Abstract

Anthropogenic climate change has been a widely studied and often discussed phenomenon within the context of global mean temperature. However, changes in precipitation have not been rigorously observed or formally attributed to human influence. Changes in precipitation due to global warming can vary quite a bit on a local and regional level and thus can be very complicated to study. This study chose the National Centers for Environmental Prediction and National Center for Atmospheric Research's Reanalysis II model generated dataset and the Climate Prediction Center's Merged Analysis of Precipitation observational dataset to study precipitation across the globe. Both datasets are spatially and temporally complete over the period of 1979 - 2005.

In addition to the change in average precipitation, the change in extreme precipitation events was also examined in order to try and better understand the changes occurring to the distribution of precipitation events. The study found that the NCEP Reanalysis II dataset had troubles resolving the fine spatial scale necessary to model the physics of precipitation while the CMAP dataset had troubles accurately resolving precipitation totals on small time scales. Both had difficulty correctly determining precipitation patterns around the South Pole. The effects from El Nino appear to only have a strong presence in the Western and Equatorial Pacific. Both datasets generally demonstrated positive trends in rainfall across latitudes with negative trends occurring near the equator. Extreme events appear to have larger, more positive trends than the annual averages.

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I. Introduction

Anthropogenic climate change has been a widely studied and often discussed phenomenon with respect to global mean temperature. Recent studies have shown that the observed temperature rise in the latter half of the twentieth century appears to be outside the normal pattern of climate variability and have strongly attributed this rise to human forcing (Mitchell et al, 2001). While changes in temperature are of great importance, precipitation changes have the potential to profoundly impact human quality of life due to their influence on agriculture, the availability of drinking water and economic losses from extreme events (Meehl et al, 2000). However, changes in precipitation have not been as rigorously observed or formally attributed to human influence as changes in temperature (Lambert et al, 2004).

Precipitation data tend to have a low signal to noise ratio and few contiguous and reliable datasets are in existence. Limited rain gauge data is available post-1900 from weather stations over continental land surface. Satellite data measurements were begun in 1979, but issues exist due to drift in orbit as well as the accuracy of reading true precipitation versus moisture in the atmospheric column (Lambert et al, 2004). Both physical observations and satellite measurements experience problems measuring frozen precipitation around the polar regions (Zhang et al, 2007). The physical relationships governing precipitation are linked quite closely on a local and regional level and thus can be very dependent on the model's precipitation processes and resolution. Therefore, spatial patterns of precipitation change can vary quite widely between models (Hegerl et al, 2004).

We would like to address the current uncertainty in trends of extreme precipitation events by conducting a synthesized analysis of two popular and widely distributed data sources and comparing our results to those from previously published studies. Our study chose the National Centers for Environmental Prediction and National Center for Atmospheric Research's Reanalysis II dataset (Kanamitsu et al, 2002) along with the Climate Prediction Center's Merged Analysis of Precipitation dataset (Xie and Arkin, 1997) to study precipitation across the globe. Both are freely available as downloads from the website of the National Oceanic and Atmospheric Administration's Earth System Research Laboratory's Physical Sciences Division.

We would like to use these data sources to not only study the change in average precipitation over time, but also the change in extreme precipitation events. For this study, we define an extreme precipitation event at each grid point as the period of five consecutive days (also known as a pentad) with the largest precipitation total for that year. Analyzing the occurrences of these extreme events over time in conjunction with the annual average allows for a better understanding of the changes occurring to the distribution of precipitation events (Meehl et al, 2000). Since large-scale circulation of the atmosphere is greatly influential on latitudinal patterns, trends will also be averaged across grid points on each latitude into "zonal plots" in order to help illustrate precipitation trend patterns specific to polar regions, equatorial regions and the mid-latitudes (Zhang et al, 2007).

II. Methods

We have identified two currently available data sources as good metrics of precipitation across the globe. The first is the National Centers for Environmental Prediction and National Center for Atmospheric Research's Reanalysis II dataset (hereon referred to as NCEP Reanalysis II). The second is the Climate Prediction Center's Merged Analysis of Precipitation dataset (hereon referred to as CMAP). Due to the completeness and ease-of-access of both datasets, they are popular choices for researchers who hope to examine climate variables over time.

NCEP Reanalysis II data is based on all available observational time series data. This data is then analyzed, compared and "cleaned" in order to ensure consistency across all data. The combined data is then assimilated into weather prediction models to generate spatially and temporally complete data for a wide variety of variables. Although the observational temperature is used to continually "nudge" the state of the atmosphere in the model, precipitation is only used to initialize the model. The precipitation output is mainly the result of forcing from incoming radiation and the state of the atmosphere. The NCEP Reanalysis II datasets provide precipitation rate for the period of 1979-2005 on a complete global grid of T62 resolution which translates to roughly 200 kilometers grid spacing (Kanamitsu et al, 2002).

The CMAP data is a dataset focused on precipitation across the globe. Rain gauge data is merged with several different sources of satellite data and then compared and "cleaned" for consistency. Due to the observational nature of this dataset, limited overlap exists and incomplete global coverage causes a few data points to represent large regions of the globe (particularly near the poles). The satellite data is also limited by the satellite's excellent ability to provide instantaneous rainfall estimates but poor ability to provide a rainfall total over a given time period. The natural drift that occurs in both the path over the Earth's surface and the height within the atmospheric column also limits the reliability of satellite data. This dataset is also spatially and temporally complete for precipitation rate across the period of 1979-2005 on a grid of 2.5^{o} longitude by 2.5^{o} latitude which translates to roughly 275 kilometers grid spacing (Xie and Arkin, 1997).

Additional analysis comparing temporal and spatial trends in precipitation from both datasets to those attributable to El Nino was also conducted. Monthly values of the Southern Oscillation Index (hereon referred to as SOI), a sea level pressure differential between Tahiti and Darwin, Australia, were used as a proxy for intensity of El Nino. This data was provided by the National Center for Environmental Prediction's Climate Prediction Center.

All data manipulation, trend analysis and generation of graphics was done using the Matlab software package. Additional support was provided by the MEXCDF, SNCTOOLS and NetCDF Toolbox packages for Matlab maintained by John Evans at Rutgers University and the M-Map Toolbox for Matlab maintained by Rich Pawlowicz at the University of British Columbia, Canada.

III. Results

Since the data sources used in this study spanned a time period of 27 years, an initial concern was that any trends in precipitation may be clouded by El Nino events. El Nino is a pattern of climate variability that occurs with a periodicity of three to seven years with strong observational links to precipitation patterns. A sustained warming in sea surface temperatures in the Western Equatorial Pacific result in a fall in air pressure over the Indian Ocean and Australia along with a simultaneous rise in air pressure over Tahiti and the Eastern Pacific. This alters circulation patterns and results in abnormal behavior in precipitation (Philander, 2006). El Nino has also been shown to be linked to the occurrence of extreme precipitation events in certain regions (Schubert, 2005).

