The Antarctic stratospheric warming and its impacts in 2019

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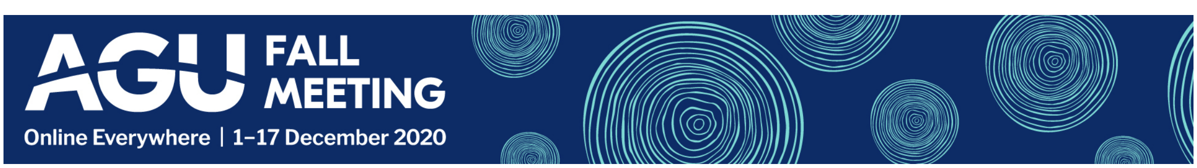
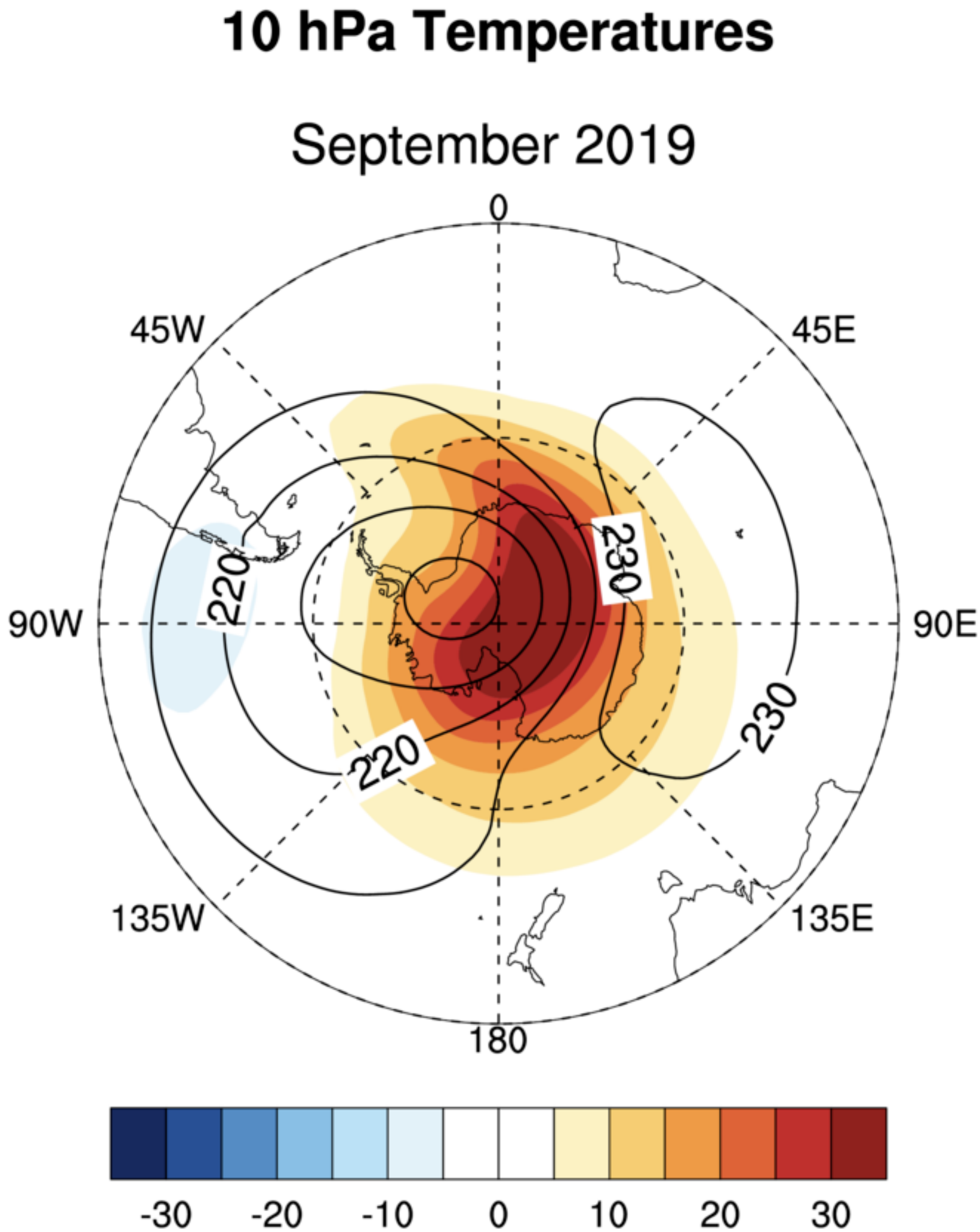


