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The seasonal cycle of pCO$_2$ and CO$_2$ fluxes in the Southern Ocean: diagnosing anomalies in CMIP5 Earth system models

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Supplementary

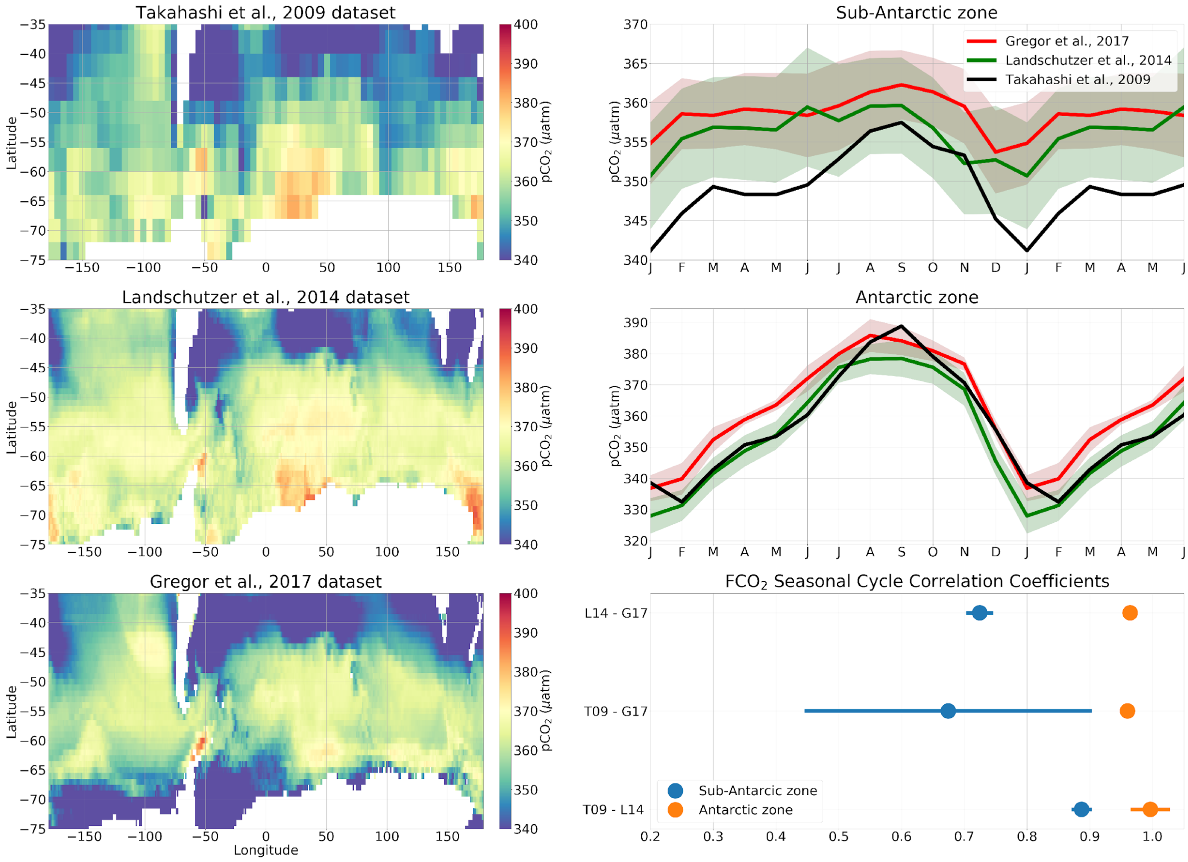

Figure. S1 pCO_2 (µatm) spatial (climatology) and seasonal cycle differences in Landschützer et al (2014), Gregor et al (2017), Takahashi et al (2009) datasets in the Southern Ocean. The seasonal cycle climatology of pCO_2 in the Sub-Antarctic and Antarctic zone is based on the period 1998 – 2011. The shaded areas show the standard deviation of the interannual variability of the seasonal cycle for this period. The uncertainty in the correlation coefficient is based on the correlation coefficient of the mean plus standard deviations seasonal cycle(s).

