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Atmospheric
Chemistry
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Supplement of

Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous

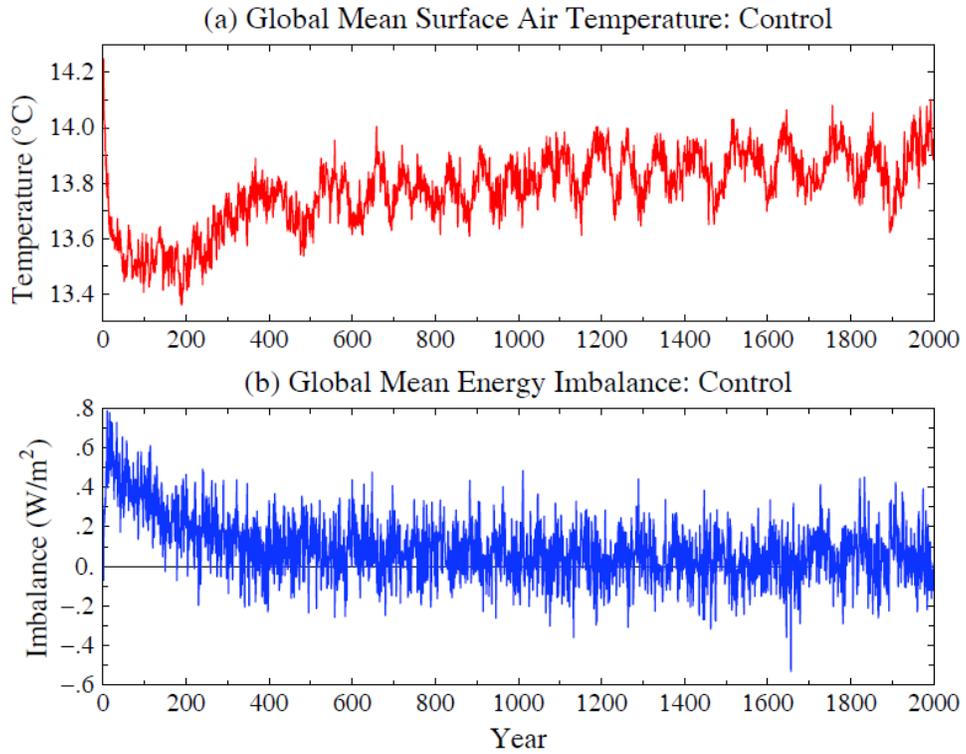
James Hansen et al.

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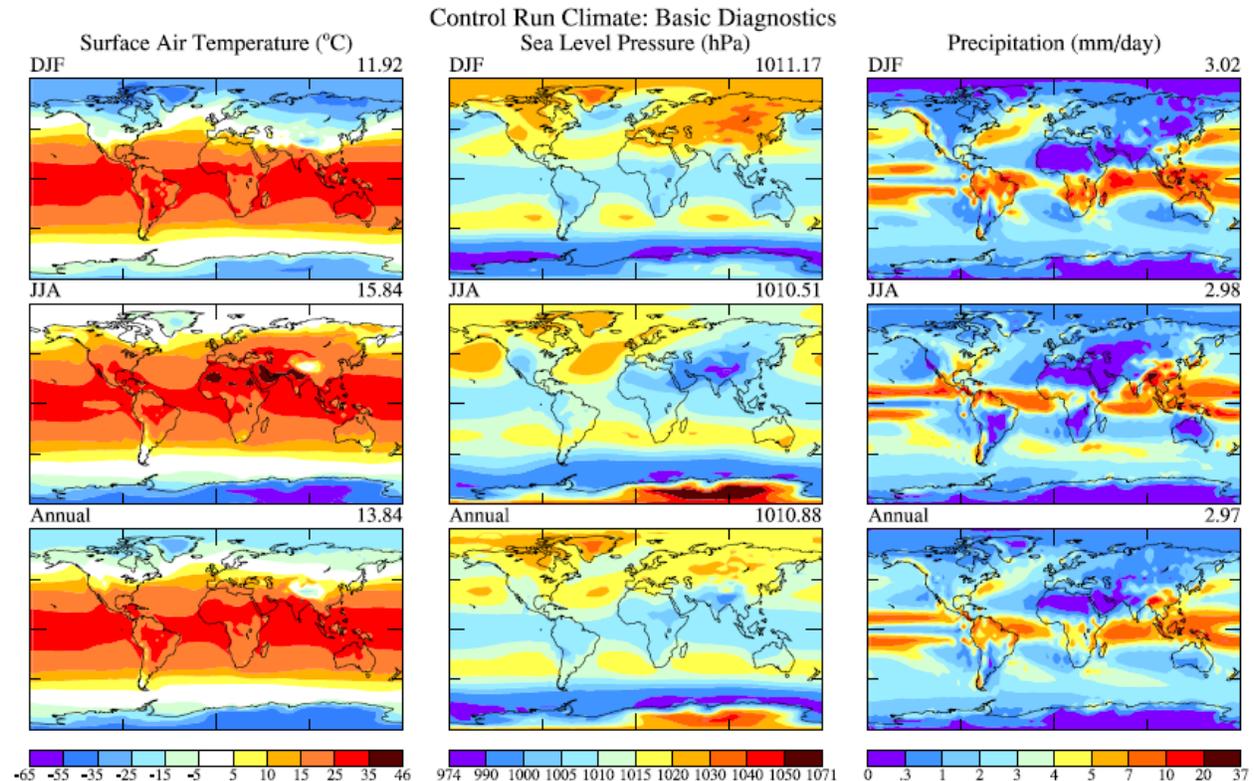
1 **Supplement S1: Figures S1-S24, and Supplements S2 and S3 with Photograph S1**

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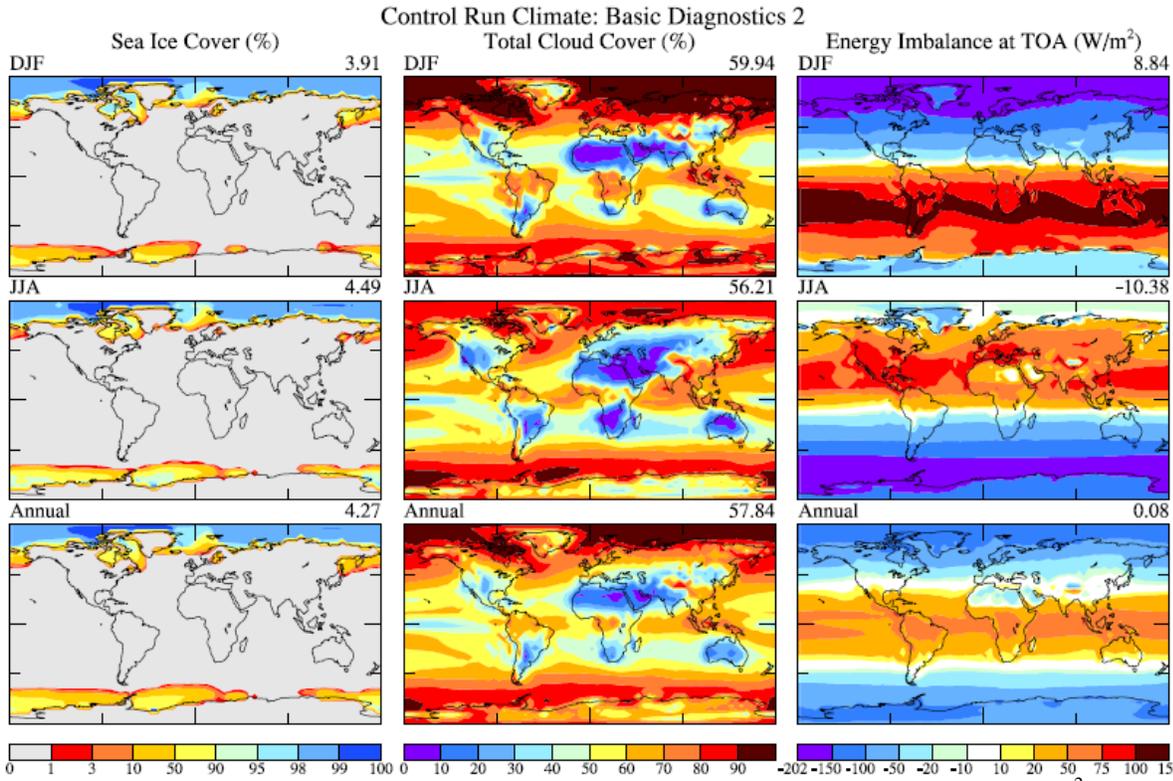
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Fig. S1. Surface air temperature ($^{\circ}\text{C}$) and planetary energy imbalance (W/m^2) in the control run.

