Connecting Antarctica to the Tropics: Understanding the Antarctic Cryosphere via the Madden Julian Oscillation

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Introduction

Recent studies found that sub-seasonal tropical forcing, specifically changes in surface wind and temperature, can cause changes in Arctic sea ice surface drift, melting, and freezing via modulation of circulation patterns (Holland and Kwok, 2012; Henderson et al., 2017). Furthermore, Henderson et al. (2014) determined that the Madden Julian Oscillation (MJO) modulates the Arctic atmosphere, and in turn, governs changes in Arctic sea ice. Trends in sea ice extent, concentration, and area hold the potential to highlight mesoscale variability in local weather and global variability in climate because the cryosphere is sensitive to changes at the air-ocean-ice interface. Thus, expanding our understanding of how the cryosphere interacts with other elements within the air-ocean coupled system helps us comprehend and predict the planet's climatological equilibrium. Preliminary findings suggest that Antarctic sea ice may respond to a MJO signal, with some geographic sectors of Antarctica showing more evidence of the teleconnection than others. This research connects existing areas of MJO – sea ice modulation scholarship to **test the following hypothesis: Antarctic sea ice varies sub-seasonally in response to forcing from the MJO**, and that response is different by geographic sector and dependent on both season and pre-existing state of the Antarctic atmosphere.

MJO – Sea Ice Modulation Pathway

What is the MJO?

- A leading mode of atmospheric tropical variability.
- Moves generally eastward around the equator on a time scale of 30-60 days.
- Characterized as a region of similar weather conditions, originating over the Indian Ocean.

How is the MJO connected to Antarctica?

- Upper tropospheric heating powered from convective cloud clusters excites Rossby waves.
- Those Rossby waves propagate eastward and poleward, modulating surface pressure and circulation, which causes sea ice variability (**Fig. 1**).

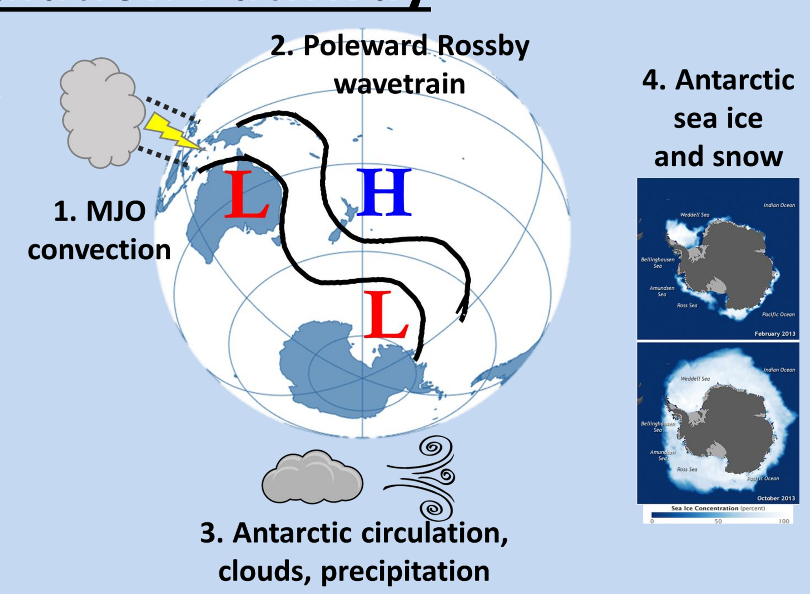


Figure 1: Hypothesis for the potential MJO-Antarctic cryosphere modulation pathway.

Data & Methods

1. National Snow and Ice Data Center (NSIDC) daily climate record of Passive Microwave Sea Ice Concentration, Version 3
   - Daily observations of sea ice concentration (SIC) at a grid spacing of 25 km from 1989 to 2019 were considered.
   - Daily change in SIC (ΔSIC) and sea ice extent (ΔSIE) were calculated by subtracting the given day from the previous day. Positive or negative ΔSIC and ΔSIE represents a net gain or loss.
   - Sea ice area (SIA) was determined by multiplying the percentage ΔSIC by 625 km^2.
   - Positive and negative changes in SIA were analyzed separately to avoid masking of any signals in a particular sector.
2. The Real-time Multivariate (RMM) Index (Wheeler and Hendon, 2004)
   - When the RMM amplitude was greater than 1.0, an active MJO was considered.