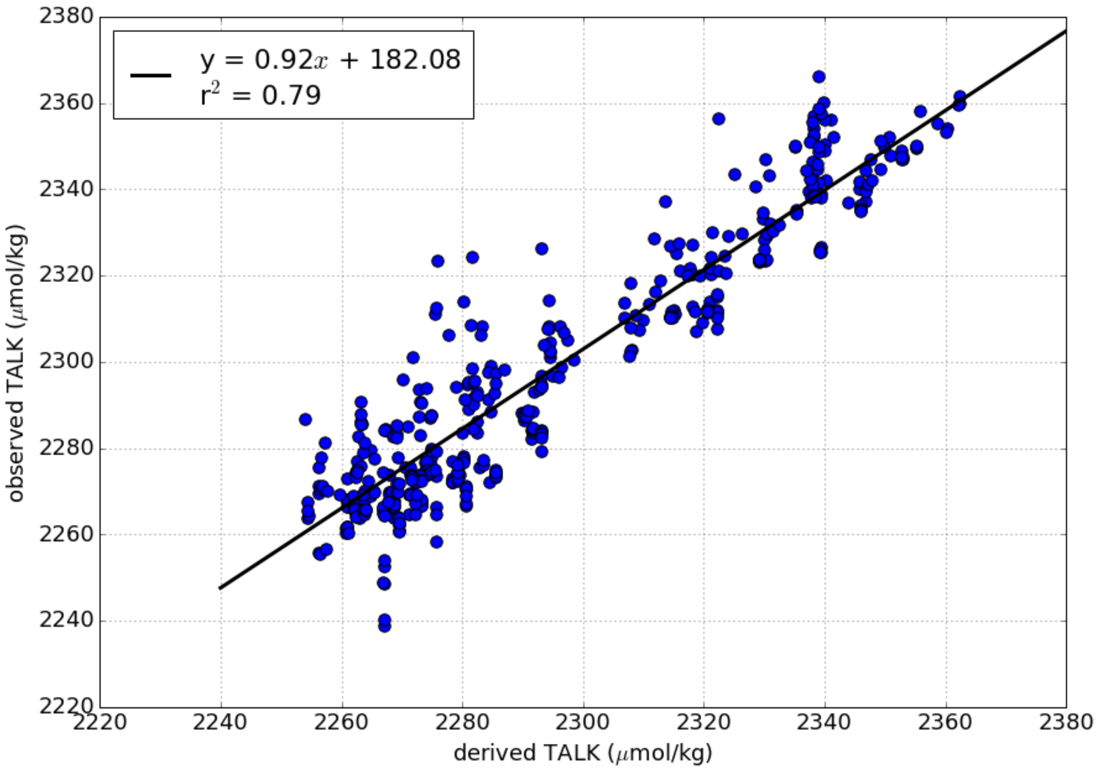

Figure S2. Regression plot comparing the derived (Lee et al., 2006) and observed TALK dataset for about 500 surface TALK samples collected in the Indian Ocean of the Southern Ocean.

