[1] Determining the rate of global sea level rise (GSLR) during the past century is critical to understanding recent changes to the global climate system. However, this is complicated by non-tidal, short-term, local sea-level variability that is orders of magnitude greater than the trend. While the non-dimensional North Atlantic Oscillation (NAO) index can explain some of this variability in the Atlantic, significant results have been largely restricted to Europe. We show that dimensional indices of the position and intensity of the atmospheric centers of action (COAs) comprising the NAO are correlated with a major fraction of the variability and trend at 5 Atlantic Ocean tide gauges since 1900. COA fluctuations are shown to influence winds, pressure and sea-surface temperatures, thereby influencing sea level via a suite of coastal oceanographic processes. These findings reduce variability in regional sea level rise estimates and indicate a meteorological driver of sea-level trends. Citation: Kolker, A. S., and S. Hameed (2007), Meteorologically driven trends in sea level rise, Geophys. Res. Lett., 34, L23616, doi:10.1029/2007GL031814.

1. Introduction

[2] Changes in the position of global mean sea level are a key indicator of the nature and scale of global climate changes [Intergovernmental Panel of Climate Change (IPCC), 2007]. Estimates of recent rates of global sea level rise (GSLR) vary considerably. Miller and Douglas [2004] determined rates of 20th Century GSLR rates to be 1.5 – 2.0 mm/yr, Wadhams and Munk [2004] suggested a lower rate of 1.1 mm/yr for the same period, and the IPCC [2007] calls for higher rates for the period 1993–2003: 3.1 ± 0.7. The difference in these calculations is non trivial, amounting to 360 km3/year of fresh water per 1 mm/yr of GSLR [Wadhams and Munk, 2004]. Debate has centered on the relative contribution of fresh water fluxes [Alley et al., 2006; IPCC, 2007; Gornitz et al., 1997], thermal expansion [Antonov et al., 2005] and anomalies in Earth’s rotation [Wadhams and Munk, 2004]. Furthermore, GSLR estimates from tide gauges appear to be ~1 mm/yr higher than rates determined from volumetric or salinity measurements [Miller and Douglas, 2004; Munk, 2002].

[3] Determining GSLR rates is complicated by non-tidal, year-to-year variability in local mean sea level that is one to two orders of magnitude greater than the long-term trend [Douglas, 2001; Hong et al., 2000], potentially masking changes in the rate of rise. The cause of this variability is largely unknown, although it has been linked to storms, winds and floods [Zhang et al., 2000], wind driven Rossby waves [Hong et al., 2000], shifts in major ocean currents such as the Gulf Stream [Emery and Aubrey, 1991], volcanically induced ocean heat content variations [Church et al., 2005], and in the Pacific Ocean, the El Nino Southern Oscillation [Douglas, 2001]. Rates of relative sea-level rise (RSLR) in the coastal zone are more variable, both spatially and temporally, than rates of GSLR. They range from –10 to +10 mm/yr [Douglas, 2001], with differences often ascribed to factors including subsidence, uplift, tectonics, freshwater fluxes, and regional thermocline effects [Cabanes et al., 2001; Emery and Aubrey, 1991; Gornitz et al., 1982].

[4] Many previous attempts to calculate rates of GSLR coped with the problem of interannual and decadal scale variability by averaging large or long-term data sets [Antonov et al., 2005; Cabanes et al., 2001]. An alternative approach is to determine the cause of this variability as a means of distinguishing between competing signals in climate records [Church et al., 2004]. In this paper we show that a major fraction of the variability and the trend in mean sea level at key sites along the Atlantic Ocean are driven by shifts in the position and intensity of the major atmospheric pressure centers that reside over the Atlantic Ocean, the Azores High (AH) and the Icelandic Low (IL).

