The volcanic eruption of 1258 A.D. and the subsequent ENSO event

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The massive volcanic eruption of 1258 A.D. had far-reaching climate and demographic impacts [*Stothers*, 2000; *Oppenheimer*, 2003]. Although the identity of the volcano responsible for the eruption remains a mystery, a tropical location is likely, given the worldwide presence of the ashes and simultaneous presence of its signal in ice cores from both poles. Using estimates of its radiative effect [*Crowley*, 2000] and a climate model of intermediate complexity [*Zebiak and Cane*, 1987], we show that the eruption is likely to have triggered a moderate-to-strong El Niño event in the midst of prevailing La Niña-like conditions. Disparate paleoclimate data document important hydroclimatic consequences for neighboring areas. We propose, in particular, that the event briefly interrupted a solar-induced megadrought in the Southwestern US.

1. Introduction

One of the very largest eruptions in the entire Holocene occurred ca 1258 A.D. [*Stothers*, 2000]. Although both its timing and location are controversial [*Oppenheimer*, 2003], tephra and sulfate aerosols are found ubiquitously in climate records within a year of the event. Its impact on top-of-atmosphere incoming solar radiation was estimated by *Crowley* [2000] as a dimming of $\sim -12\ \mathrm{W\,m^{-2}}$, about 3 times the estimated greenhouse warming perturbation since 1850. It was, by any measure the most important eruption of the past millennium. *Crowley* [2000] indicates that its ice core sulfate concentration reached eight times that of Krakatau (1883) and three times that of Tambora (1815), which accounted for the "year without a summer" [**?***Stothers*, 1984]. It is surprising that its precise location has not yet been pinpointed, though its presence in ice cores of both poles points to a tropical origin : El Chichón (Mexico) and Quilotoa (Ecuador) are the preferred candidates (*Palais et al.* [1992] ; R.Bay, personal communication). Such a radiative perturbation must have had sizable climate impacts worldwide. Indeed, *Stothers* [2000] lists an impressive body of historical evidence for the eruption having occurred early in 1258 (probably January) and having caused massive rainfall anomalies, with adverse effects on agriculture, spreading famine and pestilence across Europe. Some of these consequences are consistent with what we know of the atmospheric response to recent tropical eruptions [*Robock*, 2000], but it is difficult, to characterize the atmospheric response to such eruptions for two main reasons :

1. The shape of the volcanic veil is highly dependent on the atmospheric velocity field at the time of the injection, which determines the dispersion of the sulfate aerosols and their effect on optical thickness worldwide : the atmospheric response is a function of its initial state.

2. The direct (radiative) and indirect (dynamical) effects of the eruption are often confounded by other sources of natural variability - in particular, the near-simultaneous occurrence of El Niño events [*Robock*, 2000].

The last point is a sensitive issue. A temporal correlation between both phenomena was recognized early on, and a possible volcanic determinism of the El Niño -Southern Oscillation (ENSO) was even proposed [*Handler*, 1984], albeit on the basis of the relatively short instrumental record. However, doubt was soon cast on this explanation once ENSO began to be understood and was shown to be predictable [*Cane et al.*, 1986] without invoking volcanic forcing, and when Handler's statistical analysis was shown not to withstand a careful scrutiny [*Nicholls*, 1990; *Self et al.*, 1997].

The idea that this correlation was no accident was recently revived by *Adams et al.* [2003], who applied superposed epochal analysis to show that, since 1650, roughly two thirds of El Niño episodes have happened on the heels of a large tropical eruption. This time, a dynamical explanation was proposed, invoking the thermostat response of the tropical Pacific to uniform cooling [*Mann et al.*, 2005; *Clement et al.*, 1996]. The composites of *Adams et al.* [2003] are dominated by large eruptions, and the ENSO model used in the study tended to consistently produce El Niño events, though it also generated its own in the absence of volcanic forcing.

In the present work, we follow on this proposition and investigate the climatic consequences of the 1258 volcanic eruption. We start by describing and analyzing numerical experiment in the next section, which we then confront with an array of paleoclimate records (section 3). Discussion follows in section 4.