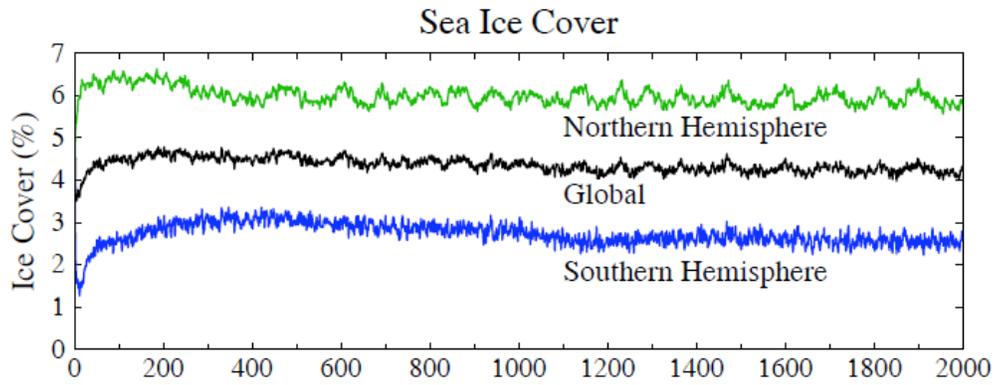


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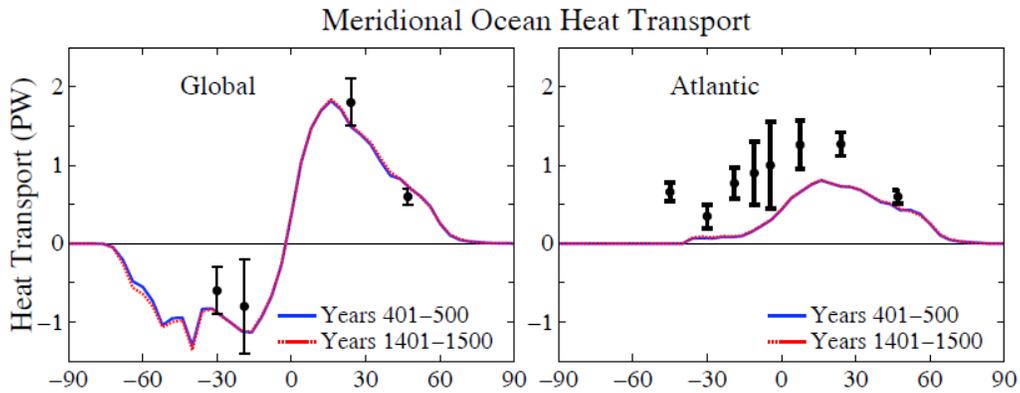
Fig. S2. Surface air temperature ($^{\circ}\text{C}$), sea level pressure (hPa) and precipitation (mm/day) in Dec-Jan-Feb (upper row), JJA (middle row) and annual mean (lower row) in the climate model control run.



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 12 **Fig. S3.** Sea ice cover (%), cloud cover (%) and top of atmosphere energy imbalance (W/m^2) in Dec-Jan-
 13 Feb (upper row), JJA (middle row) and annual mean (lower row) in climate model control run.
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 17 **Fig. S4.** Hemispheric and global sea ice cover (%) versus time in the control run.
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 21 **Fig. S5.** Poleward transport of heat (PW) by the ocean in 5th and 15th centuries of the control run.
 22 Observational estimates (black dots with error bars) are from Ganachaud and Wunsch (2003).

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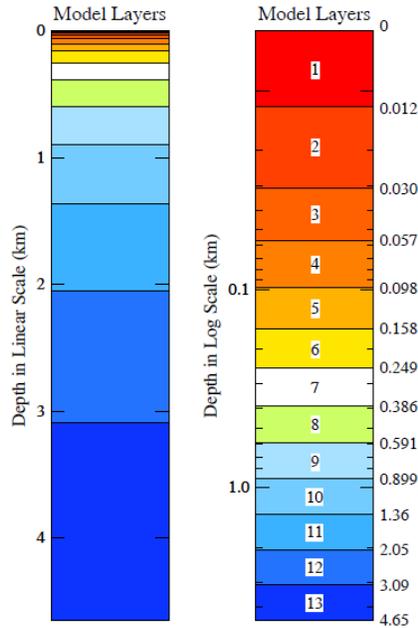
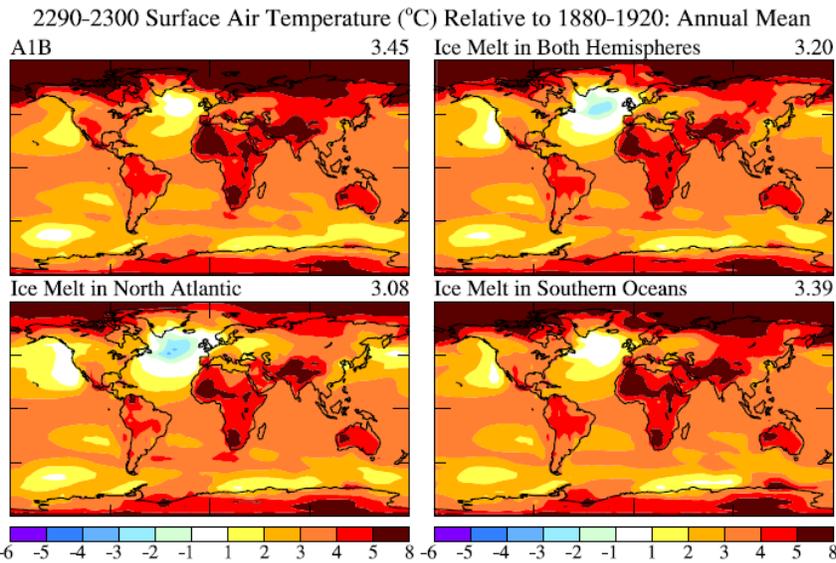
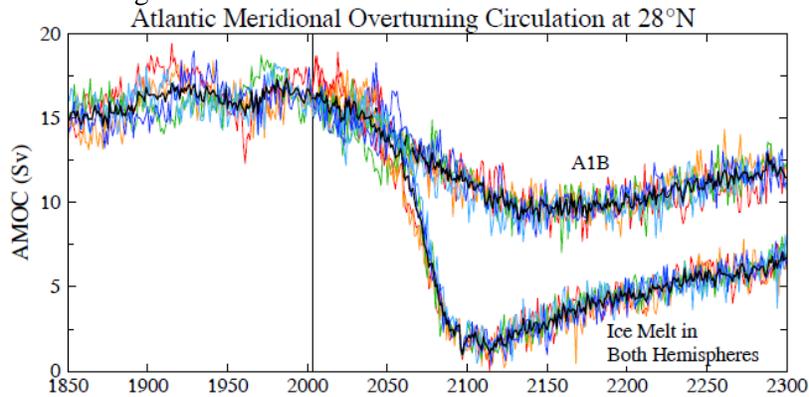


Fig. S6. Layer depths in ocean model.



