
Supplementary information

**Ocean warming and accelerating Southern
Ocean zonal flow**

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Ocean Warming and Accelerating Southern Ocean Zonal Flow

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Supplementary Table 1. CMIP6 models for the outputs of ocean potential temperature and zonal velocity (U) in historical and SSP585 simulations.

Model Names	Potential Temp. & U
ACCESS-CM2	√
ACCESS-ESM1-5	√
BBC-CSM2-MR	√
CAMS-CSM1-0	√
CanESM5	√
CESM2-WACCM	√
CIESM	√
CMCC-CM2-SR5	√
EC-Earth3	√
EC-Earth3-Veg	√
FGOALS-f3-L	√
FGOALS-g3	√
FIO-ESM-2-0	√
GFDL-CM4	√
IPSL-CM6A-LR	√
MIROC6	√
MPI-ESM1-2-HR	√
MPI-ESM1-2-LR	√
MRI-ESM2-0	√
NESM3	√
TaiESM1	√

Supplementary Table 2. Description of the partial coupling CESM1 experiments.

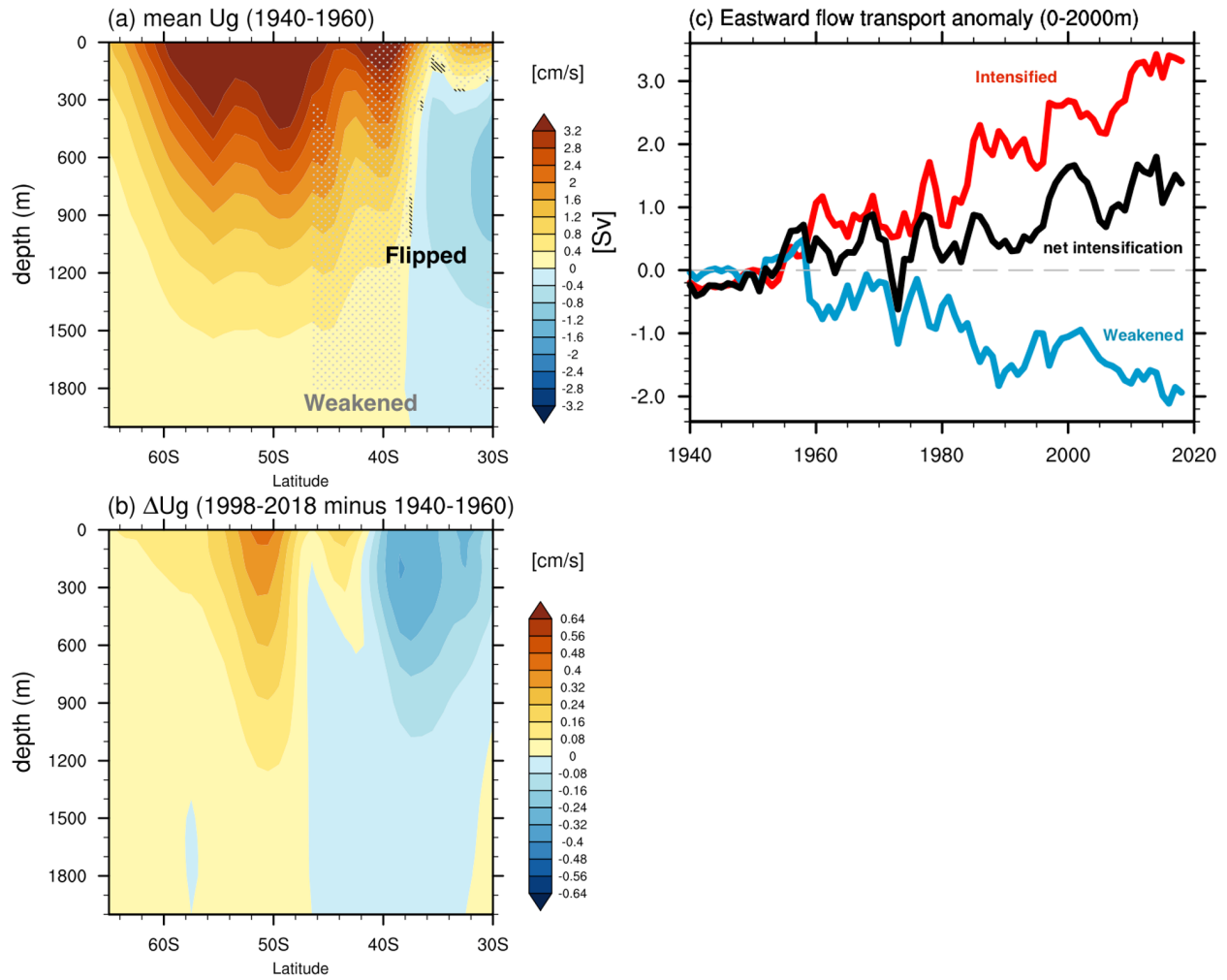
Names	Note
CTRL	Fully coupled, preindustrial control run
4×CO ₂	Fully coupled, abruptly quadrupled CO ₂
CESM1_ΔBuoy	Partial coupling with fixed wind stress from 4×CO ₂ and quadrupled CO ₂
CESM1_ΔWind	Partial coupling with fixed wind stress from CTRL and quadrupled CO ₂

Supplementary Table 3. Description of the OGCM experiments.

