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Atmospheric Response to Weddell Sea Open-Ocean Polynya

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ABSTRACT

The atmospheric conditions associated with the rare Weddell Sea open ocean polynya are investigated. The polynya has not been seen since 1976, so data on the event is scarce. The CESM high resolution model is used to investigate multiple atmospheric variables. We analyze three years of polynyas, which are also compared to three years without a polynya. The surface temperature, sensible heat flux, latent heat flux, humidity, average wind speed, precipitation, longwave flux, and shortwave flux all increased over the polynya. The sensible heat flux had a higher magnitude than the latent heat flux because conduction and convection were the primary drivers of heat flux. A combination of increased latent heat flux and humidity led to an increase in precipitation. Increased longwave downwelling flux over the polynya indicated the presence of clouds over the polynya. Lastly, the sea level pressure was consistently lower over the polynya because of the presence of a thermal low generated by thermally driven convective updrafts.

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1. Introduction

A polynya is an area of persistent open water surrounded by ice covered sea. The Weddell Sea is located in the southern ocean, off the coast of Queen Maud Land and extending hundreds of miles. Typically, this body of water freezes over during the winter. However, from 1974-76, an open ocean polynya formed in the Weddell Sea, the largest ever to be observed. (Moore et al. 2002). This particular polynya was nearly 350,000 square km in area, just smaller than the state of Montana (“Montana QuickFacts”). The Weddell Polynya has not been seen since. However, it was an area of extreme meteorlogical and oceanic significance (Carsey 1980). The first observations of the polynya at full extent were made by the Electrically Scanning Microwave Radiometer aboard the Nimbus 5 satellite (Wilheit and Sabatini 1972). These first images, with a resolution of 25-30km, show the polynya form in 1974, 1975, and 1976. Also the polynya had remarkable shape stability, often changing less than the unbounded ice edge (Carsey 1980).

The exact cause for the formation of the Weddell Sea Polynya is still unknown. However, a few theories attempt to explain the phenomenon. The first is that oceanic circulation in the Weddell Sea favors deep water polynyas because it is susceptible to thermobaric convection (Morales Maqueda et al. 2004). Another theory associates the formation with air-sea interactions over the Polynya to create and maintain the open sea. One study links the polynya formation to low winds and unusually high heat flux (Parkinson 1983). On the contrary, another study notes a mechanism by which high winds drive ice divergence, causing hyperproduction of ice and a destabilization of the water (Goosse and Fichefet 2001).

Studies on atmospheric responses are just as unknown as the reason for the development of a polynya, because we have not been able to study one with modern technology. However, there are a few variables that have some degree of certainty. The first is surface temperatures. The open water must be at or above the melting temperature of water, and the sea ice must be at or below the freezing point. Therefore, it is logical to assume the air over the polynya would be warmer. Another variable in high agreement is heat flux, and in particular the increase in latent and sensible heat flux over the polynya. Lastly, many scientists believe humidity/moisture increases over the polynyas. Still though, there are many variables that have not been explored or that do not have great agreement, such as: wind speed, radiative flux, precipitation, and surface pressure.

