (1950–99) while Arctic sea ice cover at 4x CO₂ shows substantial differences from the twentieth century.
To further establish this result as a robust response of the climate system to declining Arctic sea ice cover (which, in these experiments, is ultimately attributable to increased atmospheric CO$_2$ concentrations), I turn now to results from the six other coupled climate system models.

Figure 5. Precipitation differences (cm) over western North America due to increasing atmospheric CO$_2$ in the NCAR_CCSMv3. Differences are between 20-yr-averaged quantities for (a) winter (November-April) average at 4× CO$_2$, (b) annual average at 4× CO$_2$, (c) winter average at 2× CO$_2$, and (d) annual average at 2× CO$_2$ and (1950–99). Shaded values are statistically significant at the 95% confidence level, and the remainder of the field is shown as colored contours. The precipitation changes at (a), (b) 4× CO$_2$ are associated with a substantial decline in Arctic sea ice cover (Figure 4) and their pattern is similar to that seen in sensitivity studies with reduced Arctic sea ice cover (Figure 2); wet locus precipitation increases by up to 44% annually and dry locus precipitation decreases up to 20% annually. Precipitation changes at (c), (d) 2× CO$_2$ are much smaller than those at 4× CO$_2$ and are associated with a much smaller decline in Arctic sea ice cover (Figure 4).
3.3. Response in six other coupled models to a dynamic reduction in Arctic sea ice

3.3.1. CCCMA_CGCM3.1

At the time of CO$_2$ quadrupling, winter Arctic ice cover in the CCCMA_CGCM3.1 is reduced by 30%–80% in parts of the Greenland, Iceland, and Norwegian (GIN) Seas and the Barents Sea (Figure 6a)—much the same region where the largest ice anomalies were specified in Sewall and Sloan (Sewall and Sloan 2004) and REDICE and also the region where observed ice anomalies were applied in Deser et al. (Deser et al. 2004), Magnusdottir et al. (Magnusdottir et al. 2004), and Alexander et al. (Alexander et al. 2004). In response, winter precipitation in the CCCMA_CGCM3.1 at 4× CO$_2$ is 5–10 cm less (up to 50%) than that of (1950–99) over southern California (Figure 7a). Winter precipitation increases over that of (1950–99) by 10 to 35 cm (up to 40%) over the Pacific Northwest, the Canadian Rockies, and into southern Alaska (Figure 7a). At 4× CO$_2$, the CCCMA_CGCM3.1 has 5–10 cm less annual precipitation (up to 30%) over southern California than it did in (1950–99) (Figure 8a). MAP in the CCCMA_CGCM3.1 increases by 15 to 50 cm (up to 70%) over the central Canadian Rockies and northwestern Washington at the time of CO$_2$ quadrupling (Figure 8a).

3.3.2. GISS_ER

GISS_ER has one of the smallest sea ice decreases at the time of CO$_2$ quadrupling; Arctic sea ice cover declines by 40%–80% in parts of the GIN Seas and 20%–40% in the Bering Sea (Figure 6b). These areas of decline are, once again, similar in location to those specified in REDICE and other previous work (Alexander et al. 2004; Deser et al. 2004; Magnusdottir et al. 2004; Sewall and Sloan 2004). Although the area of ice decline is limited, the precipitation response in the GISS_ER is still similar to that seen in the two previous models. At the time of CO$_2$ quadrupling, winter precipitation in the GISS_ER decreases by 10 to 20 cm (up to 30%) over central and southern California compared to winter precipitation in (1950–99) (Figure 7b). Unlike the NCAR_CCSMv3 and the CCCMA_CGCM3.1, the GISS_ER does not show an increase in winter precipitation over the Canadian Rockies but does show an increase of 5–20 cm (up to 50%) over western Alaska and northern Washington (Figure 7b). MAP in the GISS_ER at 4× CO$_2$ decreases by 5 to 20 cm (up to 40%) over southern and central California and the American Southwest compared to (1950–99) values (Figure 8b). MAP in the GISS_ER increases by 10 to 30 cm (up to 60%) over northern Washington and western Alaska (Figure 8b).