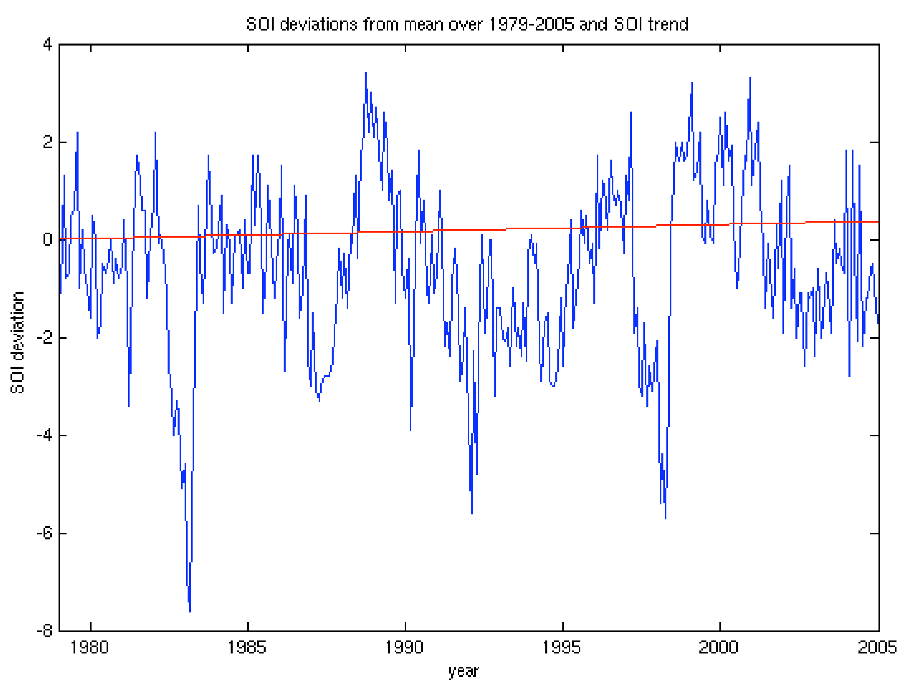

Figure 1: Monthly proxy of El Nino plotted against linear trend over time.

Figure 1 shows the monthly values over the period of 1979-2005 for the SOI, a sea level pressure differential between Tahiti and Darwin, Australia that acts as a proxy for intensity of El Nino. These values are calculated as monthly deviations from the mean for the entire time period. Strong negative values indicate the occurrence of El Nino events (readily apparent in years 1982-1983 and 1997-1998). The SOI itself appears to be undergoing a slightly positive trend over time as indicated by the linear regression line plotted alongside the data.

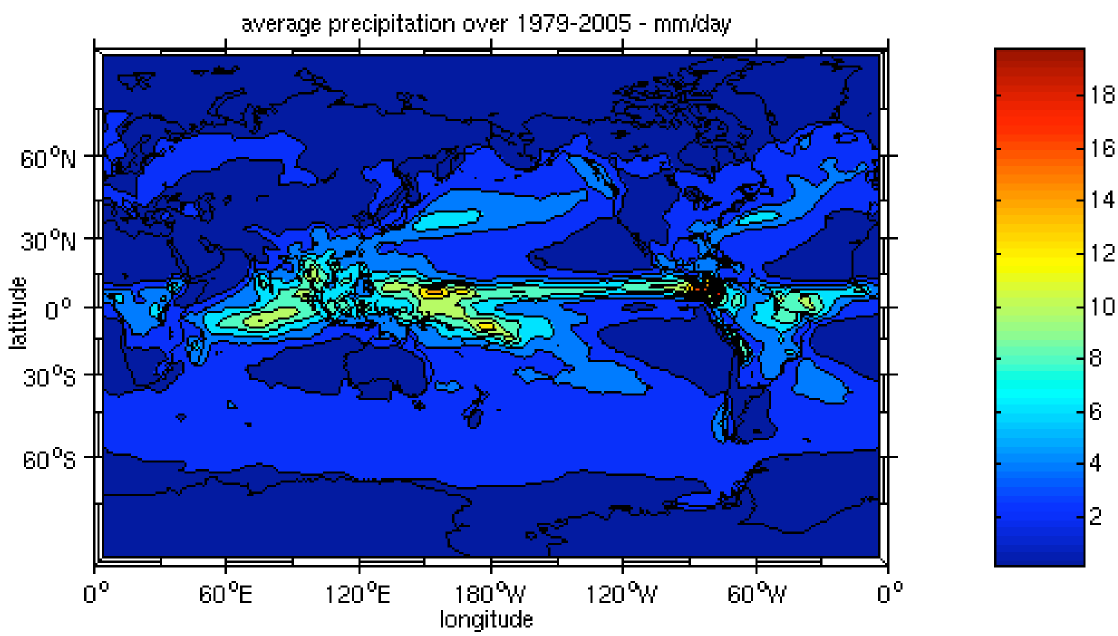

Figure 2.1: Contour map of climatology of annual averages from NCEP Reanalysis II data.

The climatology, or average values over the entire time period, for the annual means from the NCEP Reanalysis II data is plotted in Figure 2.1. This figure shows that on average the model generated large amounts of precipitation around the equator with decreasing amounts moving pole-wards as well as some pronounced dry areas in the sub-tropics. Figure 2.2 shows the trend in time of the annual average values relative to the average precipitation per day. Dark blue values indicate a decrease in precipitation over time while dark red values indicate an increase in precipitation over time. Light green indicates little to no change over time. Strong changes appear to occur along the equator and in the Western Pacific region with trends relatively close to zero occurring elsewhere. There also broadly appears to be a latitudinal patterns in trends.

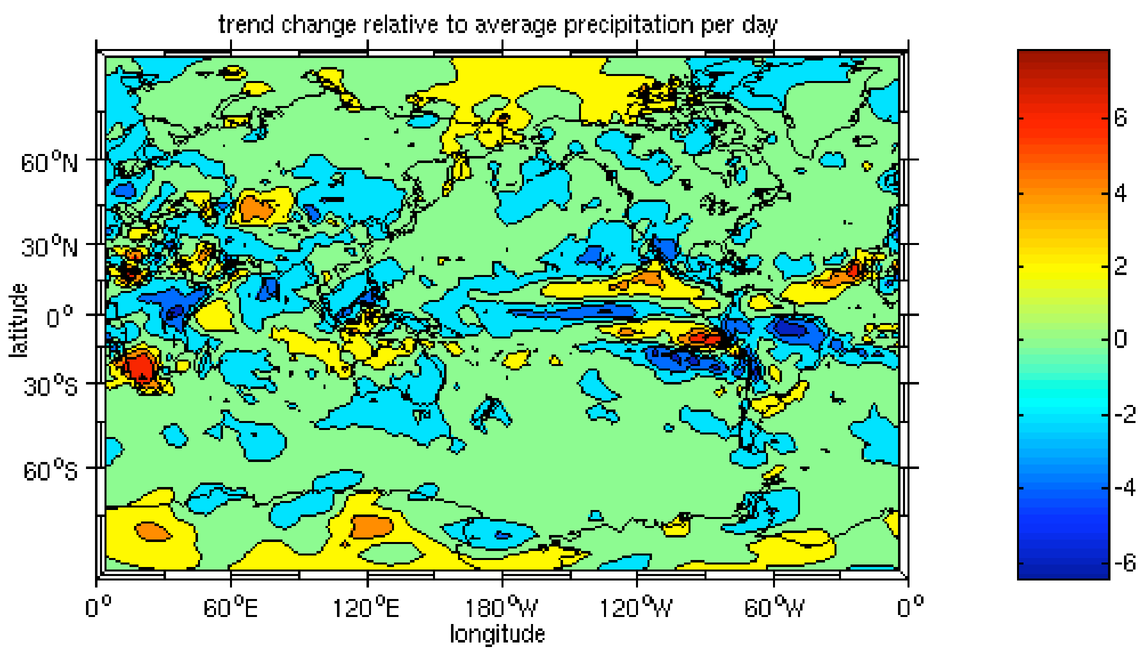

Figure 2.2: Contour map of trends in annual averages from NCEP Reanalysis II data.

This pattern of change coupled with existing knowledge of the El Nino phenomenon leads to two questions: How strongly correlated is the NCEP Reanalysis II data with the SOI and how much of the apparent trend is explained by the trend in the SOI data? Figure 2.3 shows the R correlation values for the monthly SOI data with monthly averages from the NCEP Reanalysis II data. Extreme R values occur near the Indian Ocean and along the Equatorial Pacific. The dark blue indicates an increase in precipitation during an El Nino event while dark red indicates a decrease in precipitation during an El Nino event. The distribution of strong values appears to indicate that the NCEP Reanalysis II model is correctly generating the precipitation patterns of El Nino events.

