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Contributions of atmospheric forcing and ocean preconditioning in the 2016 Antarctic sea ice extent drop

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Abstract

The 2016 Antarctic sea ice extent (SIE) drop was a rapid decrease that led to persistent low sea ice conditions. The event was triggered by atmospheric anomalies, but the potential preconditioning role of the ocean is unsettled. Here, we use sensitivity experiments with a fully-coupled regional climate model to elucidate the impact of the ocean conditions on the drop and on the persistence of the negative SIE anomalies during 2017. In particular, we re-initialize the model in January 2016 using different ocean and sea ice conditions, keeping lateral boundary forcings in the atmosphere and ocean unchanged. We find that the state of the Southern Ocean in early 2016 does not determine whether the drop occurs or not, but indeed has an impact on its amplitude and regional characteristics. Our results also indicate that the ocean initialization affects the sea ice recovery after the drop in the short term (one year), especially in the Weddell sector. The ocean's influence appears not to be linked to the ocean surface and sea-ice initialization, but rather to the sub-surface conditions (between 50 m and 150 m) and heat exchange fluctuations at the regional scale, while the atmospheric forcing triggering the drop is driven by the large-scale circulation.

1. Introduction

In the last two years, Antarctic sea ice has broken twice its historical record in terms of low extent, first in summer 2022 and then in 2023 (e.g. Turner *et al* 2022, Liu *et al* 2023). The current year, 2023, is being especially critical, with an unprecedented lack of sea ice even after the annual winter peak. The debate on the future of Antarctic sea ice is thus more active than ever, and while great attention is being paid to these recent minima, the community has not lost interest in the abrupt sea ice extent (SIE) decrease that occurred at the end of 2016.

After several years of gradual SIE increase culminated in a record high in 2014, a rapid decline in 2016 led to exceptional anomalies in December and to a historical minimum in austral summer 2016/2017. The sudden change from extreme high values to an absolute minimum in less than two years is unique to this '2016 drop', as we will call it in this study. Another exceptional feature of this event is the lack of ice recovery and the persistence of negative SIE anomalies during the following years: except for a brief parenthesis in 2020, anomalous low SIE values have been registered in Antarctica since then, in all seasons (e.g. Suryawanshi *et al* 2023).

Even though this record has now been beaten, the scientific debate around its dynamics and impacts is anything but settled, as highlighted in a recent perspective article by Eayrs *et al* (2021). The drop itself was characterized by an anomalous retreat that started in September 2016 and peaked in November. The Weddell Sea appeared as the main contributor, though all regions experienced remarkable sea ice loss throughout spring (Stuecker *et al* 2017, Turner *et al* 2017). Exceptional atmospheric conditions certainly played a major role in driving the event, especially the strong negative phase of the Southern Annular Mode in

November–December, preceded by a positive zonal wave 3 pattern from May to August (Stuecker *et al* 2017, Schlosser *et al* 2018). In turn, these anomalies in the large-scale atmospheric circulation over the Southern Ocean (SO) and their impact on sea ice may have been favored by tropical forcings from the Pacific and Indian Ocean (Stuecker *et al* 2017, Purich and England 2019, Schlosser *et al* 2018, Meehl *et al* 2019) and by the influence of the stratospheric polar vortex (Wang *et al* 2019). While the atmospheric anomalies likely triggered the event, it is still uncertain whether and how the ocean played a preconditioning role, for instance helping to amplify the response of the sea ice or to maintain the anomalies for a longer period. Some studies acknowledged but did not attempt to examine nor quantify this contribution (e.g. Turner *et al* 2017, Purich and England 2019, Schlosser *et al* 2018). In turn, numerical experiments by Kusahara *et al* (2018) suggested that sea ice and oceanic conditions in the previous summer (January 2016) could explain 13% of the total SIE reduction at the summer minimum, while Meehl *et al* (2019) provided a dynamical interpretation of how surface and subsurface warm water associated with wind stress curl anomalies and trends contributed to the rapid SIE decrease in 2016.

More recent studies have shifted the focus from the ocean's impact on the 2016 minimum only to the broader framework of the continuous SIE decline observed since then. Suryawanshi *et al* (2023) quantified the SIE decrease over 2016–2022 and related it to both atmospheric and oceanic factors, highlighting an anomalous warming in the SO mixed layer. Previously, a study by Zhang *et al* (2022) specifically addressed the contribution of the subsurface ocean in driving the negative SIE between 2016 and 2021 by using a suite of predictions with a coupled model, including a sensitivity experiment in which they replaced the ocean conditions in January 2015 with those from another year. They concluded that the subsurface SO accounted for a minor part (10%) of the 2016 drop, but that it played a key role in the following sustained SIE low values. According to their results, an anomalous subsurface warming (between 100 and 500 m) preceding the 2016 drop accounted for approximately half of the SIE difference between the periods before and after the drop. Moreover, this difference is not present in their sensitivity experiment, where such warming is missing, which supports the essential role of the subsurface heat in the persistence of the negative SIE anomalies after 2016.

In this paper, we propose a relatively simple but robust experimental set up, complementary to that of Zhang *et al* (2022), to further disentangle the impact of the local oceanic conditions on the timing, amplitude and characteristics of the 2016 drop, as well as on the subsequent persistence of the negative SIE anomalies. Specifically, we use a novel state-of-the-art, fully coupled regional model for the SO to build an ensemble of members with different conditions in the ocean in January 2016 and examine how the drop and the negative SIE anomalies afterwards are subsequently captured. We focus on relatively short time scales and investigate the (lack of) sea ice recovery right after the drop and the persistence of the negative SIE anomalies during the first months, up to one year, after the event. Our study thus gives a broader perspective of the 2016/2017 minimum by joining an analysis of the event itself with an investigation of the short-scale response, attempting at filling the gap between the earlier studies describing the individual event and its drivers and the more recent ones exploring the subsequent SIE decline on a multi-year time scale.

