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Can long-term variability in the Gulf Stream transport be inferred from sea level?

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Abstract. Recent studies by Sturges and collaborators suggest a simple, but powerful, technique to estimate climatic changes in the transport of the Gulf Stream from the difference between the oceanic sea level calculated with a simple wind-driven Rossby wave model and the observed coastal sea level. The hypothesis behind this technique is tested, using 40 years of data (1950 to 1989) obtained from a three-dimensional Atlantic Ocean model forced by observed surface data. The analysis shows that variations in sea level difference between the ocean and the coast are indeed coherent with variations of the Gulf Stream transport for periods shorter than 1 year or longer than 4-5 years. The results obtained from the three-dimensional model confirm the findings of the simple Rossby wave model that decadal climatic changes in the Gulf Stream transport vary considerably with latitude.

Introduction

The Gulf Stream plays a crucial role in long-term climatic changes of the Atlantic Ocean, as it transports large amounts of heat and mass from warm tropical regions into high latitudes. Estimations of decadal variations in the Gulf Stream transport (GST) using climatological data and diagnostic models [*Greatbatch et al.,* 1991; *Ezer et al.,* 1995] suggest that variations as large as 30 Sv (1 Sv= $10^6 m^3 s^{-1}$), compare to a mean transport of about 100 Sv, may have occurred in the past. Unfortunately, direct observations of the long-term GST are limited to the Florida Straits (e.g., *Leaman et al.,* [1987]). Variations of sea level (except near the coast) have not been directly observed for long period of time, but can be inferred from various sources such as altimeter data [*Chelton and Schlax,* 1996], simple Rossby wave models [*Sturges and Hong,* 1995; *Sturges et al.,* 1998], or full three-dimensional models [*Ezer,* 1999; *Häkkinen,* 1999]. An intriguing and simple method has been recently suggested [Sturges and Hong, Gulf Stream transport variability at periods of decades, submitted manuscript, 2000 (SH00)] to estimate decadal changes in the GST from the sea level difference (SLD) between model calculations of offshore sea level and observed coastal sea level. Observed and model SLD and GST in the Florida Straits off Miami are indeed correlated very well, as expected. However, since there are no long-term observations of SLD and GST north of Cape Hatteras, model-derived data must be used instead. The main thrust of this note is thus to verify the results of the simpler model and to investigate the time and spatial scales of SLD and GST variability and correlation.

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Analysis

The ocean model is based on the free surface, sigma coordinate Princeton Ocean Model, POM, [*Blumberg and Mellor,* 1987]; the Atlantic configuration of the model used here, with 50-100 km variable grid extending from 80°S to 80°N, has been used for climatological [*Ezer and Mellor,* 1997] and decadal variability [*Ezer,* 1999] (E99) studies. The analyses here is based on the calculations of E99 for the period 1950-1989, where

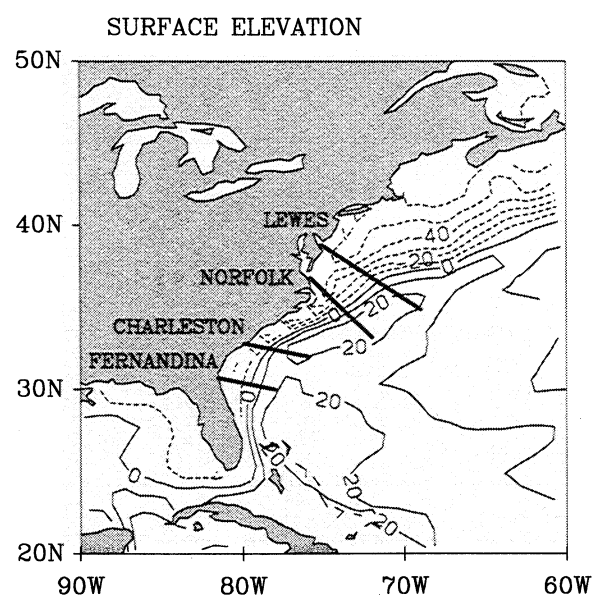

Figure 1. Annual mean surface elevation after 40 years of model calculations with climatological forcing; the three-dimensional ocean model covers the whole Atlantic Ocean but only the Gulf Stream region is shown. Contour interval is 10 cm; dashed lines represent negative values. Also shown are the four cross sections, discussed in the text. The indicated title of each section refers to the location of the coastal sea level station near the onshore side of the section.