2. Numerical Experiments

2.1. Forcing

The 1258 volcanic anomaly event is found

- in almost every ice core from Greeland and Antartica [*Langway et al.*, 1988], as well as
- in Lake Malawi sediments [34.5 °E, 1 °S], as a thick ash layer of age within dating uncertainties (±100 years) of 1258 A.D. (Thomas C. Johnson, personal communication).

This is very strong evidence that the eruption occurred in the Tropics.

The mass sulfate injection is estimated to lie between 190 and 270 Mt [*Budner and Cole-Dai*, 2003; *Cole-Dai and Mosley-Thompson*, 1999]. The radiative impact at the top of the atmosphere can be estimated via the following formula [*Pinto et al.*, 1989; *Hyde and Crowley*, 2000] :

$$\Delta F = (\Delta F)_{\mathrm{K}} \left(\frac{M}{M_{\mathrm{K}}}\right)^{2/3} \tag{1}$$

wherein M_{K} is the sulfate aerosol loading of the Krakatau (1883) eruption, estimated at about 50 Mt [*Self and Rampino*, 1981; *Stothers*, 1996], corresponding to a solar dimming of $(\Delta F)_{\mathrm{K}} =$

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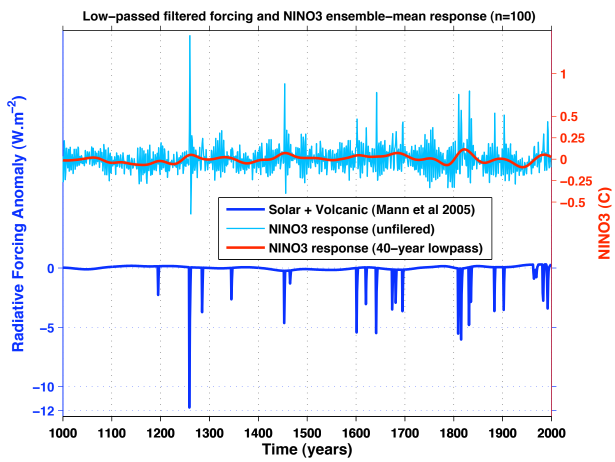

Figure 1. Response of the Zebiak-Cane model to volcanic forcing during the past millennium, for the 100-member ensemble average.

$-3.7\ \mathrm{W\,m^{-2}}$ [*Sato et al.*, 1993]. The sulfate stratospheric loadings given above translate to perturbations of -8.9 to $-11.4\ \mathrm{W\,m^{-2}}$, all extremely large, but with an error bar of about 30%. Results are qualitatively similar for all estimates within this range.

2.2. Experimental Setup

We use the model of *Zebiak and Cane* [1987], which has linear shallow-water dynamics for the global atmosphere [*Zebiak*, 1982] and the Tropical Pacific ocean [*Cane and Patton*, 1984], coupled by non-linear thermodynamics, and displays self-sustained ENSO variability. The ocean model domain is restricted to [124°E-80°W; 29°S-29°N], which means that only tropical processes are considered. The model is linearized around a constant climatology [*Rasmussen and Carpenter*, 1982].

We employ the same configuration as *Emile-Geay et al.* [2006]. The estimate of the volcanic forcing over the past millennium is that developed by *Crowley* [2000], selecting only those eruptions simultaneously present in records from both poles. All eruptions are assumed to occur in January of each year, and stay constant for 12 months. Modestly different results would ensue with an exponential decay and varying eruption times. The veil's spatial extent is uniform throughout the model domain, for simplicity.

As in *Mann et al.* [2005], the (global) volcanic forcing estimates are scaled by a factor of $\pi/2$, since the model represents only the Tropics. Because the eruption of interest was only recorded in both poles in 1259, this is the date where it is included in the model, but shifting the spike to 1258 only shifts the response a year earlier. Similar lags might be present for other eruptions.