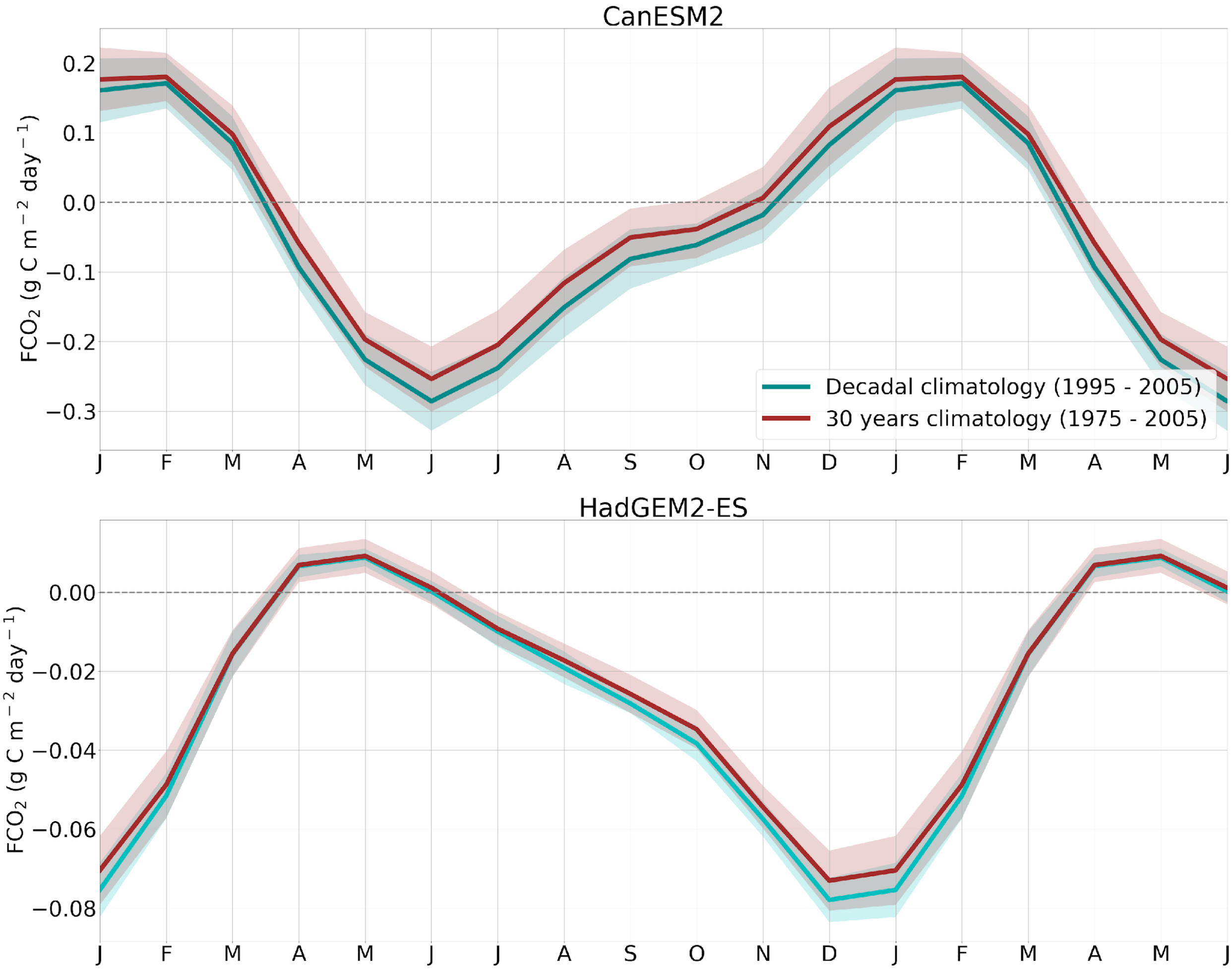

Figure. S3. Compares the seasonal cycle of Sea-Air CO_2 fluxes over 30 year (1975 – 2005 and 10 years (1995 – 2015). The shaded area shows the standard deviation.

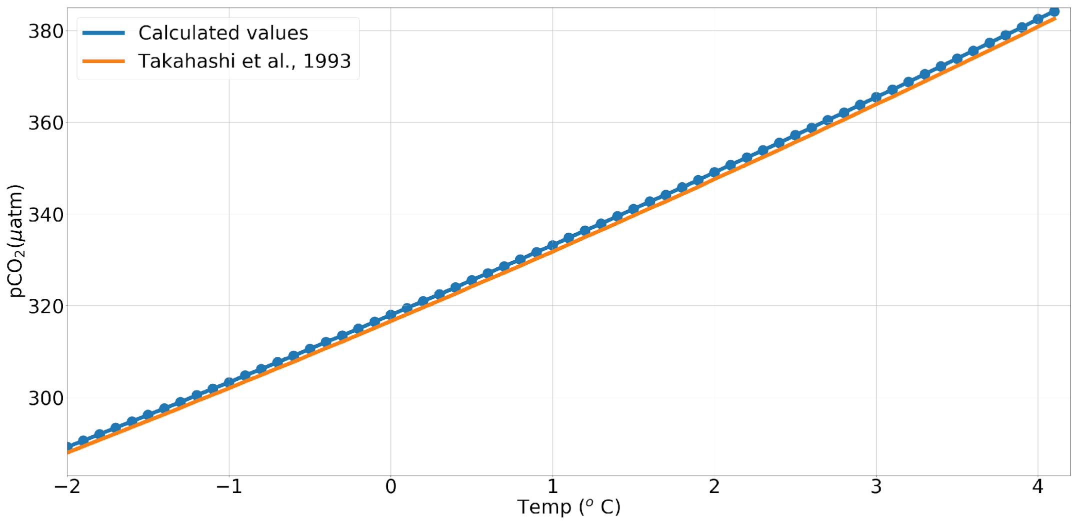

Figure. S4 in the revised supplementary material) Comparison between of dependence of pCO_2 to temperature changes according to the Takahashi et al., (1993) empirical the constant ($0.0423^{o}C^{-1}$) and the computed ratio of temperature dependence, from the carbonate system equations (CO2SYS, Pierrot, et al., 2006) using mean climatological data from GLODAP2 (Salinity, TAlk, DIC, silicate & phosphate) and pCO_2 from Landschützer et al (2014) for the Antarctic zone and a temperature range of -2.0°C to 4°C (0.1°C intervals).