2. Methods

2.1. Model description

The core of the analysis is based on a series of simulations performed using PARASO, a fully coupled regional model for the circum-Antarctic domain including interactions between the ocean, sea-ice, land, ice sheet and atmosphere. The model has been thoroughly described and validated in Pelletier *et al* 2022 and used in an ocean standalone configuration in Mezzina *et al* 2023; here, we only provide a brief summary of the ocean-sea ice and atmosphere components. The ocean-sea ice model is NEMO-LIM3.6 (Vancoppenolle *et al* 2012, Rousset *et al* 2015, Madec *et al* 2017) with a horizontal resolution of about 0.25° , 75 vertical levels, and domain limit at 30° S. The atmospheric component is represented by COSMO5.0 (Rockel *et al* 2008), which features a horizontal resolution of 0.22° on a latitude-longitude grid, 60 vertical levels, and boundary of the domain between 50 and 40° S.

As discussed in detail in Pelletier *et al* 2022, PARASO runs stably without flux correction. Similarly to other coupled models, some biases remain in the seasonal cycle, such as the almost sea ice-free conditions at the summer minimum (figure S1). In contrast, the winter peak has larger amplitude and is typically delayed compared to the observations. One of the main model biases is a nearly ice free Ross Sea from January to March, while the Indian sector typically shows an excess of sea ice from July to December (figure S2). These are well-known issues of NEMO-LIM (Vancoppenolle *et al* 2012, Rousset *et al* 2015), which are enhanced in the coupled configuration (Pelletier *et al* 2022). However, these biases are comparable to those of other

state-of-the-art models (e.g. Roach *et al* 2020, Lin *et al* 2021) and do not affect PARASO's capability of reproducing accurately the observed SIE anomalies (as discussed in section 3.1).

2.2. Experiments

First, we run a control experiment (Ctl) over 1985–2018 by forcing the model with lateral boundary conditions derived from reanalyses: ERA5 in the atmosphere (Hersbach *et al* 2020) and ORAS5 in the ocean (Zuo *et al* 2019). The fully coupled model thus evolves freely inside the regional domain and, due to the realistic forcing, is expected to well reproduce ocean, atmosphere and sea ice conditions observed over the same period (see section 3.1). Note that this set up is analogous to the standard configuration presented in Pelletier *et al* (2022) ('PARASO' in their table 4).

Additionally, a set of short sensitivity experiments is performed by integrating again the model between January 2016 (around one year before the drop) and December 2018. The set up is identical to the control run except for the initial conditions in the ocean (including sea ice), which are replaced by values from previous years from the control experiment. Namely, the state of the ocean in January 2001, 2004, 2007, 2010 and 2013 in Ctl is used to set the initial conditions for the different sensitivity runs, which constitute thus an ensemble of five members (hereafter labeled ic2001, ic2004, etc and generally called 'ic members'), plus the control experiment. Note that the six simulations share the same boundary conditions over the common period.

The main results from the sensitivity experiments rely on the assumption that the differences between the ic members arise from the distinct initial conditions in the ocean. To rule out the possibility that these differences are just a byproduct of the model's internal variability, we run an additional experiment by re-launching one of the members (ic2004) with an initial perturbation in the atmosphere (ic2004_pert). The SIE time series of the two twin experiments are very similar (figure S3), particularly over 2016–2017, which is the main period of interest, and have extremely high correlation (0.97). We can thus assume that internal model variability plays a minor role on the SIE and that the differences within the ic members are essentially due to changes in the ocean state. Furthermore, as the internal model variability is low, having one realization only for each ic member is enough for our purposes.

2.3. Data and analyses

We compare the model's results with observed sea ice concentration (SIC) from the EUMETSAT OSI SAF datasets (OSI-450 and OSI-430-b; OSI SAF 2017, Laverne *et al* 2019). For both model and observations, we use SIC to derive values of SIE by using a typical 15% SIC threshold. Different sectors are considered to compute the SIE (figure 2(a)): whole SO; Weddell (60° W–20° E); Indian (20–90° E); Pacific (90–160° E); Ross (160° E–130° W); Amundsen–Bellingshausen (130–60° W). To compute average temperature and salinity anomalies over the sectors (section 3.2), a latitudinal limit is set at 60° S.

