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Reconstructing volcanic radiative forcing since 1990, using a comprehensive emission inventory and spatially resolved sulfur injections from satellite data in a chemistry-climate model

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1. Additional information on the method to derive the 3D SO_2 mixing ratio perturbations from OSIRIS and GOMOS observations

Table S1: Volcanic SO_2 injections 2012 to 2019 derived from OSIRIS (Bourassa et al., 2012, Rieger et al., 2019). For conversion from $\Delta\beta_{ext750}$ to ΔVMR Equation 1 is used where f = 1 is normal case (as for GOMOS and SAGE II). Smaller factors if interfering previous events or cloud artifacts, larger factors if too many gaps or a large time lag to correct for removal. The factor is in parentheses if information from eruptions in the past (see last column) together with column SO_2 are used in addition because of too sparse data.

Volcano or region	Time	Latitude	SO_2 str (kt)	f	Used days
Nyamuragira, Mexico	7 Jun 2012	-1, 20	30, 4	0.3	17-28 Jun
Soputan, N.Ruiz, Mexico	27 Aug 2012	1, 5, 20	30, 15, 5	0.5	1-12 Sep
Nyamurag., Mexico, Peru	14 Oct 2012	-1, 20, -20	40, 15, 10	0.55	19-30 Oct
Nyamurag., Paluweh, N.Ruiz	7 Nov 2012	-1, -8, 5	20, 30, 17	0.5	12-23 Nov
Copahue, Lokon-Empung+	22 Dec 2012	-38, 1	10, 45	0.5	27 Dec-7 Jan
Paluweh, Karkar	3 Feb 2013	-8, -5	25, 22	0.5	8-19 Feb
Karkar, Vanuatu (+?)	10 Mar 2013	-5, -16	24, 20	0.5	15-26 Mar
Rabaul, N.R., Nyamurag	18 Apr 2013	-3, 5, -1	40, 9, 20	0.5	23 Apr-4 May
Mayon, Turrialba, Pavlof	08 May 2013	13, 10, 55	35, 24, 6	0.5	13-24 May
Rabaul, Mex.	10 Jul 2013	-3, 20	30, 15	0.5	20-30 Jul
Pacaya	15 Aug 2013	15	43	1	17-28 Aug
Sinabung, Ubinas	15 Sep 2013	3, -16	35, 8	0.5	19-30 Sep
Merapi, Nyam., Pacaya	18 Nov 2013	-7, -1, 15	30, 13, 8	0.5	22 Nov-3 Dec
Sinabung, Nyam.	9 Dec 2013	3, -1	26, 15	0.5	14-21 Dec
Sinabung +	11 Jan 2014	3	29	0.5	16-27 Jan
Kelut (-(z-5km) 10^{-11})	15 Feb 2014	-8	170	2.8	20 Feb-3 Mar
Merapi, Tung.	27 Mar 2014	-7, -1	31, 33	1	1-12 Apr
Santa Maria, Semeru	9 May 2014	15, -8	25, 39	0.67	14-25 May
Sangeaang-Api	31 May 2014	-8	60	0.67	5-16 Jun
Nyamurag., Pavlof, Fuego, Dukono (Tung)	9 Jul 2014	-1, 55, 14, 2	20, 10, 12, 20	0.67	14-25 Jul
Rabaul, Fuego	29 Aug 2014	-3, 14	36, 20	0.67	3-14 Sep
Nyamuragira	11 Sep 2014	-1	30	0.5	16-27 Sep
Ontakesan	27 Sep 2014	36	34	0.5	2-11 Oct
Sinabung, Turrialba	23 Oct 2014	3, 10	34,17	0.5	28 Oct-8 Nov
Fogo, Semeru, Ubinas	24 Nov 2014	15, -8, -16	11,33,11	0.67	29 Nov-10 Dec
Nev. Ruiz, Nya, Van.	16 Dec 2014	5, -1, -16	8, 12, 21	0.67	21 Dec-1 Jan
Nya., Van., HongaTonga	14 Jan 2015	-1, -16, -21	21, 17, 13	0.67	20-31 Jan
Van., Nya., Soputan	16 Feb 2015	-16, -1, 1	13, 13, 13	0.5	21 Feb-4 Mar