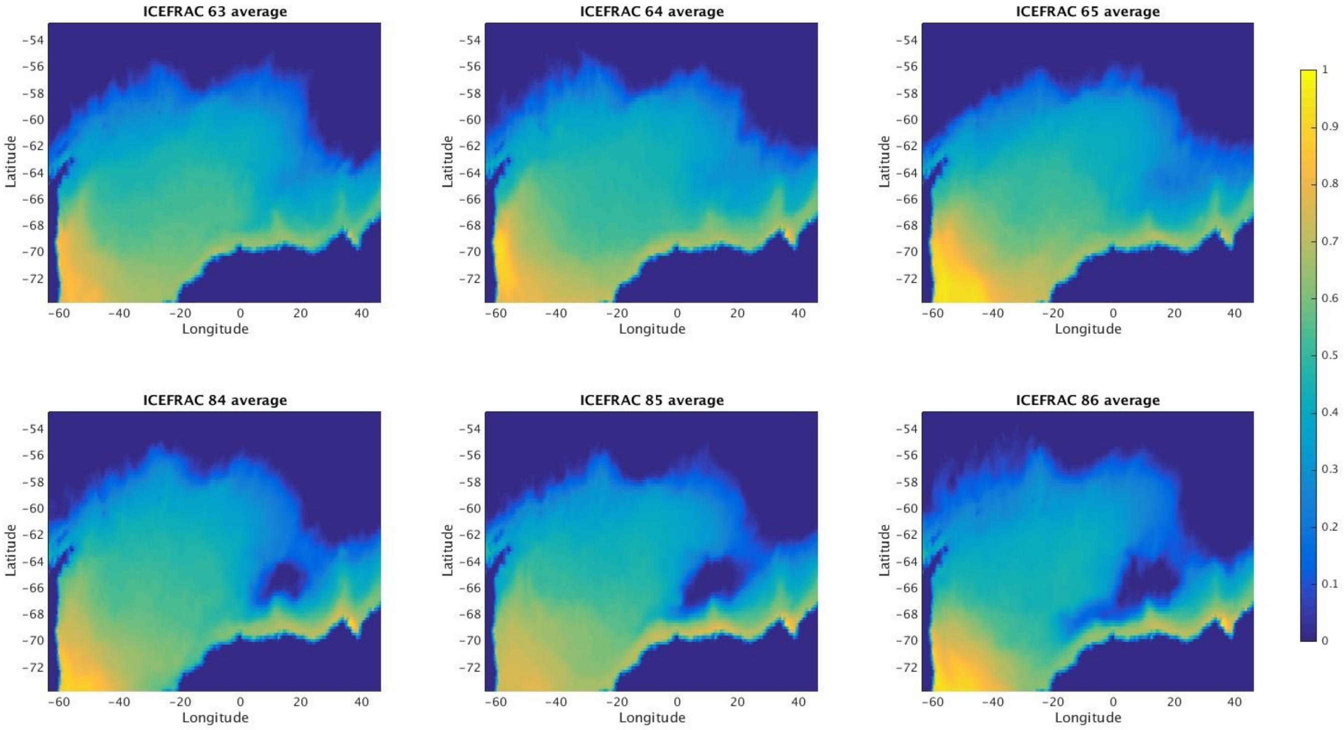

Figure 1: *Plots of yearly averaged ice fraction (ICEFRAC), a unitless variable measuring the fraction of the ocean that is covered by sea ice. The above three plots are during three years with no polynyas. The lower plots are three years with polynyas. There is a noticeable hole in the prevailing sea ice where the polynya is present in years 84, 85, and 86.*

2. Overview of Model – CESM-H

The aim of this study is to analyze a high-resolution run of the Community Earth System Model (CESM-H) over the time and region of the Weddell Sea where a polynya has formed with similar characteristics to the Weddell Sea Polynya of 1974-76. Previously known as the Community Climate System Model (CCSM), the CESM was developed by the National Center for Atmospheric Research (NCAR), and uses Community Atmosphere Model 5 (CAM5), Community Ice Code version 4, Parallel Ocean Program version 2, and Community Land Model version 4. This model run has conditions corresponding to year 2000 greenhouse gas levels (Small et al. 2014). Also, the resolution of the ocean and sea ice models is 0.1º, while the atmosphere model has a resolution of 0.25º. The model run years analyzed are 63-65 and 84-86. Model run years 63,64, and 65 show no evidence of an open ocean polynya, while years 84,85, and 86 do.

3. Results

3.1 Polynya Locations and Time Frame

The polynyas were observed in the model run data from years 84-86. As shown in figure 1, the polynyas were observed on the eastern side of the Weddell Sea with a center near 65ºS 15ºE. Each year from 84 to 86, polynyas formed in late August (~day 230) through an embayment process described by Moore et al. (2002). Figure 1 shows the Ice Fraction (Fraction of sea covered by ice) of all six observed years. The three plots on top are years 63, 64, and 65, in which no polynya formed. The bottom three plots show years 84, 85, and 86. There is a noticeable hole of no ice in these three years of the normal ice sheet extent. The 84 polynya was open from day 238-318. The 85 polynya was open from day 225-313, and 86 from 237-325 (Late August – Early November). The maximum polynya area reaches nearly 350,000 km².

3.2 Heat Fluxes

The expectation before looking at the data was that the surface temperature over the polynya would significantly rise. The model data confirms this. Looking at Figure 2, it is obvious that the polynya is significantly affecting the air temperature over the polynya. Air temperature increases are due to heat transfer between the open sea water and the atmosphere. The sea temperature must be at or above 271 K in order to not be frozen. The air temperature, in this area during this part of the year, is well below freezing, with mean temperatures around 250 K (Carsey 1980). As the wind flows over the polynya, conduction and convection warms the air. The conductive warming of the atmosphere can be explained through the sensible heat flux, which is higher over the polynya. The difference in heat fluxes of the polynya area in polynya and non polynya years can be seen in Figure 3. During the embayment process, the heat fluxt begins to rise because of a rise in the difference between air

