The relationship between precipitation in the tropics and tropical cyclone frequency

12.811 Term Project

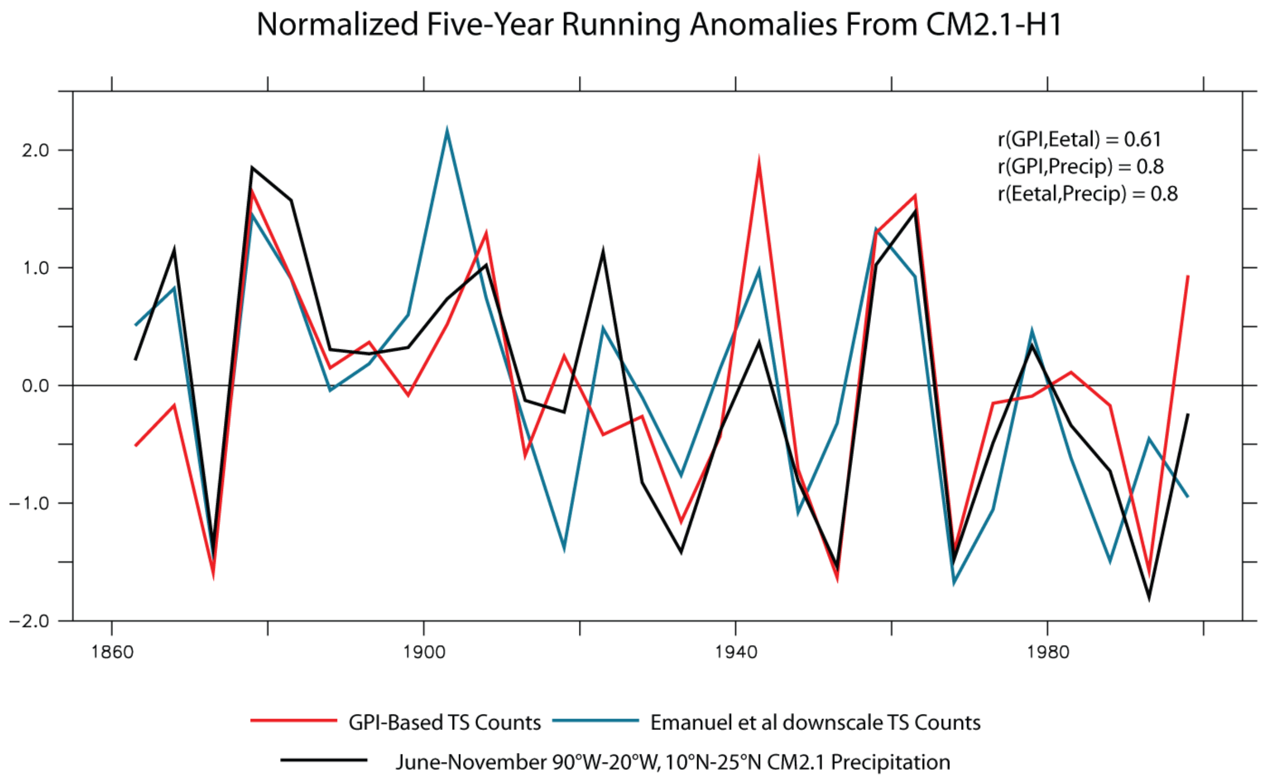
Allison Wing

This project examines the accumulated precipitation throughout the tropical cyclone season, averaged over a specified region in a given ocean basin, and attempts to determine what, if any, correlation there is between this and the number of tropical cyclones during the season. I have performed this analysis for four ocean basins; the North Atlantic, Western North Pacific, Eastern North Pacific, and North Indian Ocean. I defined the region in each basin as a region that enclosed the majority of tropical cyclone genesis points. I compared the frequency of tropical cyclone genesis to TRMM satellite-based rainfall estimates. Overall, the results indicated there is some correlation between these two fields, but there is inconsistency between the basins. Also, the small sample size (11 years) makes it difficult to draw statistically significant conclusions in some cases. Additional complications are the fact that rainfall and tropical cyclones experience a similar seasonal cycle, and that tropical cyclones contribute to the rainfall totals. Nevertheless, I will present the results obtained thus far and discuss the next steps that should be taken to make this a complete analysis.

The motivation for this project comes from an interesting result in analysis that NOAA's Geophysical Fluid Dynamics Laboratory performed on their coupled atmosphere-ocean general circulation model (CM2.1). They found that the June-November Atlantic precipitation from the model seemed to be a good proxy for tropical cyclone frequency derived from a 20th century run of the model. They took the average of precipitation over the region (90W-20W, 10N-25N) for the months of June to November. They compared this to two different ways of estimating the number of tropical cyclones in the model. Because the resolution of general circulation models is insufficient to resolve the details of tropical cyclones explicitly, their frequency must be inferred. One way of doing so is by using the genesis potential index (GPI) to count the number of storms; another is by using downscaling techniques, as Emanuel et al. (2008) did. The genesis potential index was developed by Emanuel and Nolan (2004) by using monthly reanalysis data to empirically define an index that related the spatial and temporal variability of tropical cyclone genesis to several environmental parameters. The GPI is defined as

$$GPI = |10^5\eta|^{\frac{3}{2}}\left(\frac{\mathcal{H}}{50}\right)^3\left(\frac{PI}{70}\right)^3(1+0.1V_{shear})^{-2} \ ,$$

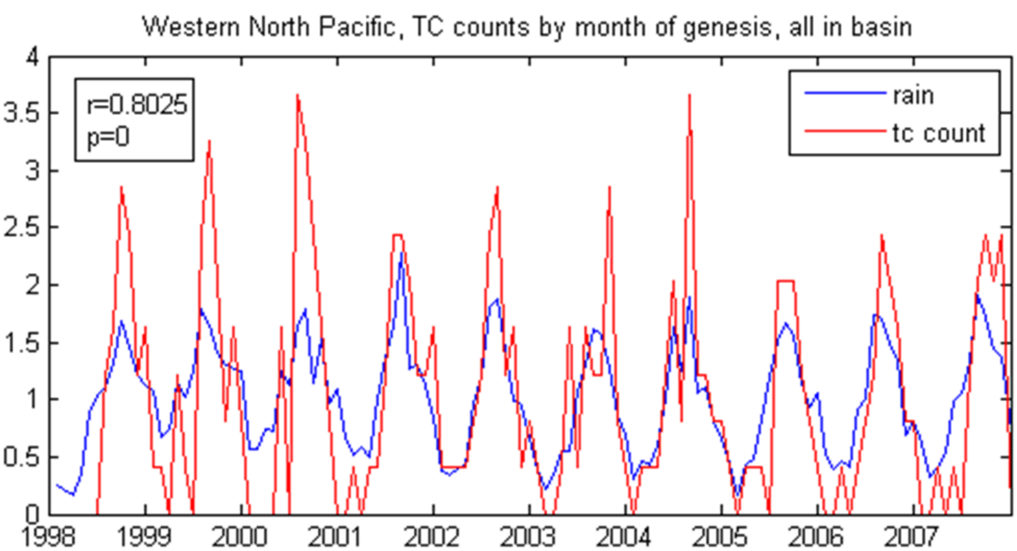
where η is the absolute vorticity at 850 hPA, $\mathcal{H}$ is the relative humidity at 700 hPa, PI is the potential intensity, and V_{shear} is the magnitude of the vertical wind shear between 850 and 200 hPa. GPI has been shown to be useful in explaining the variability of tropical cyclone genesis (Camargo et al, 2007a,b). GPI –based tropical cyclone counts in models involve identifying storms that meet environmental criteria and whose dynamical and thermodynamical variables exceed certain thresholds. The other method is to use a downscaling technique. Emanuel et al. (2008) developed a technique for downscaling involving the random seeding of all ocean basins with weak vortices whose motion is determined by a beta-and-advection model and whose intensity is determined by a coupled atmosphere-ocean numerical model. The variables need to drive the track model and intensity model are derived from the fields produced by the general circulation model. The analysis performed by GFDL on their CM2.1 found that the tropical cyclone counts based on these two methods agreed with each other well, with a correlation of 0.61. The result that motivated this project, however, was that the June-November area-averaged precipitation from the model was highly correlated with both the GPI-based and downscale tropical cyclone counts; each had a correlation of 0.8. The two quantities that were correlated were normalized five-year running anomalies from a 20th century run of the model. A plot showing these results is below (courtesy of Gabriel Vecchi, personal communication):



It is unknown as to what is causing the mean precipitation to follow genesis in the seasonal mean and the strong correlation between the two fields. This question is the motivation for this project; does this relationship hold in reality? Can a correlation between seasonal, area-averaged precipitation and tropical cyclone frequency be seen in actual data? Although I cannot replicate the exact analysis done by GFDL with their model data due to the limited length of my data set, I examined the real observations in a variety of ways in order to determine the relationship between precipitation in the tropics and tropical cyclone frequency.