Soputan, Nev.Ruiz, S. Maria, Villarrica	8 Mar 2015	1, 5, 15, -39	14, 14, 8, 5	0.5	13-24 Mar
Tungu? BatuTara?	5 Apr 2015	-1, -8	17, 22	0.67	10-21 Apr
Calbuco	25 Apr 2015	-41	292	3.3	25 Aug-5 Sep
Manam, Tungu?	8 May 2015	-4, -1	24, 25	0.67	13-24 May
Wolf, Aira+Kuchinoerabuj.	26 May 2015	0, 32, 30	63, 20	2	29 May-11 Jun
Raung	4 Jul 2015	-5	27	0.67	9-20 Jul
Cotopaxi, Raung, Suwanosjima, Manam	14 Aug 2015	0, -5, 30, -4	24, 18, 10, 16	0.67	19-30 Aug
Nev.Ruiz+Reventador, Fuego, Sum	21 Sep 2015	5, 14, 3	13, 8, 19	0.67	26 Sep-7 Oct
Sinabung, Fuego, Cotopaxi, Copahue	15 Oct 2015	3, 14, 0,-38	30, 15, 6, 13	0.67	20-31 Oct
Lascar, Sinabung, Nya., Fuego	30 Oct 2015	-23, 3, -1, 14	13,17,12, 17	0.67	4-15 Nov
Vanuatu, Tung., Telica, Rinjani	17 Nov 2015	-16, -1, 13, -5	18,20,10, 18	0.67	17-28 Nov
Vanuatu, Rev., Tengger C.?	5 Dec 2015	-16, 0, 2	16, 15, 12	0.67	10-21 Dec
Reventador, Sinabung	18 Dec 2015	0, 3	16, 16	0.57	23 Dec-3 Jan
Soputan+, Rev., Fuego	8 Jan 2016	1, 0, 14	25, 19, 5	0.67	13-24 Jan
Semeru, Fuego	10 Feb 2016	-8, 14	34, 25	1	15-26 Feb
Van.+, Tungu.	27 Feb 2016	-16, -1	24, 16	0.57	2-13 Mar
Tungu., Sinabung+, Pavlof	15 Mar 2016	-1, 3, 55	23,26,7	0.5	20-31 Mar
Rev., Sinabung +, Fuego, Aira	13 Apr 2016	0, 3, 14, 32	18, 30, 17, 6	0.67	18-29 Apr
Fuego, Nya.+Ecu., Langila, Sinabung	7 May 2016	14, -1, -5, 3	16, 18, 16, 26	0.67	12-23 May
Bulusan, Sinabung, Semeru, Mex	10 Jun 2016	13, 3, 8, 15	16, 14, 16, 10	0.57	15-26 Jun
Rinjani, Sinab., S. Maria	1 Aug 2016	-5, 3, 15	10,30,24	0.67	6-17 Aug
Sinabung+Van., Fuego	28 Aug 2016	-16, 14	42, 23	0.57	2-13 Sep
Ubinas, Sinabung	3 Oct 2016	-16, 3	16, 26	1.3	8-19 Oct
Sabancaya, Sinabung+Bulusan+	5 Nov 2016	-16, 3	38,46	2	10-21 Nov
Dukono, Van., Sabancaya	12 Dec 2016	2, -16, -16	30,28,28	1.3	15-26 Dec
Sabanc., Rev., Sinab.+Van.	10 Jan 2017	-16, 0, 3	20, 30, 23	1	15-26 Jan
Sabanc, Colima, Sinabung	4 Feb 2017	-16, 19, 3	17, 15, 25	0.67	9-26 Feb
Sabancaya, Dukono, Fuego, Manam+Van., Bogoslof, N. Chillan	5 Mar 2017	-16, 2, 14, -16, 53,-37	10, 18, 8, 28, 4, 5	0.67	10-21 Mar
Sabanc, N.Ruiz, Sinabung, Van., Klyuchevskoi	10 Apr 2017	-16, 5, 3, -16, 56	8,15,19, 17,2	0.53	15-26 Apr
Sinabung, Manam, Fuego	5 May 2017	3, -4, 14	26,10, 19	0.53	10-21 May
Sheveluch+Bogoslof	19 May 2017	57	20	1	24 May-4 Jun
S.Maria, Sheveluch+, Manam	16 Jun 2017	15, 57, -4	11,33,6	0.5	21 Jun-2 Jul

