Today I would like to talk about drivers of recent changes in the Southern Ocean climate system. A good portion of this presentation will be a synthesis of recent studies on this subject. But I will also highlight some of the work I've done over the past year, as part of my thesis work at the university of Washington. I would like to acknowledge my collaborators on this work: Steve Riser (my former advisor) and Ethan Campbell (my fellow grad student at the time).
As many of you are aware, the Southern Ocean has experienced substantial sea surface cooling and sea ice growth over much of the past four decades. The top plot shows the SST anomaly south of 50S between 1980 and 2015. The bottom plot shows the corresponding SIE anomalies. These trends were mostly circumpolar and they seemingly intensified in the early 2000s, culminating in record-breaking ice extents in 2014 and 2015. These trends are of course in contrast to what’s happening in the northern hemisphere and a lot of work has been done to explain this discrepancy.
It perhaps fair to say that we don’t fully understand what caused those trends but the leading theory is that they were driven by an intensification of the circumpolar westerlies. That is, the strengthening of winds led to an increase in northward transport Ekman layer, which caused surface and favored ice expansion. Strong evidence for this is given in the figure on the right, illustrating that anomalies Southern Ocean SST, zonal winds and SIE have essentially varied in lock-step over the past six decades.

Other studies have proposed other theories, which include changes in wind-driven ice drift and ice-ocean feedbacks. Though these mechanisms likely to be true they can only explain changes within the sea ice zone and not the broader changes seen across the Southern Ocean.
Against this backdrop of surface cooling and ice expansion, there was an abrupt and rather unexpected shift in those trends starting in late 2016. In the austral spring of that year, we observed an extraordinarily rapid melt back of the winter sea ice. By the end of 2016, sea ice cover was 20% lower than normal. Concurrent with this sea ice loss was an equally dramatic spike in SST, which peaked in early 2017. Since then, the SST anomalies has pretty much returned to normal but SIE has remained anomalously low.
Seasonal SIE and SST anomalies in 2016-2017

Sept-Nov 2016

Dec-Feb 2016-2017

• What were the mechanisms that led to these abrupt changes?

• Were these changes the result short-term (natural) variability or a culmination of longterm climate change?

If we zoom in to that late 2016-early 2017 period, we see that both the ice loss and surface warming were circumpolar in extent, with the temperature anomalies extending well beyond the winter sea ice edge.

These observations raise two key questions:...

To jump ahead to the end. I think most of the evidence points to the former but there are indications that longterm (decadal) trends played a substantial role in some regions (specifically, the Weddell Sea).
Mechanisms for abrupt changes in late 2016

- **Sustained poleward wind anomalies** (Turner et al. 2017, Schlosser et al. 2018)

- Southern Ocean wind anomalies coincided with large deviations in key modes of climate variability, i.e. El Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Southern Annular mode (SAM) (Stuecker et al. 2017, Wang et al. 2019, Meehl et al. 2019, Purich et al. 2019)

Several studies have attempted to explain these abrupt changes. The common theme among them is that late 2016 sea ice loss was due to anomalous surface winds. In this plot by Wang et al., we see that regions experienced anomalous poleward air flow coincided with areas that had the largest sea ice loss. It is argued that these winds accelerated the seasonal retreat of sea ice and advected warm subtropical air into the region.

Furthermore, several studies have linked wind anomalies to extreme deviations in both tropical and polar modes of climate variability (specifically, ENSO, the Indian Ocean Dipole, and Southern Annular Mode).
The year 2016 began with one of the strongest El Nino events on record. Like other strong El Nino events, this led to large-scale surface warming in the southern Pacific (via atmospheric teleconnections) as is seen here in this figure from Stuecker et al. 2017. However, there is a problem of timing. Past observations have shown that this south Pacific warming only persists for a couple months after the El Nino event. The abrupt changes we saw occurred almost a full year later. So, while it’s certainly possible that some effects of that early 2016 El Nino event was still lingering by the end of the year... that link is not very clear.
The impact of the IOD

Mechanisms for abrupt changes in 2016

Strong negative IOD event likely triggered anomalous poleward surface airflow in late 2016.