Average SIC and Average ΔSIC: June and October

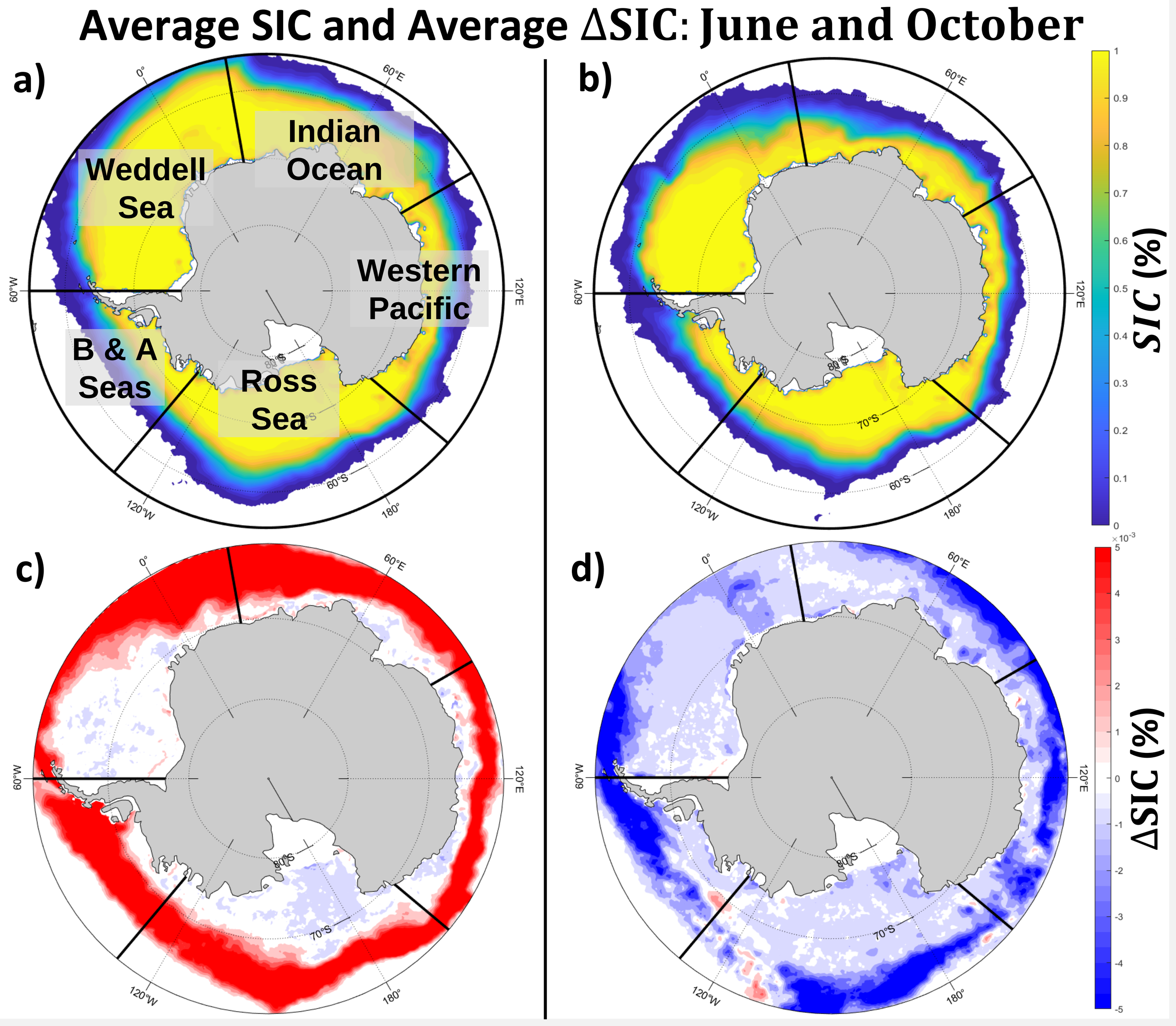
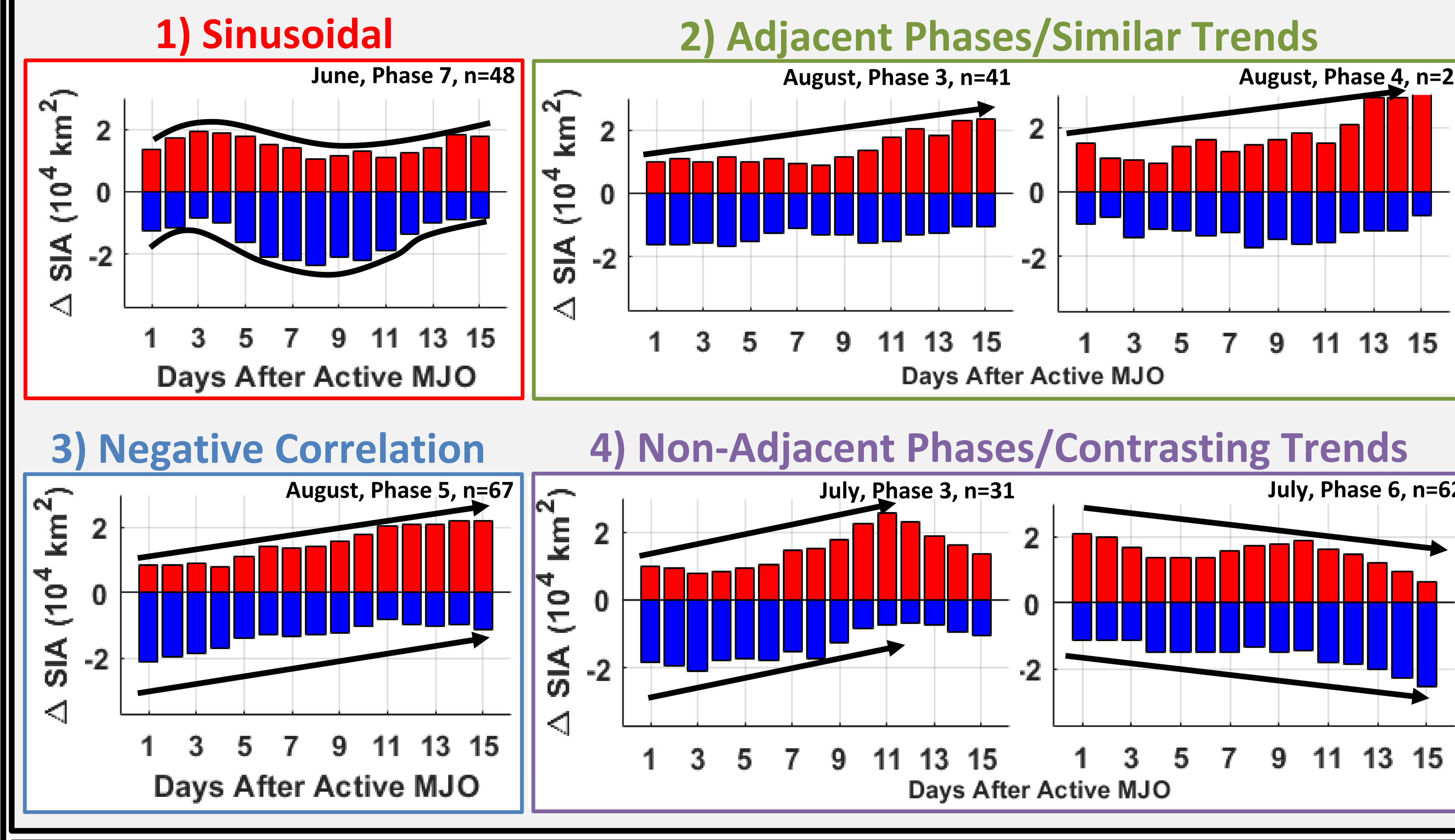


