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Continental runoff and effects on the North Atlantic Ocean Subtropical Mode Water

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Abstract. Interannual salinity variations in North Atlantic Subtropical Mode Water (STMW) are well known although the cause is less well understood. Attempts to model local salinity variation with local evaporation and precipitation have not been successful and some authors invoke advection of low salinity water as the cause. Examination of the STMW and North American river runoff data suggests that runoff may partly explain the salinity variations. It is known that low salinity water resulting from Mississippi River outflow is transported well past Cape Hatteras. Spearman Rank Correlation analysis and spectra and cross-spectra Fourier correlation analysis both show that river flow is significantly inversely correlated with STMW salinity. This result suggests that North American river flow may have an influence on the salinity of STMW.

1. Introduction

Although salinity variations in the North Atlantic Ocean are thought to be very important to global climate cycles [*Broecker*, 1991] there are few time series available for analysis and few attempts to examine the causes of salinity variations. Local evaporation, precipitation and mixing cannot explain the observed salinity variations so advection is usually mentioned as the probable cause [*Bjerknes*, 1964; *Talley*, 1996]. Observations of large amounts of freshwater from the Mississippi River in the Gulf Stream [*Atkinson and Wallace*, 1975; *Ortner et al.*, 1995] in 1973 and 1993 led to the hypothesis that the varying amount of continental runoff incorporated into the Gulf Stream from North America may partially explain some of the observed North Atlantic salinity variations. In this letter we test this hypothesis by analyzing the correlation between Mississippi River flow and the salinity of 18 Degree Water off Bermuda (Figure 1). We find a relationship between periods of high runoff and low salinity and vice versa. These results suggest that variations in continental runoff may be an important cause of salinity variability and deserve more attention.

Eighteen Degree Water or Subtropical Mode Water (STMW) is formed southeast of the Gulf Stream (Figure 1) in the winter where continental derived cold fronts cool surface waters and deepen the mixed layer [*Worthington*, 1976; *Michaels and Knap*, 1996]. While there are few long term measurements of the formation process there are long term measurements of the resulting T/S structure available from Station S near Bermuda [*Michaels and Knap*, 1996]. Several authors have noted that observed variations in STMW salinity cannot be explained by local processes [*Talley and Raymer*, 1982; *Talley*, 1996; *Joyce and Robbins*, 1996]. Talley [*Talley*, 1996] noted that ". . . the source of fresher water would be the Gulf Stream and slope water region to its north." while Joyce and Robbins [*Joyce and Robbins*, 1996] noted that " . . . the T/S variability in the surface layer is uncorrelated, which suggests some other processes such as precipitation, runoff, or possibly inter gyre exchange with the subpolar North Atlantic [*Talley*, 1996] might be key factors as well." In this paper we find a strong relationship between periods of high Mississippi River runoff and low STMW salinity and vice versa. These results strongly suggest that variations in continental runoff may be an important cause of STMW salinity variability.

2. The Data

The Mississippi River delivers on average about 600 km^3 yr^{-1} freshwater to the Gulf of Mexico. This flow represents about 64% of the total runoff flowing from the Gulf and Atlantic coasts of the United States [*Guetter and Georgakakos*, 1993]. Since the Mississippi River drains both high and low latitude parts of the United States it tends to integrate the larger scale flow patterns. While we could have used data from other rivers, the longer Mississippi River data set provides a better perspective of runoff variation and possible relations to salinity variation. The Mississippi flow data consists of 23741 daily values beginning on 1 January 1930 (Figure 2).