3.3.3 MIROC3.2_MEDRES

MIROC3.2_MEDRES has the second largest area of Arctic sea ice cover decline of all the models analyzed; winter Arctic sea ice cover decreases by 80%–90% over most of the Barents and Kara Seas by the time of CO$_2$ quadrupling and by 20%–50% over most of the rest of the Arctic basin (Figure 6c). Like the three previous models, this decline in Arctic sea ice cover is associated with a decrease in winter precipitation over California, parts of the Great Basin, and the American Southwest of 5 to 15 cm (up to 50%) and an increase in winter precipitation of 10
Figure 6. Winter (November–April) average Arctic sea ice concentration differences (%) due to increasing atmospheric CO$_2$ in six coupled Earth system models. Differences are between 50-yr averages at 4× CO$_2$ (except as noted) and (1950–99). The six models are (a) CCCMA_CGCM3.1, (b) GISS_ER, (c) MIROC3.2_MEDRES, (d) INMCM3.0, (e) MRI_CGCM2.3.2a, and (f) IPSL_CM4 (20-yr average at 4× CO$_2$). See Table 1 for model details. All six models exhibit a decrease in Arctic sea ice cover at 4× CO$_2$, but the magnitude and area vary between a high in the (c) MIROC3.2_MEDRES and a low in the (d) GISS_ER. None of these six models exhibits as much of a decline in Arctic sea ice cover as the NCAR_CCSMv3 does at 4× CO$_2$ (Figure 4a).
Figure 7. Winter (November–April) averaged precipitation differences (cm) over western North America due to increasing atmospheric CO₂ concentrations in six fully coupled Earth system models. Shaded values are statistically significant at the 95% confidence level, and the remainder of the field is shown as colored contours. Differences are between 50-yr averages at 4x CO₂ (except as noted) and (1950–99). The six models are (a) CCCMA.CGCM3.1, (b) GISS.ER, (c) MIROC3.2.MEDRES, (d) INMCM3.0, (e) MRI.CGCM2.3.2a, and (f) IPSL.CM4 (20-yr average at 4x CO₂). See Table 1 for model details. Although magnitude and location of the precipitation response varies between models (as do changes in Arctic sea ice cover (Figure 6)), five of the six models (INMCM3.0 excepted) show a decrease in precipitation in the dry locus (six-model average is a 38% decrease) and an increase in precipitation in the wet locus (six-model average is a 41% increase). These responses are broadly similar to those seen in sensitivity studies with reduced Arctic sea ice cover (Figure 2a).
Figure 8. Annual average precipitation differences (cm) over western North America due to increasing atmospheric CO₂ concentrations in six fully coupled Earth system models. Shaded values are statistically significant at the 95% confidence level, and the remainder of the field is shown as colored contours. Differences are between 50-yr averages at 4×CO₂ (except as noted) and (1950–99). The six models are (a) CCCMA(CGCM3.1), (b) GISS_ER, (c) MIROC3.2_MEDRES, (d) INMCM3.0, (e) MRI_CGCM2.3.2a, and (f) IPSL_CM4 (20-yr average at 4×CO₂). See Table 1 for model details. Although magnitude and location of the precipitation response varies somewhat between models (as do the DJF precipitation (Figure 7) and Arctic sea ice cover (Figure 6) responses), annual precipitation changes in all six models 1) are similar to those seen in DJF (Figure 7) and 2) show a decrease in dry locus precipitation of up to 36% (six-model average) and an increase in wet locus precipitation of up to 44% (six-model average). These responses are broadly similar to those seen in sensitivity studies with reduced Arctic sea ice cover (Figure 2b).
to 45 cm (up to 33%) over the Canadian Rockies and the Alaskan panhandle (Figure 7c). MAP in the MIROC3.2_MEDRES at the time of CO$_2$ quadrupling decreases by 5 to 15 cm (up to 30%) over California, the Great Basin, the American Southwest, and into the Rocky Mountains when compared to (1950–99) values (Figure 8c). MAP in the MIROC3.2_MEDRES increases over most of Alaska and the Canadian Rockies by 20 to 50 cm (up to 30%) at 4× CO$_2$ (Figure 8c).

### 3.3.4. INMCM3.0

Winter Arctic sea ice cover in the INMCM3.0 at CO$_2$ quadrupling decreases by 40%–70% in parts of the Barents and Greenland Seas compared to (1950–99) concentrations (Figure 6d). Unlike the previously discussed models, winter precipitation in the INMCM3.0 increases by 5 to 20 cm (up to 30%) over the Pacific Northwest and eastward into the Intermountain West (Figure 7d). Winter precipitation also increases by 5 to 20 cm (up to 30%) in southern Alaska at 4× CO$_2$ (Figure 7d). There is no notable decrease in winter, dry locus precipitation in the INMCM3.0 at 4× CO$_2$ (Figure 7d). MAP responses to CO$_2$ quadrupling and Arctic sea ice cover decline in the INMCM3.0 are similar to the changes in winter precipitation but more extensive and of greater magnitude. MAP increases by 10 to 30 cm (up to 37%) over Alaska, the Canadian Rockies, and northwestern interior Canada (Figure 8d). MAP decreases by 10 to 15 cm (up to 15%) over eastern New Mexico (Figure 8d).