1. INTRODUCTION



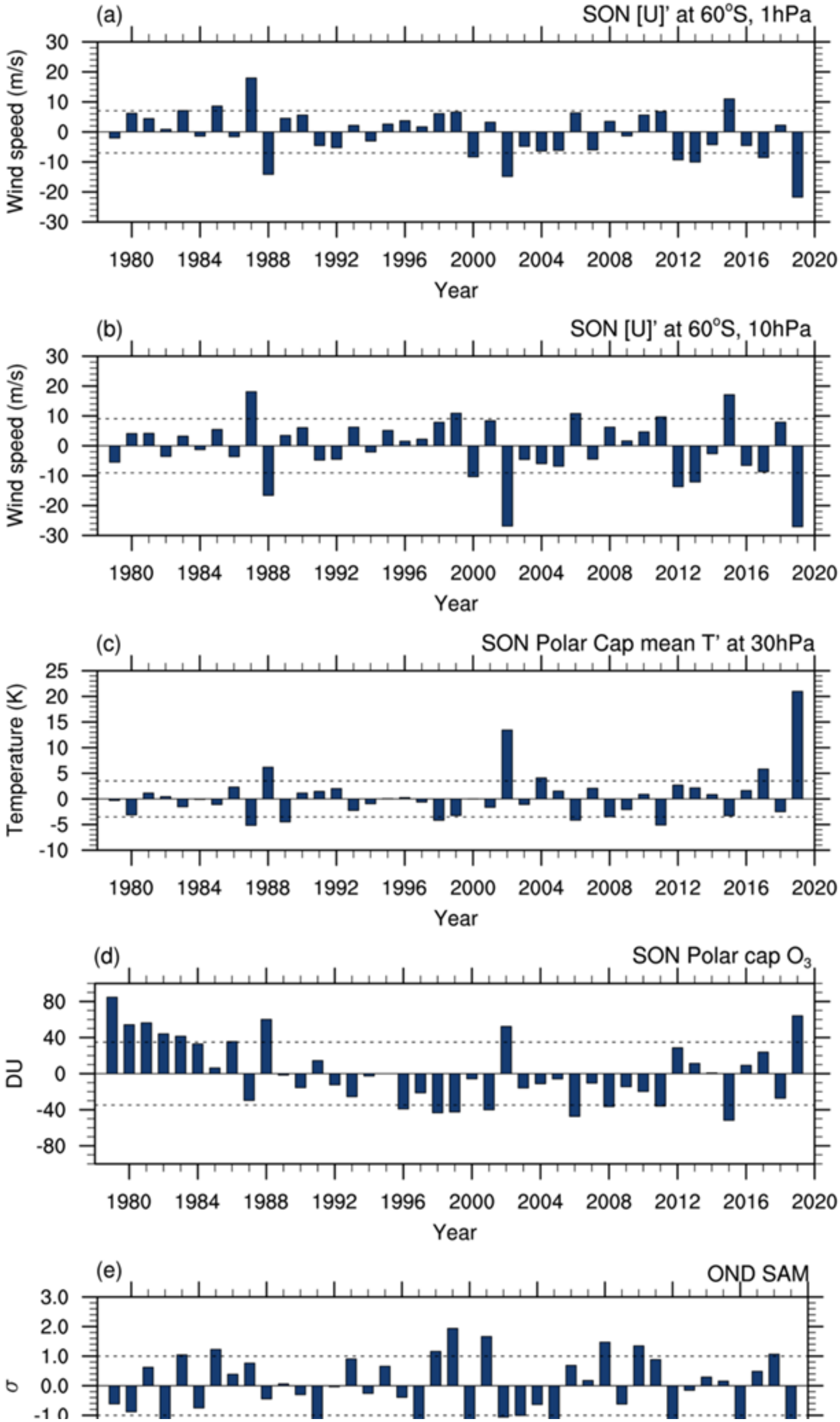
A rare sudden stratospheric warming (SSW) occurred over Antarctica in late August to mid-September 2019: stratospheric westerly jet weakened rapidly and temperatures rose dramatically over Antarctica.

Changes in the stratospheric flow were every bit as dramatic as those observed during the only other notable sudden warming observed in the Southern Hemisphere (SH): The 2002 SH sudden warming.