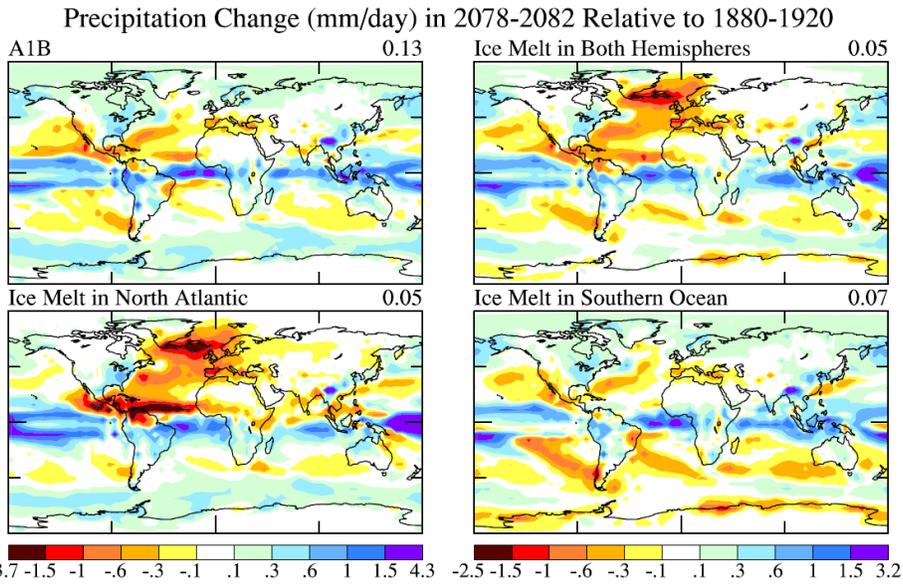
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Fig. S7. Surface air temperature change (°C) relative to 1880-1920 in 2290-2300 for the four climate forcing scenarios shown in Fig. 8.

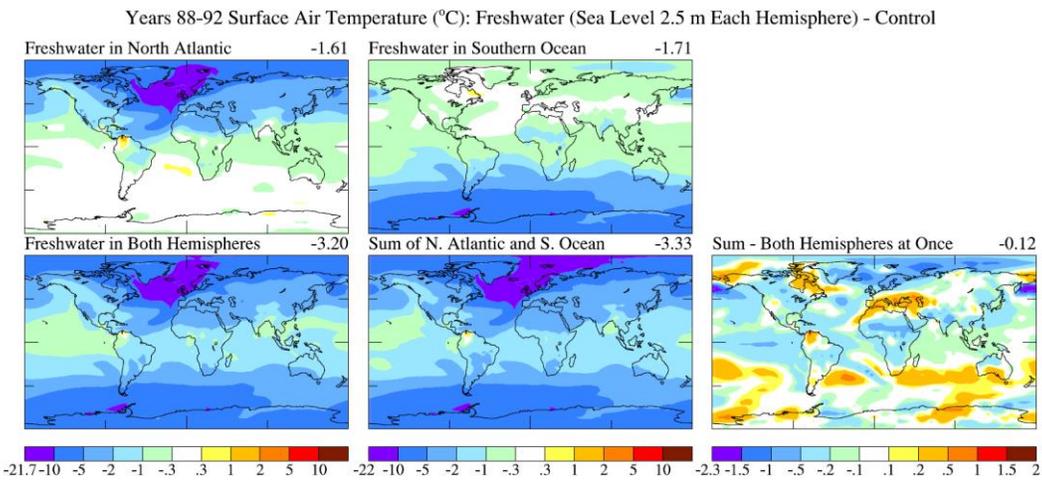


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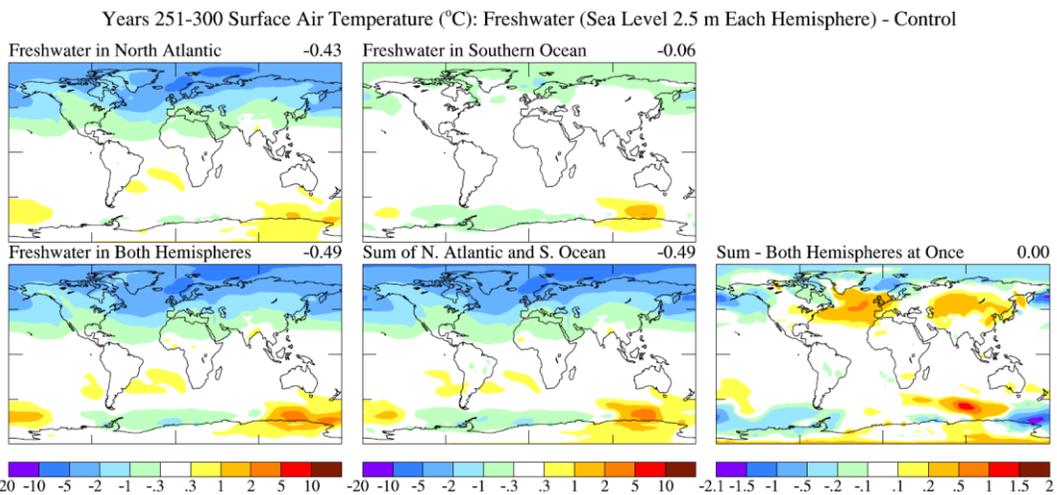
Fig. S8. AMOC strength (Sv) at 28N in five ensemble members and their mean (heavy black line) for the A1B GHG scenario and for that scenario plus ice melt in both hemispheres with 10-year doubling time reaching a maximum 5 m contribution to sea level.



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37 **Fig. S9.** Precipitation change (mm/day) in 2078-2082 for the same four scenarios as in Figs. 6 and 8.

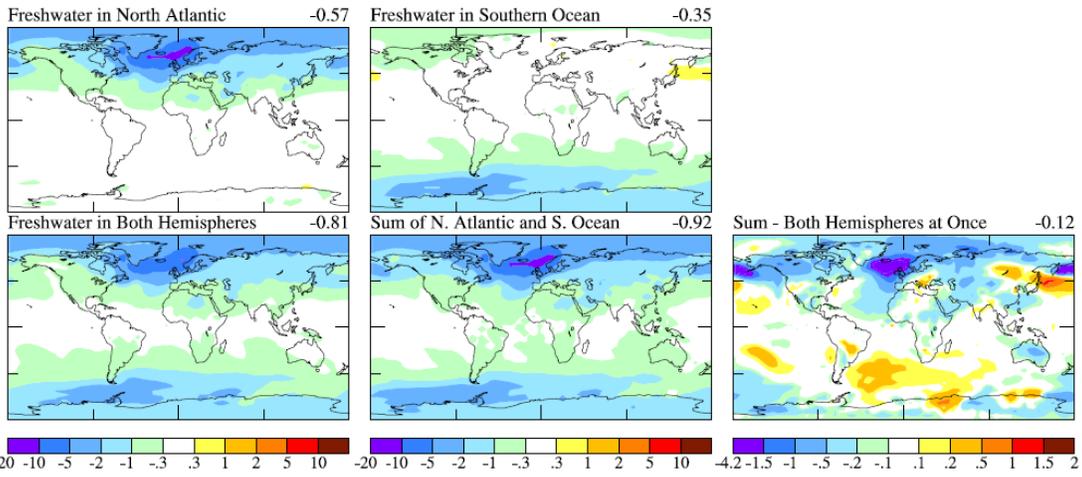


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41 **Fig. S10.** Surface air temperature change (°C) in pure freshwater experiments at time of peak cooling
42 (years 88-92) in three experiments with 2.5 m freshwater in each hemisphere. The sum of responses to
43 the hemispheric forcings is compared with the response to forcing in both hemispheres in the bottom row.