Figure 2: Southern Hemisphere 30-year average SIC for the transitional months of a) June and b) October; and the correlating average daily ΔSIC for c) June and d) October. The five sectors are as follows: 1) Indian Ocean Sector, 2) Western Pacific Sector, 3) Ross Sea Sector, 4) Bellingshausen & Amundsen Seas Sector, and 5) Weddell Sea Sector.

- June is a transitional month, as SIC increases after austral summer. Largest SIC magnitudes located in June are located in the Weddell and Ross Seas (**Figure 2a**). June average daily ΔSIC featured a net increase, while the inner region of the Ross Sea featured a strong decreasing trend (**Figure 2c**).
- October features an annual SIC maximum with the largest SIC magnitudes features in the Weddell and Ross Seas (**Figure 2b**). June average daily ΔSIC featured a net decrease, while the climate begins its transition to austral summer (**Figure 2d**).

Positive & Negative Anomalous ΔSIA Patterns of Interest



1) Sinusoidal (Fig. 3): The sinusoidal pattern is indicative of an MJO-driven response, as MJO moves approximately 1 phase every 5 days.

2) Adjacent Phases/Similar Trends (Fig. 4): Observing a similar trend in positive and/or negative anomalous ΔSIA after *adjacent MJO phases is indicative of an MJO-driven response.*

3) Negative Correlation (Fig. 5): The negative correlation pattern suggests a strong physical response during the 15 day lag period, indicative of a notable freeze-up or melt of ice, possibly associated to the MJO.

4) Non-Adjacent Phases/Contrasting Trends (Fig. 6): Observing an opposite trend in positive and/or negative anomalous ΔSIA after *non-adjacent MJO phases is indicative of an MJO-driven response.*

Results: Frequency of Patterns

Table 1: The summation table organized indicates that MJO-driven modulation of sea ice has a regional component as some sectors show more evidence of the MJO signal than others.

Criterion	Indian Ocean	Weddell Sea	Ross Sea	Western Pacific	B & A Seas	Criterion Total
Sinusoidal	7.0%	10.9%	3.1%	1.6%	2.3%	24.8%
Adjacent Phases/ Similar Trends	10.9%	0.0%	4.7%	1.6%	3.1%	20.2%
Negative Correlation	3.9%	7.8%	3.9%	1.6%	5.4%	22.5%
Non-Adjacent Phases/ Contrasting Trends	3.1%	14.0%	9.3%	3.1%	3.1%	32.6%
Sector Total	24.8%	32.6%	20.9%	7.8%	14.0%	100.0%

- The results indicate that a regional component of MJO-driven modulation is present, with the Weddell Sea, Indian Ocean, and Ross Sea sector being affected preferentially.
- A seasonal component of MJO-driven modulation is also present, with June, July, and August exhibiting the strongest relationship.