Deceleration of the mid-stratospheric vortex during 2019 was as large as that observed during the 2002 event, and the mean polar stratospheric warming exceeded that observed during the 2002 event.

This study offers an overview of the low-frequency evolution, dynamics, predictability, and surface impacts of a rare SH stratospheric warming that occurred in austral spring 2019

3. SETTING NEW RECORDS


(a)
SON [U]' at 60°S, 1hPa
Wind speed (m/s)
30
20
10
0
-10
-20
-30
1980 1984 1988 1992 1996 2000 2004 2008 2012 2016 2020
Year
(b)
SON [U]' at 60°S, 10hPa
Wind speed (m/s)
30
20
10
0
-10
-20
-30
1980 1984 1988 1992 1996 2000 2004 2008 2012 2016 2020
Year
(c)
SON Polar Cap mean T' at 30hPa
Temperature (K)
25
20
15
10
5
0
-5
-10
1980 1984 1988 1992 1996 2000 2004 2008 2012 2016 2020
Year
(d)
SON Polar cap O3
DU
80
40
0
-40
-80
1980 1984 1988 1992 1996 2000 2004 2008 2012 2016 2020
Year
(e)
OND SAM
σ
3.0
2.0
1.0
0.0
-1.0

Time series of anomalies of

(a) September-November mean (SON) [U]' at 60°S, 1 hPa;

(b) same as (a) but at 10 hPa (i.e., the springtime polar vortex index, SPVI);

(c) SON Antarctic temperature south of 60°S at 30 hPa;

(d) SON Antarctic polar cap ozone; and

(e) standardized October-December mean (OND) Southern Annular Mode (NOAA CPC monthly AAO) index.

The dashed horizontal lines in each panel indicates a unit standard deviation.

The 2019 SSW was as strong as the 2002 SSW but didn't qualify as a major SSW because the westerly vortex winds at 60S, 10 hPa never reverse.

Nonetheless, the 2019 SSW was a record-breaking major event by many other measures. For instance,

- Austral spring-time (Sep-Nov; SON) mean vortex observed at 60S, 1 hPa was the weakest on record;

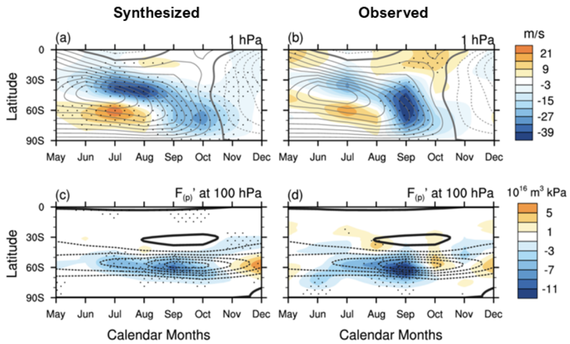
- Spring vortex observed at 60S, 10 hPa was as strong as that of 2002

- Spring vortex warming in the mid-stratosphere was the greatest on record

- Spring ozone concentration over the Antarctic region was the highest since 1979

- Subsequent late spring (Oct-Dec) Southern Annular Mode, SAM, was the most negative on record

