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Variations in the Difference between Mean Sea Level measured either side of Cape Hatteras and Their Relation to the North Atlantic Oscillation

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Abstract

We consider the extent to which the difference in mean sea level (MSL) measured on the North American Atlantic coast either side of Cape Hatteras varies as a consequence of dynamical changes in the ocean caused by fluctuations in the North Atlantic Oscillation (NAO). From analysis of tide gauge data, we know that changes in MSL-difference and NAO index are correlated on decadal to century timescales enabling a scale factor of MSL-difference change per unit change in NAO index to be estimated. Changes in trend in the NAO index have been small during the past few centuries (when measured using windows of order 60 to 120 years). Therefore, if the same scale factor applies through this period of time, the corresponding changes in trend in MSL-difference for the past few centuries should also have been small. It is suggested thereby that the sea level records for recent centuries obtained from salt marshes (adjusted for long-term vertical land movements) should have essentially the same NAO-driven trends south and north of Cape Hatteras, only differing due to contributions from other processes such as changes in the Meridional Overturning Circulation or 'geophysical fingerprints'. The salt marsh data evidently support this interpretation within their uncertainties for the past few centuries, and perhaps even for the past millennium. Recommendations are made on how greater insight might be obtained by acquiring more measurements and by improved modelling of the sea level response to wind along the shelf.

1. Introduction

This paper discusses variations in the difference between mean sea level (MSL) measured at points to the south and north of Cape Hatteras on the Atlantic coast of North America, with a focus on the role of the North Atlantic Oscillation (NAO) in determining the magnitude of the difference. It is well established from tide gauge information that, on timescales of years to decades, MSL varies differently either side of Cape Hatteras (Thompson 1986), with there being considerably greater correlation between the variability in MSL at stations on the same side than between stations on opposite sides of the Cape (see Figure 3 of Woodworth et al. (2014) or Extended Data Figure 3 of

McCarthy et al. (2015a)). It has been shown (McCarthy et al. 2015a) that some of the variability in this MSL-difference can be accounted for by variability in the NAO.

Our immediate aims in this paper are to quantify the magnitude of such NAO-related variations in MSL-difference during the past century, consider if the variations might have been unusual within the context of the past several centuries, and to understand the dynamical reasons for the differences as far as possible.

These three aims are pursued in Section 2. The first involves use of the longest MSL records located on opposite sides of Cape Hatteras (Figure 1), together with measurements of the NAO index during the 20th-21st centuries. The second is addressed using NAO index values for the past several centuries, during which instrumental measurements of the NAO have been available, together with an assumption that MSL-difference and NAO are associated to the same extent throughout. For the third aim, we consider why the NAO should have any effect on the MSL-difference at all, making use of findings from a long (60 year) run of a semi-diagnostic ocean circulation model (Annex 1) that represents, qualitatively at least, the differences in the largely-wind driven MSL variability observed either side of Cape Hatteras. In addition, we consider whether there is more to understanding the variability in coastal sea level gradient, and its relation to ocean transports, than just invoking the NAO.

If MSL-difference varies in response to NAO change by a certain amount, as determined from the tide gauge data, and if such a relationship holds over much longer timescales than the 20th-21st century of the tide gauge record, then geological measurements of MSL-difference obtained from salt marshes either side of the Cape should be consistent with these ideas. Section 3 makes use of such data spanning the past millennium (we do not venture beyond that timescale) to check whether variations in trend in MSL-difference (measured within similar time spans, or 'windows', as for the tide gauge data) have the magnitudes expected from variations in trend in the NAO. Section

4 summaries our findings and provides a discussion of a number of aspects concerning the variability in the difference of MSL either side of Cape Hatteras.

2. MSL-Difference and Its Relationship to the NAO

2.1 Tide Gauge Information

The difference between coastal MSL south and north of Cape Hatteras, and its dependence on the NAO, was investigated recently by McCarthy et al. (2015a). They found a modest correlation between south-north MSL-difference and NAO during 1920-2012 (coefficient = 0.61), when both quantities were 7-year low-pass filtered, with a slightly higher correlation (coefficient = 0.71) obtained for the second half of this period (1950-2012). It is this evident association between MSL-difference and NAO that we focus on in this paper, even though sea level south of Cape Hatteras is known to be also affected by the El Niño - Southern Oscillation (ENSO) (Park and Dusek 2013; Sweet and Park 2014; Hamlington et al. 2015) and the Atlantic Meridional Oscillation (AMO) (Frankcombe and Dijkstra 2009; Park and Dusek 2013) and, we will suggest, by runoff into the South Atlantic Bight.

Figure 2(a) presents a slightly longer record of MSL-difference. It is derived from annual values of MSL at Key West minus those at New York (Battery) during 1913-2014 (in red). Data were obtained from the Permanent Service for Mean Sea Level (PSMSL, Holgate et al. 2012) and were adjusted for the inverse barometer (IB) effect using the Hadley Centre HadSLP2r air pressure data set (Allan and Ansell 2006, www.metoffice.gov.uk/hadobs/hadslp2/). The record has been detrended over the 102 year period, removing, at least to first order, contributions to the sea level difference record due to vertical land movements (primarily Glacial Isostatic Adjustment, GIA) and also due to linear trends in sea level rise at each site. Adjustments for the pole tide (approximately 14 months period with a peak equilibrium response at 45°N with an amplitude of about 5 mm (Pugh and Woodworth 2014)) were not applied as they were considered to contribute little to the variability in MSL-difference.

Key West and New York are two of the longest records in N America. They are near complete (short gaps being filled by interpolation) and of apparent good quality. The start of their common period (1913) is determined by the commencement of continuous recording at Key West. In fact, the New York record extends back to 1856 and approximately a dozen years of data are available from Key West between 1846 and 1903 (Maul and Martin 1993). However, a gap in the New York record spanning 1879-1892 results in there being only 4 years in common additional to those in Figure 2(a), the earliest of which (1858) has an anomalously low value at Key West (Figure 2 of Maul and Martin 1993). Consequently, we have not made use of this small amount of additional data.

Figure 2(b) shows the same record with a 7-year boxcar low-pass filter. This record is similar to that shown by McCarthy et al. (2015a, Extended Data Figure 7), who made use of composite time series of several stations south and north of the Cape. However, using only Key West minus New York has some advantages. For example, Figure 2(a,b) does not have the bump around 1947-8 in the McCarthy et al. (2015a) version, which we suspect stems from runoff at stations in the South Atlantic Bight. Maps of annual precipitation anomalies from the University of Delaware (http://climate.geog.udel.edu) show that there was more rainfall than normal along the South Atlantic Bight coast in 1947-8, and high sea levels occurred in those years at stations south of Wilmington along the South Atlantic Bight coast and at some stations in the Gulf of Mexico (Zervas 2009). On the other hand, Figure 2(a) has a dip in 1996-8, which is largely due to high MSL at New York that was also observed from Providence to Wilmington (Zervas 2009), that is less apparent in the station composites of McCarthy et al. (2015a).

Figures 2(a,b) also show annual mean values of the NAO index (in blue) using the principal-component (PC) based values of Hurrell (2015). This index has also been detrended over the 102 years (a small trend of only -0.0017 units/year). The two series are moderately correlated. Correlation coefficients are 0.26 and 0.30 for all data 1913-2014 and 1950-2014 respectively, and 0.49 and 0.62 respectively after 7-year filtering (Table 1). For the shorter, earlier span of data 1913-

1949, a coefficient of only 0.12 is obtained, or -0.21 after 7-year filtering, consistent with other observations of generally weaker correlations between NAO and MSL along the N American coastline during the earlier part of the 20th century (see Andres et al. 2013 for a discussion of data north of Cape Hatteras).

The trend in the Key West minus New York MSL record changes by 3.09 mm/year, from -0.95 mm/year during 1928-1968, which is the main section of clearly declining annual mean NAO, to 2.14 mm/year during 1969-1992, which is the main section with clearly increasing NAO. In the two periods, the Hurrell NAO index changed at rates of -0.023 and 0.080 units/year respectively.

Instead of the long-shore pressure gradient of south minus north MSL-difference used above and by McCarthy et al. (2015a), one might have thought that MSL south of Cape Hatteras would have a higher correlation with the NAO than the MSL-difference, given that MSL south of the Cape is closely correlated with the strength of the subtropical gyre, and MSL to the north is not; we return to this topic in Section 4. However, over the periods 1913-2014 and 1950-2014, the observed MSL at Key West and the NAO had correlation coefficients of only 0.19 and 0.22 respectively, and 0.12 and 0.28 after the 7-year filter, which is weaker than for the MSL-difference. Meanwhile, correlations of NAO and MSL at New York yield coefficients of -0.14 and -0.18 for the two periods respectively, and -0.37 and -0.51 after the 7-year filter. Taking 1950-2009 for the later period, instead of 1950-2014, so as to exclude the anomalous negative NAO value in 2010 (see below), yields almost the same set of coefficients apart from a somewhat higher value of 0.60 for Key West using the 7-year filter.

It can be seen that, even though MSL north of Cape Hatteras is known to be a relatively noisy quantity, from a greater amount of wind-forced variability over the northern shelf than that to the south of Cape Hatteras (Woodworth et al. 2014), and even though MSL south and north are only individually correlated weakly with the NAO, there is value in employing both sets of information in the MSL-difference. In fact, this sort of relationship between correlation coefficients is expected: if there is also some large-scale variability common to north (N) and south (S) that is unrelated to the

NAO then, even if there is no correlation between the N station and the NAO, but a positive correlation between the S station and the NAO, then the S-N difference could have a higher correlation with the NAO.

2.2 NAO Trends During the Last 300 Years

Figure 2(a) shows that the NAO had a positive trend from the late 1960s to the early 1990s, and in the several decades before, and in the years afterwards, its trend was negative. However, the Hurrell (2015) PC-based values are limited to the period 1899-onwards. For information on the NAO over a longer period, one must make use of either station-based values or the 'reconstructed' estimates available from several authors. Figure 3(a) shows the annual mean 'reconstructed NAO values' of Luterbacher et al. (1999, 2002) obtained from http://www.cru.uea.ac.uk/cru/data/paleo/naojurg/. These analyses make use of instrumental air pressure measurements together with multi-proxy information (temperatures, rainfall and documentary data) within a principal component regression analysis. The NAO index is calculated from reconstructed air pressure fields up to 1900 after which fields obtained from updates to the analysis of Trenberth and Paolino (1980) are used. The resulting NAO values are available to 2001, which we have extended to the present using the Hurrell (2015) PC-based values. Figure 3(b) shows the two NAO time series are similar for most of the 20th century, although the amplitude of the Hurrell variability is larger than that of Luterbacher et al. between 1940 and 1980.

