LETTER

What chance of a sudden stratospheric warming in the southern hemisphere?

L Wang, S C Hardiman, P E Bett, R E Comer, C Kent and A A Scaife

1 Department of Atmospheric and Oceanic Sciences & Institute of Atmospheric Sciences, Fudan University, Shanghai, People’s Republic of China
2 Shanghai Institute of Pollution Control and Ecological Security, Shanghai, People’s Republic of China
3 Big Data Institute for Carbon Emission and Environmental Pollution, Fudan University, Shanghai, People’s Republic of China
4 Met Office Hadley Centre, Fitz Roy Road, Exeter, United Kingdom
5 College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, United Kingdom

E-mail: wanglei_ias@fudan.edu.cn

Keywords: sudden stratospheric warming, southern hemisphere, polar vortex, wildfire

Abstract

Sudden stratospheric warmings (SSWs) are amongst the most dramatic events in the Earth’s atmosphere and they drive extreme surface weather conditions. They have been recently linked to the hot and dry weather conditions that favour wildfires over Australia. However, the chance of a southern hemisphere event is unknown because it has only been observed once. Legitimate estimation of the frequency of SSW events requires a large sample of realistic model simulations. Here we show that the chance of an event is close to 4% per year, implying that an event will occur, on average, every 25 yr, using a state-of-the-art model that simulates SSWs accurately. It is thus not surprising that there was a near miss in the September prior to the Australian wildfire of 2019, given the 40 yr of comprehensive satellite records and just one observed Antarctic event. According to this new estimate, it would also not be surprising to see a second SSW event in the coming years in the southern hemisphere. Such a stratospheric warming event might bring further extreme surface weather conditions and natural hazards, as it may raise the risk of increased rainfall in the latitudinal band of 35–50°S. Meanwhile, the associated hot and dry weather conditions over austral subtropical continents might increase the risk of wildfires over these regions.

1. Introduction

Sudden stratospheric warmings (SSWs) are amongst the most dramatic examples of fluid dynamical variability in the climate system. They involve the complete reversal of the zonally averaged westerly winds and a rise of order 50 K in winter polar stratospheric temperature. SSW events have been detected in the northern hemisphere for as long as we have been making stratospheric observations (Scherhag, 1952), but only a single southern hemisphere event is recorded in current observations and this occurred over a decade ago, in September 2002 Krüger et al. (2005, Manney et al. 2005).

The striking inter-hemispheric asymmetry in SSW occurrence can be explained by differing climatological features caused by topography and land-sea contrast in the two hemispheres (Waugh and Polvani, 2010). The northern hemisphere stratosphere exhibits only moderate strength westerlies in its winter polar night jet, reaching around 40 m s−1, and large stationary wave amplitudes are found near the tropopause for the longest waves (wave 1, 2 and 3), which peak in amplitude at around 60°N (Pawson and Kubitz, 1996, Scaife et al. 2000). In contrast, the southern hemisphere westerlies are, on average, double the strength of those in the north. Wave amplitudes are generally below the amplitude threshold needed to induce a breakdown of the polar vortex, a reversal to zonal mean easterlies at 10 hPa and 60°S, and hence an SSW (Holton and Mass, 1976, Yoden, 1987). Instead, either a steady regime or a regime with small amplitude high-frequency oscillations on a timescale of ~10 d, apparently driven by shear instability, occurs in most southern hemisphere winters (Scaife and James, 2000).

© 2020 The Author(s). Published by IOP Publishing Ltd
Despite this, there were occasional reports of SSW events in the southern hemisphere in long climate simulations before 2002 (Butchart et al 2000). Similarly, ensembles of seasonal forecasts have also been noted to occasionally exhibit SSW events in the southern hemisphere (Seviour et al 2014). Idealized models are also able to simulate an occasional SSW under southern hemisphere-like conditions (Kushner and Polvani 2005). This is all consistent with the rare occurrence of SSW events in the southern hemisphere and with the idea that on rare occasions, accumulated wave activity fluxes from the troposphere (Matsuno 1971; Andrews and McIntyre 1976) might exceed the level needed to generate an SSW event in the southern hemisphere.

