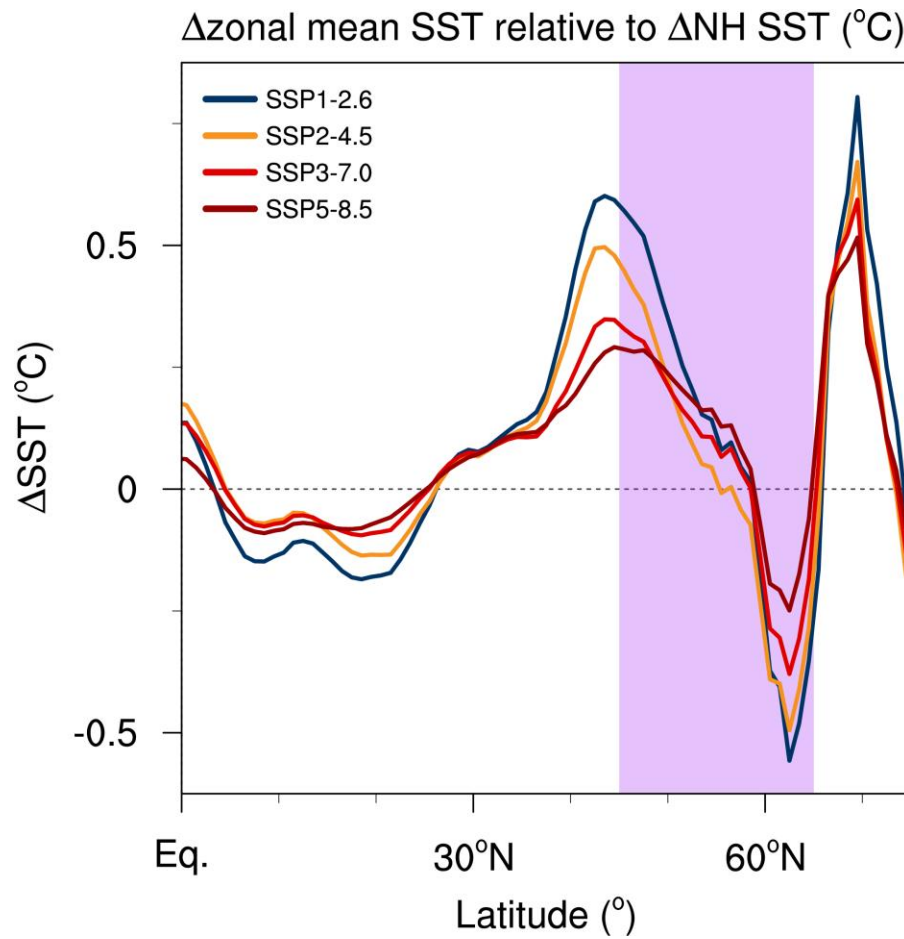
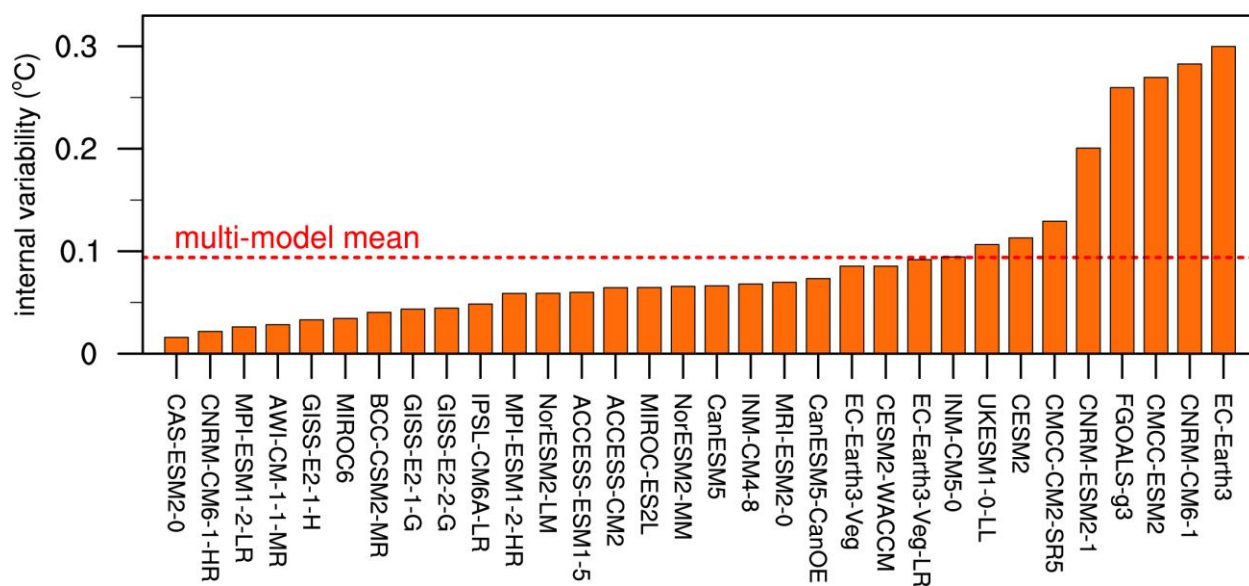