4. LOW-FREQUENCY DYNAMICS

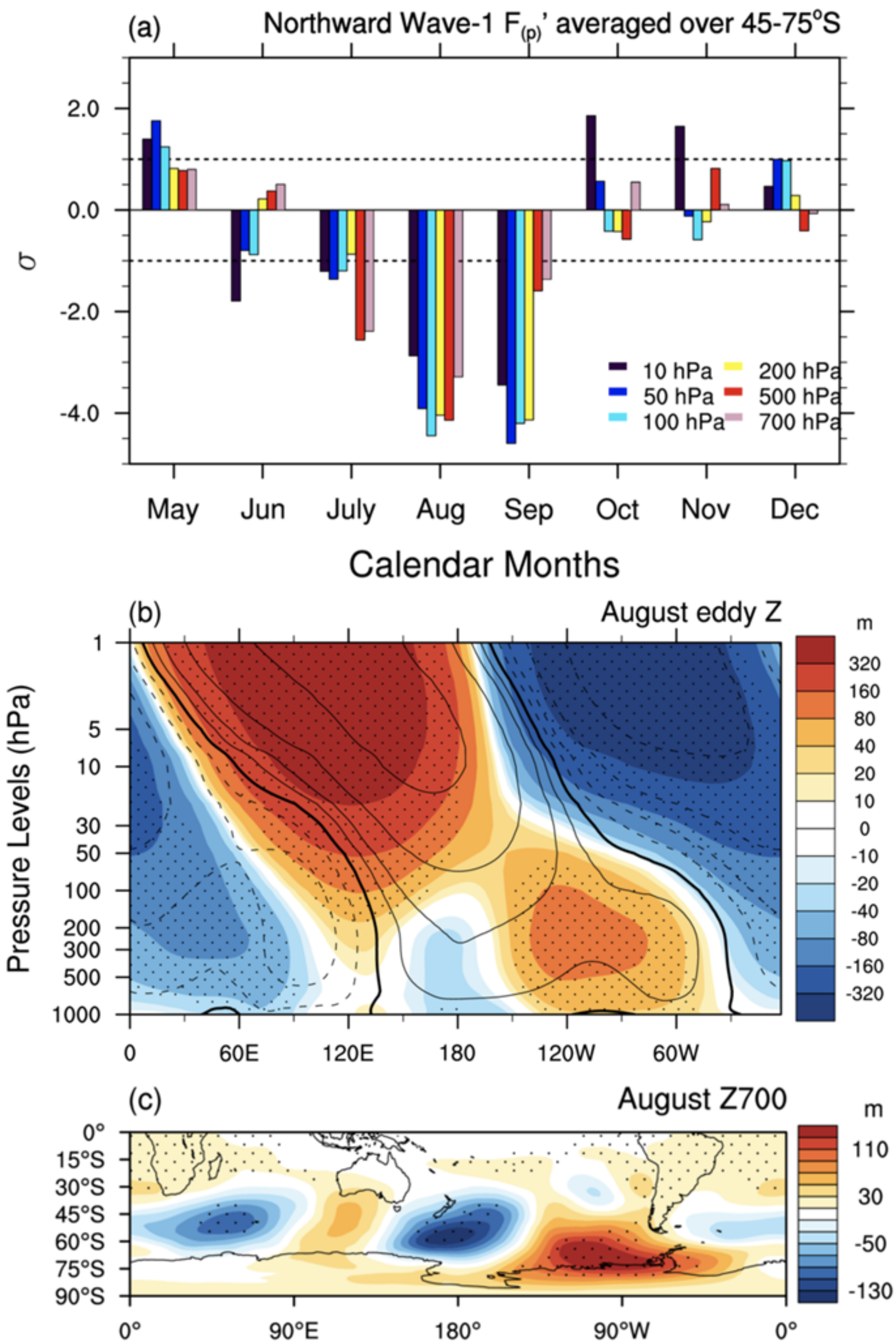


(Upper panels) (a) Synthesized and (b) observed monthly anomalies of zonal mean zonal winds at 1 hPa. The synthesized anomalies were derived from the regression onto the SON mean zonal-mean zonal winds at 60S and 10 hPa (SPVI) over 1979-2018, which was multipled by the 2019 SPVI).

The dipole zonal wind anomalies in the SH winter months of June-August in both synthesis and observation of 2019 indicate a poleward shift of the winter polar night jet, which is an important pre-condition that is known to promote more upward propagation of planetary-scale waves over the polar region

(Bottom panels) (c), (d) Same as (a), (b) but of northward eddy heat flux at 100 hPa (negative values indicate increased poleward heat flux and upward propagating wave activity in the SH).

In both synthesis and observation of 2019, poleward eddy heat fluxes anomalously increase in July to September in the higher latitudes than usual, leading to the stratospheric polar vortex weakening over Antarctica in the austral spring season.



(a) Standardized anomalies of northward wave-1 heat flux averaged over 45-75°S (with cosine weighting) at different vertical levels.

(b) Eddy geopotential height (Z) averaged over 45-75°S with cosine latitude weighting. The contours and color shadings indicate climatological and 2019 eddy patterns, respectively.

(c) Z700 anomalies for August 2019.