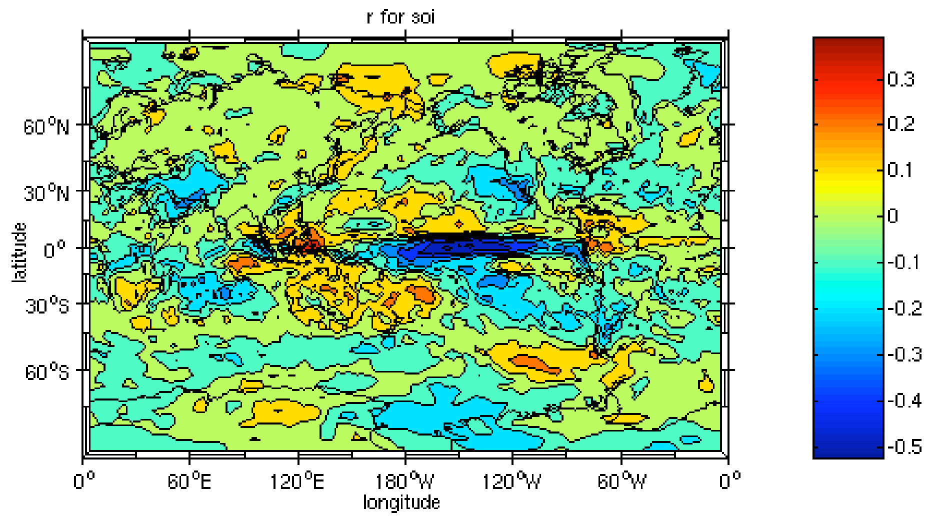

Figure 2.3: Contour map of correlation of annual averages from NCEP Reanalysis II data and the Southern Oscillation Index.

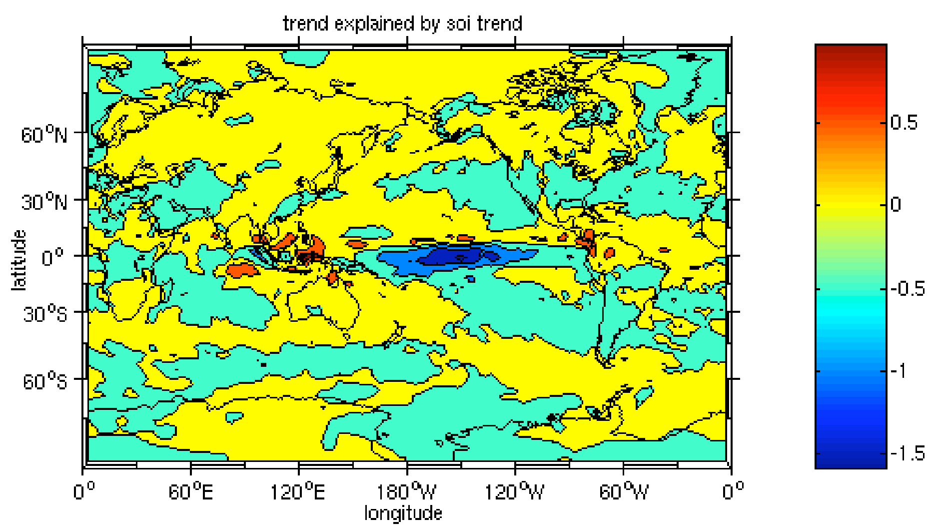

Figure 2.4: Contour map of the amount of the trend in the annual averages from NCEP Re-analysis II data attributable to the trend in the Southern Oscillation Index.

Figure 2.4 shows the amount of the relative trend for each grid point that can be explained by the linear trend in the SOI data. Strong values once again only occur near the Pacific Equatorial region. These two figures lead us to believe that, in the NCEP Reanalysis II data, El Nino only has a strong influence on precipitation around the Equatorial and Western Pacific. Since it appears the El Nino has relatively little to no influence on precipitation elsewhere, no de-trending of the data for El Nino was carried out.

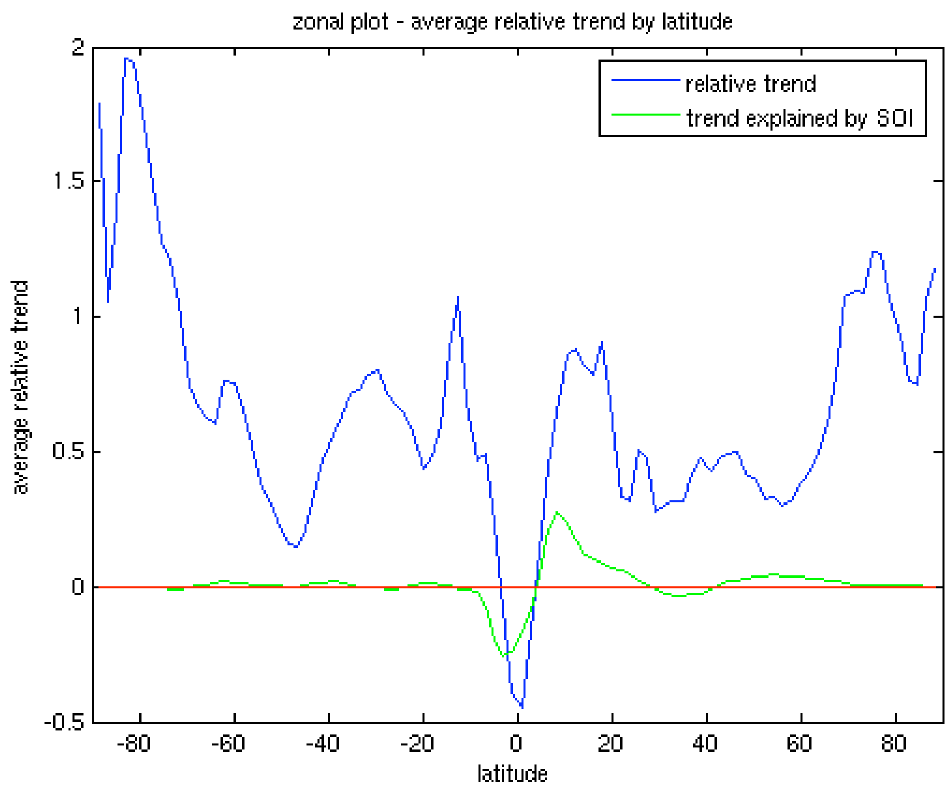

Figure 2.5: Zonal plot of relative trends of annual averages from NCEP Reanalysis II data plotted against trend explained by the trend in the Southern Oscillation Index.

Figure 2.5 is generated by averaging the relative trends by latitude along with the amount of the trend explained by the trend in the SOI data. The NCEP Reanalysis II data appears to show an increase in annual average precipitation virtually everywhere except at the equator. However, this decrease appears to be partially explained by the trend in the SOI data. There do appear to be moderate increases in the sub-tropics with large increases around the poles. Circulation patterns near the poles, especially the South Pole, are poorly constrained due to the limited data available and thus are poorly modeled. This may explain why the model shows a dramatic increase in precipitation over the South Pole.