A number of other versions of the NAO index are available. For example, there is a Hurrell station-based record extending back to 1865 but it has considerably greater variability than the PC-based version. Instead, we have included in Figure 3(b) the station-based time series from the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/nao/), which employs station air pressures from Gibraltar and SW Iceland (Jones et al. (1997) together with the 'Tim Osborn NAO update' provided on the web site) and starts in 1825. This is the longest instrumental record of the NAO (Vinther et al. 2003) and has similarities to that of the Luterbacher et al. record. Therefore, there is some

confidence that the reconstructed record is a reasonable representation of the NAO for the last two centuries. Before approximately 1780, the amplitude of the reconstructed NAO variability is smaller than in the following two centuries, and there is only approximate similarity with other versions of the NAO record in this earlier period (e.g. see Figure 10 of Cornes et al. 2013). The anomalous negative value in 2010 has been discussed by Osborn (2011).

Comparisons between the Luterbacher et al. record and other reconstructions, with a focus on the wintertime NAO for the last millennium, have been made by Trouet et al. (2009), Pinto and Raible (2012) and Ortega et al. (2015) (see also Lehner et al. 2012 and Baker et al. 2015). For example, Figure 3 of Pinto and Rable (2012) demonstrates the close agreement between versions of the wintertime index computed by different groups for the late 19th century onwards, with significant differences more apparent before that time.

Figure 3(c) shows the trends in the Luterbacher et al. annual NAO index within moving 30-year sections of the record (that we call 'windows'), 30 years being the approximate length of clearly increasing or decreasing NAO and MSL-difference discussed in Section 2.1. It can be seen that the trend leading up to 1990 (i.e. the 30 year window centred on around 1975) was almost as high as at any time in the last few 100 years. The large negative values at the end of the record are due to the anomalously low NAO in 2010. Consequently, given the associations between NAO and MSL-difference explored in Section 2.1, we can propose that the trend in MSL-difference between south and north of Cape Hatteras was also unusually high in the period leading up to about 1990, compared to other periods in the past few 100 years.

The 30-year NAO trends vary with a period of approximately 60 years. This is a similar period to that of the Atlantic Meridional Oscillation (Knudsen et al. 2011), while sixty year cycles have been remarked on with regard to variations in regional and global sea level (Chambers et al. 2012). Consequently, this aspect of the Luterbacher et al. record is of some oceanographic interest. Luterbacher et al. (1999) and Wanner et al. (2001) commented on this periodicity, and the latter

subjected the record to a wavelet analysis. Cullen et al. (2001) reviewed the Luterbacher et al. and other NAO reconstructions available at that time, pointing to the 60 or 70 year periodicity in some time series but questioning the robustness of the signal. As far as we know, Mazzarella and Scafetta (2012) is the only paper to have investigated the relevance of the ~60 year period in climate studies. At the present time, we take the Luterbacher et al. time series at its face value and whether its ~60-year cycle is real or not remains to be seen.

Consequently, one can arrive at approximate estimates of the dependence of MSL-difference south minus north of Cape Hatteras on changes in the NAO. Two methods have been used. Common to both methods is an observation that the trend in the NAO for the late 17th century onwards is essentially zero; a linear fit to the Luterbacher et al. data in Figure 3(a) gives a trend of 0.0004 units/year. Whether this value is formally consistent with zero or not is not our main interest; the point is that this mean value is much smaller than the variability in trends in windowed sections of the record.

The first method computes the ratio $r = \frac{\sigma_{MSL-DIFF}}{\sigma_{NAO}}$, where $\sigma_{MSL-DIFF}$ is the standard deviation of annual MSL-difference over the 102 years during the 20th-21st century, as shown in Figure 2(a), and σ_{NAO} is the standard deviation of the annual mean NAO index in that time. The value of r is estimated to be approximately 61 mm per NAO unit. We then use r to scale the rates of change of the NAO index of Luterbacher et al. (1999, 2002) within 60 or 120 year windows, in order to infer rates of change of MSL-difference within those windows. The NAO rates through the available record have standard deviations of 0.0046 and 0.0016 units/year for 60 and 120 year windows respectively. Therefore, the standard deviations of MSL-difference are inferred to be 0.28 and 0.10 mm/year respectively. This method assumes that rescaled NAO variability is a proxy for sea level variability, and that the relationship for interannual variations also holds at longer time scales. If the observed interannual sea level variability is dominated by other causes, but the relationship

between sea level and NAO is independent of time scale, this method will overestimate the long-term sea level response.

The second method computes r as the ratio of the difference between the rates of change of MSL-difference in the declining and increasing periods of NAO change discussed above (i.e. 1928-1968 and 1969-1992) to the difference between the rates of change in the NAO in those times. It then again uses r to scale the rates of change of NAO index in each window. In this case the ratio is estimated to be much larger at 115 mm per NAO unit. The fact that the ratio from this method is larger than from the first indicates that the sea level response to NAO could depend on timescale, and be larger at longer timescales. Therefore, this second method is the more conservative, and suggests that the standard deviation in the MSL-difference trends either side of Cape Hatteras will be of order 0.53 and 0.18 mm/year using 60 or 120 year windows respectively.

These estimates of the dependence of the trend in MSL-difference on trend in the NAO, derived from tide gauge data from the 20th-21st century, will be applied in Section 3 below to a consideration of the MSL-differences obtained from salt marsh data. (Of course, neither of these two methods takes into account the uncertainties in determining MSL-difference due to measurement errors in the geological data itself.)

2.3 The NAO and Related Wind Forcing on the North American Atlantic Shelf

The case for an association between MSL-difference and NAO has so far been made on the basis of their modest correlation (Figure 2a,b), while consideration of the variability in NAO trend for the past several centuries led to estimates of variability in MSL-difference over such timescales. However, to gain any plausible physical insight into why this association exists, a next step is to ask how changes in the NAO might be reflected in the changes in the wind field that drives the Gulf Stream, and how that manifests itself in changes in MSL-difference. The main links can be inferred from Figures 4, 5 and 6.

Figures 4(a,b) compare annual MSL measured at Key West and New York respectively with that simulated by our semi-diagnostic model (Annex 1). It has to be recognised that the model is not perfect, with correlation coefficients between measured and modelled MSL tending to be larger at northern sites, and specifically 0.43 and 0.58 at Key West and New York respectively; the latter rises to 0.69 if the years 1996-8 are excluded as mentioned above. As a consequence, the correlation coefficient between modelled MSL-difference, shown in red in Figure 4(c), and the measured MSL-difference in Figure 2(a) is only 0.44 (1996-8 excluded), being determined largely by the lower skill in simulation of Key West. Both MSL-difference time series fluctuate up and down around 1960, then increase from around 1969 to the late-1990s, after which the model time series flattens off or falls slightly. However, it has a smaller trend than the observations during the 1969-1992 period of increasing NAO.

In spite of the model limitations, we can attempt to learn something from it regarding links between MSL-difference and Gulf Stream transport in the real ocean, the mean transport (defined at 25.6° N, just south of Miami, between the US coast and 75.5° W) being estimated well by the model (29.1 Sv compared to mean and standard deviation 31.6 ± 3.1 Sv from measurements over 2004-2014, see http://www.rapid.ac.uk/rapidmoc/rapid_data/rapid_transports.php). We should expect an MSL-difference in the model across, and along, the western boundary current because of geostrophic and beta dynamics (Stommel 1948; Munk 1950), with the Coriolis force and MSL-difference in approximate geostrophic balance across the boundary, and with the pressure gradient caused by the MSL-difference in frictional balance along the boundary. Each set of MSL-differences could be considered as proxies for changes in transport, although, given our poor understanding of ocean friction, we expect the latter balance to be more uncertain than the former.

In the present model, MSL-difference across the current along 25.6° N is highly correlated with transport (coefficient = 0.78) and slightly less along-current using test positions on the shelf north and south of Miami at 24.6 and 26.6° N and 79.75° W (coefficient = 0.59). If the southern test

position is taken 1° south and east of Key West, instead of the southern Miami position, then almost the same correlation is obtained (coefficient = 0.56). The correlation remains much the same, although weakening slightly, as the northern position is moved along the coast, up to and beyond Cape Hatteras, until one arrives at a point on the shelf 1° south and east of New York (coefficient = 0.47). This is shown by the black and green lines for transport and MSL-difference respectively in Figure 4(c). However, MSL-difference using MSL exactly at the coast seems unrelated to transport (coefficient = 0.09), the correlation being weakened by differences between MSL measured at the coast or off-shore (e.g. the higher values for Key West in the early 1970s, and the sharp dip for New York in 1976-7, shown in Figures 4(a,b), are attenuated off-shore; comparison of the two MSL-difference time series in Figure 4(c) yields a correlation coefficient of 0.58). The modelled coastal MSL values, rather than the off-shore ones, are required, however, in order to simulate the features in the tide gauge observations mentioned above (Figures 4a,b).

Therefore, if the model is to be believed (and knowing how difficult it is to model coastal areas correctly), we suspect that inferences on changes in real ocean processes that depend upon volume and heat transport are likely to be much harder to make using coastal rather than off-shore shelf measurements of MSL. Second, we note that neither of the MSL-difference time series (i.e. at the coast or off-shore), nor that of transport, have much apparent association with the NAO (correlation coefficients of order 0.2, higher values being obtained for MSL off-shore in the south). We return to these issues in Section 4).

Consequently, while it has been reasonable to associate MSL-difference and NAO in the tide gauge analysis of Section 2.1, it is proved more difficult to provide a link via the ocean transport, at least as we have defined that quantity. Nevertheless, it is still possible to make a general argument that any real NAO-related forcing of the ocean circulation will be represented in MSL-difference to some extent over longer timescales. Figure 5 presents the modelled trend in sea level across the N Atlantic during the period of strengthening NAO discussed above (1969-1992), when the transports were

increasing (black and green lines in Figure 4c), the gyres also strengthened and there was a fall in sea level for northern shelf areas compared to those to the south of Cape Hatteras. (Trends are based on simple least-squares fits. A small area-average trend for the basin has been removed from this map; this area-average trend is small owing to the model's volume-conserving (Boussinesq) formulation.)

Finally, the link between changes in the NAO and the winds that drive the N Atlantic circulation can be seen from Figure 6, which makes use of the long time series of wind stress now available from the 20th Century Reanalysis Project (20CR, Compo et al. 2011). (Although changes in wind forcing are likely to be the main manifestation of the NAO, is also known to be related to changes in buoyancy forcing (Marshall et al. 2001).) For the period shown (1928-1992), when Figure 2(a) demonstrates that there was a large positive acceleration in the rate of change of MSL-difference and NAO, the annual mean 20CR wind stress field also contained accelerations (Figure 6). Strong westerlies in the N Atlantic can be seen between the two centres of action of the NAO, together with strong easterly trade winds in the south. In addition, there is a near-coastal band of strong winds along the American coast, that is largely confined to the shelf and nearby deep ocean. (More detailed comparisons with 20CR information should be undertaken with caution given the uncertainties in the data set, see Krueger et al. 2013.)

