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Sea-level variability in the northwest Atlantic during the past 1500 years: A delayed response to solar forcing?

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[1] Numerical experiments with a coupled ocean-atmosphere model (ECBilt) have shown that centennial variations in sea level (SL) in the northwest Atlantic may be associated with deep-ocean salinity anomalies generated by solar-forced variations in the North Atlantic overturning circulation. Here we compare simulated SL curves for the Gulf Stream region with reconstructed, late-Holocene SL records from Connecticut (USA). Simulated SL variations lag the solar forcing record by ca. 120 year. This lag is found to be robust over a small number of different experiments. The reconstructed SL curves visually match the solar forcing optimally when lagging it by ca. 125 yr. A quantitative test shows that the correlation is significant, while this result is not sensitive to dating uncertainties. The temporal response pattern of the simulated SL curves compares reasonably well with the reconstructions. *INDEX TERMS:* 4556 Oceanography: Physical: Sea level variations; 1650 Global Change: Solar variability; 4255 Oceanography: General: Numerical modeling; 4267 Oceanography: General: Paleoceanography; 3030 Marine Geology and Geophysics: Micropaleontology. **Citation:** van de Plassche, O., G. van der Schrier, S. L. Weber, W. R. Gehrels, and A. J. Wright, Sea-level variability in the northwest Atlantic during the past 1500 years: A delayed response to solar forcing?, *Geophys. Res. Lett.*, *30*(18), 1921, doi:10.1029/2003GL017558, 2003.

1. Introduction

[2] Variability in the ocean heat transport from the tropics to higher latitudes plays an important role in long-term climate changes. Results from recent numerical modeling studies suggest that regional sea-level (SL) variations may serve as a proxy for variations in the Gulf Stream/North Atlantic overturning circulation [*Ezer*, 2001; *van der Schrier et al.*, 2002]. *van der Schrier et al.* [2002; henceforth SWD] argued that century-scale steric SL variations in the northern North Atlantic are almost exclusively dominated by salinity variations of the deep ocean. They found that once a deep-ocean salinity anomaly is formed in the northern North Atlantic, lagging the (solar) forcing which gave rise to it by some 20 years, it is advected southward and reaches the mid-latitudes with a lag of about 100 yr. There, this deep-ocean salinity anomaly, while weakened due to diffusion, zonal spreading, and southward advection along the path of the Deep Western Boundary Current, is still sufficiently pronounced to induce steric SL changes in the Gulf Stream area.

[3] The transit time of about 100 years compares favorably with the result of a numerical simulation [*England*, 1995] of the age of seawater (the time elapsed since a given water parcel was last exposed to the atmosphere). At depths 755 m and 1622 m (containing water masses which originated in the northern North Atlantic) and near 40°N at the US east coast, the age is 80–120 yr and 50–150 yr respectively.

[4] In this study, we aim to substantiate further the suggested link between solar forcing, salinity variations and a 120-yr-delayed SL response in the northwest Atlantic by comparing SL simulations for the Gulf Stream area with SL reconstructions from Connecticut, northeast USA.

2. Deep-Ocean Salinity and Steric Sea Level

[5] In their numerical experiments, SWD used a climate model of intermediate complexity (ECBilt; *Selten et al.* [1999]), a fully coupled ocean-atmosphere-sea ice model, albeit with simplified atmospheric physics and a coarse spatial resolution ($5.6° \times 5.6° \approx 500 \times 500$ km in mid-latitudes). Solar forcing records were obtained by splicing a ^{10}Be record [*Bard et al.*, 1997] to the *Reid* [1997] estimate as well as to the more conventional *Lean et al.* [1995] scaling. The use of the 2.7 times larger Reid scaling factor is motivated by the low climatic sensitivity of ECBilt. The simulated central European winter-temperature difference between 1550–1600 AD and modern times shows, for the larger scaling, a 0.6–0.7°C cooling. Historical evidence from Switzerland indicates that this cooling was ca. 1.0°C [*Pfister*, 1992]. The mechanism of the thermohaline circulation (THC) response to the forcing is identical in the two experiments, but the signal-to-noise ratio depends on the scaling factor used.

[6] The generation of deep-ocean salinity anomalies is paced in the numerical experiments by changes in the

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temperature of the northern North Atlantic surface layer (north of 59°N, east of 45°W), which responds directly to irradiance changes, consistent with observations [*White et al.*, 1997]. Higher (lower) sea-surface temperatures (SSTs) decrease (increase) the deep water formation. The resulting sluggish (fierce) THC exposes surface waters longer (shorter) to the mid-latitude net precipitation, and decreases (increases) surface salinity. This surface-salinity anomaly further suppresses (enhances) deep water formation. It is advected to the deep ocean from where it propagates southward reaching the Gulf Stream area (25–50°N, 73–62°W) ca. 120 yr after the change in solar forcing which gave rise to it. Sea ice was found to follow changes in the (oceanic) climate rather than lead it.

