VERIFYING THE PATTERNS OF THE ANTARCTIC DIPOLE USING REANALYSIS DATA

An Undergraduate Research Scholars Thesis

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ABSTRACT

Verifying the Patterns of the Antarctic Dipole Using Reanalysis Data. (May 2015)

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The Antarctic Dipole (ADP) is a dipole-like pattern seen in various atmospheric and oceanic variables between the Atlantic and Pacific sectors of the Southern Ocean, respectively. It has been used to infer teleconnections between the Eastern Tropical Pacific (specifically to the El Niño-Southern Oscillation) and the Southern Ocean, but so far only one reanalysis has been utilized to study the ADP. Teleconnections have important implications for climate prediction and impacts. The goal of this research is to verify the previous results and conclusions achieved with the original reanalysis by examining two additional reanalyses using similar methods. Specifically, data from the original reanalysis (NCEP-NCAR's Reanalysis), as well as from the two additional reanalyses (ECMWF's ERA-Interim and NCEP-DOE's Reanalysis 2) has been used to investigate the regional Southern Ocean spatial anomaly pattern of five El Niño and five La Niña years, respectively, of four variables (Surface Air Temperature at 1000 millibars, Sea Ice Concentration, Sea Level Pressure, and Sea Surface Temperature). Additionally, regions representative of the Pacific and the Atlantic sector of the Southern Ocean were defined to create time series of the anomalies of each variable during the period 1980 to 2010 for each reanalysis. While the ADP pattern is overall consistent across all three reanalyses, the magnitude and spatial extent of the dipole varies considerably, and the time series reveal that not every year reproduces

the dipole pattern and that the sector and years defined for analysis lead to additional differences between the reanalyses. While the ADP is a dominant feature in the three reanalyses studied here, it reveals significant discrepancies among the reanalyses worth investigating in the future. This research suggests using multiple reanalyses to strengthen findings and statements on teleconnections and climate patterns.

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NOMENCLATURE

ACW	Antarctic Circumpolar Wave
ADP	Antarctic Dipole
AMIP	Atmospheric Model Intercomparison Project
CFSR	Climate Forecast System Reanalysis
ECMWF	European Center for Meteorological Weather Forecasting
ERA-40	ECMWF 40-yr Global Re-Analysis
ERA-Interim	ECMWF Interim Re-Analysis
ENSO	El Niño-Southern Oscillation
GCM	Global Circulation Model
JRA-25	Japan Meteorological Agency 25-year Reanalysis
MERRA	NASA Modern Era Retrospective-Analysis for Research and Application
NCEP-DOE	National Centers for Environmental Prediction – Department of Energy
NCEP-NCAR	National Centers for Environmental Prediction – National Center for Atmospheric Research
NCEP1	National Centers for Environmental Prediction – National Center for Atmospheric Research Reanalysis
NCEP-2	NCEP/U.S. Department of Energy Atmospheric Model Intercomparison Project 2
SAT	Surface Air Temperature
SIC	Sea Ice Concentration
SLP	Sea Level Pressure

SST	Sea Surface Temperature

CHAPTER I

INTRODUCTION

The Antarctic Dipole (ADP) is one of the many patterns discovered during the pursuit of interconnections between the tropical and the polar regions of the globe. Yuan and Martinson (2000) first stumbled upon the ADP while they were searching for connections between sea ice cover and tropical variables. After further research into their discovery, they found that this quasi-stationary wave was the source of dipole-like variations between the Atlantic and Pacific sectors of the Southern Ocean in both atmospheric and oceanic variables (Yuan and Martinson, 2001). One interesting finding was that this phenomenon appeared to be linked to two pre-existing patterns: the El Niño-Southern Oscillation (ENSO) and the Antarctic Circumpolar Wave (ACW).

The link between ENSO is a fairly simple one. A stationary Rossby wave driven by ENSO warming and cooling creates the dipole patterns for sea ice concentration (SIC), sea level pressure (SLP), and surface air temperature (SAT) (Yuan, 2004). Furthermore, an El Niño event's peak intensity in the northern hemisphere winter, for example, should affect the Antarctic region about six months later during the southern hemisphere winter, or northern hemisphere summer (Yuan and Martinson, 2000). The interconnection exhibited has important implications for predictability of atmospheric and oceanic variables in the Southern Ocean, and could lead to better forecasting of global climate patterns.

The connection to the ACW is less obvious. The ACW was defined in White and Peterson (1996) as a wave of SIC, SST, SLP, and wind pattern anomalies that propagates around the Southern Ocean from west to east. Both the ADP and the ACW exhibit fluctuating patterns, but it is unknown if and how one event causes the other. One possible case is the ADP generating fluctuations that are then propagated around the Southern Ocean as the ACW; therefore, knowing the patterns of the ADP gains importance (Yuan and Martinson, 2001).

To visualize the dipole patterns of the ADP and the link to ENSO, reanalysis data from NCEP-NCAR was used to create global anomaly maps of SAT, SIC, SLP, and SST, each averaged over five El Niño and five La Niña years (Yuan, 2004), respectively. These El Niño and La Niña year composites revealed the dipole patterns and the six-month lag between the tropical Pacific and the Southern Ocean around the Antarctic Peninsula. Yuan (2004) states that in Yuan and Martinson (2000) the NCEP-NCAR reanalysis data was enough to study the tropical-subpolar connections, and in practice this appears to be true.

Differences between reanalysis data, however, do exist, and this must be addressed. Bromwich et al. (2011) tested the consistency of five different reanalysis datasets (NCEP-2, JRA-25, ERA-Interim, MERRA, and CFSR) by examining precipitation and evaporation differences in the Southern Ocean. The Southern Ocean has always been a difficult area to model due to a lack of observational data. Without a solid base of observations to assimilate, the result is mostly model generated and thus lacks credibility. Time series of precipitation minus evaporation (P-E) revealed noticeable magnitude differences of seasonal variations. The differences were especially evident in the years after 2006 when ERA-Interim and CFSR dipped to negative values in P-E while the other three reanalysis datasets remained positive. Bromwich et al. (2011) note that some of the discrepancies among the various analyses come from the addition of new data over time.

Differences become an even bigger issue when trying to examine older data. Bromwich and Fogt (2004) examined how well ERA-40 and NCEP1 data from 1958 to 2001 matched up with observations. In order to fully grasp how well these datasets represent the real world, Bromwich and Fogt analyzed time series of reanalysis data versus observational data and of correlation values between them. The results are worrisome. Pre-1970 reanalysis data is significantly off from the observed data for both analyses, with some of the correlations dipping down into negative values (Bromwich and Fogt, 2004). After the 1970s the performances improve as new data is added, with ERA-40 performing better than NCEP1. In order to examine long-term climate trends, older data is a necessity, and with older reanalysis datasets performing so poorly one must exercise caution when using them.

Each reanalysis dataset has its own combination of resolution, number of vertical levels, observed and satellite-derived data, and assimilation system, which explains most of the differences between them (Bromwich et al., 2011). The problem with the reanalyses being so different is that any results based on just one reanalysis may come into question. In order to verify a climate pattern like the ADP, an investigation using multiple reanalyses is necessary and has been pursued in this study.

