Climate-change impact on the 20th-century relationship between the Southern Annular Mode and global mean temperature

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The positive phase of the El Niño-Southern Oscillation (ENSO) increases global mean temperature, and contributes to a negative phase of the Southern Annular Mode (SAM), the dominant mode of climate variability in the Southern Hemisphere. This interannual relationship of a high global mean temperature associated with a negative SAM, however, is opposite to the relationship between their trends under greenhouse warming. We show that over much of the 20th century this relationship undergoes multidecadal fluctuations depending on the intensity of ENSO. During the period 1925–1955, subdued ENSO activities weakened the relationship. However, a similar weakening has occurred since the late 1970s despite the strong ENSO. We demonstrate that this recent weakening is induced by climate change in the Southern Hemisphere. Our result highlights a rare situation in which climate change signals emerge against an opposing property of interannual variability, underscoring the robustness of the recent climate change.
Results

Linkage between trends of increasing GMT and positive SAM under greenhouse warming. There are many studies documenting the global warming trend and the upward trend of the SAM over the past decades. This linkage is even more conspicuous in realizations of simulated future climate, when these trends intensify, as produced by climate models contributing to CMIP3 and CMIP5 (see Supplementary Table S1 online). To illustrate this, we calculate the DJF GMT trends over the 2006–2099 period in each of the 31 available models, the SAM trends, grid-point zonal wind stress trends, and grid-point wind stress curl trends, which provide a gauge of the associated ocean circulation changes. A map of regression of GMT trends onto GMT trends, with respect to models, from 14 CMIP3 and 17 CMIP5 models (see Supplementary Table S1 online). Areas within thick contours indicate correlations significant at the 95% confidence level using Student’s t-test. Scatter plot between trends in SAM and GMT.

Observed relationship between interannual variability of GMT and circulation fields. Fig. 2 plots one-standard deviation anomalies of zonal winds and sea surface temperatures (SSTs) associated with GMT, Niño3.4, and the SAM. These are obtained through a linear regression using detrended data over the 31 years (1973–2003) of the observed data coverage. We choose this period for illustration because the ENSO-SAM correlation is highest. For clarity, we use a subscript “detrended” to indicate removal of trends in GMT, and “GMT” without the subscript to indicate an inclusion of a long-term trend. Several features emerge. Firstly, an El Niño event is associated with a higher GMTdetrended (Fig. 2a) as the tropical ocean releases heat to the atmosphere during an El Niño event. An important feature to note is that a higher GMTdetrended is linked to a negative SAM-like pattern in zonal winds (Fig. 2b), with enhanced westerlies in the mid-latitudes.
Secondly, the SAM-like zonal wind pattern seen in Fig. 2b is almost identical to that associated with an El Niño event (Fig. 2d). Finally, on interannual time scales, a positive SAM is linked to a La Niña, and vice-versa (Figs. 2e and 2f), as revealed and discussed by previous studies\textsuperscript{10,11}. The ENSO-SAM relationship means that during an El Niño event there is an increasing GMT detrended associated with both a negative SAM and a tendency for an equatorward shift of the subtropical gyre circulation. This is because the negative SAM features a decreasing mid-latitude wind stress curl and an equatorward shift in the zero-wind stress curl line as indicated by the extratropic positive and mid-latitude negative curl anomalies (see Supplementary Fig. S1 online).

There is no obvious dynamical linkage between GMT\textsubscript{detrended} and zonal wind variability. A plausible explanation is that this linkage is generated by the common forcing of ENSO: an El Niño event leads to a higher GMT\textsubscript{detrended} and a negative SAM. This interannual SAM-GMT\textsubscript{detrended} relationship, however, is opposite to that seen in the inter-model relationship between the long-term SAM trends and GMT trends (Fig. 1) in all respects. For example, on interannual time scales, a higher GMT is associated with decreasing westerlies in high latitudes (Fig. 2b), opposite to the feature of a greater GMT trend associated with trends of enhancing westerlies (Fig. 1a). Is the interannual SAM-GMT\textsubscript{detrended} relationship stable and robust?