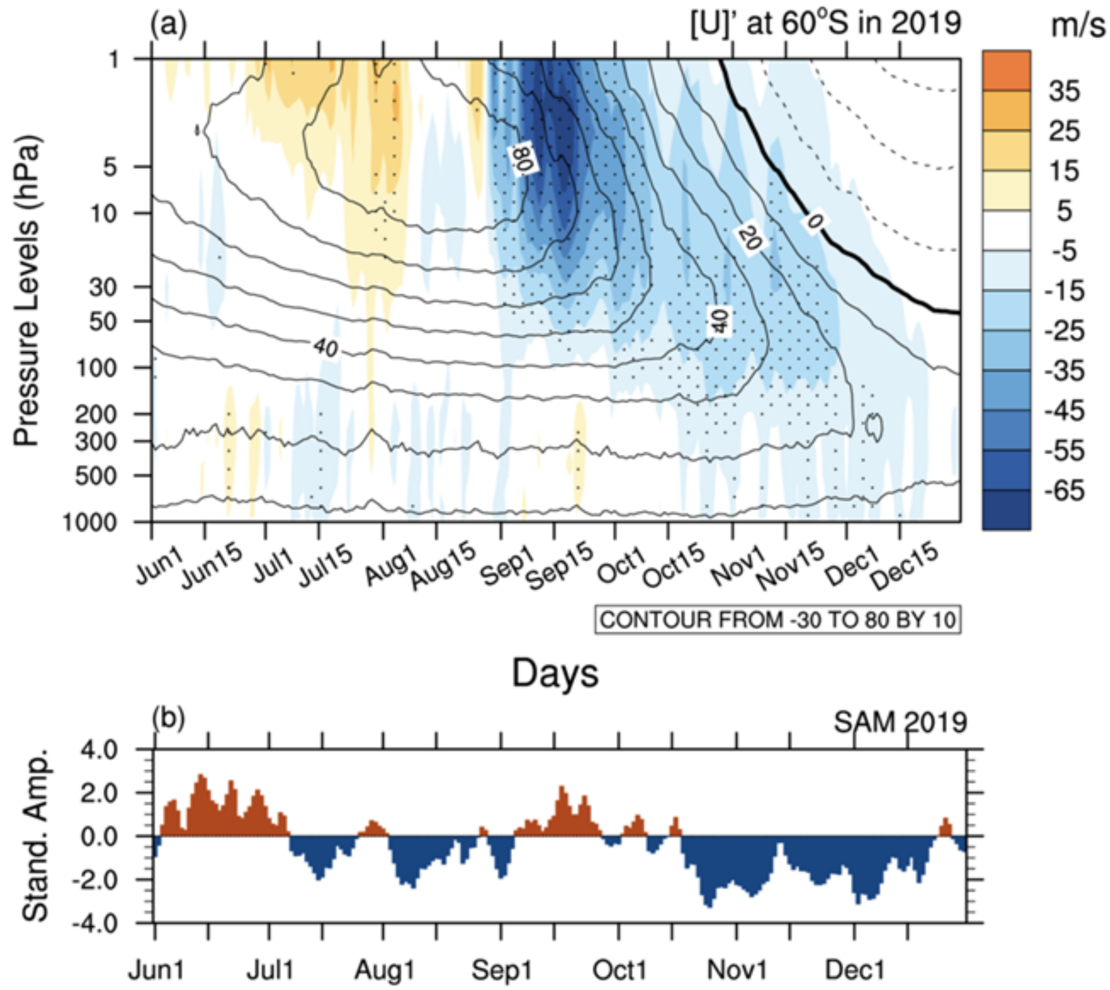
Plot (a) shows extraordinary negative amplitudes of the northward heat flux (>|3σ|) in both troposphere and stratosphere in August and September 2019, implying anomalous wave activity source could have been in the troposphere.

Plot (b) displays the anomalous August eddy geopotential height pattern of 2019, which is characterized by a stratospheric wave-1 pattern with a strong westward tilt from the troposphere, which indicates strong upward propagating wave activity.

Plot (c) displays the anomalous lower tropospheric circulation in August 2019, which is characterized by a strong and persistent anticyclonic circulation anomaly over the Bellingshausen Sea, a secondary anticyclonic anomaly south of Australia and strong cyclonic circulation anomalies in-between.

Recent studies such as Rao et al. (2020) (https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020JD032723)and Shen et al. (2020) (https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL089343#:~:text=The%20strongest%20and%20most%20persistent,(SSW)%20in%20September%202019.) showed that this August lower tropospheric circulation anomaly further amplified in September 2019 and played a key role as a source of record strong wave-1 activity propagating upward, which triggered the onset of 2019 SSW in mid-September.