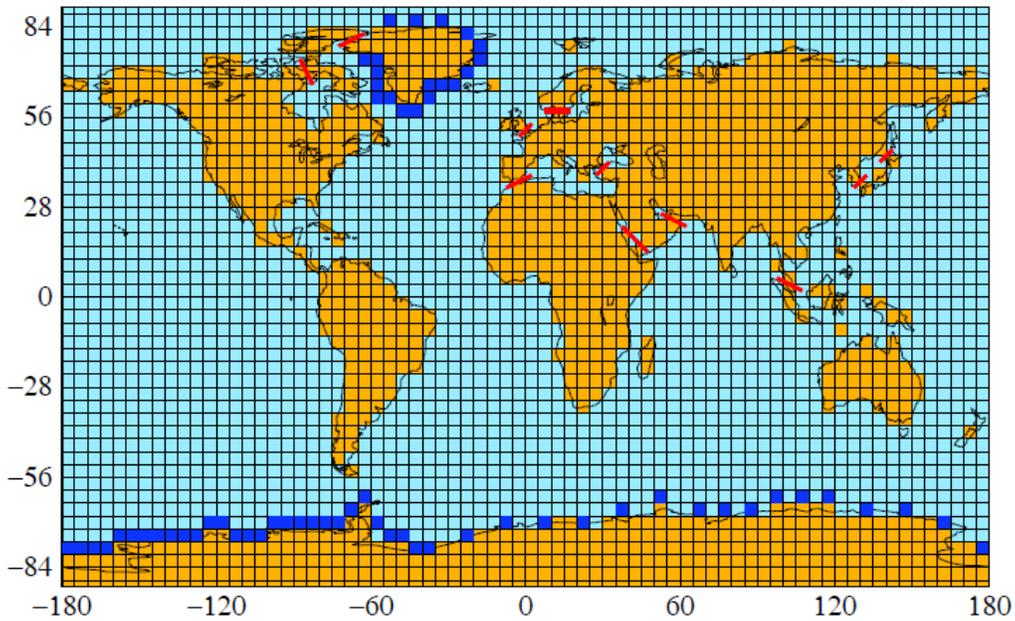
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46 **Fig. S11.** Same as Fig. S10, but for years 251-300.

Years 66-70 Surface Air Temperature (°C): Freshwater (Sea Level 0.5 m Each Hemisphere) - Control



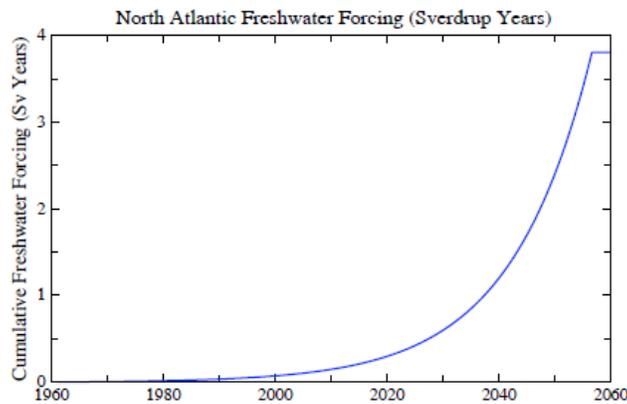
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Fig. S12. Same as Fig. S10, but for hemispheric freshwater inputs of 0.5 m at years 66-70.



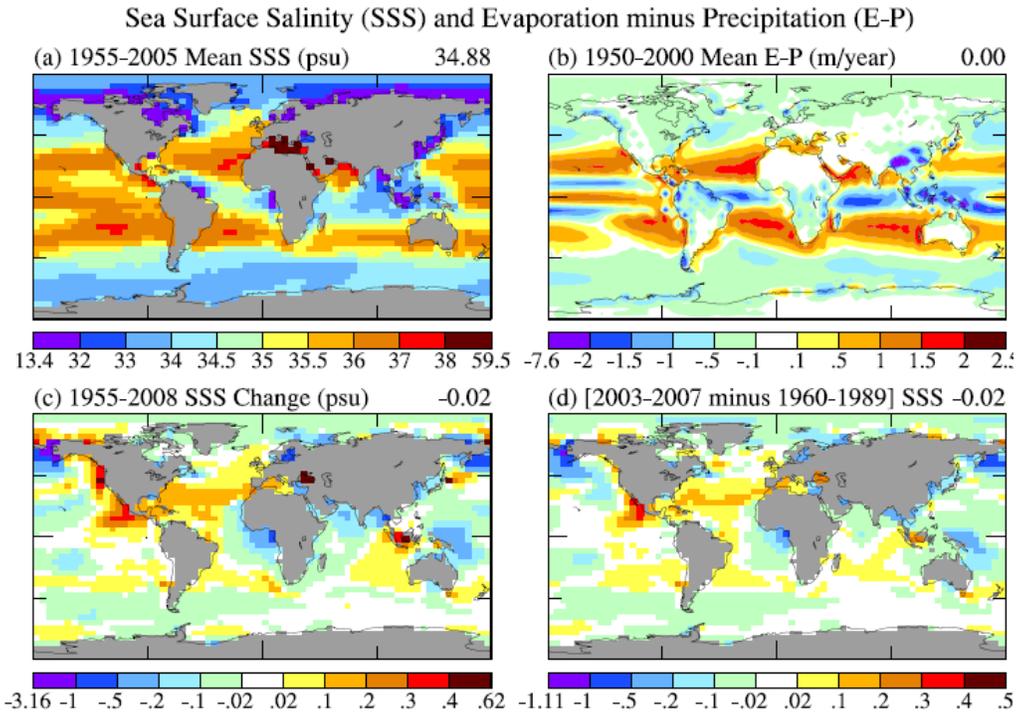
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Fig. S13. Climate model grid. Dark blue gridboxes are locations of freshwater insertion. Red lines mark the 12 straights connecting ocean gridboxes.



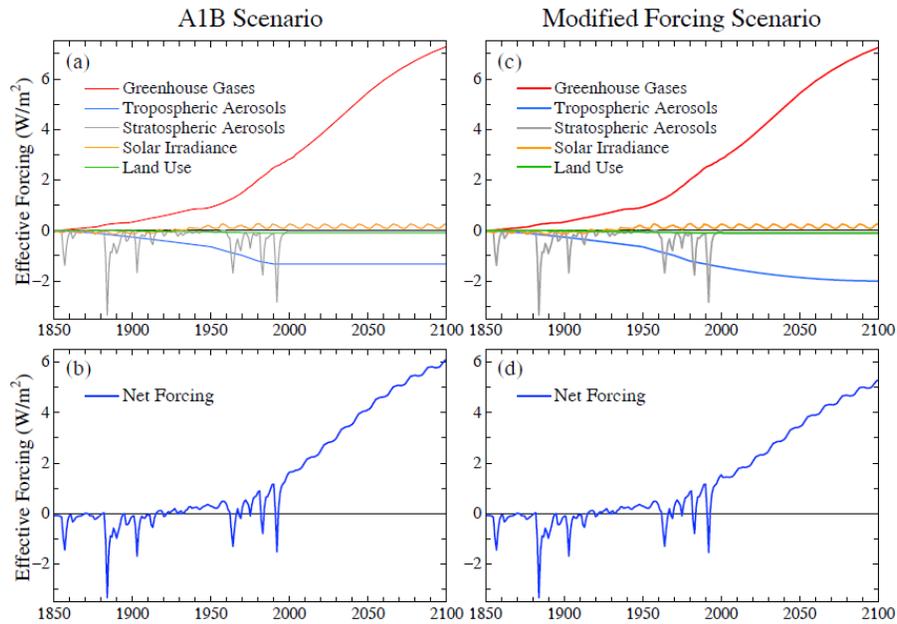
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Fig. S14. Freshwater forcing (Sv years) in the North Atlantic in modified forcings scenario, i.e., the runs that have 360 Gt freshwater injection in 2011 with freshwater at earlier and later times based on 10-year doubling. Freshwater injection onto the Southern Ocean is double the North Atlantic rate.



