Variability of the Southern Annular Mode and Southern Ocean Surface Westerly Winds in E3SM

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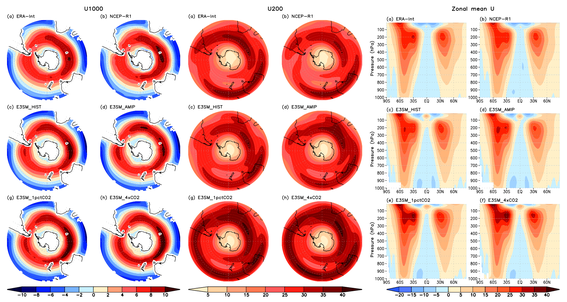
I. Introduction

- The southern annular mode (SAM), which is often referred to as the Antarctic Oscillation (AAO), has strong effects on the climate systems at high and middle latitudes of the Southern Hemisphere (SH).
- The positive phase of the SAM is characterized by lower anomalous air pressure over the Antarctic along with higher anomalous pressure over the middle latitudes.
- In the positive SAM phase, the strong westerly winds move poleward, while the westerly winds weakened in the negative phase move toward the equator.
- Changes in the SH surface zonal winds have been related with not only changes of the oceanic circulation in the Southern Ocean, but also variability and changes in the SAM.
- Studies of atmospheric reanalyses and simulations have found a poleward intensification of the surface westerly winds in the SH during the last decades. These facts are closely associated with a trend toward the positive phase of the SAM.
- Many studies have shown systematic biases of the variability and trends in the SH surface zonal winds using the climate models participating in the CMIP3 and CMIP5. The SH westerlies simulated by the CMIP3 and 5 models were weaker than average in strength and equatorward in position compared to observations and reanalyses.

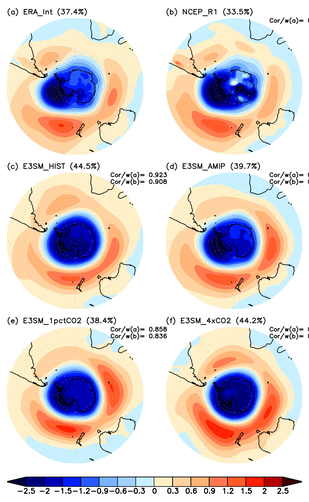
❖ E3SM characteristics for SH atmospheric circulation

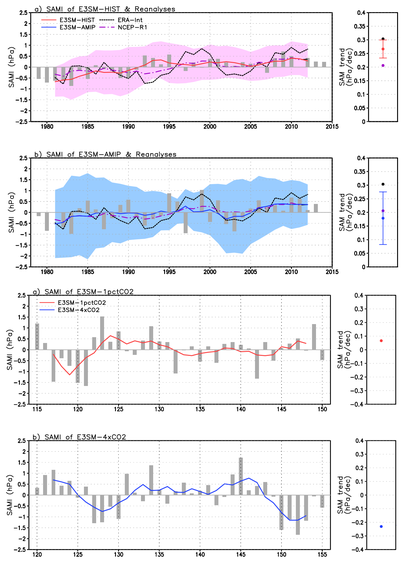


The intensity of the model's SH circulation is strongly associated with global warming, such as external CO2 forcing. This relationship affects the SAM as the dominant mode of variability in SH. It can be seen that the enhanced climatological circulation of zonal wind for increasing CO2 in E3SM simulations.

III. SAM pattern, variability, and trend

❖ Annual mean SAM Pattern and Index





Annual mean (gray bars), 5-year running mean (lines) and trend (right side of each panel) of the SAM index from two reanalyses and four E3SM simulations.

Shaded areas and vertical bars show the 95% confidence interval about the annual mean ensemble simulated trend.

In Table, asterisk (*) marks indicate statistical significance at the 95% confidence level in the Student two-tailed t-test.