Most of the previous work on the relationship between precipitation and tropical cyclones focuses on rainfall caused by a given storm or on the percentage of rainfall in a given month or season caused by tropical cyclone activity at a specific location. Shephard et al. (2007) found that tropical cyclones accounted for nearly 8-17% of cumulative rainfall during the hurricane season at different locations along the coastal southeastern United States. Groisman et al. (2004) found that tropical cyclones contributed 8% of the total autumn precipitation along the southeast United States coast. Wu et al. (2007) found tropical cyclones account for more than one third of the total precipitation between June and November at Hainan Island in China and that on average, tropical cyclones contribute 28% of the total annual precipitation of Hainan Island. Easterling et al. (2000) describe the significant contributions of tropical cyclones to rainfall in parts of the northeastern United States. Larson et al. (2005) found that, depending on the specific location and month, up to 15% of summer precipitation along the Gulf Coast of the United States and up to 20% of the summer precipitation along the Mexican coast was due to landfalling tropical cyclones. Clearly, tropical cyclones can contribute a large percentage of rainfall at certain locations over the course of the tropical cyclone season. However, the relative contribution of tropical cyclones to the precipitation over a large region of an ocean basin is more related to the objectives of this project. Rodgers et al. (2000) gave thought as to what percent of precipitation in the North Pacific is due to tropical cyclones. They used satellite SSM/I-based rainfall estimates to determine that tropical cyclones contribute 7% of the rainfall to the entire North Pacific tropical cyclone basin during the tropical cyclone seasons and 12%, 3%, and 4% of the rainfall to the western, central, and eastern third of the North Pacific, respectively. More restricted regions, such as the area east of the Philippine Islands and the area west of the Mexican coast, have substantially greater contributions of tropical cyclone rainfall to the total rainfall (30% and 40%), respectively. Rodgers et al. (2001) performed a similar analysis for the North Atlantic. They found that tropical cyclones contribute 4% of the rainfall to the entire North Atlantic tropical cyclone basin during the tropical cyclone season, and 4% and 3% of the rainfall to the western and eastern North Atlantic, respectively. The greatest contribution of rainfall from tropical cyclones is 30%, in the regions northeast of Puerto Rico, within the middle subtropical North Atlantic, and west of Africa. Overall, previous work has found that in localized regions, tropical cyclones can contribute a large percentage of the rainfall, but for the overall basin, contribute on the order of 4% (7%) for the North Atlantic (North Pacific).

This project seeks to determine what sort of relationship there is between precipitation and tropical cyclone frequency. Since previous work has indicated that tropical cyclones contribute to regional precipitation, on some scale the correlation between precipitation and tropical cyclone frequency is partially a correlation between tropical cyclones and themselves. Ideally, the precipitation due to tropical cyclones should be excluded in order to determine if there is some other relationship between precipitation and tropical cyclone frequency. In addition, there is a seasonal cycle in both fields. To illustrate this, the normalized monthly basin averaged rainfall is plotted with the normalized monthly tropical cyclone counts in the Western



North Pacific. There is clearly a strong seasonal cycle in both fields and much of the correlation may be due to this common seasonal cycle. This must be taken into account when analyzing the data. What other indications are there of a relationship between precipitation and tropical cyclone frequency? The factors that govern tropical cyclone frequency are relatively unknown. Tropical cyclone genesis is usually thought of as a finite amplitude phenomenon; there are certain environmental conditions that are favorable for genesis, but a triggering mechanism of sufficient strength (i.e. an existing disturbance) is needed for genesis to proceed. The empirically defined genesis potential index of Emanuel and Nolan (2004) has had success in reproducing temporal and spatial variations of tropical cyclone genesis with its environmental parameters; absolute vorticity, relative humidity, potential intensity, and wind shear. It is reasonable to think of these factors as defining regions favorable for genesis. Tropical precipitation, though, wouldn't seem to be controlled by these factors. On large enough space and time scales, the tropics are thought to be in a state of radiative-convective equilibrium, in which the loss of energy by long wave radiation is balanced by the transfer of energy (latent and sensible) and its redistribution throughout the atmosphere by moist convection. Thus, the amount of tropical precipitation would seem to be controlled by the amount of convection necessary to maintain radiative-convective equilibrium. However, there are some indications that convective activity may have a connection with tropical cyclone frequency. Royer et al. (1998) developed a modified genesis parameter that included a term proportional to the convective precipitation computed by a general circulation model as a proxy for convective activity. Studies using this parameter predicted changes in tropical cyclone frequency under global warming predictions consistent with other simulations (Chauvin et al., 2006).

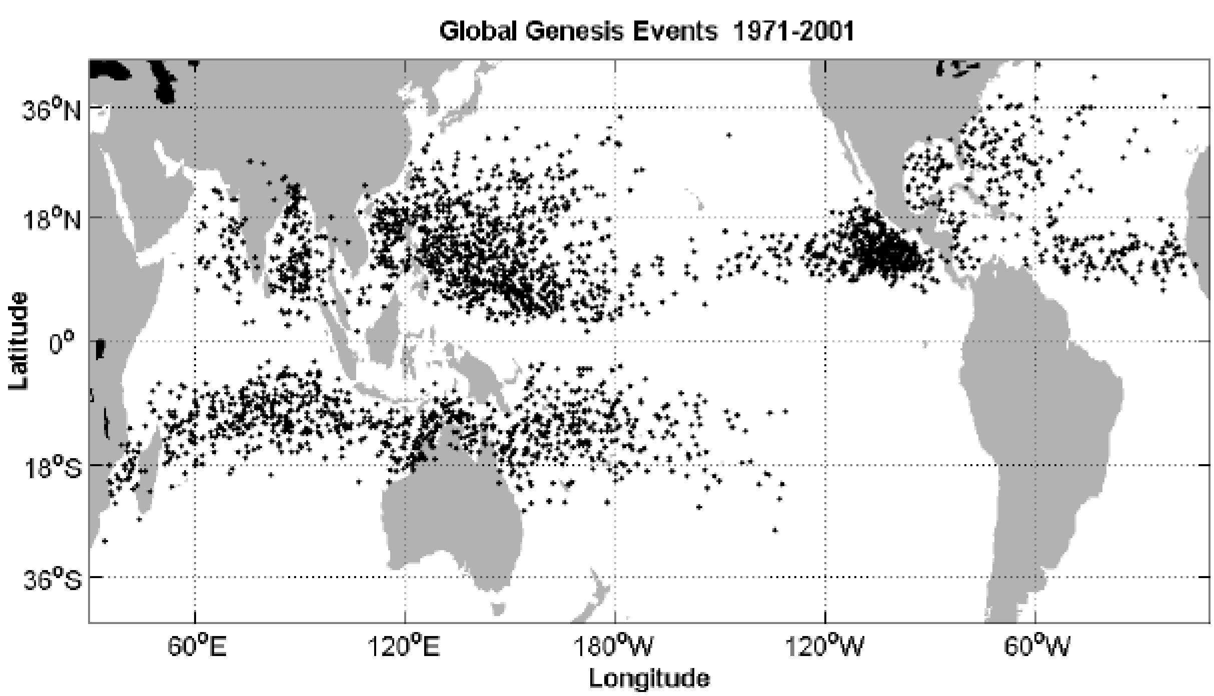
The data used in this project to assess tropical precipitation and its possible correlation with tropical cyclone frequency are satellite estimates of rainfall and the best track tropical cyclone record. The estimates of rainfall are from the TRMM 3B43 monthly 0.25° x 0.25°