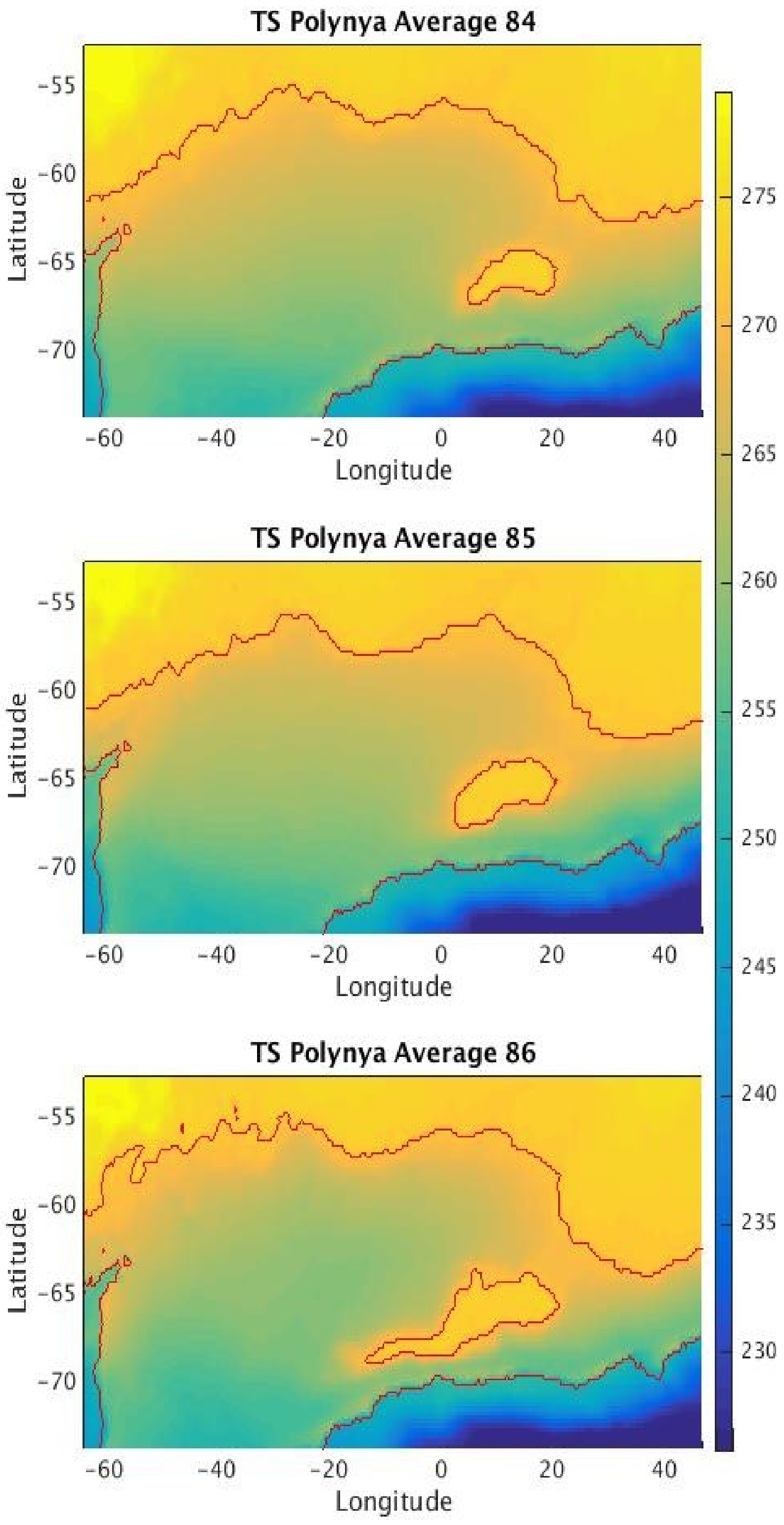

Figure 2: *Plots of daily averaged surface temperatures (TS), in Kelvin. The above three plots show anomalously high temperatures associated with the open polynyas. The temperatures over the polynyas were over 273K. Red lines indicate ice extent to 15% ice fraction.*

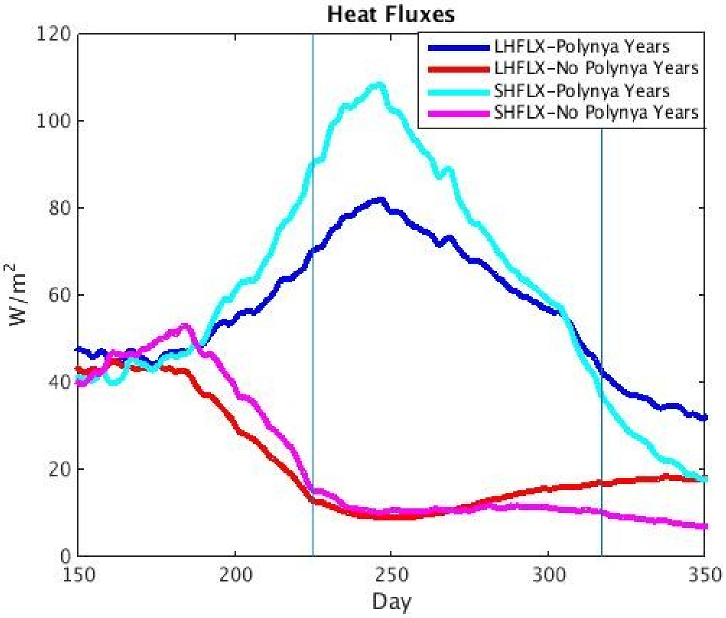

Figure 3: *Plot of 21 day centered mean heat fluxes, in W/m^2. The graph shows the average sensible heat flux (cyan) and latent hat flux (blue) of the years with a polynya, and years without a polynya (LHFLX, red; SHFLX, magenta) over the region where the polynyas were present in the Weddell Sea. There is a sharp increase in heat flux during the embayment period, when the heat flux would typically be decreasing. Heat flux reaches a maximum around the 30th day of the Polynya. Vertical light blue lines represent beginning and end of polynya.*