These winds anomalies likely accounted for some but not all of the observed sea ice loss (Purich and England, 2019)

However, a number of studies have demonstrated that a more direct forcing came from Indian Ocean. Specifically, the dramatic decline in Antarctic sea ice extent, coincided with a strong negative Indian Ocean Dipole event. Several studies have now shown the strong convective heating over the Maritime Continent triggered an atmospheric Rossby wave train that propagated into the SO and gave rise to the wind anomalies we observed in the region... That said, studies that have tried quantify the impact of these wind anomalies find that these anomalies can only account for some but not all of the observed sea ice loss. In other words, some other mechanism may have provided some additional preconditioning.
Lastly, 2016 was book-ended by a negative SAM event, which coincided with a substantial weakening of the circumpolar westerlies. This naturally led to a reduction in the northward Ekman transport. And in fact, if you were to do a mixed layer heat budget, you will find that this mechanism was a major contributor to the spike in SST observed during that time.
Drivers of the 2016-2017 Southern Ocean warming

During austral summer of 2016/2017, the anomalous Ekman transport produced roughly a 15-20 W/m² surface warming across the Southern Ocean.
To summarize all this, we don’t have a definitive answer to what caused the abrupt changes in late 2016 but one hypothesis is that they were due to an unusual synchronization of short-term atmospheric variability. The fact that SSTs quickly went back to supports this argument. That being said, the fact that SIE has remained persistently low complicates things and would indicate that some longer-timescale may be at play.
Seasonal SIC anomalies in 2018-2019

What is sustaining these low sea ice anomalies?
One such mechanism is the sustained upwelling of warm deep water. This mechanism was proposed by Meehl et al in 2019, who pointed out an apparent warming of the deep ocean in the (ice-free SO) during years leading up the 2016 sea ice collapse. Specifically, they propose that that the expansion of sea ice was intrinsically linked to the upwelling of warm water in the sea ice zone and helped to precondition the ice for the dramatic ice loss we observed. This idea has been around for a long time and it harkens back to the two-time scale response proposed Ferreira et al. 2015.
Potential impact of longterm trends

- Anomalous upwelling of warm water between 2000-2014 (Meehl et al. 2019)

Timescale of warm water upwelling is poorly constrained (e.g. Ferreira et al. 2015, Doddridge et al. 2019).

Basically, as you strengthen the circumpolar westerlies, you would expect surface cooling and ice expansion in the short term but on longer timescales, we would expect a spin up of the SO overturning circulation. This is in principle should lead to the enhancement of warm water upwelling in the sea ice zone.
Potential impact of longterm trends

It should be noted however that the timescale of this delayed warming is highly uncertain and the answer is very model dependent. In fact, one study argues that a longterm warming may not even occur due to eddy compensation.

In any case, if you were to actually look at the under-ice ocean data, there not a whole of evidence to support this argument.
Data from sea-ice region shows no clear circumpolar trend in sub-ML heat content or stratification in recent years.

Here, I’m showing data from all the Argo floats deployed south of 60S since 2006. This mostly corresponds the sea ice covered region. On the right, I’m showing mean circumpolar T and S profiles for each year. In color, I’ve highlighted 2013-2017 period. In the surface layer, you can certainly see a trend towards warmer temperature, peaking in 2017. However, the thermocline the trends are not as clear. To dig into this some more, we can compute the temperature trends just below winter ML, which I’ve highlighted here.
We are also going to a step further, break things by sector. The main takeaway here is that there is no obvious circumpolar-wide thermocline heat content. The only possible exception to that is in the Weddell Sea region, where there is an apparent warming just below the mixed layer. This is actually consistent with another of studies, including some our own past work.
Polynyas in the Weddell and Cosmonauts Seas

Enhanced upwelling promotes weaker stratification and thinner sea ice (Martinson 1990; Wilson et al. 2019).

This effect is amplified over the Maud Rise seamount.