merged TRMM and other sources estimates, combining estimates from calibrated IR, combined micro, merged IR-micro, and available rain gauge data in a global band extending from 50°S to 50°N (Huffman et al. 2007). It is a gridded product with input from multiple sensors including non-TRMM data. Over the tropical oceans, of course, there is sparse rain gauge data, so the majority of the data from those regions is satellite-derived. The monthly rain rate is an average rate over the month in units of mm/hr. Monthly accumulated rainfall is found by multiplying the monthly rain rate by the number of hours in that given month. This data product is available from 1998 to the present. The TRMM rainfall data used in this study were acquired as part of the NASA's Earth-Sun System Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The tropical cyclone data for the North Atlantic and Eastern Pacific are from the best track database of NOAA's National Hurricane Center/Tropical Prediction Center. The tropical cyclone data for the Western North Pacific and North Indian Ocean are from the US Navy's Joint Typhoon Warning Center. These tropical cyclone data sets include the 6-hourly (0000, 0600, 1200, 1800 UTC) center locations (latitude and longitude in tenths of degrees) and intensities for all named tropical cyclones. At the time of this work, the Atlantic data was available through 2008 while the Eastern Pacific, Western North Pacific, and North Indian Ocean data were available through 2007.

In order to determine the relationship between tropical precipitation and tropical cyclone frequency, I analyzed the data in a variety of ways. The first method is the closest to the same type of analysis as was done with the GFDL model data. For this method, I added the monthly rainfall at each latitude/longitude point over the course of the tropical cyclone season, and then averaged it over the specified region. The tropical cyclones were counted by the month in which they formed. The number of tropical cyclones per month was then added over the all the months in the season. This was done for all years to obtain a seasonal regionally averaged rainfall and seasonal tropical cyclone count for each year. The seasons and regions used are defined below:

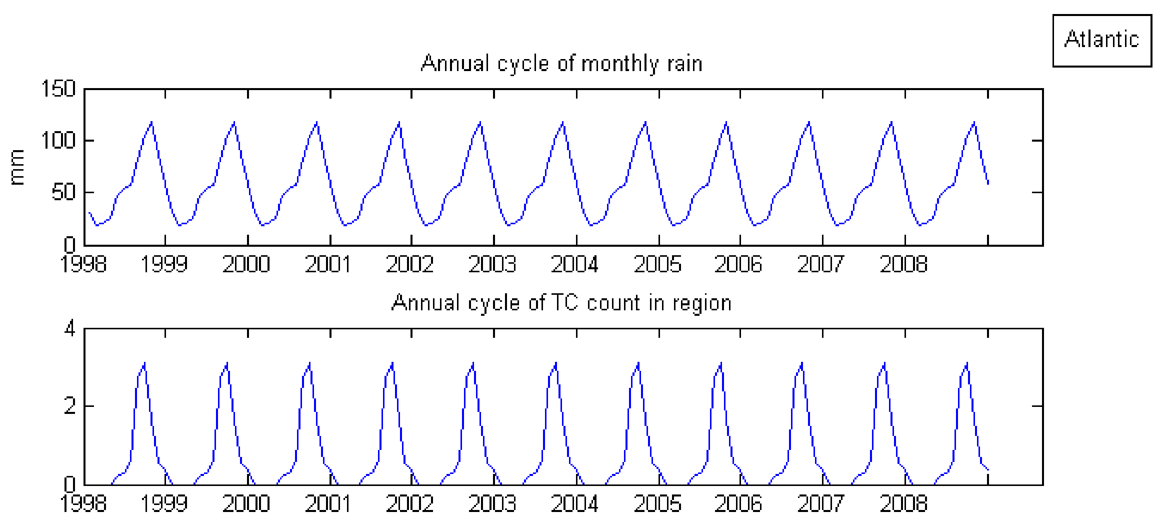
Basin	Region	Season
Atlantic	90W-20W, 10N-25N	June-November
Western North Pacific	100E-160E, 5N-25N	April-December
Eastern Pacific	120W-90W, 10N-20N	May-November
Indian Ocean	60E-100E, 10-20N	April-December

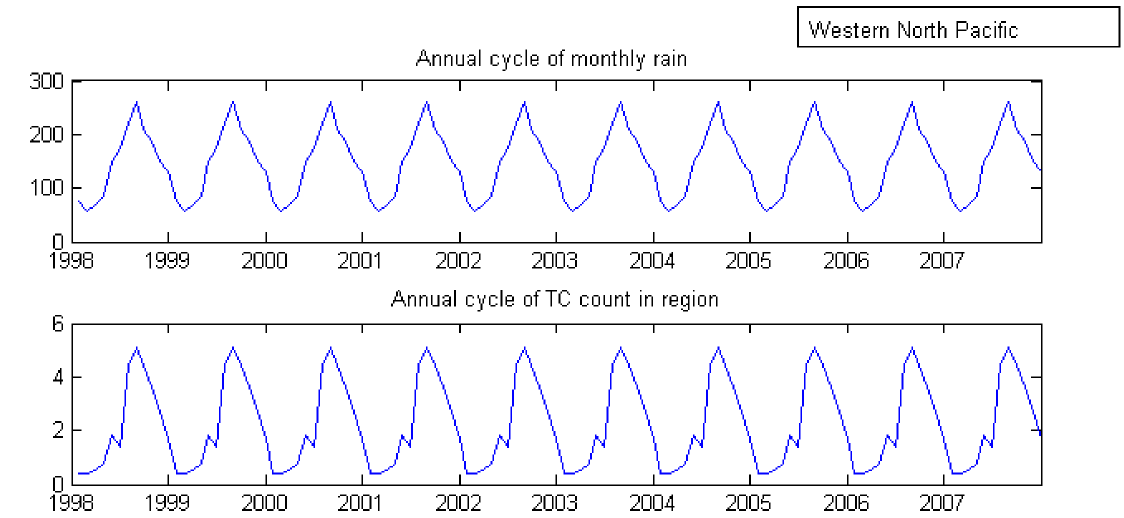
The seasons were chosen as those months that encompass most of the tropical cyclone activity for a given basin. There are occasional tropical cyclones that occur outside of these months. The regions were chosen as those that encompass most of the genesis points for a given basin. I will later discuss whether or not these were the best regions to choose. The map below shows the locations of the tropical cyclone genesis (taken from 12.811 class notes).