temperature and surface temperatures. The largest difference in heat flux occurs during the open polynya days when the atmosphere would normally be cooling and sensible heat flux would be decrease, because it is winter in this part of the world. Maximum heat flux occurs around day 250 when the difference in sea surface temperature and atmospheric temperature is at a maximum. The heat flux decreases after day 250 (day 30 of polynya) because the atmosphere is warming, and the temperature difference is decreasing. The increase in sensible and latent heat at different magnitudes is in agreement with Moore et al. (2002).

The vertical extent of the heat flux was examined at 850 hPa (~1.5km). The analysis showed the heat flux did not extend up to this height. When comparing temperature of polynya years against years without a polynya, the temperature difference was insignificant. This analysis is in agreement with Dare and Atkinson (1999), who concluded heat flux reached a maximum of 500-800 m above ground level (AGL).

3.3 Humidity

Analysis of humidity over the polynya showed moisture increased over the open water. Compared to nonpolynya years, there was approximately a 1.5 g/kg increase in daily specific humidity. 1.5 g/kg is significant during the winter months in the antarrctic, which is a desert. This also supports the evidence of increases in latent heat flux, which is associated with evaporation and condensation. A high flux of evaporation over the polynya should continue to add moisture to the atmosphere. This is in agreement with Dare and Atkinson (1999).

In addition to an increase in humidity over the polynya, the downwind edge of the polynya had higher humidity on average than the upwind edge, as seen in Figure 4. The prevailing wind flow is a west to east pattern, so the upwind edge is the west side of the polynya, and the downwind edge is the east side. The upwind air has been traveling across the dry sea ice, and as the wind comes across the polynya, it picks up moisture and travels along the polynya. At the downwind edge, it has had the highest net moisture flux. It is important to note that the air quickly dries out after leaving the moist polynya and transitioning to the sea ice on the downwind edge. Segal et al. (1996) showed similar results with relation to large lakes.

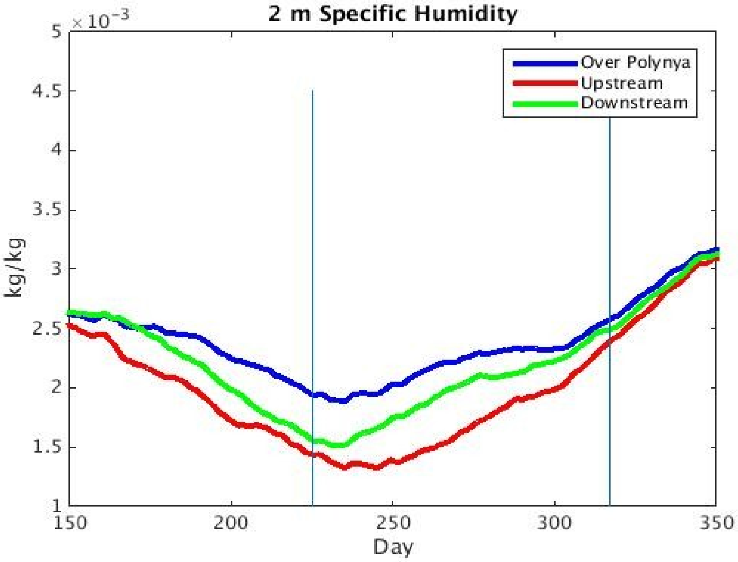

Figure 4: *Plot of 21 day centered mean specific humidity (kg/kg). Humidity directly over the polynya (blue) is highest during the days where the polynya is present. The upstream (red) edge is much drier than the downstream (green) edge.*

