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The impact of volcanic eruptions in the period 2000–2013 on global mean temperature trends evaluated in the HadGEM2-ES climate model

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Abstract

The slow-down in global warming over the last decade has lead to significant debate about whether the causes are of natural or anthropogenic origin. Using an ensemble of HadGEM2-ES coupled climate model simulations we investigate the impact of overlooked modest volcanic eruptions. We deduce a global mean cooling of around −0.02 to −0.03 K over the period 2008–2012. Thus while these eruptions do cause a cooling of the Earth and may therefore contribute to the slow-down in global warming, they do not appear to be the sole or primary cause.

Keywords: stratospheric aerosol; volcanic eruptions; climate; global warming

1. Introduction

There has been a significant interest in the perceived slow-down of global warming over the past decade (e.g. Easterling and Wehner, 2009; Meehl *et al.*, 2011; Hansen *et al.*, 2013). Meehl *et al.* (2011) (and references therein) which suggest that that recent increases in stratospheric water vapour (Solomon *et al.*, 2010), stratospheric aerosols (Solomon *et al.*, 2011), tropospheric aerosols or the record solar minimum (Kaufmann *et al.*, 2011) could all be contributory factors to this hiatus. Hansen *et al.* (2013) contend that the most significant contribution for the perceived slowdown is associated with natural variability in the El Niño/La Niña oscillations of Pacific sea-surface temperatures.

Climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) provide a comprehensive basis for evaluating and comparing an ensemble of climate model projections (Taylor *et al.*, 2012). These CMIP5 simulations adopt representative concentration pathway (RCP) scenarios which were developed to represent the possible future climate scenarios under different levels of socio-economic growth and mitigation (Moss *et al.*, 2010). These RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) represent scenarios where the radiative forcing by the year 2100 reaches 2.6, 4.5, 6.0, and 8.5 Wm^{-2}, respectively. Each scenario provides the atmospheric concentrations of various greenhouse gases and tropospheric and stratospheric aerosols that are used to drive coupled ocean–atmosphere climate models. However, as noted by Fyfe *et al.* (2013), most of the RCP simulations performed for CMIP5 (including those performed by the Met Office) have only minimal radiative forcing associated with stratospheric aerosols subsequent to around 2000. Since 2000 there have been a number of modest volcanic eruptions [volcanic explosivity index (VEI) = 3–4] that have significantly perturbed the stratospheric aerosol optical depth (AOD). The three most significant eruptions were Kasatochi in the Aleutian Islands in August 2008 (e.g. Kravitz *et al.*, 2010), Sarychev in the Kuril Islands in June 2009 (Haywood *et al.*, 2010), and Nabro in Eritrea in June 2011 (Bourassa *et al.*, 2012), each of which injected between 1.0 to 1.5 Tg SO_2 into the stratosphere. There have also been significant perturbations to the stratospheric AOD from the eruptions of Soufriere Hills in Monserrat in May 2006 and from Tavurvur, Papua New Guinea in October 2006 (Solomon *et al.*, 2011; Vernier *et al.*, 2011).

The two studies most relevant to the work presented here are those of Solomon *et al.* (2011) and Fyfe *et al.* (2013), where both suggest that the moderate volcanic activity since 2000 that has been neglected in climate simulations has contributed to a reduction in global mean temperature. Solomon *et al.* (2011) used the Bern 2.5CC intermediate complexity climate model to deduce an impact of around −0.07 K, while Fyfe *et al.* (2013) used a version of the Canadian Earth System Model (CanESM2) and again deduced an impact of around −0.07 ± 0.07 K. As different models have different transient climate sensitivities it is worthwhile assessing the impact with a different state-of-the-art coupled climate model, in this case the coupled atmosphere ocean Earth System model HadGEM2-ES (Collins *et al.*, 2011). Andrews *et al.* (2012) report that HadGEM2-ES and CanESM2 have equilibrium climate sensitivities for doubling of CO_2 of around 4.6 and 3.7 K, respectively while