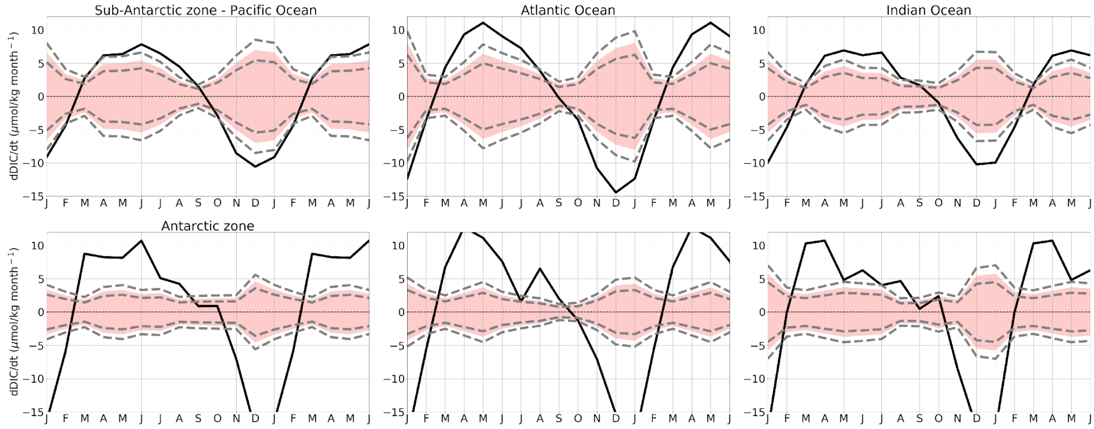

Fig. S5 Seasonal cycle of the rate change of surface total DIC (black line), and the estimated solubility DIC equivalent rate of change $(dDIC_T/dt)_{SST}$ (shaded area), for monthly data given in μmol kg^{-1} $month^{-1}$ at the Sub-Antarctic zone i.e. Pacific Ocean (first column), Atlantic Ocean (second column) and Indian Ocean (third column). The dotted line shows the uncertainty boundaries for the Revelle factor accounting to range 11.5 and 18.5. This is based on Landschützer et al (2014) pCO_2 data estimates and calculated DIC (COS2SYS, Pierrot ey., 2006)

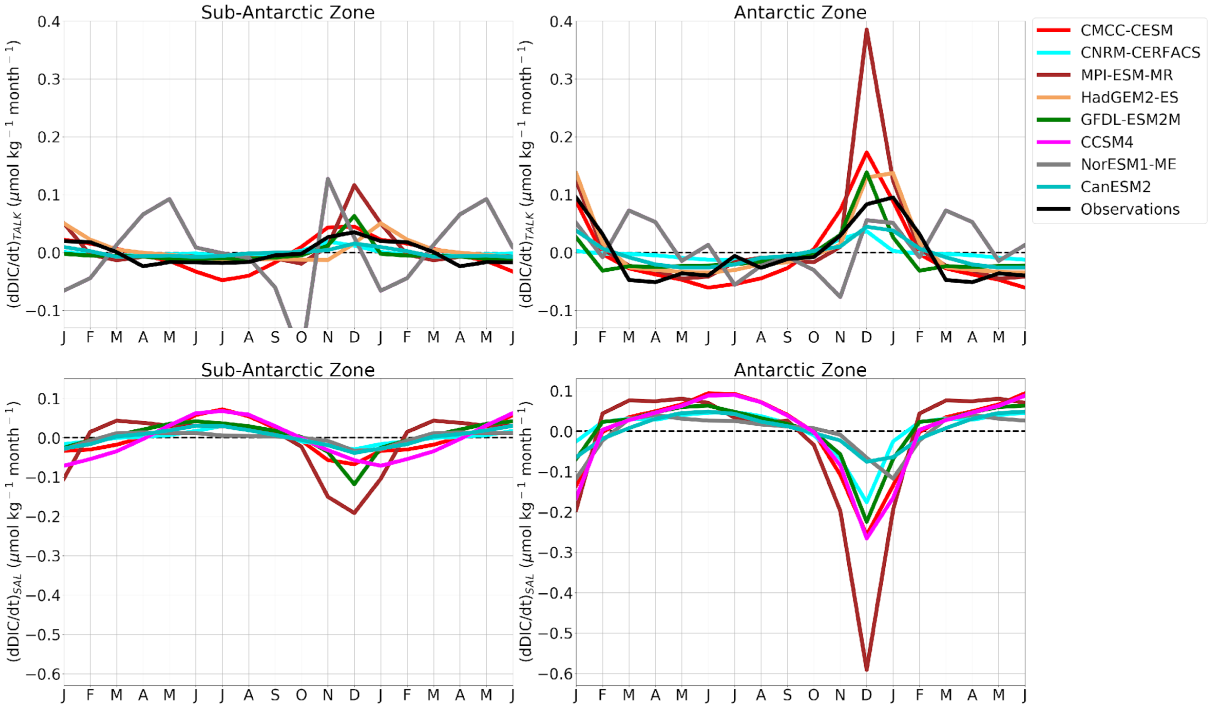

Figure. S6 Shows the seasonal cycle of the rate equivalent DIC changes driven changes in Salinity and total alkalinity computed using Takahashi et al., 1993 formulations.