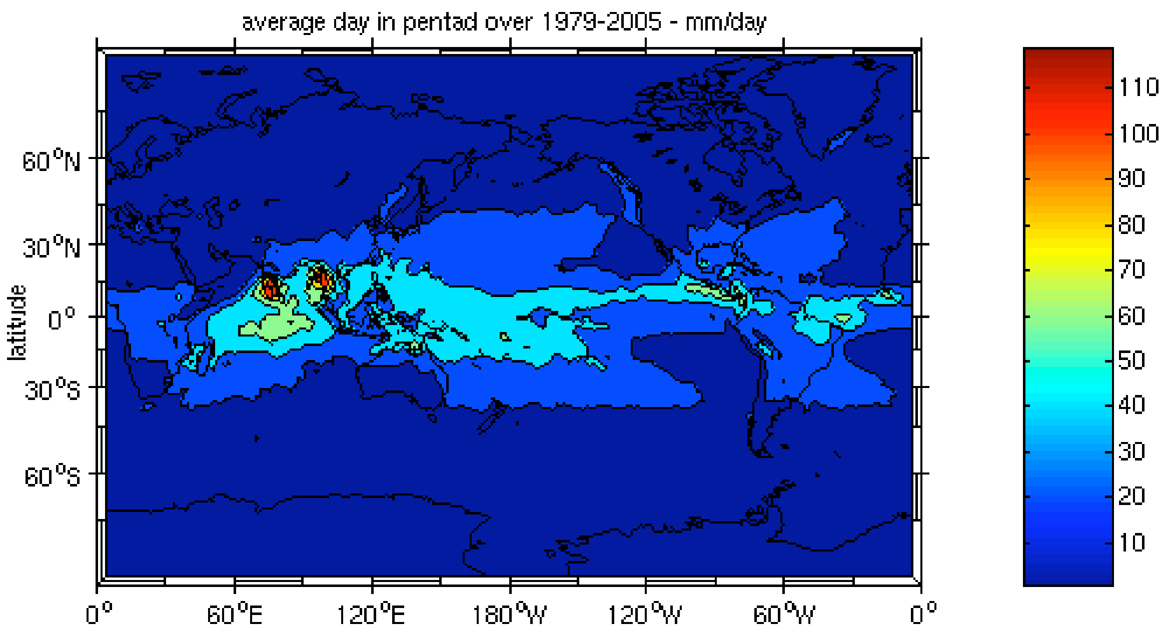

Figure 2.6: Contour map of climatology of wettest pentads from NCEP Reanalysis II data.

The climatology, or average values over the entire time period, for the wettest pentad each year from the NCEP Reanalysis II data is plotted in Figure 2.6. This figure shows that on average the model generated large amounts of precipitation just around the Indian Sub-continent with moderate values off the coasts of Central and South America. Figure 2.7 shows the trend in time of the wettest pentad per year values relative to the average precipitation per day. Once again, dark blue values indicate a decrease in precipitation over time, dark red values indicate an increase in precipitation over time and light green indicates little to no change over time. Strong changes appear to occur in small local spots with strange patterns occurring around the South Pole. There also appear to be the anticipated latitudinal patterns in trends. Since heavy precipitation is highly dependent on small regional events, individual events such as pentads are noisy and result in contour maps that are not as cohesive as those for an averaged value such as the annual mean.

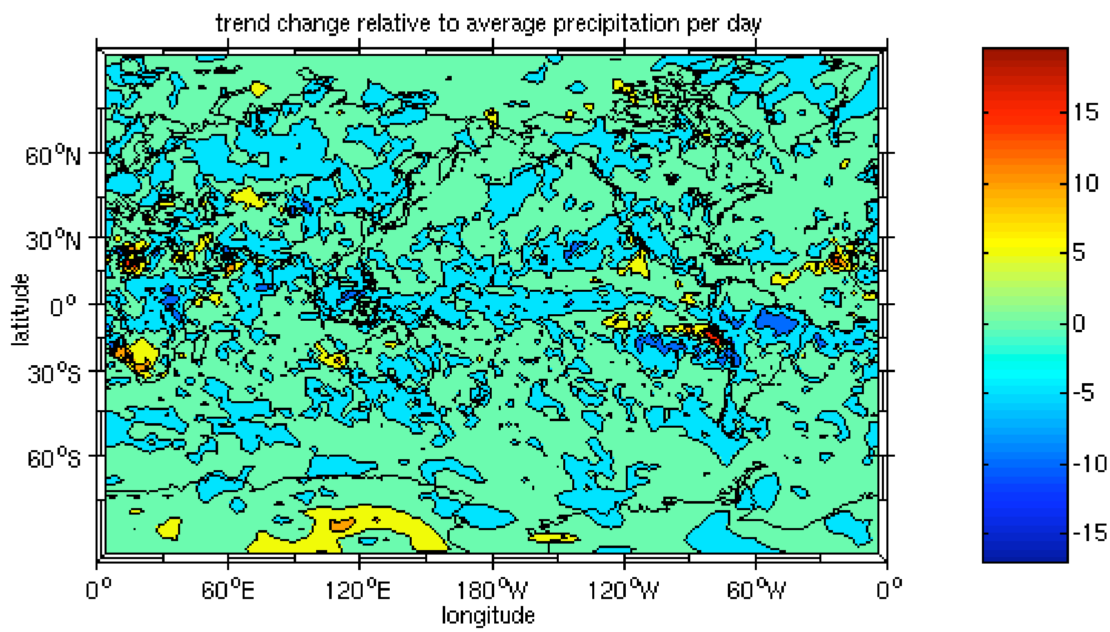

Figure 2.7: Contour map of relative trends in wettest pentads from NCEP Reanalysis II data.

Figure 2.8 is the latitudinal averaging of the relative trends for the wettest pentad plotted alongside the averaging of the relative trends for the annual averages. The shape of the changes appears to be similar with an increase in the amount of rainfall in the wettest pentad each year virtually everywhere except at the equator. However, this decrease is similarly partially explained by the trend in the SOI data. The moderate increases in the sub-tropics along with the large increase in the South Pole appear to be occurring at a faster rate in the NCEP Reanalysis II model for the wettest pentad per year versus the annual average.

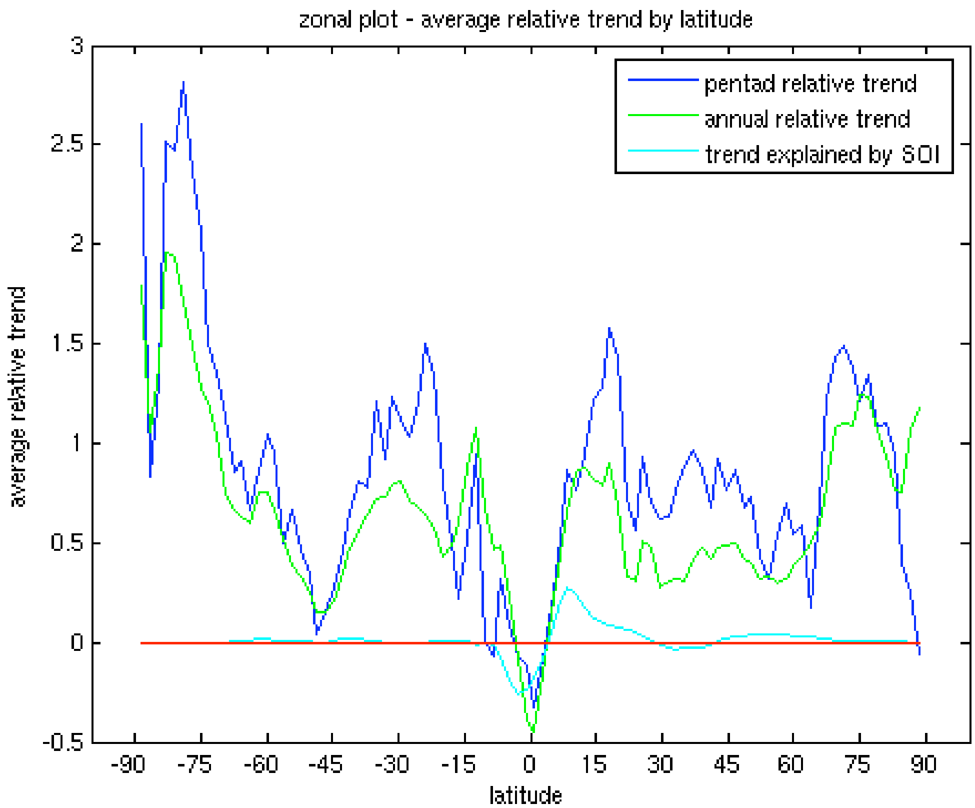

Figure 2.8: Zonal plot of relative trends of wettest pentads against zonal plot of relative trends of annual averages from NCEP Reanalysis II data and trend explained by the trend in the Southern Oscillation Index.