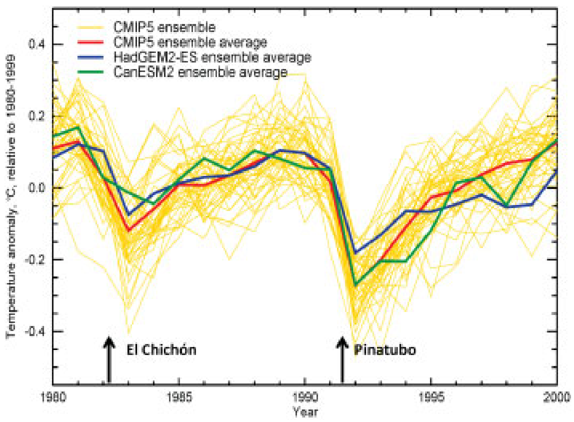

Figure 1. Submissions to the CMIP5 (volcanic and solar forcings only) simulations. The CMIP5 ensemble average is shown in red while HadGEM2-ES and CanESM2 ensemble averages are also shown. The dates of eruptions of El Chichón and Pinatubo are indicated.

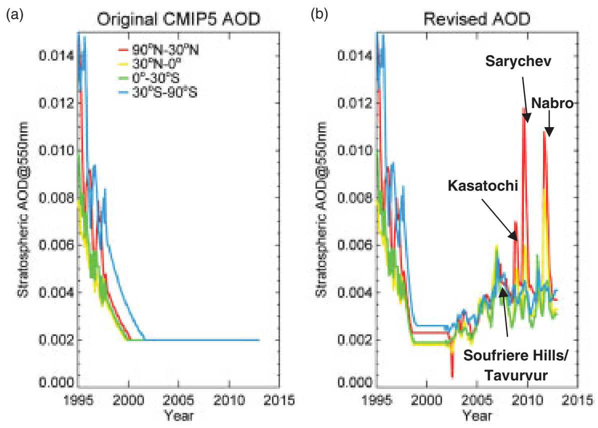

Figure 2. (a) the AODs at 550 nm in the four latitude bands as used in the CMIP5 simulations, (b) the AODs updated to include data up to 2013. Data are from updates to Sato et al. (1993). AOD perturbations from the eruptions of Soufriere Hills, Tavurvur, Kasatochi, Sarychev, and Nabro are marked in Figure 2(b).

the 15-model CMIP5 ensemble exhibit a mean of 3.4 K with a standard deviation of 0.8 K. Of the 15-model ensemble, HadGEM2-ES has the second highest equilibrium climate sensitivity. Although CMIP5 models struggle in representing the observed wetter warmer European winters subsequent to major volcanic eruptions (Driscoll *et al.*, 2012), they simulate a global mean cooling as shown in Figure 1.

HadGEM2-ES shows a somewhat smaller peak global mean cooling subsequent to the eruptions of Pinatubo and El Chichón than the mean CMIP5 ensemble, but the impact is sustained for longer, which is typical of a model with a relatively high climate sensitivity (Hansen *et al.*, 1981). The ensemble mean from the CanESM2 model is also shown. Section 2 describes the AODs applied to HadGEM2-ES, Section 3 the experimental design, before the results, and conclusions are presented in Sections 4 and 5.

2. Aerosol optical depth

The HadGEM2-ES model contribution to the CMIP5 simulations included a prescribed altitude dependent stratospheric aerosol in four equal area bands; 90°N-30°N, 30°N-0°, 0°-30°S, and 30°S-90°S from the updated data set of Sato *et al.* (1993) (Figure 2).

Figure 1(a) shows that the stratospheric AOD data end at 1997, subsequently followed by an exponential decay to a fixed value of 0.02 assumed at all latitude bands and remains at this fixed value from 1999 to 2002. Figure 2(b) shows the updated climatology of stratospheric AOD; the eruptions from moderate volcanic eruptions are clearly evident, with eruptions at high latitudes in the Northern Hemisphere (e.g. Kasatochi and Sarychev) loading the latitudinal band 90°N-30°N most heavily (Haywood *et al.*, 2010; Kravitz *et al.*, 2010) while those near the equator (Soufriere Hill and Tavurvur) load tropical regions most heavily (e.g. Solomon *et al.*, 2011; Vernier *et al.*, 2011).