Given the small sample of just one observed event, the surface impacts of SSW events in the southern hemisphere are not well documented. Nevertheless, it appears that the surface effects that follow an SSW event in the southern hemisphere are dynamically similar to the more frequent and much better documented impacts in the northern hemisphere (Baldwin and Dunkerton 1999, Kidston et al 2015, Lim et al 2019). The southern hemisphere jet stream weakens and the storm track shifts equatorward for weeks or even months after the stratospheric wind weakens substantially or reverses, corresponding to a negative shift of the southern annular mode (Hartmann and Lo 1998, Lim et al 2019). This leads to anomalous surface weather, with cooling and increased rainfall in Tasmania, southern New Zealand, and southern parts of South America and anomalously warm and dry conditions over large remaining parts of Australia (Gillett et al 2006) that can significantly increase risks of wildfire in this region (Lim et al 2019).

Here we use large ensembles of model simulations from the Met Office Seasonal Prediction System, GloSea5 (Maclachlan et al 2015), to estimate the chance of an SSW in the current climate. GloSea5 accurately reproduces the observed northern hemisphere SSW frequency (Scaife et al 2016) and exhibits state-of-the-art skill in predicting the North Atlantic oscillation and southern annular mode over monthly to seasonal time scales (Scaife et al 2014, Seviour et al 2014). These ensemble simulations are all subject to current levels of external forcing from greenhouse gases but also contain large internal variability manifested as atmospheric and oceanic sensitivity to initial conditions. They therefore correspond to multiple realisations of the current climate that are statistically consistent with the single realisation that is the observed record. We also show the expected impacts of SSW events on the surface weather in the southern hemisphere using this much larger sample of events than the single observed 2002 event.

2. Data and method

We use an ensemble of initialized simulations produced by the GloSea5 seasonal forecasting system (Maclachlan et al 2015). This is based on the Global Coupled 2 configuration of the Hadley Centre Global Environment Model version 3 (HadGEM3-GC2; Williams et al 2015). The grid spacing in the atmosphere is 0.83° in longitude and 0.55° in latitude, with 85 vertical levels up to a height of 85 km, and the global ocean resolution is 0.25° with 75 vertical levels.

Fourteen-member historical ensemble forecasts (hindcasts), running out to 216 d, are initialized on four dates per month for the 23 yr 1993–2015. We collate hindcasts from eight initialization dates from mid-May to mid-July each year, to form a final ensemble of 14 × 8 = 112 members per year, covering the period from August to mid-December each year (i.e. 2576 members in total). We use the daily mean, zonal mean, zonal wind at 10 hPa and 60°S ([U]) to characterize the stratospheric circulation. We also use the monthly-mean 1.5 m air temperature, precipitation, and air pressure at mean sea level (MSLP) to analyse surface impacts. We compare our hindcast results against data from the ERA-Interim reanalysis (Dee et al 2011) for the same period.

The fidelity of the climate model is assessed using the UNprecedented Simulated Extremes using ENsembles (UNSEEN) subsampling approach (Thompson et al 2017, Kent et al 2017). A single model ensemble member is randomly selected (with replacement) for each year to generate a sub-sample of equal size to the observations (1993–2015). This process is repeated to generate a dataset of 10 000 random subsamples. The mean, standard deviation, skewness, and kurtosis are calculated for each subsample. The model is deemed to pass the fidelity test if the corresponding ERA-Interim value falls within the 2.5–97.5 percentile range across all 10 000 subsamples derived for each statistic (figure S1 (available online at stacks.iop.org/ERL/15/104038/mmedia)).