Diagnosing the importance of winds in particular regions from model results can be difficult. However, Figure 6 demonstrates that any sea-level assessment of the NW Atlantic needs to take the shelf responses to wind as fully into account as possible, as observational studies have shown (e.g. Andres et al. 2013) and as our modelling has attempted to do. Over the longer timescales of interest to salt marshes, one would expect such spatial differences in accelerations to be less important, unless there were to be continued acceleration in wind stress, which would imply corresponding long-term changes in the NAO, and air pressure and wind fields in general, for which there is little evidence.

3. MSL-Difference over Longer Timescales than the Tide Gauge Record

In this section, we turn to consider variations in MSL-difference over timescales longer than the 102 years of the tide gauge record, and longer even than the several 100 years of the instrumental record of the NAO index.

An important source of information on sea level changes on timescales from decades to centuries, and sometimes for the past 1000-2000 years, comes from the analysis of cores obtained from salt marshes. These studies use the vertical sediment accretion rates in the upper regions of salt marshes, generally between the levels of mean high water of spring tides and the highest astronomical tide, as a substitute (or proxy) for the rate of sea-level rise. Small changes in the height of buried marsh surfaces relative to tidal datums are detected from changes in the microfossil population (primarily foraminifera) through carefully selected cores. The former tidal elevations are quantified by transfer functions that compare the fossil foraminiferal assemblages with the surveyed distributions of their counterparts in the modern marsh environment. The salt-marsh sedimentation rates are constrained by various dating techniques (primarily radiocarbon dating). The combination of microfossil analyses and high-precision dating is a powerful tool that can generate decadal-scale sea-level reconstructions with decimetre precisions. As IB corrections over many centuries are not possible, an assumption of constant air pressure is implicit in any dynamical analyses of the data. (In the present study, which involves analysis of MSL-differences rather than individual MSL records, the IB corrections can be expected to have little importance, there being virtually no change even to the tide gauge time series of Figure 2 with or without IB correction.) Barlow et al. (2013) and Shennan et al. (2015) provide detailed descriptions of the methods employed by salt marsh researchers.

Kemp et al. (2015) have recently reviewed the salt marsh records from the US coast. Four long records are now available from Florida, North Carolina, New Jersey and Connecticut, describing sea level change during the past 2000 or 2500 years (Figure 1). Each record has been described individually in detail in a series of papers (Kemp et al. 2011, 2013, 2014, 2015). The records have been used in a number of studies of sea level changes and their impacts along this coastline (e.g.

Miller et al. 2013), and of contrasting aspects of sea level change either side of the North Atlantic (Long et al. 2014). Most recently, Kopp et al. (2016) have used these data together with tide gauge and other salt marsh information from around the world in a study of temperature-driven global sea level variability in the Common Era, and have made the North American and other salt marsh data available via https://www.ncdc.noaa.gov/paleo/study/19823.

One can refer to the Florida record in particular as it is the only one south of Cape Hatteras. It has poorer temporal resolution than the three others, although it is as good in the sense that slices of core generated an equally good age-depth model. The temporal resolution is poorer primarily because of the low rate of GIA which means each cm of core in Florida represents approximately three times as much time as in New Jersey, for example. Kemp et al. (2014) combined the salt marsh measurements with data from the Fernandina Beach tide gauge in order to maximise the amount of sea level information available for analysis at this location, an approach later followed for the Connecticut salt marsh data which was combined with a regional tide gauge time series constructed from the records of seven gauges in Long Island Sound (Kemp et al., 2015).

Once each record has been detrended over its entire record length to remove the contribution to relative sea level change from vertical land movement (assuming a linear rate of movement which is reasonable for GIA over 2000 years), the four records demonstrate a similar recent history, with an increase in the rate of sea level rise during the second part of the 19th century, accelerating until the rate reaches ~2-2.5 mm/year at present (Figure 8 of Kemp et al. 2015). The authors estimate rates of sea level rise during the 20th century of ~1.9 mm/year for Connecticut, New Jersey and North Carolina respectively, and ~1.5 mm/year for Florida, each of these above the longer-term background rates at each site. From change point analysis of their salt marsh time series, Kemp et al. (2015) conclude that the '20th century' sea level rise commenced around 1865-1873 similarly in Connecticut, New Jersey, North Carolina and Florida, a conclusion consistent with the later analysis of Kopp et al. (2016).

Figure 7 shows MSL-difference and rates of change of MSL-difference for the past 1000 years derived from salt marsh records south and north of the Cape, with each record adjusted to remove a long-term component due to GIA. The data are derived from the Errors-In-Variables Integrated Gaussian Process (EIV-IGP) model fits to each individual salt marsh record as shown in Figure 8 of Kemp et al. (2015), using the technique described by Cahill et al. (2015). Since salt marsh sample ages are uncertain, the EIV approach is necessary to also account for error in the explanatory variable (sample age), which is assumed to be accurately known in standard regression methods; the IGP component provides a practical approach to modelling non-linear time series data such as salt marsh sea level reconstructions (Rasmussen and Williams 2006; Kemp et al. 2015). As a result, the EIV-IGP approach provides continuous time series of sea level versus time, instead of the individual heights and times of measured salt marsh data points. Each time series can then be sampled at any required intervals of time, that are chosen to be increments of 50 years for the present Figure 7, which is similar sampling to the lengths of windows used to investigate trends in the NAO above. The same sampling applied to two time series enables a continuous time series of MSL-difference to be computed.

Figure 7(a) shows the time series for the MSL-difference south minus north of Cape Hatteras as represented by the Florida and New Jersey time series in the left panel of Figure 8 of Kemp et al. (2015) (reproduced here in Figure 7e), while Figure 7(b) demonstrates the difference in the rate of change of MSL south minus north of Cape Hatteras as represented by the corresponding time series in the right panel of Figure 8 of Kemp et al. (2015) (reproduced here in Figure 7f). In both (a) and (b), the inner and outer errors bars indicate the 68% and 95% credible intervals calculated by combining in quadrature the intervals for the two individual time series. The maximum MSL-difference at around 1500 in Figure 7(a) can be seen from Figure 8 of Kemp et al. (2015) to be due to low MSL during several centuries around this time (relative to the background long term trend due to GIA) in the New Jersey record, with a much smaller corresponding signal in the Florida record. Similarly, the

negative MSL-difference around 1000 is primarily due to high MSL values in New Jersey, Florida presenting a much flatter record overall.

Differences between the Florida and Connecticut salt marsh records provide an alternative to using Florida and New Jersey; Connecticut is located at a similar distance north of the New York tide gauge as New Jersey is to the south. There are differences between the New Jersey and Connecticut records. For example, they have different contributions from GIA. In addition, while the Connecticut core is considered to be free of compaction effects, some compaction cannot be ruled out within the long New Jersey core (although that is also considered to be small, Andrew Kemp, private communication). In spite of these differences, findings from Florida minus Connecticut shown in Figure 7(c,d) can be seen to lead to similar findings, within the uncertainties shown, as for Florida minus New Jersey in Figure 7(a,b).

So do the rates of MSL change measured south and north of Cape Hatteras over the past several centuries differ by more than the anticipated association between MSL-difference and NAO variability discussed above? The tentative answer is 'no': it can be seen that the salt marsh data demonstrate differences in trend south minus north for the past few 100 years of 0.5 mm/year or less (Figure 7b,d), consistent with the findings of Section 2.2.

It is harder to arrive at conclusions regarding the longer timescale variability shown in Figure 7, such as the maximum positive values for MSL-difference around 1500 and the negative values towards 1000, both of which are primarily artefacts of low-frequency MSL variations in the northern records. For one thing, most of the available NAO-proxy indices that one can compare to are more wintertime than annual measures of the NAO. In addition, there are differences between them. For example, Baker et al. (2015) suggest a sustained period of negative NAO around 1500, while Trouet et al. (2009) or Ortega et al. (2015) do not. All three tend to have large positive index values (approximately twice the magnitude of later values) in the earlier period back to 1000. Altogether, these comparisons tend to imply, if anything, an opposite relationship between MSL-difference and

NAO on longer timescales than we have considered for the past century from the tide gauge record and the last few 100 years from the instrumental NAO record.

4. Discussion

The extent to which MSL varies differently either side of Cape Hatteras, at least on interannual to multidecadal/half-century timescales, can be studied with an ocean model (Annex 1). Figure 8(a) shows the correlation between annual mean sea level at each point in the model grid with respect to that at a reference point north of Cape Hatteras, near New York (74.0°W, 40.5°N). Most of the high correlation is confined to the northern shelf, with weaker correlation for the shelf waters in the south, and does not extend throughout the NW Atlantic. Part of the reason for this localised pattern is the high wind-forced sea level variability on the shelf north of Cape Hatteras (Andres et al. 2013; Woodworth et al. 2014).

Figure 8(b) shows the corresponding distribution with respect to a point south of Cape Hatteras, near Key West, at the southernmost extent of Florida (81.8°W, 24.6°N). This is a very different situation, with coastal sea level variations at this point representative of those across a swathe of deep ocean between Florida and the central N Atlantic, roughly following the Gulf Stream. The distributions of Figure 8(a,b) remain much the same if the annual mean values are low-pass filtered using 7 or 15 year filters.

In other words, MSL measured north of Cape Hatteras represents largely the local (wind) forcing and not the sea level variability of the deep ocean, while that to the south does more closely represent deep ocean levels. Piecuch et al. (2016) have recently arrived at similar conclusions with the use of a number of data-assimilating 'ocean reanalysis' ocean models and a barotropic model.

Therefore, if there is an NAO component to the local wind forcing over the shelves and/or to the gyre circulation in general, there should be NAO-related differences between MSL measured south and north of Cape Hatteras. In fact, annual mean sea level variability along the coast south of Cape

Hatteras, as simulated by the model, is correlated moderately positively with the NAO while that to the north has approximately zero or even slightly negative correlation (Figure 9), consistent with the weak positive correlation in the south and the weak negative correlation in the north found between tide gauge data and the NAO discussed in Section 2.1, with stronger correlation between MSL and NAO off-shore in the south, as discussed in Section 2.3.

Consequently, these findings, based on our analysis of tide gauge data and on ocean modelling, are consistent with those of McCarthy et al. (2015a), in showing that a relationship exists between the trends in south-north MSL-difference and the NAO over the 102 years of available tide gauge data spanning the 20th and 21st centuries. From examination of changes in NAO trend (using 30-year windows) over the past few 100 years, for which instrumental measurements of the NAO are available, we believe that the 20th-21st centuries contained periods of NAO trend over several decades, and hence trend in MSL-difference, as large (positively and negatively) as any in the recent historical record. This led to an assessment of the amount by which one might have expected changes in MSL to vary either side of the Cape (using for example 60 or 120 year windows) during the past few 100 years. We estimated that the rates of change in MSL-difference measured using windows of this size should be of the order of several tenths to approximately 0.5 mm/year, which was found to be consistent with geological evidence from salt marshes (Figure 7).