The climatology, or average values over the entire time period, for the annual means from the CMAP data is plotted in Figure 3.1. This figure shows that on average the satellites and observational data registered large amounts of precipitation around the equator with decreasing amounts moving pole-wards. The climatology appears to be very similar to that of the NCEP Reanalysis II data although the

CMAP data has a greater number of contour layers indicating that it may capture more detail than the modeled data.

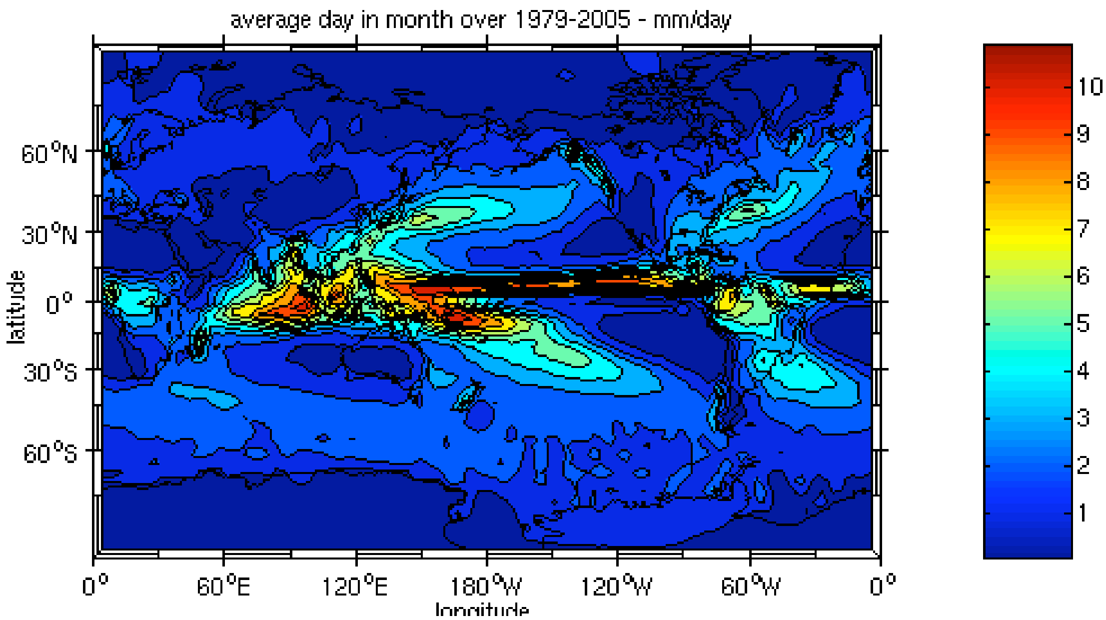

Figure 3.1: Contour map of climatology of annual averages from CMAP data.

Figure 3.2 shows the trend in time of the annual average values relative to the average precipitation per day. Here, dark blue values indicate a decrease in precipitation over time, dark red values indicate an increase in precipitation over time and dark yellow indicates little to no change over time. Two spots of strong changes appear in the South Pole and may explain why little change is apparent elsewhere. These two spots appear to coincide with the only weather stations in the South Pole and may be explained by data inconsistencies.

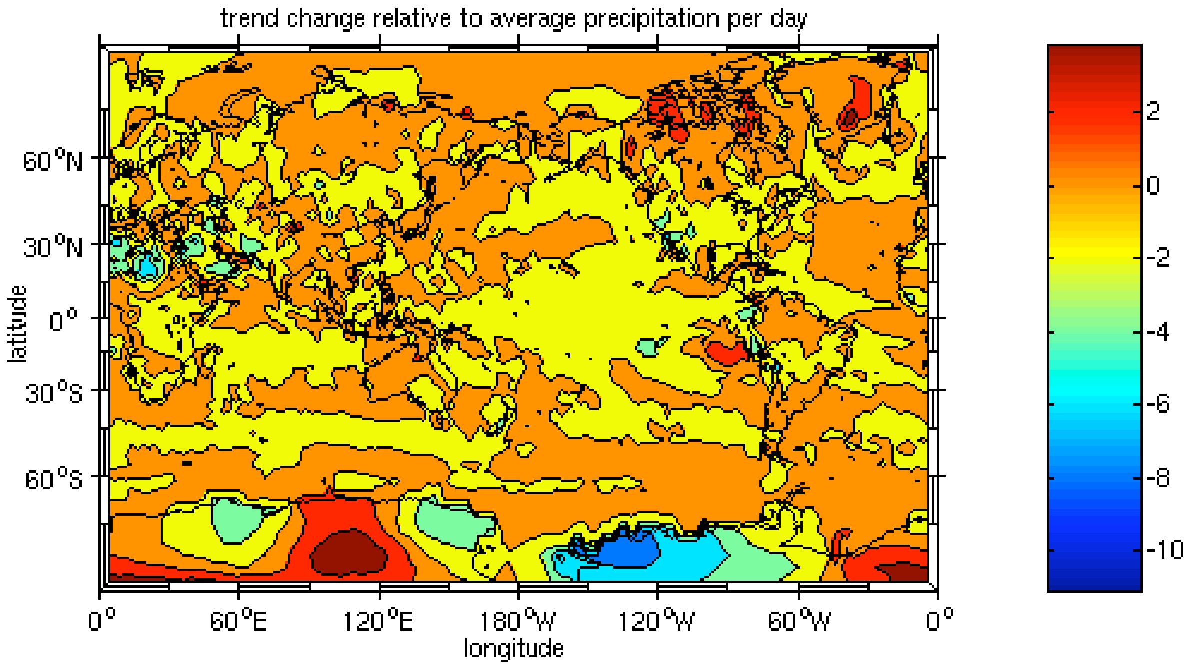

Figure 3.2: Contour map of relative trends in annual averages from CMAP data.

Once again El Nino is a concern and we raise the two questions: How strongly correlated is the CMAP data with the SOI and how much of the apparent trend is explained by the trend in the SOI data? Figure 3.3 shows the R correlation values for the monthly SOI data with monthly averages from the CMAP data. Extreme R values occur in the Western Pacific and along the Equatorial Pacific. The dark blue indicates an increase in precipitation during an El Nino event while dark red indicates a decrease in precipitation during an El Nino event. The distribution of strong values appears to indicate that the CMAP data is correctly registering the precipitation patterns of El Nino events. It also well resembles Figure 2.3 for the NCEP Reanalysis II data.

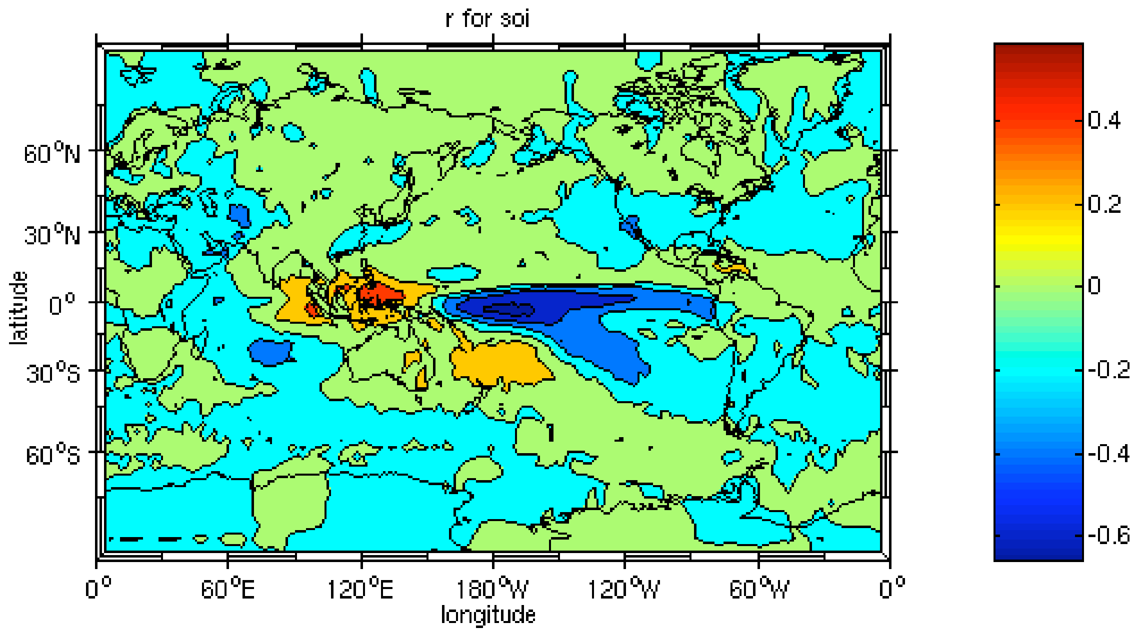

Figure 3.3: Contour map of correlation of annual averages from CMAP data and the Southern Oscillation Index.