In particular, there have been dozens of studies that have linked periods of strong upwelling to the appearance of polynyas in the Weddell Sea. Sure enough, this relationship held true in 2016, which featured one of the largest winter polynyas on record. Here, I’m showing the 2016 Maud Rise polynya at its maximum extent. The propensity for polynyas to occur near Maud Rise is nicely illustrated by the schematic from Cheon and Gordon’s recent work. On the right, is a snapshot of the polynya event in the Cosmonauts Sea, which is also very interesting but hasn’t received nearly the same some attention.
Winter polynyas in the Weddell Sea

Factors that contributed to the 2016 and 2017 polynya events:
- strong upwelling
- high mixed layer salinity
- strong storm events in close succession
- surface divergence

Average ocean ventilation during polynya events: ~250 W/m²
8-10 times greater than normal

Campbell et al. (2019)
Gordon (1978)
Potential role of longterm variability

Trend towards positive SAM-like conditions may favor more winter polynyas and deep ventilation in the Weddell Sea.

In the study I co-authored with Ethan Campbell, we went a step further and linked past Maud Rise polynya events to periods of positive SAM, which again is linked to enhanced upwelling in the Weddell Sea. Furthermore, we actually argue that this current trend towards positive SAM-like conditions may favor more winter polynyas and deep ocean ventilation in the Weddell Sea.
Summary of recent Southern Ocean anomalies

• The anomalous decline in Southern Ocean SIE in late 2016 was largely driven by poleward surface wind anomalies.

• These wind anomalies were remotely initiated by atmospheric perturbations from the tropical Indo-Pacific, with later contributions from a strong negative SAM event.

• There is no clear evidence for a circumpolar-wide upwelling of warm deep water in the Antarctic sea ice zone in the years leading up to 2016.

• However, this mechanism is likely at work at more local scales, in the Weddell Sea. The effects of this upwelling may be responsible for the persistently low Antarctic SIE.
Acknowledgements

- **Undergrad advisor:** Arnold Gordon

![Madden Julian Oscillation (MJO)](image)

![Indian Ocean Dipole (IOD)](image)

2: Indian Ocean Dipole (IOD): **Negative phase**
Questions?
Recent changes in SIC
ML heat budget
If we zoom in to that late 2016-early 2017 period, we see that both the ice loss and surface warming was circumpolar in extent. As before, we see that temperature anomalies extended well beyond ice edge, which is an important clue. So these observations raise a few questions:
The Southern Ocean seasonal mixed layer heat budget

Following Dong et al. (2007)

\[
\frac{\partial T_m}{\partial t} \approx \frac{Q_{ao}}{\rho_0 c_p h_m} - \frac{\tau_x}{\rho_0 h_m f} \frac{\partial T_m}{\partial y} - w_{ent} \frac{\partial T}{\partial z}
\]

<table>
<thead>
<tr>
<th>MLT tendency</th>
<th>Air-sea heating</th>
<th>Northward Ekman</th>
<th>Vertical entrainment</th>
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To tackle this problem, I constructed a seasonal ML heat budget for the Southern Ocean. The first study was one done by Dong et al in 2007. Much of this analysis will closely follow the procedure outline in this study. For the purposes of this exercise, we define the SO as the annular region bounded by 50S and 65S. This encapsulates much of the anomalous warming we observed in 2016 and 2017, and includes both ice free and ice covered regions. The fact that we are doing a seasonal, circumpolar-average heat budget, allows to make a few simplifications. First we note that zonal temperature gradient is much smaller than meridional temperature gradient. This allows us to ignore heat advection in the zonal direction. Second, Dong et al showed that on seasonal time scales the entrainment velocity is much greater than the upwelling velocity. With these simplifications, we arrive at the following heat budget... Changes in MLT
To construct this budget, we use a variety of sources. For MLT, we use satellite based SST from the NOAA Optimum Interpolation SST product. The air-sea and wind stress terms, we get from ERA interim reanalysis. MLD we get from individual argo floats and following Dong et al. we use density criteria of 0.03 kg/m3. To get the vertical entrainment term, we used 1D model runs initialized with Argo profiles. For all these terms, we compute monthly averages.