Station S off Bermuda has been occupied at various intervals since 1954 [*Michaels and Knap*, 1996]. The salinity data consists of a large number of individual measurements of salinity in STMW over slightly more than 41 years. We used all salinity data where the temperature was between 18 and 19°C. Since the data were from bottle or CTD casts there were many points for each day of observations. All salinity measurements within the temperature range for a single day were averaged. This process yielded 757 daily values over the 41-year period (Figure 2). The intervals between successive measurements spans a very wide range; from 1 day (4 instances) to 482 (1 instance). There were 2 cases of 2 day intervals, 1 of 3 days, 5 of 4 days, and so on up to 1 each of 83, 91, 104, 105, 127 and 143 days. The median interval between measurements is 33 days and the mode is 14 days. Nevertheless we have linearly interpolated over all gaps. This gives a record 15,132 days long beginning on April 10, 1954. In the following analysis we use the two data sets: the exact 757 values and the 15,132 interpolated values.

3. Analysis

The analysis involves examining the time series, the frequency spectra and the correlation between the [unfiltered and filtered] runoff and salinity data.

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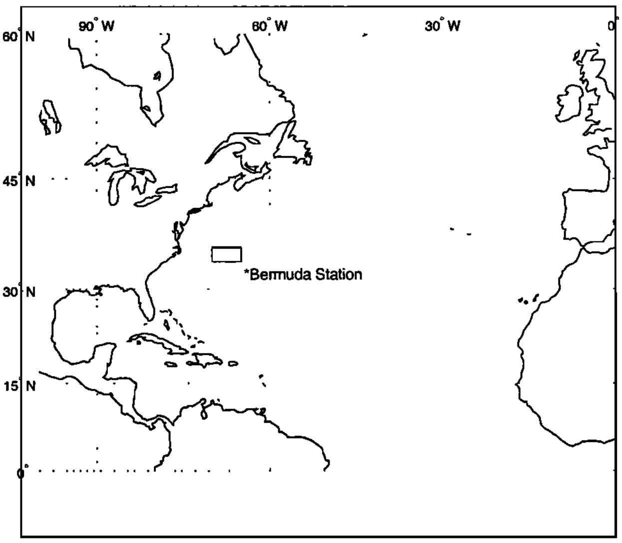

Figure 1. Location Map. The location of the Bermuda station where the time series measurements are made is indicated. STMW is formed in the area of the box.

3.1. River Flow Spectra

The 65 years of river flow data (Fig. 2, upper panel, thin line) has a strong annual signal that is obvious visually. Using Fourier methods we found that 49% of the variance was in the annual signal. The lowpass (3.6 y) flow rate data (Fig 2, upper panel, thick line) was analyzed using Fourier methods. The results showed a large, undistinguished peak in the lowest few frequency bins; as usual Fourier methods cannot separate very low frequency signals which have only a few periods in the entire record. For this reason we then used the Maximum Entropy method to examine the structure of the low frequency components.

Using the Maximum Entropy method we found that the spectrum of the low pass filtered data had four large (at least an order of magnitude greater than the background) and stable peaks. These are at periods of 36.4, 12.3, 7.6 and 5.8 years. The spectral peak at a period of 36.4 years is somewhat suspect because the data covers only about 1.5 periods of this component. However, it is the largest of the four peaks; we believe that its existence shows that there is a long period component, with a period in the range of 20 to 50 years, present in the Mississippi River flow data.

3.2. STMW Salinity Spectra

Similarly the interpolated salinity record was spectrally analyzed using Fourier methods. Again, nearly all the energy was in a large undistinguished peak in the lowest few frequency bin. The interpolated salinity data was low-pass filtered using the same filter as for the flow rate data (Fig 2, bottom panel, thick line). Applying the Maximum Entropy methods we found that this salinity record had two very narrow and large (about two orders of magnitude above the background) peaks at 11.2 years and 20.3 year periods. Least squares fitting of harmonics with these periods [*MacDonald*, 1989] to the salinity record showed that they explained 66% of the total, before filtering, variance.

It is perhaps not surprising that both these time series have spectral peaks in the same range of periods. Many geophysical time series have spectral peaks in this range of periods. The existence of these peaks does not mean that the time series are correlated. To test for correlation we performed two tests: Spearman's Rank Correlation and cross-spectral correlation analysis.