5. IMPACTS ON THE SURFACE CLIMATE

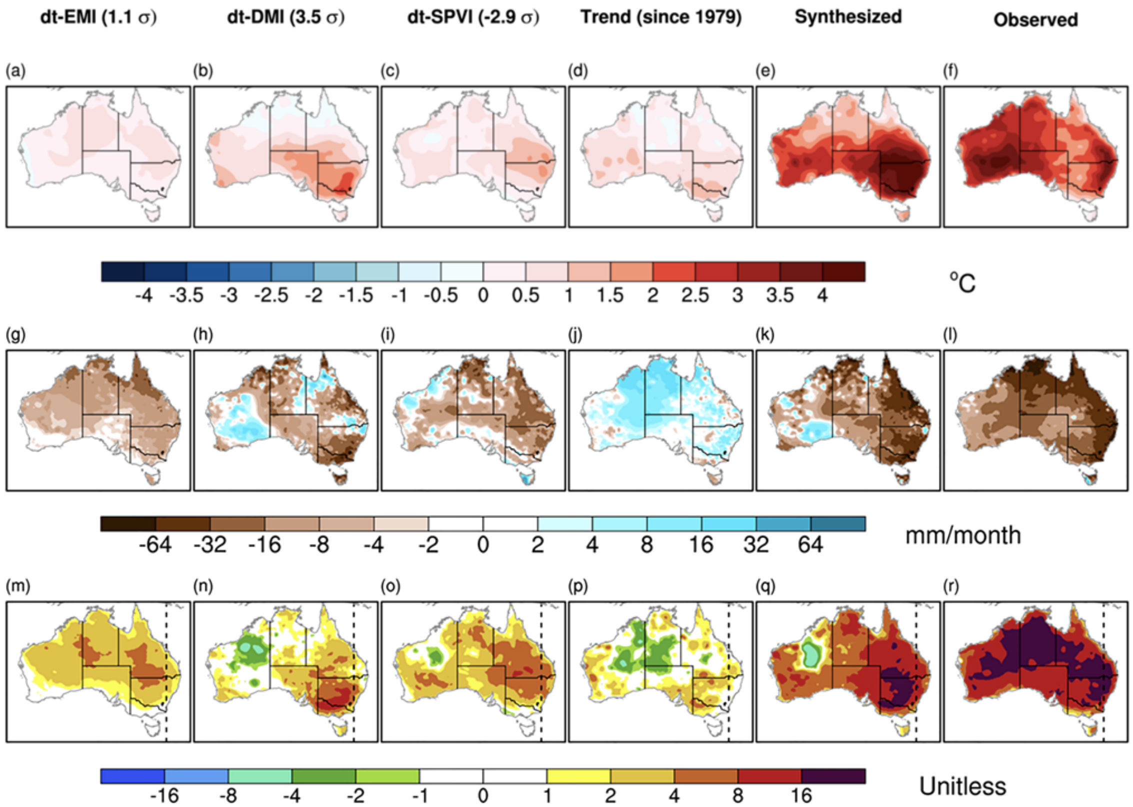


Daily anomalies of (a) zonal-mean zonal wind ([U]') at 60°S from 1000 to 1 hPa;

(b) SAM as monitored by the Antarctic Oscillation (AAO) index by NOAA Climate Prediction Center (CPC)

The 2019 stratospheric vortex weakening and warming coupled down to the surface from mid-October, leading to the record strong negative SAM for the Oct-Dec season.

Record negative SAM induced significant local climate extremes over eastern Australia, southern New Zealand, eastern South America and western Patagonia through December 2019 (not shown).



Patterns of Oct-Dec mean Australian

(top row; a-d) daily maximum temperatures;

(middle row; g-j) rainfall; and

(bottom row; m-p) daily forest fire danger index (FFDI) anomalies explained by

(a,g,m) the de-trended El Nino Modoki Index (dt-EMI);

(b,h,n) the de-trended Indian Ocean Dipole mode index (dt-DMI);

(c,i,o) the de-trended spring polar vortex index (dt-SPVI; Fig. 2a); and

(d,j,p) a linear trend of OND, using multiple linear regression built for 1979-2018.

The regression coefficients are scaled by the 2019 amplitudes of the predictors as indicated by the numbers in the parentheses in the column titles.

The synthesized anomalies of 2019 by the multiple linear regression model are displayed in (e), (k) and (q), and the observed anomalies of 2019 are displayed in (f),(l) and (r).