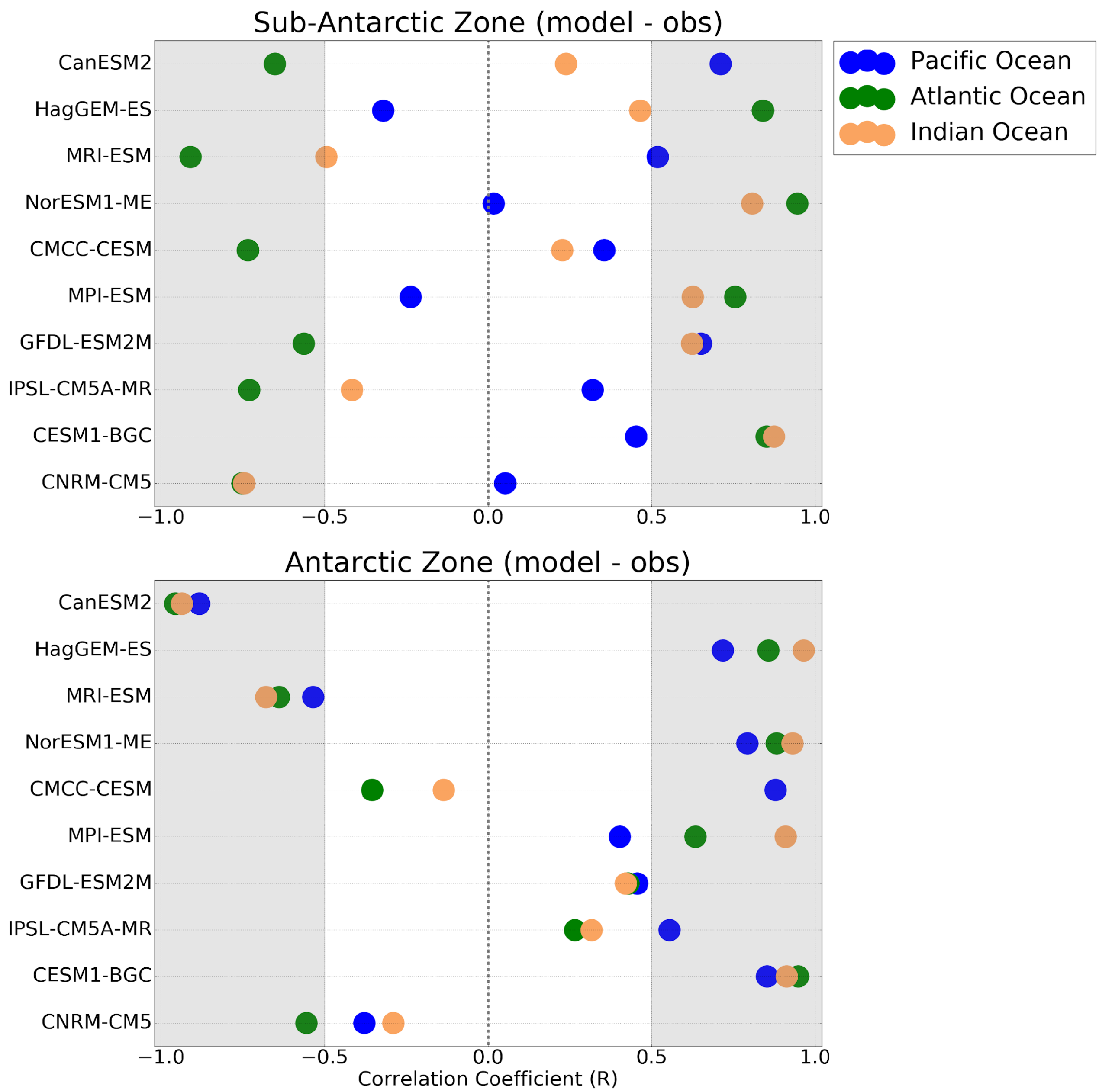

Fig. S7: The correlation coefficients (R) of the seasonal cycle of FCO_2 for observations (Landschützer et al., 2014) and CMIP5 models at the three basins of the Southern Ocean (i.e. Pacific, Atlantic and Indian) in the Sub-Antarctic (SAZ) and Antarctic Zone (AZ).