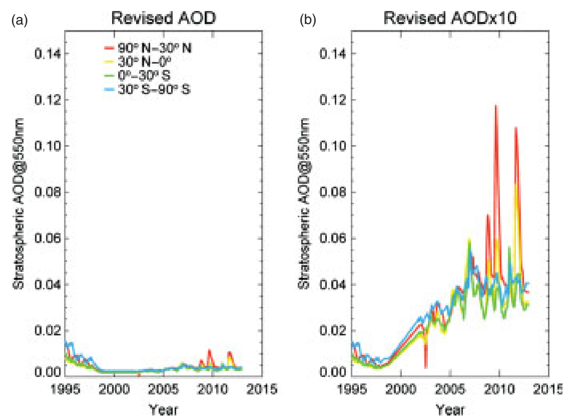

Figure 3. (a) the AODs at 550 nm in the four latitude bands updated to include data up to 2013, (b) the AODs scaled by a factor of 10 as described in the text.

Experience with HadGEM2-ES (Haywood *et al.*, 2013; Jones *et al.*, 2013) and test simulations using the revised AODs show we cannot discern a temperature signal above the significant inter-annual variability within the model using AODs of this magnitude. Therefore, the revised AODs were enhanced using the following method to prevent discontinuity in the data. Over a 4-year period from January 1998 to December 2001 (the flat period in Figure 2(b)) the revised data were multiplied by a factor which linearly increased from 1 to 10, then remaining at 10 to the end of the revised dataset. Results will be presented using the enhanced x10AODs, and also rescaling the AODs back to original values. Figure 3(a) shows the revised AODs including recent volcanic eruptions while Figure 3(b) shows the revised AODs multiplied by a factor of 10.

3. Experimental design

While increasing the stratospheric AODs by a factor of 10 will aid detection of a robust signal within the model, the significant inter-annual variability in the model will still make detection problematic. Therefore, an ensemble of simulations was performed based on estimates of historical forcing, followed by the RCP (Moss *et al.*, 2010) scenario submissions to CMIP5. An ensemble of three members had already been performed for each of the original four historical/RCP scenarios resulting in 12 original simulations; these simulations will be denoted RCP2.6_orig, RCP4.5_orig, RCP6.0_orig, and RCP8.5_orig. Twelve parallel simulations were performed for each RCP scenario where, subsequent to December 2005, the revised 10xAOD was applied to the model; these simulations will be denoted RCP2.6_AODx10, RCP4.5_AODx10, RCP6.0_AODx10, and RCP8.5_AODx10. The difference in near surface air temperature, dT, was then determined from each of the 12 pairs of simulations (i.e. $dT_{RCP2.6} = T_{RCP2.6\_AODx10} - T_{RCP2.6\_orig}$) over the 5-year period 2008–2012 which includes the eruptions of Kasatochi, Sarychev, and Nabro. Results from taking a mean over the 7-year period 2006–2012, which includes the eruptions of Soufriere Hills and Tavurvur, show little difference and are therefore not shown.

4. Results

Figure 4 shows the temperature evolution for a mean of the historical/RCP scenarios RCP_orig and the mean of the RCP_AODx10 scenarios.

The RCP_orig simulations show an increase in global temperatures over the period 2000–2012 of around 0.5 K, results that are consistent with those from other models (Knutti and Sedláček, 2012), while the results from RCP_AODx10 show little trend. Figure 4 shows that the change in near-surface global mean temperature between the RCP_orig scenarios and the RCP_AODx10 scenarios is statistically significant (at 1 standard deviation) subsequent to 2009–2010, as shown from the divergence in the red and blue lines. The global mean temperature from RCP_orig and RCP_AODx10 differs in the historical period as forcings differ slightly post-1997 leading to different realizations. Figure 4 shows a global mean rate of warming assessed from a linear regression over the period 2005–2012 of around 0.05 K $year^{-1}$ for the ensemble mean of the RCP_orig scenarios and just 0.005 K $year^{-1}$ for the RCP_AODx10 scenarios. For comparison the HadCRUT4 observational data (Morice *et al.*, 2012) is also shown, demonstrating evidence of the hiatus in global mean temperatures (trend -0.009 K $year^{-1}$) although this data may have a slight negative bias as there are fewer observations in polar regions where warming is expected to be largest.