Across August, September, and October the model exhibits a mean westerly bias in [U] but is indistinguishable from ERA-Interim in terms of the standard deviation, skewness, and kurtosis (see figure S1 for October tests). The fidelity in the model variability sets the ground for estimating the SSW occurrence. The mean bias increases from 5 m s⁻¹ in August up to approximately 15 m s⁻¹ in October (table S1). To account for this seasonality, the mean westerly bias is removed from the climate model dataset using a 10 d Gaussian filter on the observational climatology, in line with seasonal forecasting applications (Maclachlan et al 2015). Tests indicate that the results are insensitive to this smoothing (not shown). The existence of a westerly mean bias in
the stratosphere indicates that the model has relatively weak upward wave activity from the troposphere, which is common among current chemistry-climate models (Waugh and Polvani 2010). The zero zonal wind is more dynamically meaningful for wave breaking of stationary waves than that of transient waves (Waugh and Polvani 2010) and quasi-stationary planetary waves forced in the troposphere were found to play an important role in the observed 2002 event Krüger et al (2005). Although a westerly bias may lead to underestimation of the SSW frequency, the bias-correction may help reduce the underestimation (Kim et al 2017). The bias-corrected winds are thus used throughout the analysis, as the model variability is comparable to the observed.

A major SSW of the southern hemisphere stratospheric polar vortex is defined as occurring when \([U]\) becomes easterly (i.e. negative). The first day on which this occurs is defined as the ‘central date’ of the warming. We also require that \([U]\) must become westerly (positive) again before the final warming occurs, generally during November/December (see figure 1(b) of Seviour et al 2014), and that this is at least 20 d after the central warming date. This definition is consistent with that commonly used for northern hemisphere SSWs (Butler et al 2018). There are 96 SSW events among all the 2576 members of the GloSea5 hindcasts.

The chance of SSW occurrence is estimated using a ranking method from a pool of samples selected by bootstrapping (Thompson et al 2017). Each time 60% of the simulated years (i.e. 2576 × 60% = 1546 yr) are randomly selected and a subsample consists of the minimum value of zonal-mean zonal wind (i.e. the minimum polar vortex strength) for each selected year. The minimum zonal winds are ranked in each subsample, and this selection and ranking process is repeated 10,000 times to create a sample pool. Each rank thus consists of 10,000 samples of the minimum vortex strength, which are used to estimate the average chance of SSW occurrence and its 2.5%–97.5% range.

### 3. Results

Figure 1 shows the daily evolution of the stratospheric polar vortex for June to December, for the observed 1993–2015 climatology and the 2002 case when an SSW was observed in the southern hemisphere. Model simulations are also shown for the ten ensemble members simulating the strongest SSW events, out of a total of 96 ensemble members simulating SSWs, where the strength is defined by the most easterly value of \([U]\) obtained after the SSW central date. The ten ensemble member time series are qualitatively consistent with the observed 2002 time series, with the vortex being weaker than climatology throughout September, October, and November. Most SSWs occur in October in the model compared to the single observed warming in late September 2002 Krüger et al (2005).

The 2002 September SSW event was followed by pronounced southern hemisphere surface climate anomalies in the following month (figure 2), in many respects similar to a typical northern hemisphere SSW event. The overall surface anomaly fields show contrasts between high and middle latitudes, albeit with additional fine structure. The MSLP indicated an extreme negative phase of the southern annular mode in October 2002 (figure 2(a)). Correspondingly, the precipitation is anomalously high over 35–50°S and anomalously low poleward and equatorward of this band (figure 2(b); see also figure S2). In this particular case, Australia, Brazil, and South Africa were drier than normal, whereas northern Argentina, southern Chile, and parts of New Zealand and Tasmania became extremely wet. Most of the Antarctic continent and central South America experienced a warmer than average spring (figure 2(c)).

As there is only a single observed SSW in the southern hemisphere, it is not possible to distinguish the effects of the event from other internal climate variability that could mask or enhance the effect of the SSW. We therefore compare the observed case with a composite of our ten strongest simulated SSW events. These tend to occur in October and thus the November surface anomaly composites for these events are shown in figures 2(d) and (e). The ten events consist of three vortex split events, similar to the observed 2002 SSW, and seven displacement events. Unlike northern hemisphere cases which tend
to show common longitudinal phases, these events occur with random longitudinal phases and thus the negative southern annular mode pattern shown in the composite is very zonal (figure 2(d)). Nevertheless, the overall structure of surface impacts resembles that observed. Similar to the 2002 event, there is a band of increased precipitation over middle latitudes and most of southern Africa and reduced precipitation over parts of Australia and Argentina (figure 2(e); see also figure S2). Brazil and parts of South Africa are wetter, opposite to the 2002 event and assuming the model response is realistic this suggests that those anomalies in 2002 may not be attributed to the SSW event. A warmer spring also occurs in the Antarctic continent and central South America, consistent with the 2002 spring (figure 2(f)).