CHAPTER II

METHODS

In order to verify if the Antarctic Dipole's pattern is consistent in different reanalyses, the first step was to choose how to do so. Yuan (2004) chose to examine four variables for the existence of the dipole: SAT at the 1000-millibar level, SLP, SIC, and SST. Spatial anomaly patterns of these variables were created by taking the average of five significant El Niño years (1982-1983, 1986-1987, 1987-1988, 1991-1992, and 1997-1998) and five significant La Niña years (1984-1985, 1988-1989, 1995-1996, 1998-1999, 1999-2000) and then subtracting the mean of the whole time period, respectively. According to Yuan (2004), however, the length of the time periods used for each variable differed. Five seasons were examined in total: September-November (SON) of the first year, December-February (DJF) in transition to the next year, and finally March-May (MAM), June-August (JJA), and SON of the second year. The austral winter season – the northern hemisphere's summer, JJA – of the second year revealed the largest dipole pattern and thus this season was chosen to be investigated here. Instead of a global plot, however, a polar plot was created to focus on the Antarctic region. Further examination of the differences between the respective reanalyses was pursued by means of time series for each of the four variables over a period from 1980 to 2010. The time series display the anomalies averaged over a pre-defined region used to represent the Pacific and Atlantic sectors of the Southern Ocean. The time series also include markers for the El Niño and La Niña years defined above and a zero-anomaly line. The significance of the selected years for the spatial anomaly plots will be examined by averaging them and comparing the values between the reanalyses.

The first reanalysis data chosen for examination was similar to what Yuan (2004) used: SAT (at the 1000 millibar level) and SLP from the National Centers for Environmental Prediction and the National Center for Atmospheric Research's (NCEP-NCAR) first reanalysis (called Reanalysis 1 here), and SST from Reynolds & Smith (1994) NOAA Optimum Interpolation (OI) Sea Surface Temperature (SST) V2. One key difference was that Yuan used SIC data from the National Snow & Ice Data Center while this study used the SIC from Reanalysis 1. Since the goal of this research was to determine the consistency across the reanalyses, the decision was made to gather as many of the variables directly from the reanalysis itself as possible. SST was the one exception due to the lack of said data in Reanalysis 1. Another detail to note is that Yuan (2004) never specified which version of Reynolds & Smith was used, so it was decided that the most recent version of the same product would be acceptable.

The second data source chosen was the European Center for Medium-range Weather Forecasting's Interim Re-Analysis (ERA-Interim). All four variables were available in this reanalysis, so no outside sources were required. This source is called Reanalysis 3 from this point onwards.

The final data source proved to be more difficult. The original plan was to use NASA's Modern Era Retrospective-analysis for Research and Application (MERRA) reanalysis data, but problems arose. Data for SST was not provided in MERRA and an outside source could not be determined, so a full comparison to the other two reanalyses could not be made. The decision was made to choose another reanalysis. The National Centers for Environmental Prediction and the Department of Energy (NCEP-DOE) created an updated version of Reanalysis 1, called

Reanalysis 2 in this study, with, e.g., improved boundary conditions such as SST and SIC (Kanamitsu et. al., 2002). As with Reanalysis 1, SAT at 1000-millibars, SIC, and SLP were pulled directly from the reanalysis. Sea surface temperature, however, was once again not an available product. To determine what to use for this variable, research was done to discover why Yuan chose Reynolds & Smith for SST. Kalnay et.al. (1996) explain that Reynolds & Smith was used as a SST boundary condition in Reanalysis 1, so Kanamitsu et.al. (2002) was referenced to find the source of Reanalysis 2's SST boundary condition. The paper stated that Atmospheric Model Intercomparison Project II's (AMIP II) sea surface temperature data was used, thus this source was utilized to represent SST for Reanalysis 2.

All reanalysis data was collected from each agency's respective websites. The one exception was the AMIP II data, which was available at its own location. All were collected as netCDF data. Links to each will be provided in the Appendix.

With all the data collected and a goal in mind, the next step was to manipulate the reanalysis data into a physically understandable form. In research done in the previous spring semester, Climate Data Operators (CDO) were discovered as a valuable tool for editing the netCDF data. The operators were thus utilized to extract the anomalies of each year's austral winter and to create the spatial averages and the time series. The CDO-manipulated data was visualized using Python programming. Basemap was used to generate the polar plots, and matplotlib was utilized to create the time series.

CHAPTER III

RESULTS

Spatial Anomaly Averages

The defining characteristic of the ADP is the dipole pattern witnessed between the Atlantic and Pacific sectors of the Southern Ocean. Without this clear pattern, one cannot prove the presence of the ADP. Therefore, the positive and negative ENSO spatial anomaly patterns for each of the four variables are presented as regional Southern Ocean polar projections.

In Figure 1 the plots for SAT are given. The first pair – NCEP-NCAR's Reanalysis 1 – mirror those created originally in Yuan (2004) and are thus acceptable for comparison to the two new reanalyses (This mirror pattern holds true for the other three variables, so all are acceptable for comparison.) The second pair – NCEP-DOE's Reanalysis 2 – displays the same general dipole pattern as Reanalysis 1 but does not mirror it exactly. Reanalysis 1 on the whole has larger dipole magnitudes than Reanalysis 2. The exact differences between maxima and minima SAT anomalies for a region defined from 55S to 90S and from 160W to the Prime Meridian are displayed in Table 1 (the same area is used for the rest of the variables). The spatial extent differs too, with Reanalysis 2 missing a third area of maximum anomaly in the Pacific region and

Table 1. Differences between maximum/minimum SAT anomalies.

	El Niño - Pacific	El Niño - Atlantic	La Niña - Pacific	La Niña - Atlantic
Reanalysis 2 minus Reanalysis 1	-0.913°	-0.931°	+1.642°	-1.105°
Reanalysis 3 minus Reanalysis 1	-0.498°	+0.353°	+2.999°	-0.490°