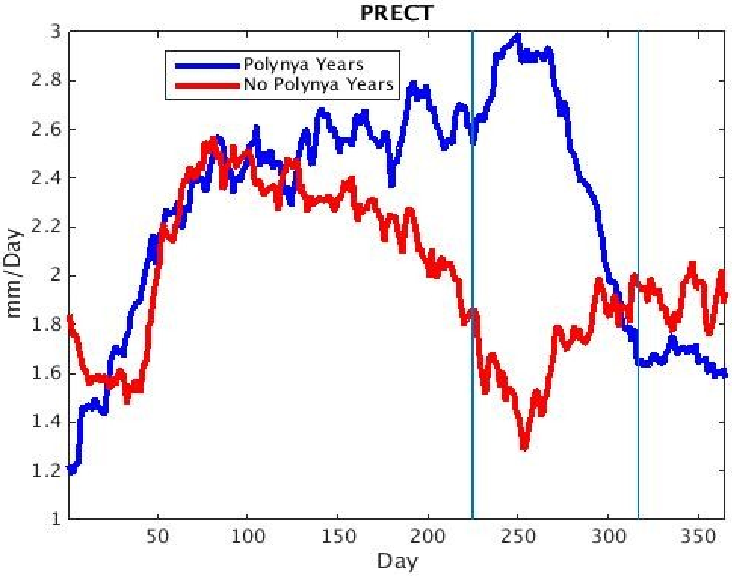

Figure 5: *Plot of 21 day centered mean precipitation(PRECT), measured in mm/Day. During years with a polynya (blue), the precipitation increases compared to years without (red).*

3.4 Precipitation

An increase in humidity seems to also have a direct impact on the precipitation in the polynya area (Moore et al. 2002). As seen in Figure 5 (above), precipitation doubles at points over polynyas compared to over sea ice. When embayment begins, around day 150, precipitation increases, which correlates to an increase in specific humidity over the polynya. Precipitation reaches a maximum from day 240-260. After the maximum is reached, there is a sharp decrease in precipitation. This corresponds to a decrease in sensible and latent heat fluxes. As the sensible heat decreases, there is less heat and convective lifting. Combined with less precipitation because of a decrease in latent heat, there is not as much potential for precipitation.

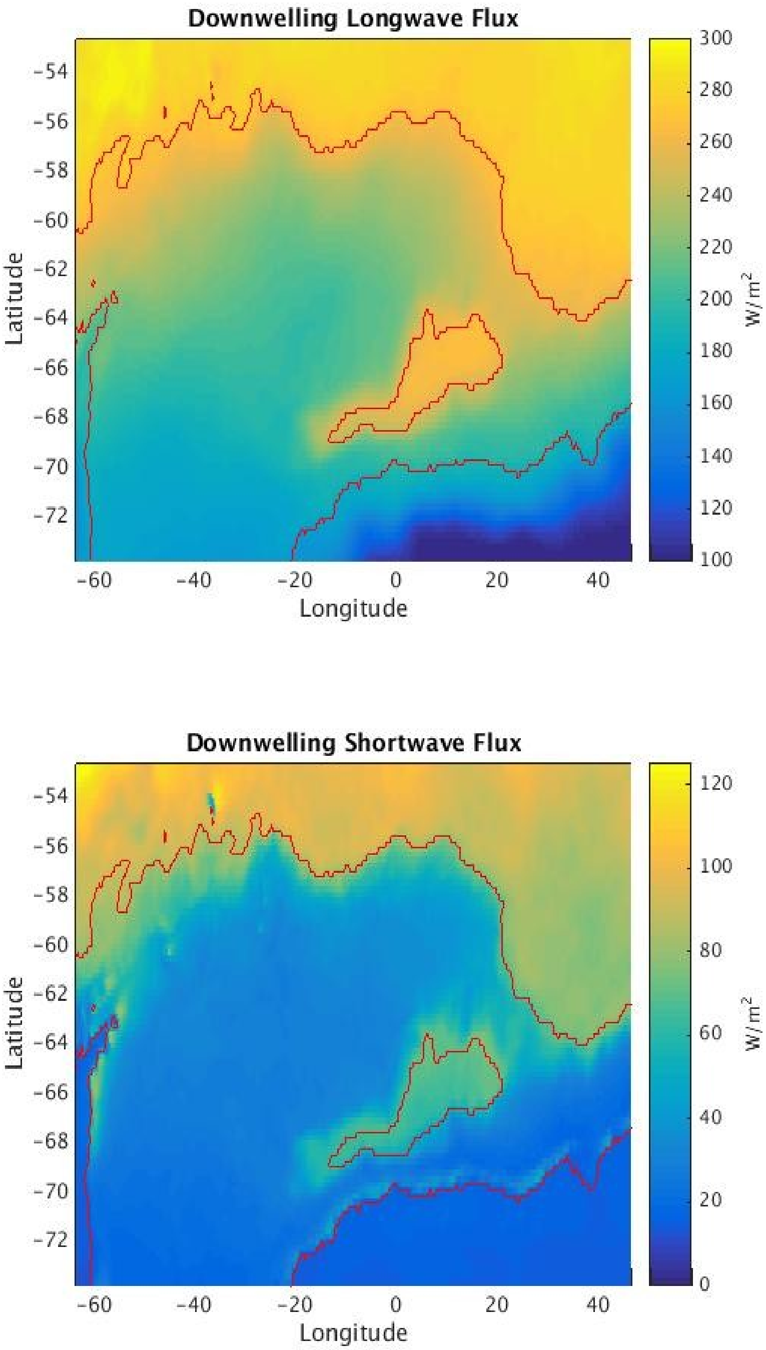

Figure 6: *Plot of year 86 longwave downwelling flux (FLDS, top), and shortwave downwelling solar flux (FSNS, bottom). Longwave fluxes over the polynya reach nearly 300 W/m², about 100W/m² higher than surrounding sea ice averages. Shortwave fluxes reach roughly 80-100 W/m² on average over the polynya, versus 30 W/m² over surrounding sea ice. Red lines indicated ice extent to 15% ice fraction.*

3.5 Radiative Flux

Downward radiative flux (longwave and shortwave radiation) increased over the polynya, as seen in Figure 6. Longwave fluxes are much larger than shortwave fluxes. This is mostly due to the fact that for this time of year, the sun does not come up so shortwave flux from the sun is nearly 0 (Moore et al. 2002).