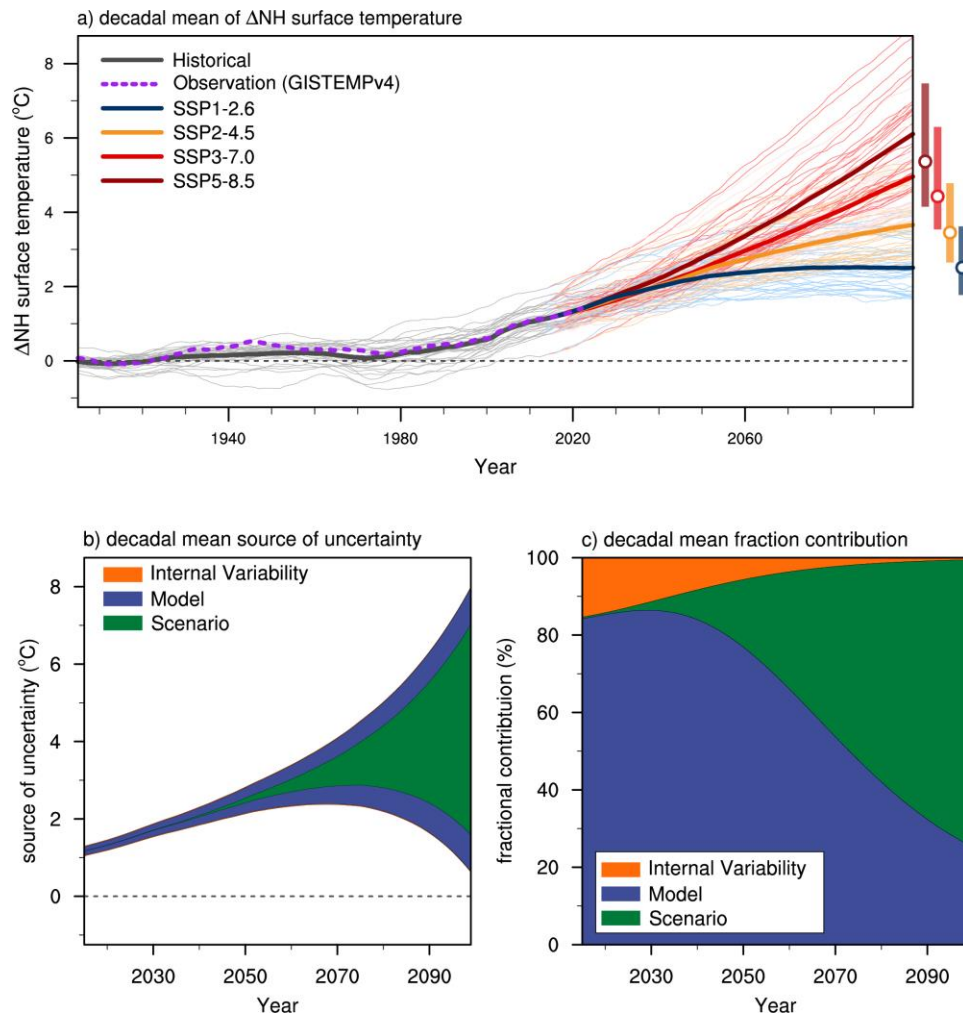


Supplementary Fig. 1. Future latitudinal mean SST changes relative to the Northern Hemisphere mean SST changes. The solid lines show the relative change in future (2070-2099) latitudinal mean SST by subtracting the NH mean SST change for each scenario from the multi-model mean of the 32 ESMs. The purple shading indicates the latitude where the warming hole occurs (45°N to 65°N).



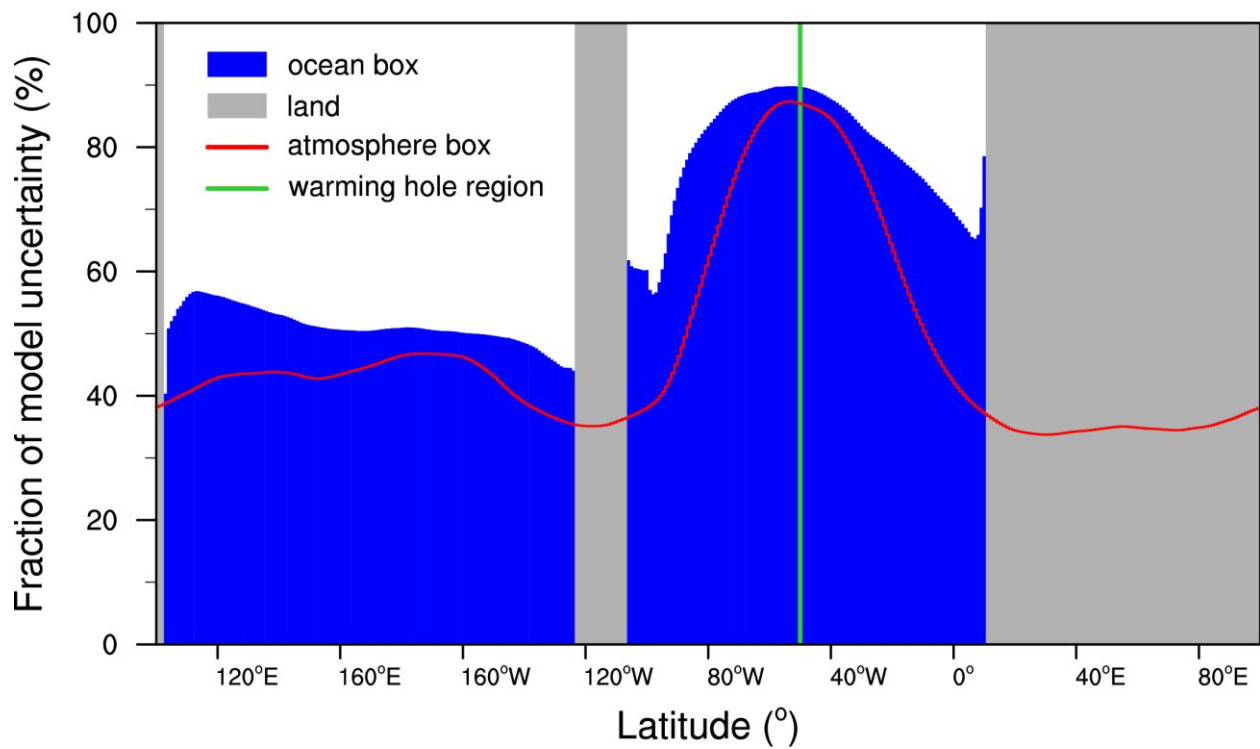
Supplementary Fig. 2. Internal variability for warming hole intensity in 32 CMIP6 ESMs.