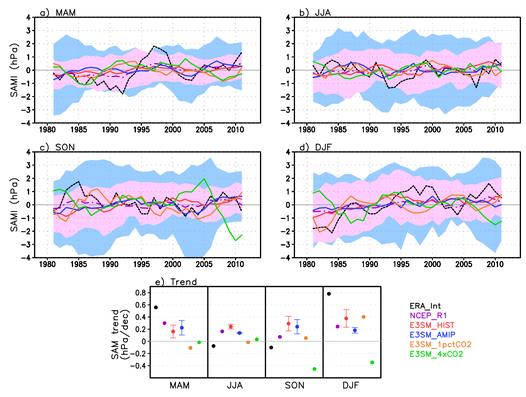
Annual Mean SAM Trends

Re-anal/Simulations	Trend (hPa/decadal)
ERA-Int	0.30
NCEP-R1	0.21*
E3SM-HIST	0.27*
E3SM-AMIP	0.18*
E3SM-1pctCO2	0.07
E3SM-4xCO2	-0.23

- Positive SAM patterns, characterized by lower SLP over Antarctica and higher SLP in the mid-latitudes of the SH, can be seen.
- In the four sets of model simulations, the SAM patterns are generally well reproduced with high spatial pattern correlation coefficients.
- The E3SM-HIST and AMIP simulations show similar intensity in the strongest positive and negative centers compared to the observations and indicate lower center intensity than the two CO_2 simulations.

- The HIST and AMIP simulations of the E3SM model have successfully reproduced the positive SAM trends.
- Both CO_2 simulations of the E3SM models produce lower annual mean SAM trends relative to the two other simulations.
- The trends in E3SM-HIST, AMIP, and 1pctCO2 simulations carry the signals in response to time-varying forcings, while the trend in 4xCO2 simulation is likely due to adjustment to the abrupt external climatic changes by CO_2 forcing (such as elimination of latitudinal warming differences), as well as model internal variability.

❖ Seasonal mean SAM Index



Seasonal Mean SAM Trends (hPa/decadal)

Re-anal/Simulations	Trend (MAM)	Trend (JJA)	Trend (SON)	Trend (DJF)
ERA-Int	0.56	-0.08	-0.10	0.78*
NCEP-R1	0.30*	0.16	0.07	0.24*
E3SM-HIST	0.16*	0.24*	0.29*	0.38*
E3SM-AMIP	0.22	0.14	0.24	0.18
E3SM-1pctCO2	-0.11	-0.02	0.05	0.40
E3SM-4xCO2	-0.02	0.03	-0.45	-0.35

- The spreads in terms of confidence interval of interannual variability for E3SM-AMIP are larger than those for E3SM-HIST, while the spreads for the trend of the seasonal mean SAM index are similar or reversed. The reason may be because the variability of the ensemble members is phase-locked to that of the observed SST in AMIP simulations.
- The seasonality of the SAM trend for E3SM-AMIP in all seasons is bigger than that of E3SM-HIST. This fact may imply that the SST produced by the coupled model (E3SM-HIST) has weaker variability than the observed SST used in the E3SM-AMIP, as far as the influence on the SAM mode is concerned.
- The negative trend in annual mean SAM of the E3SM-4xCO2 simulation may be largely affected by the negative SAM trends during SON and DJF seasons.

II. Data and Methods

❖ Data used

Reanalyses		E3SM (Energy Exascale Earth System Model) data			
ERA_Interim (480x241, 512x256)	NCEP/NCAR_R1 (144x73, 192x94)	HIST (*EM: 5) (256x128)	AMIP (EM: 3) (256x128)	1pctCO2 (256x128)	4xCO2 (256x128)
Sea Level Pressure (SLP), Surface Zonal Wind Stress (TAUX)					
1979-2014 (36 years)				115-150 (last 36 years)	120-155 (last 36 years)

* EM: Number of ensemble member
** AMIP, 1pctCO2 and 4xCO2 simulation data are part of the E3SMv1 DECK experiments

❖ Methods

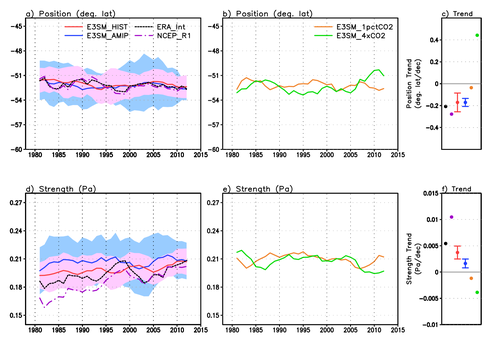
➢ Definition of the SAM Index and Pattern

- SAM mode: Leading empirical orthogonal function (EOF 1st mode) of the SLP anomalies over a domain extending south of 20ºS
- SAM Index: The first principal component time series (PC1)
- SAM pattern: Regression of the SLP anomalies onto the standardized SAM index calculated by subtracting the mean and dividing by the standard deviation

