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1 Ocean Salinities Reveal Strong Global Water Cycle 2 Intensification during 1950-2000

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11 **Abstract: 116 words; Body text: 2233 words (excluding introductory paragraph)**

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13 **Summary sentence: New estimates of water cycle intensification inferred from observed**
14 **ocean salinity changes suggest a 4% intensification has occurred from 1950 to 2000, twice the**
15 **response projected by current generation global climate models.**

16 **Abstract: Fundamental thermodynamics and climate models suggest dry regions will become**
17 **drier and wet regions will become wetter in response to warming. Efforts to detect this long-**
18 **term response in sparse surface observations of rainfall and evaporation remain ambiguous.**
19 **We show ocean salinity patterns express a clearly identifiable fingerprint of an intensifying**
20 **water cycle. Our 50-year observed global surface salinity changes, combined with changes**
21 **from global climate models, present robust evidence of an intensified global water cycle at a**
22 **rate of $8 \pm 5\%$ per degree of surface warming. This rate is double the response projected by**
23 **current generation climate models and suggests a substantial (16-24%) intensification of the**
24 **global water cycle will occur in a future 2-3° warmer world.**

25 **Introductory paragraph:** A warming of the global surface and lower atmosphere is expected to
26 strengthen the water cycle (1-3) largely driven by the ability of warmer air to hold and to
27 redistribute more moisture. This intensification is expressed as an enhancement in the patterns
28 of surface water fluxes (evaporation and rainfall [E-P]) and as a consequence, ocean surface
29 salinity patterns. According to the Clausius-Clapeyron (CC) relation and assuming a fixed relative
30 humidity, we expect a ~7% increase in atmospheric moisture content for every degree of
31 warming of the Earth's lower troposphere (2). Of greatest importance to society, and the focus
32 of this work, is the strength of the regional pattern of evaporation and precipitation (E-P),
33 which in climate models scales approximately with CC, while global precipitation changes more
34 slowly at a rate of 2-3% °C⁻¹ (2, 4).

35 An intensification of existing patterns of global mean surface evaporation and precipitation (E-
36 P) is found along with enhancements to extreme events such as droughts and floods (1, 5) in
37 available 21st century climate projections, forced by anthropogenic greenhouse gases (GHG)
38 from the Coupled Model Intercomparison Project Phase 3 (CMIP3 (6)). This has been labelled
39 the "rich get richer" mechanism, where wet areas (compared to the global mean) get wetter
40 and dry regions drier (7). There is, however, little consistency in the seasonal changes provided
41 by model projections, and poor agreement when compared to regional observational estimates
42 (8). Additionally, atmospheric aerosols included in these projections can regionally counteract
43 the GHG-driven warming, and act to suppress the local water cycle through dynamical changes
44 (9, 10).

45 Given the above broad-scale model responses and the CC relationship, an intensification of ~4%
46 in the global water cycle (E-P) is expected to already have occurred in response to the observed
47 0.5°C warming of the Earth's surface over the past 50-years (11). However, obtaining a global
48 view of historical long-term rainfall pattern changes is made difficult due to the spatially sparse
49 and short observational record. Long, high-quality land-based records are few and northern
50 hemisphere biased (12). Direct high quality long-term rainfall estimates over oceans (which

51 comprise 71% of the global surface area and receive over 80% of global rainfall (13); Fig. S1) are
52 very scarce, with most global observational products dependent on data contributions from
53 satellites, themselves sensitive to error (14, 15). Additionally, due to the short temporal
54 coverage (~15-30 years) by satellite missions, trends are likely affected by natural decadal
55 modes of variability, and may dominate much of the measured changes (3). This challenge is
56 exacerbated by the spatially and temporally sporadic nature of rainfall, making the derivation of
57 broad-scale averages of small multidecadal changes from a sparse network of observing
58 stations error-prone (16). These difficulties are evident in the differing signs of long-term trends
59 between reconstructed rainfall datasets (17, 18). Discrepancies among air-sea evaporative flux
60 products (19) undermine their use in resolving long-term water cycle changes. As a result, we
61 do not yet have a definitive view on whether the Earth's water cycle has intensified over the
62 past several decades from atmospheric observing networks (12, 20).

63 It has long been noted that the climatological mean sea surface salinity (SSS) spatial pattern is
64 highly correlated with the long-term mean E-P spatial pattern (21) (Fig. 1A, D), reflecting the
65 balance between ocean advection/mixing processes and E-P forcing at the ocean surface (21-
66 23). Several studies of multidecadal SSS changes reveal a clear pattern where increasing
67 salinities are found in the evaporation dominated mid-latitudes and decreasing salinities in the
68 rainfall dominated regions such as the tropical atmospheric convergence zones and polar
69 regions (22, 24-27). These previous studies have used optimally averaged pentadal historical
70 ocean data (24) or the difference between pre-2000 and post-2000 climatologies (27), the latter
71 period being strongly supported by the modern baseline provided by the Argo Programme (28)
72 to investigate long-term salinity changes in the global ocean. Using a direct local fit of trends to
73 historical and Argo data simultaneously (25), we map the multidecadal linear SSS trends back to
74 1950 (Fig. 1D, G). Over the last 50-years SSS changes reflect an intensification of the mean SSS
75 patterns. This strong and coherent relationship is expressed through the high spatial pattern
76 correlation coefficient (PC) of ~0.7 (Figure S2) between the mean SSS and independent

77 estimates of long-term SSS change (24, 25, 27). Following the “rich get richer” mechanism (7),
78 salty ocean regions (compared to the global mean) are getting saltier, while fresh regions are
79 getting fresher. This robust intensification of the observed SSS pattern is qualitatively consistent
80 with increased E-P if ocean mixing and circulation are largely unchanged.

81 [Figure 1 about here]

82 In trying to quantitatively relate SSS changes and E-P changes previous studies have made
83 strong simplifying assumptions. One estimate of a global 3.7% E-P intensification from 1970s to
84 2005 (27) is based on the assumption of an unchanging ocean mixing and advection field, with
85 the additional assumption that no salt or freshwater exchange has occurred over this time with
86 the deep ocean below 100m. However, several studies have shown subsurface salinity changes
87 have occurred during the 20th century (24, 25), with many of the largest signals expressed at
88 depths greater than 100m. Another study used subsurface salinity changes on isopycnals to
89 deduce E-P changes at the surface density outcrops (26). This approach is error prone as broad-
90 scale salinity changes on density surfaces can largely be explained by the subduction of broad-
91 scale warming and not E-P changes alone (25). To avoid such strong assumptions and explore
92 the use of SSS pattern changes as a water cycle diagnostic, we use the most comprehensive
93 simulations available to date of the historical and future global climate - the CMIP3 simulations
94 of the 20th century (20C3M) and Special Report on Emissions Scenarios (SRES) 21st century
95 future projections (6). Within these simulations we investigate the relationship between SSS
96 and E-P pattern changes. These simulations capture the full range of complex dynamical
97 changes in response to greenhouse gas (GHG) forcing, which include: ocean surface (and
98 subsurface) temperature changes, dynamical shifts to ocean and atmospheric circulation, upper
99 ocean stratification changes as well as the regional effects of aerosols on water cycle operation.

100 To quantify and compare the strength of broad-scale SSS pattern intensification in both
101 observations and CMIP3, zonal ocean basin (Pacific, Atlantic and Indian) averages were formed

102 for both the mean SSS and its 50-year (1950-2000) linear trends. A linear regression is
103 undertaken using the basin zonal averages of the climatological mean SSS (x-axis) anomaly
104 against the SSS change pattern (y-axis; Fig. 1J). We define the resulting slope of this relationship
105 as the pattern amplification (PA) and the correlation coefficient (R) as the pattern correlation
106 (PC). A key advantage of this analysis is its insensitivity to the mean spatial climatological biases
107 in model fields (29) when compared to observations, since the model change fields are
108 compared to their own model climatology. We formed the PA and PC metrics for each model
109 simulation and our observational analysis (Fig. S2 presents comparative global zonal mean
110 analyses for available global SSS studies).

111 Analysis of trends in observed SSS indicates that from 1950 to 2000 the SSS PA is 8% with a PC
112 of 0.7 (Fig. 1J). Similar to observations, many models show a high PC ($\sim 0.7-0.9$) between the
113 climatological mean SSS and the corresponding climatological mean E-P. However, most 20C3M
114 model simulations show a weaker than observed spatial pattern correlation (PC) and pattern
115 amplification (PA) between the 50-year SSS mean and SSS change patterns (Fig. 1D, G vs E, H &
116 F, I), and do not uniformly provide a realistic simulation of observed surface mean SSS patterns
117 or its change over 1950-2000 (Fig. 1D, G; Fig. S6, Table S2). Our examples of the simulations
118 that most closely replicate the observed spatial change and mean patterns (Fig. 1E, H) and
119 those that produce an almost inverse spatial change pattern (Fig. 1F, I) compared to the
120 observed results (Fig. 1D, G), illustrate the range of responses found in CMIP3 (Fig. 1). Some
121 models show similar numbers to those observed (Fig. 1E, H, K) while others have very low
122 values of both PA and PC (Fig. 1F, I, L), indicating no clear SSS pattern amplification. Such
123 discrepancies raise a key question: What controls this difference in the modelled SSS response
124 and how is this related to water cycle changes?

125 [Figure 2 about here]

126 The PA and PC methodology can also be used when considering other variables, such as the
127 surface water flux (E-P). CMIP3 simulations show a relationship between SSS PA and the E-P PA
128 (Fig. 2B). This key result supports the use of SSS PA as a diagnostic of a changing water cycle,
129 and also provides a relationship in which to consider the observed SSS PA for 1950-2000. The
130 CMIP3 SSS patterns amplify at twice the rate of E-P patterns (Fig. 2B). The reason that E-P PA
131 drives a stronger response in SSS PA for CMIP3 is not clearly understood, and requires further
132 investigation, but the relationship between them is compelling.

133 When investigating water cycle changes, it is important to consider the coincident global
134 surface warming, the natural framework of water cycle amplification. If expressed in a per
135 degree warming context, such water cycle rate changes can then be directly compared to other
136 studies, both oceanographic and atmospheric in their origins (Table S3, Figure S9).

137 For both the 20C3M and SRES CMIP3 simulations, we find a clear relationship between the rate
138 of global average surface warming (ΔT_a) and the rate of SSS PA and PC strength (Fig. 2A).
139 20C3M simulations in which the warming rate is low (generally those with comprehensive
140 aerosol schemes; contrast diamonds and circles in Fig. S5; Table S1) feature low SSS PA, with
141 spatial change patterns having only slight correspondence to the spatial mean pattern and
142 consequently a low SSS PC (illustrated by the simulation in Fig. 1F, I, L). The stronger warming
143 SRES simulations express a clearer and larger pattern amplification response ($PC > 0.5$) than
144 most 20C3M simulations (Fig. 2A). The increase in PC with enhanced PA suggests a signal-to-
145 noise process is operating, where in weakly warming simulations model internal variability
146 dominates the change signal. A PC-weighted line of best fit through the 93 CMIP3 simulations
147 suggests that SSS patterns intensify with warming at $8\% \text{ }^\circ\text{C}^{-1}$ (Fig. 2A), which is half of our 1950-
148 2000 observed rate ($16\% \text{ }^\circ\text{C}^{-1}$; Fig. 2A). As expected, based on past analyses of CMIP3 (2), the E-
149 P PA is also linearly related to surface warming rates (Fig. 2C) with the model line of best fit
150 below CC ($4.5\% \text{ }^\circ\text{C}^{-1}$). Also in agreement with many previous analyses (1, 2), total global
151 average rainfall is linearly related to warming rates but with a distinctively weaker slope than

152 surface water flux, near $3.1\% \text{ } ^\circ\text{C}^{-1}$ (Fig. 2D). The stronger SSS PA response to warming and
153 tighter agreement among CMIP3 when compared to that for the E-P PA (Fig. 2A vs C) suggests
154 that long-term SSS pattern changes provide a clearly identifiable, highly detectable and
155 particularly sensitive measure of long-term water cycle changes. It is likely that ocean mixing
156 and circulation act to integrate and smooth the temporal and spatial patchiness of E-P fluxes at
157 the ocean surface and provide a smoothed SSS anomaly field, which facilitates detection of
158 broad-scale, persistent changes.

159 To independently demonstrate the strong relationship between 50-year salinity change and an
160 enhanced water cycle, the response of an ocean-only model to an idealised 5% E-P pattern
161 increase was explored. We used a version of the MOM3 ocean model, forced with E-P fields
162 obtained from the NCEP reanalysis. A linear trend in E-P was imposed to achieve a 5% increase
163 over 50-years. The resulting spatial pattern of SSS change strongly mirrors the observed and
164 CMIP3 ensemble mean patterns, but with smaller absolute magnitudes (Fig. 3A, C, D vs 3B). The
165 salinity pattern amplification is expressed for surface and subsurface changes (Figs. S7 & S8; see
166 supporting online material). Therefore in a global ocean-only model, spatial salinity patterns
167 enhance in response to an intensified E-P. A similar spatial response to the observed changes
168 are found in CMIP3 but only for the strongly warming 20C3M simulations ($>0.5^\circ\text{C}$; Fig. 3D vs
169 3C). Those simulations with less than the observed warming over 1950-2000 often incorporate
170 aerosol effects which act to reduce warming (contrast diamonds and circles in Fig. S5), and thus
171 under predict the subsequent water cycle amplification as expressed in SSS changes.

172 [Figure 3 about here]

173 Despite their scatter, estimates from the CMIP3 ensemble show a weaker salinity pattern
174 amplification per degree of warming ($8\% \text{ } ^\circ\text{C}^{-1}$; Fig. 2A) than has been observed ($16\% \text{ } ^\circ\text{C}^{-1}$; Fig.
175 2A). Using the modelled relationship between SSS PA and E-P PA from the CMIP3 ensemble
176 (which shows that SSS PA increases at twice the rate of E-P PA (Fig. 2B)), and applying this

177 relationship to our observed SSS PA estimate, we infer that over the past 50 years the global
178 water cycle has amplified by 4%. Using the observed 0.5°C surface warming estimate (11), this
179 inferred water flux amplification of 8% °C⁻¹, is close to that predicted by the CC relationship
180 (~7% °C⁻¹). This rate of change is consistent with many other independent observational
181 estimates (Table S3, Fig. S9) which all provide evidence that an observed global water cycle
182 amplification has occurred. However, CMIP3 ensemble averages of E-P PA produce a rate well
183 below this of 4.5% °C⁻¹ (Fig. 2C).

184 A change to freshwater availability in response to climate change poses a more significant risk
185 to human societies and ecosystems than warming alone. Changes to the global water cycle and
186 the corresponding redistribution of rainfall will affect food availability, stability, access and
187 utilisation. We show that ocean salinity is a particularly sensitive marker of water cycle change
188 which provides us with a salty ocean freshwater “gauge” from which to monitor over 71% of
189 the Earth’s surface. Using ocean observations we show the “rich get richer” mechanism is
190 already operating, with fresh regions becoming fresher and salty regions saltier in response to
191 observed warming. Our results support a water cycle intensification rate consistent with the CC
192 relationship under fixed relative humidity. In a future greenhouse gas forced 2-3°C warmer
193 world (30), this implies a 16-24% amplification of the global water cycle will occur, nearly
194 double the CMIP3 response.

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209

210 **Author Contributions** P.J.D. conceived the study, completed the analysis and shared responsibility for
211 writing the manuscript. S.E.W. assisted in the analysis and shared responsibility for writing the
212 manuscript. R.J.M. undertook the idealised model simulations. All authors contributed to the final
213 version of the manuscript.