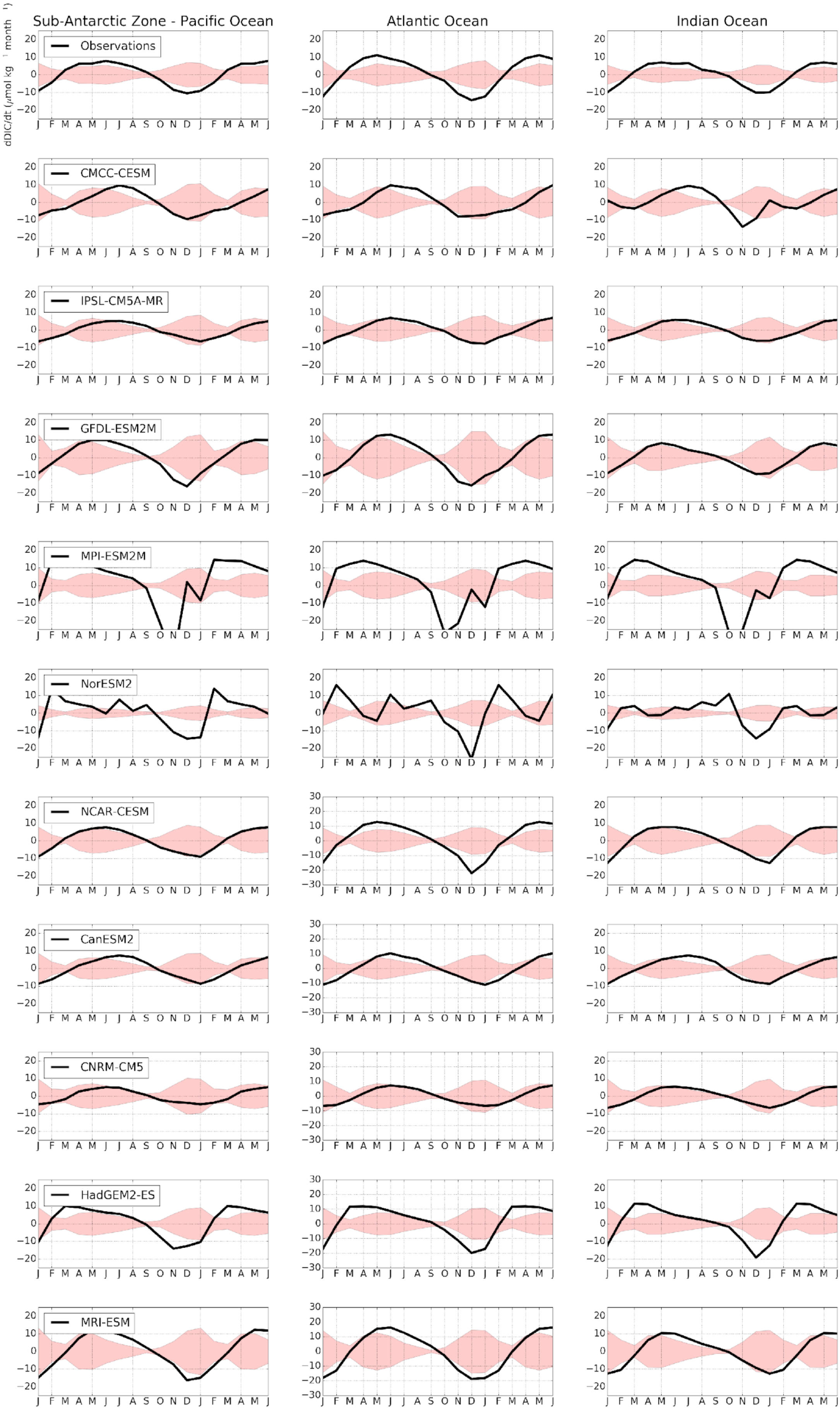
Sub-Antarctic Zone - Pacific Ocean
Atlantic Ocean
Indian Ocean
dDIC/dt (μmol kg⁻¹ month⁻¹)
Observations
CMCC-CESM
IPSL-CM5A-MR
GFDL-ESM2M
MPI-ESM2M
NorESM2
NCAR-CESM
CanESM2
CNRM-CM5
HadGEM2-ES
MRI-ESM
J F M A M J J A S O N D J F M A M J

Figure. S8a. Seasonal cycle of the rate of change of DIC $\left(\frac{\partial DIC}{\partial t}\right)_{Tot}$, black line and the estimated maximum DIC variability equivalent driven by temperature$\left(\frac{\partial DIC}{\partial t}\right)_{SST}$ $shaded\ area$, for monthly data given in μmol kg^{-1} month^{-1} at the Sub-Antarctic zone i.e. Pacific Ocean (first column), Atlantic Ocean (second column) and Indian Ocean (third column). The estimated equivalent temperature driven solubility DIC changes (shade area) is compared to the total surface rate of change (black line) such that when $\left|\left(\frac{\partial DIC}{\partial t}\right)_{SST}\right| > \left|\left(\frac{\partial DIC}{\partial t}\right)_{Tot}\right|$, the role of temperature dominates instantaneous pCO_2 variability and conversely when$\left|\left(\frac{\partial DIC}{\partial t}\right)_{SST}\right| < \left|\left(\frac{\partial DIC}{\partial t}\right)_{Tot}\right|$, DIC process are is the dominant mode of instantaneous pCO_2 changes.