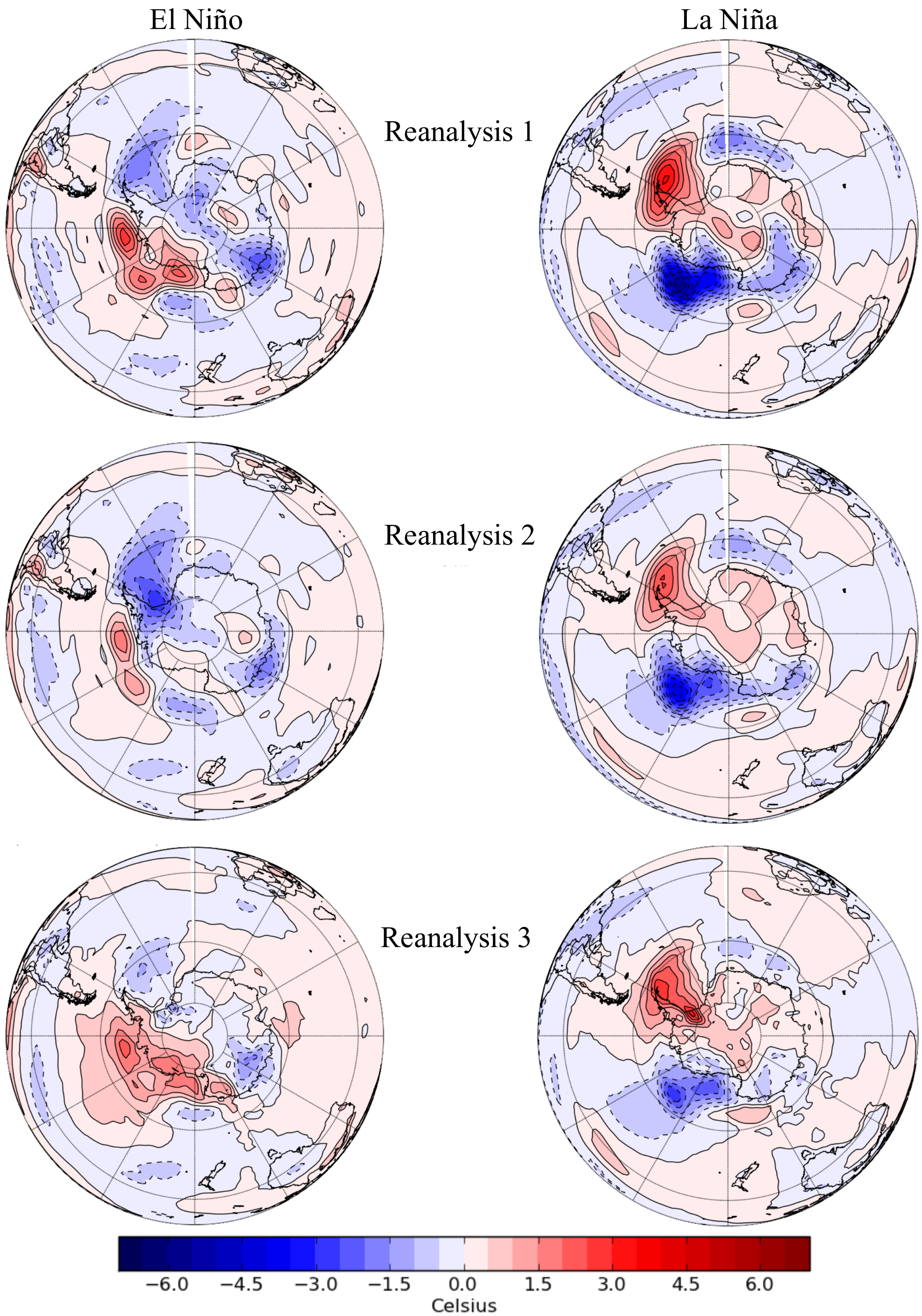

Figure 1. Polar projections of SAT spatial anomaly patterns. Top panels: Reanalysis 1, middle panels: Reanalysis 2, bottom panels: Reanalysis 3. The El Niño (1983, 1987, 1988, 1992, 1998) anomalies are plotted on the left. The La Niña (1985, 1989, 1996, 1999, 2000) anomalies are plotted on the right.

adding a minimum anomaly region near the Weddell Sea coastline in the Atlantic region. The La Niña phase displays a similar magnitude difference, but spatially the two reanalyses are fairly consistent. The third pair – ECMWF's ERA-Interim (Reanalysis 3) – seem to have even weaker El Niño anomalies than Reanalysis 2, but the differences shown in Table 1 are not as large and suggest that Reanalysis 3 is actually closer to Reanalysis 1's values. The spatial extent, therefore, gives the illusion of greater difference with the much smaller area of negative anomaly in the Atlantic region and more spread out positive anomalies in the Pacific region. The La Niña phase is consistent between the two spatially, but the magnitudes vary, especially in the Atlantic.

Figure 2 contains the spatial anomaly patterns for SIC. As expected the maximum and minimum anomalies are mainly contained in the areas where ice concentrations varies the most: along the edge of the ice pack. It is hard to tell initially that there are any differences between Reanalysis 1 and Reanalysis 2. Calculations of the differences in Table 2, however, reveal that there are differences and that some of them are significant, especially during El Niño in the Pacific region. Spatially there is a slight difference in the clustering of maximum/minimum anomalies, but they all lie within the same general location in both regions for each ENSO phase. There is a change in sign for the waters beyond the ice pack, but it is small enough that it is not seen as significant. The Reanalysis 3 plots again display overall weaker values for magnitude in Table 2, and the

Table 2. Differences between maximum/minimum SIC anomalies.

	El Niño - Pacific	El Niño - Atlantic	La Niña - Pacific	La Niña - Atlantic
Reanalysis 2 minus Reanalysis 1	+6.057%	-0.649%	-3.868%	+1.098%
Reanalysis 3 minus Reanalysis 1	+12.694%	-3.214%	-3.352%	+8.478%

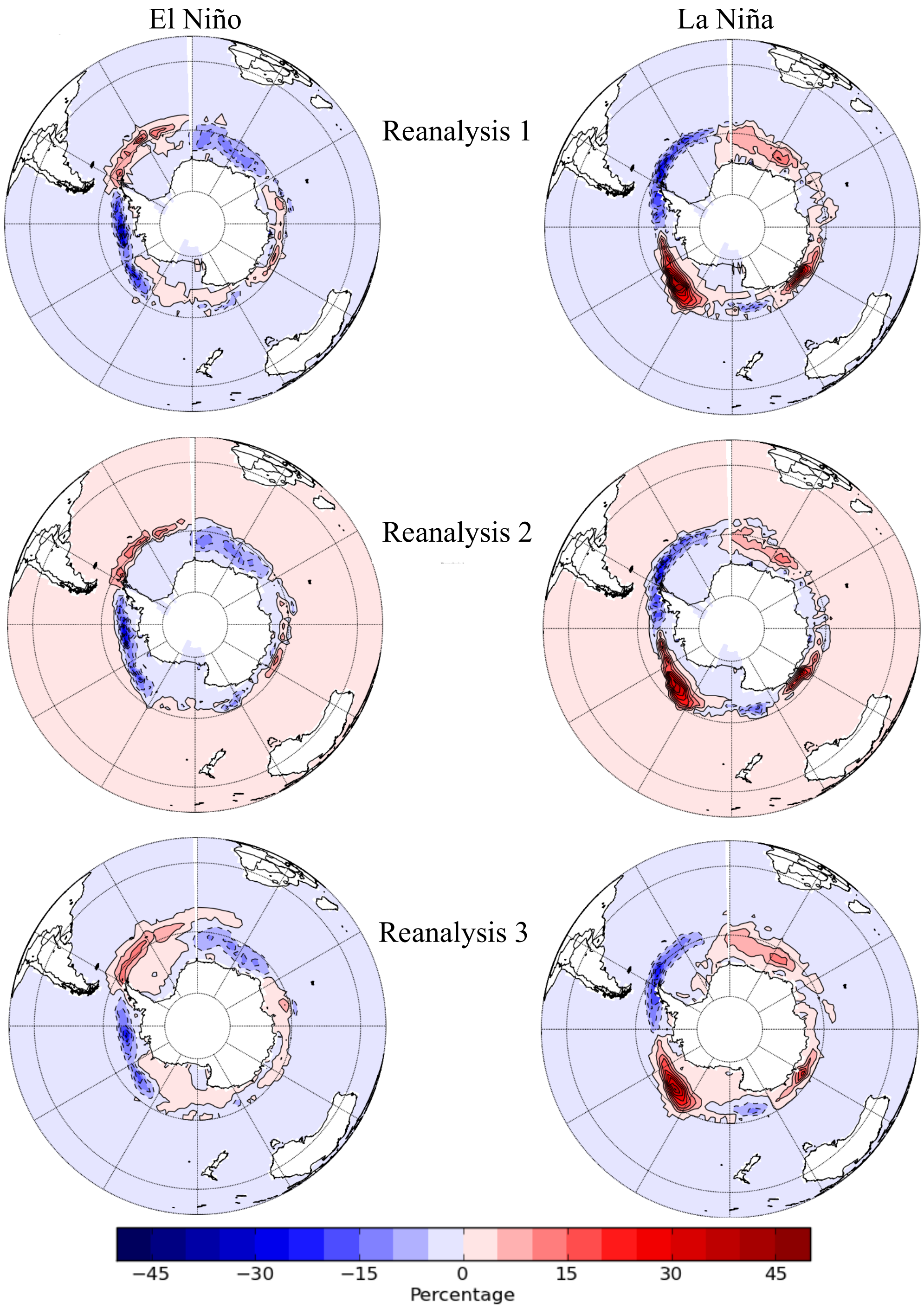

Figure 2. Polar projections of SIC spatial anomaly averages. Same format as Figure 1.

plots in Figure 2 show more variation in spatial extent. The variations, however, are mainly seen for the smaller anomalies; the larger anomalies are still contained in an area similar to Reanalysis 1.