Longwave downwelling flux values are on the magnitude of around 100W/m² greater over the polynya than the sea ice surrounding it. The increase in longwave flux is due to two major effects. The first effect is increased cloud cover reflecting longwave radiation back to the surface. Our data set did not include a cloud cover variable, but many reports indicate an increase in cloud cover over open ocean polynyas (Moore et al. 2002; Morales Maqueda et al. 2004). In addition, since moisture and precpitation have already been shown to increase in sections 3.3 and 3.4, a logical conclusion would be that cloud cover also increases because clouds must be present for there to be precipitation. The net effect of cloud cover with respect to longwave flux is to increase the magnitude (Garrett et al. 2002; Curry et al. 1996). As cloud cover increases, the longwave flux emitted by the warm water is reflected back to the surface, creating a positive feedback loop on the polynya. As the radiation is reflected back, the water warms, and more evaporation occurs. This evaporation eventually becomes a cloud, reflecting back more radiation. Additionaly, warmer temperatures emit longwave radiation at greater magnitude. This positive

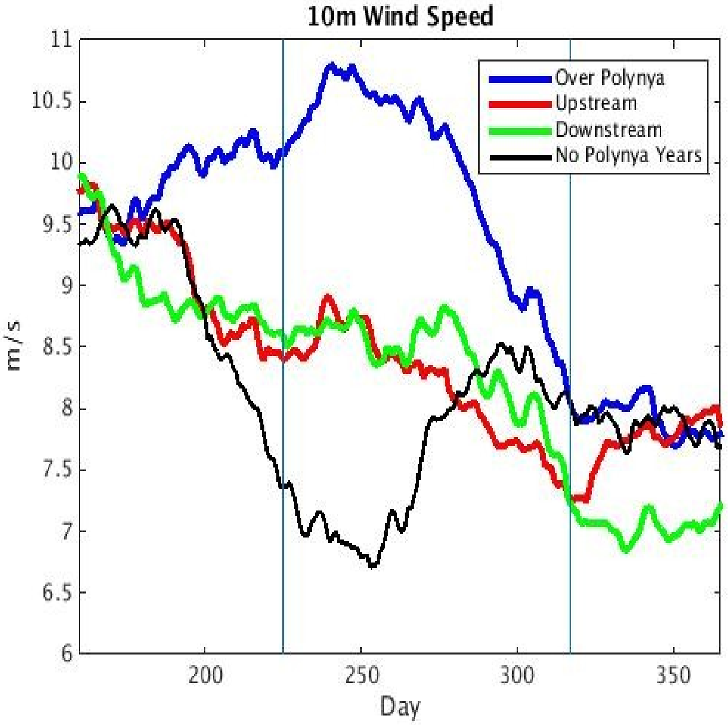

Figure 7: *Plot of 21 day centered mean 10 m wind speed (U10) from days 150-360 of years 84, 85, 86 of the model. The daily average wind speed over the polynya (blue) is largest over span of polynya (indicated by vertical blue lines). The upstream and downstream wind speeds (21 day centered mean during years 84, 85, 86; red and green respectively) were less than the winds over the polynya, but more than the winds in the same area when there is no polynya (black). The non polynya years were 63, 64, 65.*

feedback loop is possibly one of the conditions keeping the polynya open (Morales Maqueda et al. 2004). The second major factor increasing downwelling radiation is an increase in solar radiation, which does emit a portion of longwave radiation in addition to shortwave radiation.

Shortwave fluxes are seen at much smaller magnitudes over the polynya than longwave fluxes. However, shortwave fluxes are still nearly 60 W/m^2 higher compared to surrounding sea ice values. The higher shortwave fluxes over the polynya is due to absorptive properties. The surrounding sea ice has a hig albedo, and at this zenith angle, water is a good absorber of shortwave radiation (Moore et al. 2002). Therefore, incoming solar radiation is reflected off of the sea ice, and is absorbed by the water. Clouds forming over polynyas also have high albedos and contribute to reflected shortwave radiation, but cloud albedo is still less than the ice albdeo (Curry and Ebert 1992). Therefore, the net effect of clouds is still warming (Morales Maqueda et al. 2004).