### 3.3.5. MRI_CGCM2.3.2a

In the MRI_CGCM2.3.2a, winter Arctic sea ice cover decreases by 50%–90% in the Barents and Kara Seas and along the east coast of Greenland at CO$_2$ quadrupling (Figure 6e). Winter precipitation in the MRI_CGCM2.3.2a at 4× CO$_2$ increases by 10 to 45 cm (up to 50%) over (1950–99) levels along the west coast of North America from northern California to the Aleutian Islands and decreases by 5 to 10 cm (up to 50%) in southern New Mexico and northwestern Mexico (Figure 7e). MAP shows a similar response to increasing CO$_2$ and declining Arctic sea ice cover with increases of 10–50 cm (up to 30%) along the west coast of North American and decreases of 5–10 cm in southern Arizona and northwestern Mexico (up to 50%; Figure 8e).

### 3.3.6. IPSL_CM4

At CO$_2$ quadrupling, winter Arctic sea ice cover in the IPSL_CM4 has decreased by 30%–40% in the Barents Sea, 50%–60% in the Greenland Sea, and 40%–70% in the Labrador Sea compared to (1950–99) concentrations (Figure 6f). Winter precipitation at CO$_2$ quadrupling increases in western North America by 10 to 45 cm (up to 40%) from northern California to southern Alaska when compared to (1950–99) (Figure 7f). Winter precipitation in the IPSL_CM4 decreases by 5 to 15 cm (up to 50%) in northern Mexico and New Mexico (Figure 7f). MAP at 4× CO$_2$ mirrors the winter changes with increases of 10 to 45 cm (up to 35%) from northern California to the Aleutians compared to (1950–99) (Figure 8f). Decreases in MAP range from 10 to 20 cm (up to 50%) across northern Mexico, New Mexico, and southern Arizona (Figure 8f).
4. Discussion

In all seven coupled models, quadrupling of atmospheric CO$_2$ concentrations results in a reduction in Arctic sea ice cover. In most cases, the ice line and, consequently, the locations of reduction are similar in all models (Figures 4a and 6). The magnitude of the reduction in Arctic sea ice cover is variable, however, with the largest decrease in the NCAR_CCSMv3 (Figure 4a) and the smallest decrease in the GISS_ER (Figure 6b). There is a slight (0.052) but significant ($r^2 = 0.90$) positive correlation between the magnitude of the winter Arctic sea ice cover decline and decreases in winter dry locus precipitation (Figure 9a). Increases in wet locus precipitation show a slightly less significant ($r^2 = 0.88$) negative correlation ($-0.062$) with winter Arctic sea ice decline (Figure 9a). The negative correlation between increased wet locus precipitation and winter Arctic sea ice cover persists in annual averaged precipitation ($-0.18$) but is less significant ($r^2 = 0.68$) (Figure 9b). Decreases in dry locus annual precipitation are slightly ($-0.06$) but significantly ($r^2 = 0.89$) negatively correlated with declining winter Arctic sea ice cover.

Regardless of the absolute magnitude of reduction in Arctic sea ice cover, six of the seven coupled models show a northward shift/enhancement of existing precipitation patterns with wet locus precipitation increasing and dry locus precipitation decreasing (no change in dry locus precipitation for the INMCM3.0; Figures 5a,b, 7, and 8). The lack of a dry locus precipitation change in the INMCM3.0 may be attributable to the fact that this model has no change in the ice cover of the Greenland Sea, a region that Deser et al. (Deser et al. 2004) found storm tracks to be particularly sensitive to and a region in which all the other analyzed models have reduced ice cover. As storm activity and precipitation over western North America are greatest during the winter months, this northward shift/enhancement of the existing precipitation pattern and the similarity between winter and annual precipitation changes lend further support to the hypothesis of shifting storm tracks that is clearly outlined in both Sewall and Sloan (Sewall and Sloan 2004) and REDICE and reinforced by other authors who have also found that changes in winter ice cover of the Arctic Ocean can influence the path and intensity of winter storms (Alexander et al. 2004; Deser et al. 2004; Magnusdottir et al. 2004). While the winter precipitation decreases account for most of the change in dry locus MAP, the positive change in wet locus annual precipitation is larger than the winter anomaly and, therefore, reflects the influence of precipitation increases in the dry season. As the intensification of wet locus precipitation is not as robust in the sensitivity studies with prescribed Arctic ice cover, it is likely that this dry season intensification is due to some other facet of CO$_2$ forcing/climate warming and not a consequence of changing Arctic sea ice cover. In addition, the change in sign of the correlation between declining winter Arctic sea ice cover and declining annual averaged and winter dry locus precipitation (small though the correlation may be) clearly indicates that, while Arctic sea ice cover certainly has significant influence on winter storm tracks in the Northern Hemisphere, factors other than Arctic sea ice cover contribute to annual precipitation changes at the time of CO$_2$ quadrupling; given the accepted impacts of CO$_2$ on climate (e.g., Houghton et al. 2001), this is not surprising.