[5] One potential driver of Atlantic Ocean sea level is the North Atlantic Oscillation (NAO) [Woof et al., 2003]. It is often described by a non-dimensional measure of the pressure difference between two stations chosen to represent the mean state of the IL (Reykjavik, Iceland) and the AH (Lisbon, Portugal) [Hurrell, 1995]. While this “NAO index” provides a reasonable first approximation of atmospheric conditions in the North Atlantic, a detailed decomposition of these atmospheric Centers of Action (COA) is warranted because they are physically distinct in origin and move about the basin in space and time [Rossby, 1939]. The position and intensity of the IL is a result of the track of extra-tropical cyclones, while the corresponding AH properties are governed by the downward fluxes of the Hadley cell. Since these systems are non-stationary, pressure variations at a fixed location may reflect changes in a COA’s position and not its intensity. To quantify changes in the COAs, objective indices of the pressure, latitude and longitude of each COA (Figure 1) were calculated using gridded sea level pressure data [Hameed et al., 1995] (Text S1 of the auxiliary material). While previous studies attempted to link sea-level variability to the NAO index, significant results have been limited primarily to northern Europe, leaving variability in the much of the Atlantic basin unexplained [Woof et al., 2003]. Since the AH and the IL...
can influence winds, atmospheric pressure and temperature distributions worldwide [Hurrell, 1995; Rossby, 1939], we hypothesize that shifts in their position and intensity should affect sea level by controlling coastal set up and regional inverse barometer and thermosteric effects.

2. Methods
[6] We considered tide gauge records at key locations chosen to be representative of the regional extremes over the North Atlantic: Halifax, NS, CA; New York, NY USA; Charleston, SC, USA; Stockholm, SWE; and Cascais, PRT (Table 1). Previous research has indicated that a tide gauge can be representative of both the variability and trend in regional (100s – 1000s km) sea level processes [Emery and Aubrey, 1991; Holgate, 2007; Hong et al., 2000]. Revised local reference data (RLR) of annual mean sea level were obtained from the Permanent Service for Mean Sea Level (PSMSL) [Woodworth and Player, 2003]. Four data permutations are presented here: raw annual means provided by PSMSL (RAW), means in which the trend was adjusted for glacial isostatic adjustment (GIA), means that were corrected for the inverse barometer effect (IB), and means that were adjusted for IB and GIA (IB+GIA) (Table 1, Text S2). GIA rates were determined using the recent and respected Ice5G (VM2) model [Peltier, 2004]. Since GIA models can yield different rates, calculations based on alternative GIA models are available in Texts S2, S3, and S4.

3. Regressions and Correlations
[7] Changes in the position of the AH, i.e. its latitude (AH Lat) and/or longitude (AH Long), are significantly correlated with sea-level changes at all the stations, with and without the GIA and IB corrections, suggesting that AH movements are a key meteorological driver of sea level change at these locations, and often more important than similar IL properties (Text S2) However, changes in the AH Pressure (AHP) are only significantly correlated with sea-level changes in the two European Stations; at Cascais the correlation is not significant on the IB corrected data. Sea-level changes are correlated with changes in the position of the IL at Charleston, Halifax (RAW, GIA and GIA+IB) and Stockholm (GIA and IB + GIA), while changes in its intensity are correlated with sea level at Cascais (RAW and GIA) and Stockholm (GIA and IB + GIA).

[8] The strongest evidence for a north-south dipole, as predicted from NAO theory [Hurrell, 1995], appears in Europe. Sea level is negatively correlated with AHP and positively correlated with ILP at Cascais, while the inverse is true at Stockholm, suggesting that these correlations reflect known physical phenomena [Hurrell, 1995]. However, there is less evidence for a north-south dipole on the American Atlantic coast; e.g. sea level at Charleston and Halifax are both positively correlated with IL Long and AH Lat and AH Long. GIA adjustments increase the strength and number of univariate correlations most at Stockholm, an area of pronounced isostatic uplift [Peltier, 2004]. The IB correction appears to have little impact on many univariate correlations, though its importance is increased in multiple regressions discussed later on.

[9] To assess the influence of the COAs on sea level we examined pressure, wind and sea surface temperature (SST) composite anomalies during periods of anomalously high AH Lat and years of anomalously eastern AH Long using NCEP/NCAR reanalysis data [Kalnay et al., 1996] (Figure 2). We see that northward shifts in AH Lat are associated with wind anomalies of up to 7 m/sec directed towards Scandinavia and central North America and away...
from Iberia. Years in which the AH is located further eastward also yield wind anomalies up to 5 m/sec in a similar direction. These wind anomalies are hypothesized to effect wind-driven coastal setup and wind-driven Rossby waves that can also influence coastal sea level [Hong et al., 2000]. The high pressure anomalies of 2–10 mbar that extend from western Europe to North America during northward shifts in the AH (and to a lesser extent eastward shifts in the AH) likely lower sea level via the inverse barometer effect. The converse presumably occurs in years of low AH pressure. Finally, in years when the AH is shifted northward, there are SST anomalies of 0.4–1.2 °C that extend from eastern North America to Europe, which may affect thermosteric sea level. Thermosteric sea-level change depends on the integral over the water column of temperature change. In shallow waters this is likely to be small.