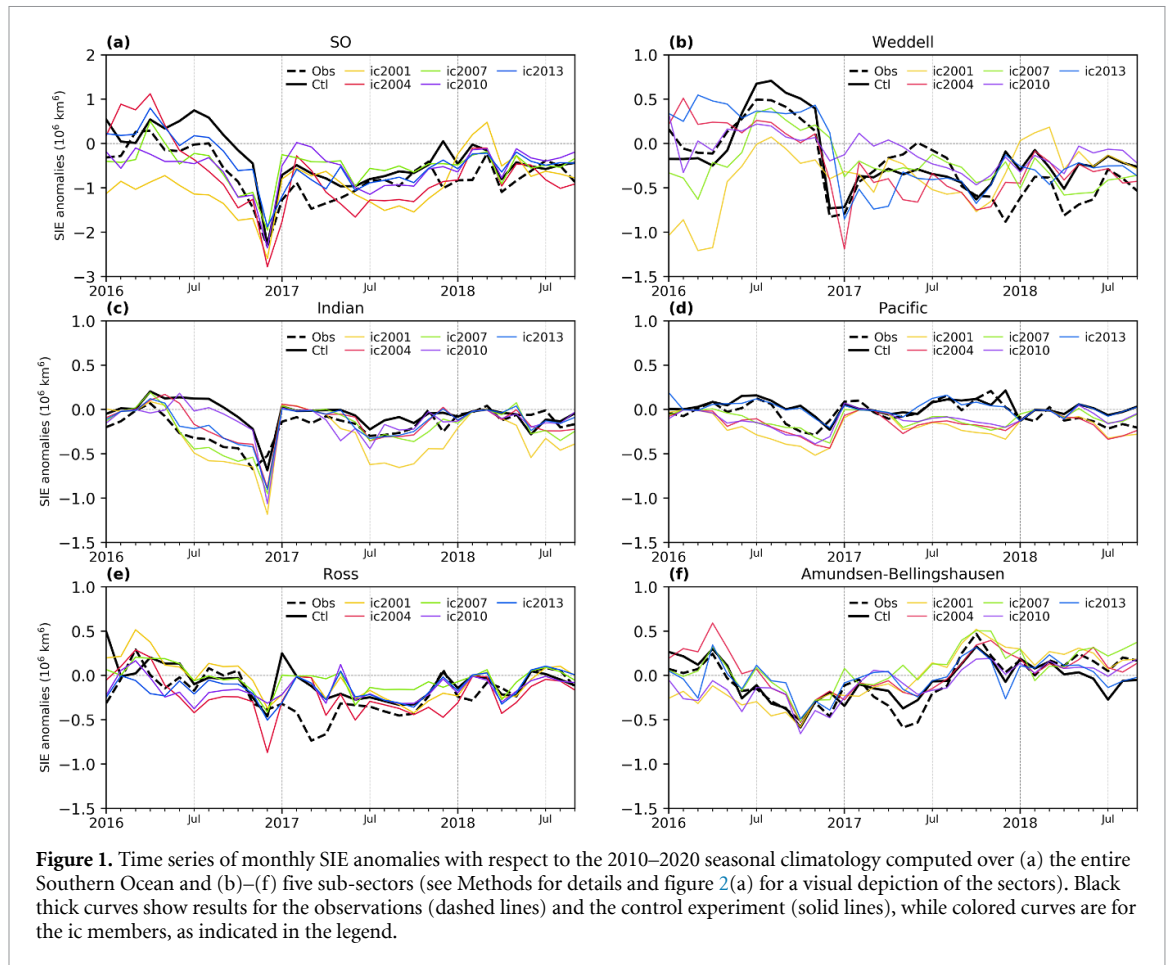
Throughout the paper, the analysis focuses on the period 2016–2018. Due to the contrasting trends of Antarctic SIE over the satellite era (e.g. Parkinson 2019), we chose a short reference time around the 2016 drop to estimate the field anomalies: namely, they are computed with respect to the 2010–2020 seasonal climatology.

In section 3.1, we discuss the contributions of the different sectors to the drop and to the persistence of the negative anomalies during the following year, which are detailed in table 1. The contributions 'during' the drop are computed as the November 2016–January 2017 SIE anomalies over that sector divided by the SIE anomalies over the entire SO during the same period. We chose NDJ to encompass the temporal variability of the drop, which does not occur in December in all regions. The contributions to the persistence are computed similarly but using the period from January 2017 to December 2018.

3. Results

3.1. Observations and control experiment

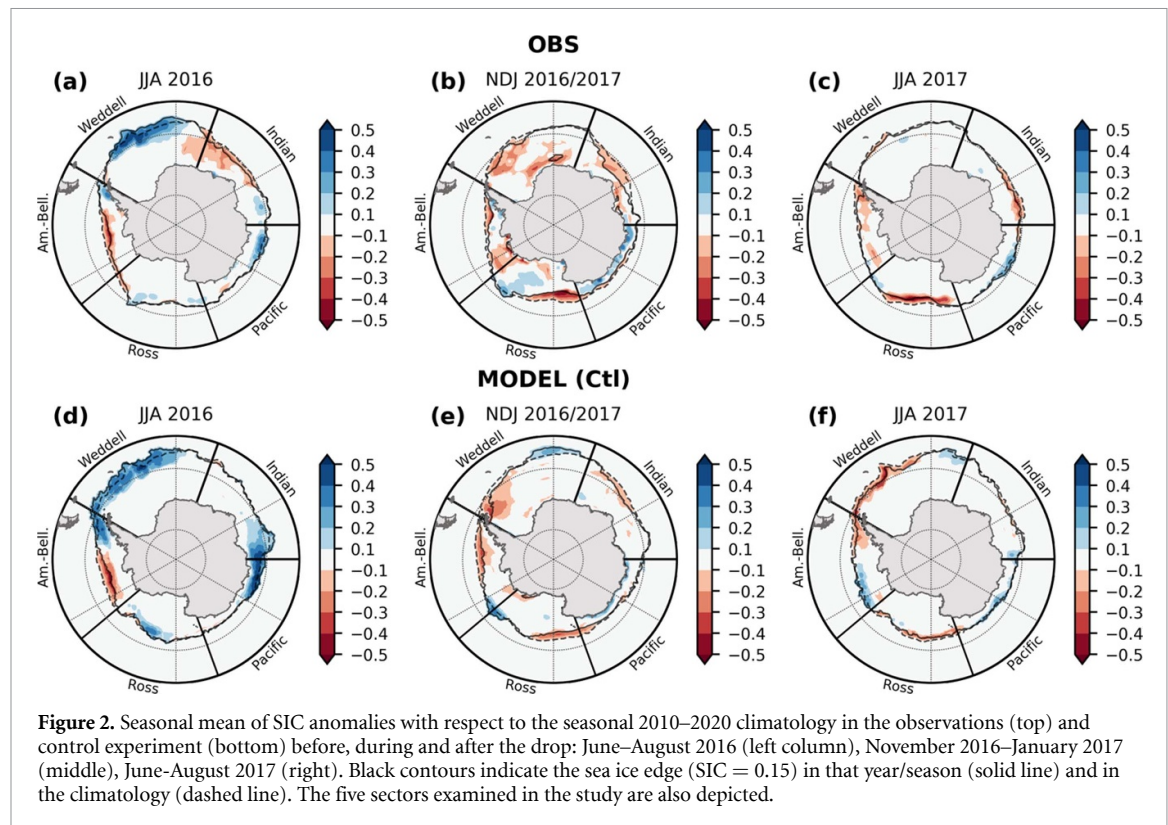
The observed total Antarctic SIE anomaly over the entire SO between 2016 and 2018 is well reproduced by the model in the control experiment (figure 1(a), cf dashed and solid black curves). Even though the model exhibits excessive extents earlier in the run (March–November 2016), it captures the spring 2016 drop accurately. This is true in terms of both timing, with the minimum reached in December, and amplitude, with the largest negative anomalies around 2.2 million km² in both the observations and model. After the drop, the observed persistence of the negative anomalies is also reproduced in the simulation. The model still tends to generally underestimate the negative anomalies and occasionally misses some lows (e.g. March 2017) but, similarly to the observations, the SIE never fully recovers after the drop.