[7] The model's equation of state (linear in salinity, quadratic in temperature) underestimates geopotential thickness changes due to temperature variations by a factor of ca. 1.5. However, SWD found that geopotential thickness changes due to salinity variations are an order of magnitude larger than those due to temperature variations. Therefore, this model feature does not affect the dominance of salinity on deep-ocean geopotential thickness.

[8] The influence of solar radiation on the strength of the THC has been shown earlier by *Cubasch et al.* [1997], while changes in northern North Atlantic salinity through THC variations have been found in a range of models (e.g. [*Winton and Sarachik*, 1993]. The mechanism relating SST variations, via the overturning to variations in deep ocean salinity seems to be supported by the few existing observations [*Hass*, 1996].

3. Phase Shift Between Reconstructed Sea-Level Variations and ^{14}C-Production Rate

[9] Independent of the numerical simulations, we addressed the possible relation between SL and solar forcing using recent SL reconstructions from Connecticut (CT). We first examine in detail a reconstruction from Clinton (CT) [*van de Plassche*, 2000]. In constructing the marsh-accumulation record for the older part (450–975 cal yr AD) of this mean high water (MHW) curve, it was noted that the error boxes (marsh-surface estimates) with narrow calibrated radiocarbon ages coincide with a high rate of marsh accumulation, and vice versa (Figure 1b). Since a precise calibrated age implies intersection of the radiocarbon age with a steep section of the Δ^{14}C-calibration curve (Figure 1a), and such a section reflects a period of decreased solar activity, these data suggest that increased rates of marsh accumulation occurred during periods of reduced solar activity, and vice versa, possibly with a phase shift. The associated curve of MHW changes (Figure 1c), detrended for isostatic crustal subsidence (0.8 ± 0.1 mm/yr; [*Peltier*, 1998 (Figure 23)]) and compaction (ca. 0.2 mm/yr and assumed linear), is consistent with the pattern of marsh accumulation, implying that local MHW variations during the period 450–975 cal yr AD responded comparably to changes in solar activity (note: continued marsh accumulation (650–675 AD) is not inconsistent with the early stages of the contemporaneous MHW fall; see also *van de Plassche*, [2000] and *Kelley et al.* [2001]).

[10] We inspected the phase relationship between MHW variations and solar activity for the detrended SL record in more detail by visually comparing it with the 100-yr filtered Δ^{14}C record [*Stuiver et al.*, 1998] (Figures 2a and 2b). The gaps in the Clinton curve are erosional and ecological hiatus in the record. The result leads us to the tentative conclusion that the reconstructed SL changes (from Clinton) lag the changes in Δ^{14}C by roughly 125 yr, suggesting the possibility that this SL record reflects a delayed response of the climate-ocean system to variations in the sun's activity.

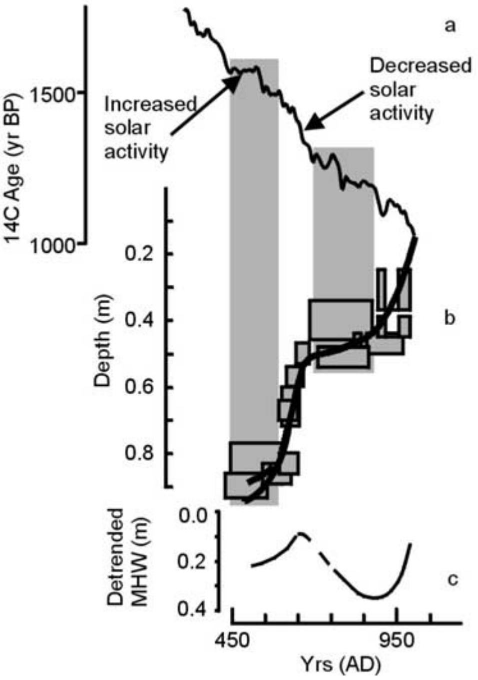

Figure 1. Comparison of (a) the atmospheric Δ^{14}C curve for the period AD 350–1050 with (b) a marsh-accumulation record from Clinton, CT and (c) the associated detrended sea-level curve from Clinton. The dashed part of the curve represents an interpolation due to missing data.