214

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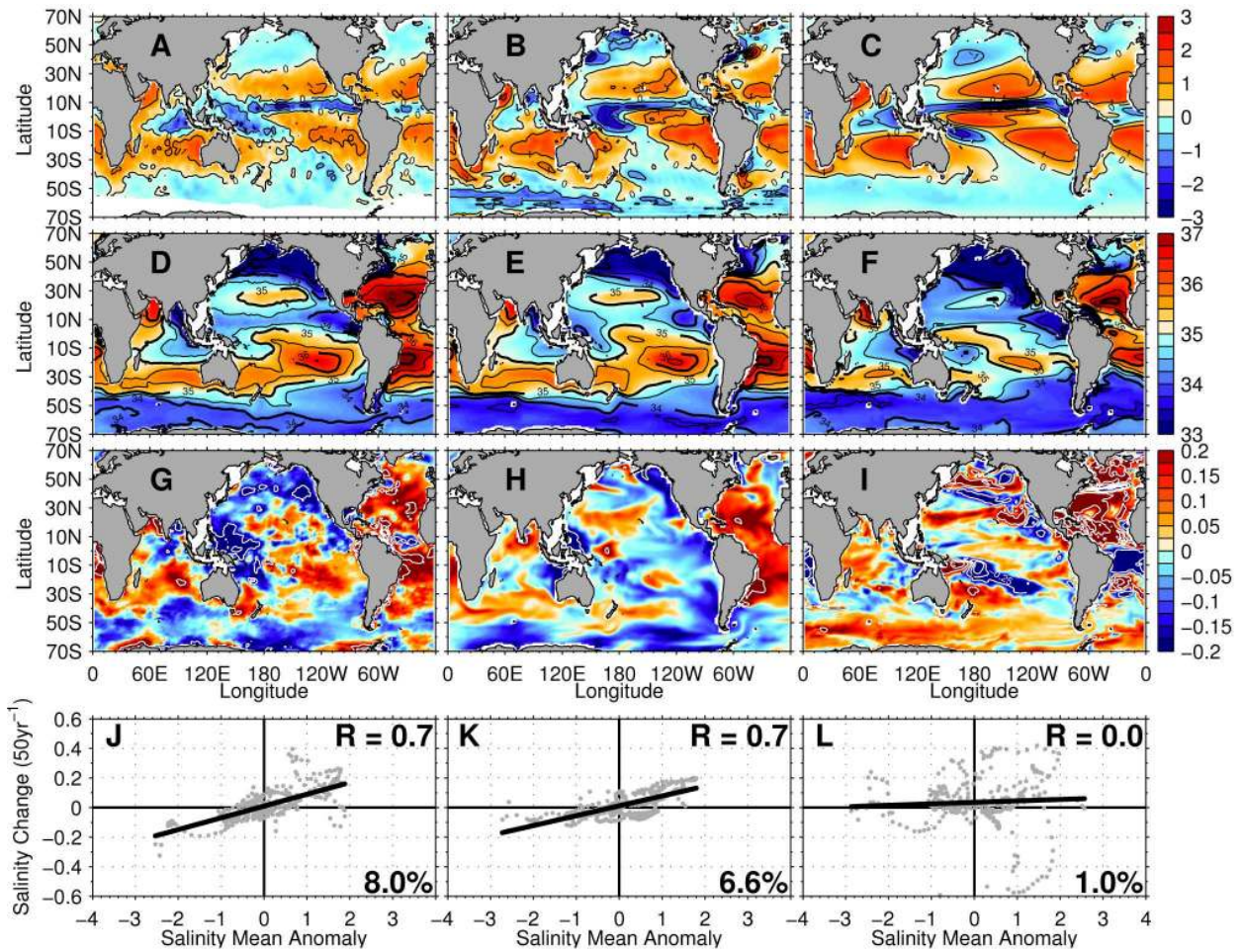
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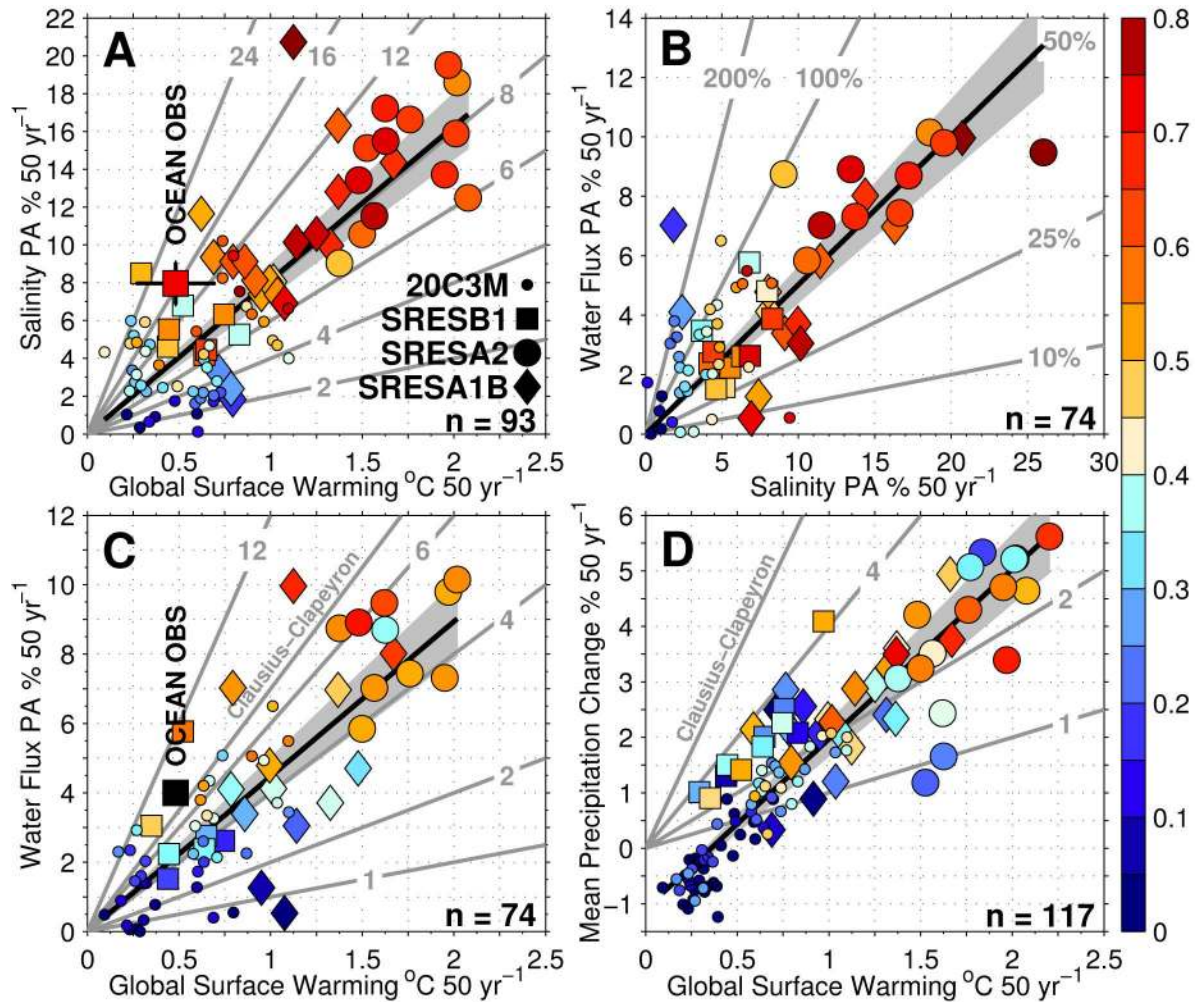
280

281 **Figures**

282

283 Figure 1. Observed and selected CMIP3 20C3M simulations of surface salinity and water fluxes. Surface mean
 284 water flux 1950-2000 ($E-P \text{ m yr}^{-1}$; A, B, C). Surface mean salinity 1950-2000 (PSS-78; D, E, F). Surface salinity change
 285 1950-2000 ($PSS-78 \text{ } 50 \text{ yr}^{-1}$; G, H, I). Basin zonal-mean surface salinity trends (y-axis) versus surface mean salinity
 286 anomaly (with surface basin zonal mean removed; PA & PC; J, K, L). The observed result of Durack & Wijffels (2010);
 287 D, G, J) and (A) the observed result of Josey *et al.* (1998) for 1980-1993. Results from the Canadian Centre for
 288 Climate Modelling & Analysis: CGCM3.1 (T63) model (B, E, H, K), and results from the United Kingdom MetOffice:
 289 HadGEM1 model (C, F, I, L). For A-C black contours every 1 m yr^{-1} . For D-F, black contours represent surface mean
 290 salinity every 1 PSS-78 for bold lines and 0.5 for thin. For G-I, white contours represent surface salinity change
 291 every 0.25 PSS-78.

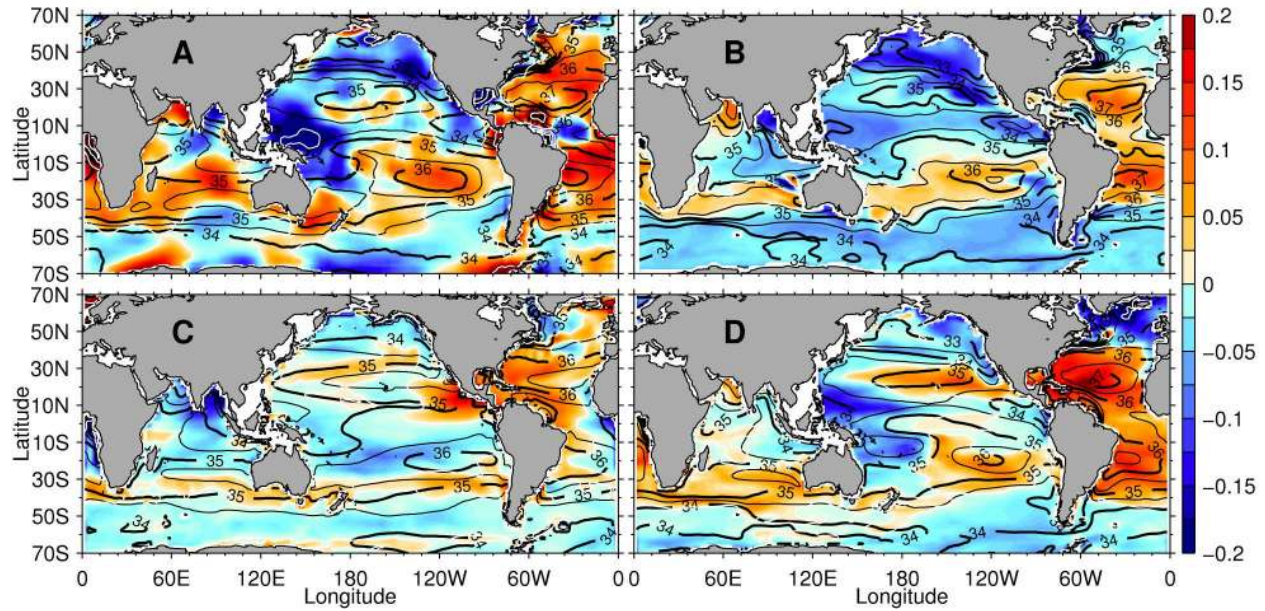
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293

294 Figure 2. Pattern amplification and pattern correlations from the available CMIP3 simulations compared to new
 295 observational estimates. The number of individual simulations which have been analysed for each variable is noted
 296 in the bottom right hand corner of each panel. A) The surface salinity pattern amplification (PA; y-axis) versus the
 297 corresponding global average surface temperature change (ΔT_a ; x-axis), colours are the salinity pattern correlation
 298 (PC). B) Water flux (E-P; y-axis) PA versus surface salinity PA (x-axis), colours are the salinity pattern correlation
 299 (PC). C) Water flux (E-P; y-axis) PA versus global average surface temperature change (ΔT_a ; x-axis), colours are the
 300 E-P pattern correlation (PC). D) Global spatial average precipitation change, rather than pattern amplification (ΔP ;
 301 y-axis) versus global average surface temperature change (ΔT_a ; x-axis), colours are the precipitation PC. Grey lines
 302 express constant proportional change. Grey shading (99% C.I.) bounds the PC-weighted linear best fit to the model
 303 ensemble for a line intersecting 0 (y-axis; A, B, C) and -1.1 (y-axis; D) in black. The 20th century (20C3M; 1950-2000)
 304 simulations are presented in small circles, and the three 21st century projected scenarios (SRES; 2050-2099) are
 305 shown as squares for B1, large circles for A2 and diamonds for A1B. All simulations have been de-drifted using an
 306 appropriate pre-industrial control simulation for the period 1900-2049.

307



308

309 Figure 3. Patterns of 50-year surface salinity change (PSS-78 50yr^{-1}). A) The 1950-2000 observational result of
 310 Durack & Wijffels (2010). B) From an ocean model forced with an idealised surface 5% E-P enhancement (50yr^{-1} ;
 311 see text). C) For an ensemble mean from 1950-2000 of the CMIP3 20C3M simulations which warm less than $<0.5^\circ\text{C}$
 312 (24 simulations; see Table S2). D) For an ensemble mean from 1950-2000 of the CMIP3 20C3M simulations which
 313 warm greater than $>0.5^\circ\text{C}$ (26 simulations; see Table S2). In each panel, the corresponding mean salinity from each
 314 representative data source is contoured in black, with thick lines every 1 (PSS-78) and thin lines every 0.5 (PSS-78).

315 **Supporting Online Material for**

316 Ocean Salinities Reveal Strong Global Water Cycle Intensification during 1950-2000

317

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319

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322 Published XX Month Year on Science Express

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325 This PDF file includes:

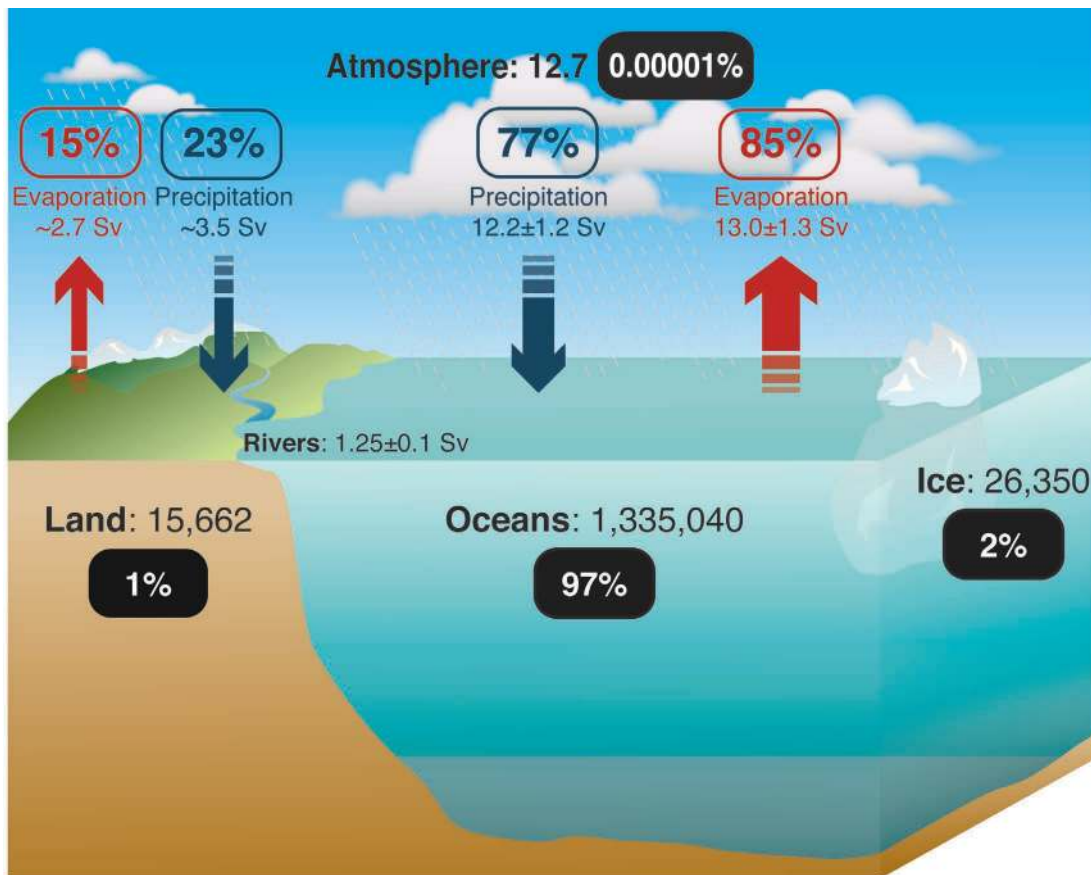
326 SOM Text

327 Figs. S1 to S9

328 Tables S1 to S3

329 References

330

331 **Supporting Online Material**

Reservoirs represented by solid boxes: 10^3 km^3 , fluxes represented by arrows: Sverdrups ($10^6 \text{ m}^3 \text{ s}^{-1}$)
 Sources: Baumgartner & Reichel, 1975; Schmitt, 1995; Trenberth et al., 2007; Schanze et al., 2010

332

333 Figure S1. Adapted schematic (after Schmitt, 1995 and updated after Trenberth *et al.*, 2007 and Schanze *et al.*,
 334 2010) represents the key role of the ocean in the global water cycle – around 80% of the Earth’s surface water
 335 fluxes occur at the ocean surface. Reservoir estimates represent storages in 10^3 km^3 , flux estimates represent
 336 transports in Sverdrups ($10^6 \text{ m}^3 \text{ s}^{-1}$) and values within boxes represent the approximate percentage of total
 337 storages (black boxes) or flux estimates (rainfall = blue; evaporation = red) for the global surface.