The red dashed line indicates the multi-model mean.

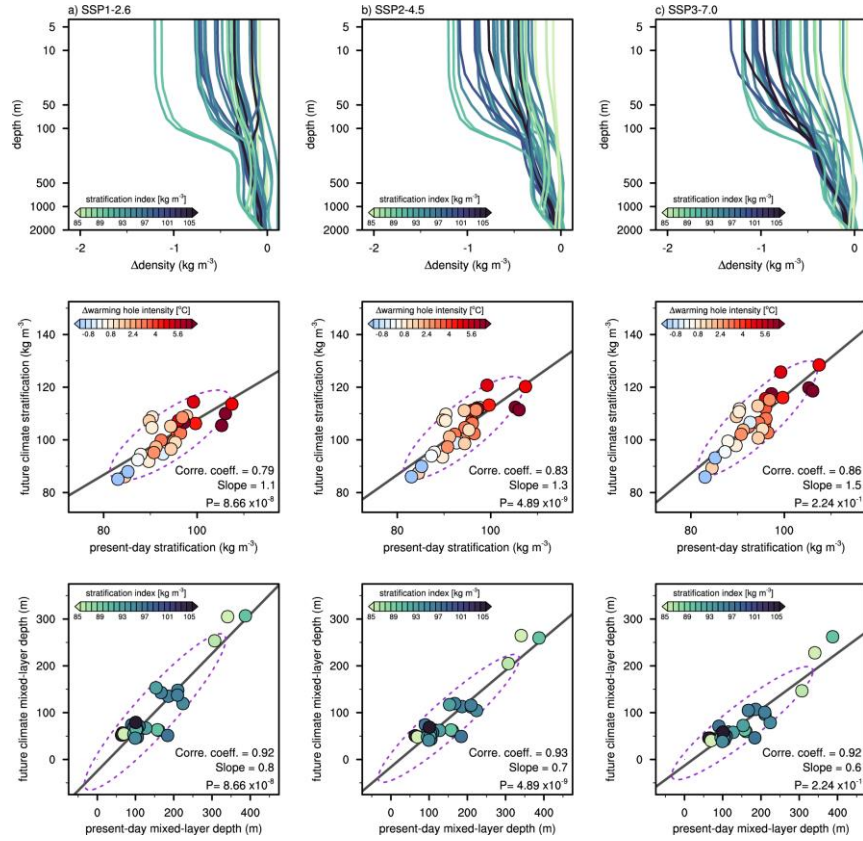


Supplementary Fig. 3. Time series of surface temperature in the northern hemisphere (NH)

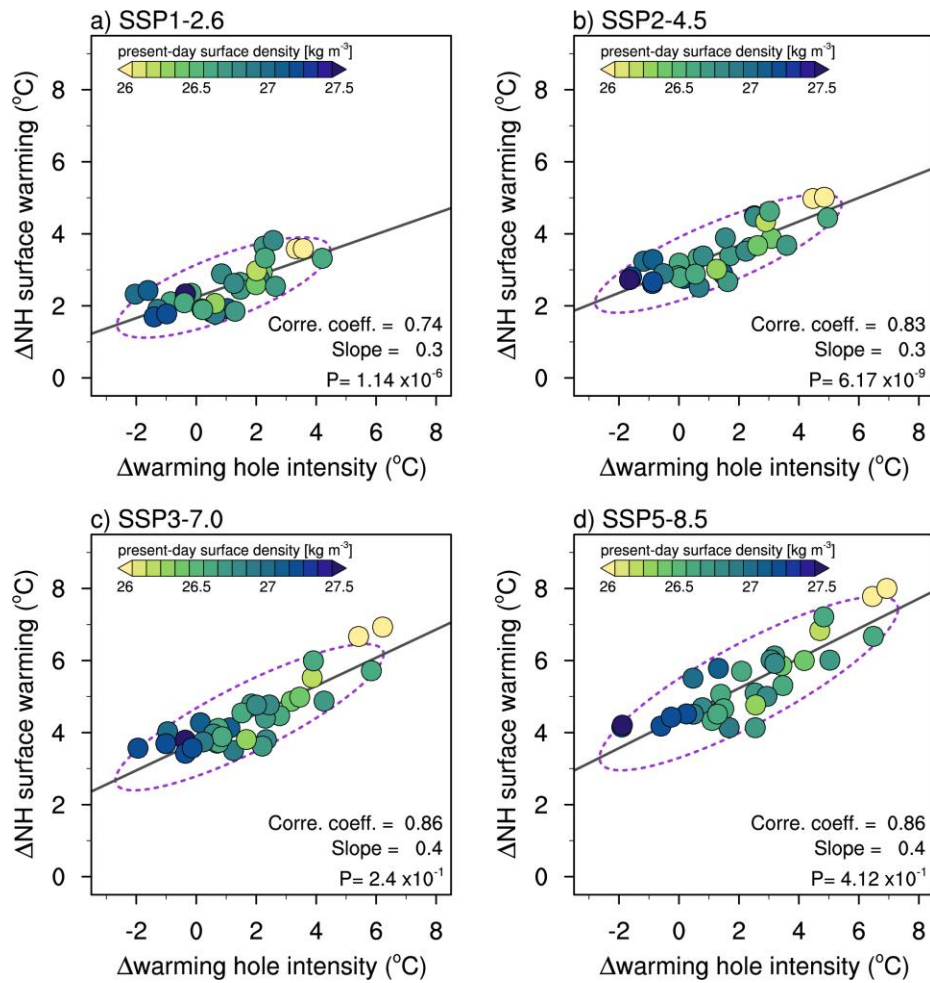
and the source of uncertainty. a, Decadal running means of the NH surface temperature from multi-model ensemble mean (MMEM) with observations (GISTEMP v4, purple dashed line), all relative to 1850–1900. The thick lines illustrate the MMEM of each scenario and the thin lines illustrate each earth system model (ESM). The bars illustrate the 90% range (5–95%) of the future change of NH surface warming during 2070–2099 among CMIP6 ESMs with MMEM (circles). **b,** Source of uncertainty in the multi-model multi-scenario mean projection of the NH surface warming. **c,** Fractional contribution of each source to the total uncertainty of the NH surface warming.