[11] The error margins inherent in radiocarbon dating may render fortuitous some or all of the satisfactory matches between the 125-yr back-shifted Clinton SL curve and the proxy record for solar activity. We tested the robustness of this result for dating uncertainties as follows. Different realizations of the Clinton SL curve are made by randomly selecting individual ages within the $\pm 1\sigma$ range of each of the 48 independent measurements (Table 1 in *van de Plassche et al.* [1998] and in *van de Plassche* [2000]). The optimum correlation and associated lag of each SL realization with the solar forcing record is computed, and we tabulate how many times a particular correlation-lag combination occurs (correlation rounded off to the 2nd decimal, lag in separate years). Figure 3 shows this distribution for 10^8 different realizations of the SL curve. We conclude from this figure that a correlation of 0.67–0.80 at a lag of 110–140 yr is a robust result. The reason for the robustness is that 54% of the measurements have a dating uncertainty of $\leq$50 yr. Measurements with a relatively large dating uncertainty happen to have neighboring points with much smaller dating uncertainties. The correlations are significant at the 95% level in a standard two-sided *t*-test for n = 11 independent samples, where n is obtained as the record length (1100 yr, taking gaps in the SL record into account) divided by the filter period of the Δ^{14}C record (100 yr).

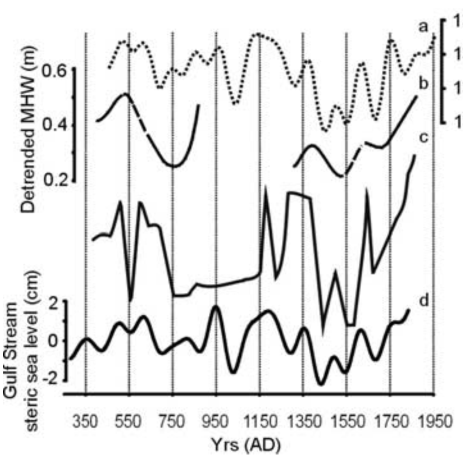

Figure 2. Comparison of (a) the solar irradiance reconstruction based on the Δ^{14}C record with sea-level reconstructions from (b) Clinton, CT, (c) Farm River marsh, CT, and (d) average of two 2000-yr long ECBilt simulations of sea level in the Gulf Stream area. The sea-level curves have been shifted 125 yr back in time.

[12] A few other SL reconstructions exist. The curve for Farm River marsh (CT) (*Varekamp et al.* [1999]), when shifted back in time 125 yr, corresponds well with the Δ^{14}C curve, both in overall pattern and in detail back to ca. AD 1300 and between AD 500–750 (Figure 2c). The younger (post-1440 AD) part of a SL reconstruction from Machiasport, Maine (ME) [*Gehrels et al.*, 2002], when shifted back 125 yr, correlates well with solar variability. However, the older part of this curve, as well as a SL reconstruction from Wells (ME) [*Gehrels et al.*, 2002] correspond poorly, possibly reflecting dominance of local SL variations in the Gulf of Maine [*Bisagni et al.*, 1996]. As the ECBilt model does not resolve small-scale hydrography, the ME curves have not been included in the present study.

4. Simulations and Reconstructions

[13] In order to compare the reconstructed SL curves with simulations we extended the 1000-yr solar irradiance record used by SWD back in time by matching it to the Δ^{14}C record (no high-resolution ^{10}Be record is at present available for the earlier period). The correlation between the 100-yr filtered record used by SWD and Δ^{14}C is 0.86. This indicates that ocean variability plays a relatively minor role in modifying Δ^{14}C (see also, [*Bard et al.*, 1997]). We performed two additional 2000-yr simulations which differ in their initial state. These were taken, 100 yr apart, from a long control simulation. The simulated northern North Atlantic and Gulf Stream SL records are shown in Figure 4. The latter have highest correlation (of 0.75) at lag 120 yr to the irradiance forcing.

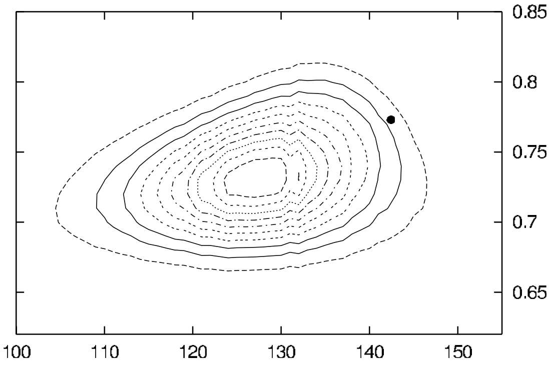

Figure 3. Optimum correlation and associated lag (in yr) of the solar forcing and 10^8 different realizations of the reconstructed sea level, randomly chosen within the dating uncertainty (see text). The contour interval is 5×10^4, the outer line is the 5×10^4 contour. The dot represents the location of the original sea-level record.