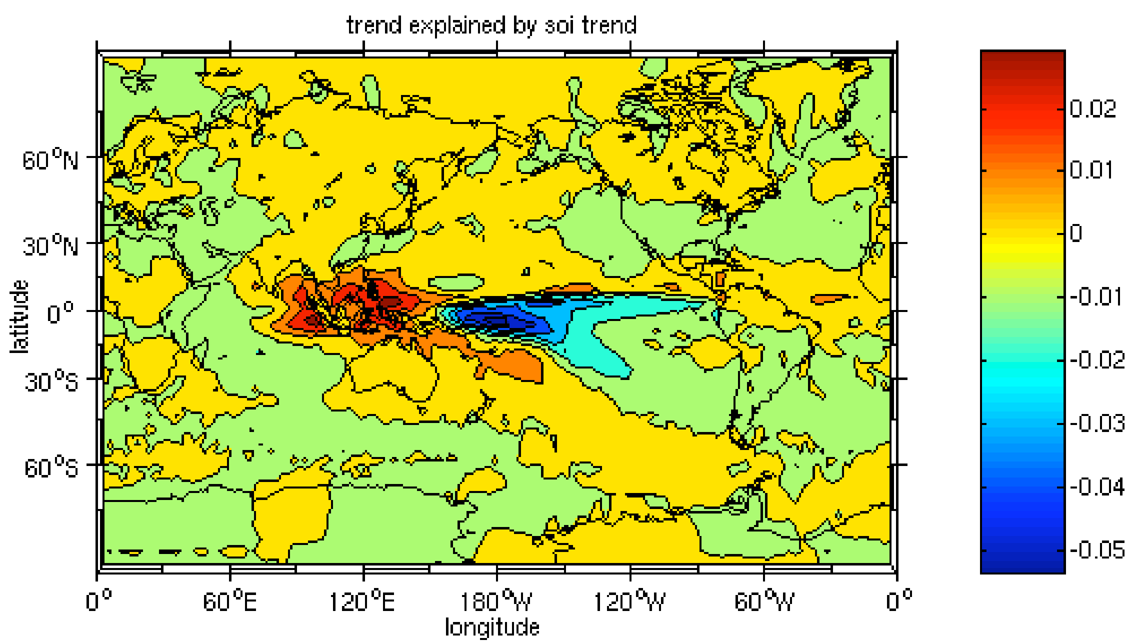

Figure 3.4: Contour map of the amount of the trend in the annual averages from CMAP data attributable to the trend in the Southern Oscillation Index.

Figure 3.4 shows the amount of the relative trend for each grid point that can be explained by the linear trend in the SOI data. The strongest values once again only occur near the Western Pacific and Equatorial Pacific regions, although these pale in comparison to the values from figure 2.4 from the NCEP Reanalysis II data. Since once again it appears the trend in El Nino has relatively small influences on precipitation elsewhere, no de-trending of the data for El Nino was carried out in the CMAP analysis either.

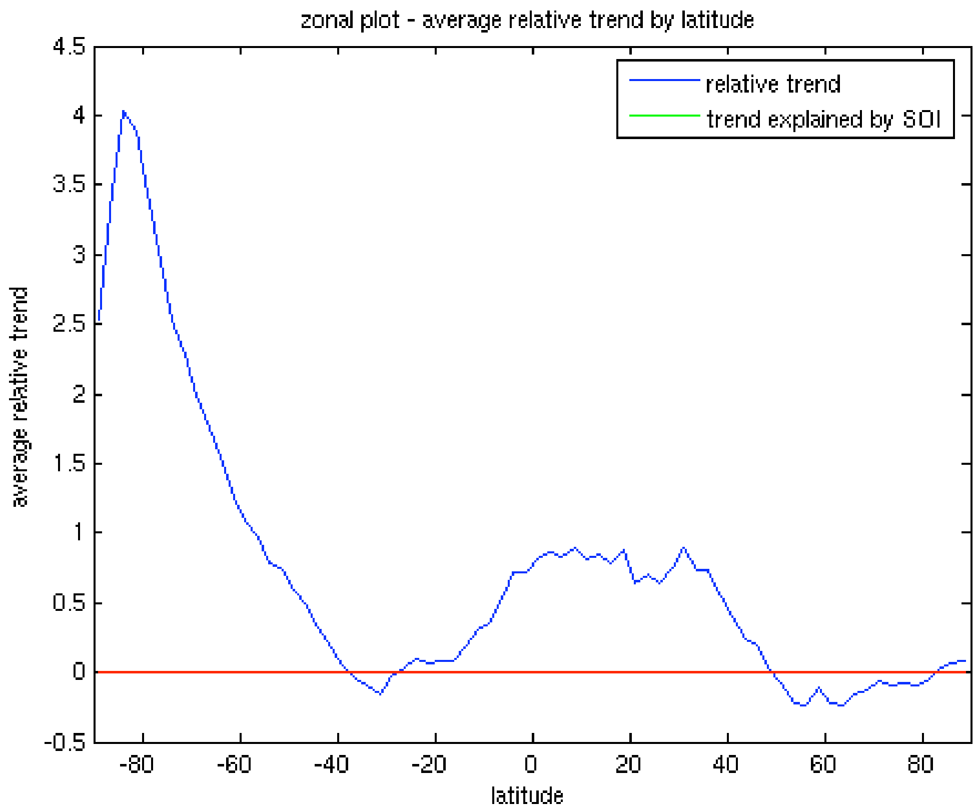

Figure 3.5: Zonal plot of relative trends of annual averages from CMAP data plotted against trend explained by the trend in the Southern Oscillation Index over entire latitudinal range.

Figure 3.5 is generated by averaging the relative trends by latitude along with the amount of the trend explained by the trend in the SOI data. The full zonal plot for the CMAP data confirms the suspicion that the observed behavior near the South Pole is deviates largely from the trends observed elsewhere. Figure 3.6 is generated similarly to Figure 3.5 but with a cut off at -45° latitude instead. This better allows us to note the trends in the rest of the dataset. Once again there appears to largely be an increase in annual average precipitation. The negative trend observed in the NCEP Reanalysis II data at the equator seems absent in the observational data although there is a slight dip in the positive trend at approximately 20° latitude. It is also apparent that, unlike with the NCEP Reanalysis II data, the trend in the SOI over time explains almost none of the observed trend in precipitation over time in the CMAP data.

