THE ROLE OF NATURAL VARIABILITY AND ANTHROPOGENIC CLIMATE CHANGE IN THE 2017/18 TASMAN SEA MARINE HEATWAVE

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Two GCM ensembles indicate that the record sea surface temperatures during the 2017/18 Tasman Sea marine heatwave were virtually impossible without anthropogenic influence. However, natural variability was important in the atmospheric initiation of the event.

CLIMATOLOGICAL CONTEXT. Commencing in November 2017, a marine heatwave (MHW) developed over a very large area extending from west of Tasmania to east of New Zealand (ABoM and NIWA 2018). However, unlike in 2015/16, which was due largely to intensification of the southward transport in the East Australian Current Extension (Oliver et al. 2017) and mainly localized along the southeast Australian coast, the 2017/18 event was more closely tied with local air–sea heat fluxes (see the online supplemental material). The 2017/18 event was more widespread compared to the 2015/16 event, including covering the entire Tasman Sea. Moreover, the mixed layer depth in the Tasman Sea was at a record shallow level during the 2017/18 event, allowing for very warm SSTs to develop, whereas during the 2015/16 event this depth was close to average. Coincident with the MHW was New Zealand's hottest summer on record, and Tasmania's hottest November on record (ABoM and NIWA 2018). Figure ES1 in the online supplemental material demonstrates that the 2015/16 event was the longest (308 days) and the 2017/18 event was the most intense (2.5° vs 1.8°C maximum intensity).

Based on remotely sensed sea surface temperatures (SSTs) available back to 1982, and application of the MHW definition developed by Hobday et al. (2016), this surface-intensified MHW was the most intense (maximum intensity of 2.5°C above climatology) and second-longest on record (221 days between October 2017 to April 2018) for the region of interest (see the methods section and the online supplemental material). The event was also remarkable in that most of the event warming was confined to shallow depths (<30 m), in particular around the western Tasman Sea. Unlike the 2015/16 southeast Australia MHW, which warmed through the water column to at least 100–200-m depth (Oliver et al. 2017), we note that the 2017/18 event deepened below 30-m depth in mid-December in the western Tasman Sea, but always remained <100 m for this area. The event coincided with another outbreak of Pacific Oyster Mortality Syndrome, caused by a virus in the Pacific oyster exacerbated by temperature stress (see Green et al. 2014; Ugalde et al. 2018).

During November 2017, mean sea level pressure (MSLP) was persistently high in the Tasman Sea

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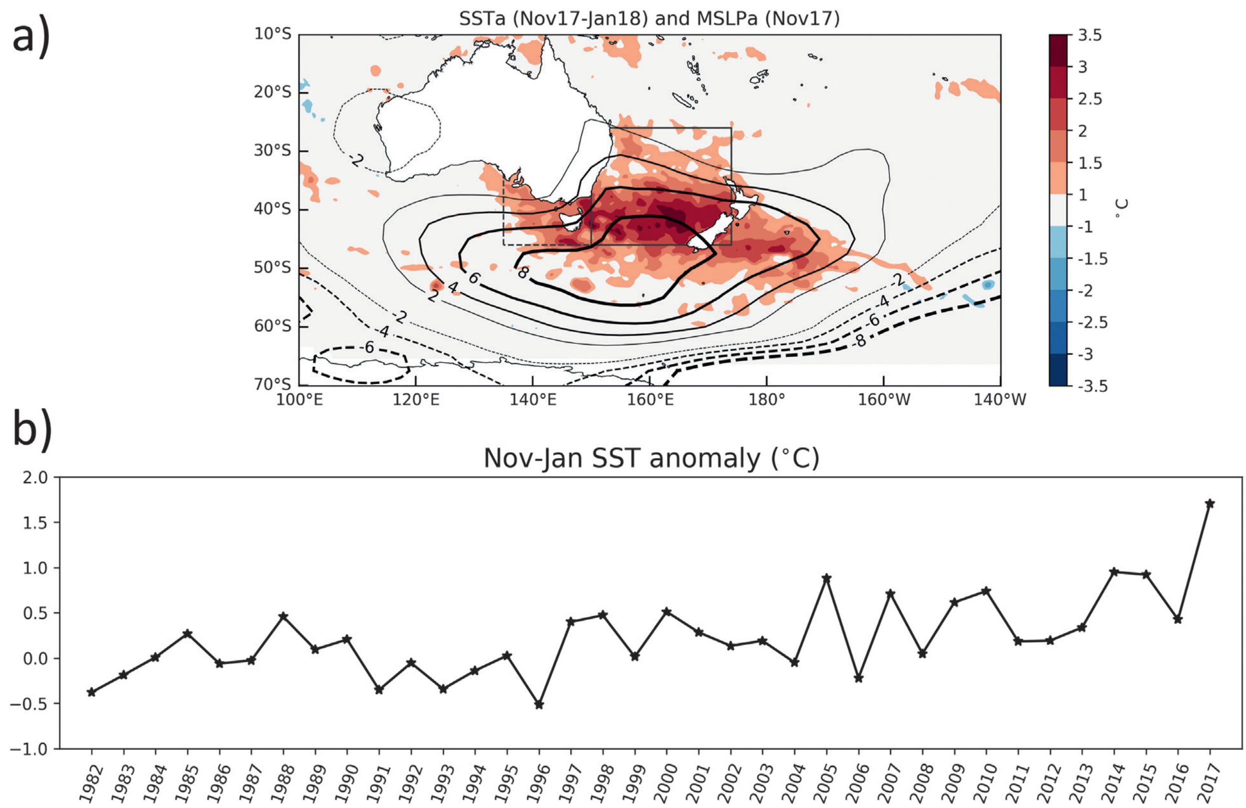