Table 1. Cross section locations (CL-coast, OL-ocean), mean sea level difference (SLD) and mean net Gulf Stream transport (GST) across each section.

Name	CL	OL	SLD	GST
Lewes	(75.1°W, 38.8°N)	(69.9°W, 34.9°N)	82.3 cm	39.4 Sv
Norfolk	(75.8°W, 36.8°N)	(72.0°W, 33.2°N)	68.1 cm	40.7 Sv
Charleston	(79.9°W, 32.8°N)	(75.9°W, 32.0°N)	39.6 cm	27.3 Sv
Fernandina	(81.5°W, 30.7°N)	(78.0°W, 30.0°N)	37.6 cm	26.8 Sv

the model is forced by monthly mean plus interannual anomalies of surface wind stress and surface temperature data obtained from the Comprehensive Ocean-Atmosphere Data Set (COADS) [*da Silva et al.*, 1994]. The mean seasonal cycle and model climate drift, based on climatological calculations, are removed; the analyzed monthly anomaly fields reflect interannual and decadal variabilities in the atmospheric forcing, as well as basin-scale oceanic modes.

Figure 1 shows the annual mean surface elevation (or sea level) after 40 years of climatological integra-

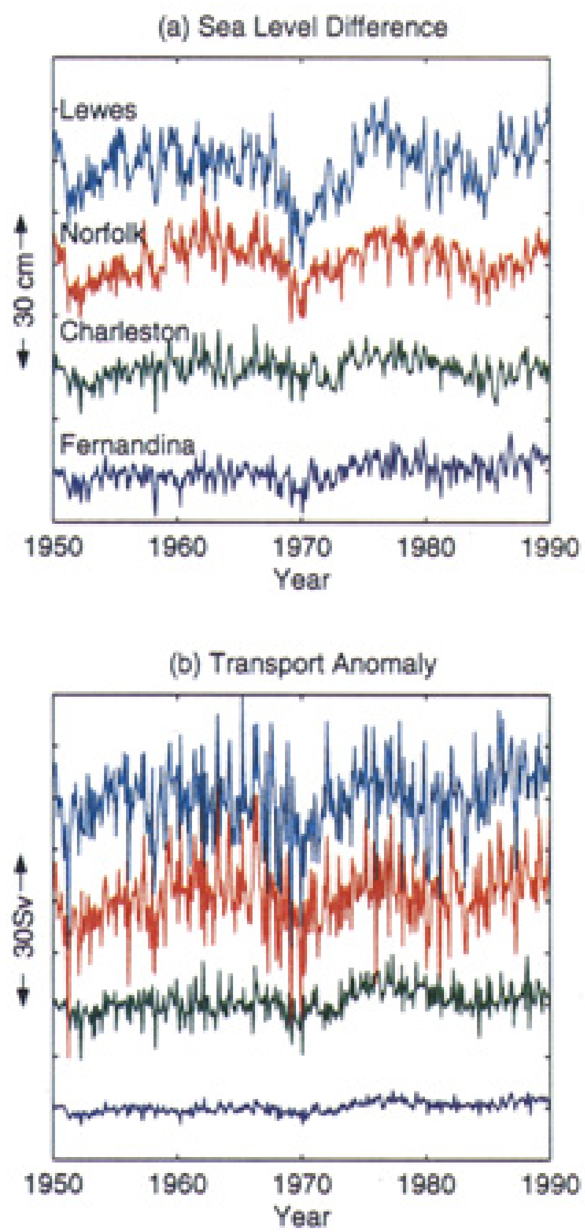

Figure 2. Time series of monthly anomaly values of (a) the sea level difference (in cm) between the offshore and the coastal ends of each section, and (b) the transport across each section (in Sv).