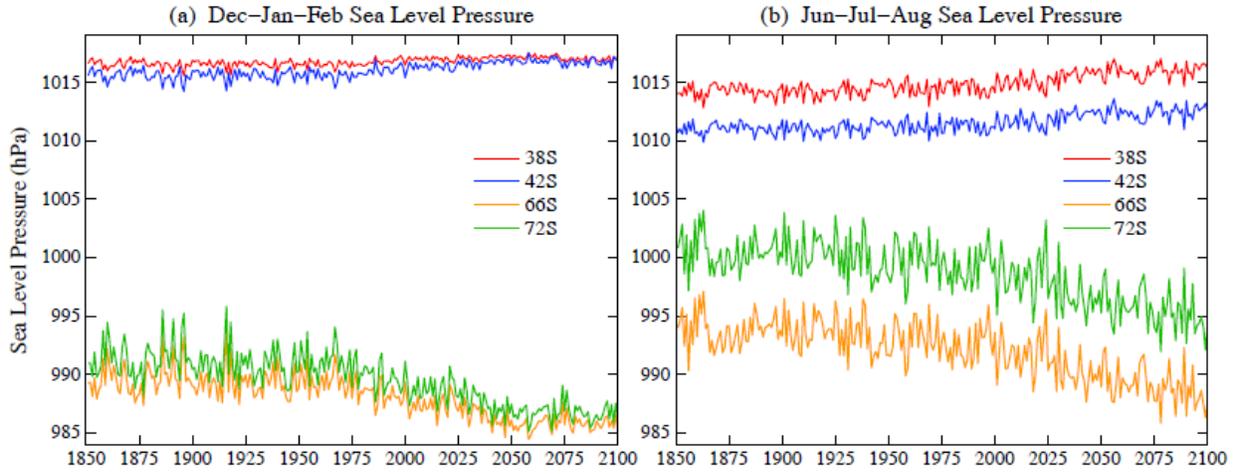
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Fig. S15. (a) Simulated sea surface salinity (psu), (b) evaporation minus precipitation (m/yr), and (c,d) salinity change (m/yr), periods being chosen to allow comparison with observations, as discussed in text.

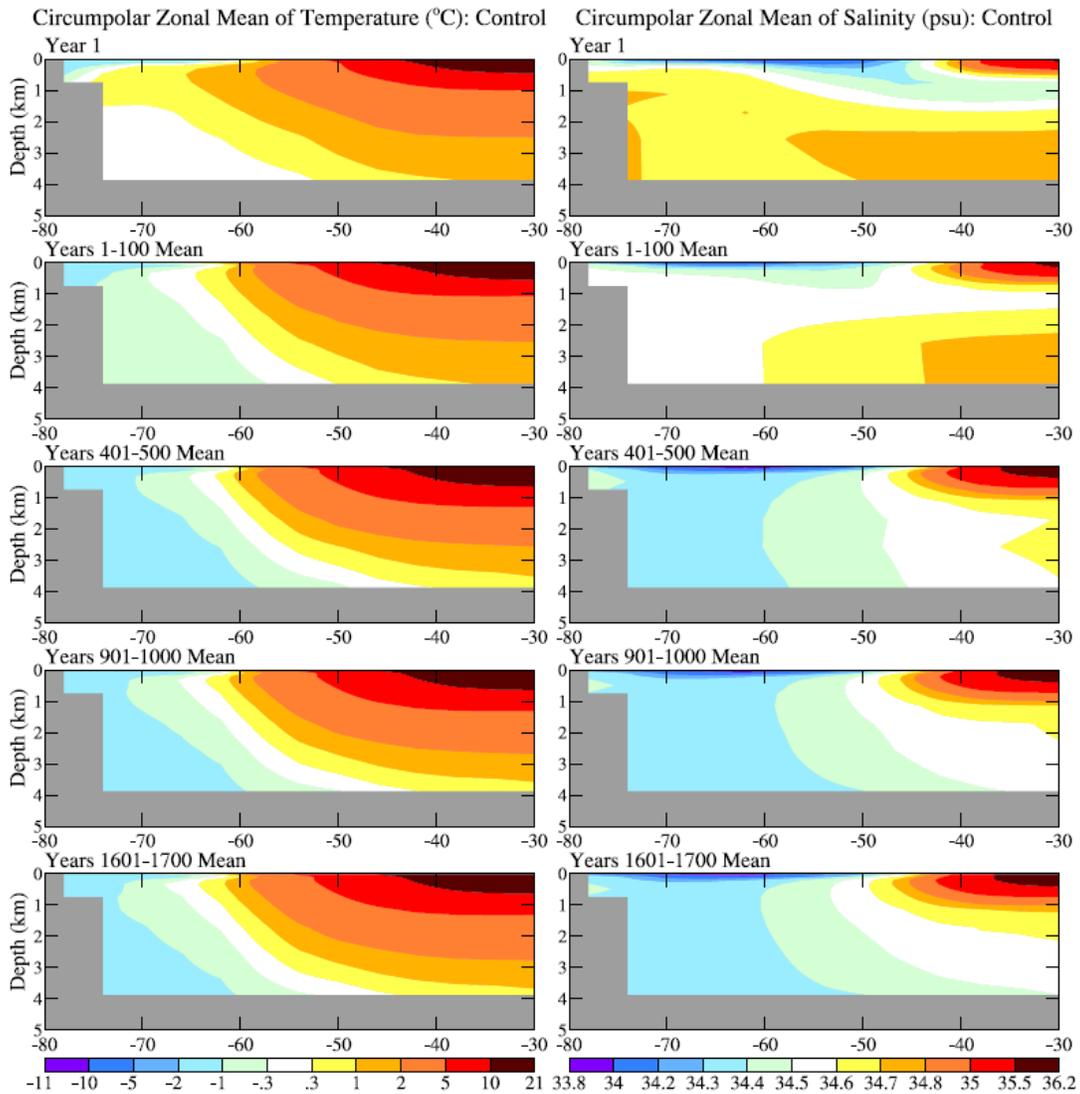


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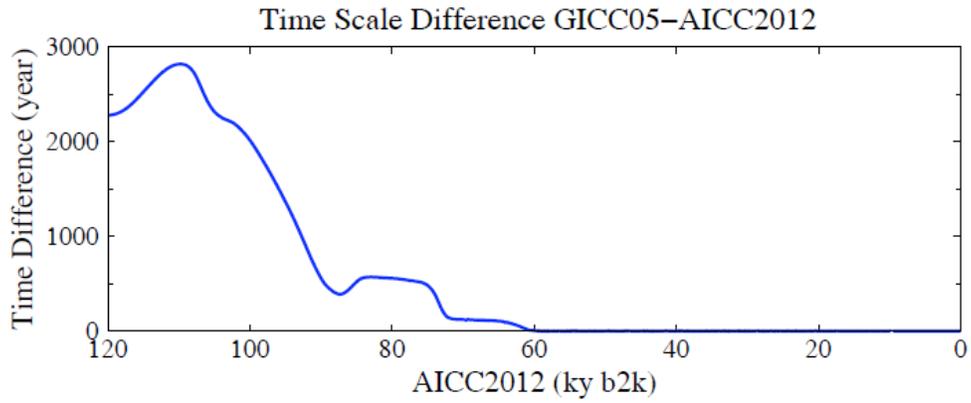
Fig. S16. Effective global climate forcings (W/m^2) in our climate simulations relative to values in 1850.