Overall, the main features of the observed time series, namely the drop and the following persistence of the negative anomalies, are well captured by the model. Furthermore, the two time series are highly correlated (0.82 over 2016–2018, 0.61 over 2010–2020). The model can be thus considered as a valid tool for our investigation, with the limitations detailed in section 2.1.

The spatial patterns of SIC anomalies before, during and after the drop show that not all sectors contribute equally and simultaneously to the anomalous lack of sea ice (figure 2). During the winter preceding the drop (JJA 2016, figures 2(a) and (d)), negative anomalies are observed in the Amundsen–Bellingshausen and Indian sectors, which are compensated by an excess of sea ice in the Weddell region. In the model, almost no anomaly is found in the Indian sector, which is possibly due to biases in the climatology (see section 2). Around the peak of the event (NDJ 2016/2017), additional negative SIC anomalies in the Ross and Weddell Seas seem to dominate, especially in the observations (figures 2(b) and (e)). Finally, for a few months after the SIE minimum (JJA 2017), negative SIC anomalies persist mainly at the ice edge in the Ross and Indian sectors, slightly shifted eastward with respect to the previous months. Additionally, the model displays prominent anomalies in the Weddell region, which are instead minor in the observations (figures 2(c) and (f)). The regional differences can be also examined in the time series of the SIE anomalies computed over the distinct sectors (figures 1(b)–(f)), where it emerges that in the Pacific and Indian regions the observational minimum occurs earlier than December (figures 1(c) and (d)). Computing the relative contributions of each sector to the total SIE minimum in NDJ (see section 2), we confirm that, as found in previous studies, the main driver of the event is the Weddell Sea, accounting for around 30% of the total anomalies (see table 1). It is followed by the Indian sector, which explains around 25% of the total SIE anomalies in NDJ. Important contributions also stem from the Ross and Amundsen–Bellingshausen sectors, while a marginal role is played by the Pacific one (table 1).

Despite the overall satisfactory performance, our model does not capture all the observed features at the regional scale (figures 1(b)–(f)). Over the examined period (2016–2018), the model performs well in the Weddell and Amundsen–Bellingshausen sectors, with a correlation with the observed SIE time series of ~ 0.8 , but worse in the Indian and Ross regions, where the correlation decreases to ~ 0.4 . In particular, we note that



some discrepancies are present between the model and observations before (e.g. Indian, figure 1(c)), during (e.g. Bellingshausen–Amundsen, figure 1(f)) and after (e.g. Ross, figure 1(e)) the event. The correlation slightly increases to ~ 0.5 in the Indian and Ross sectors when the entire reference period (2010–2020) is considered, but still reflects the model's biases in the mean state in these two regions, namely the extreme lack of sea ice in the Ross Sea during summer and the excessive abundance in the Indian sector during winter and spring, as described in section 2. This distinct regional behavior results in different estimates of the contributions of the Ross sector to the total SIE drop (table 1), which is underestimated in the model. This is likely not related to a model's failure in capturing the drop, but to a too quick recovery right after, which leads to positive anomalies already in January 2017 (figure 1(e)). Previous studies indicate the Ross Sea as the second main driver of the drop, but only for November, with mixed contributions from the Indian sector at different times before the event (e.g. Turner *et al* 2017). Although our model performs modestly the Indian sector, it is consistent with the observations in suggesting this region as the second main contributor to the drop when considering the full NDJ period.

From the regional SIE time series, it is also possible to gain further information about the persistence of the negative anomalies after the event, complementing the maps of SIC anomalies described above (figure 1). During the first year following the drop, on average, negative anomalies are present in all sectors except the Pacific, which is also a minor contributor to the drop itself (table 1). A quick recovery is present in the Indian sector, especially in the model, and only slight negative anomalies persist (figure 1(c), table 1). The average SIE anomalies from January to December 2017 are also weakly negative in the Amundsen–Bellingshausen Sea (table 1), but the temporal evolution is different (figure 1(f)). After an initial slight increase, a new low is reached in late fall and a full recovery follows at the end of the second winter. The main contributors to the persistent negative SIE anomalies in the SO are the Weddell and Ross Seas (table 1). In the Ross sector, the sea ice never recovers in the observations and even undergoes a second low in late 2017, in contrast to the model, which simulates a quick increase leading to positive SIE anomalies in early 2017. The two then converge at the end of winter, both displaying negative anomalies until the end of the year (figure 1(e)). Both model and observations consistently show continuous negative anomalies in the Weddell Sea, even though a slight comeback is present in the observations in early summer (figure 1(b)).