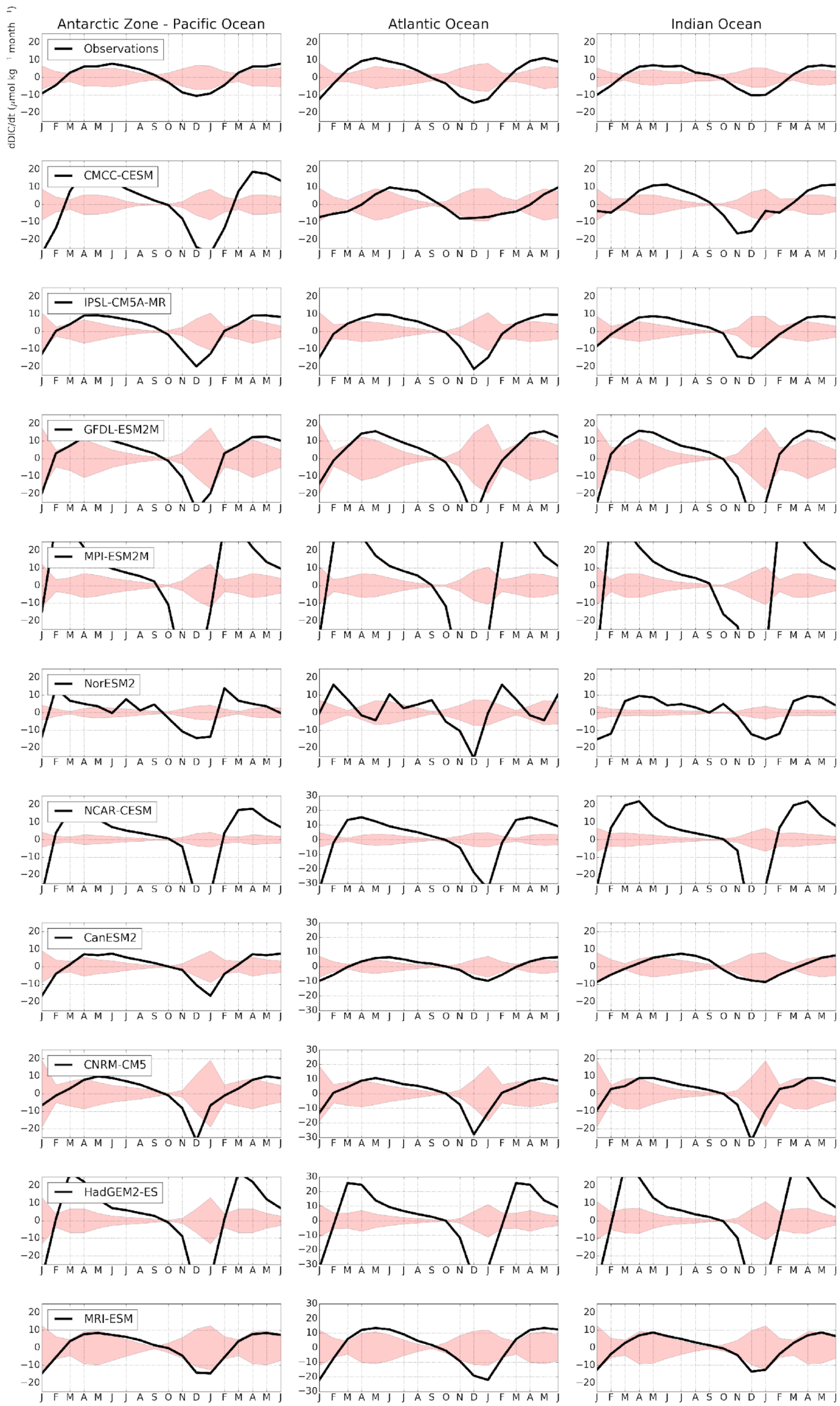
Antarctic Zone - Pacific Ocean
Atlantic Ocean
Indian Ocean
dDIC/dt (μmol kg⁻¹ month⁻¹)
Observations
CMCC-CESM
IPSL-CM5A-MR
GFDL-ESM2M
MPI-ESM2M
NorESM2
NCAR-CESM
CanESM2
CNRM-CM5
HadGEM2-ES
MRI-ESM
J F M A M J J A S O N D J F M A M J

Fig. S8b. Same as Fig. 2a for the Antarctic zone.