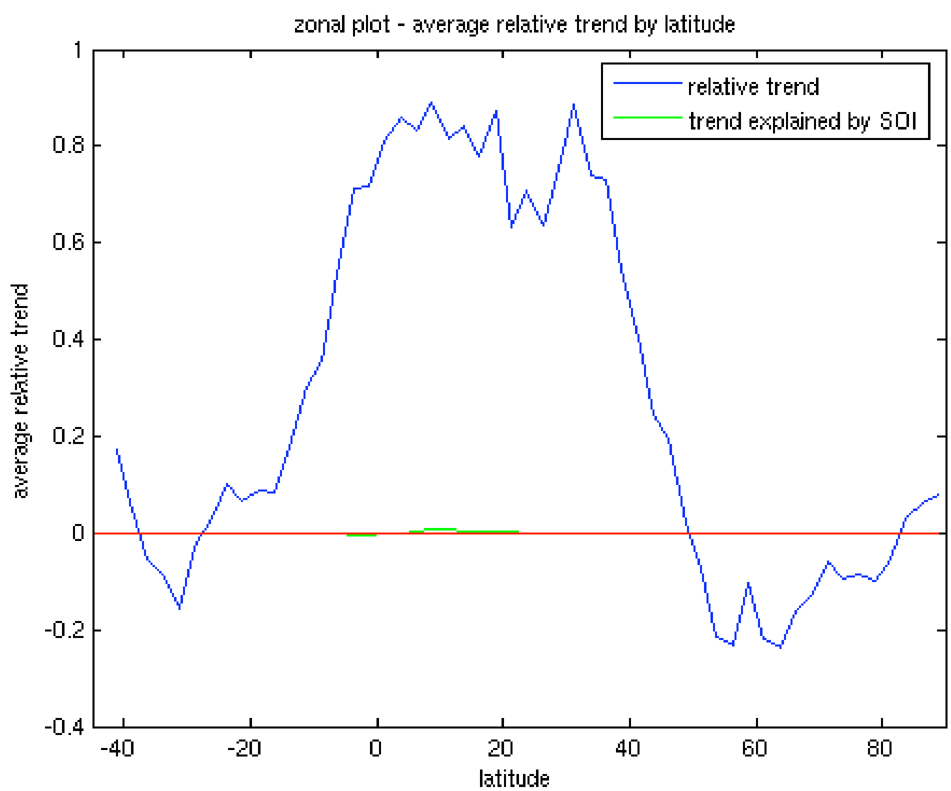

Figure 3.6: Zonal plot of relative trends of annual averages from CMAP data plotted against trend explained by the trend in the Southern Oscillation Index excluding the South Pole.

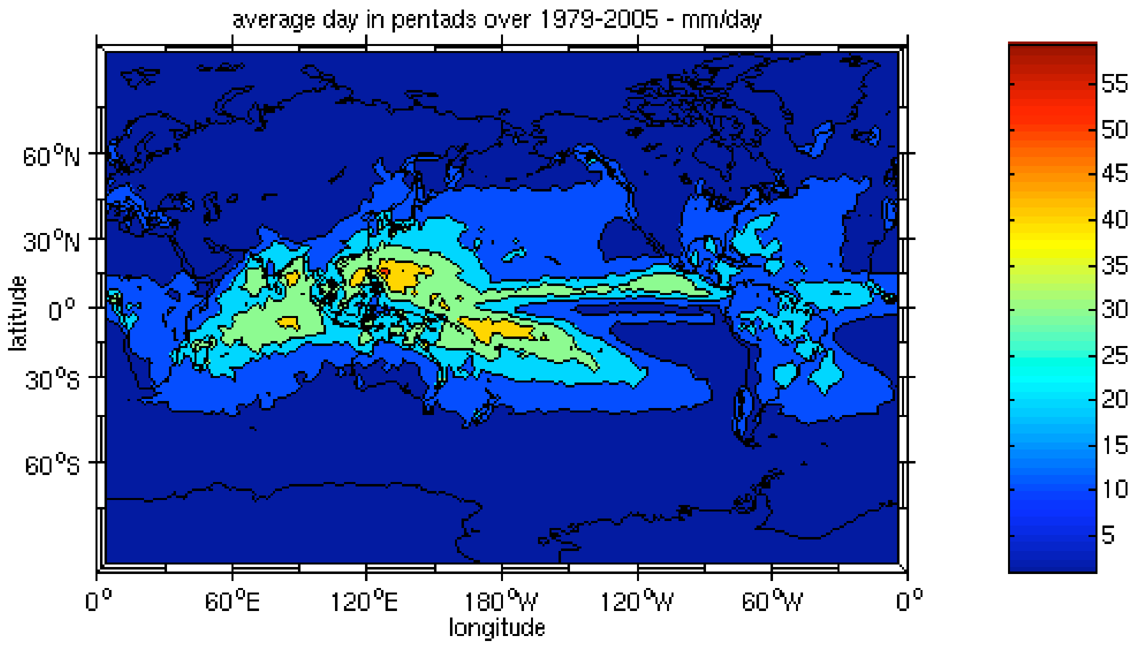

Figure 3.7: Contour map of climatology of wettest pentads from CMAP data.

The climatology, or average values over the entire time period, for the wettest pentad each year from the CMAP data is plotted in Figure 3.7. In comparison to figure 2.6, this figure shows additional contours of heavy rainfall. Figure 3.8 shows the trend in time of the wettest pentad per year values relative to the average precipitation per day. Once again, dark blue values indicate a decrease in precipitation over time, dark red values indicate an increase in precipitation over time and light green indicates little to no change over time. Similar to the pentads from the NCEP Reanalysis II data, the contour plot of CMAP pentads appears to have strange patterns in the South Pole.

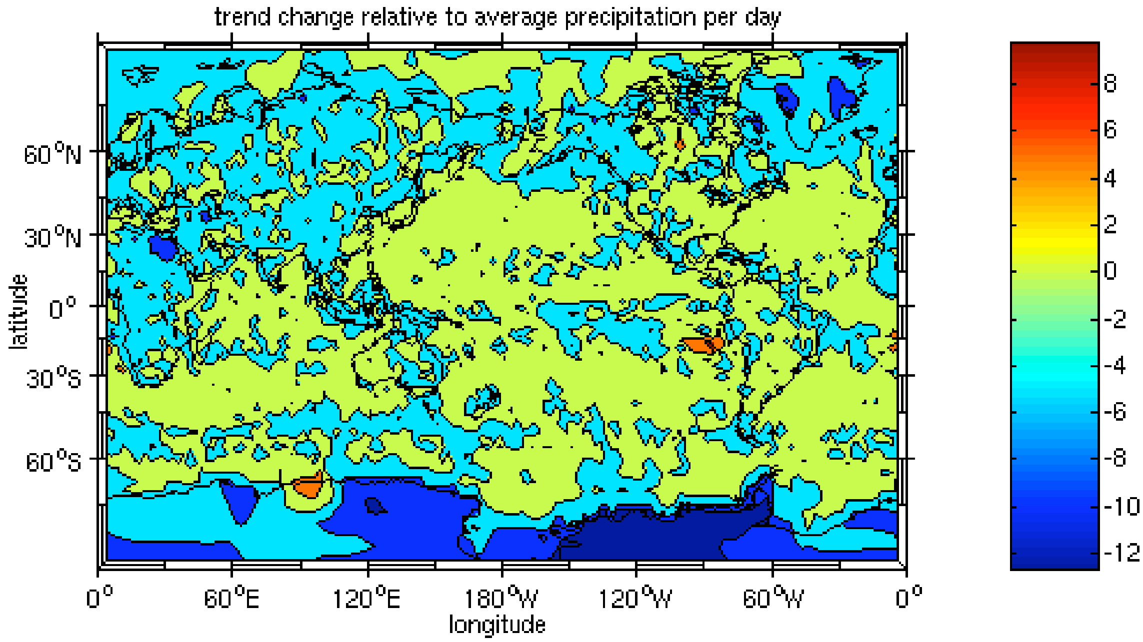

Figure 3.8: Contour map of relative trends in wettest pentads from CMAP data.