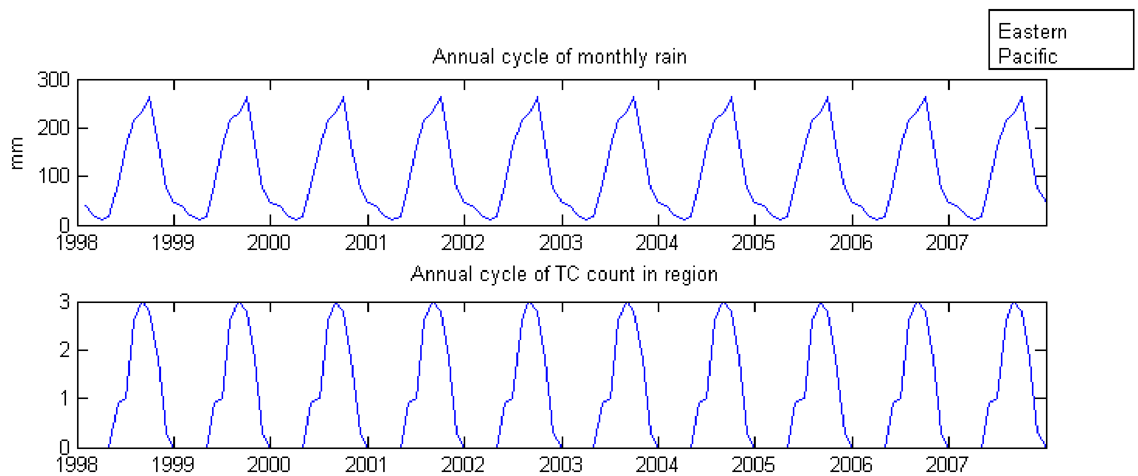


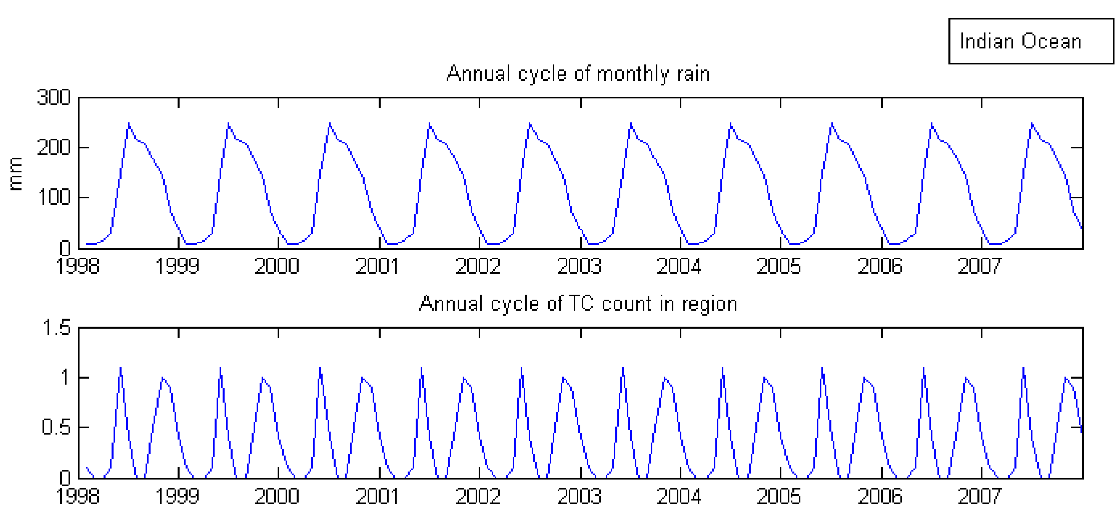
The time series for the first method of analysis contains one value for rainfall and one value for tropical cyclone count for each year; this method will be referred to as "yearly" analysis. There are two types of yearly analysis. The first one counts all the tropical cyclones that occurred in the basin over the defined season. The second type only counts tropical cyclones that passed through the defined region within the basin at any point along their track and occurred in the defined season. The second method of analysis looks at a separate time series for each month (all the Junes, all the Julys, etc…). A monthly regionally averaged rainfall is obtained for each month as well as the number of tropical cyclones forming in that month. The tropical cyclone counts are again looked at in two different ways; all those that occurred in the basin, or the subset including only those that passed through the defined region. The third method of analysis averages the rainfall over the region for each month and counts the number of tropical cyclones forming in that month (either all in the basin or only those that passed through the defined region). The time series for this method of analysis contains one value for rainfall and one value for tropical cyclone count for each month, for all years in the data set; this method will be referred to as "monthly" analysis. The time series for each of the above methods are normalized by their respective means. The fourth method of analysis is the same as the monthly analysis, but subtracts the annual cycle from this in order to obtain anomalies from it. This method will be referred to as "monthly anomaly" analysis. An annual cycle is defined for both monthly regionally averaged rainfall and tropical cyclone count. It is defined as the mean of all Januarys, mean of all Februarys…mean of all Decembers. An 'annual cycle' time series is constructed by taking this sequence of means and repeating for the 10 years of the data record. The annual cycles computed for each basin are shown on pages 11-12. Note that the annual cycle for tropical cyclone frequency in the Indian Ocean is bimodal per year. The annual cycle time series is then normalized by its mean, as is the monthly time series for both rainfall and tropical cyclone count. The normalized annual cycle for rainfall (tropical cyclone count) is then subtracted from the normalized monthly rainfall (tropical cyclone count) to obtain monthly rainfall and tropical cyclone count anomalies. Correlation coefficients and p-values are then computed for the time series of each method. The methods of analysis are summarized below.

1. Yearly analysis: seasonal accumulated precipitation averaged over the region, tropical cyclones counted by month of genesis
2. Separate time series for each month for all years of record (all Junes, all Julys, etc…) for monthly precipitation averaged over the region, tropical cyclones counted by month of genesis
3. Monthly analysis: monthly precipitation averaged over the region, tropical cyclones counted by month of genesis
4. Monthly anomalies: anomalies of monthly precipitation averaged over the region from the annual cycle of precipitation, anomalies of monthly tropical cyclone count from the annual cycle of tropical cyclone frequency.

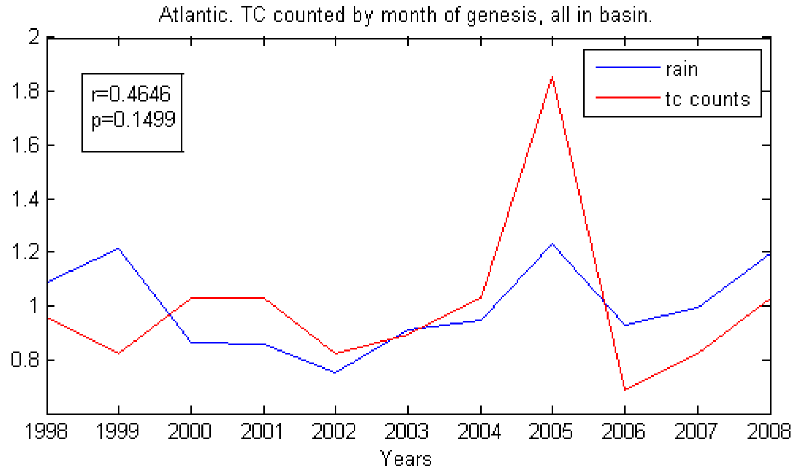


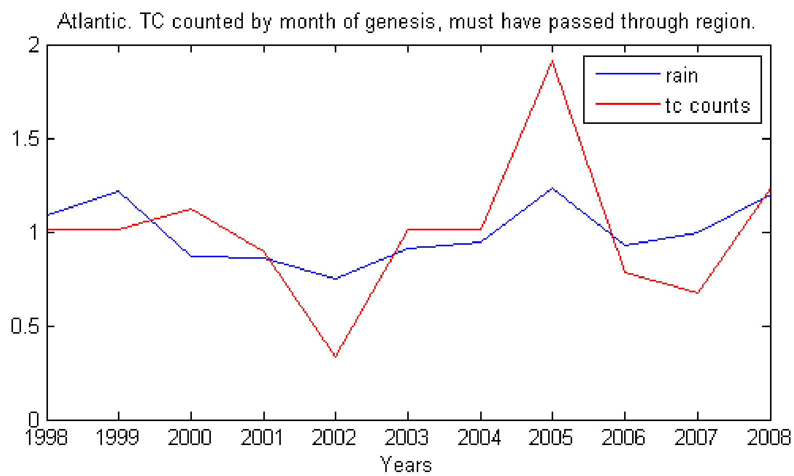

Western North Pacific
Annual cycle of monthly rain
300
200
100
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007
Annual cycle of TC count in region
6
4
2
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