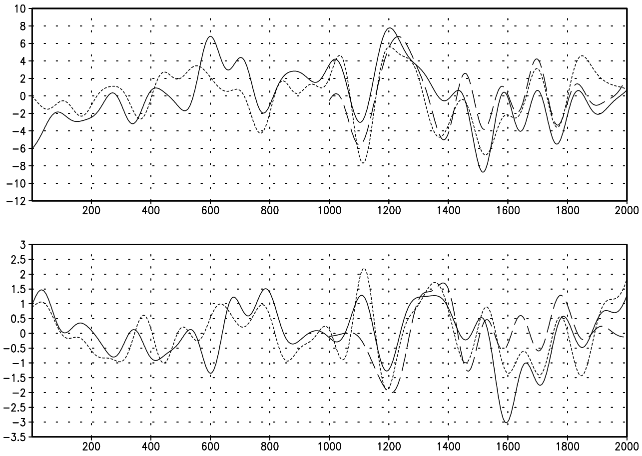

Figure 4. Steric sea-level anomalies (in dynamic cm) in (a) the northern North Atlantic for the two 2000-yr ECBilt simulations (solid and dots) and the 1000-yr simulation of SWD (dashed) are observed some 100 yr later in (b) the Gulf Stream region. All records are 100-yr lowpass filtered.

[14] Comparing the reconstructed and the (averaged) simulated SL curve for the Gulf Stream area shows that the numerical computations reproduce several features of the SL reconstructions reasonably well (Figure 2, note: the SL curves have been backshifted 125 yr). Notable discrepancies are the lack of a negative oscillation around AD 1025 in the SL reconstructions, while the simulated negative oscillation around AD 750 is recovered in the Clinton SL curve only. Part of these discrepancies may be resolved within the SL dating uncertainties (50–200 yr at $\pm 1\sigma$). More importantly, the numerical simulations show that some differences between forcing and the SL curves are to be expected due to internal climate variability. This important point is illustrated by the cross-correlation between the two simulated SL records which is 0.58 over the first 1000 yr, a period characterized by small-amplitude irradiance variations, increasing to 0.80 in the latter 1000 yr period which has larger irradiance variations.

[15] The large discrepancy between the amplitude of reconstructed SL variations (ca. 10–40 cm) and simulated variations (ca. 4 cm) seems due partly to the flat bottom and coarse resolution of the ocean model. These model features lead to excessive diffusion and zonal spreading, flattening out anomalies in deep ocean hydrography while they are advected southward. By comparison, the maximum amplitude of centennial winter SL excursions along the US east coast in the 1700 yr control run of the state-of-the-art Hadley Centre coupled climate model (HadCM3) varies from ca. 19 cm near Cape Hatteras to ca. 7 cm in the slope

water between 40°N and 50°N (*van der Schrier et al.*, in prep.). A second potential source for the discrepancy may be that the ecological response characteristics, sediment compaction and the sampling strategy are not likely to result in a simple stationary low-pass filter of SL changes, as is assumed when processing the simulated SL data. Other sources of inconsistency between the simulated and reconstructed SL curves could be the neglect of volcanic dust forcing [*Crowley*, 2000] and of ocean-mass changes due to changes in ice volume.

5. Concluding Discussion

[16] We have argued that US east coast SL reconstructions show a ca. 125-yr lagged response to solar variability. High correlations (>0.65) and the lag are shown to be robust for the ^{14}C dating uncertainties. A physical mechanism is proposed on the basis of numerical simulations with a coupled atmosphere-ocean GCM of intermediate complexity. Considering the uncertainties in the conversion to SL of paleoecological data, the simplifications in the model, and the noisiness of the system, the simulated SL curves agree with the reconstructions as well as can be expected.

[17] The solar variability-climate link is not ultimately known, except for a small change in solar irradiance [*Willson and Hudson*, 1991]. There are, however, indications for influences via large-scale modes of the atmospheric circulation, e.g. [*Shindell et al.*, 2001]. Incorporating solar activity solely by prescribing total irradiance changes is a conventional but preliminary approach. A more advanced approach will come within reach only when long transient simulations can be made with climate models which include full stratospheric dynamics.

[18] The fate of the overturning during the Little Ice Age (LIA) is, from the marine geological perspective, controversial. Some data suggest a slackened meridional overturning [*Bianchi and McCave*, 1999], while *Keigwin and Boyle* [2000] argue that the evidence is inconclusive. The present study suggests an increased overturning during the coldest period of the LIA (ca. 1400–1550), as evidenced by the reduced SL in the Gulf Stream area some 120 yr later.

[19] **Acknowledgments.** This research was sponsored by the Dutch National Research Programme (NRP) on Global Air Pollution and Climate Change; registered under nr. 951268, entitled: “Ocean-climate variability and sea level in the North Atlantic region since AD 0”.

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