The dashed vertical line in (m-r) marks 150°E as the area east of it experienced intense and prolonged bushfires in the OND season in 2019.

Year 2019 was not only recorded for the occurrence of a rare stratospheric warming over Antarctica but also for the occurrence of record strong positive Indian Ocean Dipole (IOD) mode and strong central Pacific (CP) El Nino, all of which are well known drivers of hot and dry conditions over Australia in its spring-early summer.

Australia experienced extreme hot and dry conditions in its spring-mid summer seasons of 2019, which were conducive of the devastating wildfires (bushfires) over many parts of the country but especially over the far eastern seaboard in the subtropics.

Our multiple linear regression analysis suggests that the record strong spring polar vortex weakening and associated record strong negative SAM was a primary driver of the hot and dry conditions in subtropical eastern Australia and explained 29% of the observed fire danger weather conditions over the far east where the wildfires were the most severe in Oct-Dec. In comparison, the positive IOD and CP El Nino accounted for 14% and 13%, respectively. The long-term linear trend since 1979 explained about 8% of the observed fire danger weather conditions.

2. DATA & METHODOLOGY

Data:

Japanese Reanalysis-55

Real-time forecasts and hindcasts produced from the five operational seasonal forecast systems (see the predictability section for details)

Method:

Anomalies of 2019 were computed relative to

- 1979-2018 climatology for the observational analysis

- 1990-2012 hindcast climatology for real-time forecast anlaysis

Statistical Analysis:

Statistical **syntheses** of 2019 anomalies were derived from 1) the regression onto one or multiple predictors over the period of 1979-2018 and 2) the resultant regression coefficient(s) being scaled by the 2019 amplitude of the predictor(s) to see the changes in 2019 expected from the statistical relationship

7. CONCLUSION

· The 2019 SSW was as strong as the 2002 SSW despite not exhibiting the reversal of the westerly vortex winds to qualify as a major SSW. New records were set in austral spring 2019 for the vortex weakening at the stratopause, the Antarctic warming in the mid-stratosphere and the high ozone concentration.

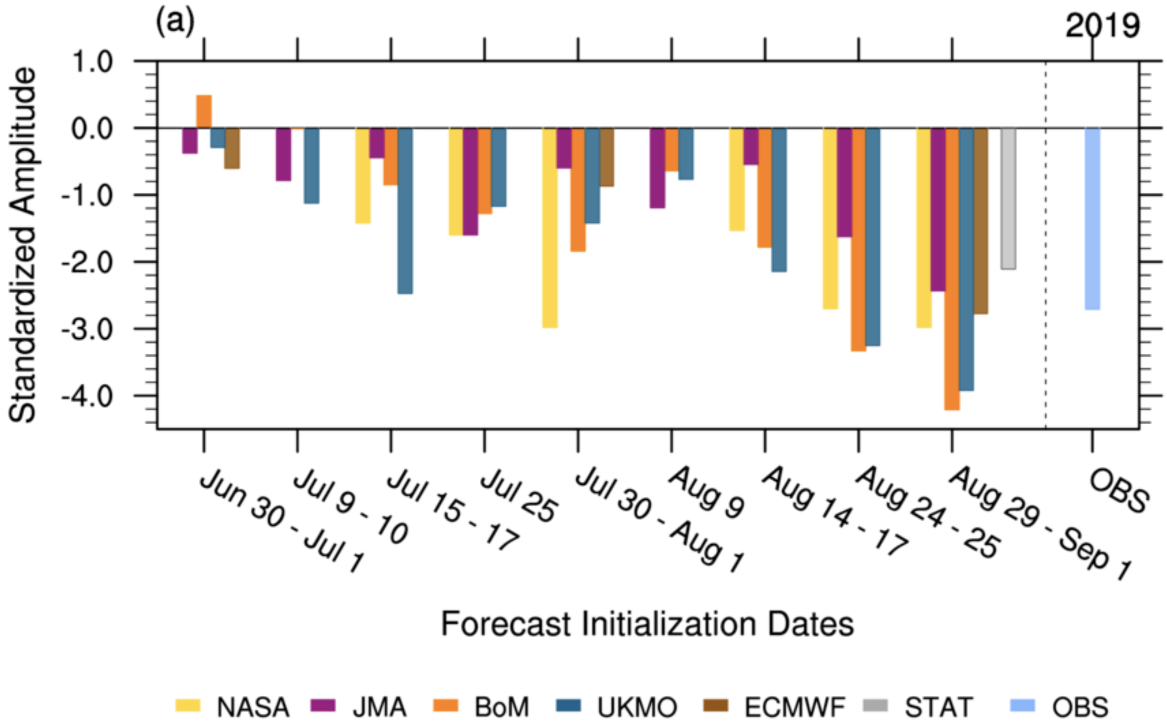
· The 2019 event closely followed the canonical development of SH stratospheric warming events with a poleward shifted polar night jet in early winter and record-high monthly mean upward propagating wave-1 activity in August, which emanated from the lower troposphere with distinctive anticyclonic circulation anomalies centered over the Bellingshausen-Amundsen Seas.