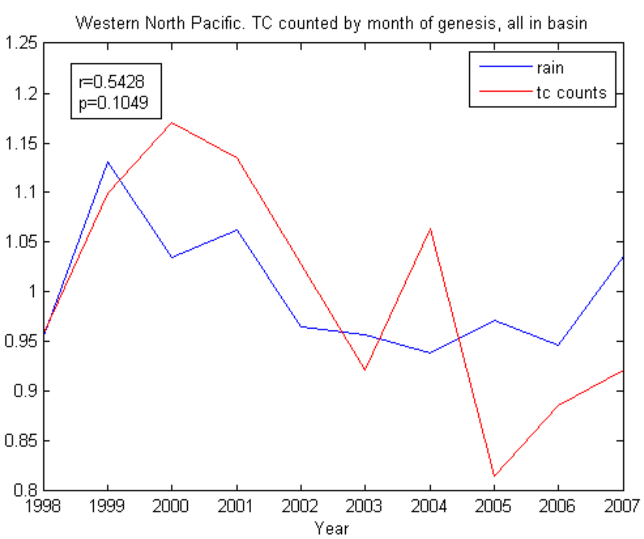

Eastern Pacific
Annual cycle of monthly rain
mm
300
200
100
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007
Annual cycle of TC count in region
3
2
1
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

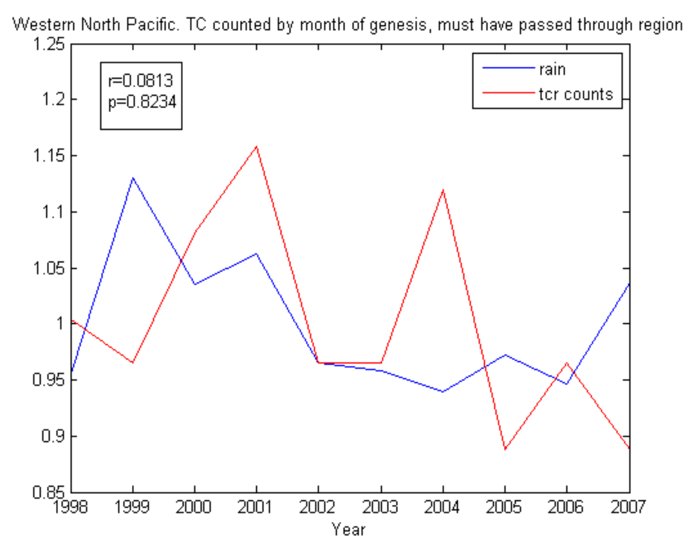

Indian Ocean
Annual cycle of monthly rain
mm
300
200
100
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007
Annual cycle of TC count in region
1.5
1
0.5
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

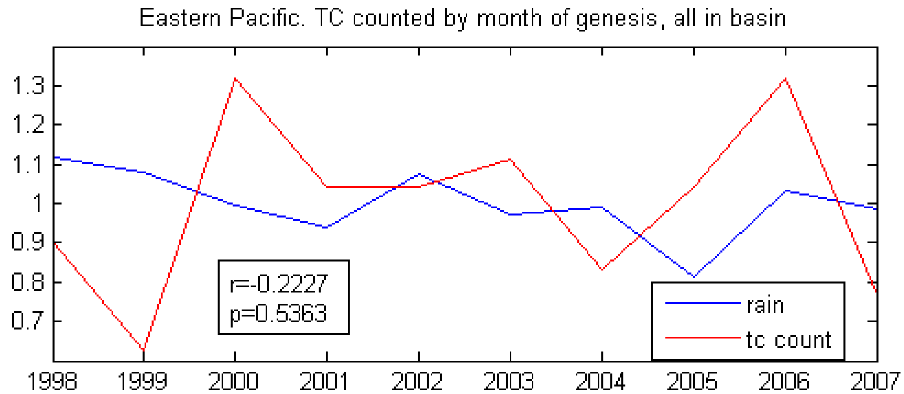
The results of the analysis using the various methods described above vary by basin. Overall, the results indicated there is some correlation between these two fields, but there is inconsistency between the basins. The first method, yearly analysis, yields the most inconsistent results. In the Atlantic, the correlation between seasonal regionally averaged precipitation and seasonal tropical cyclone counts is 0.4646 with a p-value of 0.1499 when all tropical cyclones in the basin are counted. This is really not a statistically significant correlation, which is not surprising given the limited degrees of freedom (only 11 years of data). However, when the tropical cyclone count is restricted to those storms that actually pass through the region within the Atlantic that the rainfall is averaged over, the correlation improves to 0.6997 with a p-value of 0.0165. This is statistically significant at the 95% confidence level. This result makes sense, that the number of tropical cyclones that form in the region of interest is more closely related to the precipitation averaged over the region than the number of tropical cyclones in the entire basin. Yearly analysis for the Western North Pacific gives a different result. When all tropical cyclones in the basin are counted, the correlation coefficient is 0.5428 with a p-value of 0.1049 (nearly significant at the 90% confidence level), but when the tropical cyclone counts are restricted to those that passed through the region, there is no correlation at all. This is somewhat surprising because the defined region is a fairly large one in the Western North Pacific and should therefore include nearly all the tropical cyclones. There is no correlation between precipitation and tropical cyclone frequency for the yearly analysis of the Eastern Pacific, for neither all the tropical cyclones in the basin nor only those in the specified region. On the other hand, there are strong correlations for both cases of the yearly analysis in the Indian Ocean. Plots of these results are shown on the next two pages. Clearly, the yearly analysis does not give a clear picture of the relationship between precipitation and tropical cyclone frequency, given the inconsistencies between the results of the various basins.

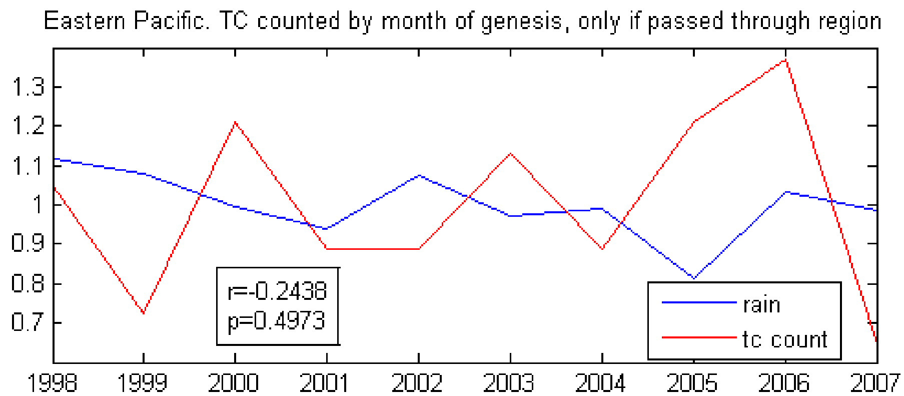


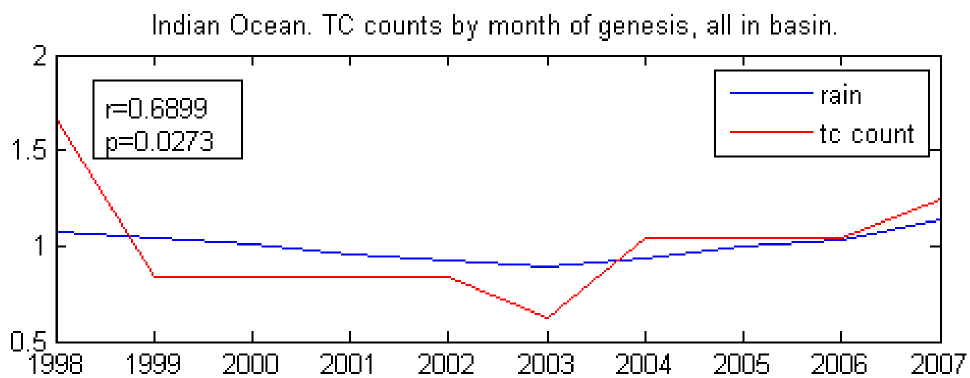


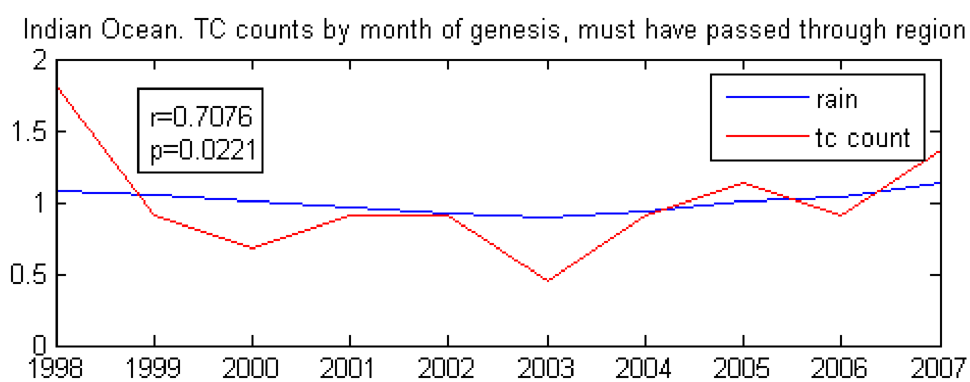





Eastern Pacific. TC counted by month of genesis, all in basin
1.3
1.2
1.1
1
0.9
0.8
0.7
r=-0.2227
p=0.5363
rain
tc count
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007