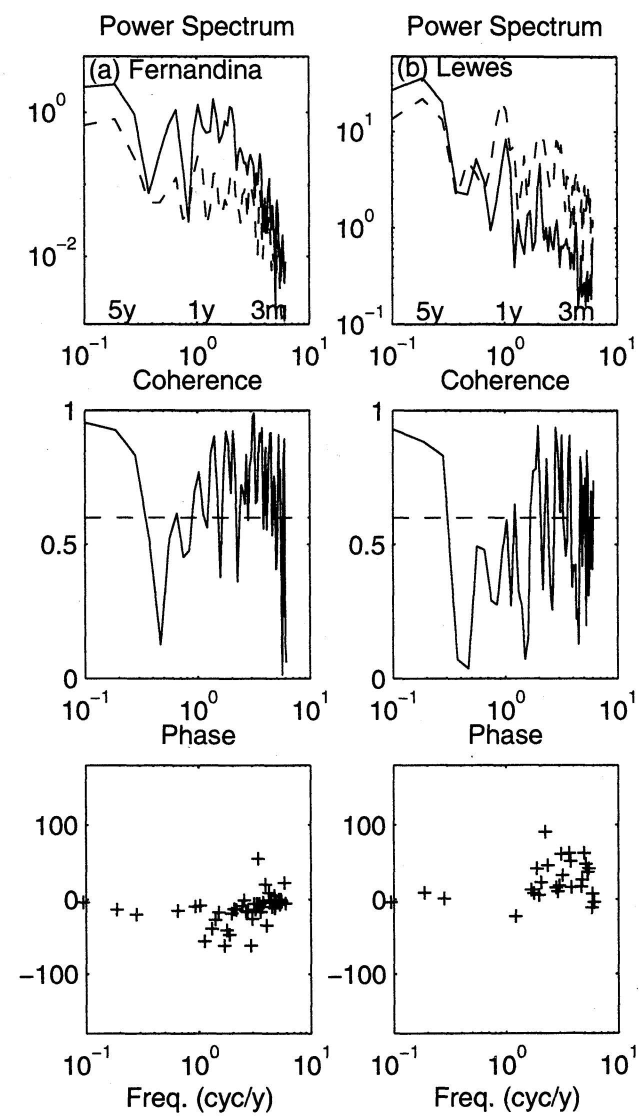

Figure 3. Spectral analysis of (a) Fernandina and (b) Lewes records. Top panels are Power spectra of SLD (in cm^2, solid line) and GST anomaly (in Sv^2, dash line). Middle and bottom panels are the coherence and phase differences between SLD and GST; phases are shown for frequencies with a coherence larger than 0.6. A coherence value of 0.8 is equivalent to a 95% confidence level.

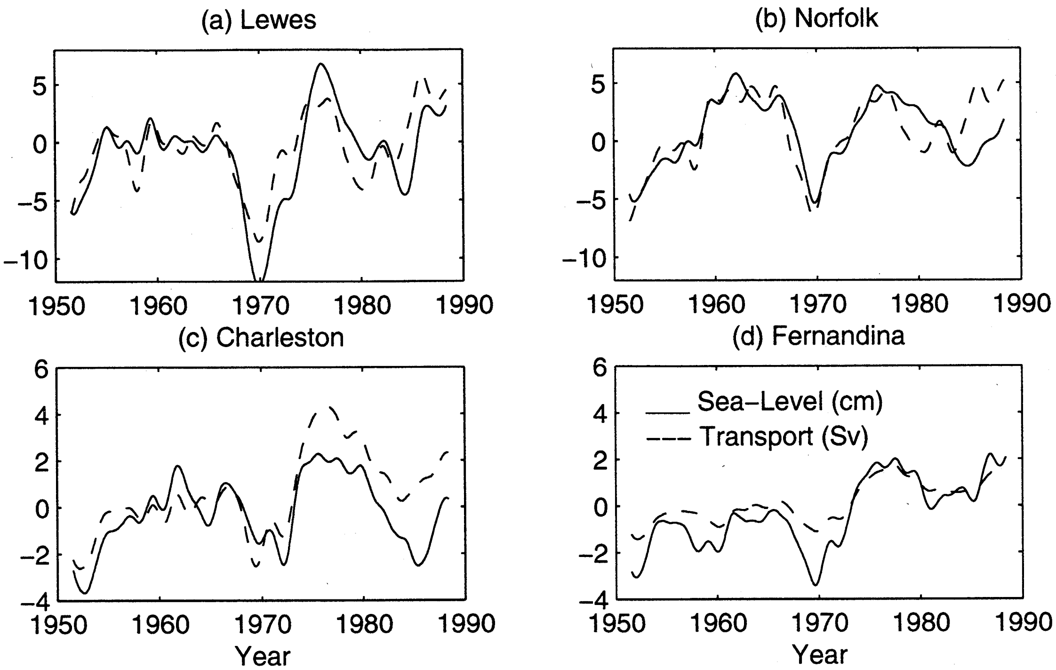

Figure 4. Low frequency variability (after applying a low-pass filter to remove periods shorter than 2 years) of SLD (solid lines) and GST anomalies (dash lines) for (a) Lewes, (b) Norfolk, (c) Charleston and (d) Fernandina. Note that the y-axes in (c) and (d) are stretched by a factor of 2 relative to (a) and (b).