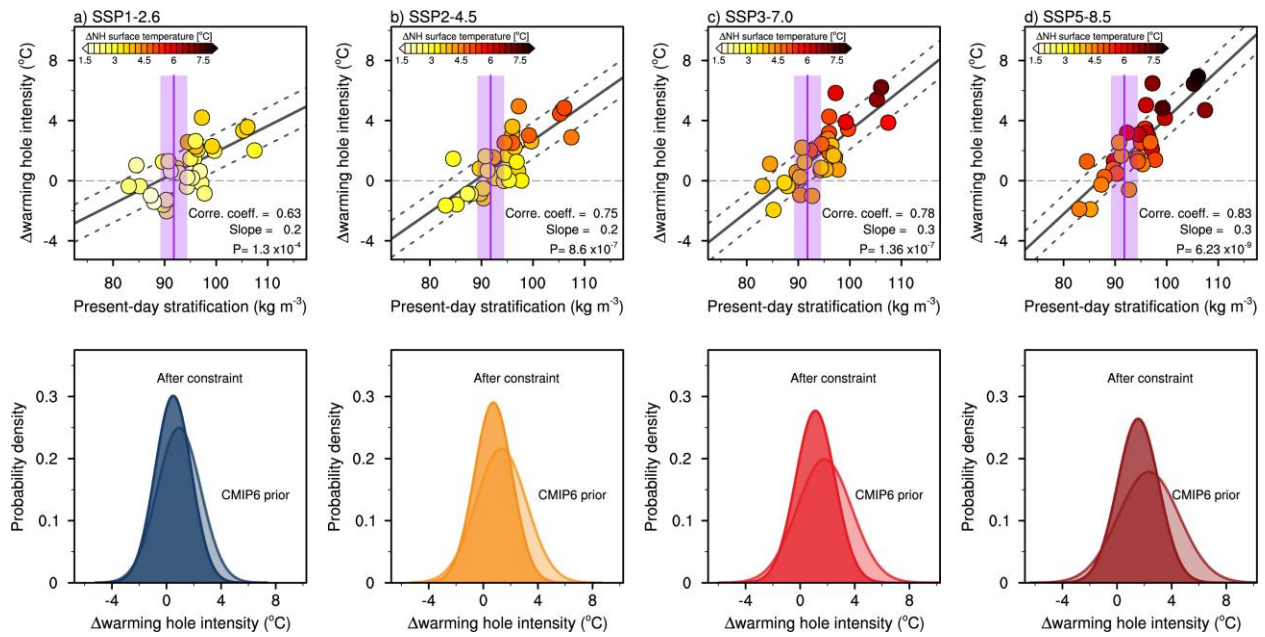
Supplementary Fig. 4. Sensitivity test of the model uncertainty fraction on warming hole latitude. The ratio of the model uncertainty to total uncertainty in the grid box as a function of longitude at latitudes (45°N–65°N) corresponding to the warming hole region. The blue bars indicate the grid box for the ocean and the red line indicates the grid box for the atmosphere. The green vertical line is the warming hole region, and the grey area illustrates land area.