Implicit in this simple exercise is an assumption that variability in MSL-difference and NAO are correlated to the same extent as one goes back in time. We have shown above that the correlation is weaker for the 20th -21st centuries as a whole than for the mid-20th century onwards (see also the discussion in Andres et al. 2013) and if the correlation differed significantly through the centuries that would invalidate our estimates of possible range in MSL-difference. Moreover, we suspect that the modest correlation of MSL-difference and NAO for the 20th -21st centuries obtained above occurs because this period experienced several decades of positive and negative trend in both quantities that corresponded to their full range of variability over a much longer period (cf. Figure 3c), and

therefore any correlations longer term are likely to be weaker. (The need to detrend the tide gauge MSL-differences in Figure 2, to remove the contribution of differential vertical land movements, may also introduce uncertainty in the lower-frequency component of MSL-difference used for comparison to the NAO.) However, in support of our approach is the general plausibility of a dynamical connection between NAO and MSL-difference and therefore the likelihood of a positive, if weak, correlation on decadal to century timescales (Section 2.3).

It is evident from the tide gauge analyses (Figure 2) and ocean modelling that only small (centimetric) changes in sea level difference south and north of Cape Hatteras are associated with the NAO. Figure 5 makes a similar point on how small the NAO-associated changes in sea level are across the basin. This figure refers to a period of several decades in which the trend in the NAO index was as large as any in the last few hundred years (Figure 2c), and in which sea surface height in the subpolar gyre decreased, and that in the subtropical gyre increased, by only ~1 mm/year with a small transfer of water between the gyres.

Although we have shown that there is some association of the NAO with the variability in MSL-difference, the NAO is clearly not the whole story with regard to the overall MSL variability along this coast. For example, if one removes the possible NAO contributions to MSL variability in the semi-diagnostic model, by regressing MSL against NAO index at each model point (the latter as the independent variable), then Figures 8(a,b) are not altered significantly in coastal areas, nor even in much of the neighbouring deep ocean in spite of there being modest correlation between MSL and NAO as shown in large parts of Figure 9. In addition, we have shown in Section 3 that a firmer association of NAO and MSL-difference over multi-century to millennium timescales is yet to be established.

This brings us to discussion of other processes which may or may not be connected in some way with the NAO, and which could result in different sea level south and north of Cape Hatteras. For example, the sea level acceleration in recent decades at stations in the Middle Atlantic Bight to the

north of Cape Hatteras, and not to its south, has been discussed in the context of changes in the MOC (Boon 2012, Sallenger et al. 2012; Kopp 2013; Piecuch and Ponte 2015). Whether this is the case remains to be seen: Woodworth et al. (2014) concluded that any MOC-related changes in coastal sea level during the 20th-21st centuries will have been masked by the effects of local winds.

Of greater interest (and more relevant to the interpretation of salt marsh data) is the question of whether there have been significant MOC-related changes over longer (e.g. century to millennium) timescales. As a rough guide, one can consider the estimate of a 2 cm decrease in western boundary sea level at 43 °N for an increase of 1 Sv in the MOC transport (Bingham and Hughes (2009), see also Yin et al. (2009), Lozier et al. (2010) and Yin and Goddard (2013). This estimate could be uncertain by approximately 40% depending on details of effective thermocline depth.) An argument can be made for a decrease in this sensitivity, from 2 cm/Sv at 43 °N to essentially zero south of Cape Hatteras and along the Florida coast, which fits to the coastal spatial mean dynamic topography (MDT) signals shown for this region in Woodworth et al. (2012) and Higginson et al. (2015). In those studies, there is a ~30 cm drop in MDT as one progresses northwards along the coast from Florida to Cape Hatteras. A smaller MOC would reduce the Gulf Stream flow resulting in less of a northward fall in sea level.

Therefore, the fluctuation in MSL-difference of approximately 12 cm between 1000 and 1500 in Figure 7 would correspond to a 6 Sv increase in the MOC, which may be compared to an estimated present-day MOC transport of approximately 18 Sv (McCarthy et al. 2015b). Similarly, a complete MOC shutdown collapse would have produced a 36 cm decrease in MSL-difference (or say 2-4 mm/year if taking place over a century), which Figure 7 shows clearly never occurred in the last millennium. To put these estimates into a future context, the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Collins et al. 2013) project an MOC reduction by 2100 of 11% (RCP2.6) to 34% (RCP8.5), which translates to 4-12 cm of sea level rise at 43 °N, or an MSL-difference decrease of that amount, which is a century-scale signal of order 1 mm/yr.

Any other sea level changes along the coast (apart from those due to vertical land movements, primarily GIA, which one can assume to have approximately the same rates over the past few centuries) must be due to 'geophysical fingerprints', such as those due to the mass balance of Greenland (Tamisiea and Mitrovica 2011; Kopp et al. 2015), and to the many glaciological and hydrological processes that result in 'eustatic' sea level changes. A geophysical fingerprint due to melting of the Greenland ice sheet equivalent to a global-average sea level rise of 1 mm/year would produce a rate of rise measured in Florida that is several tenths of mm/year larger than that in Nova Scotia (Tamisiea and Mitrovica 2011). Any 'eustatic' signals arising from other glaciological or terrestrial hydrological changes or Antarctic melting could be much larger and be represented equally in the salt marsh measurements along the coastline.

There are ways in which more could be learned about these topics. For example, more and better salt marsh records are needed south of Cape Hatteras, although considerable time and effort has already been expended searching for such sites with decent accumulations of peat (Andrew Kemp, private communication). From a modelling perspective, more insight is needed on how the shelves respond to atmospheric and deep ocean forcing, which implies more improvements to models than simple increase in resolution, while extended monitoring is required of shelf hydrography. As the altimetry record lengthens, and reliable altimeter data become available near to the coast, then more will be learned about shelf responses to various forcings. For example, we suggest that the contribution of runoff to coastal sea level variability, considered many years ago by Meade and Emery (1971), be revisited.

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Annex 1: Ocean Circulation Model

Our ocean circulation model takes the form of a 'semi diagnostic' dynamical analysis of historical temperature and salinity data spanning 1950 to 2009. It was used previously in studies of overturning variability (Lozier et al. 2010), thermocline depth and ocean heat content variability and gyre-scale steric changes in sea level (Williams et al. 2014, 2015) and MSL variability along the Atlantic coast of North America (Woodworth et al. 2014).

The historical temperature and salinity changes are derived from a global analysis of the available hydrographic data, including recent Argo data, by the UK Met Office (Met Office Statistical Ocean Reanalysis; see Smith and Murphy (2007), and Smith et al. (2015)). The historical temperature and salinity data are assimilated into the Massachusetts Institute of Technology general circulation model (Marshall et al. 1997) in a semi-diagnostic manner; see Williams et al. (2014, 2015) for further model details. The model assimilation includes an initial 1-month spin up and then a further 12 months integration to cover an annual cycle. The model includes forcing by monthly mean wind stresses from the National Centers for Environmental Prediction (NCEP) - National Center for Atmospheric Research (NCAR) reanalyses (Kistler et al. 2001, www.cdc.noaa.gov). The dynamical adjustment does not include explicit surface heat or freshwater fluxes, but includes a weak artificial relaxation of temperature and salinity to the initial temperature and salinity data on a timescale of 36 months. This initialisation and assimilation procedure is repeated for each separate year.

The model assimilation is applied on a 1/5 ° x 1/6 ° (longitude x latitude) grid with 23 levels in the vertical for the period 1950-2009. (A coarse resolution 1° version of the grid is used for model testing.) The subsequent changes in sea level are then evaluated from these dynamically-adjusted model fields for each year. The model analyses are ideal for the present study as there is only a limited dynamical adjustment, responding to the hydrographic initialisation and wind forcing; the semi-diagnostic model does not determine its own hydrography as a consequence of surface heat

and freshwater fluxes as most other models do, so that there is limited model drift from the repeated initialisations from the historical data.

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Table 1. Summary of the correlations between annual MSL-difference, or MSL at Key West or New York, and the principal-component (PC) based annual mean values of the NAO of Hurrell (2015), referred to in the text.

MSL-difference

Period	Filter	N	N'		Correlation Coefficient	Significance(%)	Best Lag	Corr-Lag
1913-2014	-	102	64	85	0.26	95	0	
	7-yr	96	13	13	0.49	68	0	
1950-2014	-	65	43	58	0.30	68	0	
	7-yr	59	8	8	0.62	68	0	
1913-1949	-	37	23	32	0.12	-	4	0.39
	7-yr	31	4	4	-0.21	-	8	0.59
Key West								
1913-2014	-	102	45	85	0.19	68	-10	-0.19
	7-yr	96	13	13	0.12	-	-10	-0.33
1950-2014	-	65	32	58	0.22	68	4	-0.26
	7-yr	59	8	8	0.28	-	0	
New York								
1913-2014	-	102	58	85	-0.14	68	4	-0.21
	7-yr	96	13	13	-0.37	68	-10	-0.42
1950-2014	-	65	41	58	-0.18	68	8	0.24
	7-yr	59	8	8	-0.51	68	-10	-0.58

Notes: N indicates the number of years of data available within each period, or the number after boxcar filtering. For the unfiltered annual means, N' indicates the effective sample size in the time series of MSL-difference (or MSL for Key West or New York) and NAO respectively, after accounting for serial correlation using the lag-1 autocorrelation method of Maul and Martin (1993). For the filtered annual means, N' is set at N divided by the filter full-width. A significance test for either 68 or 95% significance is made using the lower of the two N' values. Best lag indicates the lag in years for which a maximum correlation between MSL-difference (or MSL) and NAO is obtained; a positive lag indicates that MSL-difference (or MSL) lags the NAO. Corr-lag shows the maximum correlation given by that lag. A maximum lag of ±10 years is allowed.

Figure Captions

1. Locations mentioned in the text: Cape Hatteras, the Key West (KW) and New York (NY) tide gauges (red dots) and the Florida, North Carolina, New Jersey and Connecticut salt marshes (yellow dots). The 500 m isobath indicated by the blue line shows the extent of the continental shelf.

2(a). Annual values of MSL at Key West minus those at New York (red), detrended over the full record length (1913-2014), together with the detrended Hurrell PC-based NAO index (blue). (b) MSL-difference and NAO after application of a 7-year low-pass filter. In (a) and (b) the NAO is scaled to have the same standard deviation as the MSL-difference.

3(a). Annual mean NAO values of Luterbacher et al. (1999, 2002) up to 2001, extended to the present using the Hurrell (2015) PC-based values. (b) The Luterbacher et al. NAO reconstructed values (red) compared to the Hurrell (2015) PC-based values (blue) and the Jones et al. (1997) station-based values (black), (c) Secular trends in the NAO values of (a) within 30-year windows. Trend values are plotted at the middle of the 30-year window.