tion; the Gulf Stream separation is quite realistic for a coarse resolution model of this type. Also shown on this small portion of the model domain are the four cross sections used by SH00 (the offshore locations have been slightly changed from SH00 in order to capture the entire transport of the model Gulf Stream). Table 1 summarizes the locations and time mean SLD and GST across those sections. Note the increase in SLD and GST downstream the Gulf Stream. The GST represents the net northward transport across each section, i.e., the northward Gulf Stream transport minus the return southward recirculating transport, including the deep western boundary current (see *Ezer and Mellor* [1997] for detail). Figure 2 shows the monthly anomaly of the SLD and GST records for the four sections. Note that the high frequency variability in the Middle Atlantic Bight (Lewes and Norfolk) after the Gulf Stream has separated from the coast is larger in amplitude than the variabilities in the South Atlantic Bight (Charleston and Fernandina); this result is consistent with observations. Some coherent long-term trends can be seen however, in all four locations for both SLD and GST records.

Figure 3 shows the power spectra, the coherence module and phase difference between SLD and GST for the northernmost and the southernmost locations. The spectra show high energy in low frequencies associated in the model with long Rossby waves and inter decadal North Atlantic changes (E99). High frequency variabilities in GST, associated with meandering of the Gulf Stream and fast moving barotropic waves, are more energetic than SLD variabilities north of Cape Hatteras than south of Cape Hatteras and vise versa, as seen also in Figure 2. An interesting result is that SLD and GST have large coherence (with only a small phase difference) for periods shorter than one year or longer than 4-5 years. Although the 40-year record is not long enough to calculate a statistically significant coherence for decadal and longer variabilities, qualitative comparisons can be made by looking at the records after high frequencies (periods shorter than two years) are removed with a low-pass filter (Figure 4). The comparison shows a considerable agreement in the long-term variability of SLD and GST and provides support to the hypothesis set forth by SH00. The four sections show similarities in the inter decadal changes of the Gulf Stream, indicating for example a weaker transport around 1970 and larger transports in the late 1950s to early 1960s and in the middle 1980s; these results are qualitatively consistent with other transport change estimates [*Levitus*, 1990; *Greatbatch et al.*, 1991; *Ezer et al.*, 1995; *Ezer*, 1999], and are also consistent with decadal variations in meridional heat flux [*Häkkinen*, 1999] associated with the North Atlantic Oscillations (NAO). There are however, considerable differences in amplitudes between the four sections, owing to the latitudinal dependency of propagation speed and occurrence of Rossby waves, as indicated by SH00; local recirculation gyres may also contribute to the spatial differences. The result points out the difficulty in estimating GST variability from a single section.

Discussion and conclusions

Simulations of forty years of Atlantic Ocean variabilities are used to test the hypothesis that offshore sea level variations when compared with coastal sea level data can provide an estimate of variations in the Gulf

Stream transport and thus may be used to infer climatological changes of the North Atlantic Ocean. Ocean minus coastal Sea level differences were found to be coherent with the net transport across four sections, for long-term periods associated with climatic changes and propagation of long-Rossby waves, but also for short periods of a few months associated with the meandering Gulf Stream. The method proposed by SH00 may be valid as long as the dynamics is mostly geostrophic. Small, but non-negligible discrepancies between variations of SLD and GST as evident in Figure 4, may relate to ageostrophic dynamics, local Ekman transports and local changes in recirculation gyres. It is interesting to note that the long-term SLD trend and the decadal variability (in particular at Fernandina, where high frequency noise is small, Figure 4d) closely resemble the global warming signal of the upper ocean as recently reported by *Levitus et al.,* [2000]; this similarity is explained by the fact that the offshore sea level rise in the model reflects the observed global warming trend.

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