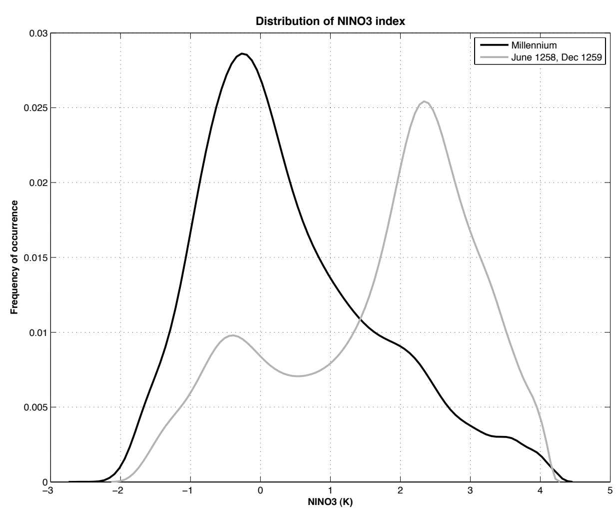

Figure 2. Intra-ensemble distribution of the monthly NINO3 index in the period June 1258- Dec 1259 (light gray curve), compared to the reference distribution computed over the entire millennium (black curve). We used a kernel density estimation with a Gaussian kernel and a width of 0.29°C.

2.3. Results

In Fig 1 we show the 100-member ensemble mean response of the NINO3 index, in order to isolate the effect of boundary conditions over the model's strong internal variability.

A striking result is the occurrence of El Niño events in the year following major tropical eruptions, such as Tambora (1815) and Krakatau (1883), and 1258. This result can be explained by the "thermostat" mechanism [*Clement et al.*, 1996] : the strong upwelling (sharp thermocline), and surface divergence in the eastern equatorial Pacific (EEP) make the SST harder to change by radiative forcing alone. In contrast, the deeper thermocline and small heat transport in the Western Pacific Warm Pool make it more sensitive to alterations of the surface energy balance. Given a uniform

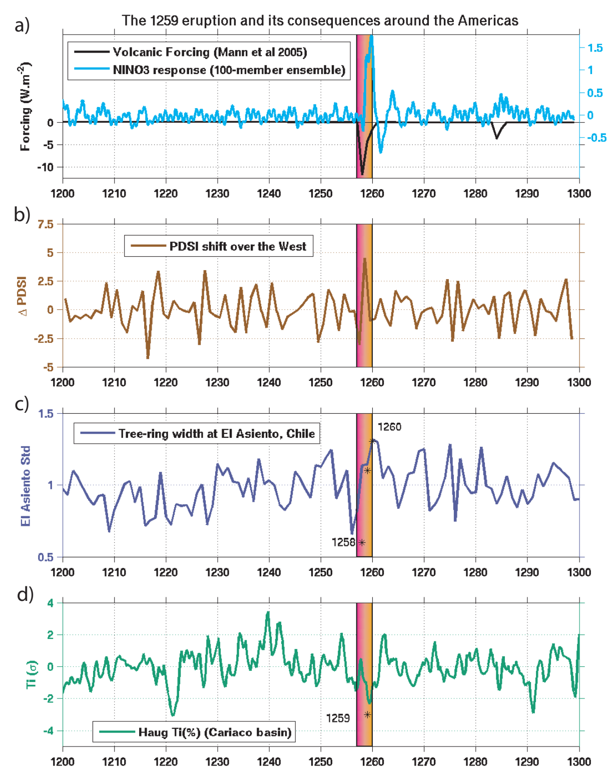

Figure 3. Multiproxy view of the 1258 eruption : (a) Volcanic forcing (black curve) in $\mathrm{W\,m^{-2}}$ and 100-member ensemble mean response of NINO3 in the Zebiak-Cane, with a 20-year lowpass (light blue curve). (b) year-to-year change in PDSI over the american West [*Cook and Krusic*, 2004] (c) Standardized tree-ring width at El Asiento, Chile [*Luckman and Villalba*, 2001] (d) Titanium percentage in core 1002 from the Cariaco basin [*Haug et al.*, 2001] . The time series is expressed in standard deviation units.

reduction in incoming surface radiation, the SST will therefore cool faster in the West, initially reducing the zonal SST gradient. This provokes a slackening of the trade winds , which promotes a further reduction of the SST gradient, via the *Bjerknes* [1969] feedback : the upshot of those air-sea interactions is that a uniform solar dimming results in more El Niño-like conditions. Conversely, a uniform radiative increase produces La Niña-like conditions. In individual simulations, an El Niño event may or may not occur, but a higher ensemble-mean NINO3 means that events are favored. In other words, it is the likely behavior of the system, though some eruptions - especially weaker ones - may not follow the rule. El Niño events are known to have occurred in 1814 and 1884 [e.g. *Self et al.*, 1997], but their potential link to the eruptions will not be contended here.