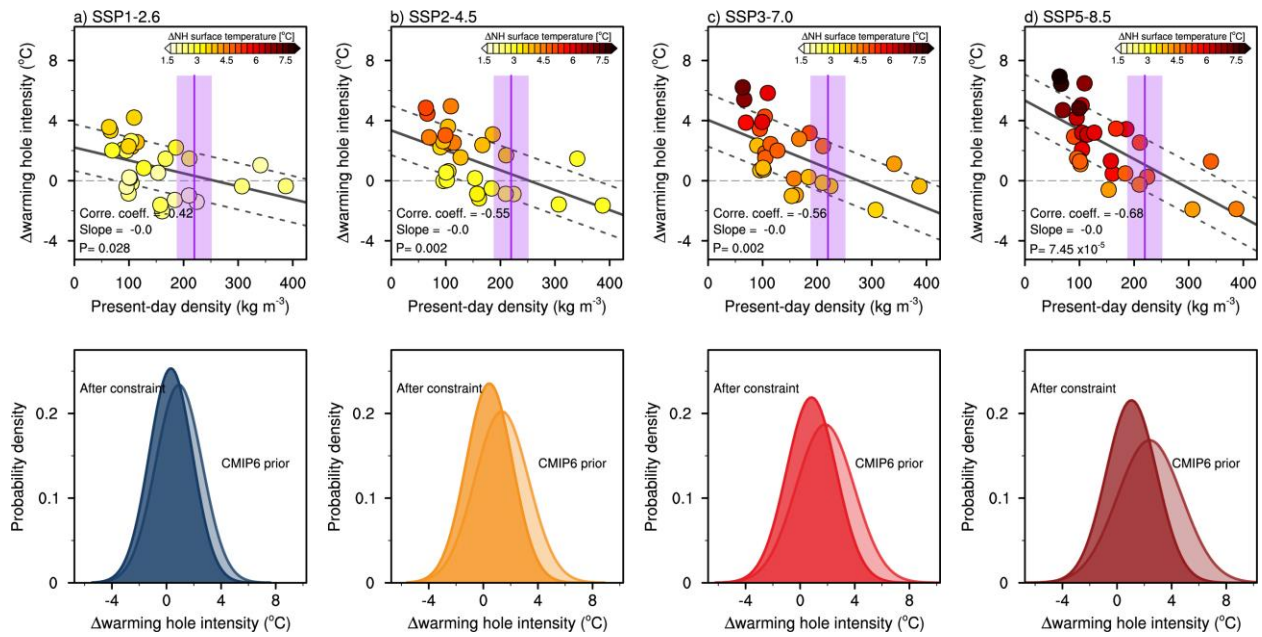
Supplementary Fig. 5. Future oceanic density and warming hole intensity. Future changes of the oceanic density in the North Atlantic subpolar region in the present-day from 32 CMIP6 ESM under (a) SSP1-2.6, (b) SSP2-4.5, and (c) SSP3-7.0. The middle panel illustrates a statistically significant (P -value < 0.001) relationship between future climate and present-day for the stratification in the North Atlantic subpolar region. The bottom panel same as the middle panel except for the mixed-layer depth instead of stratification. The line colors in the top panel and scatter shading in bottom panel indicate corresponding stratification in the present-day. The shading in the bottom panel indicates corresponding changes of the future warming hole intensity. The purple dashed ellipse indicates the 5–95% range, derived from the multivariate normal distribution. The correlation coefficient (Corre. coeff.), slope, and P -value obtained by a two-tailed Student's t -test are also provided with a regression line (solid black).



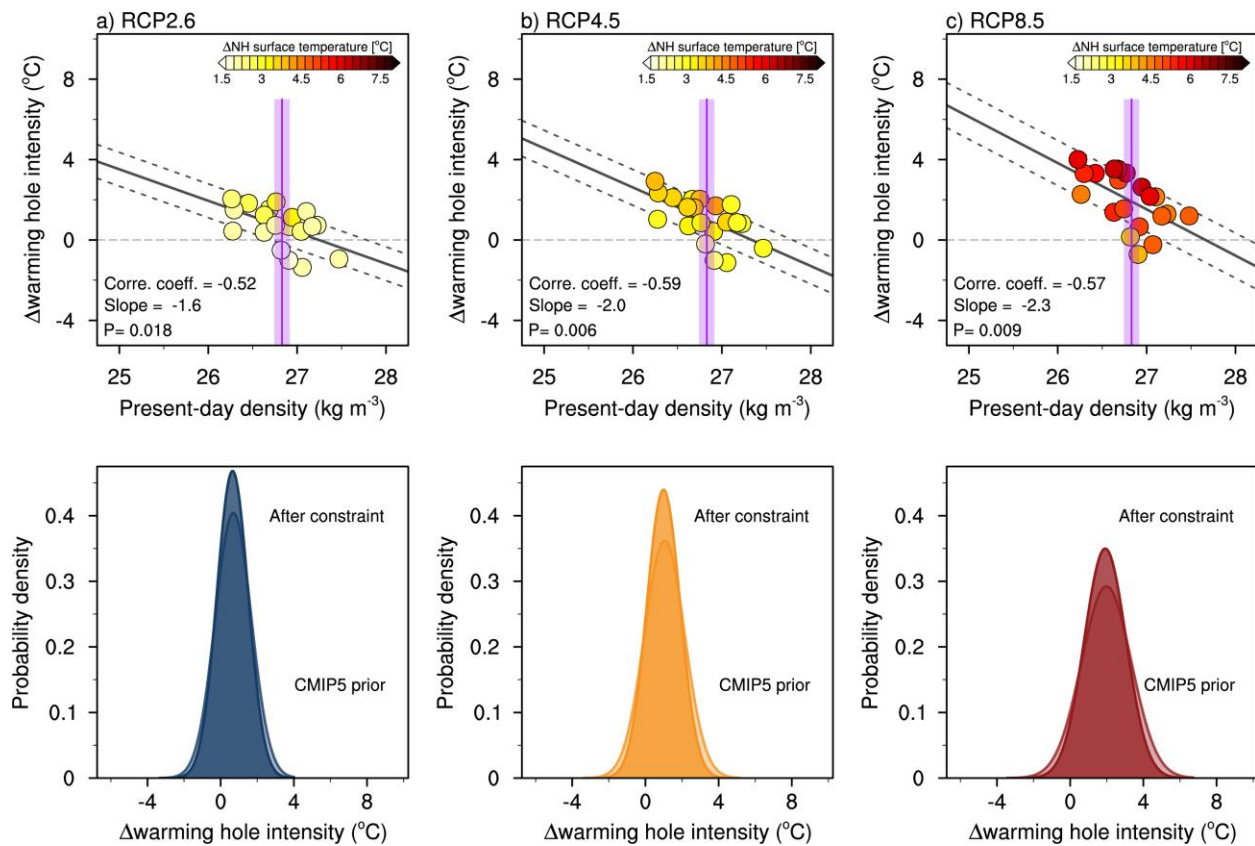
Supplementary Fig. 6. Statistically significant (P -value < 0.001) relationship between future changes of the northern hemisphere surface warming and the warming hole intensity. a, SSP1-2.6, b, SSP2-4.5, c, SSP3-7.0, and d, SSP5-8.5 scenarios. The shading corresponds to the present-day surface density in the North Atlantic subpolar region. The purple dashed ellipse indicates the 5–95% range derived from the multivariate normal distribution. The correlation coefficient (Corre. coeff.), slope, and P -value obtained by a two-tailed Student's t -test are also provided with a regression line (solid black).