Figure 3 contains the spatial anomaly patterns for SLP. Although the high- and low-pressure anomalies still display a dipole pattern they are not confined to the pre-defined Atlantic and Pacific sectors. For this reason Table 3 focuses on the high and low areas themselves as opposed to the previous tables' focus on Atlantic and Pacific regions. The magnitude of Reanalysis 1 and Reanalysis 2's respective positive and negative anomalies are similar for the El Niño low and the La Niña high, but vary more for the El Niño high and the La Niña low. The El Niño high especially seems to be more variable in both magnitude and in spatial extent. The high-pressure anomaly of Reanalysis 1 is more concentrated over the western side of the Antarctic Peninsula and curves along the coast, while the anomaly of Reanalysis 2 has its higher magnitude values at the base of the peninsula. Comparison to Reanalysis 3 reveals a similar pattern for the magnitudes (save for the El Niño low which has a much larger difference), right down to the El Niño high pressure being the outlier in similarity. The spatial extent, however, changes more between them. The low-pressure anomaly for El Niño stretches northeastward into the Atlantic region and drastically shrinks the area of the high-pressure anomaly there. The center of high-

Table 3. Differences between maximum/minimum SLP anomalies.

	El Niño - Low	El Niño - High	La Niña - Low	La Niña - High
Reanalysis 2 minus Reanalysis 1	+0.014 mb	-0.932 mb	+0.637 mb	-0.019 mb
Reanalysis 3 minus Reanalysis 1	-0.314 mb	-1.964 mb	-0.172 mb	+0.063 mb

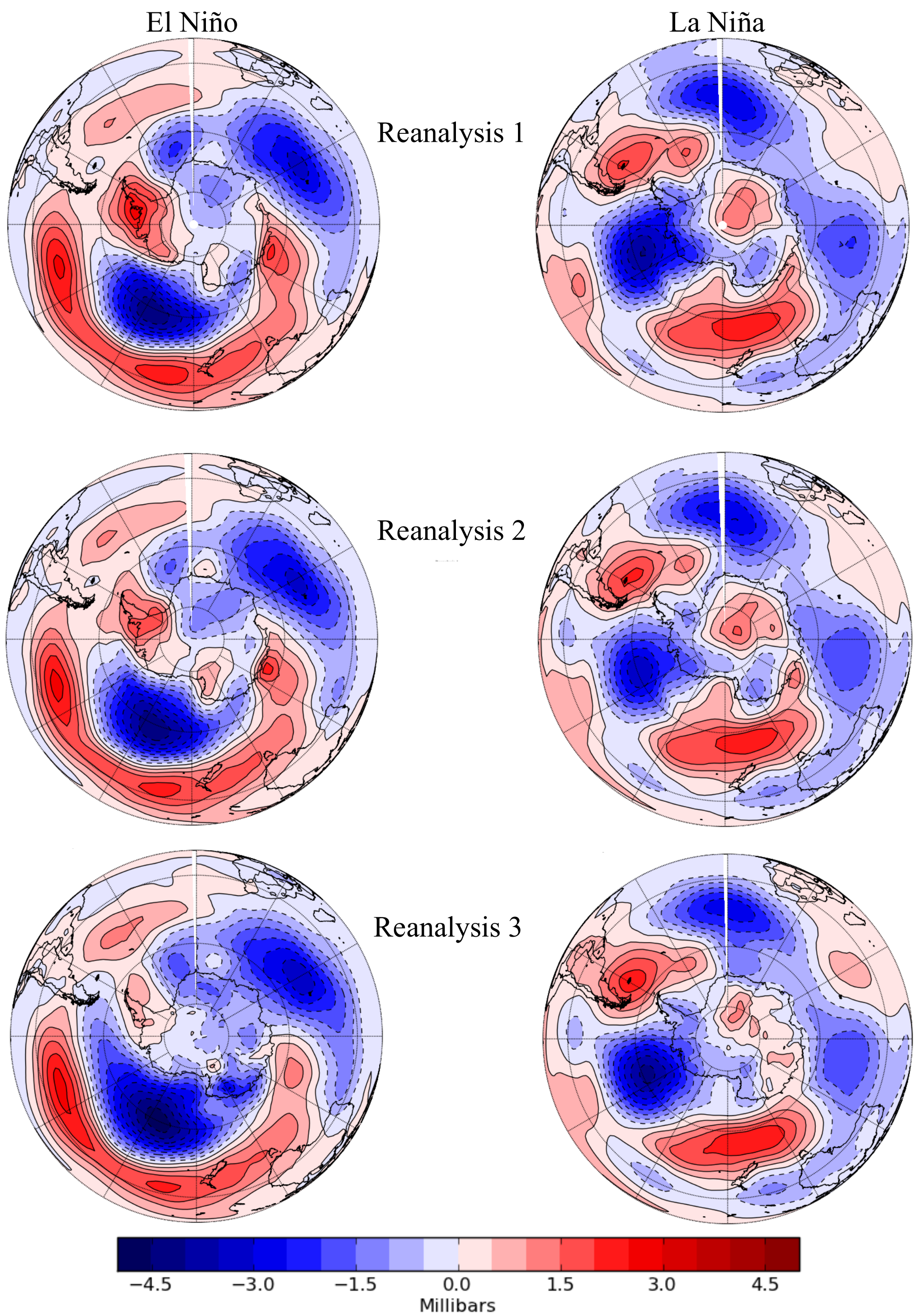

Figure 3. Polar projections of SLP spatial anomaly averages. Same format as Figure 1.

pressure anomaly in the eastern Atlantic in Reanalysis 1 is also diminished in Reanalysis 3.

Figure 4 contains the spatial anomaly patterns for the final variable, SST. Of the four variables presented, SST appears to be the most unchanging between the three reanalyses when first examined. Table 4, however, illustrates that for the magnitudes differences still exist. One important fact to keep in mind is that the heat capacity for water is much larger than that of air. A change of even one degree in SST can represent a significant uptake of heat, so although the differences in Table 4 are small they are still noteworthy. An interesting result is how Reanalysis 2 and Reanalysis 1's smallest difference is for the Atlantic El Niño phase, but the same area and phase have the largest difference for the Reanalysis 3 and Reanalysis 1 comparison. The spatial extent is mostly consistent, except for a few areas. One is the Ross Sea. Reanalysis 1 has a small portion of positive SST anomaly in the sea during El Niño – Reanalysis 2 has the same feature – but Reanalysis 3 has the area completely filled with negative SST anomaly. The La Niña composite has the same pattern, but now Reanalysis 3 has the area filled in completely with positive SST anomaly. Reanalysis 3 is the only reanalysis of the three to switch the sign of the anomaly in the Ross Sea depending on the ENSO phase.

All four variables have been presented, and all four display the dipole pattern originally seen in

Table 4. Differences between maximum/minimum SST anomalies.