338 **Observational surface salinity change analysis**

339 For this analysis, new estimates of the surface salinity climatological mean and the 50-year
 340 (1950-2000) surface salinity change fields were obtained. These analyses used both the
 341 available quality-controlled historical hydrographic profiles, along with more recent data
 342 from the global Argo Program to determine long-term trends over the 50-year timescale
 343 (Durack & Wijffels, 2010).

344

345 The results presented in this analysis provide a broad-scale, globally consistent view of
 346 coherent, long-term global salinity changes which agree with many of the long-term
 347 regional salinity changes presented in many independent studies (Durack & Wijffels, 2010 -
 348 Table 1; Durack *et al.*, 2011). The key advantages of the new approach are its near global

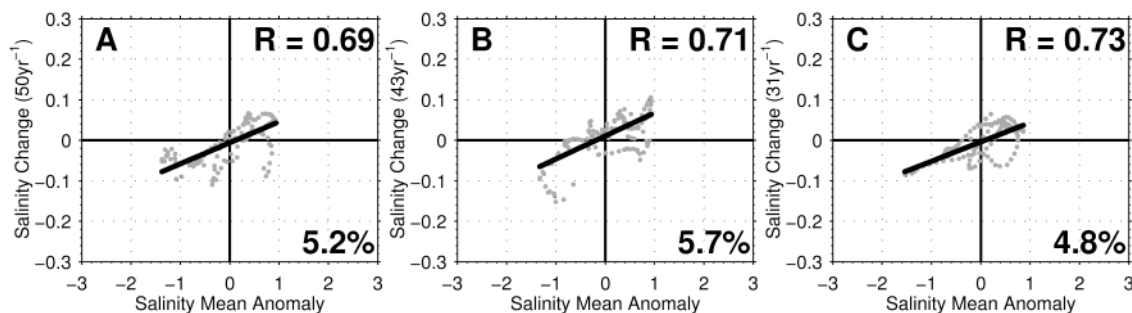
349 coverage (marginal seas and high-latitude seas $>70^\circ$ are excluded), and the methodology
 350 which is optimised to reduce biases due to seasonal and spatial sampling, particularly in the
 351 historical data, by fitting the mean climatology and trends concurrently. An attempt to
 352 remove biases associated with strong ENSO cycles is also an advantage of this analysis. In
 353 the sparsely historically observed Southern Hemisphere oceans, the analysis relies on Argo's
 354 ability to highly resolve the mean, seasonal and ENSO ocean responses. This methodology
 355 reduces aliasing by these observed phenomena into the multidecadal trend, with a 50-year
 356 temporal analysis long enough to account for many modes of cyclical climate variability. Due
 357 to the availability of ocean profile data, the varied temporal global sampling also means that
 358 any "simple" average represents different eras in different parts of the ocean (Durack &
 359 Wijffels, 2010; Figure 2B, D), and by fitting the trend and mean climatology at the same
 360 time, errors due to a biased climatology are avoided.

362 Comparisons to previous observational surface salinity change estimates

363 Many estimates of salinity changes throughout the global ocean have been published. We
 364 selected two key global studies (Boyer *et al.*, 2005; Hosoda *et al.*, 2009) and provide
 365 quantified comparisons to directly compare the robustness of salinity pattern amplification
 366 magnitudes between independent estimates. As noted in some detail in Durack & Wijffels
 367 (2010, Table 1) many salinity change estimates exist, and the results presented by Durack &
 368 Wijffels (2010) tend to agree with the broad-scale conclusions of previous estimates of
 369 change.

370
 371 In order to quantitatively compare the surface salinity results it was necessary to form
 372 global zonal means for both climatological mean surface salinity and the surface trend fields
 373 for the representative studies. This analysis differs from the main text, as basin zonal, rather
 374 than global zonal means have been used. In the case of Boyer *et al.* (2005) their data is
 375 freely downloadable off the NODC website. For Hosoda *et al.* (2009) only their global zonal
 376 mean values were available from their published figures 2A and 2B. For comparison, Figure
 377 S2 captures the global zonal mean results for each study.

378



379
 380 Figure S2. Global zonal mean surface salinity comparison for the analyses of A) Durack & Wijffels (2010), B)
 381 Boyer *et al.* (2005) and C) Hosoda *et al.* (2009; using their global zonal mean results)

382

383 It is clear that each independent study suggests that the "rich get richer" mechanism is
 384 operating upon ocean salinity, with a linear relationship present in each analysis suggesting
 385 fresh waters are getting fresher and salty waters are getting saltier. They all share similar
 386 spatial pattern correlation (PC) values of ~ 0.7 , however magnitudes of PA are more variable,

387 with the Durack & Wijffels (2010) estimate (A) suggesting a representative median value for
388 these three independent studies of ~5% over their 50-years of analysis.

389 **CMIP3: Model drift correction**

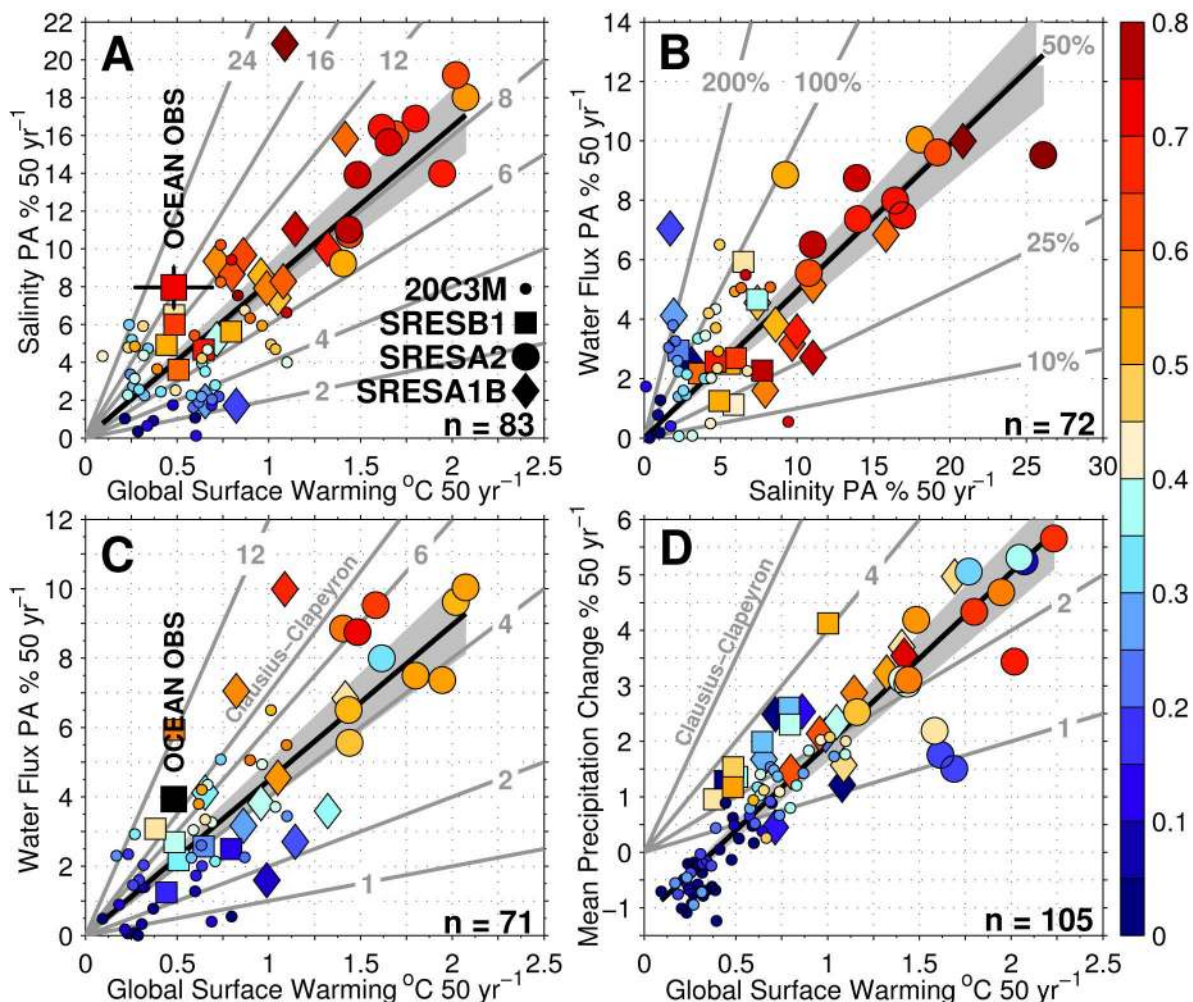
390 Model (or climate) drift is an inherent problem in current state-of-the-art climate modelling
391 systems. Drift is the term applied to a systematic bias in model fields, which can be
392 attributed to deficiencies in the modelling system, with this feature primarily a problem
393 with ocean simulations. These manifest due to many different reasons, primarily on two
394 timescales. Rapid drift occurs and is most likely due to errors introduced when coupling the
395 ocean and atmosphere model subcomponents, and is referred to as “coupling shock”.
396 Longer term drift can be attributed to the slow adjustment of the modelled deep ocean, and
397 the most likely causes of this drift can be linked to unresolved/sub-grid scale physics
398 (exclusion of eddies, localised boundary flows), poor initialisation (deficiencies with
399 “first/best guess” climatologies), imposed flux adjustments (mostly deprecated in CMIP3)
400 and insufficient model “spin-up” (incomplete initialisation of the coupled model, so that a
401 pseudo-equilibrium climate state in the model is never reached).

402

403 In order to effectively obtain the most accurate estimate of the transient greenhouse gas
404 (GHG) forced signal from a climate model simulation, and in particular the low signal-to-
405 noise externally forced 20C3M simulations, it is necessary to attempt to account for drift. It
406 is also necessary to attempt to account for high and low-frequency variability, which can
407 influence resolved trends. For this reason multidecadal trends over 50-years (1950-2000)
408 are considered in this analysis, with an expectation that modelled climate variability will be
409 fairly small over 50-year timescales when compared to the transient GHG-forced response
410 (see following CMIP3: Assessment of Modelled Internal Variability section and Figure S4).
411 For the analysis presented here, drift was determined from the 1900-2049 period associated
412 with the initial (run1: 1950-2000) 20C3M simulation, and the spatial pattern and magnitude
413 was then removed from all the transient 20C3M simulations for each representative
414 simulation. A test was undertaken to ensure that the differences in the time of 20C3M
415 initialisation of the corresponding PICNTRL did not largely affect the result, and this was
416 found to be a sound assumption, with the exception of the gfdl_cm2_0 run1. However as
417 salinity was only available for run1 (and not the subsequent run2 or run3) for this model it
418 didn't affect the analysis. The 1900-2049 period was selected as it bounded 1950-2000 (50-
419 years either side), the period over which trends were obtained from 20C3M simulations and
420 directly compared to the new observed estimates for the same period. Additionally, use of
421 this early period ensured a larger ensemble of CMIP3 data was available, as available
422 PICNTRL runs tend not to extend beyond 2100.

423

424 In order to test the sensitivity to this method of drift removal, a duplicated analysis was
425 undertaken using the 2000-2149 period - this period bounding 2050-2099, the period over
426 which SRES analyses were undertaken. A decrease in the total number of simulations
427 available for this analysis was found, due to a reduction in available concurrent PICNTRL
428 data (Figure S3 vs Figure 2), however they key results expressed in Figure 2 are largely
429 reproduced in this adapted analysis (Figure S3).



430

431 Figure S3. Representative change responses from the available CMIP3 simulations compared to new
 432 observational estimates of ocean salinity changes. Following Figure 2, however all SRES fields have been de-
 433 drifted using an appropriate pre-industrial control simulation for the period 2000-2149, rather than 1900-2049
 434 (Fig. 2). The number of individual simulations which have been analysed for each variable is noted in the
 435 bottom right hand corner of each panel. A) The surface salinity pattern amplification (PA; y-axis) versus the
 436 corresponding global average surface temperature change (ΔT_a ; x-axis), colours are the salinity pattern
 437 correlation (PC). B) Water flux (E-P; y-axis) PA versus surface salinity PA (x-axis), colours are the salinity pattern
 438 correlation (PC). C) Water flux (E-P; y-axis) PA versus global average surface temperature change (ΔT_a ; x-axis),
 439 colours are the E-P pattern correlation (PC). D) Global spatial average precipitation change, rather than pattern
 440 amplification (ΔP ; y-axis) versus global average surface temperature change (ΔT_a ; x-axis), colours are the
 441 precipitation PC. Grey lines express constant proportional change. Grey shading (99% C.I.) bounds the
 442 correlation-weighted linear best fit to the model ensemble for a line intersecting 0 (y-axis; A, B, C) and -1.2 (y-
 443 axis; D) in black. The 20th century (20C3M; 1950-2000) simulations are presented in small circles, and the
 444 three 21st century projected scenarios (SRES; 2050-2099) are shown as squares for B1, large circles for A2 and
 445 diamonds for A1B.

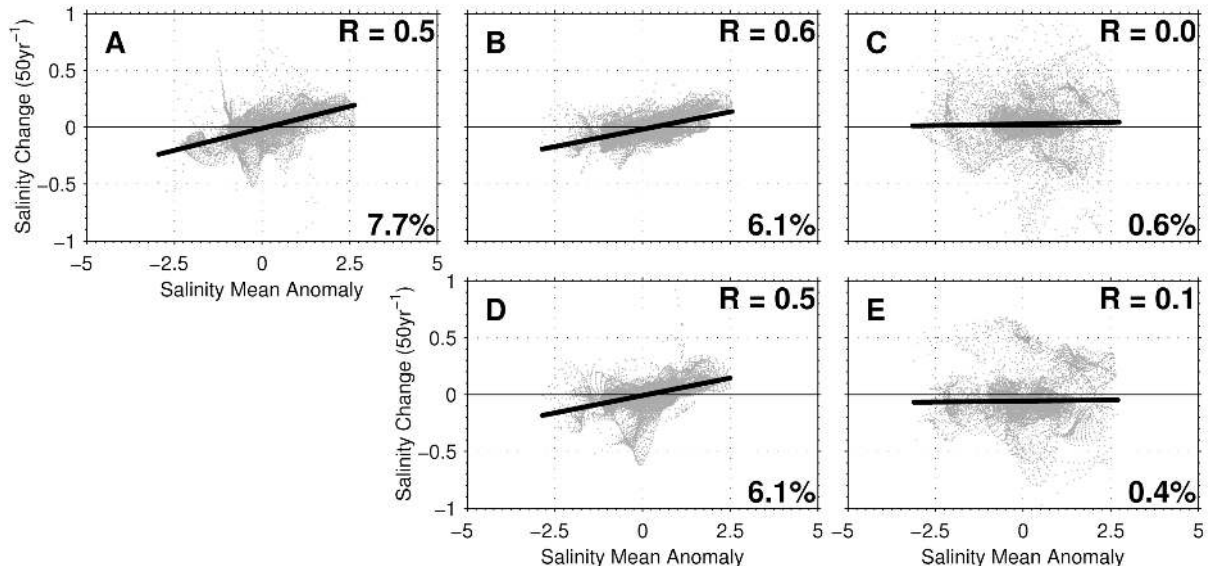
446 **CMIP3: Assessment of Modelled Internal Variability**

447 To further test whether modelled variability has influenced the CMIP3 results an additional
 448 analysis was undertaken to compare the 50-year (1950-2000; 20C3M) analysed results to
 449 change patterns obtained over the full length (~150-years) of the simulations expressed in
 450 Figure 1. As observational data coverage is only available for 1950-onwards, this test is not
 451 possible for the observational estimates. However, investigating modelled variability is

452 insightful when considering what is cyclical versus transient change. For this additional
 453 analysis, surface salinity patterns were assessed for their full temporal trends, so 1850-2000
 454 for the cccma_cgcm3_1_t63 and 1860-2000 for ukmo_hadgem1.