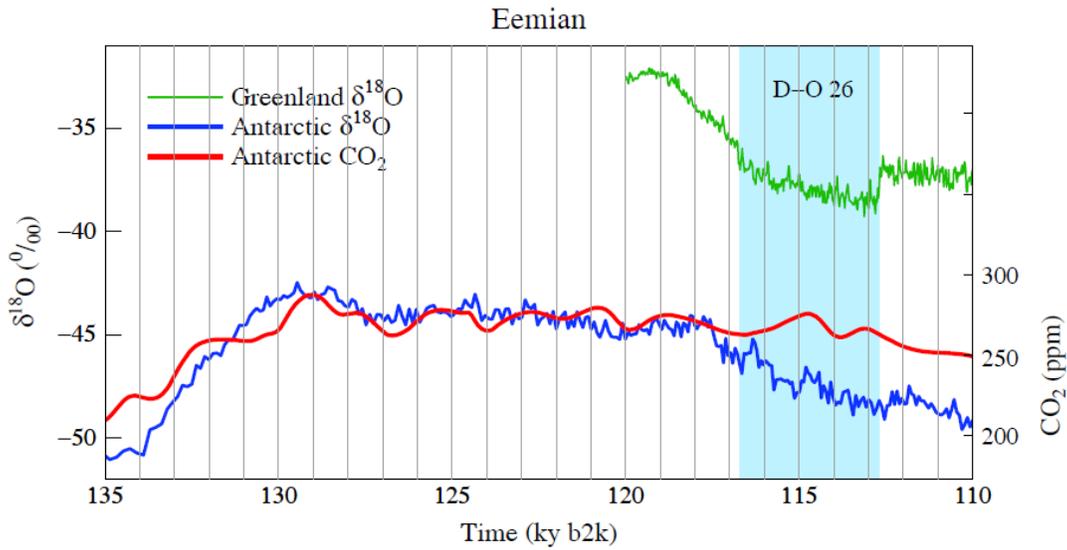
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69 **Fig. S17.** Sea level pressure (hPa) at four latitudes in (a) Dec-Jan-Feb and (b) Jun-Jul-Aug. Model is
70 driven by “modified” forcings including ice melt reaching the equivalent of 1 m sea level by mid-century.
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74 **Fig. S18.** Ocean temperature (°C) and salinity (psu) in the control run.
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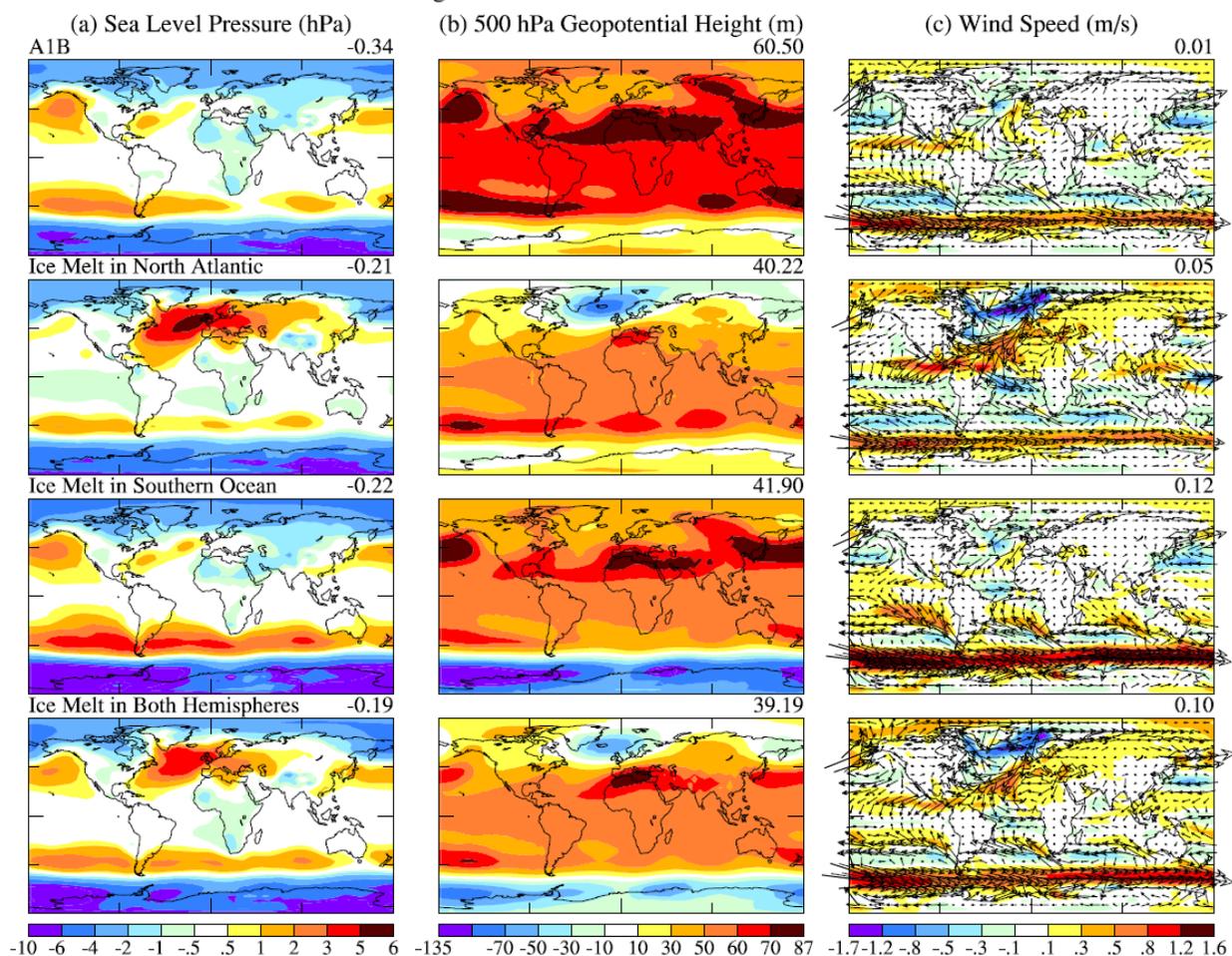


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 78 **Fig. S19.** Difference (years) between the GICC2005modelext and AICC2012 time scales (Bazin et al.,
 79 2013; Veres et al., 2013; Rasmussen et al., 2014; Seierstad et al., 2014).
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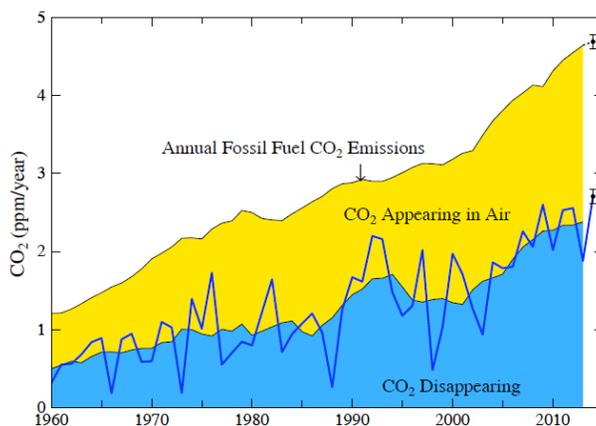
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 83 **Fig. S20.** Expansion of data from Fig. 27b,c. CO₂ increases during D-O 26 lag Antarctic temperature
 84 rises by 1500-2000 years.