4. Annual MSL at Key West (a) and New York (b) measured (red) and simulated by the high resolution version of the semi-diagnostic model (black). (c) Model MSL-difference at the coast (red) and using nearby points on the shelf 1 degree south and east of New York and Key West (green), together with modelled anomalies of Gulf Stream volume transport (Sv) at 25.6° N between the US coast and 75.5° W (black). The MSL-difference curves are scaled to have the same standard deviation as the volume transport.

5. Trends in sea level from the high resolution version of the semi-diagnostic model over the period 1969-1992, a period of clearly increasing NAO, with a basin average 0.35 mm/year removed.

6. A map of the 2-dimensional values of quadratic coefficient in time series of annual wind stress obtained from regression fits to 20CR data over the period 1928-1992. Units are 10^{-4} N/m^2 per year^2. Arrows indicate the direction in which wind stress accelerated in this period.

7. (a) MSL-difference, and (b) rate of change of MSL-difference south minus north of Cape Hatteras as represented by the Florida and New Jersey time series in the left and right panels respectively of Figure 8 of Kemp et al. (2015), reproduced here in (e) and (f) respectively. A small offset has been applied so that the average MSL-difference appears to be approximately zero in (a). In both (a) and (b), the inner and outer errors bars indicate the 68% and 95% credible intervals calculated by combining in quadrature the intervals for the two individual time series. (c,d) are as for (a,b) but using the Connecticut record of Kemp et al. (2015) instead of New Jersey. Figures (e) and (f) reproduce the individual Florida (red), New Jersey (green) and Connecticut (blue) time series of detrended MSL and its rate of change respectively from Figure 8 of Kemp et al. (2015).

8. (a) Correlation coefficients of detrended annual mean values of sea level in the semi-diagnostic model over the period 1950-2009 with those at a reference point near to New York (74.0°W, 40.5°N). Contours are every 0.2. (From Woodworth et al. 2014). (b) As (a), but showing correlations of sea level with those at a reference point near to Key West (81.8°W, 24.6°N).

9. Correlations over the period 1950-2009 between annual means of sea level from the semi-diagnostic model and annual mean North Atlantic Oscillation (both quantities detrended). Contours are shown every 0.2.

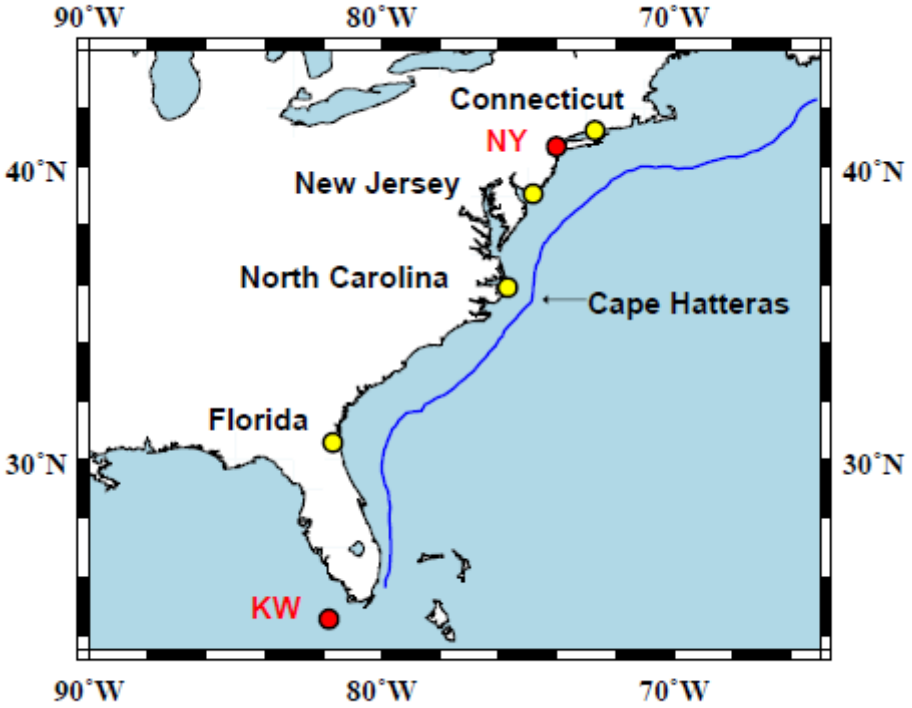
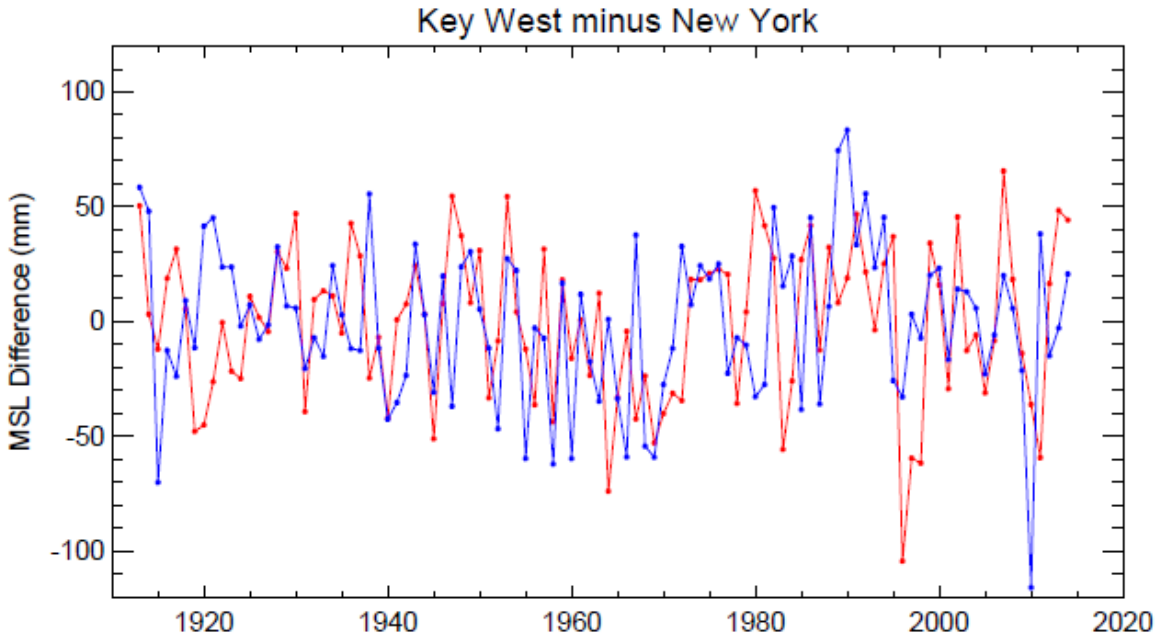
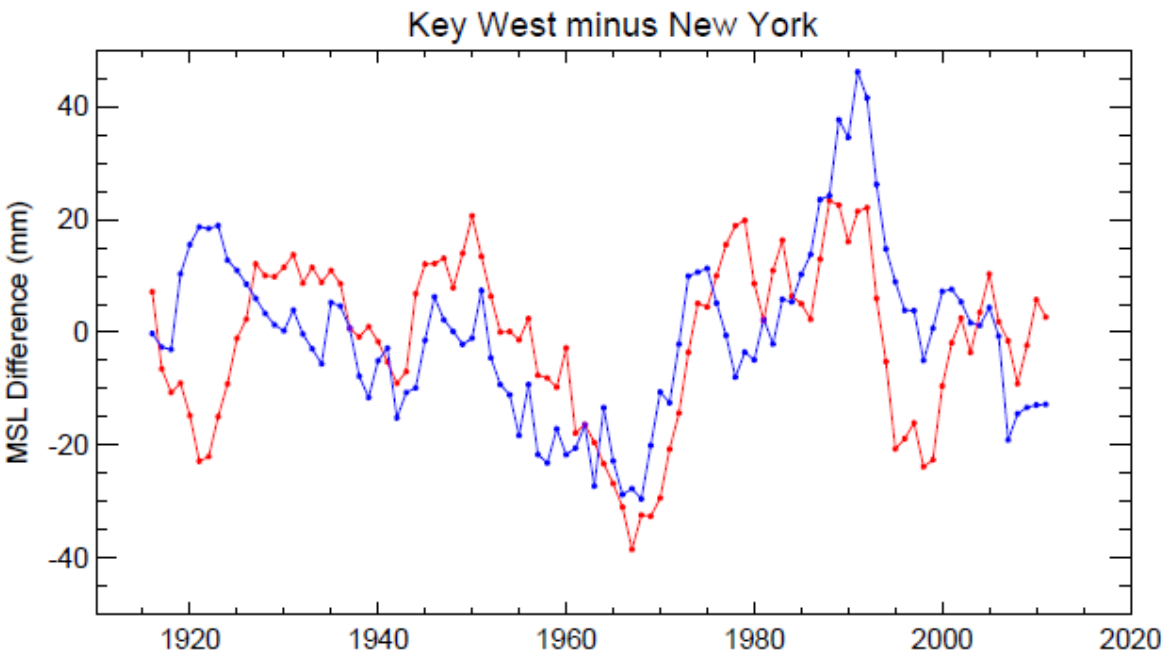


Fig.1 Locations mentioned in the text: Cape Hatteras, the Key West (KW) and New York (NY) tide gauges (red dots) and the Florida, North Carolina, New Jersey and Connecticut salt marshes (yellow dots). The 500 m isobath indicated by the blue line shows the extent of the continental shelf.