455

456 The observed result presented in Figure 1J is reproduced below (Figure S4A). To further
 457 enhance variability the full spatial analysis is considered, rather than the zonal ocean basin
 458 averages presented in Figures 1 & 2. When comparing the results from this full grid analysis
 459 (Figure S4A) to the zonal mean analysis (Figure 1J) it is clear that spatial smoothing has
 460 enhanced the pattern correlation (PC; 0.5 – Figure S4A vs 0.7 Figure 1J). However, the
 461 surface salinity pattern amplification (PA) is approximately equivalent for each of the
 462 analyses; 7.7% (Figure S4A) compared to 8% (Figure 1J). Model analyses for 50-years are
 463 presented in Figure S4B, C and ~150-years in Figure S4D, E respectively. Considering the
 464 cccma_cgcm3_1_t63 model and the 50-year analysis, a slight increase in PC is also apparent
 465 due to the spatial smoothing (0.7 Figure 1K vs 0.6 Figure S4B), however reported PA is 6.1%
 466 for both the 50-year (Figure S4B) and ~150-year analysis (Figure S4D), with a decrease in PC
 467 for the ~150-years (0.6 vs 0.5). For ukmo_hadgem1 similar results are found, with similar PA
 468 values recorded across all analyses (1.0% Figure 1L vs 0.6% and 0.4% Figure S4C, E) and
 469 correspondingly low PC. This additional analysis supports the use of the 50-year periods
 470 used in this study, as these 50-year periods are truly representative of the full 20th century
 471 simulated change (Figure S4).



472

473 Figure S4. Examples of pattern amplification for global ocean surface salinity – values are plotted point-wise
 474 for the analysed surface response. Unlike Figure 1, fields are not spatially smoothed using the basin zonal
 475 mean approach. for A) the 1950-2000 observed result B) Canadian Centre for Climate Modelling & Analysis:
 476 CGCM3.1 (T63) for 1950-2000 C) United Kingdom MetOffice: HadGEM1 for 1950-2000 D) Canadian Centre for
 477 Climate Modelling & Analysis: CGCM3.1 (T63) for 1850-2000 E) United Kingdom MetOffice: HadGEM1 for
 478 1860-2000

479

480 **CMIP3: The Role of Aerosols and other Forcing Agents**

481 The effect of comprehensive aerosol schemes is known to provide a general cooling effect
 482 and a corresponding dampening effect on local water cycle operation (Ramanathan *et al.*,
 483 2001; Ming *et al.*, 2010; Chen *et al.*, 2011). In CMIP3 20C3M simulations which incorporate
 484 volcanic aerosols forcing also generally include other aerosol effects such as black and
 485 organic carbon and sulphates (Table S1).

486

487 Table S1. Forcings and flux corrections used in CMIP3 simulations of 20th century climate change (Updated
 488 from Santer *et al.*, 2007). The letter 'Y' denotes inclusion of the specific forcing for the selected model. G: well-
 489 mixed greenhouse gases; O: tropospheric and stratospheric ozone; SD: sulphate aerosol direct effects; SI:
 490 sulphate aerosol indirect effects; BC: black carbon; OC: organic carbon; MD: mineral dust; SS: sea salt; LU: land
 491 use change; SO: solar irradiance; VL: volcanic aerosols. For flux corrections (FC) the following notation is used;
 492 Freshwater: F; Heat/momentum: H.

Model	Representative numbers	G	O	SD	SI	BC	OC	MD	SS	LU	SO	VL	FC
bccr_bcm2.0	1	Y	-	Y	-	-	-	-	-	-	-	-	-
cccma_cgcm3_1_t47	2,3,4,5,6	Y	-	Y	-	-	-	-	-	-	-	-	F,H
cccma_cgcm3_1_t63	7	Y	-	Y	-	-	-	-	-	-	-	-	F,H
cnrm_cm3	8	Y	Y	Y	-	Y	-	-	-	-	-	-	-
csiro_mk3_0	9,10,11	Y	Y	Y	-	-	-	-	-	-	-	-	-
csiro_mk3_5	12,13,14	Y	Y	Y	-	-	-	-	-	-	-	-	-
gfdl_cm2_0	15	Y	Y	Y	-	Y	Y	-	-	Y	Y	Y	-
gfdl_cm2_1	16	Y	Y	Y	-	Y	Y	-	-	Y	Y	Y	-
giss_aom	17,18	Y	-	Y	-	-	-	-	Y	-	-	-	-
giss_model_e_h	19,20,21,22,23	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-
giss_model_e_r	24,25,26,27,28,29,30,31,32	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-
iap_fgoms1_0	33,34,35	Y	-	Y	-	-	-	-	-	-	-	-	-
ingv_echam4	36	Y	Y	Y	-	-	-	-	-	-	-	-	-
ipsl_cm4	37	Y	-	Y	Y	-	-	-	-	-	-	-	-
miroc3_2_hires	38	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-
miroc_3_2_medres	39	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-
miub_echo_g	40,41,42	Y	-	Y	Y	-	-	-	-	-	Y	Y	F,H
mpi_echam5	43,44,45	Y	Y	Y	Y	-	-	-	-	-	-	-	-
mri_cgcm2_3_2a	46,47,48,49,50	Y	-	Y	-	-	-	-	-	-	Y	Y	F,H
ncar_ccsm3_0	51,52	Y	Y	Y	-	Y	Y	-	-	-	Y	Y	-
ncar_pcm1	53,54,55	Y	Y	Y	-	-	-	-	-	-	Y	Y	-
ukmo_hadcm3	56,57	Y	Y	Y	Y	-	-	-	-	-	Y	-	-
ukmo_hadgem1	58	Y	Y	Y	Y	Y	Y	-	-	Y	Y	-	-

493

494 So how do aerosols affect the reported water cycle changes as expressed in surface salinity,
 495 surface water flux pattern amplification (PA) and corresponding pattern correlations (PC)?
 496 The results presented in Figure 2 included all available simulation results from the 20C3M as
 497 well as the available SRES (A1B, A2 and B1) simulations. As volcanic aerosol emissions are
 498 not readily predictable into the future, these agents were excluded from SRES simulations,
 499 however have been included in around half of the available 20C3M simulations (Table S1).

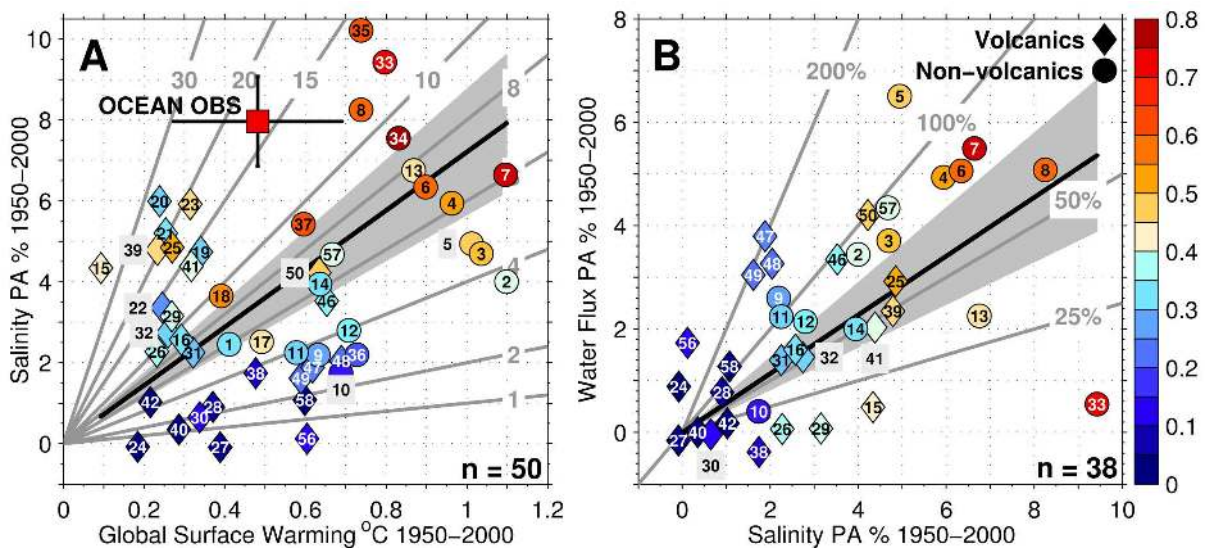
500

501 Representative change responses for many aspects of water cycle operation were presented
 502 in Figure 2. To concentrate on aerosol effects, Figure S5 reproduces the results presented in
 503 Figure 2A, B just for the 20C3M simulations. This sub-suite of simulations can then be
 504 assessed on whether they included volcanic aerosol effects, or whether they didn't (Table
 505 S1).

506

507 There appears to be a clear pattern of enhanced global surface warming in non-volcanic
 508 models (Figure S5A; contrast circles vs diamonds), with corresponding larger PA (Figure S5A
 509 colours) when compared to the volcanically-forced simulations. A clear pattern of low-

510 warming simulations with low PA (Figure S5A; left-bottom), compared to high-warming
 511 simulations with comparatively higher PA (Figure S5A; right-top) is apparent. This tends to
 512 suggest that a clear signal-to-noise process is in operation, with a more coherent salinity PA
 513 response expressed in the stronger warming simulations, whereas many of the low-warming
 514 simulations show no such coherent salinity PA. When comparing the PA of both surface
 515 salinity and surface water flux (Figure S5B) this clear split appears even more clearly, with
 516 low salinity PA simulations also having low water flux PA (Figure S5B; left-bottom) and
 517 simulations with comparatively high salinity PA also having high surface water flux PA. There
 518 appears a clear increase in PA (Figure S5B; colours – blue to red) from the lower left (noise)
 519 to the upper right (signal), with simulations with large PA values tending to be those which
 520 report a larger warming (Figure S5A).
 521



522
 523 Figure S5. Pattern amplification (PA) rates for all available 20th century (20C3M; 1950-2000) de-drifted CMIP3
 524 simulations. Diamonds represent 20C3M simulations which include volcanic aerosol forcing, circles are
 525 simulations without volcanic aerosol forcing. The number of individual simulations which have been analysed
 526 for each variable is noted in the bottom right hand corner of each panel. For A) Surface salinity (y-axis) versus
 527 the corresponding global average surface temperature change (ΔT_a ; x-axis). B) Water flux (E-P; y-axis) versus
 528 surface salinity (x-axis). Colours are the salinity pattern correlation (PC) for both panels A & B. Grey lines
 529 express constant proportional change. Grey shading (99% C.I.) bounds the correlation-weighted linear best fit
 530 to the model ensemble for a line intersecting 0 in black.
 531

532 The full ranges of CMIP3 20C3M change responses for 1950-2000 are contained in Table S2.
 533 These results include global change estimates for the 5 variables analysed, including; salinity
 534 and water flux (E-P) pattern amplification, ocean and global surface temperature and global
 535 mean rainfall changes (ΔP). For reference a comparative non-exhaustive selection of
 536 observed estimates from available data products is also included in the lower section of
 537 Table S2. The range of surface salinity responses, and spatial patterns of the associated drift
 538 estimates (see section above), along with 1950-2000 climatological surface salinity and
 539 water flux (E-P) means are contained in Figure S6.
 540

541 Table S2. Integrated global surface values for 1950-2000 trends resolved from available 20th century (20C3M)
 542 CMIP3 experiments, de-drifted by their corresponding pre-industrial control in: sea surface salinity (basin
 543 zonal-mean) pattern amplification (PA; %), ocean water flux (E-P) (basin zonal-mean) pattern amplification (PA;
 544 %), area-weighted global ocean surface temperature (°C), area-weighted global surface temperature (°C) and
 545 area-weighted global surface mean precipitation change (%). A non-exhaustive selection of observational
 546 estimates from available data products are found in the lower section of the table for comparison. Trends have
 547 been obtained over the period in parentheses and scaled to represent directly comparable 50-yr changes.

#	Model	Salinity (%PA)	E-P (%PA)	Ocean Temperature (°C)	Global Temperature (°C)	Rainfall (Δ P)
1	bccr_bcm2_0.20c3m.run1	+2.5	-	-	+0.41	+0.1
2	cccma_cgcm3_1_t47.20c3m.run1	+4.0	+3.4	+0.73	+1.10	+2.0
3	cccma_cgcm3_1_t47.20c3m.run2	+4.7	+3.7	+0.66	+1.04	+1.7
4	cccma_cgcm3_1_t47.20c3m.run3	+5.9	+4.9	+0.66	+0.96	+2.0
5	cccma_cgcm3_1_t47.20c3m.run4	+4.9	+6.5	+0.67	+1.01	+2.1
6	cccma_cgcm3_1_t47.20c3m.run5	+6.3	+5.1	+0.61	+0.90	+1.8
7	cccma_cgcm3_1_t63.20c3m.run1	+6.6	+5.5	+0.74	+1.10	+1.8
8	cnrm_cm3.20c3m.run1	+8.3	+5.1	-	+0.74	+1.1
9	csiro_mk3_0.20c3m.run1	+2.2	+2.6	+0.42	+0.63	+1.0
10	csiro_mk3_0.20c3m.run2	+1.7	+0.4	+0.45	+0.69	+0.9
11	csiro_mk3_0.20c3m.run3	+2.2	+2.2	+0.38	+0.58	+0.8
12	csiro_mk3_5.20c3m.run1	+2.8	+2.1	+0.44	+0.71	+1.5
13	csiro_mk3_5.20c3m.run2	+6.8	+2.3	+0.59	+0.87	+1.4
14	csiro_mk3_5.20c3m.run3	+3.9	+2.0	+0.47	+0.64	+1.1
15	gfdl_cm2_0.20c3m.run1	+4.3	+0.5	+0.02	+0.09	-0.7
16	gfdl_cm2_1.20c3m.run2	+2.6	+1.6	+0.21	+0.29	-0.6
17	giss_aom.20c3m.run1	+2.5	-	+0.35	+0.49	+0.5
18	giss_aom.20c3m.run2	+3.7	-	+0.27	+0.39	+0.4
19	giss_model_e_h.20c3m.run1	+4.7	-	-	+0.34	-0.2
20	giss_model_e_h.20c3m.run2	+6.0	-	-	+0.24	-0.6
21	giss_model_e_h.20c3m.run3	+5.2	-	-	+0.25	-0.4
22	giss_model_e_h.20c3m.run4	+3.4	-	-	+0.25	-0.7
23	giss_model_e_h.20c3m.run5	+5.9	-	-	+0.31	-0.7
24	giss_model_e_r.20c3m.run1	-0.1	+0.9	+0.13	+0.18	-0.8
25	giss_model_e_r.20c3m.run2	+4.9	+2.9	+0.13	+0.27	-0.9
26	giss_model_e_r.20c3m.run3	+2.3	+0.1	+0.12	+0.23	-1.1
27	giss_model_e_r.20c3m.run4	-0.1	-0.2	+0.22	+0.39	-0.7
28	giss_model_e_r.20c3m.run5	+0.9	+0.8	+0.20	+0.37	-0.6
29	giss_model_e_r.20c3m.run6	+3.2	+0.1	+0.15	+0.27	-0.8
30	giss_model_e_r.20c3m.run7	+0.6	-0.0	+0.15	+0.34	-0.7
31	giss_model_e_r.20c3m.run8	+2.3	+1.4	+0.18	+0.32	-0.8
32	giss_model_e_r.20c3m.run9	+2.7	+1.5	+0.13	+0.26	-0.9
33	iap_fgoals1_0_g.20c3m.run1	+9.4	+0.5	+0.48	+0.80	+0.8
34	iap_fgoals1_0_g.20c3m.run2	+7.5	-	-	+0.83	+1.2
35	iap_fgoals1_0_g.20c3m.run3	+10.2	-	-	+0.74	+0.7
36	ingv_echam4.20c3m.run1	+2.2	-	+0.53	+0.73	+1.4
37	ipsl_cm4.20c3m.run1	+5.4	-	+0.42	+0.60	+0.9
38	miroc3_2_hires.20c3m.run1	+1.7	-0.4	+0.37	+0.48	-0.1
39	miroc3_2_medres.20c3m.run1	+4.8	+2.3	+0.16	+0.23	-0.5
40	miub_echo_g.20c3m.run1	+0.4	+0.00	+0.13	+0.29	-0.3
41	miub_echo_g.20c3m.run2	+4.4	+2.0	+0.21	+0.32	-0.4