So to compute any of these terms is not trivial and there a lot of nuances here that I don’t have time get into but I’ll just mention that most difficult term to obtain is the vertical entrainment term. And the reason of this is that entrainment across the SO, like most other places, is to large extent driven by storms. Storms occur on the time scale of hours. Argo floats only sample 7-10 days. So if you rely on changes in MLD that floats see, you underestimate that entrainment that actually happens. Because of that, a lot of studies often infer the impact entrainment as residual. Here, we actually attempt to compute it directly.
A reassessment of the Southern Ocean seasonal mixed layer heat budget

\[ \frac{\partial T_m}{\partial t} \approx \frac{Q_{ao}}{\rho_o c_p h_m} - \frac{\tau_x}{\rho_0 h_m f} \frac{\partial T_m}{\partial y} - \frac{W_{ent}}{\partial z} \]

Heat budget approximately closes on seasonal timescales (good agreement with Dong et al. 2007).

Budget also accounts for record Southern Ocean warming in 2016-2017.

Now putting all this together, here is what we get. The thick black line shows the rate of change of the mixed layer temperature. This is what we are trying to explain. The orange, blue and green lines show the temperature contributions from atmospheric heating, meridional Ekman advection and vertical entrainment. Here we see that air-sea heating is the largest driver of MLT variability. We also see that the other flux terms generally act to cool the ML. Sum those flux terms together, gives us this red dashed line. Here we see that the heat budget approximately closes on seasonal time scales.
A reassessment of the Southern Ocean seasonal mixed layer heat budget

\[
\begin{align*}
\frac{\partial T_m}{\partial t} &\approx \frac{Q_{ao}}{\rho_o c_p h_m} - \frac{\tau_x}{\rho_o h_m f} \frac{\partial T_m}{\partial y} - W_{ent} \frac{\partial T}{\partial z} \\
&\quad - \frac{\partial T_{ml}}{\partial T} + \frac{\partial T_{adv}}{\partial T} - \frac{\partial T_{ent}}{\partial T} 
\end{align*}
\]

2016-2017 Southern Ocean surface warming was primarily due to anomalous air-sea heating and northward Ekman transport.

To uncover the drivers of the 2016-2017 warming event, we look at the monthly anomalies. To do this, I computed a monthly averaged climatology for each term, then removed that climatology from each time series. This shows that anomalous air-sea heating and weaker than normal northward Ekman transport were the primary drivers of the 2016-2017 warming event.
Lastly, I would like to highlight that the MLD across the SO was much shallower than normal. This shoaling was evident as early as the winter of 2016 and persisted into 2017. As is evident from our heat budget, shallower MLDs will tend to amplify the surface warming caused by air-sea heating and Ekman transport. Furthermore, for the case of anomalous heating, what really matters is the relative change in MLD compared to the climatology. So here I showing the MLD anomalies as fraction of the MLD that's normally observed. So, it is evident that even small amount of shoaling that occurred in the summer had a large impact on ML heat budget.
Drivers of the 2016-2017 Southern Ocean warming

Mostly due to **sensible and latent heat flux anomalies**.

That is, the ocean was losing less heat to the atmosphere than normal.

To dig into this is even more, we now zoom in to that 2016-2017 period and look at the spatial pattern of those terms. This plot shows anomalies in the air-sea heat flux during that period. During Sep-Nov, this term provided an anomalous heating of about 20-40 W/m² across the Southern Ocean. Much of that was due to anomalies in sensible and latent heat fluxes. In absolute terms, sensible and latent heat fluxes tend to cool the surface ocean. Therefore, these positive heating anomalies reflect the fact that the ocean was losing less heat to the atmosphere than normal. What I’m not show here, is that the pattern of these heating anomalies also coincided with the anomalous advection of warm, moist air from lower latitudes.
Drivers of the 2016-2017 Southern Ocean warming

Next we look at the heat flux anomalies due to the Meridional Ekman transport. Heating via this mechanism was apparent as early as the winter of 2016 but peaked during the summer of 2016-2017. This coincided with a dramatic weakening of the circumpolar westerlies. **Across the Southern Ocean, zonal winds were about 15-20% weaker than normal and because of that there was a sharp reduction in the northward advection of cool surface waters.**
The abrupt decline in Antarctic SIE in late 2016 was driven by a combination of short-term atmospheric variability (associated extreme deviations in the IOD and ENSO) plus long-term upper ocean variability associated with SAM.