Fig. 1. (a) Average sea surface temperature anomalies from November 2017 to January 2018 (colors), and November mean sea level pressure anomalies (solid and dashed contours), relative to the background climatology from 1961–90. The Tasman Sea region is indicated by the solid box, with the western extension indicated by the dotted box. (b) Time series of regionally averaged November–January SST anomalies based on the daily NOAA OI SST v2 gridded dataset. For details on how the SST anomalies were calculated in NOAA OI SST relative to 1961–90, please see Oliver et al. (2017, 2018a).

(Fig. 1a). Although the driving atmospheric pattern ceased at the end of November 2017, warm SSTs persisted well into 2018 (ABoM and NIWA 2018). This very high atmospheric pressure initiated the event, which persisted under strong atmospheric blocking (Pook and Gibson 1999) and brought clear skies and weak winds conducive to intense ocean surface warming for a number of weeks (ABoM and NIWA 2018). An atmospheric heatwave also occurred during the third week of November 2017, which most likely generated strong atmosphere–ocean heat fluxes into the near-surface layer of the ocean. Given the atmospheric priming of the MHW, it is of interest to determine whether there is an anthropogenic signal behind the setup, and the resulting SST signature. Using two different general circulation model (GCM) ensembles, we demonstrate a substantial anthropogenic influence on the record magnitude of the Tasman MHW, as well as a continually significant role of climate variability on the underpinning atmospheric mechanisms.

DATA AND METHODS. For the SST analysis, we define our region as the Australian Bureau of Meteorology's Tasman Sea region (26°–46°S, 150°–174°E), but with the western boundary extended westward to 135°E to also include the observed warming off Tasmania's west coast (see Fig. 1a). We analyzed monthly average SST anomalies from November 2017 to January 2018 (Fig. 1a). We employed the daily NOAA OI SST v2 0.25° gridded dataset, which spans 1982–2018 (Banzon et al. 2016), and monthly HadISST 1° gridded data (Kennedy et al. 2011a,b), which span 1871–2017. Following Oliver et al. (2017, 2018a), we applied a correction to the OI SST anomalies so that they are referenced to a 1961–90 baseline. Based on this calculation, the average SST anomaly for the Tasman region over November 2017–January 2018 was +1.70°C. This is the hottest November–January anomaly since at least the start of our SST series (Fig. 1b).

Thresholds for November MSLP and the monthly mean blocking index (BI; see the supplemental material) were calculated from NCEP–NCAR Reanalysis