#	Model	Salinity (%PA)	E-P (%PA)	Ocean Temperature (°C)	Global Temperature (°C)	Rainfall (ΔP)
42	miub_echo_g.20c3m.run3	+1.0	+0.2	+0.16	+0.22	-0.5
43	mpi_echam5.20c3m.run1	-	-	-	+0.48	+0.6
44	mpi_echam5.20c3m.run2	-	-	-	+0.24	-0.2
45	mpi_echam5.20c3m.run3	-	-	-	+0.44	+0.9
46	mri_cgcm2_3_2a.20c3m.run1	+3.5	+3.3	-	+0.65	+1.1
47	mri_cgcm2_3_2a.20c3m.run2	+1.9	+3.8	-	+0.62	+1.1
48	mri_cgcm2_3_2a.20c3m.run3	+2.0	+3.3	-	+0.69	+1.5
49	mri_cgcm2_3_2a.20c3m.run4	+1.6	+3.0	-	+0.59	+0.8
50	mri_cgcm2_3_2a.20c3m.run5	+4.2	+4.2	-	+0.63	+1.4
51	ncar_ccsm3_0.20c3m.run1	-	-	-	+0.32	-0.2
52	ncar_ccsm3_0.20c3m.run3	-	-	-	+0.52	+0.2
53	ncar_pcm1.20c3m.run1	-	-	-	-	-
54	ncar_pcm1.20c3m.run3	-	-	-	-	-
55	ncar_pcm1.20c3m.run4	-	-	-	-	-
56	ukmo_hadcm3.20c3m.run1	+0.1	+1.7	-	+0.60	+0.5
57	ukmo_hadcm3.20c3m.run2	+4.7	+4.3	-	+0.67	+0.3
58	ukmo_hadgem1.20c3m.run1	+1.1	+1.3	+0.40	+0.60	+0.2
20C3M Models		20	16	16	23	23
20C3M Simulations		58	47	63	78	73
20C3M De-drifted Simulations		50	44	41	70	68
Ensemble Mean		+3.7	+2.0	+0.33	+0.50	+0.3
Ensemble Standard Deviation		+2.4	+1.8	+0.20	+0.25	+0.9
Observational Estimates		Salinity (%PA)	E-P (%PA)	Ocean Temperature (°C)	Global Temperature (°C)	Rainfall (ΔP)
Durack & Wijffels (2010; 1950-2000)		+8.0		+0.49		
Boyer <i>et al.</i> (2005; 1955-1998)		+5.2				
Wijffels <i>et al.</i> (in prep; 1960-2008)				+0.56		
HadCRUT3 (1950-2009)					+0.54	
GISTEMP (1950-2009)					+0.53	
Levitus <i>et al.</i> (2009; 1955-2009)				+0.25		
HadSST2 (1950-2009)				+0.37		
HadSST3 (1950-2006)				+0.27		
Kaplan V2 (1950-2009)				+0.24		
ERSST V3b (1950-2009)				+0.31		
OAFflux V3 (1958-2008)			+6.4			
GPCP V2.1 (1979-2008)						-3.7
GPCP V2.2 (1979-2010)						-4.7
CMAP (1979-2008)						-6.0

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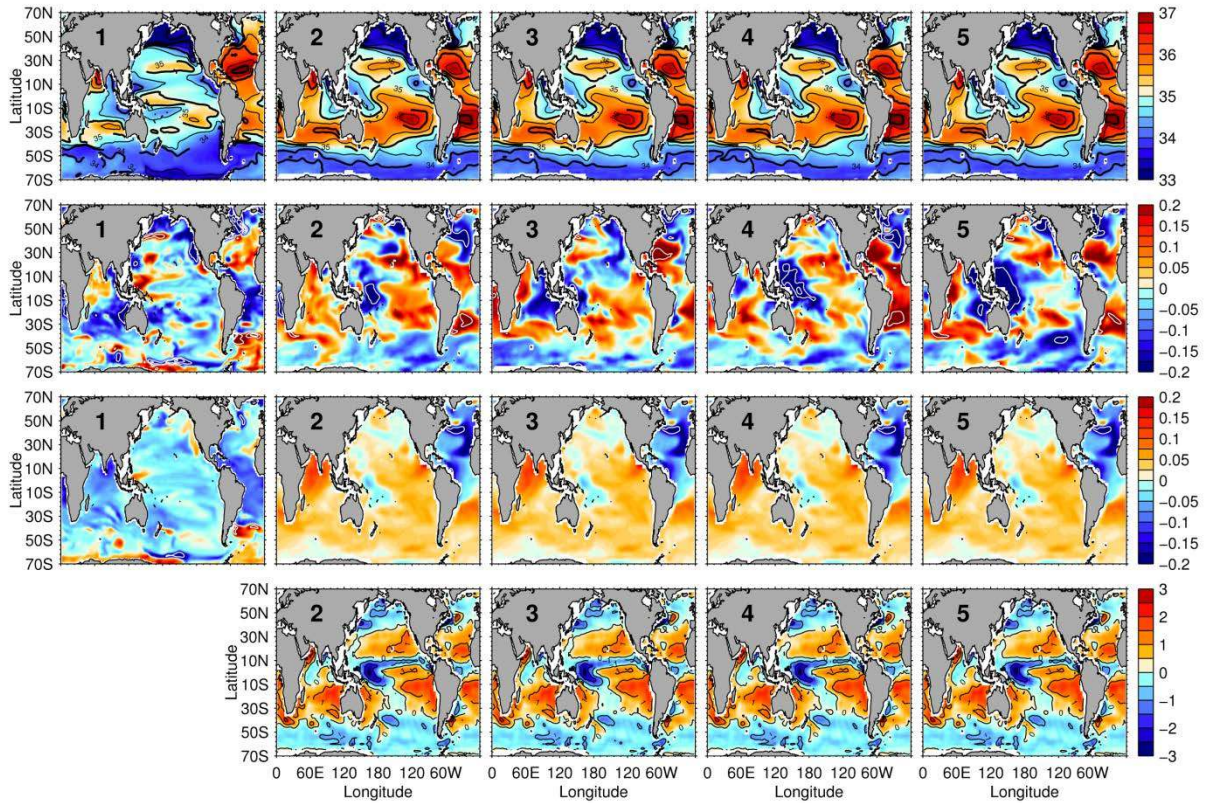
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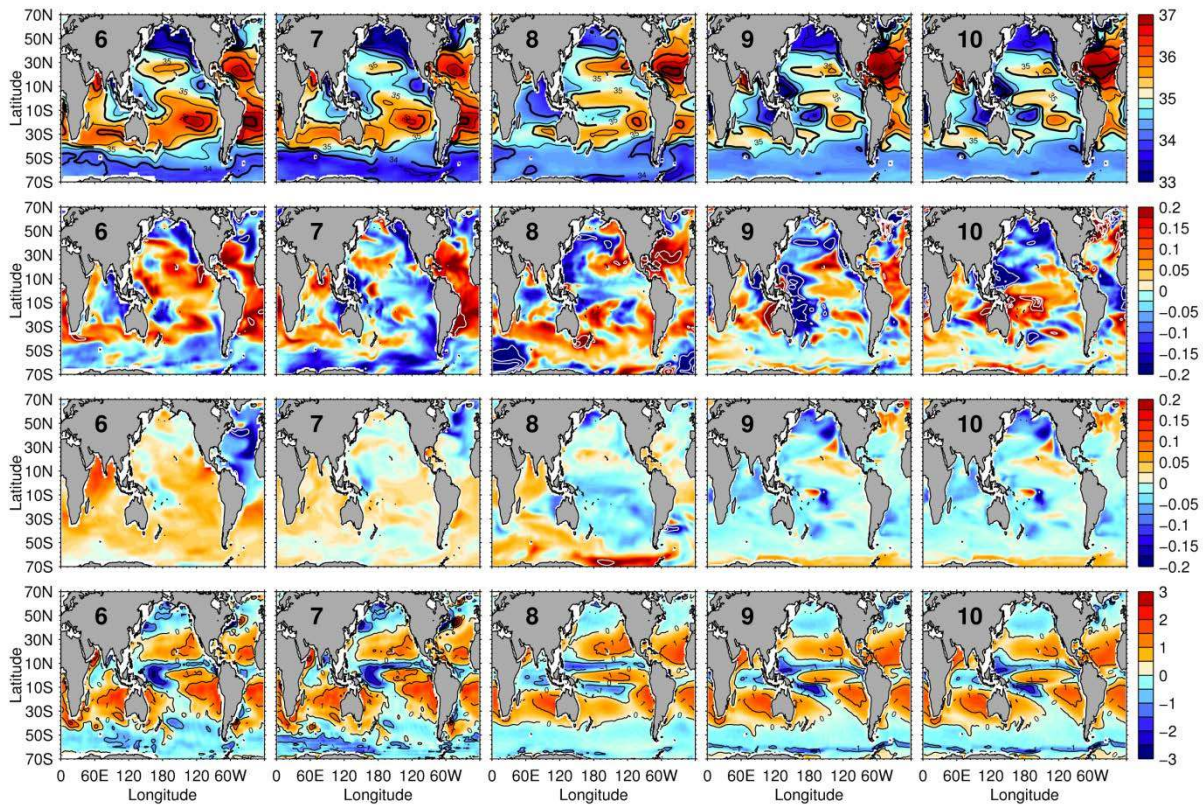
554

In order to present the full range of CMIP3 20C3M spatial salinity responses, each of the 58 available model salinity patterns are expressed in Figure S6. These panels show the 1950-2000 mean salinity (top row), the 1950-2000 linear trend (2nd row), the corresponding drift, as captured by a linear trend from the corresponding preindustrial control (PICNTRL) over the years 1900-2049 (3rd row), and the 1950-2000 mean E-P (bottom row).

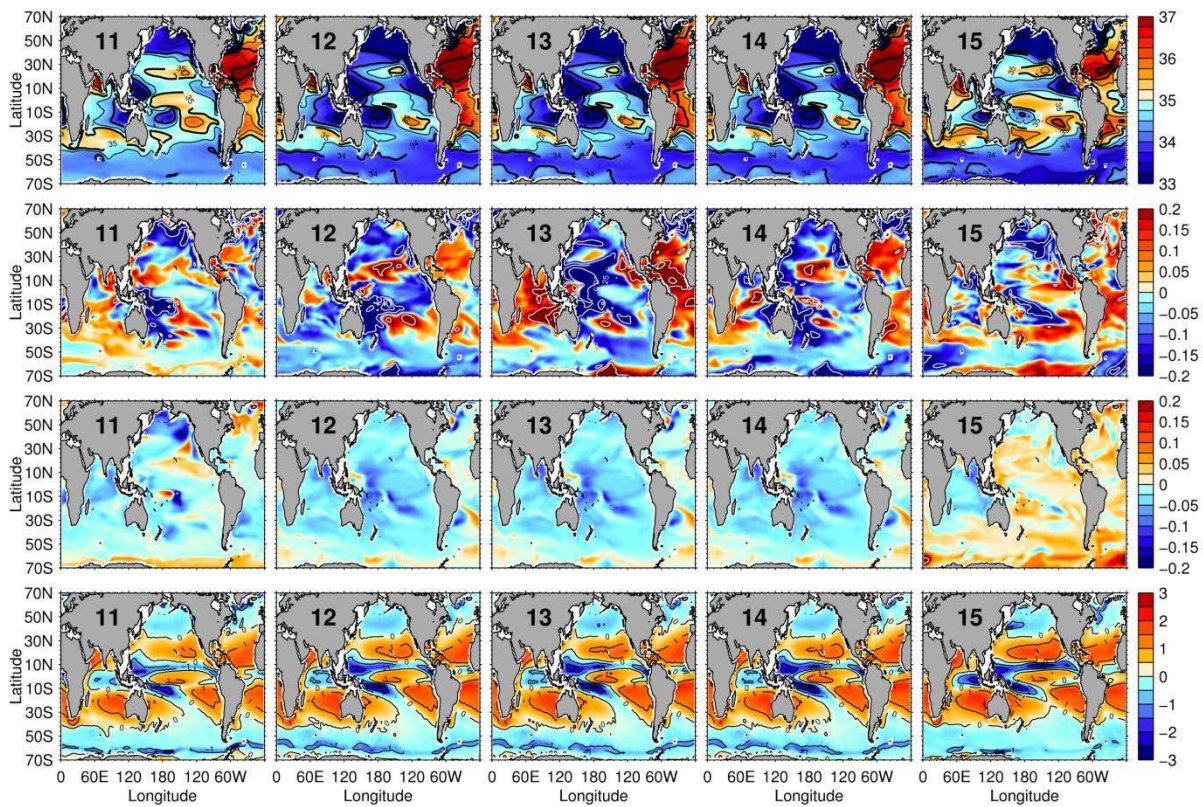
555 Figure S6. Ocean salinity amplification is expressed by 23 CMIP3 global climate models in their 20C3M
 556 simulations for the period 1950-2000. Top vertical panel represents surface mean salinity for 1950-2000,
 557 second vertical panel represents 20C3M surface salinity change for 1950-2000, third vertical panel represents
 558 the corresponding PICNTRL drift as determined for 1900-2049 and the lowest vertical panel represents surface
 559 mean water flux (E-P) for 1950-2000. Panel numbers represent each model/simulation as numbered in Table
 560 S2.