Although both the boundaries and the magnitude of the changes in the wet and
Figure 9. Correlation between winter (November–April) Arctic sea ice cover decline (x axis) and precipitation changes in the wet (blue) and dry (red) loci in the (a) winter and (b) annual average. Winter precipitation decline in the dry locus is positively (0.052) correlated to declining winter Arctic sea ice cover ($r^2 = 0.90$). Winter precipitation increase in the wet locus is negatively ($-0.062$) correlated to declining winter Arctic sea ice cover ($r^2 = 0.88$). In the annual average, wet locus precipitation increases continue to be negatively correlated to declining winter Arctic sea ice cover ($-0.18$) though the correlation is less significant ($r^2 = 0.68$). Annual average dry locus precipitation switches from a positive to a negative correlation with declining winter Arctic sea ice cover ($-0.061$; $r^2 = 0.89$).
dry loci in western North America vary between models, results from all seven coupled GCMs provide support for the sensitivity study results; as CO₂ increases and Arctic sea ice cover declines, the precipitation regime over western North America will shift and already wet regions will get wetter by ~40% (annual average over seven models) and already dry regions will dry by ~30% (annual average over seven models).

Although all seven coupled models show an enhancement of the existing precipitation pattern over western North America, the exact locations of the wet and dry loci vary slightly from model to model; this is most likely due to various model-specific characteristics (e.g., resolution of the simulation). In an effort to move beyond model-specific results and provide a realistic assessment of where precipitation is likely to increase/decrease, I return to the mean annual and winter averaged precipitation from the Climate Prediction Center (CPC) Merged Analysis of Precipitation [CMAP (Xie and Arkin 1996); Figure 1] and apply the average increase/decrease from the seven coupled models to the locations of observed precipitation loci. In the CMAP precipitation, parts of Washington, Oregon, Idaho, California, Nevada, Utah, Arizona, Colorado, and New Mexico receive 20 cm or less precipitation in the winter (Figure 1b). Based on an average decrease of dry locus winter precipitation of ~40% (seven-model average), winter precipitation over these regions might be expected to decrease by 4–8 cm as CO₂ increases and Arctic sea ice cover declines. Based on an average decrease in dry locus MAP of ~30%, MAP over parts of Washington, Oregon, Idaho, California, Nevada, Utah, Arizona, Colorado, and New Mexico might be expected to decrease by up to 3 cm under declining Arctic sea ice cover, and MAP over the Rocky Mountain Interior might decrease by 3 to 12 cm. Winter precipitation increases of up to 40% might be expected over the coastal Pacific Northwest, the Canadian Rockies, and southern Alaska with winter precipitation totals increasing by 35 to 40 cm. These winter precipitation increases can be expected to contribute to increases in MAP of ~40% (40 cm) centered over the Canadian Rockies and the Alaskan panhandle.

5. Conclusions

Changes in Arctic sea ice cover have the potential to drive changes in midlatitude climate. In this study, I have reinforced the finding that a reduction in Arctic sea ice cover will shift precipitation patterns over western North America by 1) reproducing previous results in an updated, higher-resolution version of the NCAR atmospheric GCM; 2) analyzing results from a still higher resolution, fully coupled version of the NCAR CCSM; and 3) analyzing the results from six additional coupled climate system models.

Reproduction of the original Sewall and Sloan (Sewall and Sloan 2004) result in both the REDICE sensitivity study and the fully coupled NCAR_CCSMv3 suggests that the modeled response is dependent on neither model, resolution, nor experimental design. Rather, a reduction in Arctic sea ice cover is clearly linked to shifts in the precipitation regime over western North America with northern regions getting wetter by up to 44% and southern regions drying by up to 20% (Figures 2a,b and 5a,b).

Although the specific magnitude and location of the precipitation responses are not as clear as those from REDICE or the coupled NCAR_CCSMv3 (which, not
surprisingly, closely resemble those of the stand-alone atmospheric component), all of the results from the coupled models analyzed show a common response to increasing atmospheric CO$_2$ concentrations and the resultant decline in Arctic sea ice cover. All seven coupled models show increases in winter precipitation over northwestern North America, and six of the seven (INMCM3.0 excepted) show decreases to the south (Figures 5a and 7). All of the models exhibit this same pattern in MAP with northwestern North America getting wetter by ~40% and southwestern North America drying by ~30% (Figures 5b and 8). When the magnitudes of these precipitation responses are applied to the locations of precipitation in the CMAP precipitation, they predict that, as Arctic sea ice cover declines, MAP over southern California, the Great Basin, the American Southwest, and parts of the Rocky Mountain west should decrease by 4–8 cm while MAP from northern California to the Aleutians should increase by up to 40 cm. These numbers represent a substantial redistribution of water resources in western North America and, as such, represent a potential climate impact resulting from an observable consequence of climate change—the decline in Arctic ice cover.

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References