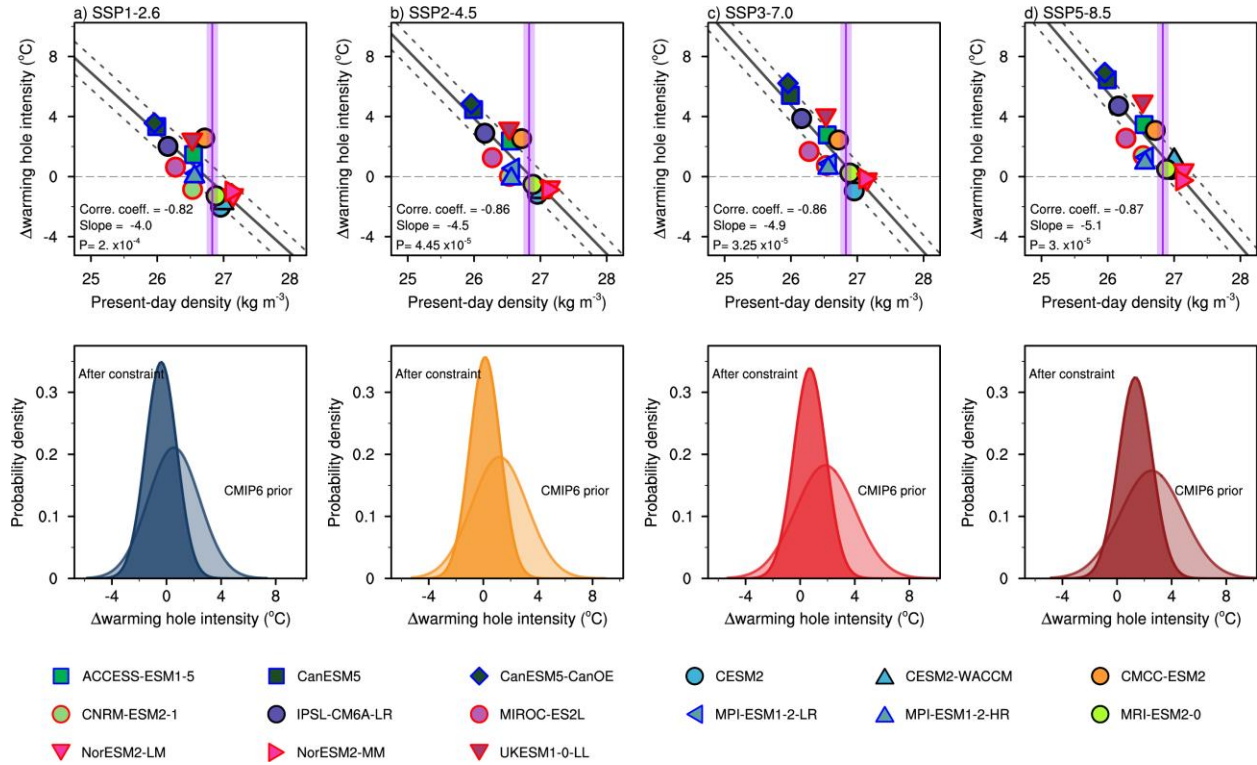
Supplementary Fig. 7. Emergent constraint on the future warming hole intensity change. a-d, In the top panel, projected changes in the warming hole intensity under (a) SSP1-2.6, (b) SSP2-4.5, (c) SSP3-7.0, and (d) SSP5-8.5 scenarios versus stratification in the warming hole region in the present-day climate (1981–2010). The solid black line follows the linear regression of 32 CMIP6 models, while the dashed black lines indicate prediction errors with one standard deviation, indicating 68% confidence intervals. The solid vertical purple line (shading) indicates the climatology (one standard error) of the WOA18. The slope and P-value are obtained by a two-sided Student's t-test. The shading indicates the corresponding changes of the surface temperature in the northern hemisphere. The bottom panel illustrates probability density functions for the projected warming hole intensity changes before ('CMIP6 prior', transparent) and after ('after constraint', opaque) the emergent constraint is applied.