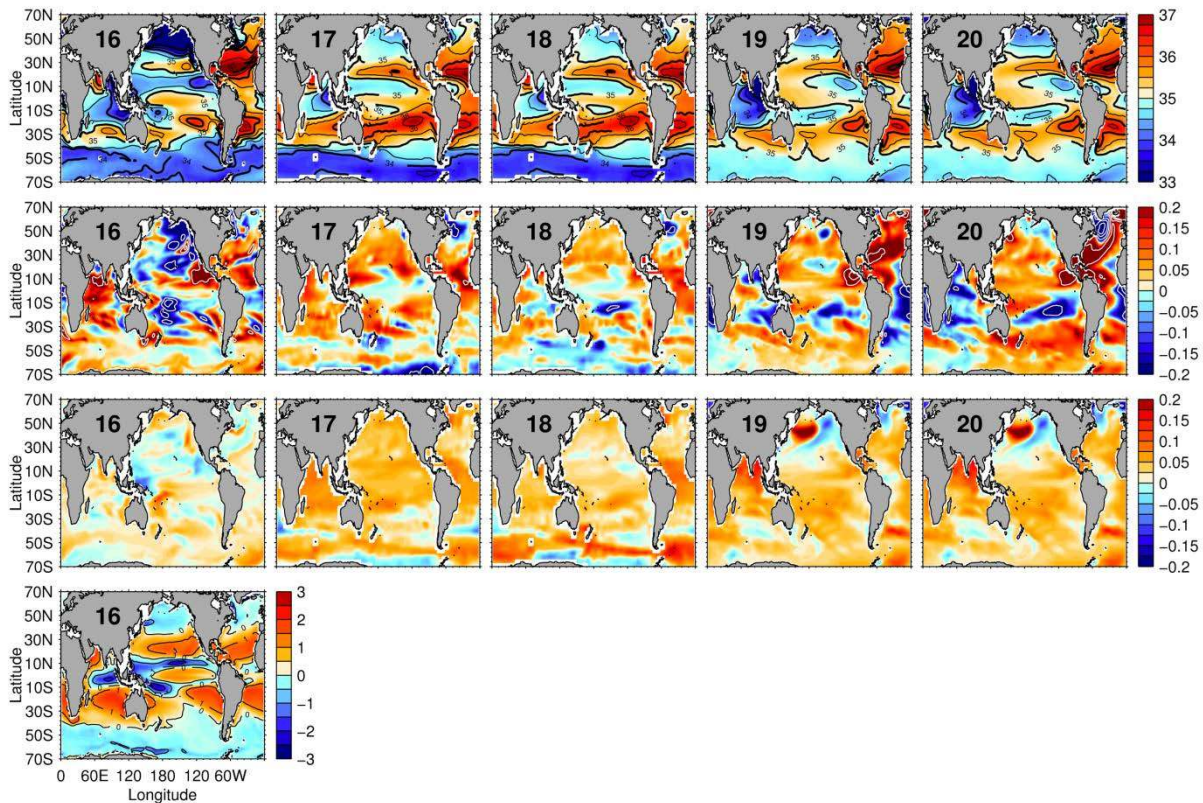
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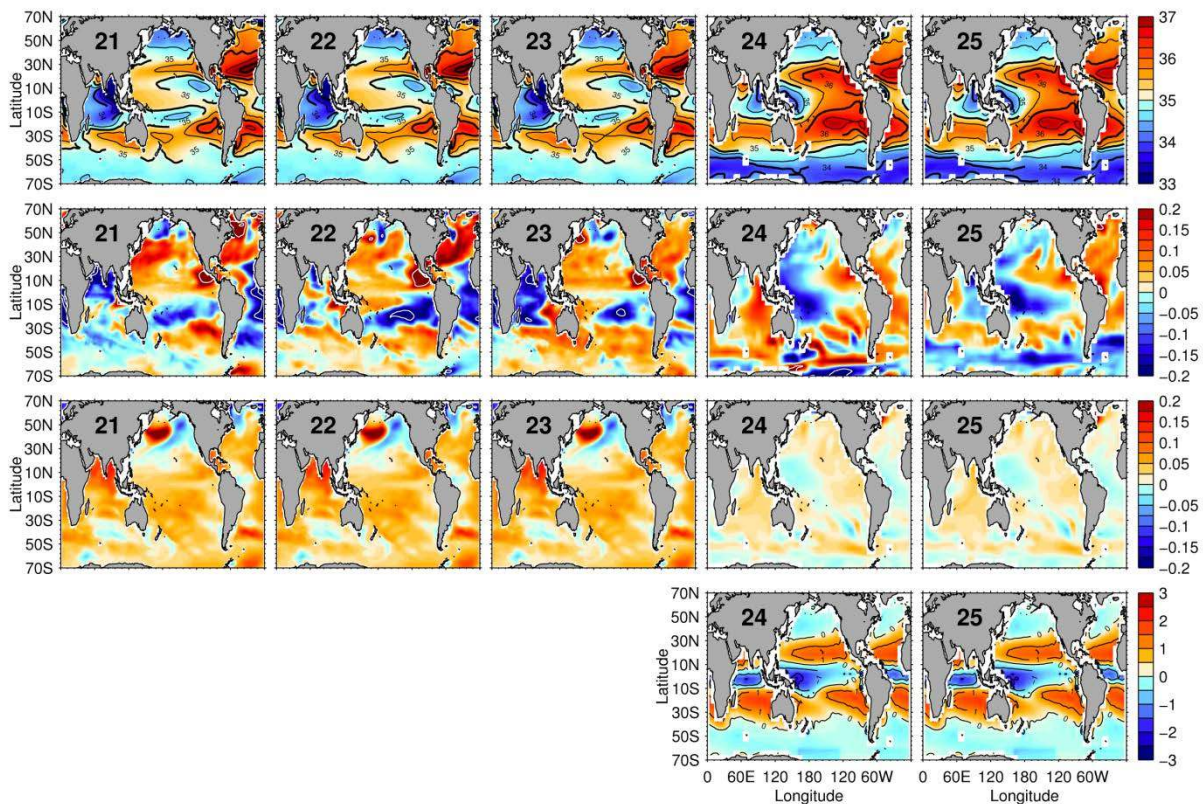
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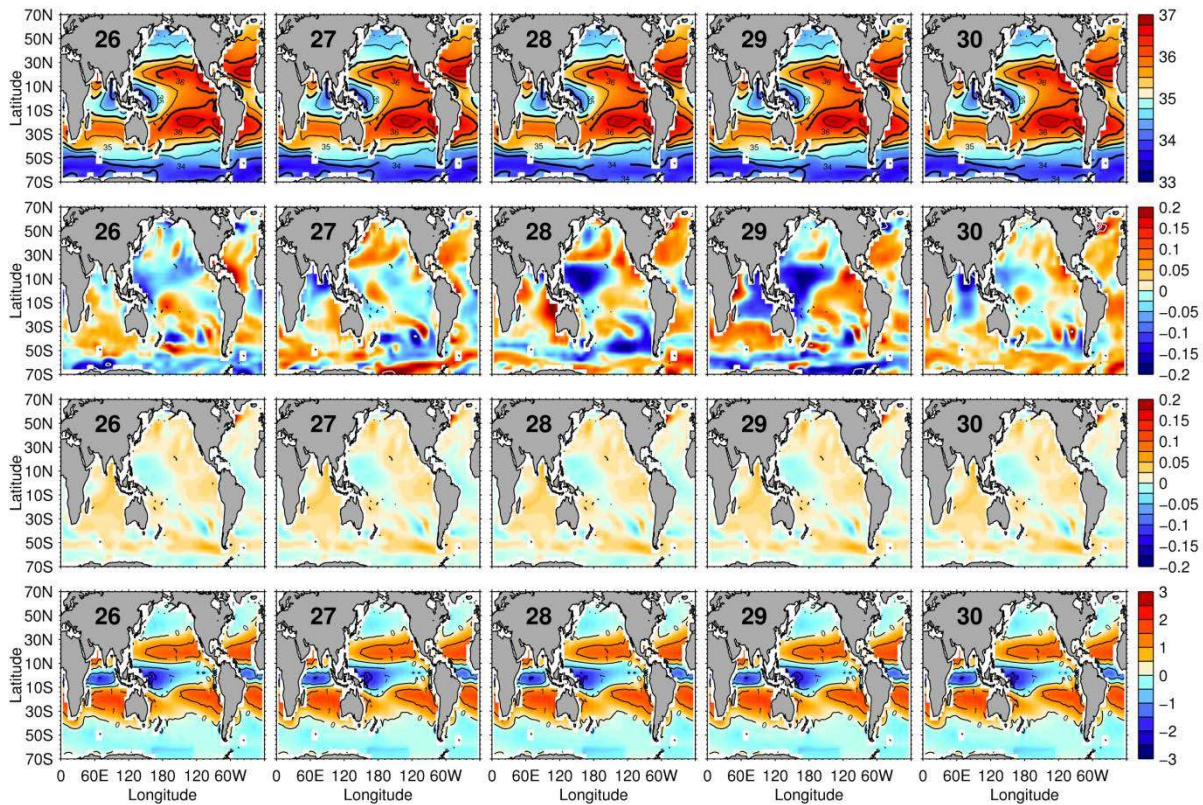
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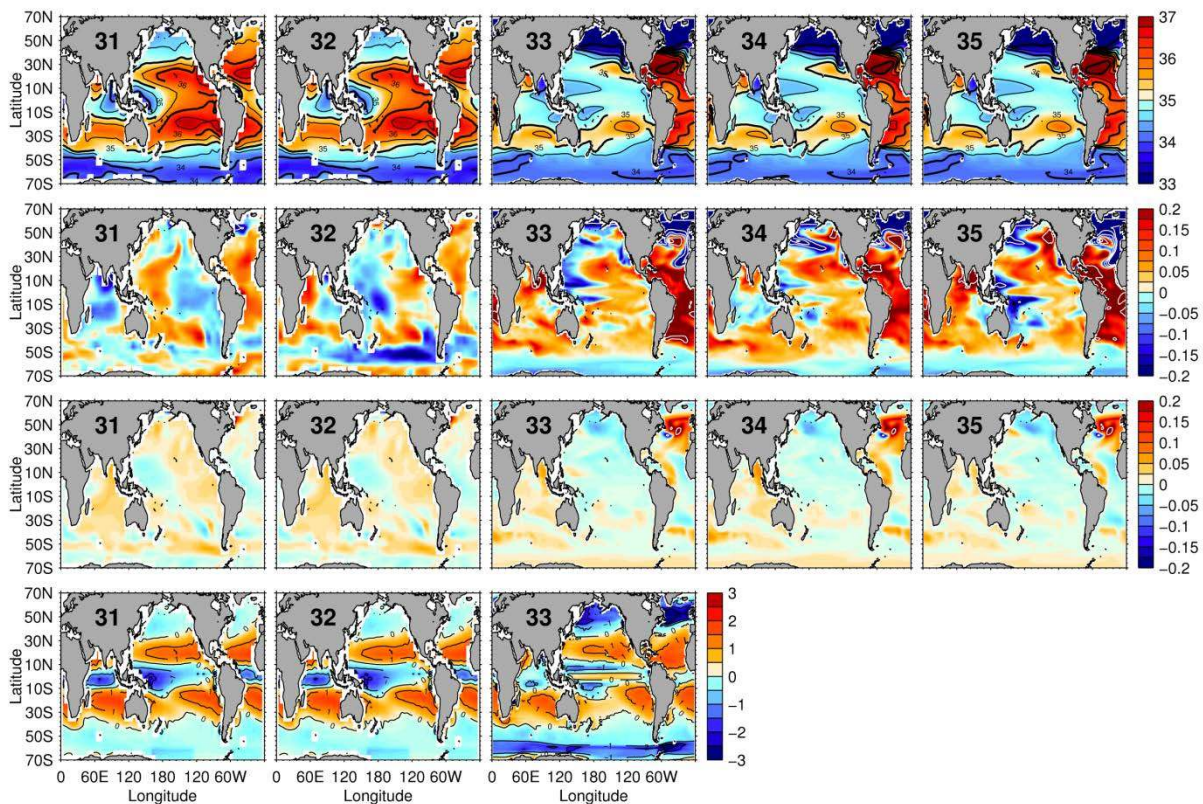
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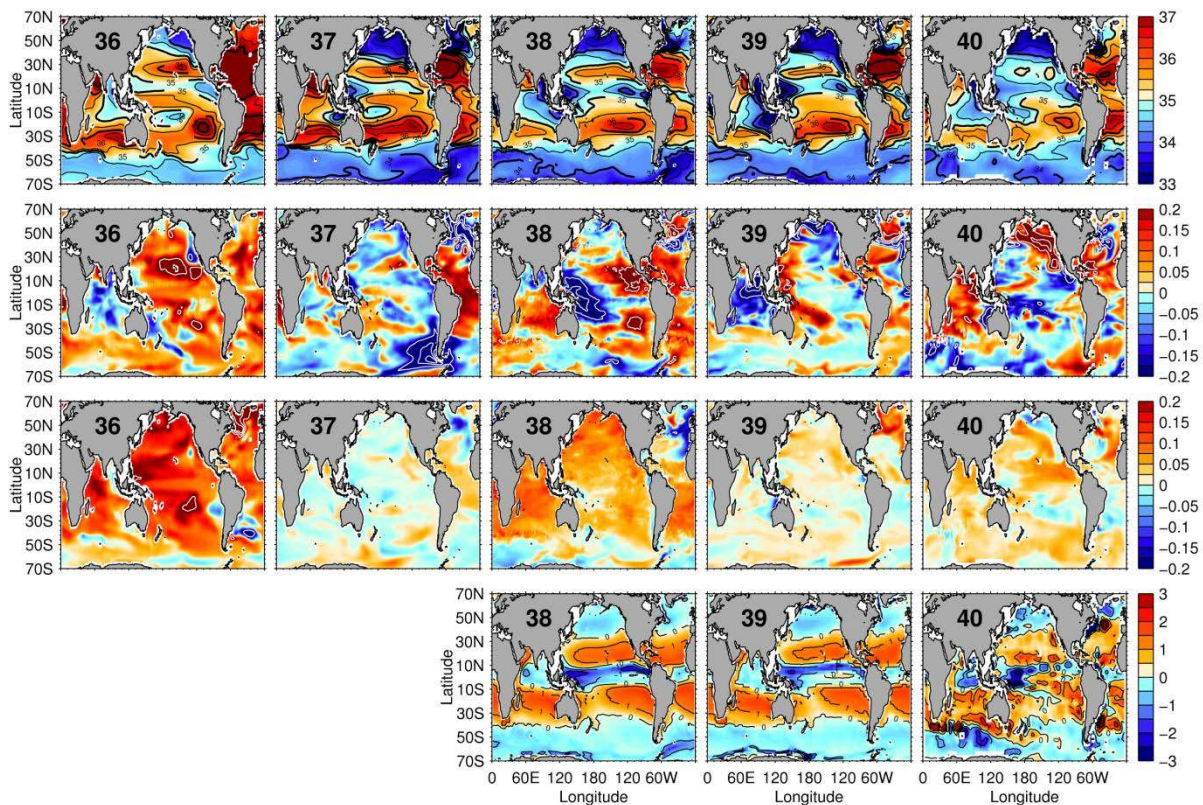
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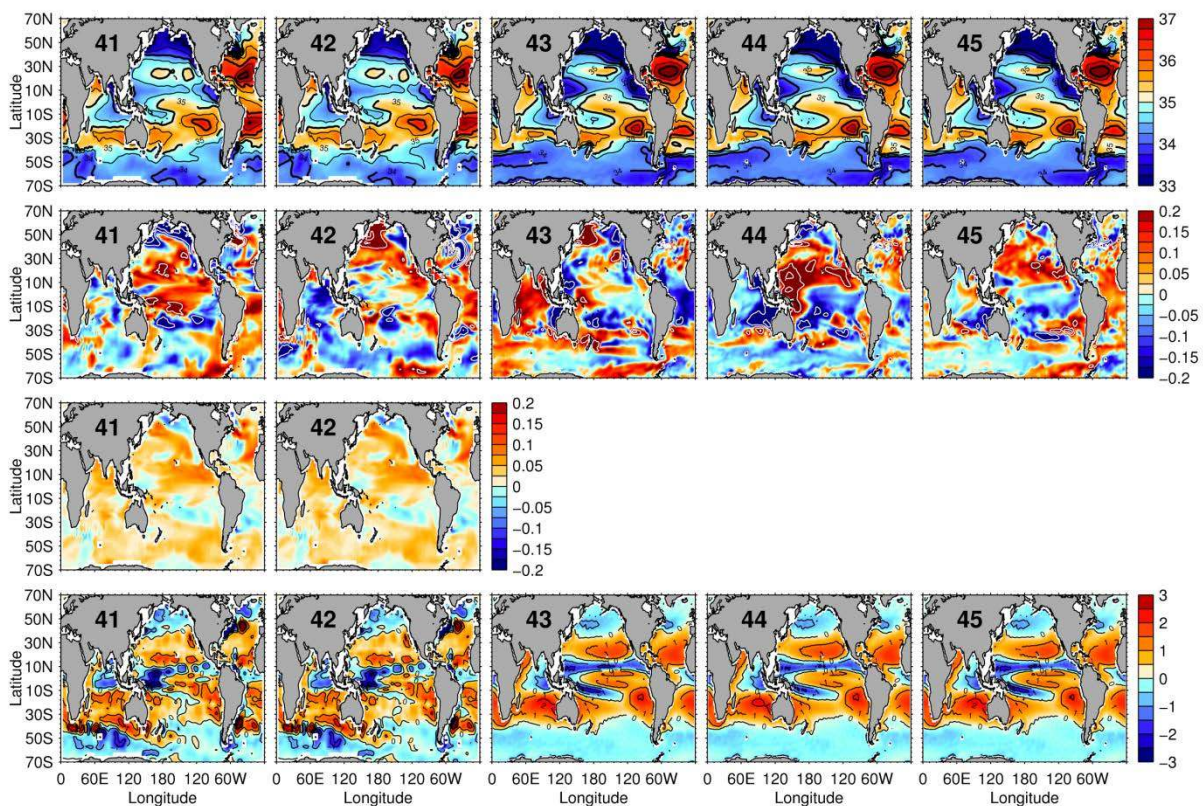
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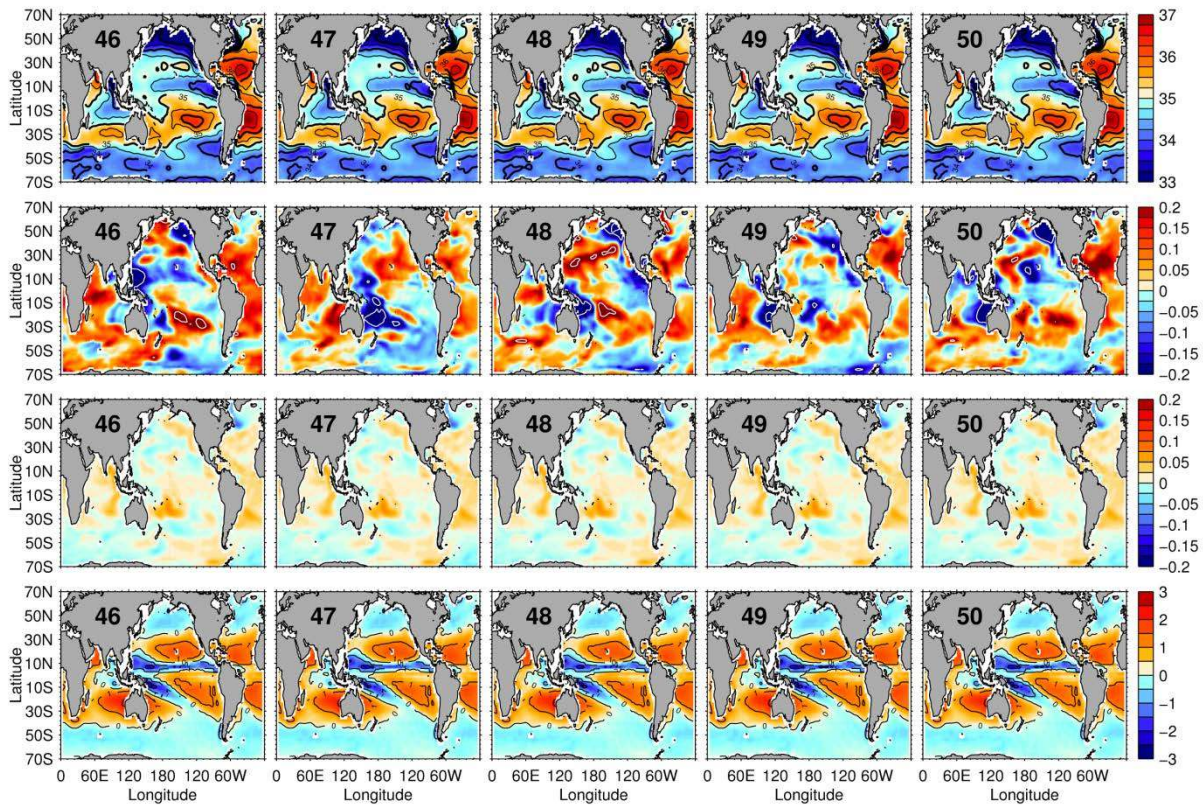
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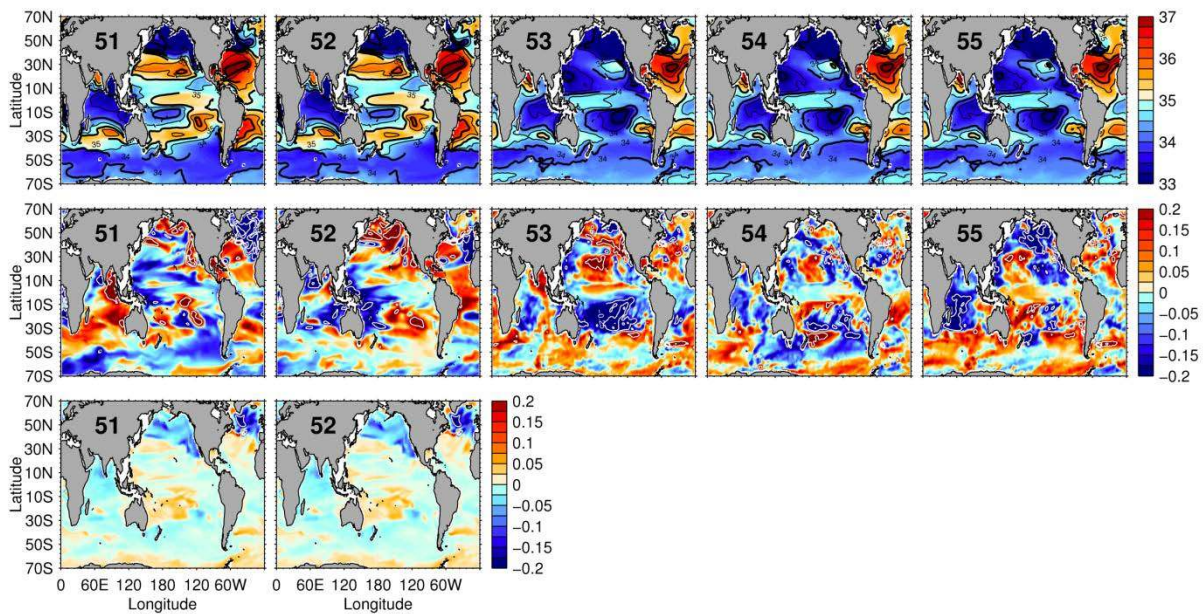
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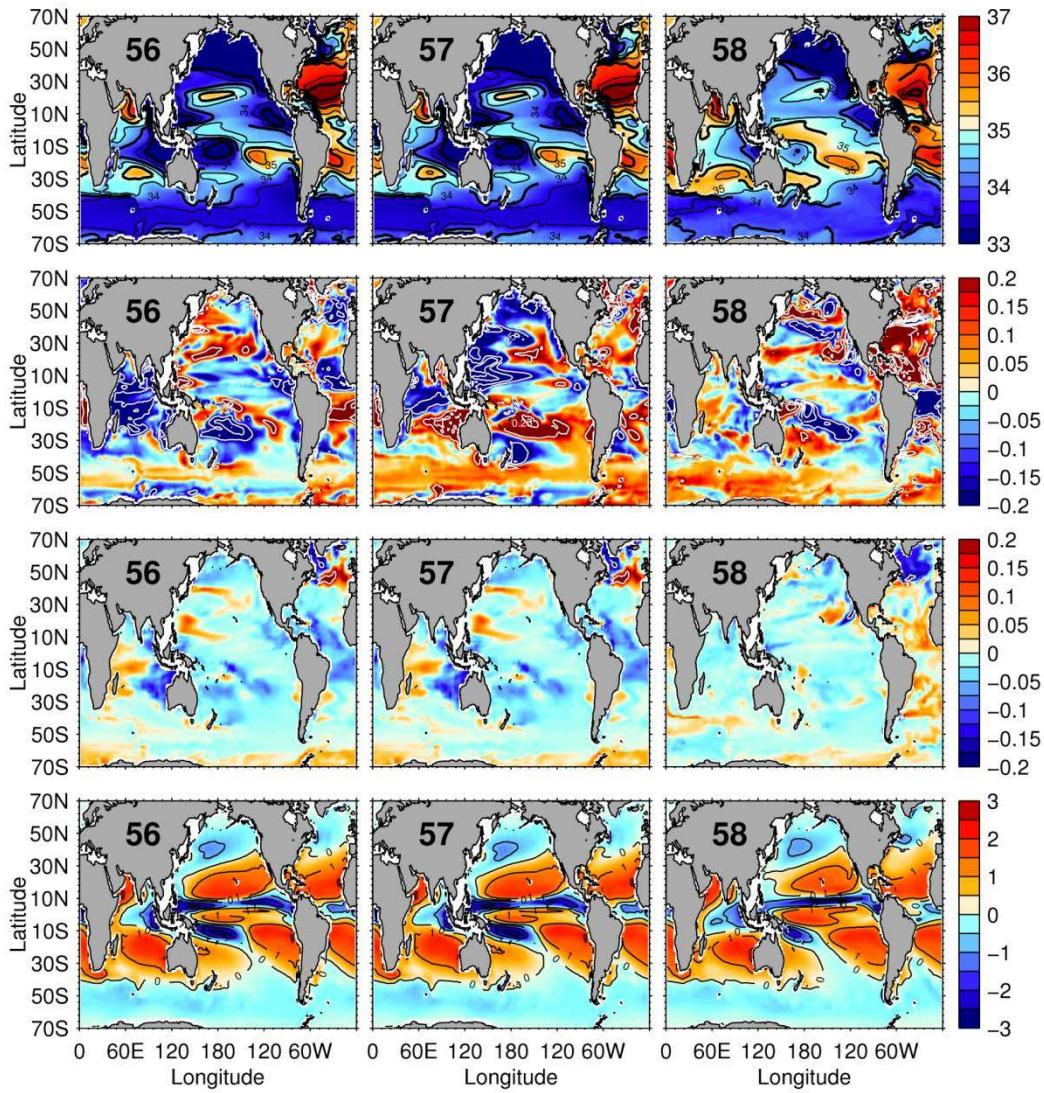
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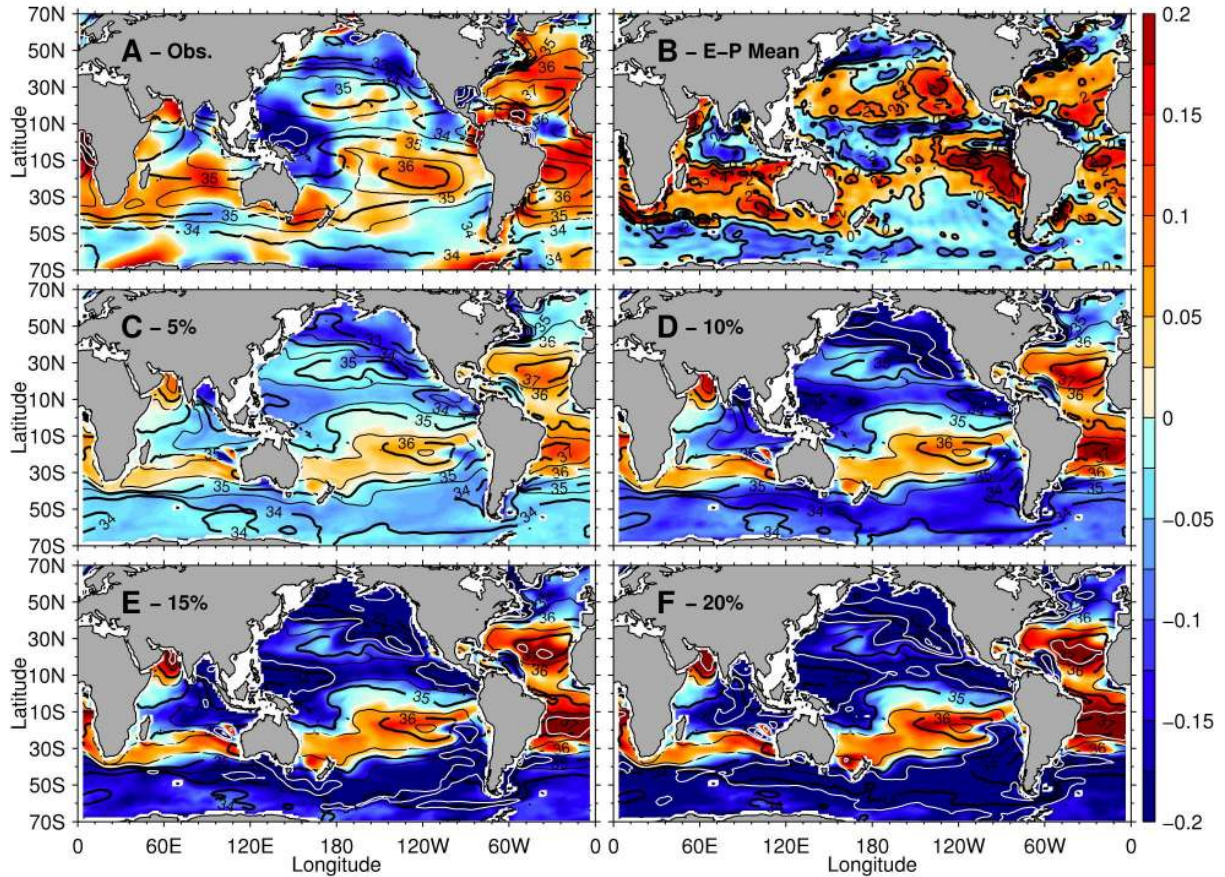
574 **Idealised Ocean-model Experiments**