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Understanding the controls on GSLR requires differentiating between processes that redistribute water across ocean basins and changes in ocean volume. A critical component of this problem is determining the cause of inter-annual and decadal scale oscillations in sea level with cm to dm scale amplitudes [Hong et al., 2000]. To demonstrate that much of these local sea-level changes are correlated with shifts in the position and intensity of the COAs, we constructed a series of multiple regressions relating the COA indices to sea level at each of the five tide gauges. To look for interactions between COA forcing of sea level and deep-ocean processes, we lagged the data for up to six years. Regression outputs are summarized in Table 1, and Text S3, while the complete regression equations and effective number of degrees of freedom are in Texts S2 and S4. Individual regression terms, all significant at the 95% level, contribute ~10% of the total variance in local sea level. These regressions suggest that sea-level change is a complex, multi-factorial phenomena with contributions from long-term shifts in the position and intensities of the COAs.

### 4. Discussion

[11] These regressions suggest that a large fraction of the annual mean sea-level variability at these five Atlantic Ocean stations is correlated with shifts in the position and intensity of the COAs (Table 1, Texts S2 and S4). Overall, our multiple regressions can account for 59–79% of the variability in the RAW sea level data and 24–79% of the IB + GIA adjusted data (Table 1). These findings suggest that meteorological processes drive coastal sea-level variability by redistributing water, heat, and the response of the ocean to atmospheric pressure across the ocean basin (Figures 2 and 3). COA driven sea-level change is consistent with earlier studies on this topic [Church et al., 2004; Emery and Aubrey, 1991; Hong et al., 2000], but provides a single comprehensive theory that accounts for much last century’s Atlantic Ocean sea level variability. For example, we find lags between local sea level and the COAs of up to six years, which is consistent with work demonstrating a six-year travel time between NAO-related heat flux in the Labrador Sea and heat flux and sea level at Bermuda [Curry et al., 1998]. The link between sea level and the IL Long at Charleston and Halifax is intriguing because the IL Long affects the position of the Gulf Stream northwall [Hameed and Piontkovski, 2004], and oceanographers have long...
Figure 2. Wind, pressure, and sea surface temperature anomalies comparing years when the Azores High has shifted northward vs. years when it has shifted southward and below and years when the Azores High has shifted eastward vs. years when it is westward. A key result is that shifts in the AH influence winds that can drive Rossby waves that affect coastal sea-level variability [e.g., Hong et al., 2000]. Also potentially important are shifts in the latitude of the Azores high that appear to affect sea surface temperatures (top right) which may influence thermocline sea level anomalies. Data and image source: NCEP/NCAR; Kalnay et al. [1996].
speculated that changes in the Gulf Stream’s position could affect coastal sea level [Emery and Aubrey, 1991]. Northward shifts in the AH (Figure 2) are coupled to a SST anomaly that corresponds with the general position of the Gulf Stream, further suggesting a link between COAs and the ocean. COA shifts also affect global wind fields, which are thought to be responsible for Rossby waves that influence sea level when they interact with the coast [Hong et al., 2000].

There are trends in the multiple regressions relating (Table 1, Figure 3), suggesting that long-term changes in local sea level are associated with changes in the position or intensity of the COAs. Analysis of historical climate data [e.g., Kalnay et al., 1996] strongly suggests a physical basis for these correlations. The northward shift in the AH (Figure 1) is associated with an increase in the mid-latitude eastward wind anomaly (Figure 2) that can affect coastal set up and thereby sea level’s position in central North America (Figure 3). Northward AH movements also appear to increase the flow of water into Scandinavia and away from Iberia, potentially contributing to a sea-level rise in northern Europe and sea-level fall in southern Europe, in spite of isostatic or tectonic motions in the opposite direction. For the regressions of the RAW data, the regression slope ranges from −2.38 mm/yr in Stockholm to 2.26 mm/yr in Charleston, which accounts for 61–78% of the raw RSLR (Table 1, Figure 3). This value changes to 38–110% when GIA is accounted for and 51–78% when both GIA and IB are considered (Table 1). These finding suggest that the long-term movement of the COAs, and particularly the AH,
have led to large scale atmospheric and oceanographic shifts that effected the volume of water along both coasts of the Atlantic basin.