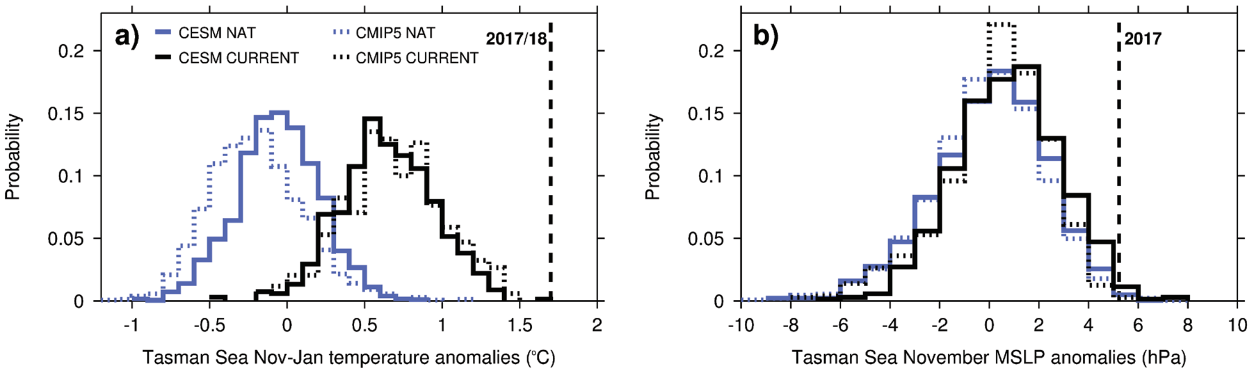
(NCEP1) data (Kalnay et al. 1996). We note that shortcomings in NCEP1 have been characterized in previous studies (e.g., Angélil et al. 2018). However, at the time of writing, no other reanalysis product included published data to the end of 2017, which also dated back to pre-1979. During November, the respective BI and MSLP anomalies of 15.5 m s^{-1} and +5.2 hPa relative to 1961–90 were computed for 150°E and the smaller Tasman Sea region (26°–46°S, 150°–174°E).

Our analysis employed two GCM model ensembles. The Community Earth System Model (CESM) Large Ensemble (see supplemental material and Kay et al. 2015), where skin temperature (TS; a proxy for SST), MSLP and the zonal wind at 500 hPa (U500; from which the BI was computed), were extracted and relevant monthly anomalies for each simulation against 1961–90 were calculated and averaged. Eight CMIP5 models were utilized (see the supplemental material; Taylor et al. 2012) for the analysis of monthly anomalies of SST and MSLP, calculated against each model's historical 1961–90 period.

Using two GCM ensembles allows for a more robust attribution statement. CMIP5 provides an estimate of human influence accounting for differences across various models, such as climate sensitivity, model physics and parameterization schemes, and resolution. The large ensemble of CESM provides an estimate accounting for the influence of internal variability. We initially performed a standard fraction of attributable risk (FAR) analysis (Allen 2003) for each variable, based on the observed and reanalysis anomalies defined above. For each period, 10,000 FAR values were calculated by bootstrapping with replacement of 50% of the relative ensemble sample size. However, given the rarity of the Tasman Sea MHW and the initiating synoptic system (see the results section), a FAR analysis did not produce much useful information. SST FAR values yielded 1, due to the non-occurrence of the Tasman MHW in the relative HistoricalNat and Control simulations. We therefore present the likelihood of extreme SSTs and MSLP and BI values exceeding those of the 2017/18 event showing best estimate values based on all available model data.

RESULTS. Figure 2 shows the observed and modeled probability density functions (PDFs) of November–January SST/TS and November MSLP anomalies for the natural and current (2008–27 under RCP8.5 simulations) worlds. Especially for SST/TS, there is a clear shift in the PDFs (Fig. 2a) toward much warmer conditions under anthropogenic forcing in both model ensembles. MSLP (Fig. 2b) shows a slight shift toward more positive conditions. Figure 2c displays the changes in likelihood in SST/TS, MSLP, and BI. According to both ensembles, the overall intensity of the 2017/18 Tasman MHW could not have occurred without anthropogenic influences: the observed anomaly did not occur within the CESM control experiment, or any of the CMIP5 HistoricalNat simulations. This is a much stronger signal that that detected for many atmospheric heatwaves (e.g., Otto et al. 2012; Lewis and Karoly 2013; Christidis et al. 2015). Moreover, according to CMIP5 (CESM) the overall magnitude of the Tasman Sea MHW had very little (no) chance of occurring under current anthropogenic influence, highlighting the remarkable and extreme nature of the observed event. In the case of CESM, the response to anthropogenic forcing is not enough during the current period (or until at least 2035) to simulate the intensity of the Tasman MHW. This could be due to CESM's climate sensitivity, its ocean–atmosphere coupling strength, the exclusion of key but unknown features of marine heatwaves, or a range of other reasons that should be explored in further research. The event is projected to become much more frequent by the middle of the century, increasing to a 41% (56%) chance in the period 2041–60 under the CMIP5 (CESM) high-emissions scenario, where both model ensembles experience more rapid increases in SSTs compared to earlier time periods. MHWs like the Tasman Sea event are also significantly more likely under the Paris 1.5° and 2°C global warming targets. It is worth noting that natural climate variability would have played a key role in the general occurrence of this MHW; that is, while we find that anthropogenic climate change was critical in increasing the likelihood of the event intensity, it was unlikely to be wholly responsible. Other, less intense, Tasman Sea MHWs would still occur naturally in the absence of anthropogenic influence.