As the global mean temperature response in the RCP_AODx10 simulations is statistically significantly different, we present the regional impacts on temperature and precipitation. These analyses are intended to show the geographical areas where these volcanic

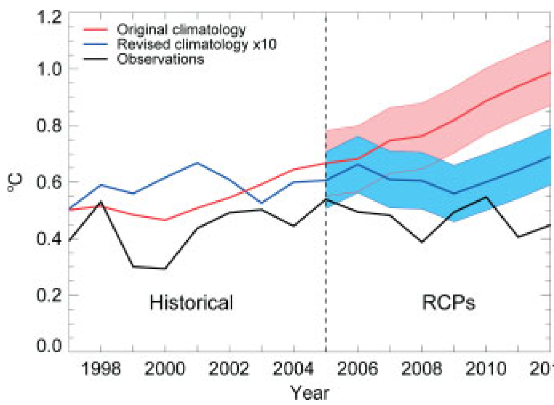

Figure 4. The evolution of near-surface air temperature averaged over all members of RCP_orig and RCP_AODx10. The red and blue envelopes represent the natural variability represented by one standard deviation derived from the ensembles of detrended RCP simulations. The black line shows the observed global annual mean temperatures derived from HadCRUT4 (Morice *et al.,* 2012) normalized to zero over the period 1961–1990.

eruptions have their most significant impact. Fyfe *et al.* (2013) showed maximal temperature impact in the Northern Hemispheres at high latitudes (although the temperature impact was only just significant at 95% confidence) and a global mean decrease in precipitation consistent with other studies (e.g. Robock, 2000; Gillett *et al.*, 2004; Trenberth and Dai, 2007; Haywood *et al.*, 2010). Figure 5 shows the mean changes in temperature and precipitation from the ensemble of RCP_AODx10 simulations.

Figure 5(a) shows that, as expected, the maximum impact of temperature is in the Northern Hemisphere over non-ocean regions areas as the thermal inertia of the oceans tends to suppress rapid temperature changes. A growing body of work (e.g. Held *et al.*, 2005; Jones *et al.*, 2007; Haywood *et al.*, 2013) has shown how state-of-the-art climate model precipitation patterns respond to hemispherically asymmetric forcings. A negative forcing in the Northern Hemisphere preferentially cools the Northern Hemisphere and north Atlantic sea-surface temperatures which strengthens the cross-equatorial Hadley cell; this is associated with a southward shift of the ITCZ (Ceppi *et al.*, 2013; Haywood *et al.*, 2013). Thus as shown in Figure 5(b), precipitation, particularly over the Sahel and the Atlantic Ocean is shifted to the south.

We stress that the results presented above assume a stratospheric AOD that has been artificially enhanced by a factor of ten. To provide a realistic estimate of the impact on global mean temperatures, the temperature changes are rescaled by dividing by a factor of 10, i.e. back to the observed values. This rescaling makes the assumption that the model temperature response is proportional to the AOD perturbation, which is a reasonable approximation in HadGEM2-ES for the AOD perturbation applied here (e.g. Haywood *et al.*, 2013). Table I summarizes the impact of including updated AODs on the global mean and hemispheric

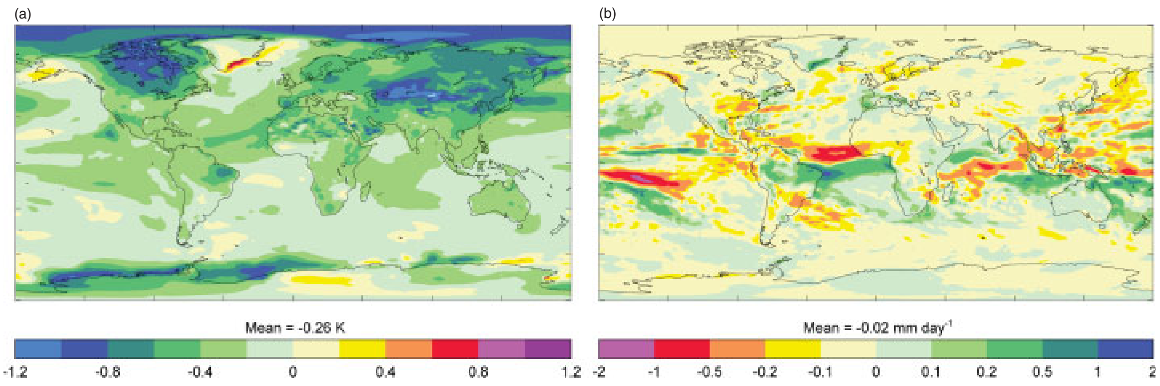

Figure 5. The ensemble mean changes owing to the updated RCP_AODx10 simulations when compared with the RCP_orig simulations for the 5-year period 2008–2012: (a) temperature (K), (b) precipitation (mm day^{-1}).