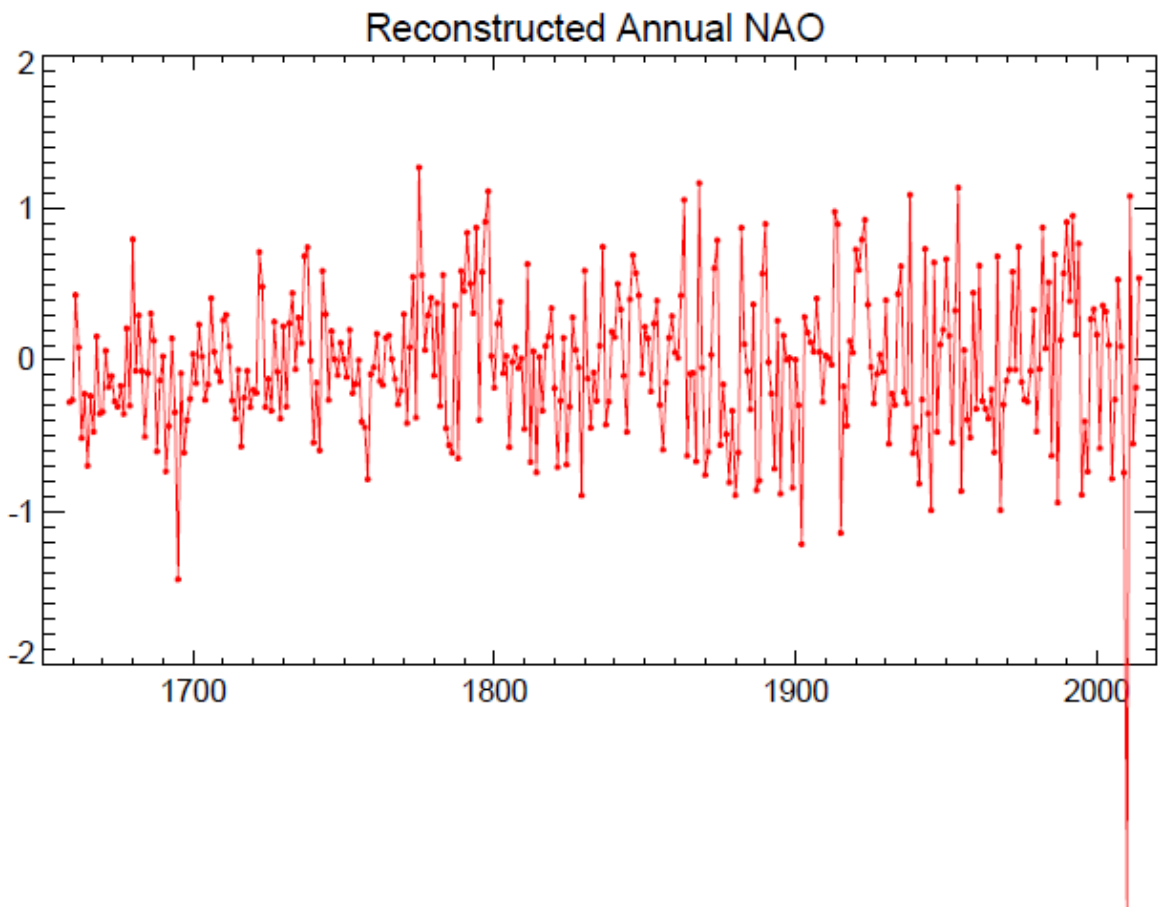


(a)

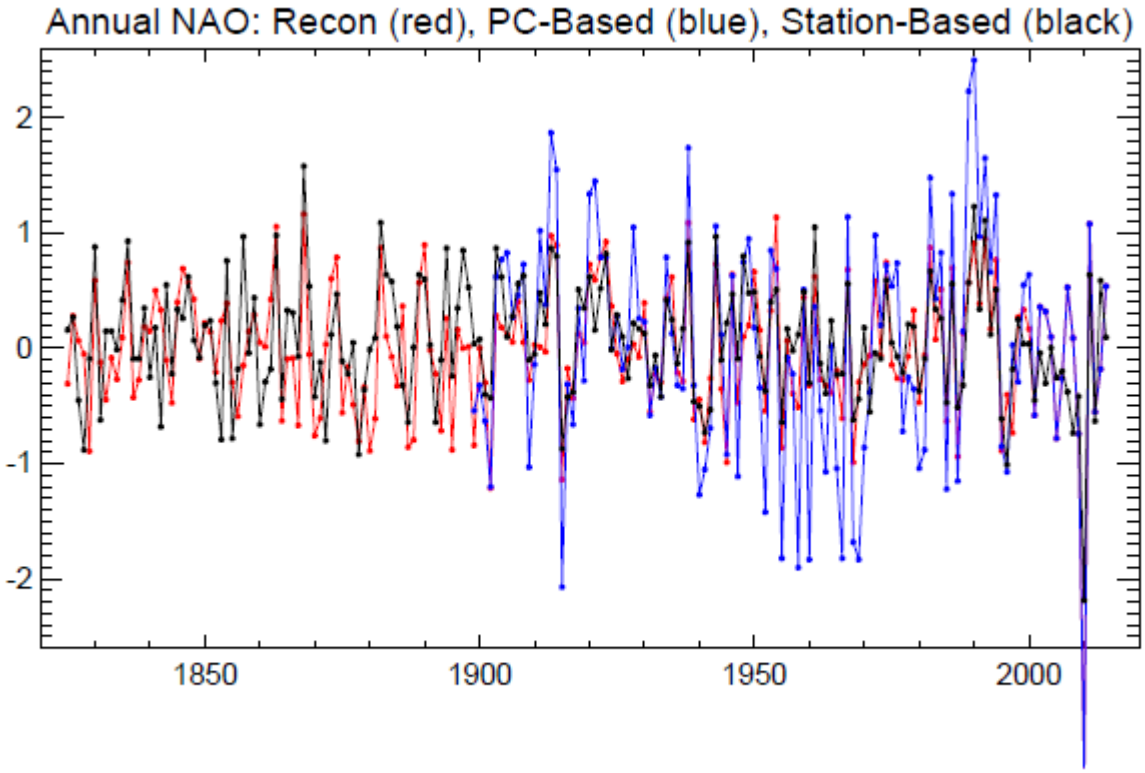


(b)

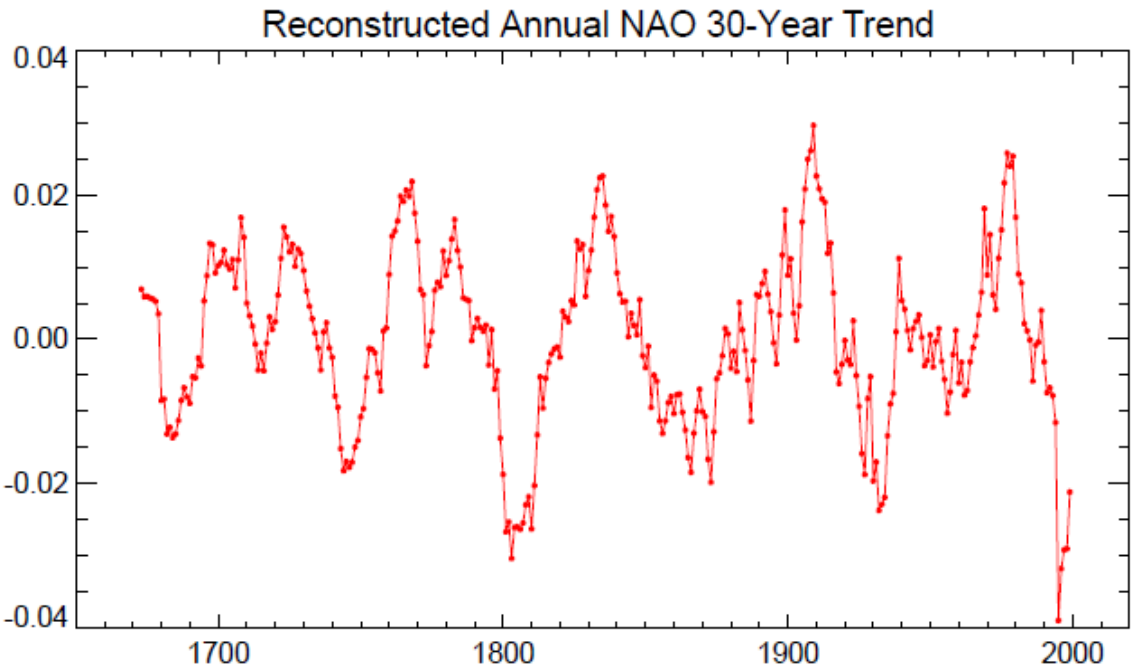
Fig.2 (a). Annual values of MSL at Key West minus those at New York (red), detrended over the full record length (1913-2014), together with the detrended Hurrell PC-based NAO index (blue). (b) MSL-difference and NAO after application of a 7-year low-pass filter. In (a) and (b) the NAO is scaled to have the same standard deviation as the MSL-difference.



(a)


Annual NAO: Recon (red), PC-Based (blue), Station-Based (black)
2
1
0
-1
-2
1850
1900
1950
2000

(b)


Reconstructed Annual NAO 30-Year Trend
0.04
0.02
0.00
-0.02
-0.04
1700
1800
1900
2000

(c)

Fig.3 (a). Annual mean NAO values of Luterbacher et al. (1999, 2002) up to 2001, extended to the present using the Hurrell (2015) PC-based values. (b) The Luterbacher et al. NAO reconstructed values (red) compared to the Hurrell (2015) PC-based values (blue) and the Jones et al. (1997) station-based values (black), (c) Secular trends in the NAO values of (a) within 30-year windows. Trend values are plotted at the middle of the 30-year window.

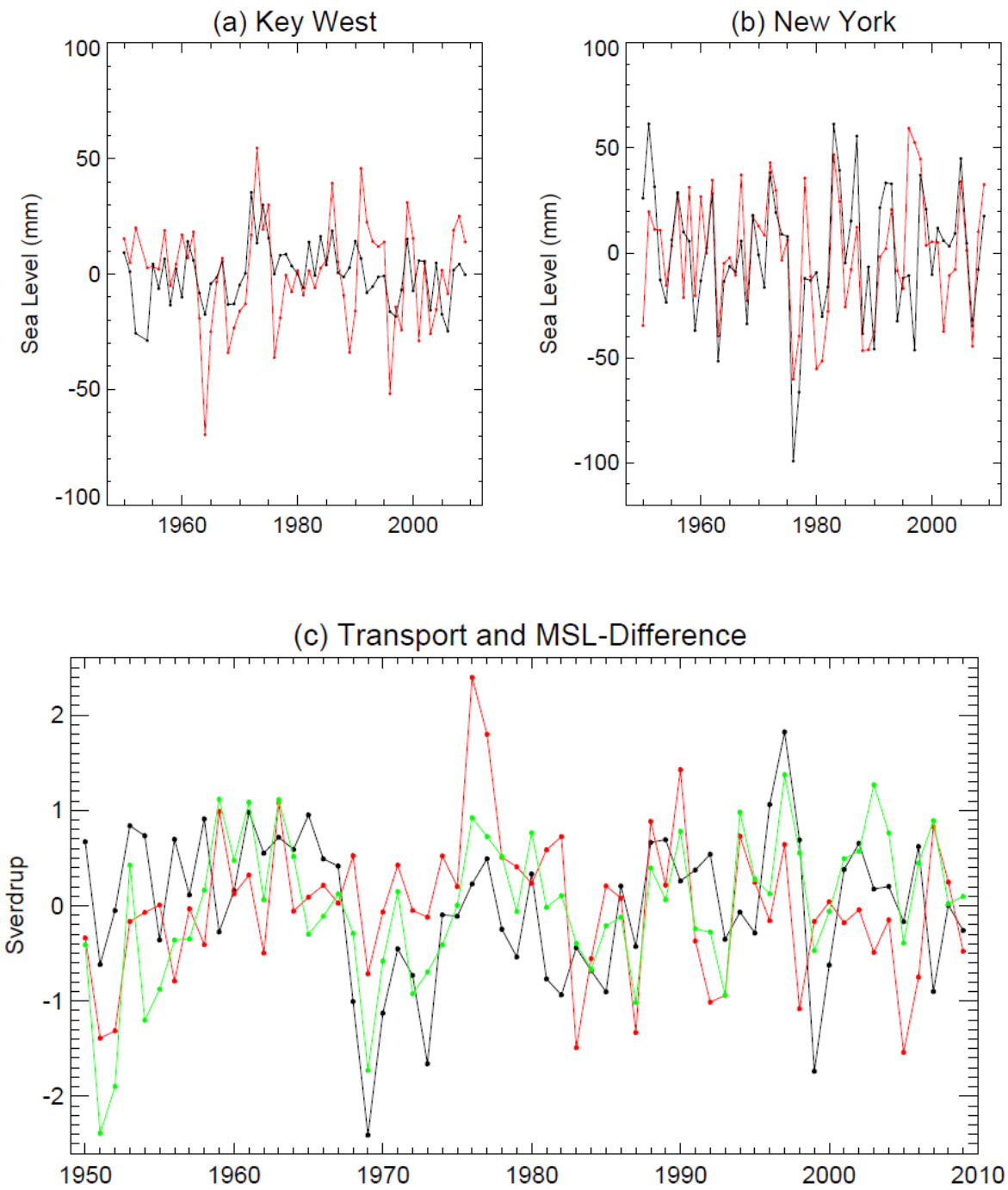


Fig.4 Annual MSL at Key West (a) and New York (b) measured (red) and simulated by the high resolution version of the semi-diagnostic model (black). (c) Model MSL-difference at the coast (red) and using nearby points on the shelf 1 degree south and east of New York and Key West (green), together with modelled anomalies of Gulf Stream volume transport (Sv) at 25.6° N between the US coast and 75.5° W (black). The MSL-difference curves are scaled to have the same standard deviation as the volume transport.