	El Niño - Pacific	El Niño - Atlantic	La Niña - Pacific	La Niña - Atlantic
Reanalysis 2 minus Reanalysis 1	-0.114°	+0.085°	-0.086°	+0.109°
Reanalysis 3 minus Reanalysis 1	-0.137°	+0.379°	-0.065°	+0.147°

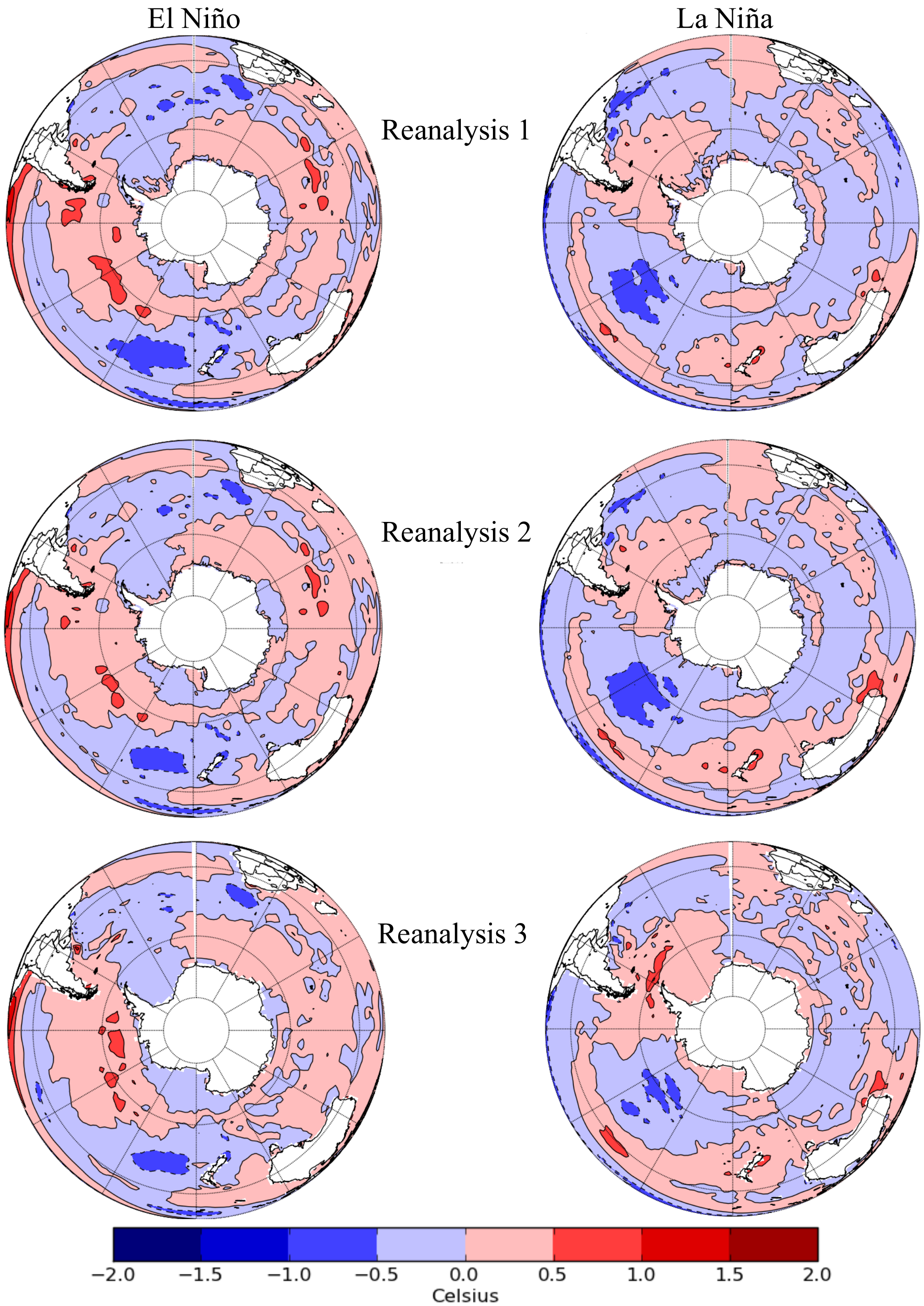

Figure 4. Polar composite plots for SLP. Same format as Figure 1.

Yuan (2004). Moreover the dipole pattern flips based on whether the year is in the El Niño or La Niña phase of ENSO. This pattern was expected for Reanalysis 1, but now there is confirmation that the same pattern exists in Reanalysis 2 and in Reanalysis 3.

Time Series

As seen in the spatial anomaly pattern plots, the dipole is consistent across all three reanalyses. The El Niño and La Niña averages also revealed that despite this consistency there are considerable differences in magnitude and spatial extent of the anomalies. These differences, however, can be even larger when the analysis parameters are narrowed further.

To show this, specific areas were chosen to represent the Atlantic and Pacific sectors of the Southern Ocean. The Atlantic region was defined from 70W to 30E and from 60S to 80S. The Pacific region was defined from 160E to 70W and from 60S to 80S. In physical terms, the Atlantic box ranges from the Drake Passage in the west to the edge of the Weddell Sea in the east. The Pacific box ranges from the Drake Passage in the east to the edge of the Ross Sea in the west. The east to west dimensions were chosen to capture as much of the dipole pattern seen in Yuan (2004) as possible for all four variables. The north to south dimensions were influenced by the SIC data: any farther north than 60S would have included too many zero values and skewed the data, and any farther south than 80S would have included missing value data from land. Since the goal was to keep as much consistency across the four variables as possible, the north to south constraint was kept the same for both boxes.

Figure 5 contains the three time series for SAT. In these time series, a dipole is present when the

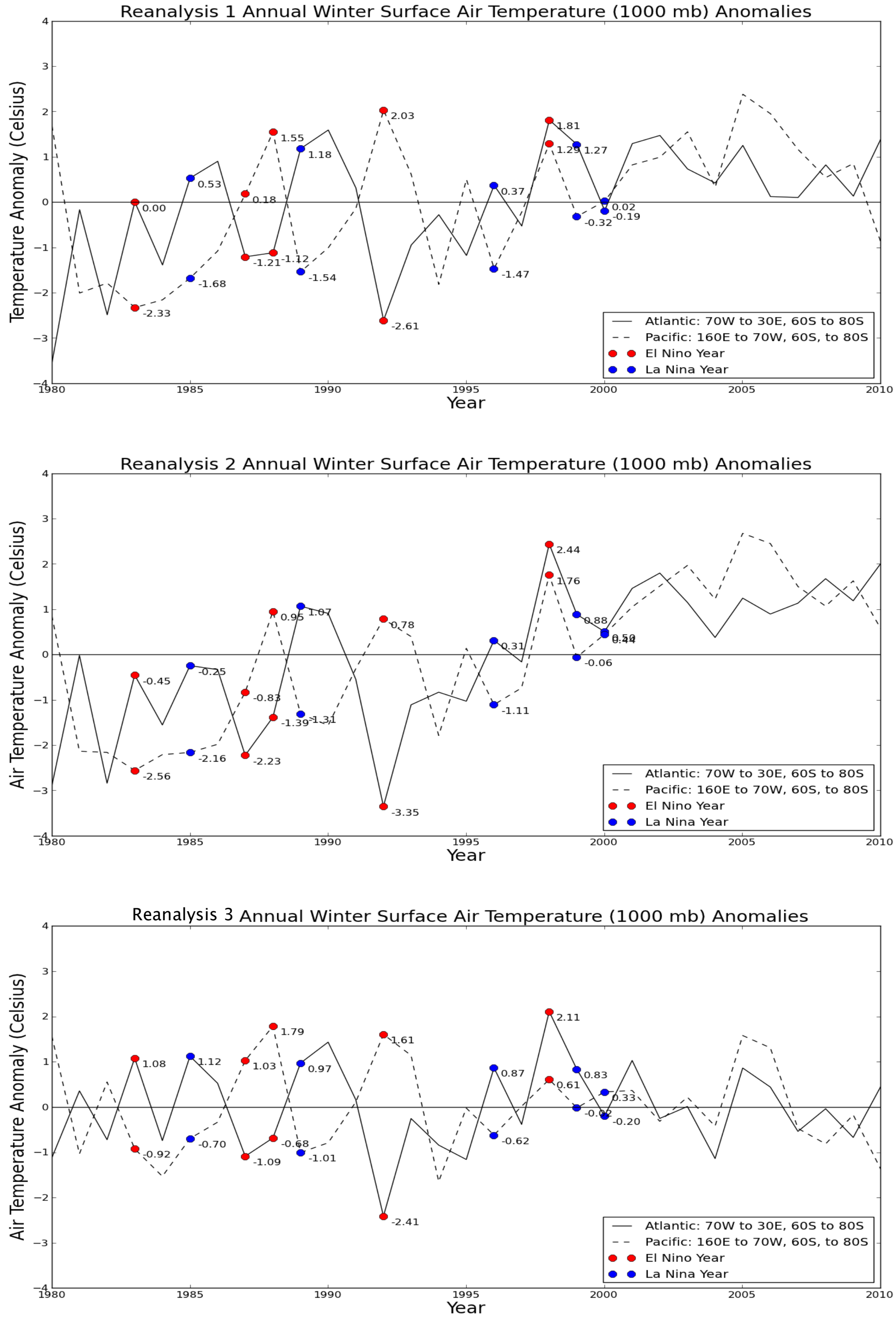

Figure 5. Time series from 1980 to 2010 for annual SAT anomaly. Top panel: Reanalysis 1, middle panel: Reanalysis 2, bottom panel: Reanalysis 3.