3.3. Spearman's Rank Correlation

To test for correlation we used Spearman's Rank Correlation coefficient [*Lehmann*, 1975; *Press*, 1994]. To calculate this coefficient we must use data points from both time series at corresponding times. In order to do this, for the zero lag case, we pick the set of values of flow rate on those days, and only those days, for which we have salinity values: the 757 pairs. For any non-zero lag we do the same with the values of the flow rate coming from the set of days for which we have salinity values but each shifted by the lag. The results of this calculation are shown in Figure 3. The top panel in Figure 3 shows the plot of the Spearman's Rank Correlation coefficient vs. the lag (solid line). The lag was varied from -2000 to 2000 days. Over a broad range of lags (-1000 to 1000 days) the correlation coefficient is more negative than -0.4 and has a broad peak near a lag of -400 days where it is about -0.6. The anti-correlation is what one expects: increasing flow from the Mississippi should result in a decrease in salinity and vice versa.

To further test the correlation we also calculated Spearman's Rank Correlation using the filtered flow rate and filtered interpolated salinity series. This is shown in Figure 3 (upper panel) by the dotted curve. In general, both Rank Correlation's agree, although there are differences in detail. These are expected when comparing results from measured 757 and the interpolated 15,132 pairs.

The significance of the Spearman's Rank Correlation is found by calculating the statistic t, with $t = r[(n-2)/(1-r^2)]^{1/2}$ where r is the value of Spearman's Rank Correlation coefficient and n is the number of pairs used in its calculation. This statistic is approximately distributed as Student's t with n-2 degrees of freedom. Thus we can calculate the probability that the null hypothesis, that the two time series are uncorrelated, is true. This probability (Figure 3, lower panel) is zero for lags between -1500 and 1500 indicating that the correlation is significant.

The question of how the time series may be correlated with runoff leading salinity may be explained by the fact

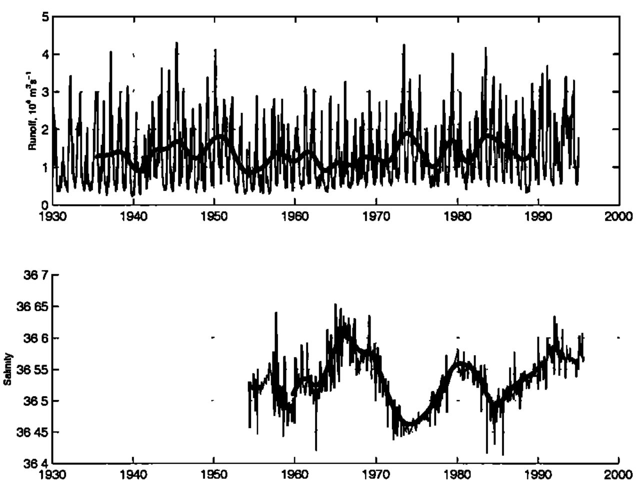

Figure 2. River flow and salinity. Upper Panel: Unfiltered (thin line) and low-pass filtered (thick line) Mississippi River daily flow. Lower Panel: Unfiltered (thin line) and low-pass filtered STMW salinity(thick)