Eastern Pacific. TC counted by month of genesis, only if passed through region
1.3
1.2
1.1
1
0.9
0.8
0.7
r=-0.2438
p=0.4973
rain
tc count
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

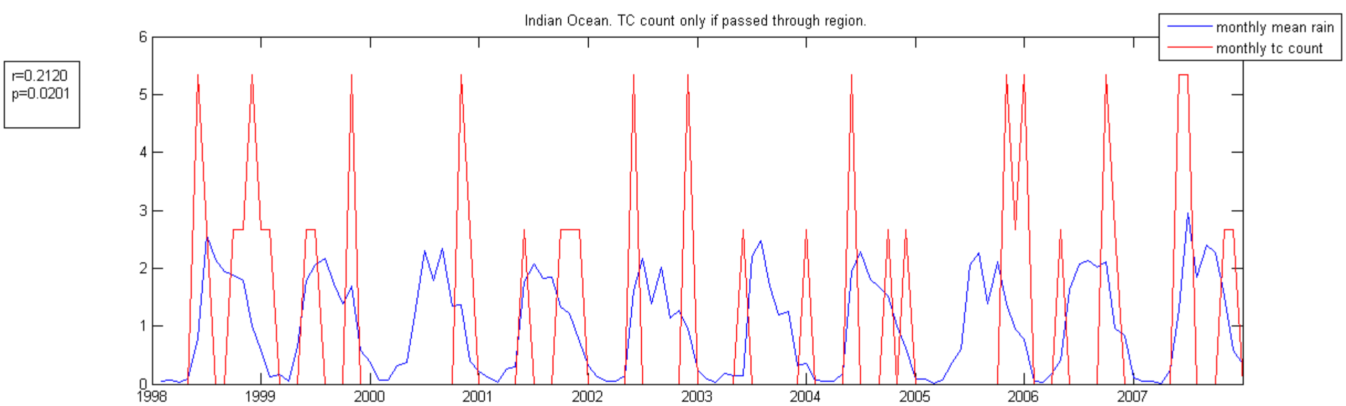

Indian Ocean. TC counts by month of genesis, all in basin.
2
1.5
1
0.5
r=0.6899
p=0.0273
rain
tc count
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007


Indian Ocean. TC counts by month of genesis, must have passed through region
2
1.5
1
0.5
0
r=0.7076
p=0.0221
rain
tc count
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

The second method of analysis, in which there is a separate time series over all years for each month, attempts to isolate the relationship between precipitation and tropical cyclone frequency only in specific months (i.e. all Junes). Although each basin has a slightly different tropical cyclone season, and different basins have different months of peak activity, because all the basins are in the Northern Hemisphere, they are at least all active during the same general time of the year. The results presented are for when only tropical cyclones that passed through the region of interest are included; the results for including all tropical cyclones in the basin were not substantially different. The month of November was the only month in which there was a significant correlation between precipitation and tropical cyclone frequency in all four basins. In the Atlantic, this correlation is 0.5987; in the Western North Pacific, the correlation is 0.8124; in the Eastern Pacific the correlation is 0.7207; in the Indian Ocean, the correlation is 0.5873. All are significant to the 90% confidence level. The results for this method of analysis are summarized in the below table. Bolded correlation coefficients are significant at the 90% confidence level.

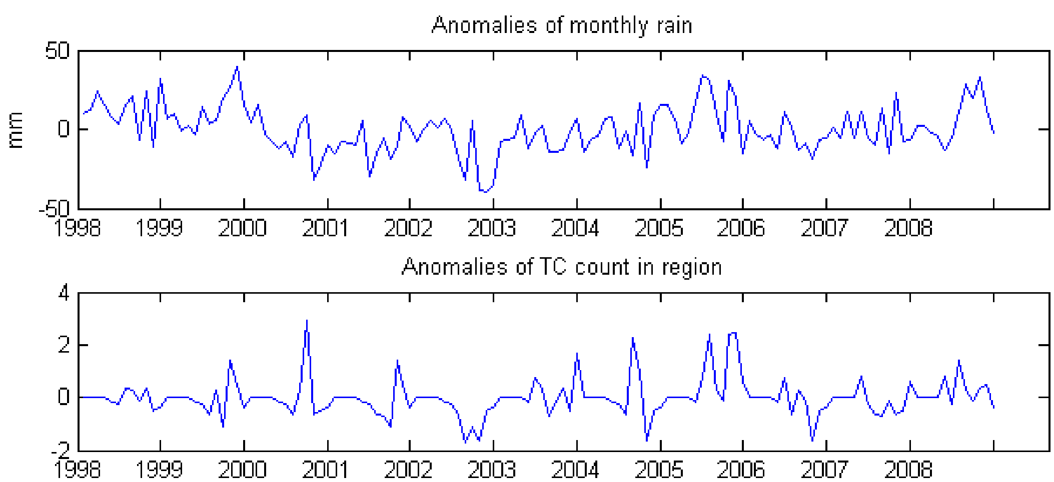
	Atlantic		**Western North Pacific**		**Eastern Pacific**		**Indian Ocean**	
	r	p	r	p	r	p	r	p
April	N/A	N/A	**0.752**	0.0121	N/A	N/A	0.2669	0.456
May	N/A	N/A	**0.8664**	0.0012	**0.6087**	0.0618	0.1957	0.5878
June	**0.5607**	0.0727	**0.7368**	0.0151	**0.4054**	0.0251	**0.7968**	0.0058
July	**0.8403**	0.0012	**0.6094**	0.0614	0.4142	0.2341	N/A	N/A
August	0.206	0.5434	0.4213	0.2253	-0.0971	0.7896	N/A	N/A
September	0.2216	0.5126	0.535	0.1111	0.1845	0.6099	0.305	0.3914
October	**0.6692**	0.0243	0.3227	0.3631	**0.6201**	0.0558	0.4745	0.1659
November	**0.5987**	0.0516	**0.8124**	0.0043	**0.7207**	0.0187	**0.5873**	0.0742
December	N/A	N/A	0.2051	0.5698	N/A	N/A	**0.8589**	0.0015

The third method, monthly analysis, gives strong correlations for the Atlantic, Western North Pacific, and Eastern Pacific, but no correlation for the Indian Ocean. An example of the results from this analysis is on page 6. Although that plot is for the case of including all the tropical cyclones in the basin, if it is restricted to only those that passed through the region of interest it does not affect the results significantly. The correlation coefficients are 0.6983, 0.8031, 0.8339, and 0.2120 for the Atlantic, Western North Pacific, Eastern Pacific, and Indian Ocean, respectively. All are significant to the 95% confidence level or better. It is clear from the plot on page 6 that these correlations are strongly influenced by the common annual cycle in the monthly rainfall and monthly tropical cyclone count. The results would be more meaningful if the annual cycle were removed, which is done next. The effects of the annual cycle also probably explains why there is *not* a strong correlation for the Indian Ocean; while there is an annual cycle in the rainfall, the tropical cyclone count is bimodal in each year. This is illustrated in the plot below.