The observations and control experiment both indicate the Weddell sector as the main contributor to the drop and to the persistence of the SIE anomalies at the Antarctic scale. However, they do not agree on the exact roles of the Ross and Indian sectors, whose contribution are underestimated in the model, particularly

Table 1. Relative contributions of the different sectors to the SIE anomalies during the drop (NDJ) and during the first year after the drop (January to December 2017).

	Contribution to drop %		Contribution to persistence %	
	Obs	Ctl	Obs	Ctl
Weddell	29.4	30.4	38.6	60.3
Indian	26.4	25.1	17.2	9.5
Pacific	6.4	7.0	−4.3	−7.6
Ross	20.3	13.4	38.5	25.4
Am.-Bell.	17.5	24.0	10.1	12.4

concerning the persistence of the SIE anomalies after the drop (table 1). Though we acknowledge that the contribution of the Weddell region to the persistence may be overestimated in our experiments and that other sectors may also be responsible for the persistence, considering the good performance of the model, in the next sections we will mostly focus on this region, while keep describing the general features.

3.2. Sensitivity experiments

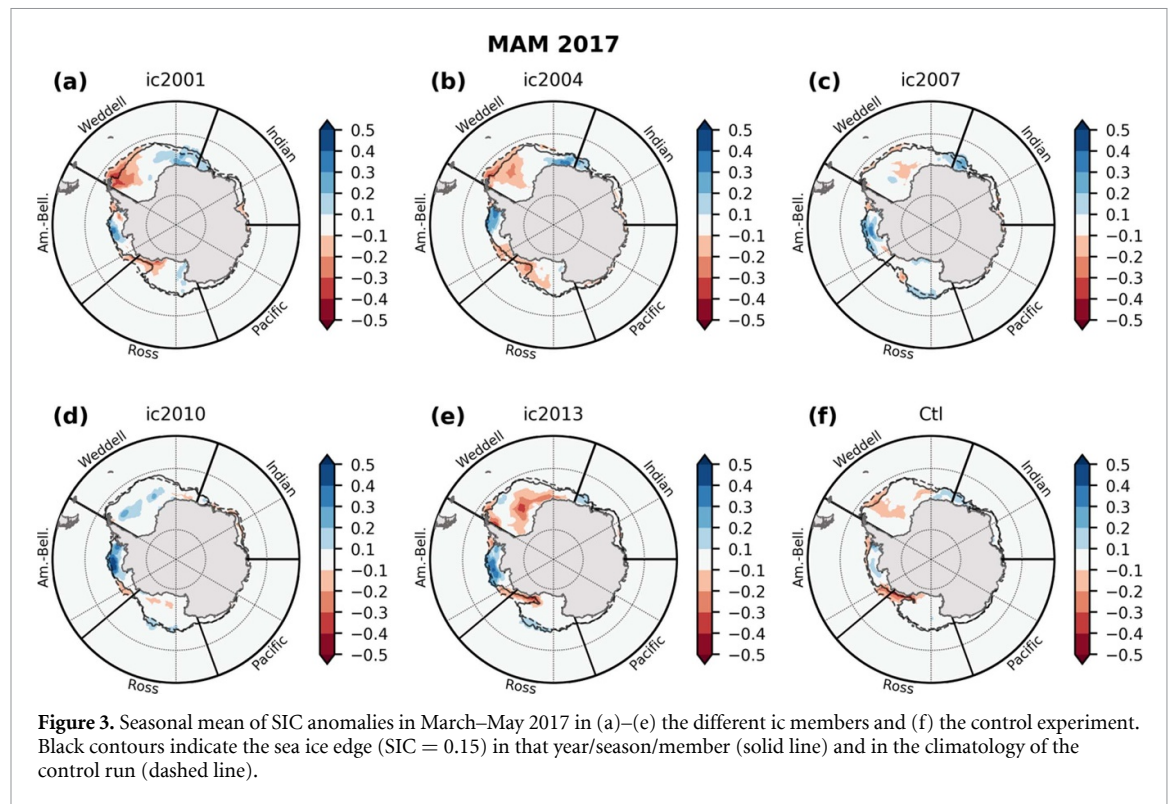
To clarify the role of the local ocean conditions in the 2016 drop and their contribution to the subsequent lack of sea ice recovery, we have designed the set of sensitivity experiments described in section 2.2. Since the five ic members, which run from 2016 to 2018, only differ in the initial state of the ocean inside the domain, any discrepancy in terms of timing and amplitude of the 2016 minimum, as well as in the persistence of the negative SIE anomalies, can be attributed to changes in the initial conditions of the SO. The members' time series of the total SIE anomalies, computed with respect to the climatology of the control experiment, are shown in figure 1 (colored lines). The members span a variety of conditions: two members (ic2004, ic2013) start with more sea ice than usual, similarly to the control experiment; two members (ic2007, ic2010) begin with slightly less sea ice; finally, one member (ic2001) already shows prominent negative anomalies at the beginning of the run. However, this situation is not necessarily reflected at the regional scale so that, for example, ic2001 begins with positive anomalies in the Ross Sea despite the global negative ones (figure 1(e), yellow line), while the opposite happens for ic2010 in the Weddell Sea (figure 1(b), purple line). The spread in the initial conditions is also not homogeneous among the sectors, with little differences found in the Indian, Pacific and Amundsen–Bellingshausen regions, and the largest spread in the Weddell Sea.