- The latter mechanism contributed to the reoccurrence of polynyas in the Weddell Sea and is

*Longterm internal variability within the Antarctic region may contributed to the sea ice decline in some regions (i.e. the Weddell Sea).
Polynya stuff
Factors that contributed to the 2016 and 2017 polynya events:
- strong upwelling
- high mixed layer salinity
- strong storm events in close succession
- surface divergence

And from these float data we saw evidence of deep mixing that extended well beyond the normal depth of mixed layer, which is shown here in white. After analyzing the float data as well as meteorological conditions leading up to the events, we concluded that the following factors were key contributors to the initiation of these polynyas. The first is strong upwelling. **This is something we inferred from reanalysis winds, which showed anomalous negative wind stress curl during the months that leading up to the 2016 polynya.** Concurrent with that was higher than normal mixed layer salinity. This meant that stratification was much weaker than normal. Lastly, we found that the initiation of both the 2016 and 2017 events coincided with the passage of powerful storms that featured strong surface winds and anomalous surface divergence.
Furthermore, current trends in surface winds may actually favor an increase in polynyas in the future. If we take a step-back and assess all the Weddell sea polynya events in the past, we see that these events tend to occur when the Southern Annular mode or SAM is in its positive phase. Positive SAM is associated with a deepening of the Weddell Sea low, a decrease wind stress curl (which favors upwelling) and an increase in the number winter storms. What I want to emphasize here is this that these variables all appear to have longterm trend. So on one hand surface freshening trends will tend to reduce winter polynyas. But, on the other hand, we have surface trending in favor more polynyas. At this point, I think it is unclear which effect will dominate in the immediate future.
climate indices
Drivers of the 2016-2017 Southern Ocean warming

The impact of SAM

Late 2016/early 2017 negative SAM event was associated with a dramatic weakening of the circumpolar westerlies.

Hypothesis: the 2016-2017 anomalies were due to an unusual synchronization of tropical and extratropical modes of climate variability.
Now, whenever something weird happens in the global climate system, there is a good chance that ENSO had something to do with it. And sure enough, in early 2016 there was a strong El Nino event, this is shown here by the nino34 index. This event also happened to be one of the strongest on record. Like other El Nino events, 2015-2016 El Nino event caused anomalous warming in the Southern Ocean. This is primarily the result of atmospheric teleconnections. This plot from Stuecker et al shows that this warming was centered over the eastern Pacific.

However, during previous El Nino events this remote warming usually goes away as El Nino event wanes... if you fast-forward several months, you typically find El Nino events are usually followed wide spreading cooling across the southern ocean. However, in late 2016, the opposite happened. Even though ENSO was in a neutral, if not weak La Nina state, the Southern Ocean was still anomalous warm more so than it was during the actual el nino. This suggests that the 2015-2016 El Nino was not the direct cause of the Southern Ocean anomalies that saw in late 2016/early 2017.
However, a number of studies suggest that there was another culprit and that is the Indian Ocean Dipole. The IOD is essentially ENSO’s lesser known counterpart in the Indian Ocean. And similar to ENSO, the IOD refers to anomalies in the zonal SST gradient across the equatorial Indian Ocean. Negative IOD is sort of equivalent to La Nina event, i.e. warmer SSTs in the eastern IO and enhanced precipitation. In late 2016, there was a very strong negative IOD event and associated with that was an extremely strong precipitation event. The precipitation event quite literally had a ripple effect that was felt all over the world. Here, we have a plot from Wang et al. 2019 showing an atmospheric Rossby wave train in the upper troposphere that was emanating from the Maritime Continent into the Southern Ocean. At the surface level....
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