Results: Teleconnections between the MJO and Antarctic Sea Ice Area

July Anomalous ΔSIA: B & A Seas

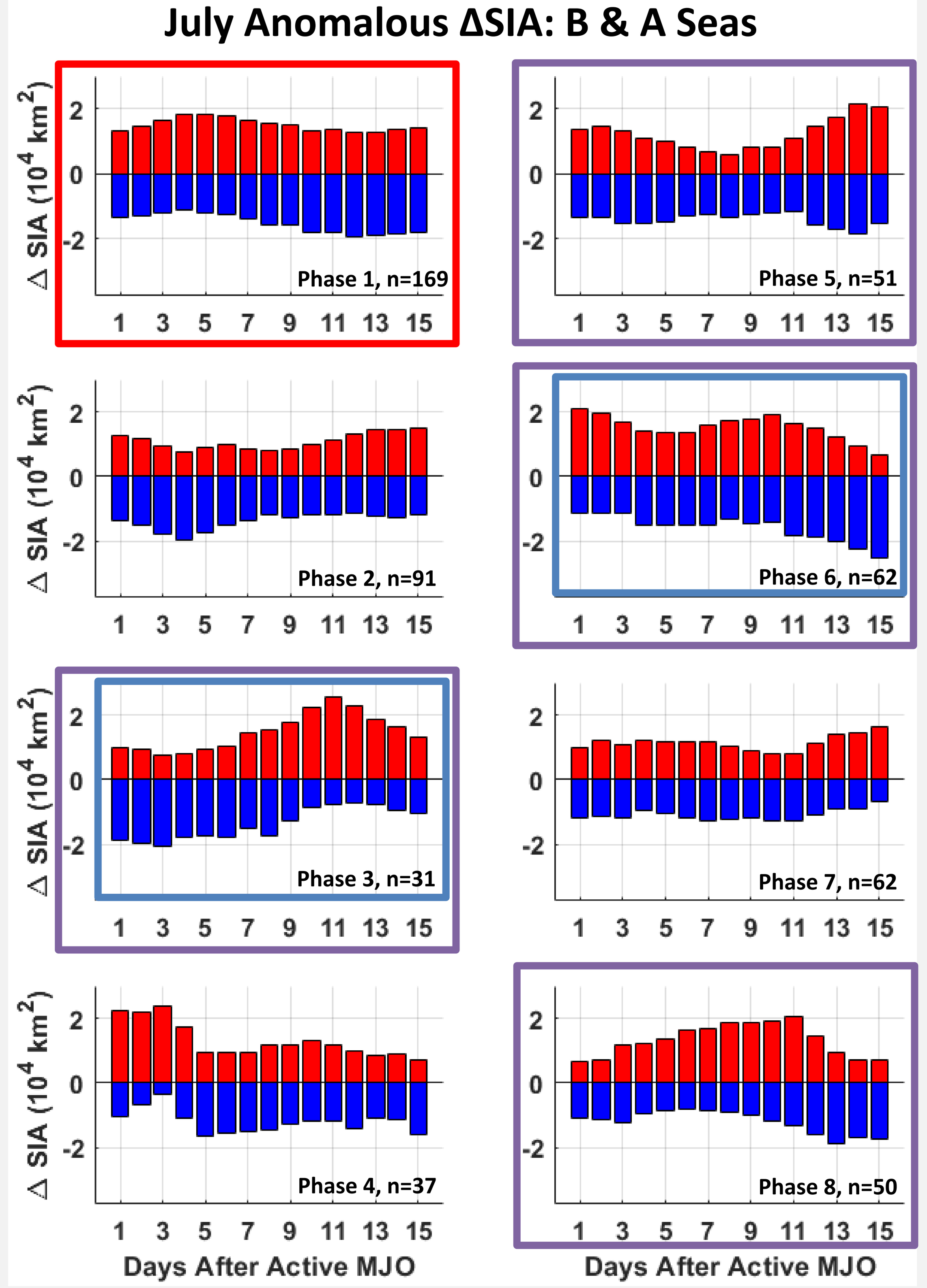


Figure 7: Bellingshausen and Amundsen Seas positive and negative anomalous ΔSIA in July binned by phase of the MJO, where "n" refers to how many times an active MJO occurred from 1989 to 2019.

- After MJO Phase 1 in July, anomalous daily ΔSIA in the Bellingshausen and Amundsen Seas exhibited a ***sinusoidal pattern*** throughout the 15 day lag period after an active MJO (**Figure 7**).
- After MJO Phase 1 in August, anomalous daily ΔSIA in the Ross Sea exhibited a similar ***sinusoidal pattern*** (**Figure 8**).
- Neighboring or ***adjacent MJO phases***, are expected to have similar trends, as seen during August in the Ross Sea during Phases 3 & 4 (**Figure 8**).
- During Phases 3 & 4, negative anomalous daily ΔSIA trends increasingly negative throughout the 15 day lag period.
- *Opposite* or ***non-adjacent phases***, such as Phases 3 & 6 and 5 & 8 in July in the Bellingshausen and Amundsen Seas (**Figure 7**) or Phases 5 & 8 in August in the Ross Sea (**Figure 8**), feature opposite signals.
- The anomalous positive and negative ΔSIA during Phases 3 & 6 in the Bellingshausen and Amundsen Seas also meet the ***negative correlation*** criterion (**Figure 7**).