Figure 3.9 is the latitudinal averaging of the relative trends for the wettest pentad from the CMAP data. It is readily apparent that once again the South Pole us exhibiting strange behavior. The trends apparent in the pentads do not share the same shape over latitudes as those apparent in the annual averages. Virtually everywhere along the zonal plot, there appears to be a negative trend in the wettest pentad per year. It is a known issue that while satellites can resolve instantaneous rainfall amounts well, averaging rainfall totals over short periods of time is extremely hard. Although CMAP appears to approximate monthly totals well, the pentads seem to be exhibiting abnormal behavior patterns.

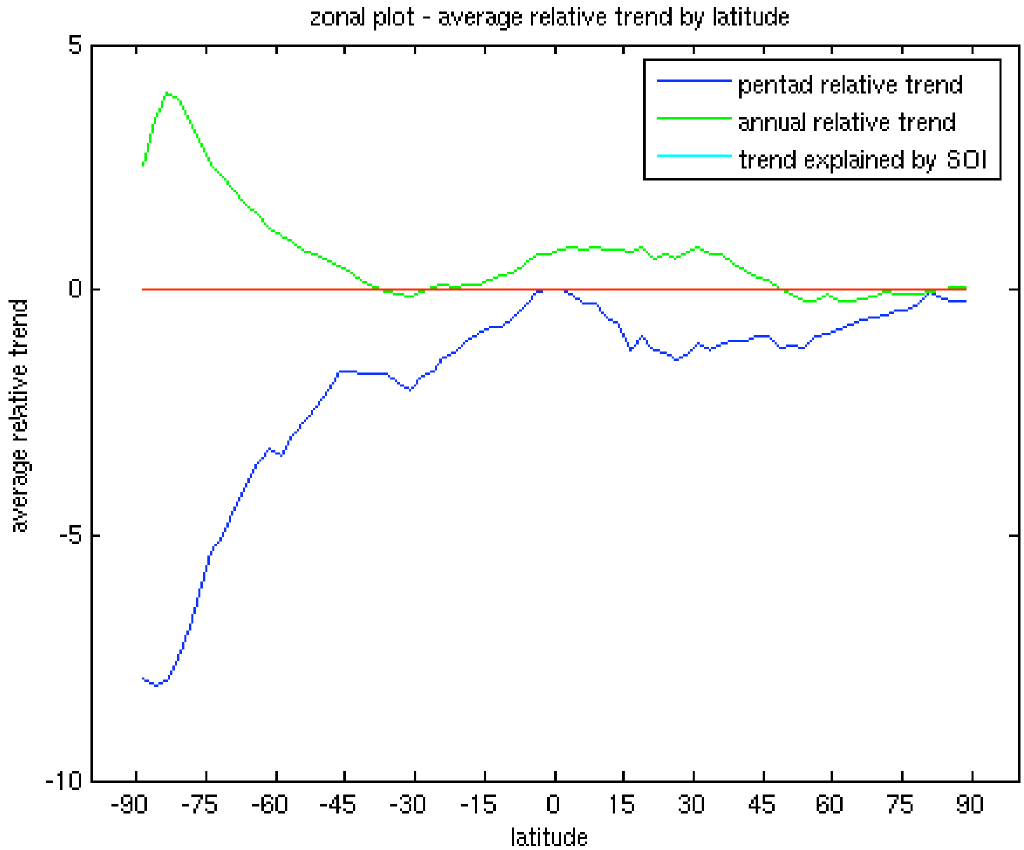

Figure 3.9: Zonal plot of relative trends of wettest pentads against zonal plot of relative trends of annual averages from CMAP data and trend explained by the trend in the Southern Oscillation Index.

IV. Conclusions

Although both the NCEP Reanalysis II modeled data and the CMAP satellite and observational data appear to get larger scale precipitation patterns of El Nino in the Western and Equatorial Pacific to agree in the averaged climatologies, they seem to fail in the trends. The NCEP Reanalysis II model appears to lack the spatial resolution in the physical relationships governing precipitation necessary to evaluate trends over time while CMAP's satellites are incapable of resolving rainfall totals on smaller time scales.

It is also readily apparent that the polar regions are very poorly understood, especially the South Pole. The modeled data does not appear to capture the polar circulation patterns correctly, while CMAP relies too heavily on the limited weather station data available there. Frozen precipitation is very difficult to measure at a weather station due to the abundance of micro-circulation patterns which sometimes cause precipitation to not always fall vertically.

With time, the inconsistencies in the CMAP dataset from observational data collection methods should decrease. Better analytical methods for satellite data interpretation and better calibration techniques for comparing satellite data to rain gauge data will lead to better incorporation into the observational record of satellite data. Advances in computing technology and power alongside an increasingly better understanding of the physics of climate dynamics will help the next generation of Reanalysis data be more accurate.

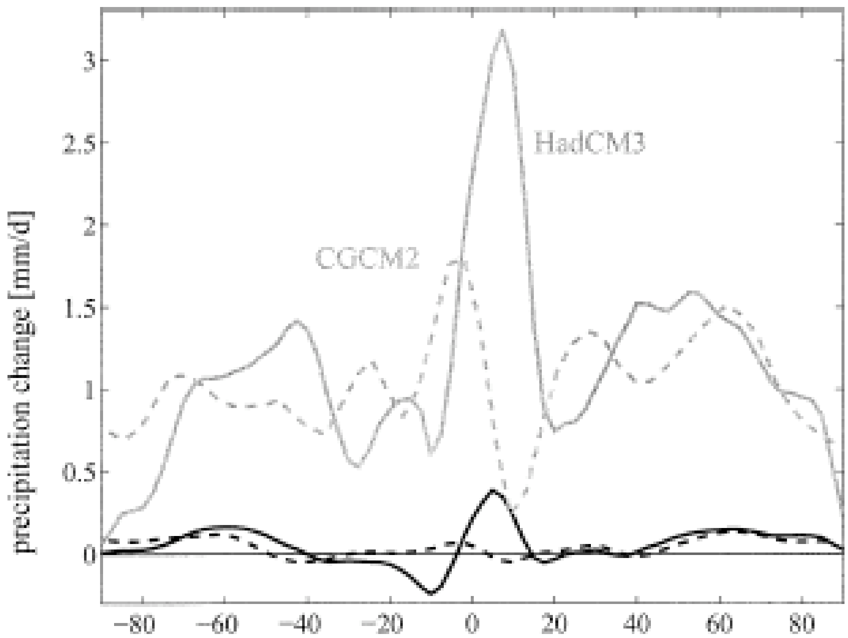

Figure 4: Zonal plot from Hegerl et al, 2004, representing precipitation change from 1975-1990 from model simulations with annual averages represented in black and wettest 10-days period represented in gray. Solid lines represent model output from HadCM3, and dashed lines represent model output from CGCM2.

Even though both data sets have some trouble resolving precipitation, there appears to be a similar shape in the trends over time between the two. The difference in the equatorial dip in the NCEP Reanalysis II data and the 20^{o}N dip in the CMAP data still remains to be resolved. Figure 4 illustrates trends generated from two different models, HadCM3 and CGCM2, in a 2004 paper by Hegerl et al which demonstrate similar shapes to those trends generated from the CMAP data. This perhaps suggests that the NCEP Reanalysis II model is shifting its precipitation patterns slightly or that the HadCM3 and CGCM2 models are too strongly constrained by the satellite data.

Although the study defined an extreme precipitation event as a running 10 day period, figure 4 also shows that extreme events were changing at a faster rate than the annual average. This appears to corroborate the trends seen in the wettest pentad per year and the annual averages from the NCEP Reanalysis II data.

When analyzing precipitation trends, it is important to use multiple data sources and acknowledge the strengths and weaknesses behind each. Common patterns that appear across data sources will likely have some strength to them and will warrant further investigation. As data collection methods and model physics become increasingly more refined, it will become easier to make conclusive statements about changes in precipitation over time.

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CMAP Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/

Southern Oscillation Index data provided by the NOAA/NCEP/CPC, Camp Springs, Maryland, USA, from their Web site at http://www.cpc.ncep.noaa.gov/