Supplementary Fig. 8. Emergent constraint on the future warming hole intensity change. **a-d**, In the top panel, projected changes in the warming hole intensity under (a) SSP1-2.6, (b) SSP2-4.5, (c) SSP3-7.0, and (d) SSP5-8.5 scenarios versus mixed layer depth in the warming hole region in the present-day climate (1981–2010). The solid black line follows the linear regression of 28 CMIP6 models, while the dashed black lines indicate prediction errors with one standard deviation, indicating 68% confidence intervals. The solid vertical purple line (shading) indicates the climatology (one standard error) of the WOA18. The slope and P-value are obtained by a two-sided Student's t-test. The shading indicates the corresponding changes of the surface temperature in the northern hemisphere. The bottom panel illustrates probability density functions for the projected warming hole intensity changes before ('CMIP6 prior', transparent) and after ('after constraint', opaque) the emergent constraint is applied.



Supplementary Fig. 9. Emergent constraint on the future warming hole intensity change in CMIP5. **a–c**, In the top panel, projected changes of the warming hole under (a) RCP2.6, (b) RCP4.5, and (c) RCP8.5 scenarios versus surface density in the warming hole region in the present-day climate (1981–2010). The solid black line follows the linear regression of 20 CMIP5 ESMs, while the dashed black lines indicate prediction errors with one standard deviation, indicating 68% confidence intervals. The solid vertical purple line (shading) indicates the climatology (one standard error) of the WOA18. The slope and P-value are obtained by a two-sided Student's t-test. The shadings indicate the corresponding changes of the surface temperature change in the northern hemisphere. The bottom panel illustrates probability density functions for the projected warming hole intensity changes before ('CMIP5 prior', transparent) and after ('after constraint', opaque) the emergent constraint is applied.



84 **Supplementary Fig. 10. Emergent constraint on the future warming hole intensity change**

85 **using 15 ESMs from CMIP6, including biogeochemical schemes. a-d, In the top panel,**

86 **projected changes in the warming hole under (a) SSP1-2.6, (b) SSP2-4.5, (c) SSP3-7.0, and (d)**

87 **SSP5-8.5 scenarios versus surface density in the warming hole region in the present-day climate**

88 **(1981–2010). The solid black line follows the linear regression of 15 CMIP6 models, while the**

89 **dashed black lines indicate prediction errors with one standard deviation, indicating 68%**

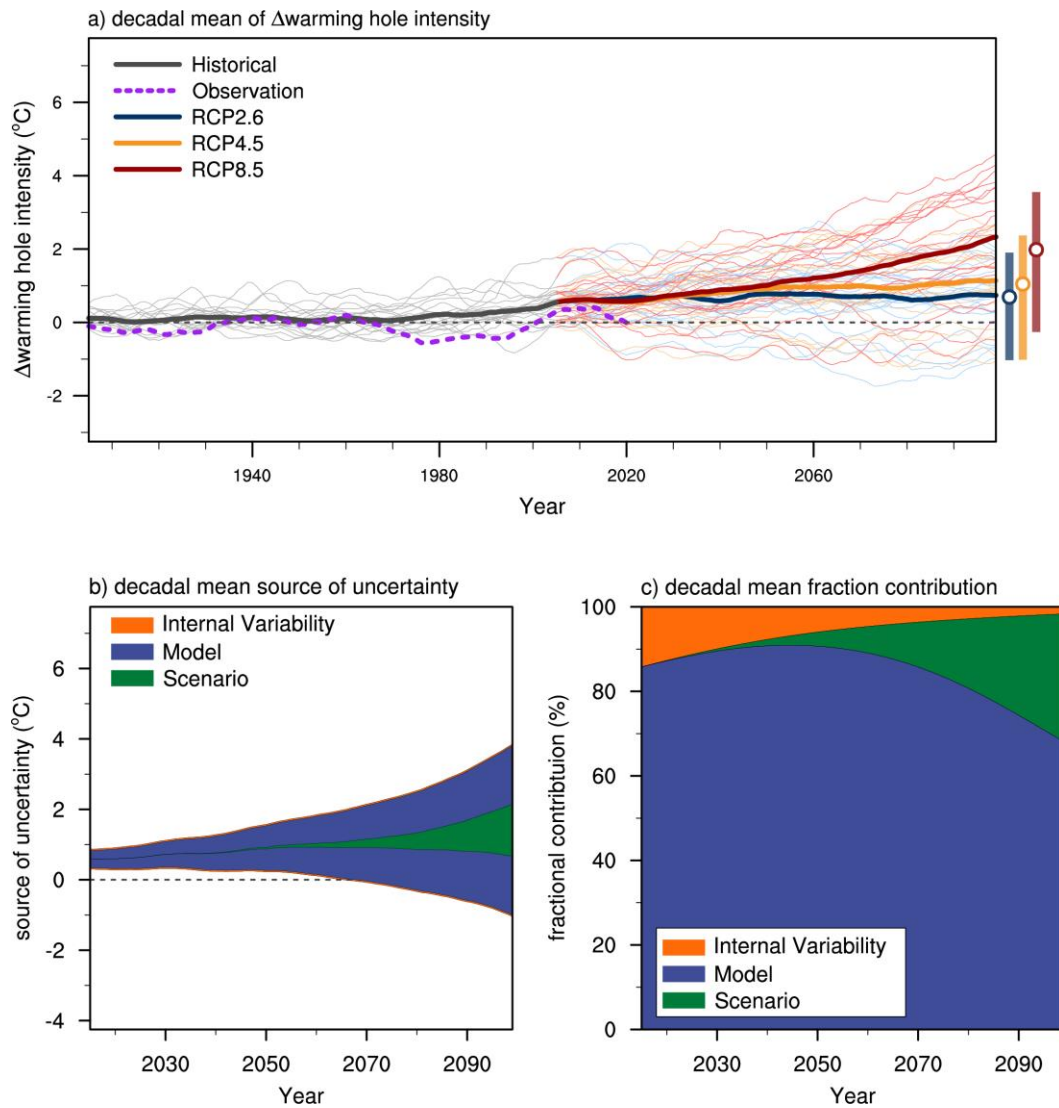
90 **confidence intervals. The solid vertical purple line (shading) indicates the climatology (one**