Change in 2078-2082 Relative to 1880-1920



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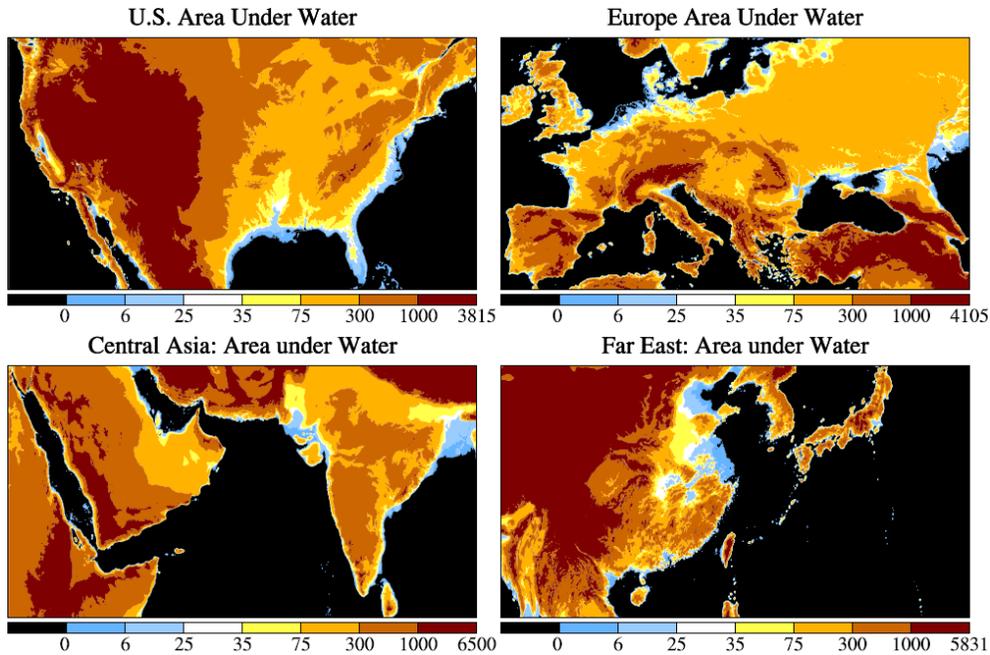
Fig. S21. Change in 2078-2082, relative to 1880-1920, of the annual mean (a) sea level pressure (hPa), (b) 500 hPa geopotential height (m), and (c) wind speed (m/s), for the same four scenarios as in Fig. 6. Numbers in upper right corners are the global mean change.



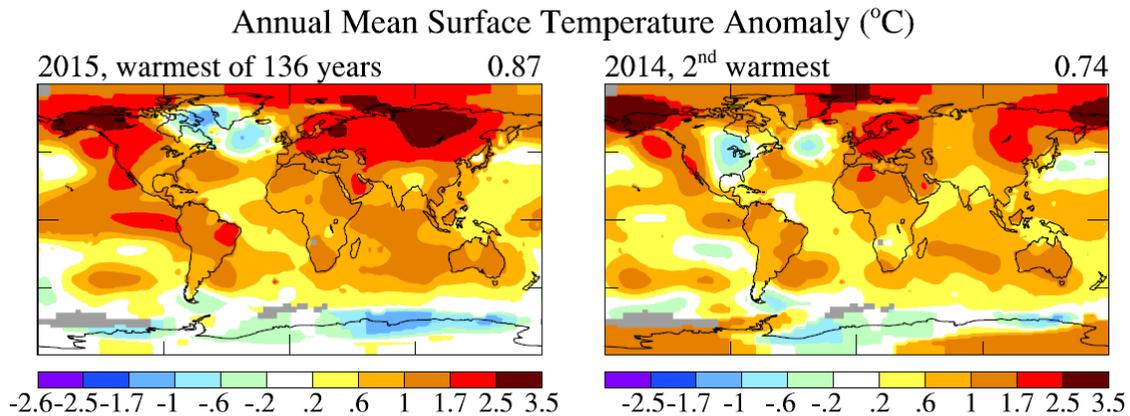
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Fig. S22. Top curve: global fossil fuel CO₂ emissions (ppm/year). Measured CO₂ increase in air is the yellow area. The 7-year mean of CO₂ being absorbed by the ocean, soil and biosphere is blue (5- and 3-year means at the end; dark blue line is annual). 2014 global emissions estimate as 101% ±2% of 2013 emissions. CO₂ emissions from Boden et al. (2013) and atmospheric CO₂ from P. Tans (www.esrl.noaa.gov/gmd/ccgg/trends) and R. Keeling (www.scrippsco2.ucsd.edu/).

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102 **Fig. S23.** Areas (light and dark blue) that nominally would be under water for 6 and 25 m sea level rise.
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106 **Fig. S24.** Observed surface temperature relative to 1951-1980 mean (update of Hansen et al., 2010; maps
107 and other graphs are updated monthly at <http://www.columbia.edu/~mhs119/Temperature/>).

108
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120

121 **Supplement S2: Eemian sea level: Evidence for early double peaks and late peak highstand**

122 In Bermuda, Land et al. (1967) were among the first to recognize both a complex Eemian sea
123 level record, and a much higher peak highstand late in the interglacial. Land et al., (1967, Fig. 5
124 and p.1005) stated: “*Later in the same (MIS 5e) interglacial period the sea rose again, at least to*
125 *+11 m (east of Spencer’s Point).*” Hearty (2002) later surveyed the same Spencer’s Point
126 deposits to a more precise +9.2 m (“+” indicates above today’s sea level).

127 In the Mediterranean, a ‘double 5e’ Eutyrrhenian (Eemian) was a prominent stratigraphic sea
128 level feature described in the 1980s (e.g., Hearty, 1986). Aharon et al. (1980) described a double-
129 5e sea level history from the Papua New Guinea and suggested the higher, late rise was the result
130 of West Antarctic ice collapse. In South Carolina, Hollin and Hearty (1990) similarly
131 documented a double 5e sea level with a rapid late rise several meters higher than the early sea
132 stand. Evidence of a rapid but brief, late rise was further described in Bermuda and the Bahamas
133 in the 1990s (e.g., Hearty and Kindler, 1995). Neumann and Hearty (1996) estimated only a few
134 hundred years to rise to and incise a +6 m notch in the Bahamas. Rapid rise to and brevity at
135 these higher levels is inferred from the prevalence of notches and rubble benches in the
136 Bahamas, in contrast to broad terraces and reefs formed earlier at the +2-3 m level. Additional
137 geological details of these carbonate platform sea level records were contained in a number of
138 interim papers, and summarized in Hearty et al. (2007). Most recently, Godefroid and Kindler
139 (2015) added: “*The MIS 5e record is remarkable. In particular, beach deposits and an intertidal*
140 *notch at +11 m above msl strongly suggest that sea-level peaked at a much higher elevation than*
141 *previously assessed, implying pronounced melting of polar ice.*”

142 In the Bahamas, less than 5% of documented Eemian exposures contain coral reefs, and no
143 Eemian *in situ* exposed reefs are known from Bermuda, so U/Th coral dating is not the primary
144 geochronological method available in these areas. Regardless, many of these sparsely distributed
145 reef deposits in the Bahamas have been U/Th dated (e.g., Chen et al., 1991; Hearty et al., 2007;
146 W. Thompson et al., 2011) and correlated with the diagnostic oolites. The geochronological age
147 of Quaternary deposits is based on 275 whole rock and 507 land snail amino acid racemization
148 (AAR) age estimates from U/Th and ¹⁴C calibrated age models (Hearty and Kaufman, 2000,
149 2009). Of key importance, the Eemian-MIS 5e in the Bahamas is defined by its position in the
150 stratigraphic sequence of the rocks, the oolitic and pristine aragonitic sedimentology, a unique
151 landsnail fauna (Garrett and Gould, 1984), and numerous additional diagnostic characteristics
152 (e.g., Hearty and Neumann, 2001, p. 1883). There is little disagreement among researchers of the
153 defining characteristics of MIS 5e in the Bahamas.