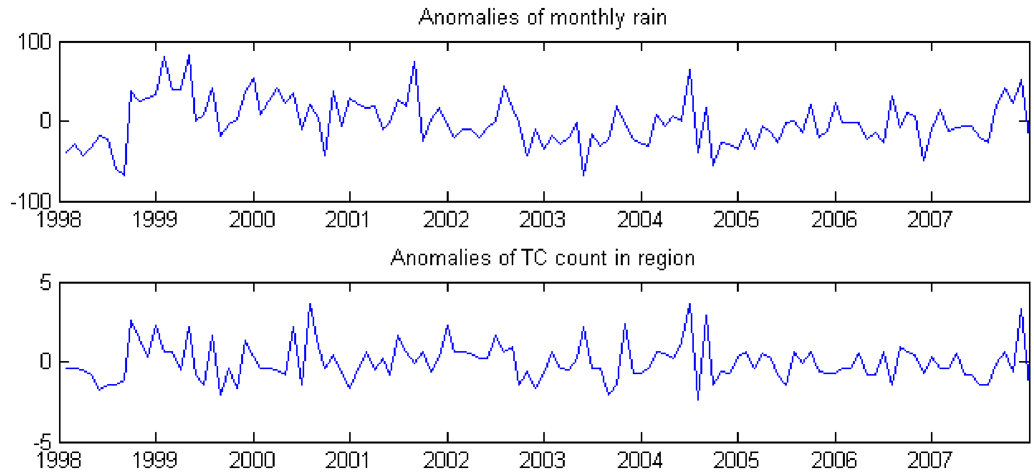


The fourth method of analysis of monthly anomalies from the annual cycle gives the most consistent results between the basins. The anomalies from the annual cycle can be quite large; in the Western North Pacific, for example, there are monthly rainfall anomalies of up to 100mm while the annual cycle goes between ~100mm and 250 mm. The actual anomalies of rainfall and tropical cyclone count in each basin are shown on pages 18-19. When comparing the anomalies of monthly regionally averaged rainfall with the anomalies of monthly tropical cyclone count (only counted if passed through the specified region), all the basins have statistically significant correlations at the 99% confidence level. The correlations are 0.4184, 0.4379, 0.3085, and 0.3566 in the Atlantic, Western North Pacific, Eastern Pacific, and Indian Ocean, respectively. The magnitude of the correlations is not particularly impressive. The correlations of ~0.3 in the Eastern Pacific and Indian Ocean are arguably too weak to consider having much importance, but there is a statistically significant relationship between the two fields in each basin of approximately the same order of magnitude. This is the main result of this project; there is a statistically significant correlation between the monthly regionally averaged rainfall anomaly and the monthly tropical cyclone frequency anomaly in each ocean basin. Although the method of analysis is not really comparable to that done by GFDL on general circulation model data, the correlations received here (~0.3, 0.4) are much less then the correlation of 0.8 that they obtained, but they are correlations, nonetheless. A table summarizing the results is on page 21.

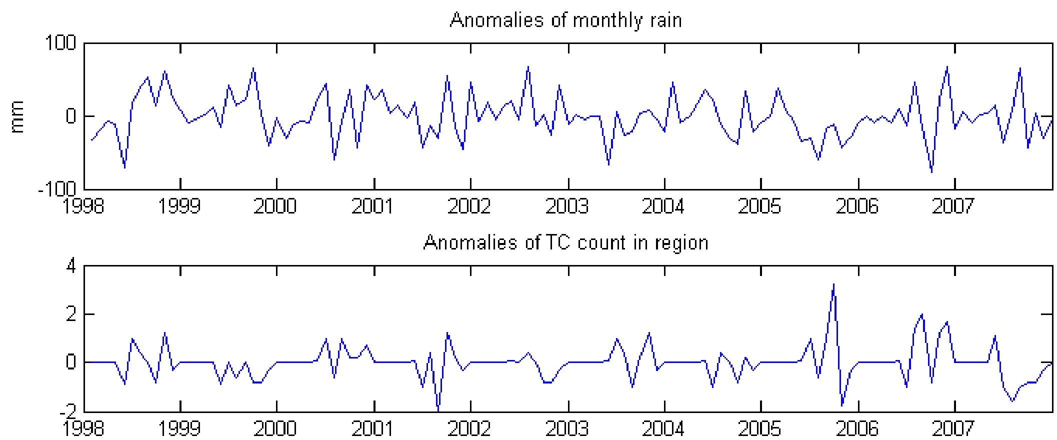
Atlantic anomalies:



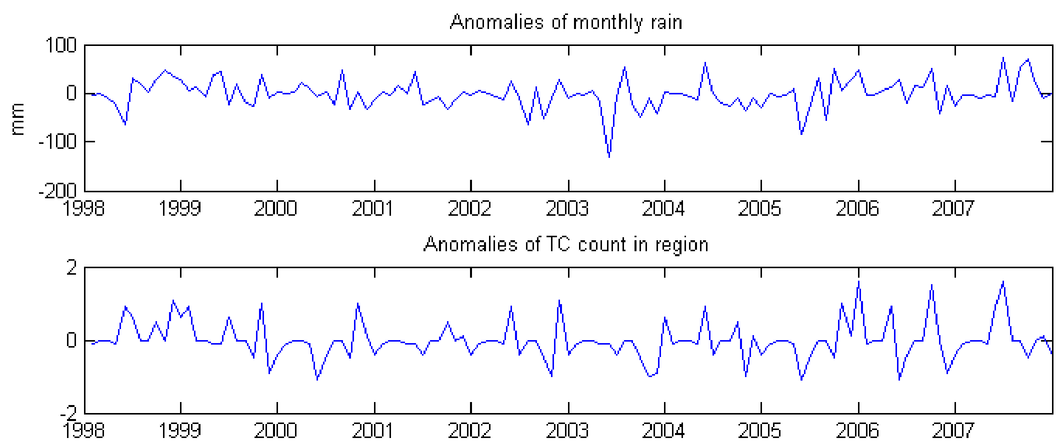
Western North Pacific anomalies:



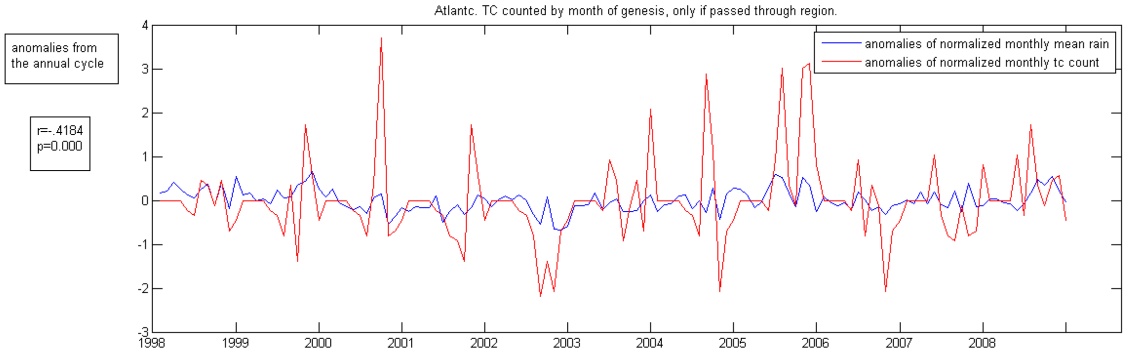
Eastern Pacific anomalies:

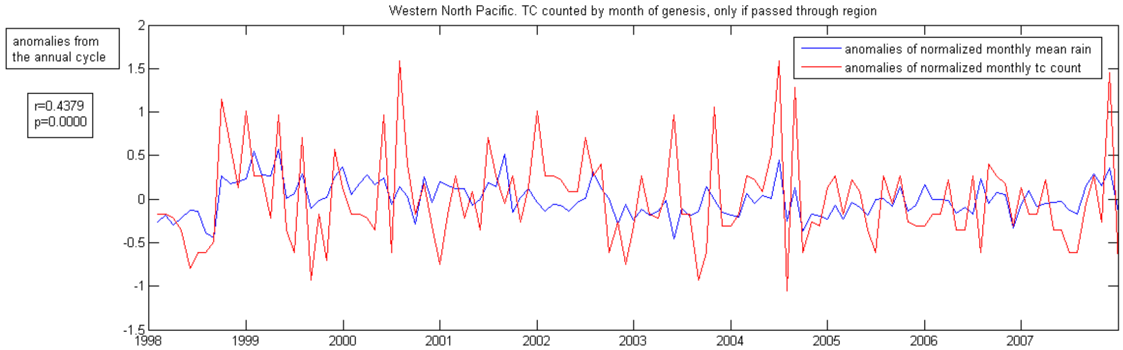


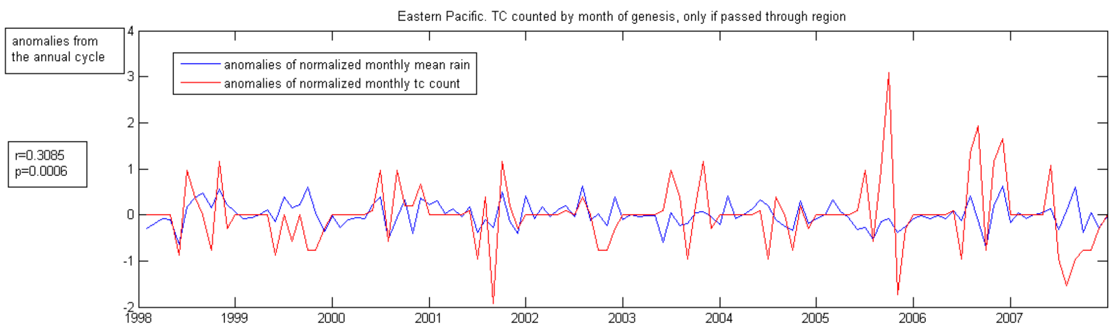
Indian Ocean anomalies:

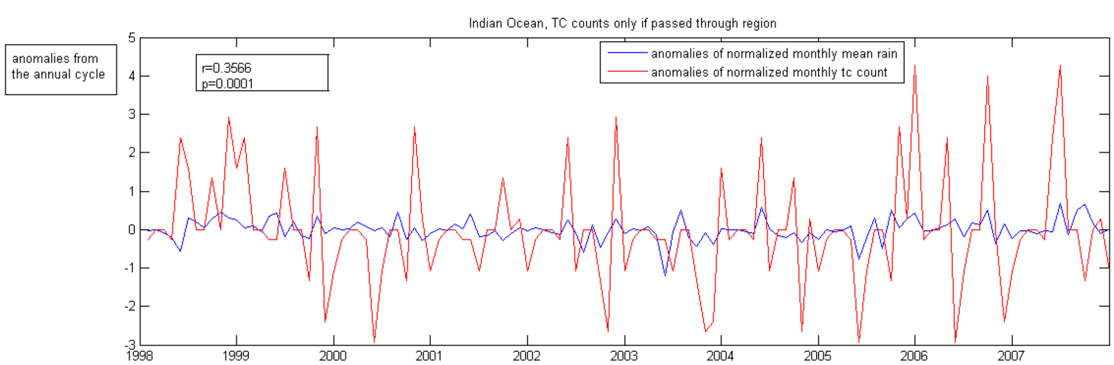


Anomalies of normalized monthly time series from the annual cycle for each basin:









Summary of results: Bolded correlation coefficients are statistically significant at the 95% confidence level or better.

Method	Atlantic		Western North Pacific		Eastern Pacific		Indian Ocean	
	r	p	r	p	r	p	r	p
yearly, all	0.4646	0.1499	0.5428	0.1049	-0.2438	0.4973	0.7076	0.0221
yearly, region	**0.6997**	0.0165	0.0813	0.8234	-0.2227	0.5363	**0.6899**	0.0273
monthly,all	**0.672**	0.0000	**0.8025**	0.0000	**0.8074**	0.0000	0.1508	0.1002
monthly,region	**0.6983**	0.0000	**0.8031**	0.0000	**0.8339**	0.0000	**0.2120**	0.0201
monthly anom, all	**0.2704**	0.0017	**0.4092**	0.0000	**0.2155**	0.0181	**0.2939**	0.0001
monthly anom, region	**0.4184**	0.0000	**0.4379**	0.0000	**0.3085**	0.0006	**0.3566**	0.0001

Although the results indicate that there is some sort of relationship between regionally averaged tropical precipitation and tropical cyclone frequency, the inconsistencies between results obtained via the various methods and between the basins prevent a definitive conclusion regarding the nature of this relationship. There appears to be a consistent relationship on the monthly time scale (the monthly anomaly results) characterized by weak correlations (~0.3, 0.4) of statistical significance. On the yearly time scale, when tropical cyclones are counted only if they pass through the specified region in the specified monthly range of the tropical cyclone season, there is a significant correlation *only* in the Atlantic and Indian Ocean basins. Therefore, there is not a consistent relationship on the yearly time scale. Furthermore, the choices of regions within the various basins may have not been the best choices. For instance, the Western North Pacific region is fairly broad and also includes some land areas. This region should perhaps be restricted further. The Indian Ocean region probably is not yielding entirely valid results because the region chosen includes part of the Indian subcontinent. The Indian Ocean should be broken up into western and eastern portions so the land areas are not included. This would be a more valid comparison with the other basins where the regions are almost entirely ocean. There is other additional work to be done to confirm the results found and make this project complete. The regions in all basins should be changed in order to examine the effect of the exact choice of region on the results. If this does not have a large impact on the results, this is evidence that they are valid. In addition, the analysis should be repeated for the Southern Hemisphere. The analysis for the Western North Pacific, Eastern Pacific, and Indian Ocean should also be extended through the year 2008. Finally, it would be informative to see how the results differ when precipitation caused directly by tropical cyclones is removed. Since previous work indicated that tropical cyclone precipitation is only a few percent of the seasonal basin-wide totals, it shouldn't affect the results too much; at least not the yearly analysis. On the monthly time scale, tropical cyclone precipitation can be a more significant proportion of the total, so this may affect the already weak correlations in that analysis. There are several ways to exclude the tropical cyclone precipitation. The simplest would be to only count precipitation from days in which there was no tropical cyclone active in the region. This would greatly reduce the amount of precipitation included in the analysis, especially given the large areas of the region, but would give a crude idea of the affect of excluding tropical cyclone precipitation. A more sophisticated method would be to add up the rainfall at all points within some radius of the center of each observed tropical cyclone, and then to subtract this from the monthly total. Both these methods, however, require data at higher temporal resolution than the monthly data currently being used. Finally, a longer precipitation data set may improve the correlations and statistical significance of the results on the yearly time scale by increasing the number of degrees of freedom.

In conclusion, satellite-derived tropical rainfall was compared to tropical cyclone frequency using a variety of analysis methods on both monthly and yearly time scales. The various methods yielded somewhat inconsistent results between the different basins (Atlantic, Western North Pacific, Eastern Pacific, and Indian Oceans). The primary result is that there is a statistically significant correlation between the monthly regionally averaged rainfall anomaly and the monthly tropical cyclone frequency anomaly in each ocean basin. This result was obtained by averaging the monthly rainfall over a specified region in each basin and subtracting the annual cycle of monthly rainfall from this. Tropical cyclones were counted by the month in which they formed and were only counted if they passed through the specified region at some point along their track. The annual cycle of monthly tropical cyclone frequency was also subtracted from the monthly tropical cyclone counts. Further work, (including changing the definition of the regions used, repeating the Southern Hemisphere, and excluding the precipitation due to tropical cyclones themselves), should be done to assess the validity of these results and make this a more complete analysis.

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