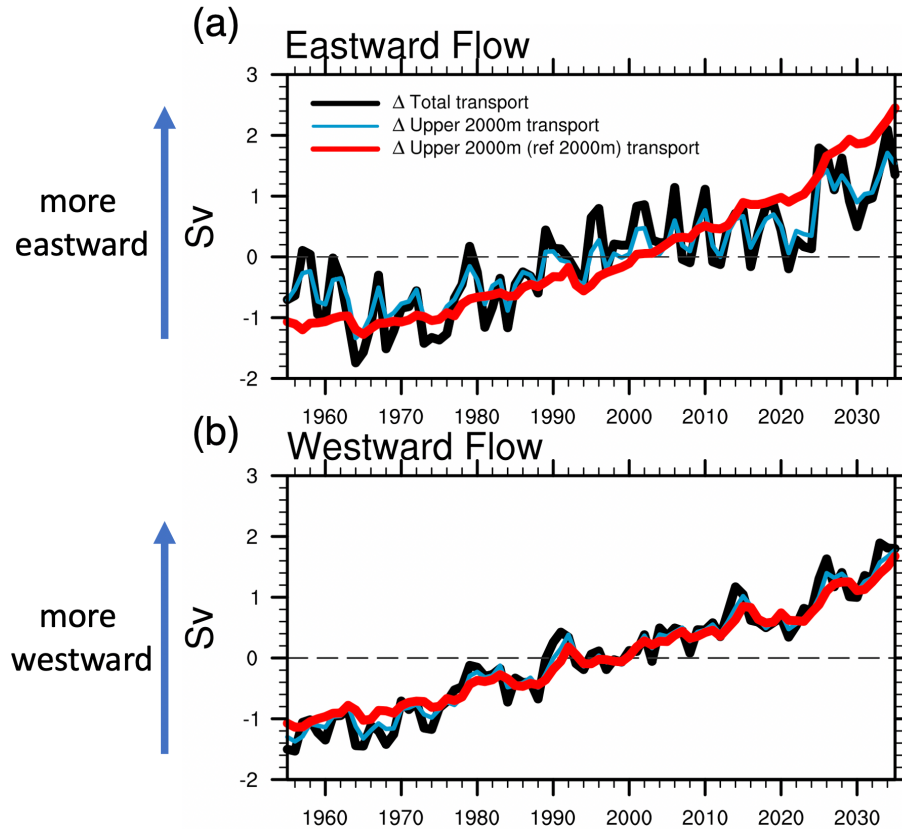
Experiment	Surface Forcing
MITgcm_CTL	Present-day monthly climatological SST (SSTClim), SSS (SSSClim) and wind stress (WindClim)
MITgcm_ΔSST	Same as MITgcm_CTL but SST is restored to SSTClim+ΔSST
MITgcm_ΔWind	Same as MITgcm_CTL but wind stress is restored to WindClim+ΔWind

Supplementary Table 4. List of CMIP6 models used in OGCM for surface forcing, including SST, SSS and surface wind.