575 For this experiment we used a version of the MOM3 ocean model (Matear & Lenton, 2008),
576 which was forced with surface water flux fields obtained from the NCEP reanalysis. These
577 experiments were constructed to test the salinity response to an idealised, linearly
578 increasing E-P forcing over an equivalent time period to the observational salinity analysis
579 (1950-2000). The model was spun-up over the representative years 1850 to 1948 with daily
580 surface fluxes. The ocean was initialised using the climatological fields of temperature and
581 salinity from the World Ocean Atlas 2001 (Conkright *et al.*, 2002). In order to minimise
582 modelled climate variability and enhance the spatial change signal in the idealised runs, a
583 single year (1948) from the NCEP-1 reanalysis (Kalnay *et al.*, 1996) was selected. This data
584 then provided the daily surface forcing fields; wind stresses, heat and water fluxes, which
585 were perennially applied to the ocean model. These 1948 annual fluxes were then used for
586 the model spin-up, 1850-1948 with both sea surface temperature (SST; Reynolds & Smith,
587 1994) and salinity (Conkright *et al.*, 2002) restored to annual climatologies on a 30-day
588 timescale. For the idealised runs, and the corresponding control run (which extended from
589 1948-2009), salinity restoring was not undertaken, however SST restoring was enabled. In
590 plots presented in Figure S7 & S8 we show the salinity change with the control run drift
591 removed, with the difference attributable to the idealised surface E-P forcing.

592
593 Linear increasing trends to surface water fluxes were imposed over the 1948-2009 period.
594 To attempt to capture the range of linear and non-linear responses to such surface water
595 flux changes, runs imposed with a 5%, 10%, 15% and 20% E-P change were undertaken,
596 additional to a control with no changes to surface water fluxes. These model runs were then
597 investigated for their surface (and subsurface) salinity changes, and compared to the
598 comparative 1950-2000 observed patterns of salinity change.

599
600 Each of the model runs (Figure S7C, D, E, F) express the surface salinity response for the 50-
601 year period over which the linear increasing trend to E-P was imposed, with the
602 corresponding control drift removed point-wise from each representative field. These
603 idealised runs tend to replicate the broad-scale patterns of the observational analysis
604 (Figure S7A). A coherent freshening of the Pacific is apparent, with the exception of a zonal
605 enhancement to surface salinities located along the subtropical salinity maxima, broadly
606 following the E-P maxima of the basin. In the Atlantic, strong surface salinity increases are
607 apparent aligned with the subtropical salinity maxima in both the North and South Atlantic.
608 In the Indian, an enhanced salinity is found in the Arabian Sea, with a strong freshening in
609 the Bay of Bengal. The enhanced salinity, associated with the subtropical salinity maxima is
610 much broader in observations when compared to the idealised model results.

611

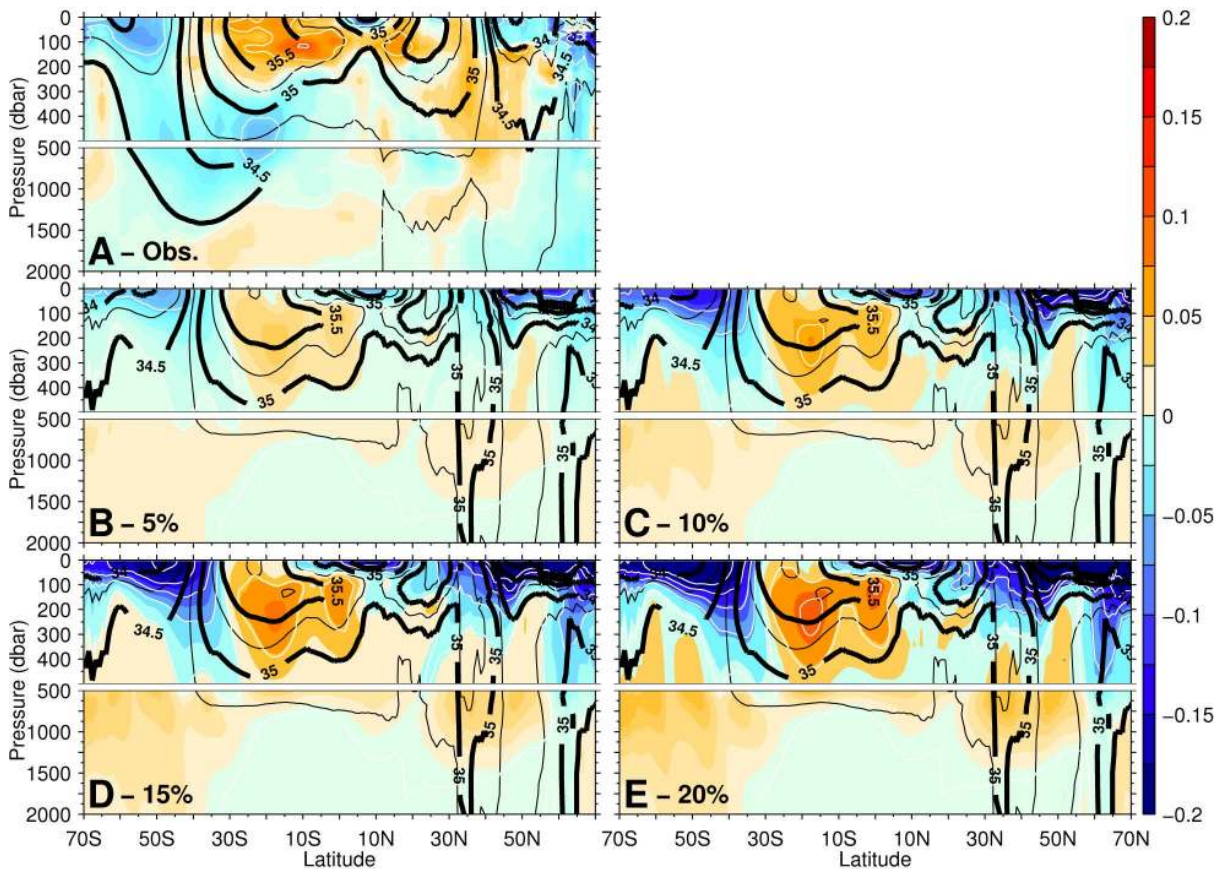


612

613 Figure S7. Patterns of 50-year surface salinity change (PSS-78 50 yr^{-1}). A) The 1950-2000 observational result of
 614 Durack & Wijffels (2010). B) The climatological annual mean surface water flux (m yr^{-1}) as obtained from NCEP-
 615 1 (Kalnay *et al.*, 1996). The idealised surface salinity response for a: C) 5%, D) 10%, E) 15% and F) 20% surface
 616 water flux enhancement over 50 years. For each panel, the corresponding mean salinity is contoured in black,
 617 with thick lines every 1 (PSS-78) and thin lines every 0.5 (PSS-78).