Pacific and Atlantic lines are on opposite sides of the zero-anomaly line. With the criteria in mind, a dipole like pattern appears to be present for each of the reanalyses, but it is not consistent across the three. The dipole pattern between the Atlantic and the Pacific sectors also does not span the entire 30-year time period. All three reanalyses have a portion of the dipole present during the late 1980s and into the mid-1990s. All three actually have a dipole present for 1980, but only Reanalysis 3 has the pattern continue from there to the late 1990s. There is clearly a difference in the consistency of the dipole for all three reanalyses, but the most interesting feature to take note of is the differences in magnitude. To highlight how important these differences are, the anomalies of the respective El Niño and La Niña years are averaged in Table 5.

Table 5. SAT anomaly averages of El Niño/La Niña Years for the Atlantic and Pacific boxes.

	Reanalysis 1	Reanalysis 2	Reanalysis 3
Atlantic El Niño Total	-0.626 °C	-0.996 °C	-0.198 °C
Atlantic La Niña Total	+0.632 °C	+0.502 °C	+0.718 °C
Pacific El Niño Total	+0.544 °C	+0.020 °C	+0.824 °C
Pacific La Niña Total	-0.998 °C	-0.840 °C	-0.404 °C

The totals vary amongst the reanalyses, but they still display the overall dipole pattern expected. It is important to note that some of the anomaly averages are close to zero; if any of the anomalies in the individual El Niño and La Niña years had been significantly higher or lower, they could have impacted the final average and upset the dipole pattern.

Figure 6 shows the time series for SIC. Reanalysis 1 and Reanalysis 2 don't have many dipole years present. Reanalysis 3 is the only one of the three to show some consistent dipole pattern

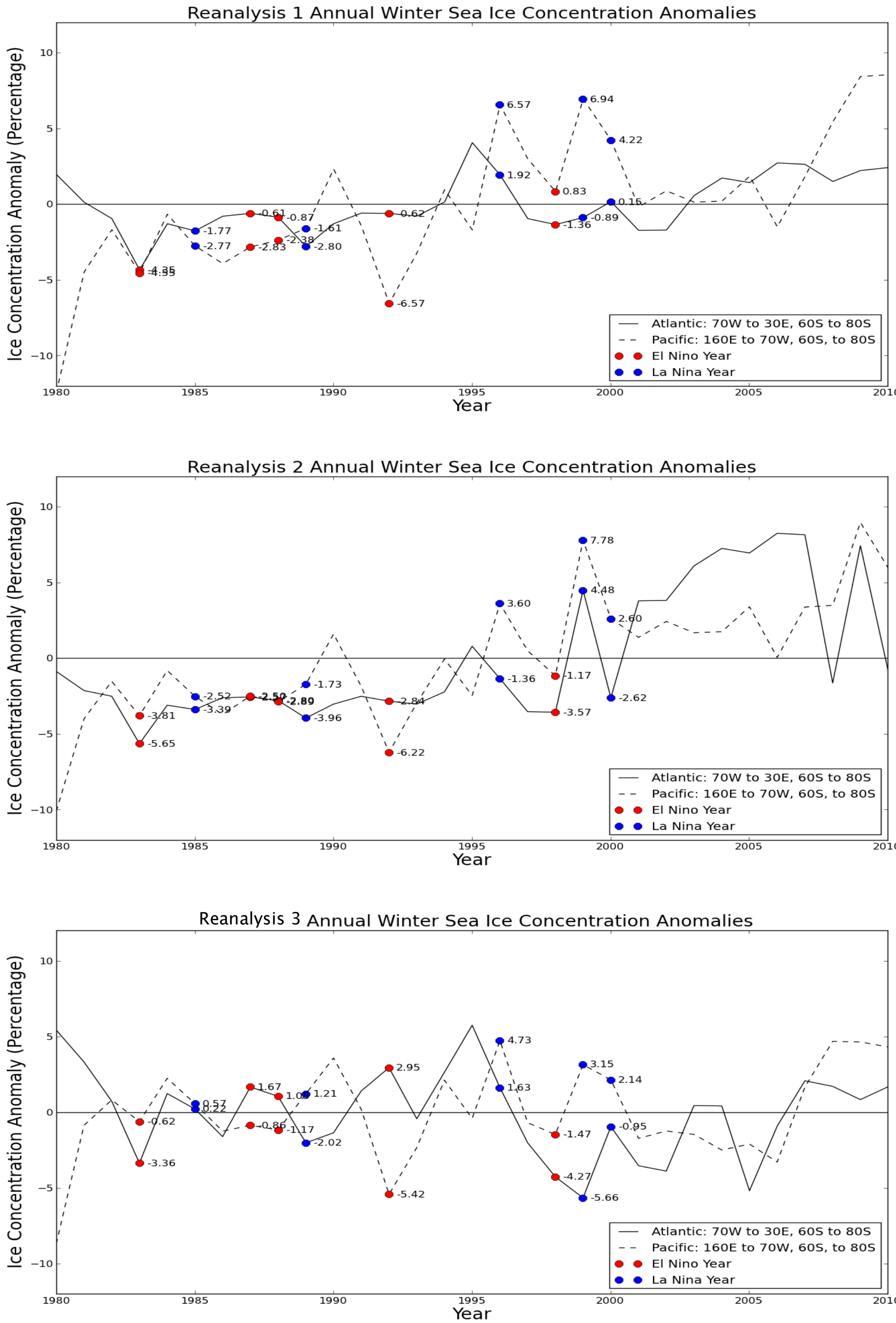

Figure 6. Time series from 1980 to 2010 for annual SIC anomaly. Same format as Figure 5.

from the mid-1980s through the early 1990s. A first glance at the time series shows significant magnitude differences over time, especially in the 21st century. Just like for the SAT time series, these differences have an impact when the El Niño and La Niña years are added together. The results are shown in Table 6.

Table 6. SIC anomaly averages of El Niño/La Niña Years for the Atlantic and Pacific boxes.

	Reanalysis 1	Reanalysis 2	Reanalysis 3
Atlantic El Niño Total	-1.562 %	-3.490 %	-0.392 %
Atlantic La Niña Total	-0.678 %	-1.370 %	-1.356 %
Pacific El Niño Total	-3.100 %	-3.318 %	-1.908 %
Pacific La Niña Total	+2.670 %	+1.946 %	+2.360 %

The most striking result is the totals for the Atlantic El Niño anomalies. Following the ADP concept, one would expect to see positive anomalies for ice concentration in the Atlantic during El Niño. The values for all three reanalyses, however, are negative. This is where the size and/or location of the selected box area play an important role. The defined Atlantic box actually reaches farther east of where the positive anomalies extended, and in doing so, negative anomaly values get mixed into the total and skew the results. A portion of the positive anomaly also lies north of the defined box and also likely plays a noticeable role in the results seen. The rest of the data acts as expected, even the Atlantic La Niña totals, which use the exact same box as the El Niño totals. The values are also still different among the reanalyses, sometimes varying by nearly 10%.