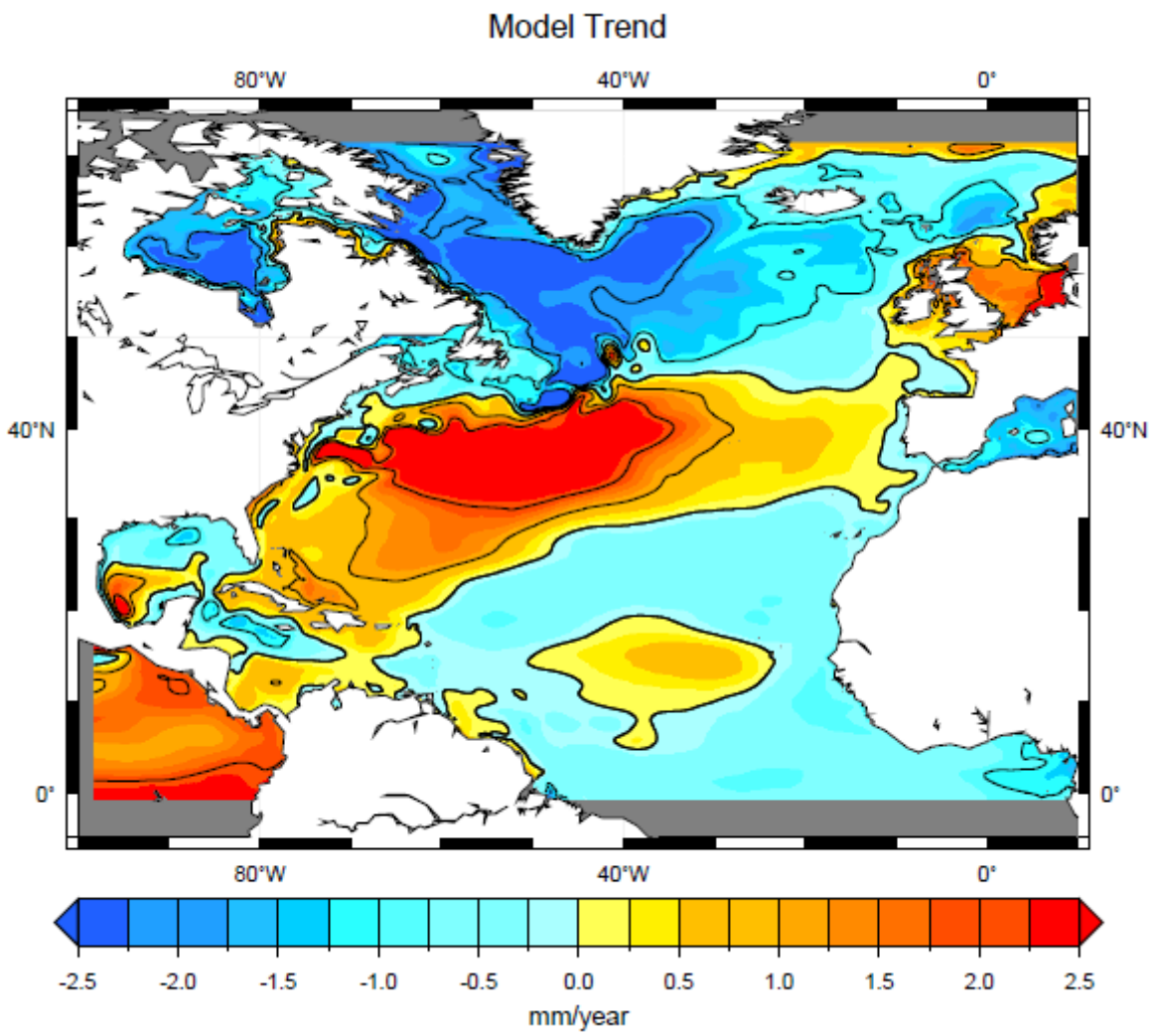


Fig.5 Trends in sea level from the high resolution version of the semi-diagnostic model over the period 1969-1992, a period of clearly increasing NAO, with a basin average 0.35 mm/year removed.

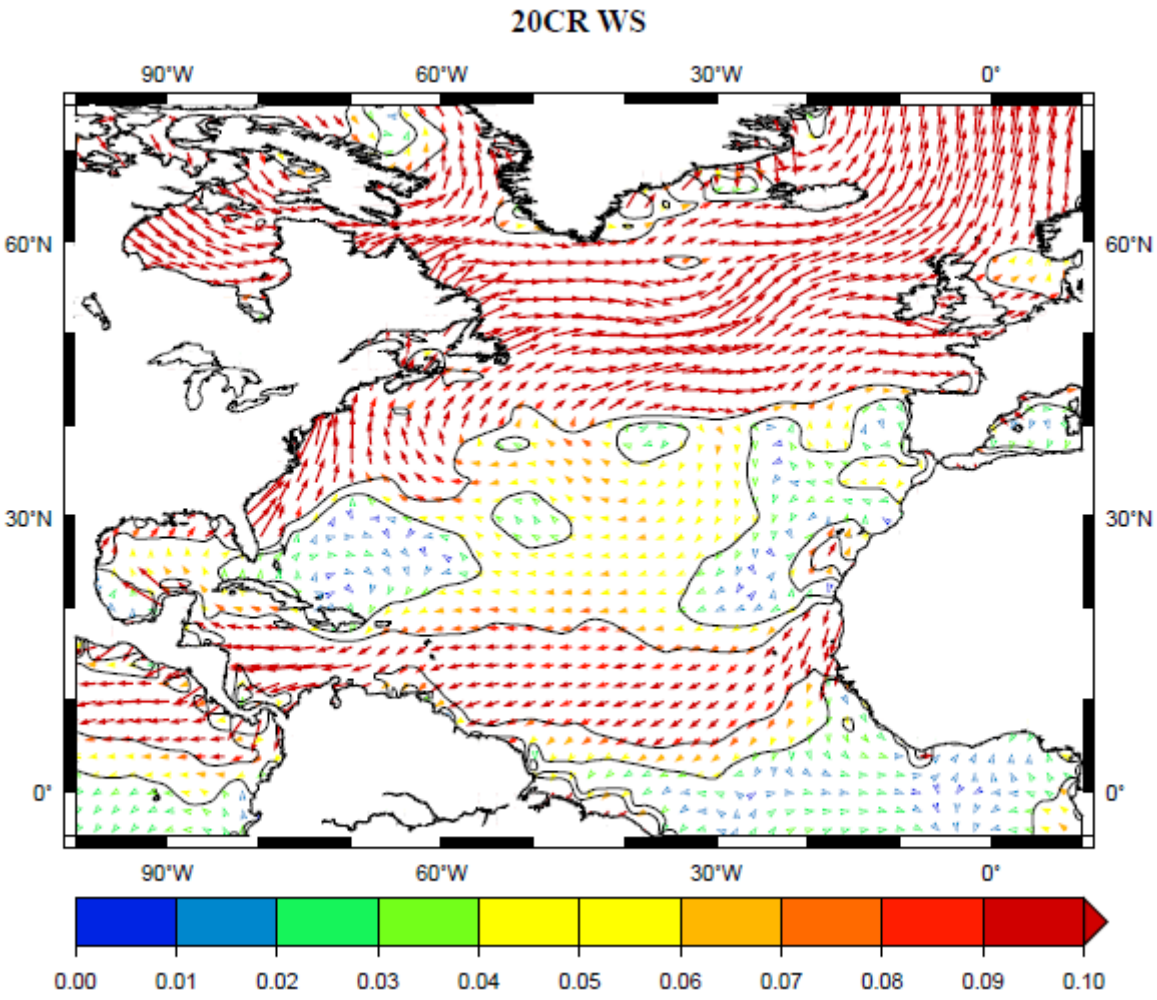
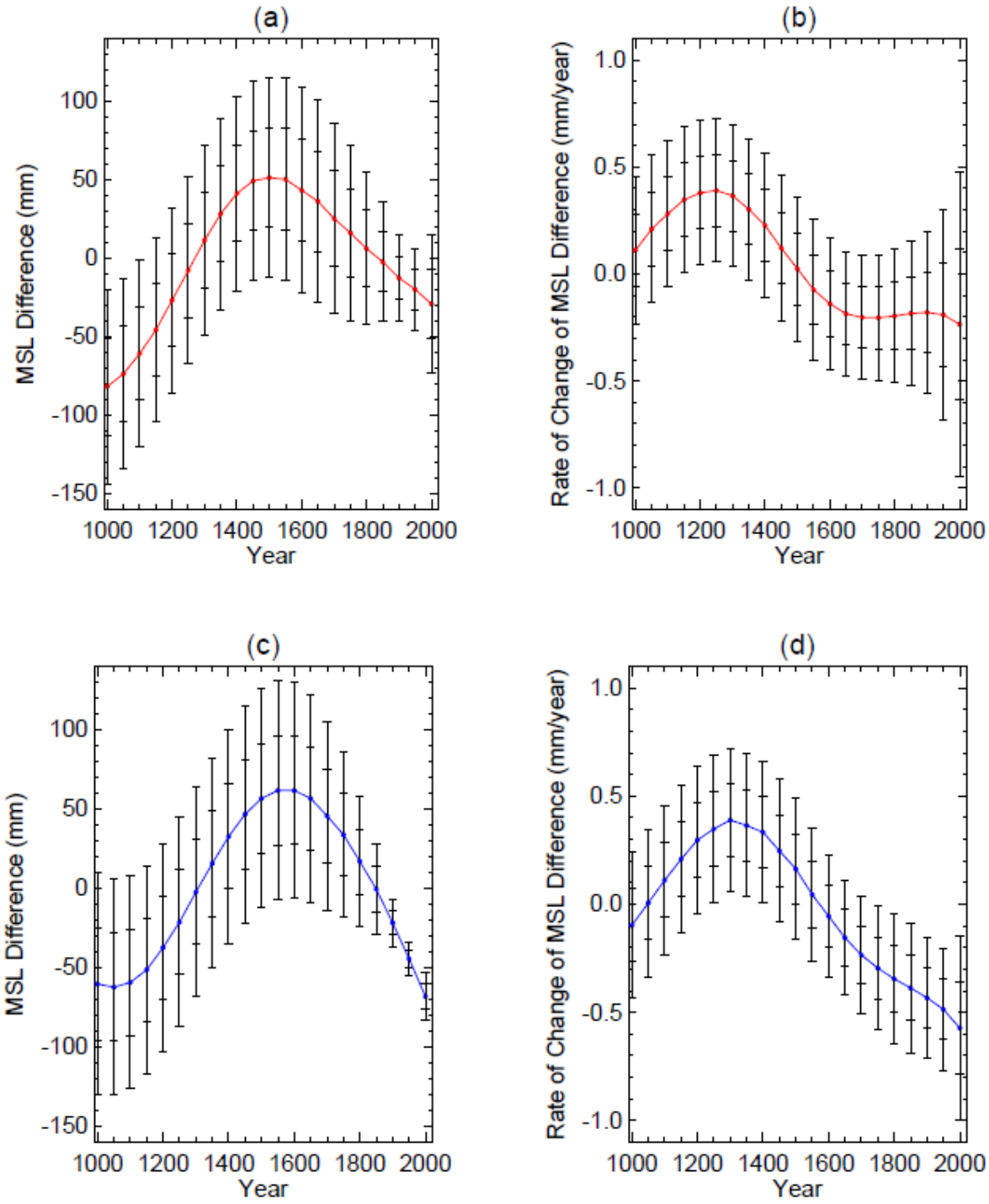