4. Summary and discussion

We estimate that the southern hemisphere is subject to rare, naturally occurring SSWs in about 4% of years on average over time (figure 3), corresponding to an event every 2–3 decades, with a total of 96 events identified out of 2576 realizations. The chance of occurrence decreases with strength (figure 3), indicating strong SSW events are less likely to occur than weak events. The observed SSW easterly strength in 2002 (about 22 m s\(^{-1}\)) is stronger than any of the simulated events, which may be associated with the mean westerly bias in the model as noted in section 2. The surface impacts resemble the event of 2002 although there are some notable differences, likely due to coincidental but unrelated variability in the particular case of 2002. In September 2019 there was also a very disturbed polar vortex in the Antarctic stratosphere. Although a near miss in terms of reaching the zero-wind threshold at 10 hPa, this event is likely to have contributed to the extensive and influential 2019 Australia wildfire, based on evidence from past events (Lim et al 2019). Thus, information on the frequency of SSW occurrence in the southern hemisphere will help society to better prepare and plan for the future climate and the associated societal impacts of these extreme events.

Finally, we note the significant progress in modelling and forecasting that makes our analysis...
possible. Since the event in 2002, long-range forecast systems have been extended to include explicit representation of the stratosphere (Butler et al 2016) and this has now become accepted as an important additional source of prediction skill (Sigmoid et al 2014, Scaife et al 2016, Lim et al 2019). While the wind variability in our model simulations is statistically similar to the observed variability in southern hemisphere stratospheric winds (figure S1), the SSW events tend to be weaker in amplitude than the 2002 event probably due to the westerly bias in the model climatology and so further work on gravity wave parameterizations (Ratnam et al 2004, Geller et al 2013) and interactive ozone schemes may benefit future simulations and predictions of southern hemisphere sudden stratospheric warmings.

Acknowledgments

We thank the European Centre for Medium-Range Weather Forecasts for providing ERA-Interim data. L W is supported by Grants 41875047 and 91837206 from National Natural Science Foundation of China (NSFC) and Grant JIHZ308132 from Fudan University. This work was supported by the Met Office Hadley Centre Climate Programme funded by BEIS and Defra.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

L Wang https://orcid.org/0000-0002-1618-1796
S C Hardiman https://orcid.org/0000-0001-9813-1209
P E Bett https://orcid.org/0000-0002-4508-7192