It is clear from Fig 1 that the 1258 eruption stands out in the context of the millennium, both in the forcing and the response, which is a 1.5°C warming in the ensemble mean. This result is virtually identical to that of *Mann et al.* [2005] (their Fig 1a), despite slight coding differences.

It is instructive to look at the distribution of NINO3 values, shown in Fig 2, which displays a very significant shift toward positive values over the period June 1258 - Dec 1259. Within the 100-member ensemble, and over that particular period, the model saw the development of a warm event(defined here as NINO3 $>$ 0.5°C for at least 6 months), in 84% of cases. In 64% of them, the index exceeded 2°C for at least 6 months, which is comparable to the strength of the 1986/87 El Niño and 31% of cases reached at least 2.5°C for that long, roughly the strength of the 1982/83 El Niño. This is to be compared with average probabilities of 40%, 19% and 11%, respectively, over the rest of the millennium, on identical 18-month intervals starting in June.

Thus, in the vast majority of cases, the model tended to produce a moderate-to-strong El Niño in response to the 1258/1259 volcanic dimming of solar irradiation. This needs to be put in the longer context of medieval climate, which was also affected by variations in solar irradiance [*Jones and Mann*, 2004]. When reconstructions thereof were added to the volcanic forcing, as in *Mann et al.* [2005], we found that the early part of the millennium (1000-1300 A.D.), a period of anomalously high irradiance (possibly related to the so-called Medieval Warm Period), the model's EEP was anomalously cold by a few tenths of a degree. The persistence of such La Niña-like conditions is consistent with evidence of an epic megadrought that struck the American West at the time [*Cook et al.*, 2004], as well as modeling results [*Schubert et al.*, 2004; **?**] and other proxy

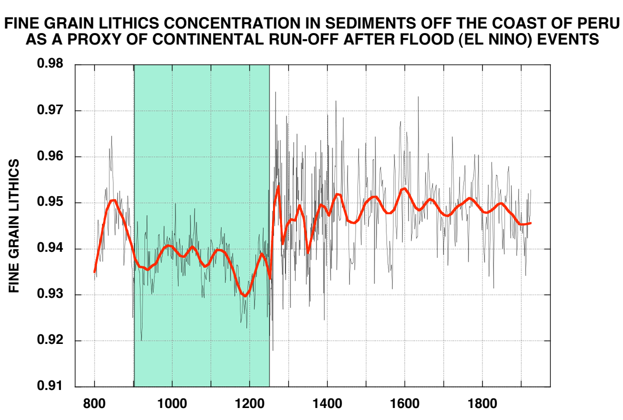

Figure 4. The record of fine-grained lithics in the context of the past millennium (from *Rein et al.* [2004]). The thick red curve is lowpass filtered, and the shaded area corresponds to the Medieval Climate Anomaly. Note the sharp transition around 1260 A.D.

evidence for medieval hydroclimate worldwide [*Herweijer et al.*, 2006].

We thus propose that the 1258 eruption produced a moderate-to-strong El Niño in the midst of prevailing La Niña-like conditions. Is the paleoclimate record consistent with such a proposition ?

3. Proxy evidence

In Fig 3 we confront the model results in panel (a) with proxy evidence from a variety of high-resolution climate records from across the globe :

1. The North American Drought Atlas [*Cook and Krusic*, 2004], which estimates the Palmer Drought Severity Index (PDSI, [*Palmer*, 1965]) over the American West ([25°N-47.5°N; 122°W-100°W]), a proxy for soil moisture which has built-in persistence. Tree-ring records from this region have been shown to be extremely sensitive to droughts, which were tied to tropical Pacific sea-surface temperature (SST) patterns [*Cole et al.*, 2002; *Seager et al.*, 2005; *Herweijer et al.*, 2006]. The decade beginning in 1250 was exceedingly dry, with some of the driest years on record (1253, 1254) over the region. Year 1258 itself reaches an extremely negative value for the PDSI, which then undergoes its biggest upward jump of the millennium (+4.52 units), bringing the drought conditions back to almost normal for 1259. This jump is presented on Fig 3b, which features the year-to-year change in the index. The most likely cause of such a jump is a strong or very strong El Niño.