618

619 Additional to a surface salinity comparison, global subsurface zonal mean comparison was
 620 also undertaken (Figure S8). A strong coherence is found between the observed result
 621 (Figure S8A) and those of the idealised simulations. In these simulations the salty southern
 622 subtropical gyre bowl is expressing a strong enhanced salinity, whereas the Northern
 623 Hemisphere response is less coherent. The high latitude freshening is also captured in this
 624 model, however the subduction of this signal into the ocean interior is weaker than in
 625 observations, particularly in the Southern Hemisphere. This feature is most clear when
 626 comparing the climatological salinity (contoured) with a deep and clear salinity minima
 627 tongue visible extending to 1500 dbar in observations (Figure S8A), with this feature
 628 noticeably absent in the model (Figure S8B-E). The independent basin changes (not shown)
 629 provide even stronger evidence that regional basin-wide salinity changes, reported in
 630 observations are linked to E-P changes at the surface. We note that this model does not
 631 provide a perfect replication of the global ocean structure, with a weaker salinity minima
 632 subduction and circulation pathway into the deep interior when compared to our
 633 observational understanding (contrast S8A vs B, C, D, E). This would then lead to difficulties
 634 in interpreting deeper ocean changes on longer timescales (> 50-years) as the model
 635 replication of such deep ocean interior changes are likely to be muted when compared to
 636 observations.
 637



638

639 Figure S8. Patterns of 50-year subsurface zonal mean salinity change (PSS-78 50 yr⁻¹). A) The 1950-2000
 640 observational result of Durack & Wijffels (2010). The idealised subsurface salinity response for a: B) 5%, C)
 641 10%, D) 15% and E) 20% surface water flux enhancement over 50 years. For each panel, the corresponding
 642 mean salinity is contoured in black, with thick lines every 0.5 (PSS-78) and thin lines every 0.25 (PSS-78).

643 When comparing these idealised model simulations to those of the CMIP3 suite it is clear
 644 that this ocean-only simulation underestimates the CMIP3 1:2 relationship between E-P PA
 645 and SSS PA (not shown, with a value near 1:1). Three reasons for these differences may
 646 include:

- 647 1) A link exists between ocean warming and the SSS trend which amplifies the resolved
 648 SSS PA
- 649 2) Net sea-ice melt in the CMIP3 simulations provides an additional freshwater source
 650 term which is not included in the idealised ocean-only simulations
- 651 3) Terrestrial storage changes as captured by CMIP3 changes the relationship
 652

653 Some preliminary investigations suggest that ocean warming when coupled with the
 654 idealised E-P forcing does increase the SSS PA – this is possibly linked to increasing ocean
 655 stratification, where a smaller control volume is experiencing the effects of the E-P forcing.
 656 Some CMIP3 analyses (Russell *et al.*, 2006; Luo *et al.*, 2009; Joo Jang *et al.*, 2011) suggest
 657 such stratification changes will occur due to climate change, however, dynamically these
 658 changes are complex (Russell *et al.*, 2006). Changes to terrestrial E-P and the resulting runoff
 659 is another potential source of ocean change with more regional effects likely, however such
 660 effects are not captured in the idealised ocean-only simulations. The reduction in summer
 661 sea-ice in CMIP3 projections, particularly in the Arctic (e.g. Zhang & Walsh, 2006; Wang &
 662 Overland, 2009) could also drive strong change, with large SSS declines in the high latitudes
 663 suggesting this process may be operating – we note again however that dynamic ice
 664 processes are not included in these idealised ocean-only simulations.
 665

666 The lack of these 3 processes in the idealised ocean-only simulations makes the CMIP3
 667 simulations a better choice in which to calibrate the E-P PA and SSS PA.

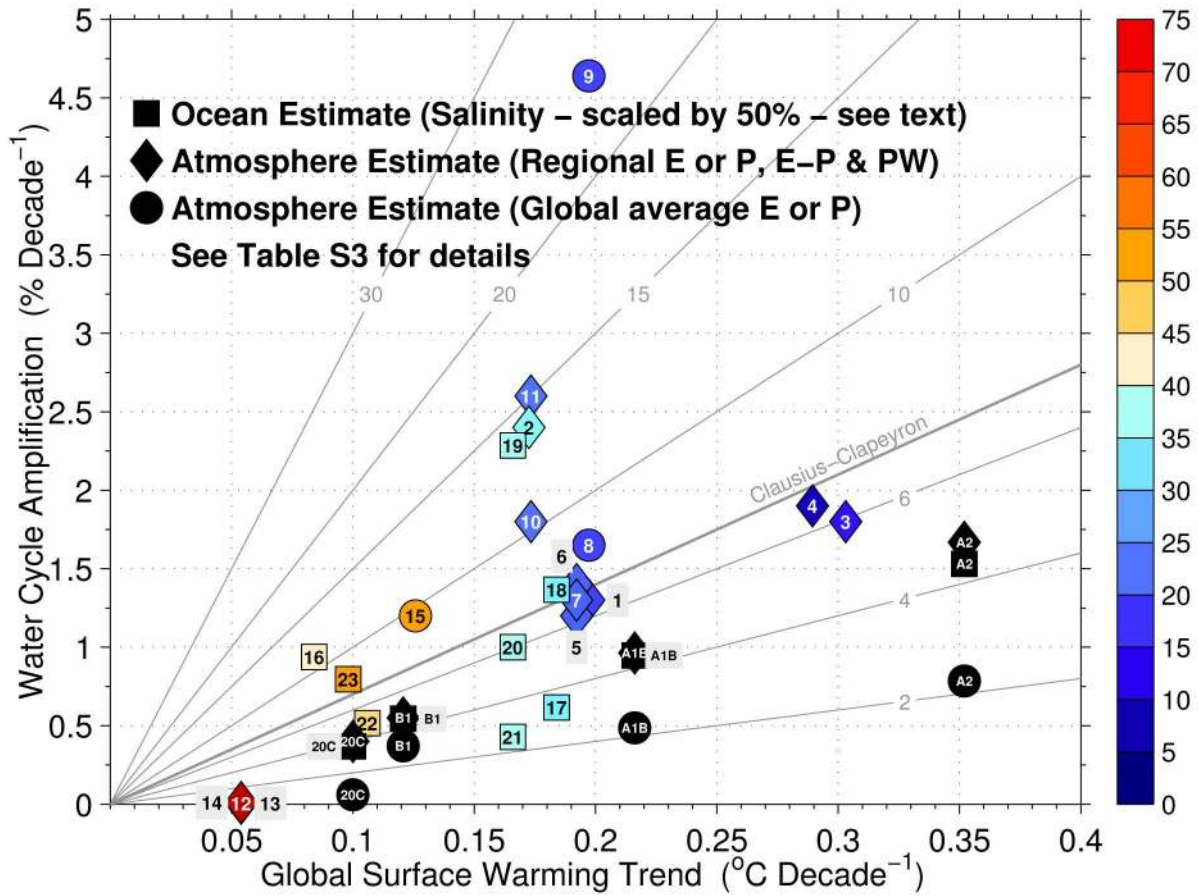
668 **Observational Estimates of Water Cycle Change**

669 Estimates of water cycle change have been obtained from numerous observational and
 670 satellite-based platforms. How do resolved changes from differing observed platforms
 671 compare to the new water cycle change estimate expressed by ocean salinity from 1950-
 672 2000? In Figure S9 we compile observed water cycle change estimates from many selected
 673 studies, with each of these expressing the explicit rate of water cycle rate per degree of
 674 global surface warming over the corresponding period of analysis, obtained from HadCRUT3
 675 (Brohan *et al.*, 2006).
 676

677 It is clear when reviewing the comparative results presented in Figure S8 that a large portion
 678 of these observed estimates suggest that a water cycle response on or near Clausius-
 679 Clapeyron ($7\% \text{ } ^\circ\text{C}^{-1}$) is apparent. It is also clear that no matter which CMIP3 ensemble mean
 680 estimate is utilised (salinity, E-P or global mean rainfall), these tend to provide conservative
 681 estimates of such changes when compared to the available observational comparisons.
 682

683 Many of the presented atmospheric estimates provide trends obtained over periods less
 684 than 30-years, and so decadal climate variability may strongly influence such short-term
 685 trends. Additionally, the use of satellite data from numerous independent missions ensures
 686 that difficulties with cross-mission calibration can strongly influence the magnitude and sign
 687 of the resolved trends (see main text).
 688

689



690

691 Figure S9. Reported observed water cycle changes (scaled in relative absolute change decade⁻¹). Colours
 692 indicate years over which reported changes are calculated (red is longer). As noted in the figure, ocean salinity
 693 estimates are presented as squares (scaled by 50% of their reported magnitudes to represent equivalent E-P
 694 change as obtained from the CMIP3 ensemble relationship, see text), atmospheric water cycling estimates
 695 (non-average global rainfall/evaporation) are triangles and average global rainfall/evaporation are circles. All
 696 ΔT_a trends were obtained from HadCRUT3 (Brohan *et al.*, 2006) using a linear fit over the corresponding years
 697 (annual data) used to determine the water cycle change estimate. More detail, including error estimates for
 698 each of the noted studies is contained in Table S1. The result suggested by this study is #23. For reference,
 699 equivalent scenario ensemble mean changes for the 20C3M (1950-2000; 20C) and SRES (2050-2099; B1, A1B,
 700 A2) simulations are included in black. Grey lines express constant proportional change; line representing
 701 Clausius-Clapeyron (CC) is 7% °C⁻¹. A total of 14 independent studies and 23 estimates of global and regional
 702 changes which express different aspects of water cycle change are presented.
 703

704 Table S3: Some representative observed water cycle changes for the 20th and early 21st century, as expressed
 705 in Figure S8. Salinity estimates are scaled by 50% (in Figure S9; unscaled salinity values are expressed below) to
 706 represent E-P changes using the relationship obtained from the CMIP3 model suite (see main text). All global
 707 warming trends were obtained from HadCRUT3 (Brohan *et al.*, 2006) as a linear trend over the period of
 708 analysis, following the MetOffice smoothed annual average temperature technique described at
 709 <http://hadobs.metoffice.com/hadcrut3/smoothing.html> (accessed 13th July 2011). Error estimates in the last
 710 column indicate formal errors resolved from the linear warming trend combined with water cycle error bounds
 711 (if available). Estimates are presented at 99% confidence for the warming plus the water cycle error.

	Author	Instrument	Region	Period	Change per Decade	Change per K
1	Trenberth <i>et al.</i> , 2005	SSM/I	Global PW	1987-2004	1.3±0.3%	7±16% K ⁻¹
2	Durre <i>et al.</i> , 2009	Radiosondes	Northern Hemisphere PW	1973-2006	2.4%	14% K ⁻¹
3	Keihm <i>et al.</i> , 2009	TMR	global PW 60°S-60°N	1992-2005	1.8±0.4%	6±9% K ⁻¹
4	Mieruch <i>et al.</i> , 2008	GOME & SCIAMACHY	Global PW	1996-2002	1.9±0.7%	7±4% K ⁻¹
5	Wentz <i>et al.</i> , 2007	SSM/I	Tropical PW	1987-2006	1.2±0.4%	6±11% K ⁻¹
6	Wentz <i>et al.</i> , 2007	SSM/I	Tropical P	1987-2006	1.4±0.5%	7±14% K ⁻¹
7	Wentz <i>et al.</i> , 2007	SSM/I	Tropical E	1987-2006	1.3±0.5%	7±13% K ⁻¹
8	Liepert & Previdi, 2009	OAFflux	Global Ocean E	1987-2004	1.6±0.8%	8±27% K ⁻¹
9	Liepert & Previdi, 2009	HOAPS	Global Ocean E	1987-2004	4.6±3.6%	24±95% K ⁻¹
10	Allan <i>et al.</i> , 2010	GPCP_V2.1/SSM/I	Tropical Hi-P	1988-2008	1.8±0.5%	10±23% K ⁻¹
11	Allan <i>et al.</i> , 2010	GPCP_V2.1/SSM/I	Tropical Lo-P	1988-2008	-2.6±0.8%	-15±9% K ⁻¹
12	Zhang <i>et al.</i> , 2007	GHCN	Land P 30°S-0	1925-1999	0.006%	<1% K ⁻¹
13	Zhang <i>et al.</i> , 2007	GHCN	Land P 0-30°N	1925-1999	-0.007%	<1% K ⁻¹
14	Zhang <i>et al.</i> , 2007	GHCN	Land P 40-70°N	1925-1999	0.01%	<1% K ⁻¹
15	Yu, 2007 (updated)	OAFflux_V3	Global Ocean E	1958-2008	1.2±0.5%	10±8% K ⁻¹
16	Curry <i>et al.</i> , 2003	Ocean profile data	E-P inferred (Atlantic salinity)	1950-1990	1.9% (5-10)	22% K ⁻¹
17	Hosoda <i>et al.</i> , 2009	Ocean profile data	E-P inferred (Global salinity)	1974-2005	1.2±1.5%	7±14% K ⁻¹
18	Hosoda <i>et al.</i> , 2009	Ocean profile data	E-P inferred (Southern Ocean salinity)	1974-2005	2.7±2.1%	15±22% K ⁻¹
19	Helm <i>et al.</i> , 2010	Ocean profile data	E-P inferred (Southern Ocean salinity)	1970-2005	4.6±1.7%	28±25% K ⁻¹
20	Helm <i>et al.</i> , 2010	Ocean profile data	E-P inferred (Northern Hemisphere Hi-latitude salinity)	1970-2005	2.0±1.1%	12±14% K ⁻¹
21	Helm <i>et al.</i> , 2010	Ocean profile data	E-P inferred (Subtropical gyres salinity)	1970-2005	-0.9±0.6%	-5±4% K ⁻¹
22	Boyer <i>et al.</i> , 2005	Ocean profile data	Global Ocean surface salinity	1955-1998	1.0±0.1%	10±7% K ⁻¹
23	This study	Ocean profile data	Global Ocean surface salinity	1950-2000	1.6±0.1%	16±7% K ⁻¹
-	This study	Ocean profile data	Pacific Ocean surface salinity	1950-2000	1.4±0.1%	15±7% K ⁻¹
-	This study	Ocean profile data	Atlantic Ocean surface salinity	1950-2000	1.4±0.1%	15±7% K ⁻¹
-	This study	Ocean profile data	Indian Ocean surface salinity	1950-2000	1.2±0.1%	12±7% K ⁻¹

712

713

714 **References and Notes**

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