Figure 7 contains the time series for SLP. As with SIC there is no definite span of years that displays the dipole pattern. Most of the years that do are interspersed and have at least one year

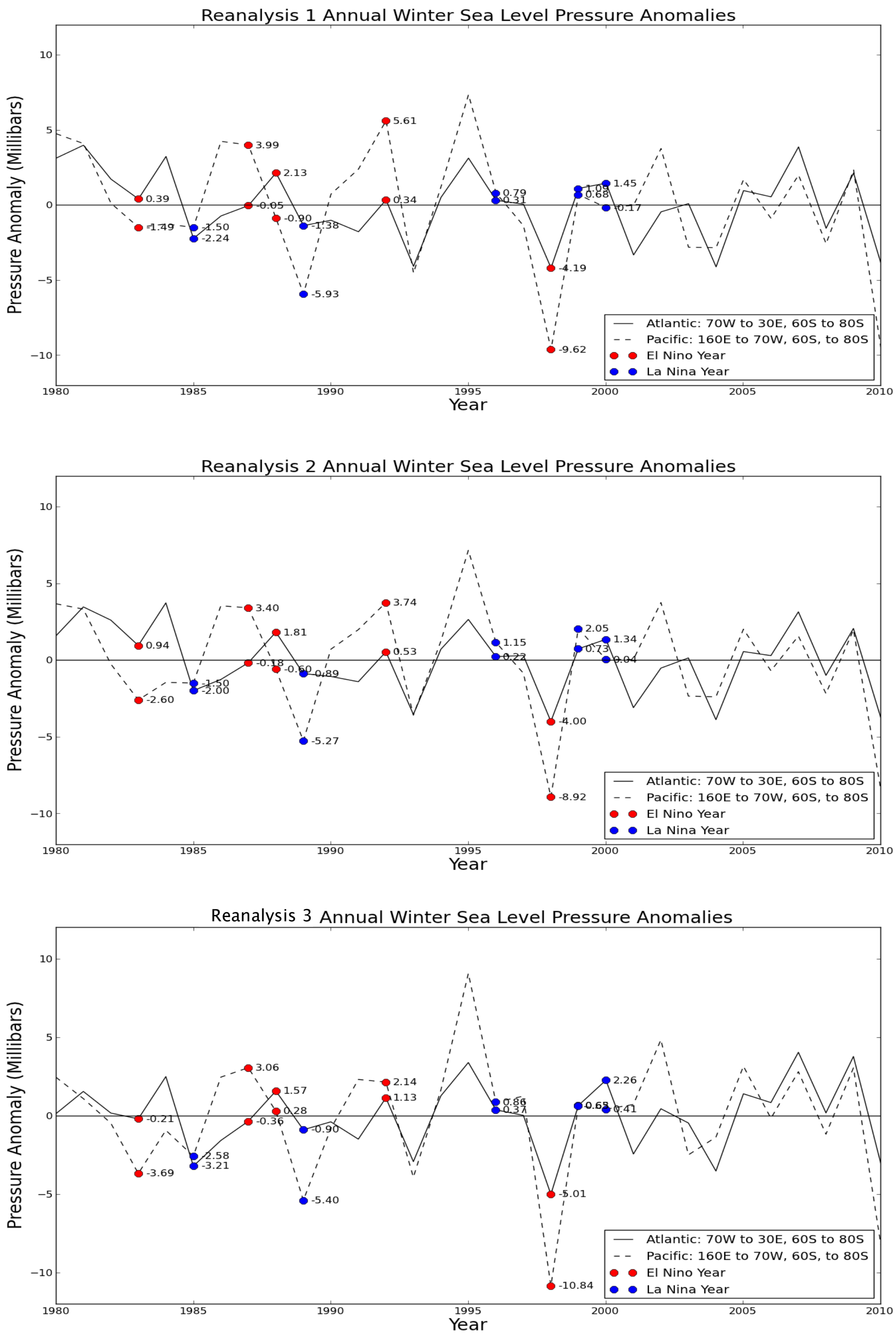

Figure 7. Time series from 1980 to 2010 for annual SLP anomaly. Same format as Figure 5.

without a dipole present between them. The overall pattern of the time series match more closely between the three reanalyses, at least in terms of the shapes of the lines. Magnitude, however, is another story. There are multiple areas where the magnitudes differ by 2 millibars or more for a specific year. Even years with smaller differences can lead to larger impacts when averaged.

Table 7. SLP anomaly averages of El Niño/La Niña Years for the Atlantic and Pacific boxes.

	Reanalysis 1	Reanalysis 2	Reanalysis 3
Atlantic El Niño Total	-0.276 mb	-0.180 mb	-0.576 mb
Atlantic La Niña Total	-0.154 mb	-0.120 mb	-0.166 mb
Pacific El Niño Total	-0.482 mb	-0.996 mb	-1.810 mb
Pacific La Niña Total	-1.226 mb	-0.706 mb	-1.212 mb

According to Table 7 there is no apparent dipole effect present in either box or ENSO phase. The anomaly totals come back as all negative, but there is a reason for this: the areas of maximum high- and low-pressure anomalies are not exactly within the Atlantic and Pacific sectors of the Southern Ocean. The values themselves vary substantially amongst the reanalyses once again.

The time series for SST are displayed in Figure 8, and Table 8 has the magnitude differences. The dipole pattern has gradually been dropping off relative to SAT, and now it is even harder

Table 8. Total SST anomaly of all El Niño/La Niña Years for the Atlantic and Pacific boxes.

	Reanalysis 1	Reanalysis 2	Reanalysis 3
Atlantic El Niño Total	+0.032 °C	+0.016 °C	+0.026 °C
Atlantic La Niña Total	+0.022 °C	+0.024 °C	+0.040 °C
Pacific El Niño Total	+0.060 °C	+0.106 °C	+0.146 °C
Pacific La Niña Total	-0.022 °C	-0.076 °C	-0.066 °C