91 **standard error) of the WOA18. The slope and P-value are obtained by a two-sided Student's t-test.**

92 **The bottom panel illustrates probability density functions for the projected warming hole intensity**

93 **changes before ('CMIP6 prior', transparent) and after ('after constraint', opaque) the emergent**

94 **constraint is applied.**



Supplementary Fig. 11. Time series of the warming hole intensity and the source of uncertainty in CMIP5. a, Decadal running means of the warming hole intensity from MMEM with observations (dashed purple line), all relative to 1850–1900. The thick lines illustrate the MMEM of each scenario and the thin lines illustrate each ESM. The bars illustrate the 90% range (5–95%) of the future change of the warming hole intensity during 2070–2099 among CMIP5 ESMs with MMEM (circles). **b,** Source of uncertainty in the multi-model multi-scenario mean projection of the warming hole intensity. **c,** Fractional contribution of each source to the total uncertainty of the warming hole intensity.

Supplementary Table 1. CMIP5 and CMIP6 models used in this study and the corresponding model centers. The CMIP5 models are written in bold and italic

Model name	Modeling center
ACCESS-CM2 ¹	The Commonwealth Scientific and Industrial Research Organization (Australia)
ACCESS-ESM1-5 ²	
AWI-CM-1-1-MR ³	Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (Germany)
BCC-CSM2-MR ⁴	Beijing Climate Center (China)
CAS-ESM2-0 ⁵	Chinese Academy of Sciences (China)
<i>CanESM2</i> ⁶	Canadian Center for Climate Modeling and Analysis (Canada)
CanESM5 ⁷	
CanESM5-CanOE ⁷	
<i>CESM1-CAM5</i> ⁸	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory, (USA)
CESM2 ⁹	
CESM2-WACCM ⁹	
CMCC-CM2-SR5 ¹⁰	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (Italy)
CMCC-ESM2 ¹⁰	
<i>CNRM-CM5</i> ¹¹	Center National de Recherches Météorologiques (France)
CNRM-CM6-1 ¹²	
CNRM-CM6-1-HR ¹²	
CNRM-ESM2-1 ¹²	
<i>CSIRO-Mk3-6-0</i> ¹³	The Commonwealth Scientific and Industrial Research Organization (Australia)
<i>EC-Earth</i> ¹⁴	EC-Earth Consortium, Rossby Center, Swedish Meteorological and Hydrological Institute/SMHI (Sweden)
EC-Earth3 ¹⁵	
EC-Earth3-Veg ¹⁵	
EC-Earth3-Veg-LR ¹⁵	

FGOALS-g3 ¹⁶	Chinese Academy of Sciences (China)
<i>GFDL-CM3</i> ¹⁷	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA)
<i>GFDL-ESM2M</i> ¹⁷	
<i>GISS-E2-H</i> ¹⁸	Goddard Institute for Space Studies, National Aeronautics and Space Administration (USA)
<i>GISS-E2-R</i> ¹⁸	
<i>GISS-E2-1-G</i> ¹⁹	
<i>GISS-E2-1-H</i> ¹⁹	
<i>GISS-E2-2-G</i> ²⁰	
<i>HadGEM2-ES</i> ²¹	Met Office Hadley Center (UK)
UKESM1-0-LL ²²	
INM-CM4-8 ²³	Institute for Numerical Mathematics, Russian Academy of Science, Moscow (Russia)
INM-CM5-0 ²⁴	
<i>IPSL-CM5A-LR</i> ²⁵	Institut Pierre-Simon Laplace (France)
<i>IPSL-CM5A-MR</i> ²⁵	
<i>IPSL-CM6A-LR</i> ²⁶	
<i>HadGEM2-AO</i> ²⁷	National Institute of Meteorological Sciences/Korea Meteorological Administration, Climate Research Division (Republic of Korea)
<i>MIROC5</i> ²⁸	Japan Agency for Marine-Earth Science and Technology (Japan)
<i>MIROC-ESM</i> ²⁸	
<i>MIROC-ESM-CHEM</i> ²⁸	
MIROC-ES2L ²⁹	
MIROC6 ³⁰	
<i>MPI-ESM-LR</i> ³¹	Max Planck Institute for Meteorology (Germany)
<i>MPI-ESM-MR</i> ³¹	
MPI-ESM-1-2-HR ³²	
MPI-ESM1-2-LR ³³	

MRI-ESM2-0 ³⁴	Meteorological Research Institute (Japan)
<i>NorESM1-M</i> ³⁵	Climate modeling Consortium consisting of Center for International Climate and Environmental Research (Norway)
<i>NorESM1-ME</i> ³⁵	
NorESM2-LM ³⁶	
NorESM2-MM ³⁶	

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107 **Supplementary Table 2. Reduced uncertainty of future warming hole changes in CMIP6**
108 **after emergent constraint.**

Reduced uncertainty Scenarios	Surface density	Stratification	Mixed layer depth
SSP1-2.6	20%	17%	8%
SSP2-4.5	31%	25%	14%
SSP3-7.0	35%	28%	15%
SSP5-8.5	39%	32%	22%

109

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