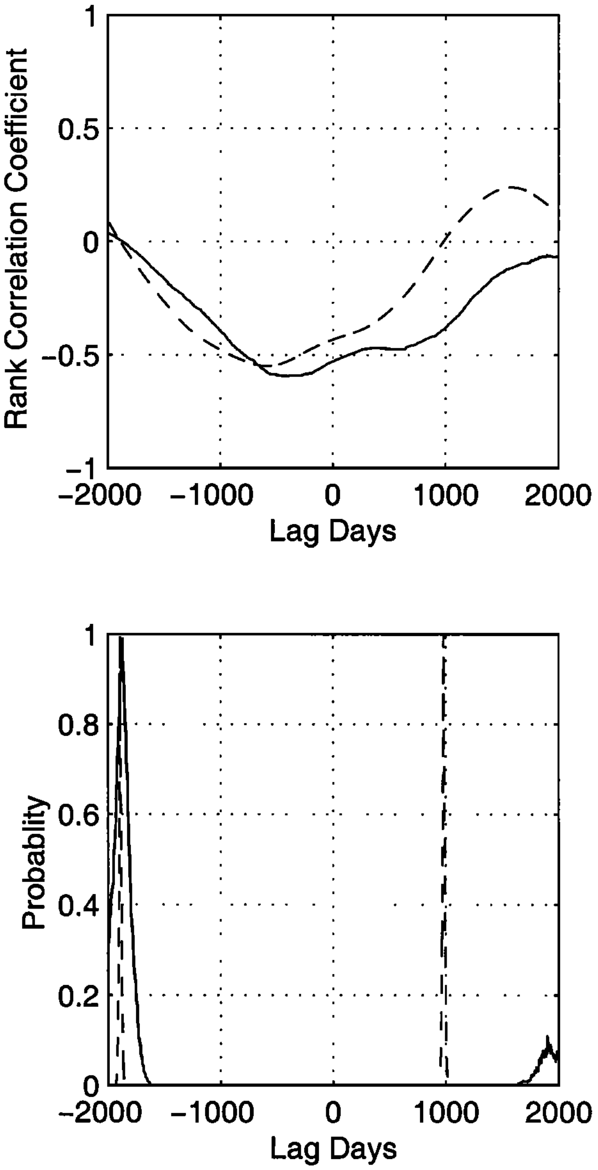

Figure 3. Spearman's Rank Correlation between unfiltered and filtered runoff and interpolated STMW salinity. Upper panel: Correlation between unfiltered (solid line) and filtered (dashed line) runoff and interpolated salinity using the Spearman Rank Correlation Coefficient at various lags; Lower panel: probability that the time series are uncorrelated.

that these time series are rather short and the salinity is correlated with prior runoff changes because all runoff changes are similar in amplitude and frequency.

3.4. Spectra and Cross-Spectra Correlation using Fourier Methods

Filtered flow rate and filtered interpolated salinity series were used to compute spectra and cross-spectra using Fourier methods. The results at low frequencies are shown in Figure 4. The spectra are normalized by dividing by the product of the appropriate variances and delta t. These spectra of the filtered data have no energy at periods greater than about 2.2 years. At the lower frequencies they have, as described above, broad undifferentiated peaks. The coherency is greater than 0.6 at the lowest frequencies where both the spectra of flow rate and salinity have significant energy. The phase in this range lies in 150 to 180 degrees; thus the two signals are nearly completely out of phase.

These results confirm the results of the Spearman's Rank Correlation coefficient calculation.

4. Discussion

Given the indications that STMW salinity and Mississippi River runoff are inversely correlated the question arises