3.2.1. The drop

Though with different evolution during the first six months, eventually all members experience a decline in the total SIE starting in winter, which then culminates in the December minimum (figure 1(a)). The amplitudes range from -2.78 to -1.88 million km^2 (which includes the 2.2 million km^2 of the observations and Ctl), but all members distinctly capture the drop, thus confirming the predominant role of the atmospheric forcing. Furthermore, we recall that in the regional coupled model used here only the atmospheric boundary conditions (north of around 40° S) are imposed. Since this lateral forcing appears to be enough to trigger the 2016 event, these results indicate that the large-scale atmospheric circulation is the fundamental driver of this event, as opposed to purely local conditions. This is further supported by the temporal correlations of the observed SIE time series with the different members (over the entire run), which shows mid to high values for three members (0.78 for ic2004, 0.67 for ic2007 and 0.57 for ic2010) a very high one for ic2013 (0.86, higher than Ctl) and only one member with a lower correlation (0.3 for ic2001), indicating again how an adequate (atmospheric) boundary forcing is sufficient to reproduce the drop and the overall sea ice conditions before and after it.

At the regional scale, it is interesting to notice that only two members (ic2004 and ic2013) simulate a strong drop in the Weddell Sea, and only in January 2017 (figure 1(b)). The other members show modest negative anomalies in both December and January (figure 1(b)). Curiously, the Indian sector seem to be a more important contributor to the total December minimum in these members than in the control experiment and in the observations (figure 1(c)). This is consistent with the fact that the ocean in this sector is warmer in all the ic members compared to Ctl (figure S4). Larger negative anomalies are also present in the Pacific (all members except ic2013; figure 1(d)), while in the Ross region there is general agreement between the control experiment and the ic members (ic2004 remarkably shows a stronger minimum; figure 1(e)).

While these small differences between how the members reproduce the 2016 drop should be related to their different initial conditions in the ocean, there is no straightforward link with the initial SIE. For



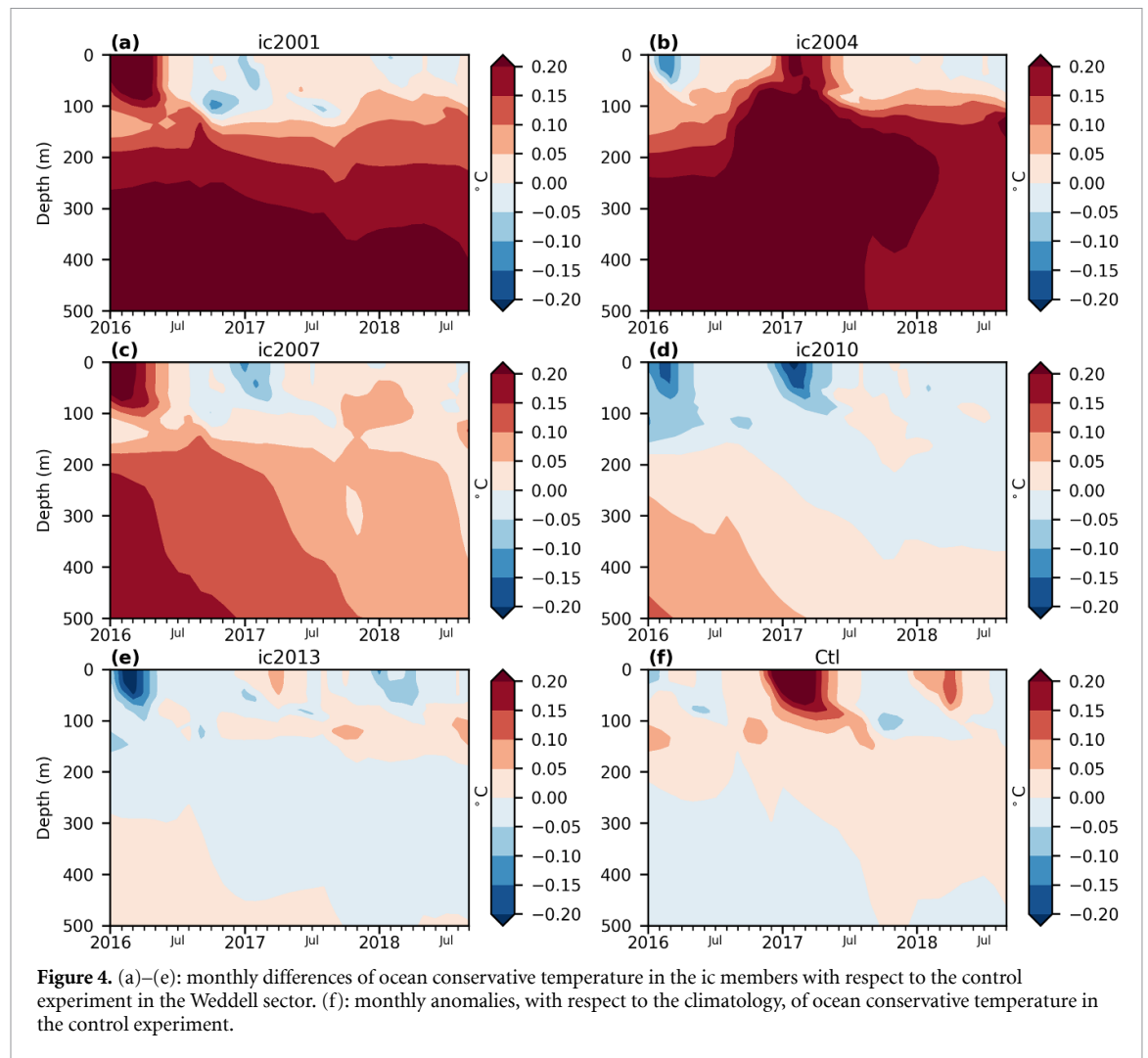
instance, ic2004 and ic2001 show the two largest drops despite beginning with very different extents in January 2016: ic2004 has initial positive anomalies while ic2001 shows the largest negative ones.