3.6 Wind

Wind speed over the polynya was recorded at 10 m AGL for all model runs. The results were twofold. First, the wind speeds during polynya years, over the polynya as well as upwind and downwind, increases when compared to the same areas of nonpolynya years. Also, the wind speed over the polynya increased in relation to wind speeds upstream and downstream of the polynya. These results are alligned with Dare and Atkinson (1999). The analysis made by Dare and Atkinson concluded there was a downward diffusion of higher momentum air aloft, and increased pressure gradient pushing downwind. Thir results showed no increase in upwind wind speed, largest winds speeds on the upwind side of the polynya, and increased winds downwind of the polynya, but not as large as over the polynya. Our analysis contradicts this. Our results show no difference between upwind and downwind winds. During the days where the polynya was open, they both average 8.5 m/s. Furthermore, our analysis shows that the upwind winds increased compared to wind speeds of years without polynyas.

3.7 Pressure

Sea level pressure is the last variable explored in this study. Sea level pressure seems to decrease over the extent of the polynya, most likely due to heating of the surface of the water. Timmerman et al. (1999) hint at the possibility of a formation of a thermal low, as they analyze the maintenance of polynyas in the Weddell Sea. As seen in Figure 9, the polynya obviously has a persistent low pressure system. The low pressure system is only present during the months where the polynya is present (August-November).

The existence of a persistent low pressure system over an open ocean polynya is most likely due to the generation of a thermal low. The large heat fluxes present over the polynya create deep thermal convective updrafts (Andreas and Cash 1999). The thermal convective updrafts are strong enough over the polynya to produce a persistent low because of the extreme temperature gradient between the open water and sea ice. As stated