August Anomalous ΔSIA: Ross Sea

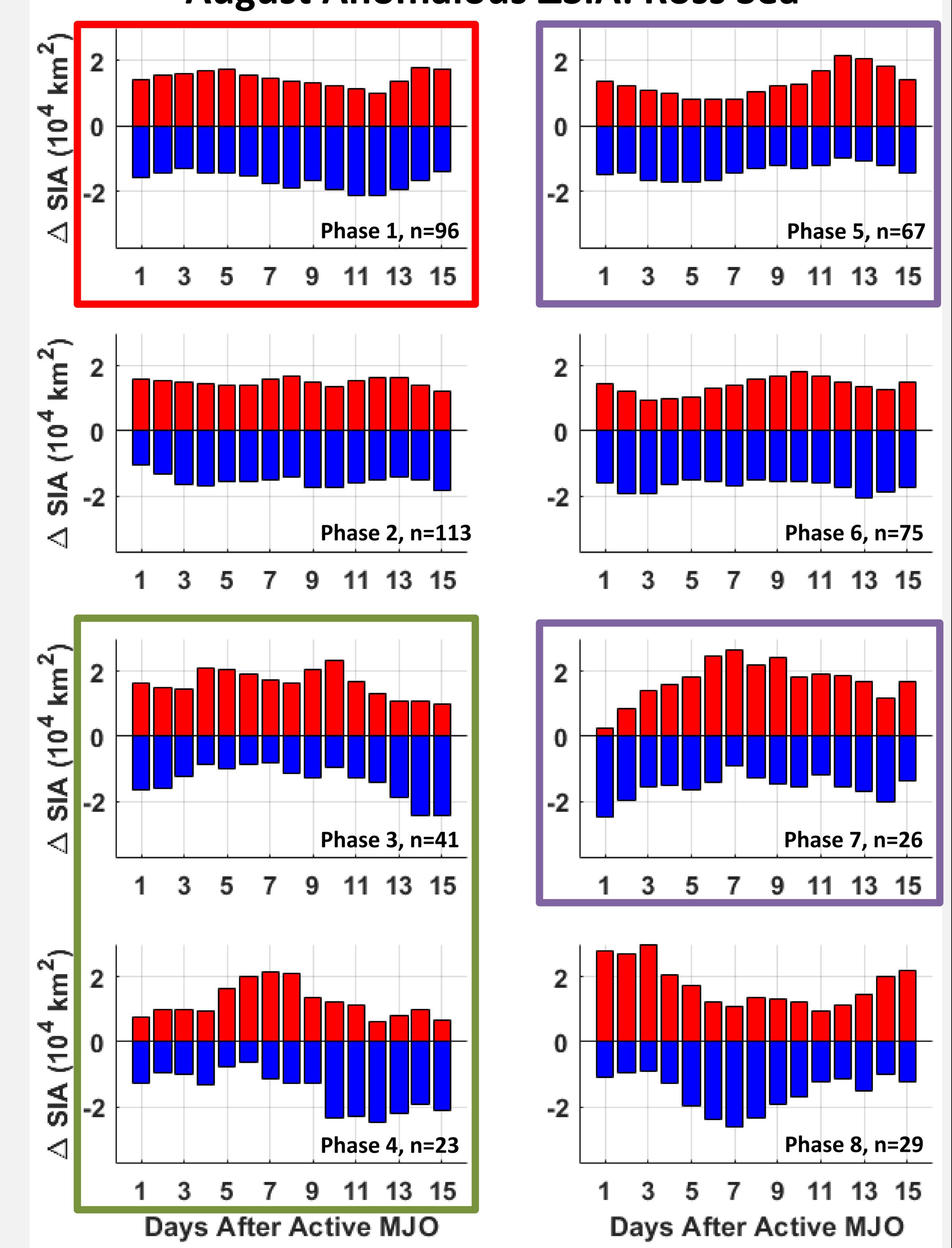


Figure 8: Weddell Sea positive and negative anomalous ΔSIA in October binned by phase of the MJO, where "n" refers to how many times an active MJO occurred from 1989 to 2019.

- **Figures 7** and **8** provide evidence that Antarctic sea ice varies sub-seasonally in response to forcing from the Madden Julian Oscillation, and that response is different by sector and dependent on both season and pre-existing state of the Antarctic atmosphere. The variability with the 15-day lag period is indicative of notable sub-seasonal scale variability.

Future work:

The next steps in this work include:

- Exploring magnitudes of anomalies per sector.
- Investigating statistical significance of what sectors and regions are preferentially affected by the MJO.
- Investigating time lags between MJO phase and ΔSIC.

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