3.2.2. Persistence of the anomalies

The evolution of the SIE after the December drop also varies slightly from member to member. Overall, they all capture the observed persistence of the negative anomalies of the total SIE (figure 1(a)), but some differences are present especially in the first months after the drop. The lateral forcing eventually prevails and after two years of simulation the members tend to converge and the spread is substantially reduced. For this reason, here we do not discuss the long-term persistence after the end of 2017.

The Weddell Sea is the region with the largest spread: the wide range of initial conditions is only partially reduced by the common boundary forcing (figure 1(b)), while in the other regions the evolution is more consistent between the members and mostly follows the control experiment (figures 1(c)–(f)). Interestingly, in the Ross Sea the drop is captured in all the experiments, including Ctl, but none of them correctly reproduces the observed short-term persistence of the negative anomalies. Instead, the model tends to simulate a rapid recovery and the members converge towards the observed anomalies already after a few months in 2017 (figure 1(e), cf solid black and colored lines). In the Weddell Sea, the members with strongest negative anomalies averaged over the first year after the drop (from January to December 2017) are ic2001, ic2004 and ic2013 (-0.45 , -0.57 and -0.5 million km^2 , respectively), all slightly below the control experiment (-0.40 million km^2) and again with no clear link to the initial SIE anomalies. The other two members, ic2007 and ic2010, also maintain the negative anomalies, but with about half the magnitude (-0.28 and -0.16 million km^2 , respectively). These differences between the members are even clearer by looking at the SIC patterns in March–April–May 2017, a few months after the drop and at the beginning of the growth seasons (figure 3). Ic2007 and ic2010 barely show negative anomalies in the Weddell Sea, similarly to the observations, (cf figures 3(c), (d) and S5(a)), while ic2001 and ic2004 present marked ones in the south-west part, at the sea ice edge, as in the control experiment (cf figures 3(a), (b) and (f)). Interestingly, while ic2013 shows some negative anomalies in a similar location, it also features prominent ones in the central part of the sector, in the inner pack (figure 3(e)).

To further clarify the role of the initial conditions in the ocean on the sea ice evolution in the Weddell Sea, we examine vertical profiles of temperature anomalies averaged over the sector, from the surface to 500 m (figure 4).



The control experiment shows warm anomalies in January 2016 between 50 and 200 m (figure 4(f)). As suggested in previous works, this water can be incorporated in the mixed layer in autumn and winter and warm the surface, thus contributing to the persistence of the negative SIE anomalies after the drop. All the ic members show persistent SIE negative anomalies after the drop, but with distinct amplitudes, and it is thus interesting to examine how those differences are related to the temperature anomalies at depth in each member with respect to the control experiment. Two of the members with stronger persistent SIE anomalies, ic2001 and ic2004, clearly present a warmer ocean throughout nearly the entire simulation and especially below 100 m (figures 4(a) and (b)).

In contrast, ic2010 is the member with weakest average SIE anomalies after the drop and shows opposite initial conditions, with a colder ocean from the surface down to almost 200 m that also endures during the entire run (figure 4(d)). Hence, for these extreme cases, the initial temperature in the ocean, in particular at the surface and subsurface, can be linked to the magnitude of the negative SIE anomalies during the year that follows the drop in a relatively straightforward way. The role of the subsurface ocean is further highlighted in figure 5, which compares the SIE anomalies in the Weddell sector (top panel, same as figure 1(b)) with the temperature differences between the ic members and Ctl (as in figures 4(a)–(e)) averaged between 50 and 150 m, in the same region. Ic2007 also features a warmer ocean than Ctl, despite maintaining slightly smaller SIE anomalies, but such warming is smaller compared to the first two members, especially between 100 and 200 m (figures 4(c) and 5(b)). Finally, ic2013 is also part of the group with strong persistent anomalies even if it is initially colder than Ctl (figures 4(e) and 5(b)). The strong cold conditions, however, are mostly found at the surface and are quickly compensated by the atmospheric forcing, already disappearing by July 2016. In contrast, the difference at around 100 m is initially very small and after few months the behavior becomes very similar to that of the control experiment (cf figures 3(e) and (f)). Differences in the initial salinity can also contribute to the distinct evolution of the SIE anomalies. For instance, all members are generally fresher

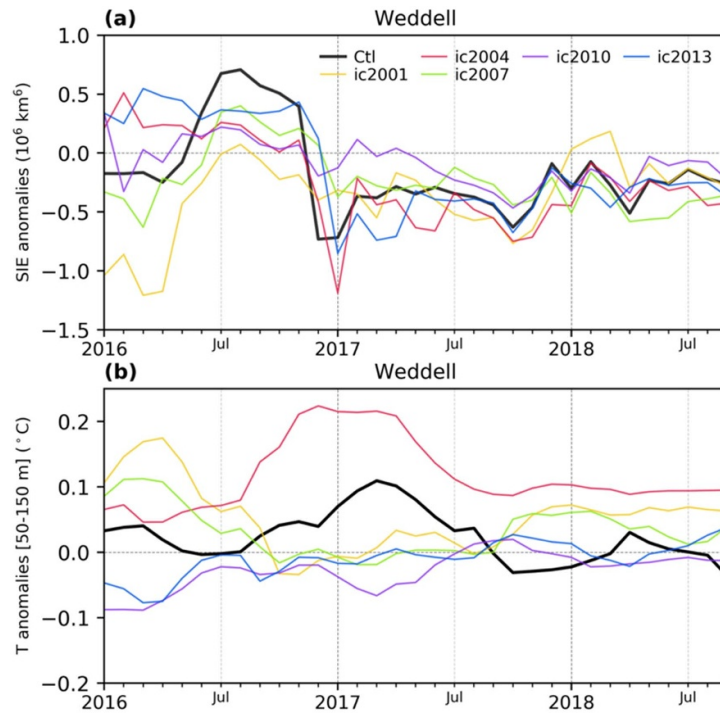


Figure 5. (a) Time series of monthly SIE anomalies in the Weddell sector, as in figure 1(b) (b) Time series of ocean conservative temperature averaged between 50 and 150 m in the Weddell sector. The colored curves depict the differences between the ic members and the control experiment, while the black curve depicts anomalies in the control experiment with respect to the 2010–2020 seasonal climatology.