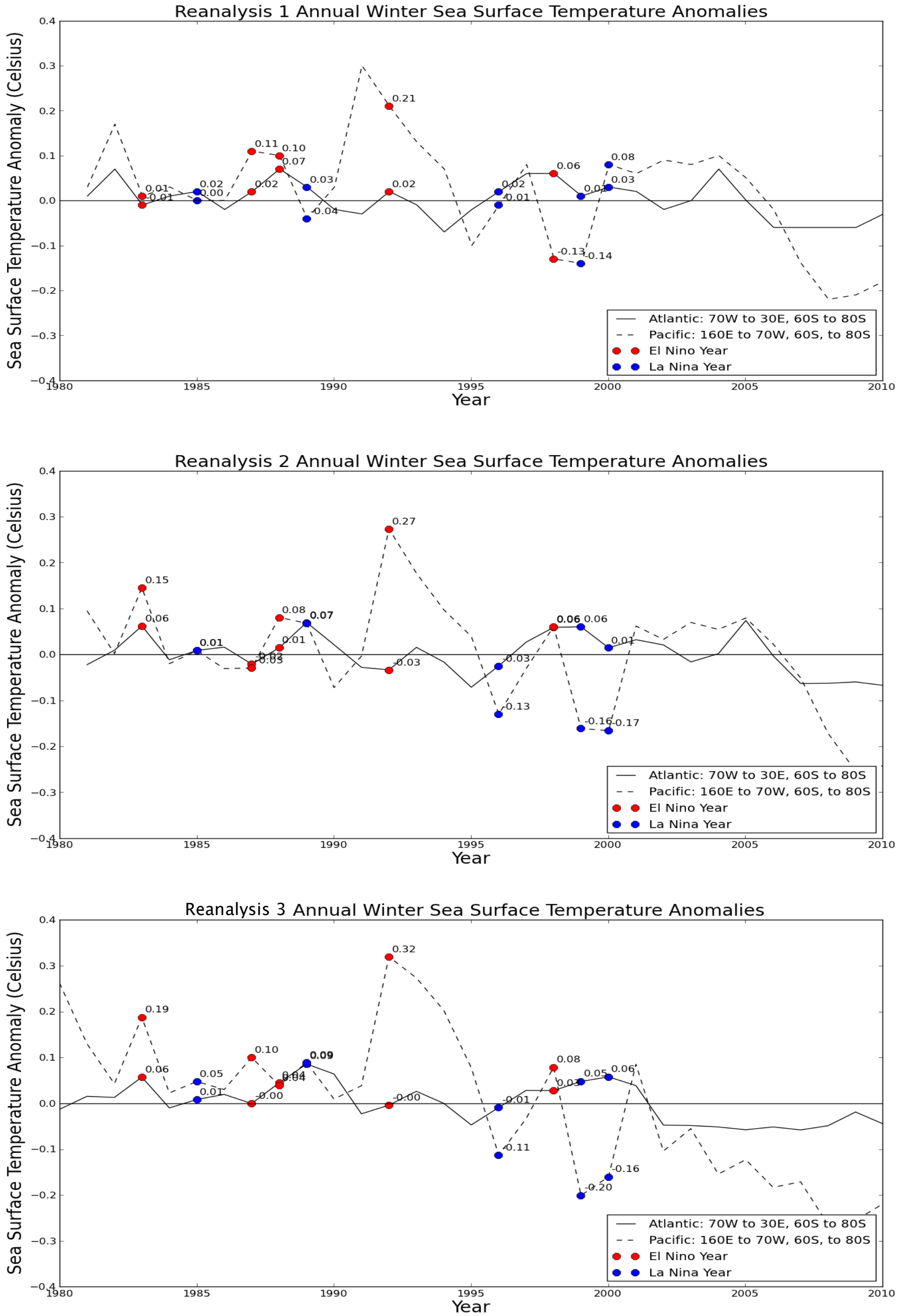

Figure 8. Time series from 1980 to 2010 for annual SST anomaly. Same format as Figure 5.

to distinguish the dipole for SST. Differences in the times series lines are the most apparent in the 21st century, a recurring theme in these variables that is interesting to note. The magnitude values for the Atlantic box in both phases of ENSO are all the same sign, replicating a similar result seen earlier for SIC and SLP. The Pacific box acts as expected with the positive anomalies appearing during El Niño and negative anomalies during La Niña, but the magnitudes vary more between the reanalyses than in the Atlantic. The Pacific box values are also larger overall than the Atlantic box's. This is most likely due to the higher peak values seen in that region.

On the whole, the three reanalyses vary consistently in terms of magnitude. The dipole pattern is most pronounced for SAT and least so for SLP. It is important to remember, however, that these results are only valid for the defined Atlantic and Pacific boxes and for the specific years chosen. If different box locations (or sizes) and a different set of years (or number of years) had been chosen, the outcome may have been different.

CHAPTER IV

CONCLUSIONS

The original intent of this research was to see if the overall pattern of the ADP – the dipole-like conditions seen between the Atlantic and Pacific sectors of the Southern Ocean in response to ENSO – that was originally detected by Yuan and Martinson (2000, 2001) and Yuan (2004) exists in other reanalyses. Using two additional reanalyses this study showed that the pattern is indeed present across all three reanalyses.

Analysis of the spatial anomaly pattern, however, reveals that there are considerable differences in the spatial extent and magnitude of the dipole between the three reanalyses. The spatial anomaly patterns of SAT and SLP display the most notable spatial and strength differences of the four variables. The reason for this is likely because these two variables are direct products of the reanalyses. The SIC and SST variables, although offered as data from the reanalyses, are in fact boundary conditions for the assimilated atmospheric global circulation model (GCM) simulation that the reanalyses are based on, and are thus not affected by the simulation. As such, differences in SIC and SST are mostly due to differences in the observational data, while differences in SAT and SLP are due to differences in the GCM and in the assimilation scheme being used for the reanalyses.

Another point of discussion is the offset nature of the positive and negative anomalies for SLP. The locations of the peak anomalies do not coincide with the chosen Atlantic and Pacific regions of the Southern Ocean; the high anomaly centered right over the Drake Passage during the El

Niño phase is one example. This offset, however, is consistent with the results seen for SAT and SIC and is expected for the region. Areas of high pressure (positive anomaly) in the southern hemisphere spin counterclockwise, so the high-pressure anomaly over the Drake Passage for El Niño would be promoting onshore winds to its west and offshore winds to its east. The onshore (offshore) winds would bring in warmer (colder) air and so are consistent with the areas of increased (decreased) SAT and decreased (increased) SIC in the Pacific (Atlantic) sector. The offset of the anomalies is therefore natural. The consequences of this offset in relation to the dipole pattern will be explored more in the discussion of the time series.

The time series, while not originally planned to be a major component of this study, revealed arguably the most important conclusions. The first key to why the time series were important comes from how they were made. The areas defined to be the Atlantic and Pacific boxes were created to broadly cover the dipole pattern found in Yuan (2004). Choosing these set regions inadvertently affected some of the variables more than others. For example, while SAT displayed a roughly ten-year period where the dipole was consistently present this was not the case for the other three variables. Looking back at the spatial anomaly patterns, one can see why: areas contributing to the dipole were simply cut off. Variables that had their anomalies extending farther north than 60°S, such as SIC and SLP, missed out on significant data that would have better represented the dipole. The east-west size of the boxes also may have included extraneous data that affected the final numbers. Additionally, the boundary between the Atlantic and Pacific boxes at the Drake Passage misappropriated sections of the anomalies between the sectors. The high-pressure region exhibited during El Niño discussed before is one example of this issue. The time series revealed that the defined area of analysis has a very important effect on the results seen and, if not taken into proper consideration, can adversely affect the outcome. Redefining the boxes to further visualize their impact could be a future area of study, along with exploring other ways besides boxes to define the areas of analysis for the dipole.

The second key to why the time series were important came from the highlighted years. Originally, the years used in the spatial anomaly patterns were marked just to point them out, but after replicating the averaging process with the exact numbers they revealed another important conclusion: the years chosen can affect the results. The years marked were the same ones used by Yuan (2004) and this specific combination only showed a consistent dipole pattern for both ENSO phases for SAT. When the numbers were added for the other three variables, either one or both phases did not represent the expected dipole. If a different combination of years had been chosen, the dipole may have been represented across the four variables differently. The years used here were chosen because they were years of significant El Niño and La Niña events. The choice of these years makes one wonder how the results would have changed if a different combination of El Niño and La Niña years, respectively, were chosen, and could be an area of future study.

These two aspects – the years chosen and the areas defined – become even more important when brought back to the original purpose of this research: to see if there are differences between reanalyses. The spatial anomaly patterns already showed that the results can vary considerably depending on which reanalysis is used. By changing the specified area for the Pacific and Atlantic sectors or changing the years for the El Niño and La Niña averages, the differences in the representation of the dipole may become larger or smaller. The finer tuned the analysis is, the more pronounced and distinct the dipole can become. This research therefore suggests that future studies should incorporate multiple sources of data and analysis methods to further support the robustness of the Antarctic Dipole.

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APPENDIX

Webpage for Reanalysis 1 data:

http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html

Webpage for Reynolds & Smith SST data:

http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html

Webpage for Reanalysis 2 data:

http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html

Webpage for AMIP II data:

http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS/amipobs_dwnld.php

Webpage for Reanalysis 3 data:

http://apps.ecmwf.int/datasets/data/interim_full_moda/