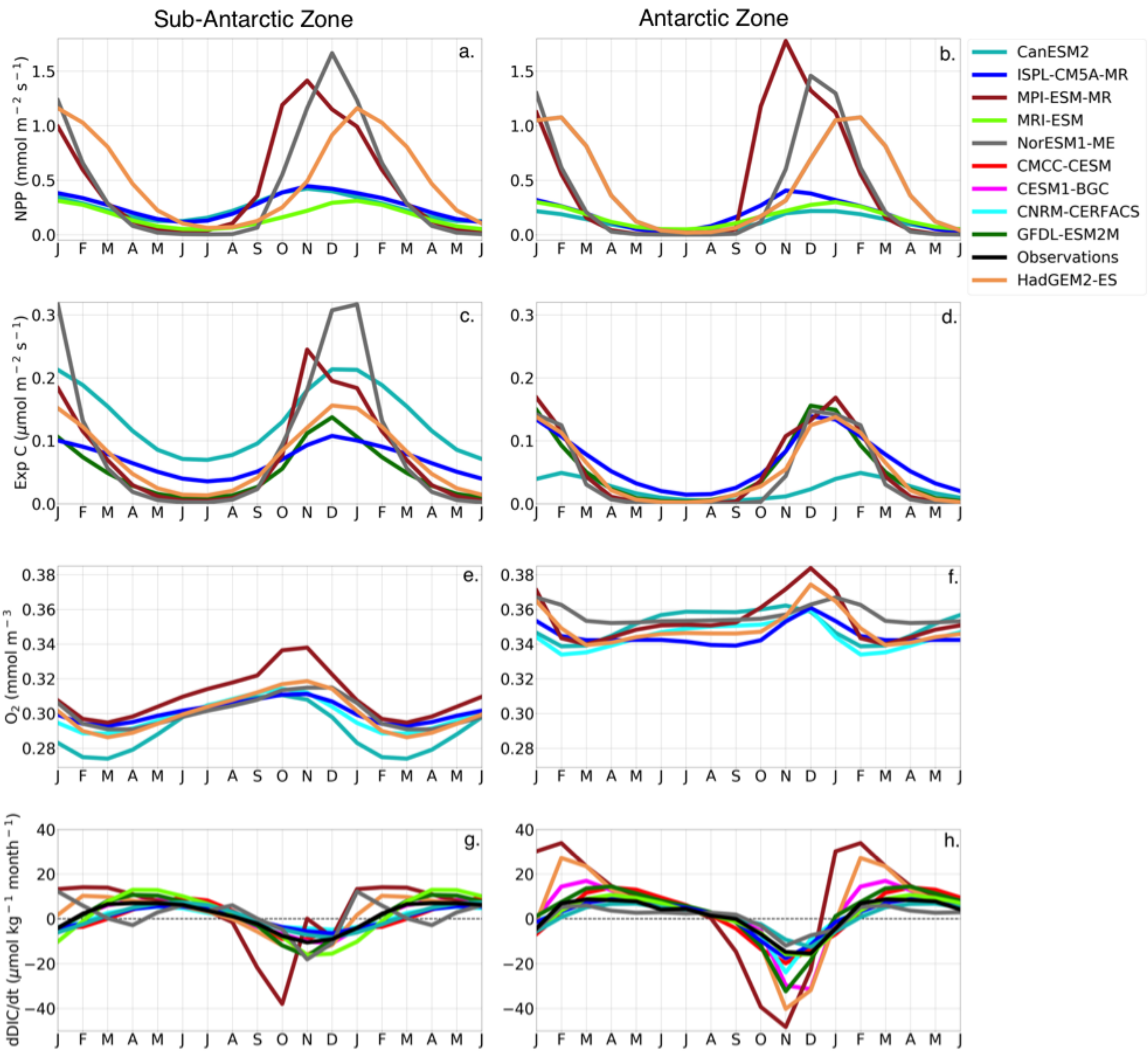

Fig. S9 Seasonal cycle of Net Primary production (NPP, mmol m^{-2} s^{-1}), export carbon at 100m (µmol m^{-2} s^{-1}), surface oxygen (mmol m^{-3}) and rate of change of surface DIC (µmol kg^{-1} month^{-1}) at the Sub-Antarctic and Antarctic zones.