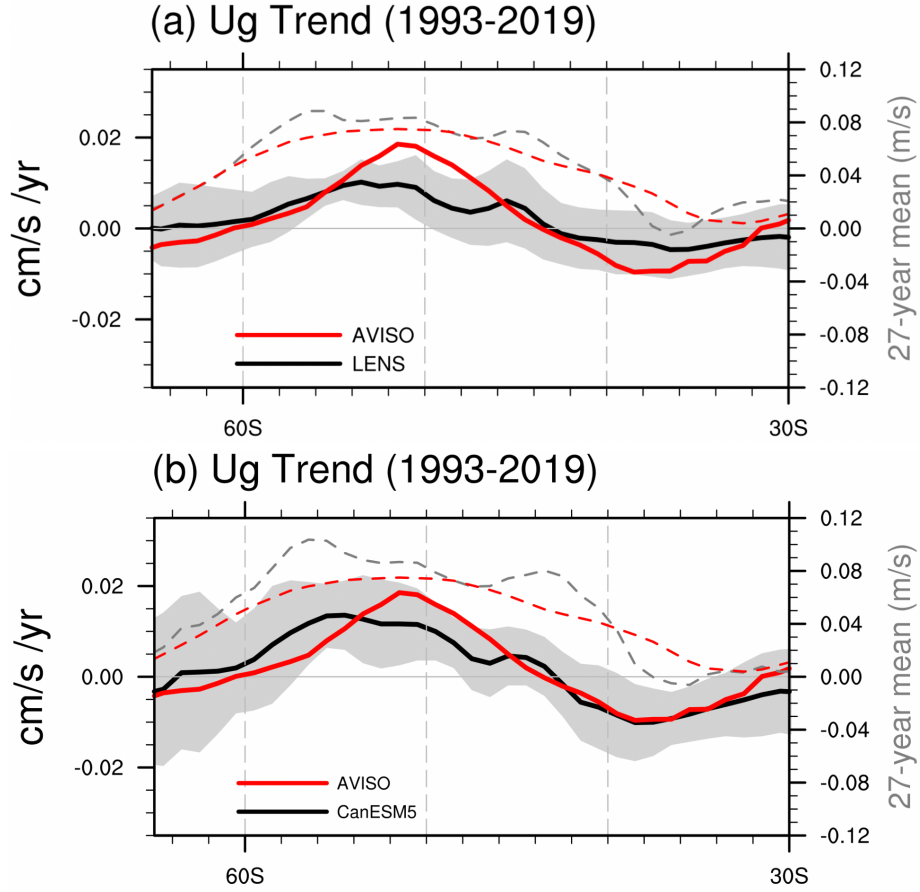
Model Names
ACCESS-CM2
ACCESS-ESM1-5
BCC-CSM2-MR
BCC-ESM1
CAMS-CSM1-0
CanESM5
CAS-ESM2-0
CESM2
CESM2-FV2
CESM2-WACCM
CESM2-WACCM-FV2
CIESM
CNRM-CM6-1
CNRM-ESM2-1
E3SM-1-0
EC-Earth3-Veg
FGOALS-f3-L
GFDL-ESM4
GISS-E2-1-G
HadGEM3-GC31-LL
INM-CM4-8
IPSL-CM6A-LR
MCM-UA-1-0
MIROC6
MIROC-ES2L
MPI-ESM1-2-HR
MRI-ESM2-0
NESM3
SAM0-UNICON
UKESM1-0-LL



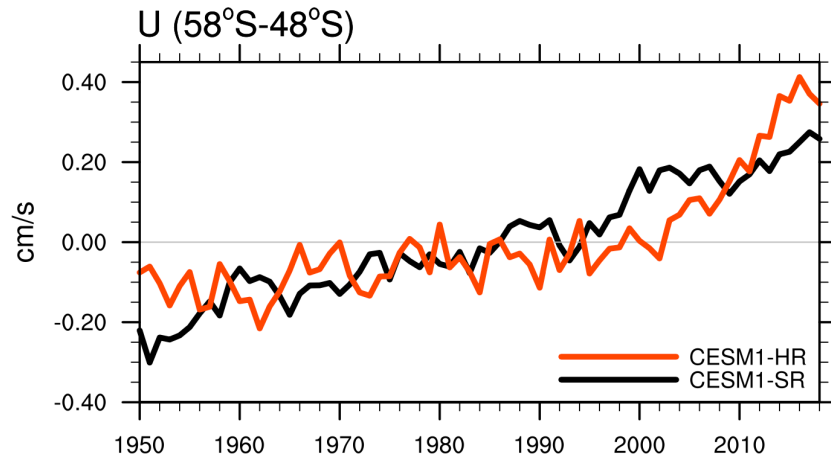
Supplementary Fig. 1. Eastward flow transport from IAP data. (a) Zonal mean of climatological U_g averaged from 1940 to 1960, from IAP data. (b) The difference ΔU_g between the 1998-2018 and 1940-1960 averages, both from IAP data. Gray dots in (a) indicate the regions where eastward flows are weakened, and black slashes indicate the signs of zonal flow are flipped. Velocity in the regions without stippling is intensified. (c) Eastward flow baroclinic transport in the upper 2000 m from 1940 to 2019 from IAP data. Blue curve shows the weakened eastward transport (weakened regions); red curve shows the intensified eastward transport; black curve is the sum of two curves, showing the net intensification of the eastward flow.