than the control experiment except ic2013 (figure S6). The saltier conditions in Ctl and ic2013 could favor deeper mixing and thus facilitate the extraction of heat at depth.

4. Summary and discussion

Through our control and sensitivity experiments performed with a novel, fully coupled regional model for the SO, we have confirmed the key role of the atmosphere in driving the sudden SIE decline that occurred in late spring 2016, which involved all sectors but was mostly due to sea ice loss in the Weddell Sea. Specifically, our results indicate that the state of the SO around one year prior to the event does not influence the occurrence of the event itself, which takes place in all the members with perturbed initial conditions in the ocean. The specific features of our experimental set up, consisting of simulations with prescribed forcing from reanalyses at the SO boundaries, allow us to emphasize the importance of the large-scale circulation patterns as fundamental drivers of the 2016 drop. Specifically, a clear role of regional atmospheric conditions is present, but it is ultimately controlled by the large-scale dynamics. While we do not investigate whether the relevant large-scale atmospheric anomalies are linked to particular forcings or modes of variability at lower latitudes (e.g. ENSO), we conclude that the large-scale anomalies are key for this and possibly other similar events and stress their importance also in the framework of future long-term changes.

Small differences appear in the ensemble concerning the amplitude of the drop (with a range of around 1 million km^2 , to be compared with the 2.2 million km^2 in Ctl) and its regional features. Our results are thus in agreement with previous studies indicating a moderate role of the ocean in the 2016 SIE drop (e.g. Kusahara *et al* 2018, Meehl *et al* 2019). They also suggest a memory effect from the ocean in the first year after the event. These impacts do not seem related to the initial conditions of the surface ocean and sea ice. In fact, the initial extent and volume anomalies (figures 1 and S7), which span different positive and negative values in the ic members, do not show any clear connection with the drop nor on the persistence of the anomalies. Similarly, temperature and salinity anomalies at the surface also have a minor effect, as they are rapidly overcome by the atmospheric forcing. Instead, the ocean's influence is rather emerging from the conditions at depth, between around 50 and 150 m. We have observed that a warmer (colder) sub-surface ocean in the Weddell sector yields stronger (weaker) negative anomalies over 2017, at least in four of the ic members. Variations in salinity also contribute to the heat exchanges with the deeper ocean. A full member-by-member thermo-dynamical interpretation is beyond our scope, but overall our results support previous findings suggesting the impact of sub-surface oceanic heat on the persistence of the low sea ice

conditions after the drop (e.g. Zhang *et al* 2022, Suryawanshi *et al* 2023) and complement them by highlighting its relevance at the shorter one-year time scale. Additionally, we also emphasize the implicit ocean's role in responding and integrating the atmospheric forcing, which is evident in how all the members reach a similar sea ice state, with persistent negative anomalies, after two years.

Our regional configuration with limited spatial domain (distinct to the global models of, e.g. Zhang *et al* 2022) and high spatial resolution again permits us to further extend our conclusions by stressing the importance of the *local* conditions in the SO, as opposed to the *global* atmospheric influence. While we have mostly focused on the Weddell Sea, the importance of the local ocean's state is also evident in other regions, such as the Indian sector, where a warmer ocean is associated with a deeper regional minimum. The Ross Sea constitutes an interesting case, since the model fails in reproducing the observed short-term persistence of the negative anomalies. Lecomte *et al* (2017) suggested that the Ross Sea temperature at depth had been increasing until 2016 and that a release of that heat would contribute to a sea ice decrease. Indeed, warmer conditions are found in the Ross Sea in our model (figure S8), which favor the melting, but the timing of the simulated heat release is possibly biased and too fast to sustain the observed duration of the negative anomalies. Overall, our results indicate that the ocean plays a role in determining the regional characteristics of the drop and its persistence, for instance by promoting the contribution of specific sectors to the drop (e.g. the Weddell Sea or the Indian Ocean) and conditioning their subsequent recovery.

This study examined the roles of the atmosphere and ocean in the 2016 drop, but our findings contribute to the current general understanding of Antarctic SIE minima. When triggering atmospheric conditions develop, the characteristics of a SIE low and its possible persistence are linked to the ocean, which should thus be considered carefully in the framework of the ongoing unprecedented sea ice conditions.

Data availability statements

The OSI-SAF data are available at <https://osi-saf.eumetsat.int/products/osi-450> (1979–2015) and <https://osisaf.eumetsat.int/products/osi-430-b-complementing-osi-450> (2015 onwards).

The full PARASO sources are available to CLM-Community members; additionally, all PARASO sources except the COSMO parts are publicly available. Details on how to access these source files and the separate components of PARASO can be found in Pelletier *et al* 2022 (see their Code and data availability section).

The data cannot be made publicly available upon publication because the cost of preparing, depositing and hosting the data would be prohibitive within the terms of this research project. The data that support the findings of this study are available upon reasonable request from the authors.

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