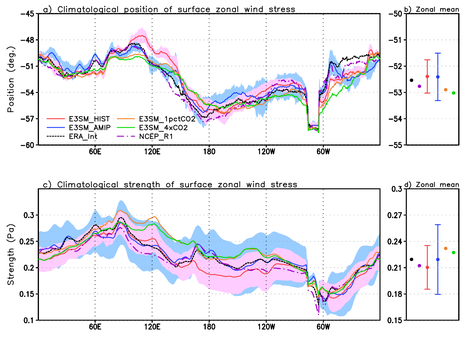
➢ Strength and Position of Surface Zonal Wind Stress (TAUX)

- E3SM simulations and reanalyses wind stress data was first interpolated onto a 0.5x0.5 degree horizontal grid.
- The strength of the surface TAUX: Maximum of the zonal mean TAUX between 70ºS and 20ºS
- The latitudinal position of the surface TAUX: Latitude at the maximum of SH surface TAUX

IV. Position and strength in SH surface TAUX



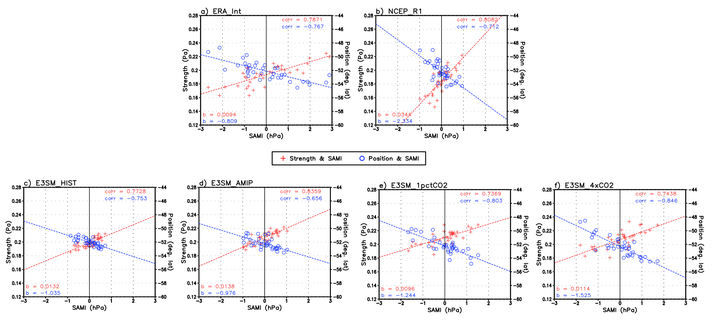
Left: Changes in the annual mean SH surface zonal wind stress (a and b) position and (d and e) strength. Trends of (c) position and (f) strength in the SH surface zonal wind stress. Shaded areas and vertical bars show the 95% confidence interval about the annual mean ensemble simulated trend.



Right: Climatological (a) latitudinal position and (c) strength by longitude of SH surface zonal wind stress and (b, d) their zonal-mean for the reanalyses and E3SM simulations. Shaded areas and vertical bars show the 95% confidence interval about the ensemble simulated annual mean variability.

- A poleward (equatorward) shift and strengthening (weakening) in trend of the SH surface TAUX are very close to the positive (negative) trend in the SAM index.
- Climatological zonal mean from the two CO_2 forcing simulations (E3SM-1pctCO2 and 4xCO2) have relatively poleward position (enhanced strength) compared to HIST and AMIP.
- Compared to the climatological position for the CMIP3 and CMIP5 climate models, the E3SM-HIST simulation represents an improvement with the position more consistent with that derived from the reanalysis.

V. Relationship between the SAMI and surface TAUX



- The relationship between the variability in the SAM index and the kinematic properties (latitudinal position and strength) of the SH zonal-mean surface TAUX for annual mean of 36 years.
- An increasing of the SAM index is related to a strengthening of surface TAUX strength, while a poleward movement in surface TAUX position is associated with a strengthening of the SAM index.
- In the relationship between surface TAUX strength and SAM index for the E3SM simulations, the CO_2 simulations show more gentle slope values than E3SM-HIST and AMIP simulations, while the CO_2 simulations have steeper slopes than the other simulations in the relationship between surface TAUX position and SAM index.

VI. Summary and Conclusion

❖ We assess the ability of two ensembles of E3SM simulations, E3SM-HIST and AMIP, to reproduce the SAM characteristics compared to observations over the satellite era. The variability and change of the SAM in the two CO_2 experiments (E3SM-1pctCO2 and 4xCO2) are also analyzed to show the model sensitivity in response to different types of increasing CO_2 forcings.

❖ All E3SM simulations capture the dominant characteristics of the SAM in the SH, though there are some differences in the location and intensity of the centers for the meridional dipole structure.

❖ The E3SM-HIST, AMIP, and 1pctCO2 simulations show an increasing trend in the annual mean SAM index, while the E3SM-4xCO2 simulation indicates a negative SAM trend.

❖ The E3SM-HIST and AMIP simulations showed the negative (positive) trend in the position (strength), similarly to both observations.

❖ For climatological position and strength of annual surface TAUX, the two CO_2 forcing simulations were slightly poleward and stronger than both E3SM-HIST and AMIP, and the E3SM-HIST was relatively equatorward and weaker compared to observations.

❖ The overall results of SH climate variability in these simulations are a promising indication for the E3SM coupled climate system. In addition, the historical simulations provide useful information to better understand the atmospheric variability and ocean circulation in the SH through the model performance.

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