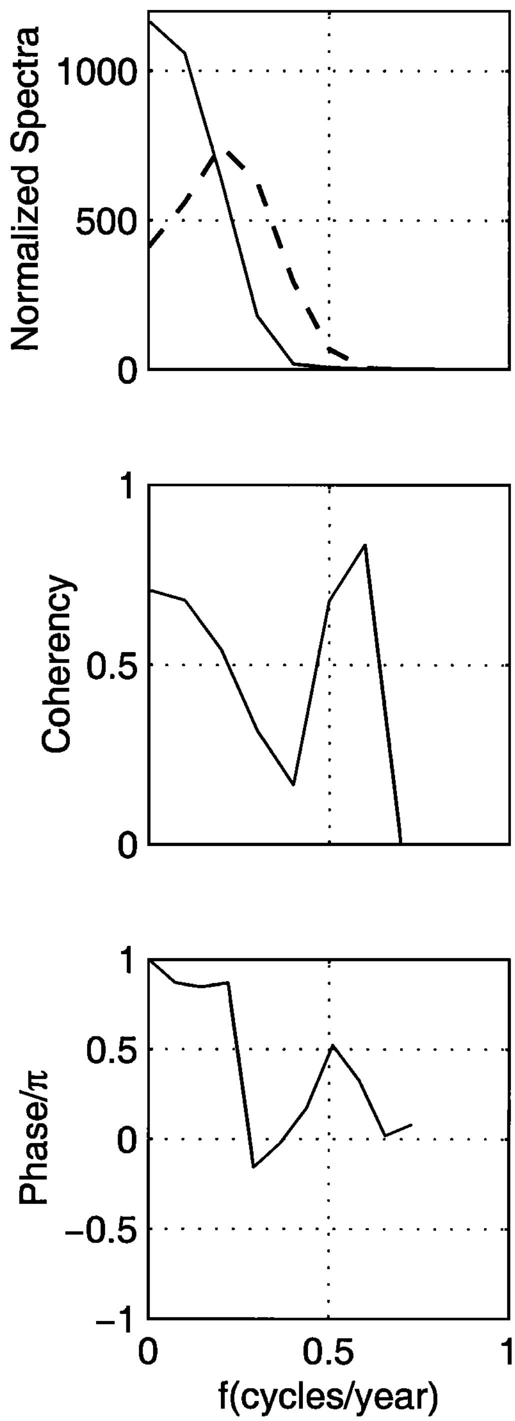

Figure 4. Cross spectra correlation between filtered runoff and salinity. Upper Panel: Normalized spectra of filtered runoff and STMW salinity; Middle Panel: Coherency between filtered salinity and runoff; Lower panel: Phase relationship between filtered salinity and runoff.

as to whether the volume of freshwater that might be transported to the formation area is sufficient to change the salinity of the STMW by the amount observed. Approximately 400 to 800×10^3 km^3 of STMW is formed each year [*Marsh and New*, 1996]. The salinity variations observed in the STMW are in the 0.1 to 0.2 range. Rough calculations suggest that about 1100 to 4400 km^3 freshwater would be required to cause the observed salinity variations. During years of high runoff such as 1972 or 1993 the flow of the Mississippi River alone amounted to ca. 500 km^3 during the summer and fall [*Goolsby*, 1994]. Of course the Mississippi is not the only river contributing to freshwater supply to the North Atlantic. The total flow from east and south coasts amounts to about 880 km^3 per year [*Guetter and Georgakakos*, 1993]. While these annualized amounts are not sufficient to cause the observed salinity anomalies alone, when we consider that the anomalies occur over nearly a decade (Figure 2) the amounts of freshwater available from North American runoff appear to be sufficient to produce a significant percentage of the observed anomalies.

The advection of water from the Gulf of Mexico and other North American shelf waters is known. Drifters are routinely released in the Gulf of Mexico and tracked as they exit via the Straits of Florida. Plate One in [*Ortner et al.*, 1995] shows the path of one such drifter. The total drift time from the mouth of the Mississippi River to the Keys was about one month and it took an additional month to reach Cape Hatteras. From Cape Hatteras to the STMW formation area is at least three months for a total transit time of at least five months. Since the STMW formation area lies south of the Gulf Stream eastward or southward winds may be required to advect low salinity water to the area. This of course happens during the late winter when STMW formation occurs.

STMW salinity variability is no doubt significantly affected by the North Atlantic Oscillation and other large scale climatic processes. NAO type climate variability processes no doubt cause the variation in runoff that we have examined. Those same processes also cause local changes in E-P at the STMW formation site however our evidence suggests that some of the observed salinity variations may be caused by river runoff.

5. Conclusion

Our results suggest that there is a real possibility that continental runoff variability may be a more significant cause of oceanic salinity variability than previously thought. Based on these results several questions come to mind: Does runoff entrained in the Kuroshio have a similar effect on the North Pacific?; Does Amazon and Gulf of Guinea runoff effect salinity in the tropical North Atlantic where Subtropical Underwater is forming? Unfortunately, there have been few systematic measurements of oceanic salinity at resolutions sufficient to determine the causes of interdecadal variations in oceanic salinity.

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