154 *What gives carbonate platforms such as Bermuda and the Bahamas the unique quality of*
155 *preserving such a detailed geologic record?* Because carbonate sediments, particularly ooids,
156 respond and cement quickly, the highly mobile sediments that mantle flat-topped carbonate
157 platforms effectively record and preserve rock evidence of short-lived energetic events such as
158 storms and rapid sea level changes. Corals and coral reefs respond too slowly and cannot record
159 such brief changes. Likewise, similar short-term events are not preserved on coasts dominated
160 by siliciclastic or volcanic sediments (e.g., US East Coast and much of Caribbean region) due to
161 the instability and slowness of cementation (>10⁶ yr) of non-carbonate sediments.

162 In a global multidisciplinary review of MIS 5e, Hearty et al. (2007) assembled shoreline
163 stratigraphy, field information, and geochronological data from 15 sites to construct a composite
164 curve of Eemian sea level change. Their reconstruction has sea level rising in the early Eemian
165 to +2-3 m. Mid-Eemian sea level may have fallen a few meters to a level near today’s sea level.

166 Sea level then rose rapidly in the late Eemian to +6-9 m, cutting multiple bioerosional notches in
167 older limestone in the Bahamas and elsewhere.

168 Along the northeast Yucatan Peninsula, Mexico, Blanchon et al. (2009) used a sequence of coral
169 reef crests to investigate coral reef “back-stepping”, i.e., the fact that coral reef building moves
170 shoreward as sea level rises with a higher temporal precision than possible with U-series dating
171 alone. They documented an early +3 m sea level jump by 2-3 m to +6 m within an “ecological”
172 period, i.e., within several decades, in the late Eemian about 121 ky b2k based on U/Th ages. W.
173 Thompson et al. (2011) reexamined the Eemian using corrected U-series coral reef data from the
174 Bahamas and interpreted a mid-Eemian sea level at +4 m at 123 ky b2k, a maximum at +6 m at
175 119 ky b2k, and at 0 m at some time in between. Note that no known coral reef crests are higher
176 than +2-3 m across the entire archipelago (Hearty and Neumann, 2001; p. 1883).

177 In Western Australia, O’Leary et al. (2013) assembled one of the most comprehensive Eemian
178 sea level studies that includes: 1) 28 “far field” study sites along the 1400 km coastline; 2)
179 application of a multi-disciplinary approach using geomorphology, stratigraphy, and
180 sedimentology; 3) high-precision U/Th dating and screening of over 100 in situ corals; and 4)
181 incorporation of GIA correction regionally yielding a more precise eustatic sea level history.
182 The O’Leary et al. (2013) analyses suggest that sea level was relatively stable at 3-4 m in most of
183 the early-mid Eemian, followed by a brief but rapid (<1000 yr) late-Eemian sea level rise to
184 about +9 m. U-series dating of the corals has the sea level rise begin at 119 ky b2k and peak sea
185 level at 118.1 ± 1.4 ky b2k.

186 The far field *eustatic* sea level changes documented across Western Australia (O’Leary et al.,
187 2013) agree closely with the relative sea level shifts from near and mid field Bermuda and the
188 Bahamas (Hearty et al., 2007). Nearly all global sites in the Hearty et al. (2007) study showed
189 the same *relative* changes: early prolonged stability, a minor mid regression, then finally rapid
190 upward shifts of 3 to 5 m late in the Eemian. Such rapid sea level changes require ice sheet
191 growth and melting, regional glacio-isostatic adjustment (GIA), or both.

192 **Additional References (others are in the main text)**

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- 215

216 **Supplement S3: Ocean wave splash near the location of Eleuthera boulders**

217 Cox et al. (2012) discuss the inadequacy of hydrodynamic modeling to realistically describe
218 movement of boulders by large storms. Specifically, they found that storms in the North Atlantic
219 had thrown boulders as large as 80 tons to a height 11 m AHW (above high water mark) on the
220 shore on Ireland's Aran Islands, the specific storm on 5 January 1991 being driven by a low
221 pressure system that recorded a minimum 946 mb (equivalent to a category 3 hurricane). Winds
222 gusted to 80 knots and the closest weather station to the Aran Islands recorded gale force winds
223 for 23 hours and sustained winds of 40 knots for five hours. The storm waves built on swell
224 previously developed by strong winds during the prior two weeks.

225 Cox et al. (2012) note that existing hydrodynamic modeling equations would not lift the
226 boulders, and they cite two reasons to disregard those equations. First, they note that wave
227 height measurements frequently reveal waves twice the SWH (significant wave height) of wave
228 models. Second, existing wave equations do not include the effects of reflection from cliff and
229 shoreline, and the attendant wave amplification. Cox et al. note that wave heights at shoreline
230 cliffs can be much greater than the equilibrium height of approaching deep-water waves. The
231 waves steepen as they shoal, impact the coast, reflect back, meet advancing wave crests causing
232 a mixture of constructive and destructive interference, with intermittent production of very large
233 individual waves capable of quarrying and transporting large blocks and boulders.

234 These considerations help explain why megaboulders (as large as ~1000 tons) on Eleuthera
235 are only found just south of the Glass Window Bridge at the apex of an embayment that funnels
236 the waves before they encounter a steep shoreline cliff (Figs. 1-3 of Hearty, 1998; see also
237 Hearty, 1997). The special effect of the location and shoreline cliff is shown in a photo (Fig. 1).
238 Despite relatively calm conditions on Eleuthera, as indicated by the waters in the photo,
239 immediately southwest of the narrow Eleuthera island, the northeast side of Eleuthera was being
240 battered by large waves generated in the North Atlantic by the 1991 "Perfect Storm". The
241 Perfect Storm originated as an extratropical low east of Nova Scotia that tracked first toward the
242 southeast and then west, sweeping up remnants of Hurricane Grace, which deepened the low.
243 The storm eventually reached a peak intensity with sustained winds of 75 mph (120 km/h), a
244 category 1 hurricane, making landfall on Nova Scotia on 2 November. The shoreline cliffs
245 immediately south of the Glass Window Bridge, facing slightly east of due north (Fig. 3 Hearty,
246 1998), were battered by the deep long-period waves generated by the storm in the North Atlantic.

247 Irregularity of ocean splash in this setting probably helps account for how an unsuspecting
248 bread truck driver, seduced by the relative calm and fair weather (Fig. 1), was swept off the road
249 by one of the bursts as water swept across the road. The truck was thrown/washed well into the
250 shallow waters on the Caribbean-facing side of the island – the driver escaped in these relatively
251 calm waters to the southwest, but his rusted out truck frame remains there today.

252 Further confirmation of the ability of storm waves to lift large boulders was provided
253 recently by May et al. (2015). Despite the fact that this storm did not have the "advantage" of
254 being stationary for the long period required to develop deep powerful waves, the typhoon
255 produced longshore transport of a 180 ton block and lifted boulders of up to ~24 tons to
256 elevations as high as 10 m. May et al. (2015) conclude that these observed facts "...demand a
257 careful re-evaluation of storm-related transport where it, based on the boulder's sheer size, has
258 previously been ascribed to tsunamis."

259 **Additional References (others are in the main text)**

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Photograph S1. Photo taken 31 October 1991 from a few hundred meters offshore of the southern protected bank-side at the narrow part of Eleuthera near the Glass Window Bridge, looking northeast (Tormey, 1999; see text). The telephone pole on the left and the 15-20 m cliff provide scale.