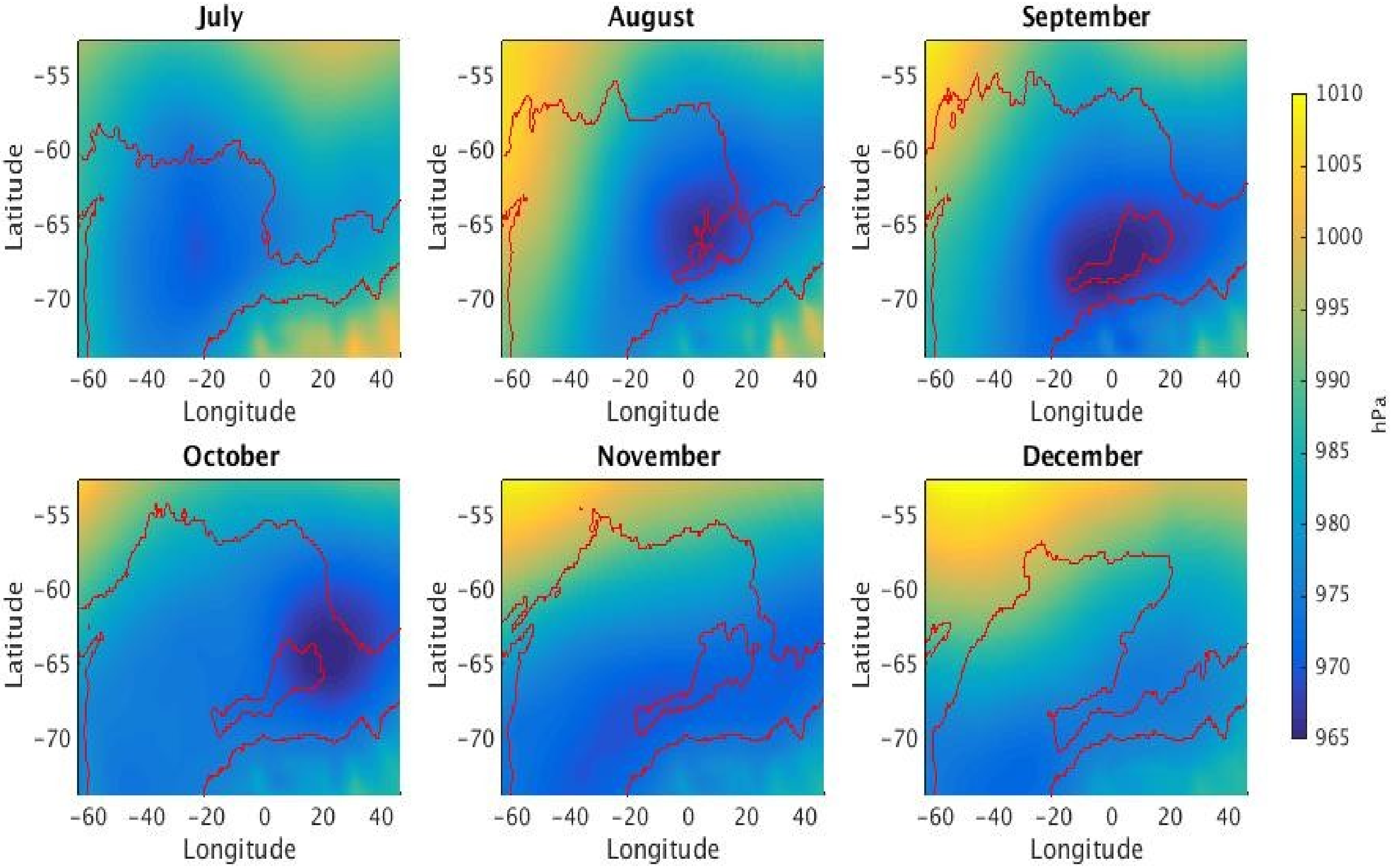

Figure 9: *Color plots of sea level pressure(PSL), measured in hPa, over the year 86 polynya during the months of July-December. Each month is the average sea level pressure for the entire month. The polynya is open this year from late August to early November. Red lines indicate sea ice extent to 15% ice fraction.*

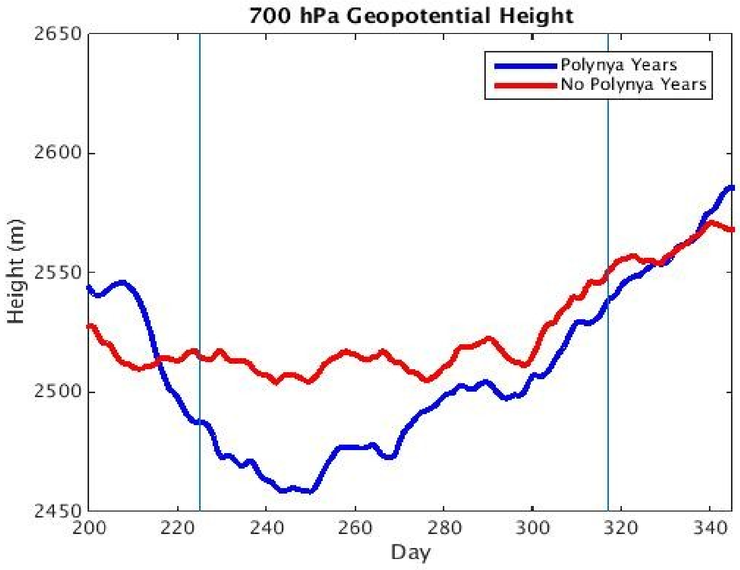

Figure 8: *Plot of 21 day centered mean 700 hPa geopotential height (Z700) for days 200-345 of years with polynya (84,85,86; blue) and without a polynya (63,64,65; red). Vertical blue lines indicate days polynya was present. Graph indicates geopotential heights for polynya years were lower, meaning pressure was also lower for these years.*

earlier in section 3.2, the temperature trace from the polynya can not be detected at the 850 hPa level, but the pressure level effects caused by the thermal low can be. Strong thermal lows can reach 500 mb affecting geostrophic flow aloft, but most extend to 700 hPa. Figure 8 shows the 700 hPa geopotential height daily centered averages for polynya years and nonpolynya years. As shown, the geopotential heights over the polynya are lower, indicating lower pressures over the polynya. The combination of lower sea level pressure and lower geopotential heights aloft indicate the presence of a thermal low.

4. Conclusion

The temperature and heat flux variables have been widely discussed before this study, and the findings of our analysis are in good agreement with many prior reports (Dare and Atkinson 1999;

Timmerman et al. 1999; Moore et al. 2002; Prasad et al. 2005). The surface temperature over the polynya was significantly higher than over the surrounding sea ice, and the temperature signal did not extend high into the atmosphere (lower than 850 hPa; Dare and Atkinson 1999). Sensible heat flux was stronger over the polynya than latent heat flux. Latent heat flux would be higher if there was more wind present to drive evaporation. Instead, conduction and convection are the primary catalysts of heat flux, which is why sensible heat flux is high.

The latent heat flux is lower than sensible, but still higher than normal during this time and higher than the surrounding sea ice. Therefore, the humidity increases over the polynya. Increased humidity and temperature forces increases in precipitation over the polynya. Increases are on the order of 2-3 mm/day of rain.

Longwave and shortwave downward flux increase over the polynya. The increase in humidity and longwave downwelling flux indicate the presence of clouds over the polynya. Clouds absorb and emit longwave radiation emitted by the Earth, so the presence of cloud would increase the downwelling flux. Shortwave downwelling flux increases because the open water absorbs more of the suns emitted shortwave radiation. The surrounding sea ice has a high albedo, which reflects the radiation. Even the clouds have a lower albedo, which means the clouds are overall a heating mechanism in the Antarctic by increasing both longwave and shortwave downwelling flux.

Lastly, surface pressure was shown to be lower over the polynya area than the same area in years without a polynya. This is due to the thermal convective updrafts produced by the warm open waters of the polynya. The warm convective updrafts create a thermal low that helps generate a persistent low pressure over the polynya. The thermal low can be detected all the way up to 700 hPa.

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