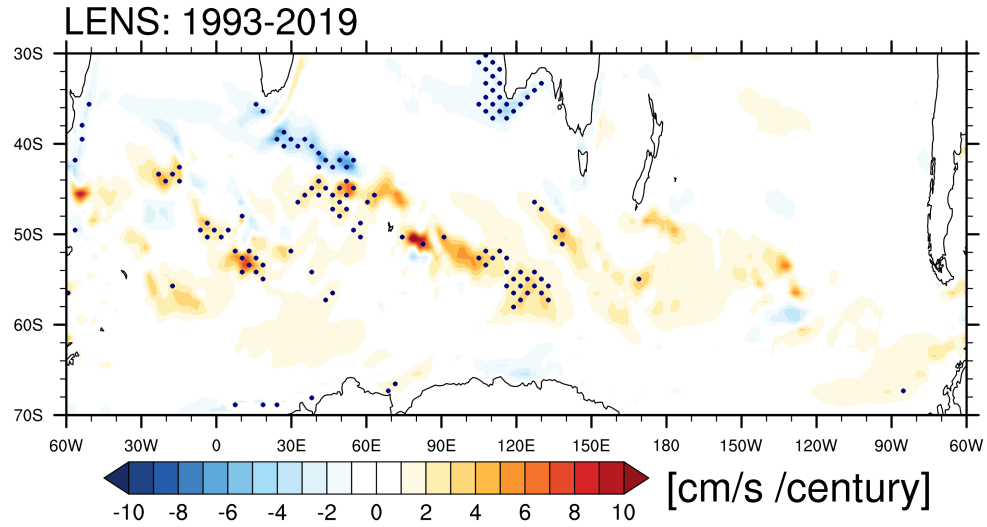
Supplementary Fig. 2. Time series of eastward flow transport and westward flow transport from CMIP6. (a) Eastward flow transport and (b) westward flow transport anomalies integrated within 30°S-65°S from 1955 to 2035 based on Extended Data Fig. 4. Positive change indicates intensification of zonal flow.



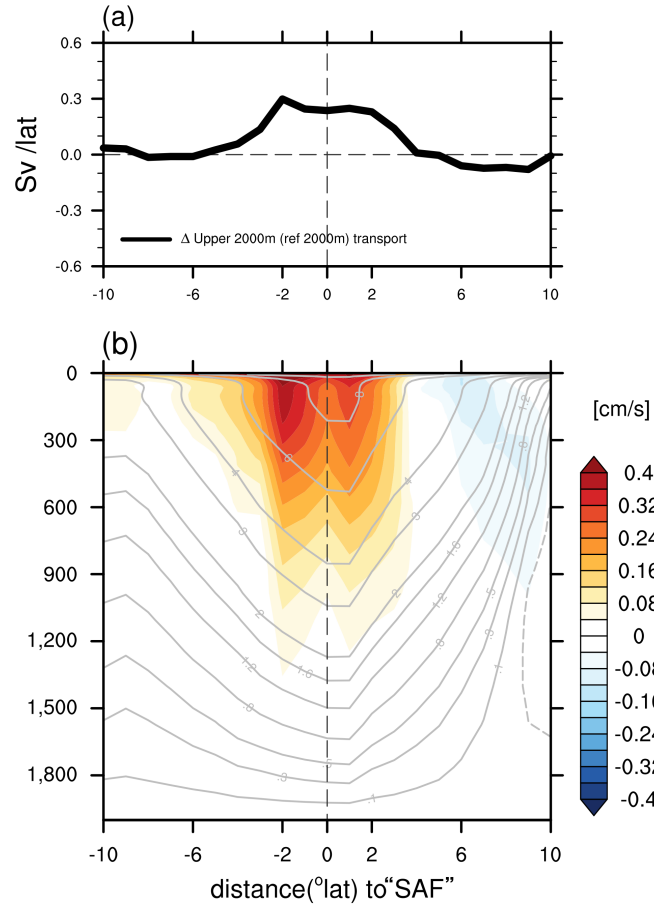
Supplementary Fig. 3. Forced zonal geostrophic velocity change with internal variability. (a) Trend of zonal mean surface U_g (cm/s/yr) from AVISO and LENS for 1993-2019. The black curve is the LENS ensemble mean and shading is ± 1 standard deviation from all of the ensemble members. Dashed curves are climatologies of zonal mean U_g (m/s) from AVISO and LENS. (b) Same as (a) but for the comparison between AVISO and CanESM5 large ensemble simulations.



Supplementary Fig. 4. Time evolution of upper 100 m zonal velocity averaged between 58°S and 48°S from CESM1-SR (black curve) and CESM1-HR (red curve).



Supplementary Fig. 5. Surface zonal velocity trend from 1993 to 2019 from LENS ensemble mean. Stippling indicates the region where signal-to-noise ratio exceeds 1, where the signal is the ensemble mean trend and noise is estimated as the 1 standard deviation across the trends from 40 members .



Supplementary Fig. 6. Streamwise mean of zonal velocity change with a shifting “SAF”. As in (c)-(d) in Extended Data Fig. 8, but including change of the “SAF” position between two periods: 1940-1960 average and 1998-2018 average.