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Atmospheric Chemistry and Physics Discussions

Interactive comment on "An empirical model of global climate – Part 1: Reduced impact of volcanoes upon consideration of ocean circulation" *by* T. Canty et al.

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We thank Davide Zanchettin, Oliver Bothe, Johann Jungclaus, Katja Lohmann, and Claudia Timmreck for taking the time to read our manuscript and providing thoughtful interactive comment.

Their comment focuses on our interpretation of Zanchettin et al., 2012a, hereafter ZTG12. Our numbered sections denote replies to the numbered statements of their comment.

1. Specifically, they note that the first citation to ZTG12 on page 23858, where we state "ZTG12 suggested the strengthening of the AMOC would maximize about 10

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years after a major volcanic eruption", is fine but that the citation to ZTG12 on page 23860, where we had stated the AMO is at a local minimum ∼10 yr after peak SOD, requires revision. Zanchettin et al. clarify in their interactive comment that the AMOC and AMO are not exchangeable.

We agree that our second citation to ZTG12 requires revision. We are aware that the AMOC refers to the Atlantic Meridional Overturning Circulation, that the AMO refers to the Atlantic Multidecadal Oscillation, and that these two terms are not exchangeable. We regret that the second citation to ZTG12 in our submitted manuscript, which is incorrect, suggested that we may have been treating AMO and AMOC as being interchangeable.

Zanchettin et al. describe two studies not cited in our submitted paper. Otterå et al. (2010) shows the AMOC and AMO are out of phase by about 10 years in the Bergen Climate Model. Menary et al. (2012) examine the AMOC on centennial time scales within the COSMOS Earth System Model (COSMOS-ESM). Both papers highlight the fact that the "AMOC and AMO are not fully exchangeable descriptors of simulated North Atlantic oceanic variability". Section 2 of ZTG12 calls the ocean-sea ice model MPIOM and calls the atmosphere model ECHAM5. Therefore, we assume that the COSMOS-ESM model called described in the interactive comment is the same as the ECHAM5/MPI-OM model described in ZTG12.

In our submitted paper, we relied heavily on the study of Medhaug and Furevik (2011) (hereafter MF11). This study included an analysis of AMO and AMOC from the Bergen Climate Model (BCCR-BCM2.0), the ECHAM5/MPI-OM model, as well as 8 other coupled atmosphere/ocean models. Table 4 of MF11 shows that the various models have a wide range for the temporal lag needed to obtain maximum correlation between the AMO (area weighted SST for 60W to 0W, 0 to 60N, detrended using a linear fit) and AMOC (defined as the maximum in the annual meridional stream function, in units of Sv, poleward of 20N and below 500 m). The shortest lag is 1 year, for the ECHO-G model. The longest lag is 28 years, for the MIROC3.2 (MED) model (for this model, the peak correlation occurs outside of the maximum allowable lag). The BCCR-BCM2.0 entry in Table 4 of MF11 has a lag between AMO and AMOC of 21 years, longer than all other models except MIROC3.2 (MED). MF11 emphasize that the time rate of change of AMO is nearly in phase with AMOC for 7 of the 10 models, "indicating that there is a linkage between AMOC strength and warming or cooling of the Atlantic surface waters" (page 400, MF11). It is this linkage between AMOC and the temperature of the north Atlantic that is vital for the validity of the study.

Upon revision, we will take care to clarify any other instances where AMO and AMOC may have been inadvertently exchanged in our manuscript.

2. Zanchettin et al. point out that additional information regarding volcanic influence on north Atlantic upper ocean potential temperature can be obtained from Figure 11 of ZTG12. They also suggest the studies by Mignot et al. (2011) and Miller et al. (2012) may be worthy of consideration in the paper as well.

We believe the most salient point of this comment is that "the response of North Atlantic SSTs to strong volcanic eruptions is typically confined to the first few post eruption years". We will emphasize this salient point, upon revision, in any citation to ZTG12. The Miller et al. (2012) paper focuses on the possible volcanic triggering to the onset of the Little Ice Age. The Mignot et al. (2011) paper examines volcanic impact on the North Atlantic over the last 1000 years. Mignot et al. (2011) highlight that the AMOC could respond in a different manner (i.e., either intensification or weakening) due to the seasonality of the eruption, the intensity, and the cumulative response to multiple eruptions. We will cite both of these papers, upon revision.

3) Finally, Zanchettin et al. note that the 20th century volcanic eruptions considered in our paper "may not be the best choice" to constrain the sensitivity of simulated North Atlantic SST and AMO to volcanic forcing.

Ensemble simulations shown in Figure 2 of Zanchettin et al. (2012b) indicate that for 20th century eruptions, the observed NAVI (North Atlantic Variability Index) can only be clearly linked to the eruption of Mt. Pinatubo.

ZTG12a examined the response of SST to nine tropical volcanic eruptions, starting with an unnamed eruption in 971, including Tambora in 1815, and ending with Krakatoa in 1884. Significant effects of volcanic aerosol on SST are found only for the largest eruptions (Figure 5 of Zanchettin et al. (2012b), which exceed the strength of any eruptions during the 20th century.

Our analysis begins in 1900 because this period, to present, contains the most reliable modern instrument record for temperature and other elements of our study. As stated in our paper:

"Data needed for our analysis becomes more scarce and uncertain prior to 1900. Also, some of the key figures in IPCC (2007) important for to our work, such as Figs. TS.23 and 9.14, begin around 1900. Finally, our time period covers the same set of major volcanic eruptions examined by Wigley et al. (2005)."

In the future, we hope to extend our framework to cover Krakatoa and Tambora.

Finally, we emphasize that Figure 5 of Zanchettin et al. (2012b) is vitally important for our study. As noted in the Interactive Comment, the ensemble simulations of NAVI exhibit “fluctuations in individual simulations [that] are practically indistinguishable from fluctuations characterizing other periods of either internally-driven or externally generated variability”. In our paper, we use a regression model to relate variability in the observed AMO to various global temperature anomalies (i.e., global surface, land only surface, global lower atmosphere, land only lower atmosphere). The inferred strength of volcanic cooling is shown to be sensitive to how the AMO signal is detrended. Of course, we do not know how the AMO would have behaved in the year or two after the major eruptions of the 20th century, had these eruptions not occurred. We show that prior to three of the four major volcanoes of the 20th century (Santa María, Agung, and Pinatubo), the AMO had began to cool prior to the eruption. It is plausible, we believe, to ascribe this behavior to internally-driven variability, which extended post eruption.

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We shall reference Zanchettin et al. (2012b) upon revision.

We close this reply by reiterating that page 97 of the 2007 IPCC report states "major volcanic eruptions can thus cause a drop in mean global surface temperature of about half a degree Celsius that can last for months or even years". The actual drop in the global mean surface temperature following the eruption of Mt. Pinatubo was actually about 0.3 degree Celsius, as shown in Figures TS.23a and Figure 9.5a of IPCC (2007) as well as Figure 10 of our paper. We show that a significant portion of this cooling, perhaps nearly half, could have been due to variations in the strength of the AMOC (which would have occurred several years prior to the eruption of Pinatubo), as reflected in the AMO at the time just prior to the eruption of Pinatubo. Clearly, as detailed in the Interactive Comment by Davide Zanchettin and colleagues, further research is needed to better understand internal variations of the strength of the AMOC, the response of the AMOC to volcanic perturbation, and the use of the AMO as a proxy for prior changes in the strength of the AMOC.

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