The influence of climate variability is embedded in our analysis of MSLP and BI associated with this MHW. The MSLP anomaly slightly increases in likelihood in CESM to 1% and 3% in the current and future climates. There is even less change in CMIP5, with the observed anomaly not occurring under natural conditions, and only increasing to 1% under the current and all future climates. However, the respective forced and unforced MSLP PDFs are statistically significantly different, indicating a small but detectable change toward higher MSLP under enhanced greenhouse warming. The observed November BI in CESM displays a doubling in frequency between the control and current and future climates, with likelihoods of 3% and 6%. Although the observed MSLP anomaly



c)

Variable	Event Anomaly	CESM N	CESM C	CESM F	CMIP5 N	CMIP5 C	CMIP5 F	CMIP5 1.5°C	CMIP5 2°C
SST	+1.7°C	0%	0%	56%	0%	<1%	41%	3%	11%
MSLP	+5.2 hPa	0%	1%	3%	0%	0%	1%	1%	1%
Blocking Index	+15.5ms^{-1}	3%	6%	6%					

Fig. 2. Probability distributions of (a) November–January SST anomalies and (b) November MSLP anomalies over the Tasman Sea in the natural (blue) and current world (black) ensembles for both CESM (solid lines) and CMIP5 (dashed). The 2017 event is marked by a vertical dashed line. (c) Event likelihoods (best estimates), based on the SST, MSLP, and BI values associated with the event, under the natural (N) and current-world (C) ensembles, a future high-emissions world of 2050 (F), a 1.5°C world, and a 2°C world in CESM and CMIP5.

is still quite rare in the current and future periods, the measured anthropogenic influence underpinning MSLP is consistent with prior research that Southern Hemisphere pressure is tending toward a positive phase in the Southern annular mode (SAM; Gillett et al. 2013; Gillett and Fyfe 2013). A positive SAM results in anomalously high pressure over southern Australia during summer, analogous to that observed in Fig. 1. While both changes in stratospheric ozone and increases in greenhouse gases contribute to this trend, greenhouse gases will likely dominate under a high-emissions scenario (Swart and Fyfe 2012), as used here. Evidence from our analysis suggests that, while detectable, the anthropogenic influence on the initiating atmospheric pressure system is substantially less than for the record SSTs experienced during the Tasman Sea MHW. This indicates the considerable influence that climate variability has, and will continue to have, on MHWs in the Tasman Sea.

Moreover, evidence from our analysis suggests that the regional blocking aspect of the atmospheric setup was also made more likely due to human influences, although this is also still quite rare under current and future climates.

CONCLUSIONS. Results from two GCM ensembles, which collectively strengthen the robustness of our attribution statement, indicate that the overall intensity of the 2017/18 Tasman MHW was virtually impossible without anthropogenic forcing. Both ensembles agree that events of similar magnitude dramatically increase in likelihood (become more common) in the current and especially future climates. Moreover, the fact that CESM does not simulate the intensity of the 2017/18 Tasman MHW under current levels of atmospheric greenhouse gases illustrates how unusual the event was. There is some evidence from CESM that the likelihood of the initiating surface atmospheric pressure system has also increased due to climate change, but to a lesser extent than the MHW itself. Moreover, the atmospheric blocking that was responsible for the prolonged period of high MSLP (which in turn induced SST warming) also displays some anthropogenic influence, although this detected influence is also less than that on the SST signature. Thus, climate variability has an ongoing important role in the physical setup of Tasman Sea MHWs, which are initiated by atmospheric processes.

We therefore conclude that the majority of the anthropogenic influence on the 2017/18 Tasman MHW is embedded in the overall rising background SSTs due to global ocean warming, with a small amount of influence also on the event-initiating sea level pressure.

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