References

Andrews D G and McIntyre M E 1976 Planetary waves in horizontal and vertical shear: the generalized Eliassen-Palm relation and the mean zonal acceleration J. Atmos. Sci. 33 2031–48
Baldwin M P and Dunkerton T J 1999 Propagation of the Arctic oscillation from the stratosphere to the troposphere J. Geophys. Res. 104 30937–46
Butchart N, Austin J, Knight J R, Scaife A A and Gallani M L 2000 The response of the stratospheric climate to projected changes in the concentrations of well-mixed greenhouse gases from 1992 to 2051 J. Clim. 13 2142–59
Butler A H and Gerber E P 2018 Optimizing the definition of a sudden stratospheric warming J. Clim. 31 2337–44
Butler A H et al 2016 The climate-system historical forecast project: do stratosphere-resolving models make better seasonal climate predictions in boreal winter? Q. J. R. Meteorol. Soc. 142 1413–27
Dee D P et al 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Q. J. R. Meteorol. Soc. 137 553–97
Geller M A et al 2013 A comparison between gravity wave momentum fluxes in observations and climate models J. Clim. 26 6383–405
Gillet N P, Kell T D and Jones P D 2006 Regional climate impacts of the southern annular mode Geophys. Res. Lett. 33 L23704
Hartmann D L and Lo F 1998 Wave-driven zonal flow vacillation in the southern hemisphere J. Atmos. Sci. 55 1303–15
Holton J R and Mass C 1976 Stratospheric vacillation cycles J. Atmos. Sci. 33 2218–25
Kent C, Pope E, Thompson V, Lewis K, Scaife A A and Dunstone N 2017 Using climate model simulations to assess the current climate risk to maize production Environ. Res. Lett. 12 054012
Kidston J, Scaife A A, Hardiman S C, Mitchell D M, Butchart N, Baldwin M P and Gray L J 2015 Stratospheric influence on tropospheric jet streams, storm tracks and surface weather Nat. Geosci. 8 433–40
Kim J, Son S-W, Gerber E P and Park H-S 2017 Defining sudden stratospheric warming in climate models: accounting for biases in model climatologies J. Clim. 30 5329–40
Krüger K, Naujokat B and Labitzke K 2005 The unusual midwinter warming in the southern hemisphere stratosphere 2002 a comparison to northern hemisphere phenomena J. Atmos. Sci. 62 603–13
Kushner P J and Polvani L M 2005 A very large, spontaneous stratospheric sudden warming in a simple AGCM: a prototype for the southern hemisphere warming of 2002? J. Atmos. Sci. 62 890–7
Lim E, Hendon H H, Boschat G, Hudson D, Thompson D W J, Dowdy A J and Ashlär B J M 2019 Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex Nat. Geosci. 12 896–901
Madlachlan C et al 2015 Global seasonal forecast system version 5 (GloSea5): a high-resolution seasonal forecast system Q. J. R. Meteorol. Soc. 141 1072–84
Manney G L, Sabutis J L, Allen D R, Lahoz W A, Scaife A A, Randall C E, Pawson S, Naujokat B and Swinbank R 2005 Simulations of dynamics and transport during the september 2002 antarctic major warming J. Atmos. Sci. 62 690–707
Matsuno T 1971 A dynamical model of the stratospheric sudden warming J. Atmos. Sci. 28 1479–94
Pawson S and Kubitz T 1996 Climatology of planetary waves in the northern stratosphere J. Geophys. Res. 101 16987–96
Ratnam V M, Tsuda T, Jacobi C and Aoyama Y 2004 Enhancement of gravity wave activity observed during a major southern hemisphere stratospheric warming by CHAMP/GPS measurements Geophys. Res. Lett. 31 L16101
Scaife A A, Austin J, Butchart N, Pawson S, Keil M, Nash J and James I N 2000 Seasonal and interannual variability of the stratosphere diagnosed from UKMO TOVS analyses Q. J. R. Meteorol. Soc. 126 2663–604
Scaife A A and James I N 2000 Response of the stratosphere to interannual variability of tropospheric planetary waves breakQ. J. R. Meteorol. Soc. 126 275–97
Scaife A A et al 2016 Seasonal winter forecasts and the stratosphere Atmos. Sci. Lett. 17 51–56
Scaife A A et al 2014 Skillful long-range prediction of European and North American winters Geophys. Res. Lett. 41 2514–9
Scherhag R 1952 Die explosionsartigen stratosphärenwärmerungen des spätwinters, 1951–1952 Ber. Deut. Wetterd. (U.S. Zone) 6 51–63
Seymour J, Monaghan M, Hardiman S C, Gray L J, Butchart N, Maclachlan C and Scaife A A 2014 Skillful seasonal prediction of the southern annular mode and Antarctic Ozone J. Clim. 27 7462–74
Sigmond M, Scinocca J F, Kharin V V and Shepherd T G 2014 Enhanced seasonal forecast skill following stratospheric sudden warmings Nat. Geosci. 6 98–102
Thompson V, Dunstone N J, Scaife A A, Smith D M, Slingo J M, Brown S and Belcher S E 2017 High risk of unprecedented UK rainfall in the current climate Nat. Commun. 8 107
Waugh D W and Polvani L M 2010 Stratospheric polar vortices Geophys. Monogr. Ser. 190 43–58
Williams K et al 2015 The Met Office global coupled model 2.0 (GC2) configuration Geosci. Model Dev. 8 1509–24
Yoden S 1987 Bifurcation properties of a stratospheric vacillation model J. Atmos. Sci. 44 1723–33