Multidecadal variability of the interannual GMT-SAM relationship. It turns out that the interannual SAM-GMT\textsubscript{detrended} relationship undergoes considerable fluctuations (blue, Fig. 3a) over the 20th century. An evolution of the relationship, together with that of the ENSO-GMT\textsubscript{detrended} (red) and the ENSO-SAM (green) is calculated using a 31-year sliding window. Data are linearly detrended within each window before the correlation analysis. To test the robustness of our result, we also use HadISST v.1.1\textsuperscript{37} in place of ERSST.v3b\textsuperscript{35,36} to generate the equivalent plot to Fig. 3. The result is similar (see Supplementary Fig. S2 online). Overall, the evolution supports the notion that without climate change signals, ENSO simultaneously drives variability of GMT\textsubscript{detrended} and the SAM, resulting in an ENSO-GMT\textsubscript{detrended} and ENSO-SAM relationship\textsuperscript{10}, both stronger than a SAM-GMT\textsubscript{detrended} relationship when the correlation is negative (comparing green and blue curve of Fig. 3a). The central feature to emphasize is the strong multidecadal fluctuation of the SAM-GMT\textsubscript{detrended} relationship. Early in the century (e.g., the 31-year period centred at 1901), the relationships among these climate indicators are similar to that since early 1970s; strong correlations are seen in both periods. Equivalent maps to Fig. 2 for this early period show a strong resemblance (see Supplementary Fig. S3 online). Further, there is a collapse in the SAM-GMT\textsubscript{detrended} relationship in the decadal period at around 1940 towards what is consistent with the inter-model relationship between GMT trends and the SAM trends (Fig. 1). However, this does not imply a similar mechanism, as we will discuss below.

The SAM-GMT\textsubscript{detrended} correlation during the 1940 reversal period is generally not statistically significant above the 95% confidence level by Student’s \textit{t} test. This is illustrated in Fig. 4, similarly constructed as in Fig. 2. There is no well-defined SAM pattern associated with the GMT\textsubscript{detrended} (Fig. 4b). During this decadal period, ENSO is generally weaker than during the 31 years of the 1973–2003 period (comparing Fig. 4c with Fig. 2c, see also Supplementary Fig. S4 online). Although still influencing GMT\textsubscript{detrended}, ENSO no longer induces a SAM pattern (Fig. 4d), and the SAM in this period is not coherent with ENSO (Figs. 4e and 4f), as the impact from the weak ENSO is unable to be manifest out of stochastic noises. Thus, the role of ENSO in linking GMT\textsubscript{detrended} and the SAM, seen at the beginning
and the SAM in the 20th Century.

Given that global warming has been occurring over the 20th century, we expect a signature in the evolution of the SAM-GMT relationship beyond the fluctuating ENSO influences on an interdecadal time scale. As discussed in the context of Fig. 1, the relationship between the long-term SAM and GMT trends is opposite to that between the SAM and GMT\textsubscript{detrended}. To this end, we repeat the sliding-window correlation analysis without detrending (Fig. 3b), i.e., retaining climate change signals. An indication of an impact on the SAM-GMT\textsubscript{detrended} relationship by climate change (trends) emerges. During the 31-year period with a weak ENSO (see Supplementary Fig. S4 online), centred at approximately 1938, the trends in the SAM and GMT add to the reversed correlation (comparing blue curves in Fig. 3a and b), enabling it to reach a statistically significant value at the 95% confidence level by Student's $t$ test. This suggests that climate change might play a part in further weakening the SAM-GMT\textsubscript{detrended} relationship.

A more prominent signature is recorded in the period since the early 1970s, when data from early 1980 onward are included in the 31-year correlation. During this time the SAM and the GMT have been trending upward strongly; the former is in part due to Antarctic Ozone depletion\textsuperscript{23,27,28}, and the latter, due to greenhouse warming. The strong coherence between the long-term trends of the SAM and GMT offsets the SAM-GMT\textsubscript{detrended} negative correlation due to interannual variability. Since the 1980s, ENSO has been rather strong, and the world experiences the 1982/83 and 1997/98 super-El Niño events, the strongest of the century. However, there is no a statistically significant trend in Niño3.4 apart from the well-known climate shift in the mid-1970s. Despite the well-defined SAM pattern associated with the strong ENSO (Fig. 2d) in association with the strong ENSO-SAM correlation (green, Fig. 3b), the SAM-GMT correlation weakens (circled blue curve, Fig. 3b) once long-term GMT and SAM trends are included; the opposite relationship between long-term SAM and GMT trends to that between SAM-GMT\textsubscript{detrended} results in a change in correlation from a negative to a positive value, though the positive correlation is not statistically significant. It also means that, the occurrences of the weakening SAM-GMT relationship commencing around 1920 and 1970 are caused by completely different dynamic processes: the former is due to weak ENSO variability with a minimum in the 1940s, whereas the latter is due to an impact from climate change. This recent weakening in the SAM-GMT relationship occurs in spite of strong ENSO variability during this period, which should have strengthened the relationship.