Table I. The global-mean and hemispheric mean near-surface temperature changes (K) owing to volcanic eruptions derived over a 5-year mean period. The standard deviations shown are derived from the annual variability and therefore consist of sample sizes of 15.

	5 year mean: 2008–2012, $n = 15$			
Simulation	Global mean dT	NH mean dT	SH mean dT	Natural variability (standard deviation)
RCP2.6	−0.028 ± 0.004	−0.036	−0.020	0.08
RCP4.5	−0.030 ± 0.004	−0.045	−0.015	0.09
RCP6.0	−0.021 ± 0.006	−0.030	−0.012	0.17
RCP8.5	−0.024 ± 0.005	−0.030	−0.018	0.10
Mean	−0.026	−0.035	−0.016	0.11

temperatures for each of the RCP scenarios after rescaling to the original AODs.

Table I shows that the mean perturbation to global mean temperatures is between approximately -0.02 and -0.03 K (−0.026 K, standard deviation 0.005 K), representing a statistically significant cooling (95% confidence). We also calculate the standard deviation of the mean temperature of each of the RCP scenario ensembles to determine the model variability in the absence of perturbations to the stratospheric AOD, i.e. the natural variability in the model for each of the RCPs. The mean standard deviation in the temperatures is around 0.11 K suggesting that the temperature changes induced by the volcanic eruptions alone are swamped by natural variability.

5. Discussion and conclusions

While the stratospheric AOD has undoubtedly increased over the past decade owing to the presence of a number of modest volcanic eruptions (e.g. Haywood *et al.*, 2010; Kravitz *et al.*, 2010; Vernier *et al.*, 2011) our results, along with the studies of Solomon *et al.* (2011) and Fyfe *et al.* (2013), suggest that the temperature change associated with these volcanic eruptions is not the sole or primary driver of the global warming hiatus. Our estimates suggest that, if these relatively minor volcanic eruptions were included in climate scenarios, the modelled climate in HadGEM2-ES would cool by a mean of around -0.02 to -0.03 K over the period 2008–2012. Our estimates of the induced cooling are somewhat less than the -0.07 K estimated by Solomon *et al.* (2011) and Fyfe *et al.* (2013). This reduced impact in HadGEM2-ES appears at least partly due to the higher climate sensitivity in HadGEM2-ES which manifests itself in a longer response time for instantaneous forcings (Hansen *et al.*, 1981). Andrews *et al.* (2012) also document a reduced initial climate sensitivity compared with the long-term equilibrium climate sensitivity in HadGEM2-ES compared with CanESM2. Additionally, the averaging period is different and the volcanic forcing differs. Fyfe *et al.* (2013) perform an average over the decade 2002-2012 using volcanic AODs derived from Vernier *et al.* (2011), while we restrict our analyses to the 5-year period 2008–2012 using AODs derived from updates to Sato *et al.* (1993).

Given that the standard deviation owing to natural variability in the simulations is 0.11 K, a global mean temperature perturbation of -0.02 to -0.03 K from modest volcanic eruptions alone is undetectable in HadGEM2-ES and assuming that the variability in the model is reasonably representative of the real-Earth is also likely to be undetectable in observations. Kravitz *et al.* (2010) have already suggested that the eruption of Kasatochi will have an undetectable climatic impact above natural variability. Haywood *et al.* (2010) suggested a maximal impact from the eruption of Sarychev at extreme northern latitudes of up to −0.05 K in the 2 months immediately following the eruption, although the response in their nudged simulations will isolate only the response to changes in surface radiative fluxes over land regions. A final caveat is that this study assumes that including stratospheric aerosols via climatologies of AOD alone is sufficient to represent the impact on radiative forcing and on global mean surface temperatures. No variation in stratospheric aerosol size distribution (Heckendorn *et al.*, 2009) or aerosol indirect effects on liquid or ice-clouds (Kuebbeler *et al.*, 2012) are included in any CMIP5 simulations. These, or other factors, could lead to nonlinear temperature responses compared with those of larger eruptions (Ben Santer, pers. comm.).

The message emerging from this and other studies is clear: while these eruptions do cause a small cooling of the Earth and may therefore contribute to the perceived hiatus in global mean temperatures, they do not appear to be the sole or primary cause.

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