Fig.6 A map of the 2-dimensional values of quadratic coefficient in time series of annual wind stress obtained from regression fits to 20CR data over the period 1928-1992. Units are 10^{-4} N/m^2 per year^2. Arrows indicate the direction in which wind stress accelerated in this period.


(a)
MSL Difference (mm)
100
50
0
-50
-100
-150
1000 1200 1400 1600 1800 2000
Year
(b)
Rate of Change of MSL Difference (mm/year)
1.0
0.5
0.0
-0.5
-1.0
1000 1200 1400 1600 1800 2000
Year
(c)
MSL Difference (mm)
100
50
0
-50
-100
-150
1000 1200 1400 1600 1800 2000
Year
(d)
Rate of Change of MSL Difference (mm/year)
1.0
0.5
0.0
-0.5
-1.0
1000 1200 1400 1600 1800 2000
Year

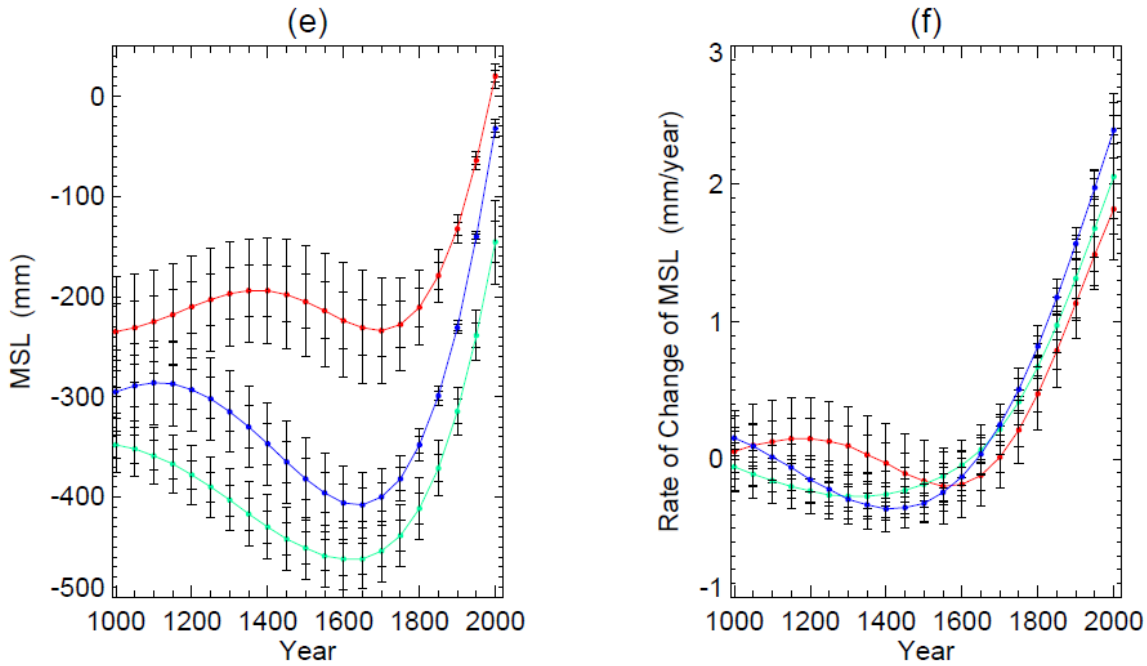


Fig.7 (a) MSL-difference, and (b) rate of change of MSL-difference south minus north of Cape Hatteras as represented by the Florida and New Jersey time series in the left and right panels respectively of Figure 8 of Kemp et al. (2015), reproduced here in (e) and (f) respectively. A small offset has been applied so that the average MSL-difference appears to be approximately zero in (a). In both (a) and (b), the inner and outer errors bars indicate the 68% and 95% credible intervals calculated by combining in quadrature the intervals for the two individual time series. (c,d) are as for (a,b) but using the Connecticut record of Kemp et al. (2015) instead of New Jersey. Figures (e) and (f) reproduce the individual Florida (red), New Jersey (green) and Connecticut (blue) time series of detrended MSL and its rate of change respectively from Figure 8 of Kemp et al. (2015).

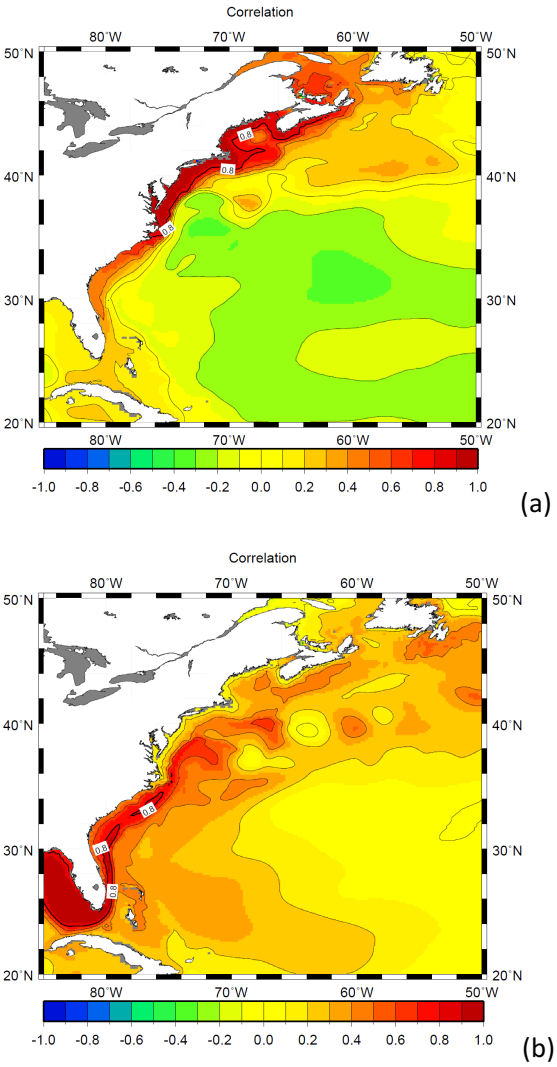


Fig.8 (a) Correlation coefficients of detrended annual mean values of sea level in the semi-diagnostic model over the period 1950-2009 with those at a reference point near to New York (74.0°W, 40.5°N). Contours are every 0.2. (Copied from Woodworth et al. (2014)). (b) As (a), but showing correlations of sea level with those at a reference point near to Key West (81.8°W, 24.6°N).

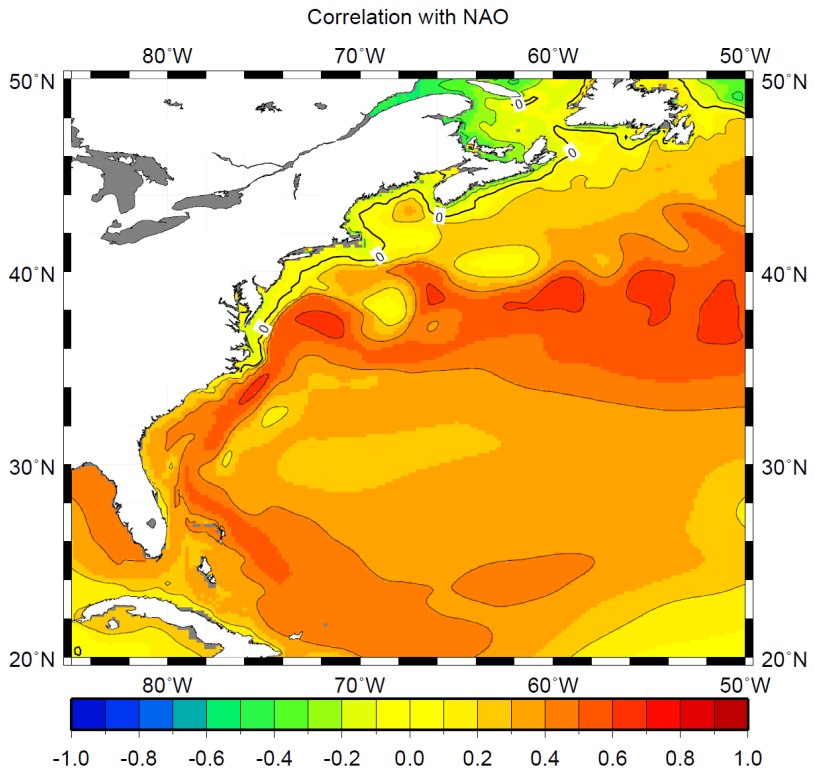


Fig.9 Correlations over the period 1950-2009 between annual means of sea level from the semi-diagnostic model and annual mean North Atlantic Oscillation (both quantities detrended). Contours are shown every 0.2.