The opposite relationship between the long-term SAM and GMT trends and between interannual SAM and GMT\textsubscript{detrended} variability is intriguing in many respects. It provides an example that global warming signals need not project onto existing teleconnections, i.e., between ENSO and the SAM, despite the fact the impact of global warming does cause an upward trend of the SAM. This is a distinct situation, which we believe is a rare one, and has important implications for climate change detection. It means that the association of an upward GMT trend with an upward trend in the SAM occurs despite an opposing relationship from interannual variability. Thus, the emergence of a robust symbiosis of the observed increasing GMT trend and the upward SAM trend in recent decades represents a robust climate change signal that manifests despite the impact of the strong ENSO over the past decades that damps the SAM trend.

**Discussion**

This study highlights that the interannual relationship between the GMT and the SAM undergoes significant multidecadal fluctuations over the 20th century through their common forcing by ENSO variability. An El Niño increases GMT but also forces a negative SAM,
leading to a GMT-SAM negative correlation. This negative correlation collapses, even reverses, during the 31-year period centred at the 1940s and during the period since the early 1970s when raw anomalies are used. However, these two periods of reversal are caused by different dynamics. During the 1940s reversal period ENSO is weak and, although still influencing GMT, does not induce a SAM pattern. Since the late 1970s, the negative correlation collapses despite the strong ENSO-SAM relation associated with the strong ENSO over the period. We show that this collapse is triggered by a global warming-induced trend in GMT and the SAM: an increasing GMT trend is associated with an upward SAM trend, a feature also seen in the inter-model statistics using CMIP3 and CMIP5 models.

This study also shows that climate change signals can emerge against an opposing property of interannual variability. In such a situation, the emerging linkage of the upward SAM trend with an increasing GMT trend, despite a suppressing effect from the recent strong interannual SAM-ENSO relationship, highlights the robustness of the climate change signals in the Southern Hemisphere. This will be particularly useful for climate change detection using climate models. It suggests that realistic simulations of the intensity of ENSO and the SAM, and their relationship will have a direct relevance for climate change detection and climate projection.

**Methods**

**Data.** Wind stress data from NOAA 20CRv2 (20th-Century Reanalysis, Version 2), which provide a comprehensive global atmospheric circulation data set spanning from 1870 to 2010, are used to construct an austral summer SAM index over the 20th century. This is carried out by applying an empirical orthogonal function (EOF) analysis to austral summer zonal winds, in the domain of 20°S–70°S. We define a SAM index as the time series of the first EOF. The index has a correlation with the observation-based SAM index from Marshall of 0.93 over the period since 1958, statistically significant at the 99.9% confidence level by Student’s t test (see Supplementary Fig. S6 online). NOAA Extended Reconstructed SST version 3b (ERSST.v3b), generated using in situ SST data and improved statistical methods to allow stable reconstruction using sparse data, is deployed to construct an ENSO index (Niño3.4) and SST anomaly pattern associated with the SAM and Niño3.4. To test the robustness of our results, we use the Met Office Hadley Centre’s SST data set (HadISST) v.1.1 in place of ERSST. HadISST v.1.1 includes in situ sea surface observations and satellite derived estimates at the sea surface, the SST bucket corrections have been applied to gridded fields from 1870 through 1941, and a blend of satellite AVHRR and observations are used in the modern periods.

**Model simulations.** To illustrate that a greater GMT trend tends to be associated with a greater SAM trend, we use the SST and wind stress data from the IPCC Special Report on Emission Scenario (SRES) A2 simulations submitted to coupled model intercomparison phase 3 (CMIP3 SRESA2, 14 models), in which CO₂ concentration increases by 840 ppm at the end of the 21st century and the radiative forcing increases by 7 W/m². We also use these variables from the Representative Concentration Pathways (RCP) 8.5 simulations submitted to coupled model intercomparison phase 5 (CMIP5 RCP8.5, 17 models), which is characterized by a rising radiative forcing pathway leading to 8.5 W/m² (and about 940 ppm of CO₂) by 2100 (for an identification of models, see Supplementary Table S1 online). Although multiple realizations may exist for an individual model, we only use the first to ensure that all models are equally represented. For the model data, we derive SAM index as described above.

**Seasonality.** All calculations in this paper are based on data in the austral summer (December, January, and February, DJF). In this season, the observed SAM trend is rather pronounced and ENSO peaks.

**Graphic software.** All maps and plots were produced using licensed MATLAB.

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