[13] The difference between the raw rate of RSLR and the rate of RSLR determined from the regressions yields a residual rate of local sea-level rise, which may provide a useful measure of local sea-level trends because it is largely free from the confounding effects of isoracy and COA-influenced processes. Results are particularly encouraging for the three North American tide gauges. Using the Ice5G (VM2) model [Peltier, 2004], the residual rate of RSLR is 0.66 mm/yr in Halifax, 0.66 mm/yr in New York and 0.65 mm/yr in Charleston (Table 1). This suggests a regional rate of residual sea level rise with substantially less variability than the 1.40–2.15 mm/yr range yielded by a GIA correction alone. Furthermore, the inferred rate of sea-level rise is higher in western Atlantic tide gauges than the eastern Atlantic tide gauges, which is in agreement with earlier findings by Church et al. [2004]. Since COAs influence local temperature, pressure and precipitation (Figure 2), these regressions partially account for local thermosteric effects, regional freshwater fluxes and the inverse barometer effect [Hameed et al., 1995; Hurrell, 1995; Rossby, 1939]. However, these regressions do not account for all processes that drive RSLR, e.g. sediment compaction and volcanically induced changes in ocean heat content [e.g., Church et al., 2005].

[14] Estimates of average rate of sea-level rise for the entire North Atlantic Ocean vary slightly depending on the assumptions chosen. Depending on the assumptions chosen these estimates range from 0.93 ± 0.39 mm/yr (for the RAW data, and ignoring Stockholm were complications associated with GIA are obviously greatest); 0.49 ± 0.25 mm/yr (for GIA + IB data, not including Stockholm), and 0.59 ± 0.14 (for the GIA + IB data, not including Stockholm; see Table 1 and Text S3). While the IB +Ice4G (VM4) and IB+ Ice 5G (VM4) analyses yield negative rates of RSLR at Stockholm, they produce higher average rates (VM4) and IB+ Ice 5G (VM4) analyses yield negative rates of RSLR at Stockholm, they produce higher average rates for the four other gauges, 0.93 ± 0.46 and 0.72 ± 0.33 mm/yr respectively (Text S3).

[15] There are several implications of these results. Replicating decadal scale variability in global climate models has proven difficult [Church et al., 2005]. While other factors are almost certainly at play [Cabanes et al., 2001; Church et al., 2005; IPCC, 2007], our results suggest that a previously under-appreciated form of climate variability, spatial shifts in the COAs, may also drive local sea-level variability and trends in the Atlantic Ocean. Despite recent attempts, until now that type of clear linkage has not been well demonstrated on both Atlantic coasts [Woolf et al., 2003]. Additionally, atmospheric centers of action exist in all ocean basins (e.g. the Aleutian Low, the Hawaiian High, the South Atlantic High, etc) and these methods can be readily extended to sea-level studies world wide.

[16] Several authors have recently noted an important sea level 'enigma.' 20th C. rates of GSLR determined from tide gauges are ~1 mm/yr higher than rates of GSLR determined from volume estimates [Miller and Douglas, 2004; Munk, 2002]. Previous research into this enigma typically focused on asymmetries in Earth’s rotation [Mitrovica et al., 2006], or better constraining water and heat budgets [Antonov et al., 2005]. Our results yield rates of recent sea level rise that are closer to Wadhams and Munk’s [2004] 1.1 mm/yr than Miller and Douglas’s 1.5–2.0 mm/yr. This result suggests that meteorological trends are an important driver of sea-level change, which could close the enigmatic gap in GSLR rates if our results were to be replicated worldwide. While these findings may down grade rates of warming induced sea-level change along Atlantic shorelines, they might not reduce estimates of climate change impacts, as it is often meteorologically driven sea-level changes that are most damaging to coastal ecosystems and infrastructure [Scavia et al., 2002].

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