2. A record of tree-ring width from El Asiento, Chile, which is the most ENSO-sensitive tree-based record of the past 1000 years over South America [*Luckman and Villalba*, 2001] (Fig 3c). The standardized width is a proxy for fractional expected growth, which is dominated by water supply. Typically, wetter years yield thicker rings. While the 1258/59 jump (+0.48 units) is not the largest in the record in absolute terms (cf the return to near-normal conditions after the severe drought of 1304, +0.89 units), it is also consistent with a moderate-to-strong El Niño.

3. Titanium content (%) in the Cariaco basin sediments core at ODP Site 1002 (10°N, 65°W) as in [*Haug et al.*, 2001]. This record (Fig 3d) is best interpreted as a proxy for rainfall over northern South America, which El Niño tends to reduce, thereby decreasing the riverine flux of titanium into the core. The core was analyzed at 50 μm resolution over the 12$^{\text{th}}$ century, providing unprecedented detail on ITCZ dynamics during this time window. Despite the uncertainties of the age model published in *Haug et al.* [2001], notable Ti minima are observed synchronously with upward jumps in PDSI ca 1220, 1259, 1289 and 1299, consistent with the occurrence of El Niños at those times.

In Fig 4 we show the record of fine-grain lithics off the Peruvian coast, taken as a proxy for ENSO rainfall [*Rein et al.*, 2004]. A spike is indeed present around 1258 (within dating uncertainties), shortly before the end of the period of low ENSO activity that prevailed from about 800-1250 A.D. This is broadly synchronous with the Medieval Warm Period, which seemed to have ended by a sharp return to wetter conditions over Peru ca 1260 A.D.

4. Discussion

Thus the evidence is that the Americas did record signals consistent with a moderate-to-strong El Niño in 1258/1259, which came on the heels of a major, prolonged La Niña-like anomaly during the Medieval Warm Period [*Rein et al.*, 2004]. This can be explained by the "thermostat" response of the Tropical Pacific to the massive volcanic sulfate aerosol loading reconstructed for that time, in the midst of a period of strong solar irradiance. However, we must acknowledge the incompleteness of the model physics and uncertainties in both the forcing and dataset considered for validation.

Uncertainties in the forcing are of order 30% (section 2). Also, while the simplicity of the model is necessary to allow the study of the coupled system over the length of the millennium, it creates caveats that are inherent to its formulation [*Clement et al.*, 1999]. While the chain of physical reasoning linking volcanic and solar forcing to equatorial SSTs (the "thermostat" mechanism) is certainly correct as far as it goes, the climate system is complex and processes not considered in this argument, such as cloud feedbacks and thermocline ventilation, might be important.

Proxy records are imperfect by nature, so only the convergence of independent indicators can give confidence in a result. A more direct measure of tropical Pacific SSTs would be desirable, but is unavailable at this time. One could also turn to more remote ENSO proxies, but it then becomes difficult to disentangle the direct, local effects of the volcanic veil and the more indirect ENSO teleconnections [*Santer et al.*, 2001]. There is no obvious way to separate these, since the geographical distribution of the sulfate stratospheric cloud is unknown, and the El Niño need not have been exceptional in amplitude. Targeted experiments in a coupled general circulation model featuring a realistic ENSO cycle and using idealized volcanic forcing for 1258 would shed light on this issue.

There is an apparent paradox in our results. If volcanoes can cause El Niños, it would seem that ENSO could not be predicted unless one could predict volcanic eruptions. Yet all current prediction schemes, many of which have demonstrated considerable skill [e.g. *Goddard et al.*, 2001], use only climate information. However, in common with *Adams et al.* [2003] and *Mann et al.* [2005], we have shown only that outsized volcanic eruptions are highly likely to generate an El Niño; more moderate eruptions create only a slight bias toward more warm events (see Fig 1). Hence there is no inconsistency between results on the impact of volcanic eruptions on ENSO and studies such as *Chen et al.* [2004], which shows that all major El Niño events since 1856 could be forecast up to 2 years ahead solely with knowledge of initial SSTs.

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