· The 2019 stratospheric vortex weakening and warming coupled down to the surface from mid-October and resultant record negative SAM induced significant local climate extremes over eastern Australia, southern New Zealand, eastern South America and western Patagonia through December 2019.

· Among the well-known large-scale drivers of Australian climate for its warm seasons, the SH springtime polar vortex weakening appears to have been the most influential contributor to the hot and dry and therefore fire-prone climate conditions over the subtropical eastern seaboard of Australia, which suffered from severe and prolonged wildfires during the late spring and early summer period.

· The occurrence of the 2019 vortex weakening was foreseeable from July, and its extreme amplitude was skilfully predicted from late August by most of the state-of-the-art forecast systems analyzed in this study.

6. PREDICTABILITY



Dynamical and statistical forecasts of standardized spring-time polar vortex index (SPVI; Sep-Nov mean zonal-mean zonal wind anomalies at 60S, 10 hPa) for 2019 relative to the hindcast climatology of 1990-2012.

Dynamical forecasts were produced from the operational systems of the Australian Bureau of Meteorology (BoM ACCESS-S1), the European Centre for Medium-Range Weather Forecasts (ECMWF-SEAS5), the Japan Meteorological Agency (JMA/MRI-CPS2), NASA (GEOS-S2S-2), and the UK Met Office (UKMO GloSea5).

Statistical forecast was made by a multiple linear regression model using two predictors: the June-July mean zonal-mean zonal wind anomaly at 60S, 1 hPa and the partial July-August mean poleward heat flux anomaly averaged over 45-75S at 100 hPa, which was made independent of the June-July mean wind at 1 hPa.

Most of the systems predicted a substantially weaker vortex ($< -1\sigma$) for initializations in late July

An extraordinary weakening ($< -2\sigma$) for initializations in late August.

From the time when the vortex started its sudden weakening and warming in the observations (i.e., late August to early September), the BoM and UKMO systems, which are based on the same model, overpredicted the vortex weakening and the ECMWF system underpredicted it relative to their standard deviations, while NASA and JMA made skillful forecasts for it

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ABSTRACT

We explore the mechanism, predictability and hemispheric-wide surface impacts of a rare stratospheric warming that occurred above Antarctica during austral spring (September to November) 2019, using the Japanese 55-year reanalysis set for the period 1979-2019.

From late August to mid-September, the stratospheric polar vortex suddenly weakened, and the stratospheric temperatures dramatically rose over the Antarctic polar cap. The deceleration of the vortex observed at 10 hPa was as drastic as that of the first ever observed major sudden stratospheric warming in the SH during 2002, while the mean warming in the mid-stratosphere (~30 hPa) over the course of spring 2019 broke the previous record of 2002 by ~50%. The key mechanism for this event was a poleward shift of the polar night jet near the stratopause during mid-winter and subsequent record strong planetary wavenumber-one activity propagating from the troposphere in August, which acted to dramatically weaken the polar vortex.

The easterly wind anomalies and positive temperature anomalies moved downward to the surface during October to December, causing the index polarity of the Southern Annular Mode (SAM) to become record-negative for the season. The record negative SAM played a key role in inducing significant local climate extremes over eastern Australia, southern New Zealand, eastern South America and western Patagonia. Especially, the strong negative SAM was the key driver of the extreme hot and dry conditions over subtropical eastern Australia in late spring 2019 that, in turn, were conducive for the severe wildfires that occurred during that time.

State-of-the-art dynamical sub-seasonal to seasonal forecast systems skilfully predicted the upward propagating wavenumber-one activity in August, the significant vortex weakening of austral spring 2019, and subsequent development of negative SAM from late July.