Fuego, Sinabung+, Sheveluch+	5 Jul 2017	14, 3, 57	22, 21, 4	0.44	10-21 Jul
Sinab., Cristobal+Fuego, Sheveluch+Bogoslof	8 Aug 2017	3, 13, 54	31,27,5	0.67	13-24 Aug
Tinakula, Ambae	21 Oct 2017	-10, -15	60	1	13-18 Nov
Agung, Ambae, Peru	27 Nov 2017	-8, -15, -5	22,7,12	0.67	29 Nov-9 Dec
Mayon, Vanuatu, Peru	22 Jan 2018	13, -15, -5	7, 20, 16	0.67	27 Jan-6 Feb
Fuego, Vanuatu	1 Feb 2018	14, -15	20, 17	0.67	3-13 Feb
Sinabung, Vanuatu	19 Feb 2018	3, -15	14, 21	0.67	24 Feb-6 Mar
Ambae, Vanuatu	26 Mar 2018	-15	60	1	30 Mar-9 Apr
Ambae	6 Apr 2018	-15	91	1.3	7-17 Apr
Sabancaya	15 May 2018	-16	16	(0.67)	From Feb 2017
Fuego	3 Jun 2018	14	15	(0.67)	From May 2016
Fernandina.	17 Jun 2018	0	8	(2)	From Apr 2009
Agung, Sabancaya	28 Jun 2018	-8, -16	33, 23	(1.8, 1)	From Feb 2016
Sierra Negra	8 Jul 2018	-1	24	(6)	From Apr 2009
Vanuatu	20 Jul 2018	-15	228	(2)	Apr 2018+Feb 2016
Manam, Sabancaya	25 Aug 2018	-3, -16	25, 12	(1.2, 0.5)	May 2015
Krakatau, Sabancaya	23 Sep 2018	-6, -16	5, 11	0.33	28 Sep-9 Oct
Manam, Soputan, Rev.	4 Oct 2018	-3, 1, 0	33	0.67	9-20 Oct
Nev.Ruiz, Saban.	24 Oct 2018	5, -16	22, 11	0.5	25 Oct-5 Nov
Fuego, Saban., Krak	6 Nov 2018	14, -16, -6	46	0.67	11-22 Nov
Fuego, Saban., Papua	26 Nov 2018	14, -16, -3	29	0.5	1-12 Dec
Saban., Manam, Soputan, Vanuatu	8 Dec 2018	-16, -3, 1, -16	24, 8, 4, 6	0.61	12-23 Dec
Krakatau, Vanuatu, Sabancaya	23 Dec 2018	-6, -16, -16	33	0.71	27 Dec-7 Jan
Krakatau, Sabancaya, Manam	4 Jan 2019	-6, -16, -3	34	0.57	9-20 Jan
Manam, Sabancaya	24 Jan 2019	-3, -16	23, 14	0.5	28 Jan-8 Feb
Manam, Sabancaya	14 Feb 2019	-3, -16	12, 13	0.5	19 Feb-2 Mar
Manam, Sabancaya, Mexico, Chile	19 Mar 2019	-3, -16	6, 12 34	0.67	24 Mar-4 Apr
Sabancaya, Manam, N.Ruiz, Gamalama	20 Apr 2019	-16, -3,5,1	31, 12, 15, 7	(0.57)	Apr-May + Apr 2017
Sinabung, Manam, Sabancaya	25 May 2019	3, -3, -16	11,20,21	(0.64)	Apr-May 2017
Raikoke	22 Jun 2019	48	196	4	15-25 Jul
Raikoke, Ulawun	29 Jun 2019	48, -5	221,107	(0.5)	15-25 Jul, May 2017
Ubinas, Raikoke, Manam	19 Jul 2019	-16, 48, -3	72, 141, 15	(1)	24 Jun-4 Aug, Oct 2016
Ulawun, Mexico	3 Aug 2019	-5, 20	111, 12	2	8-25 Aug
Ubinas, Chile	16 Aug 2019	-16	27	1	21 Aug-10 Sep

Table S2: As Table S1 but for GOMOS where it is used as most important instrument

Volcano or region	Time	Latitude	SO_2 str (kt)	f	Used days
Nyamuragira, Awu + Tengger	12 Jun 2004	-1, 4, -8	20, 18	1	21 Jun-6 Jul
Pacaya, Galeras	17 Jul 2004	15, 1	11, 11	0.85	21-31 Jul
Galeras	11 Aug 2004	1	15	1	15-20 Aug
Vanuatu, Rinjani + Kerinci	30 Sep 2004	-16, -8, -2	7, 15	0.5	9-14 Oct
Manam, Soputan	30 Oct 2004	-4, 1	8, 11	0.53	8-18 Nov
Manam, Nyiragongo	24 Nov 2004	-4, -1	18, 11	0.67	3-8 Dec
Nyiragongo, Reventador	4 Dec 2004	1, 0	19, 5	0.52	13-23 Dec
Vanuatu, Soputan	24 Dec 2004	-16, 1	15, 16	0.93	28 Dec-2 Jan
Sierra Negra, Dabbahu	25 Oct 2005	-1, -13	16, 22	2.2	23 Nov-3 Dec
Rabaul	23 Jan 2006	-5	25	0.5	27 Jan-6 Feb
Cleveland	14 Mar 2006	53	8	1	23 Mar-7 Apr

2. Forcing at the top of the atmosphere, new model version considering stratospheric aerosol above the tropopause and old versions with aerosol only above the 100hPa-level

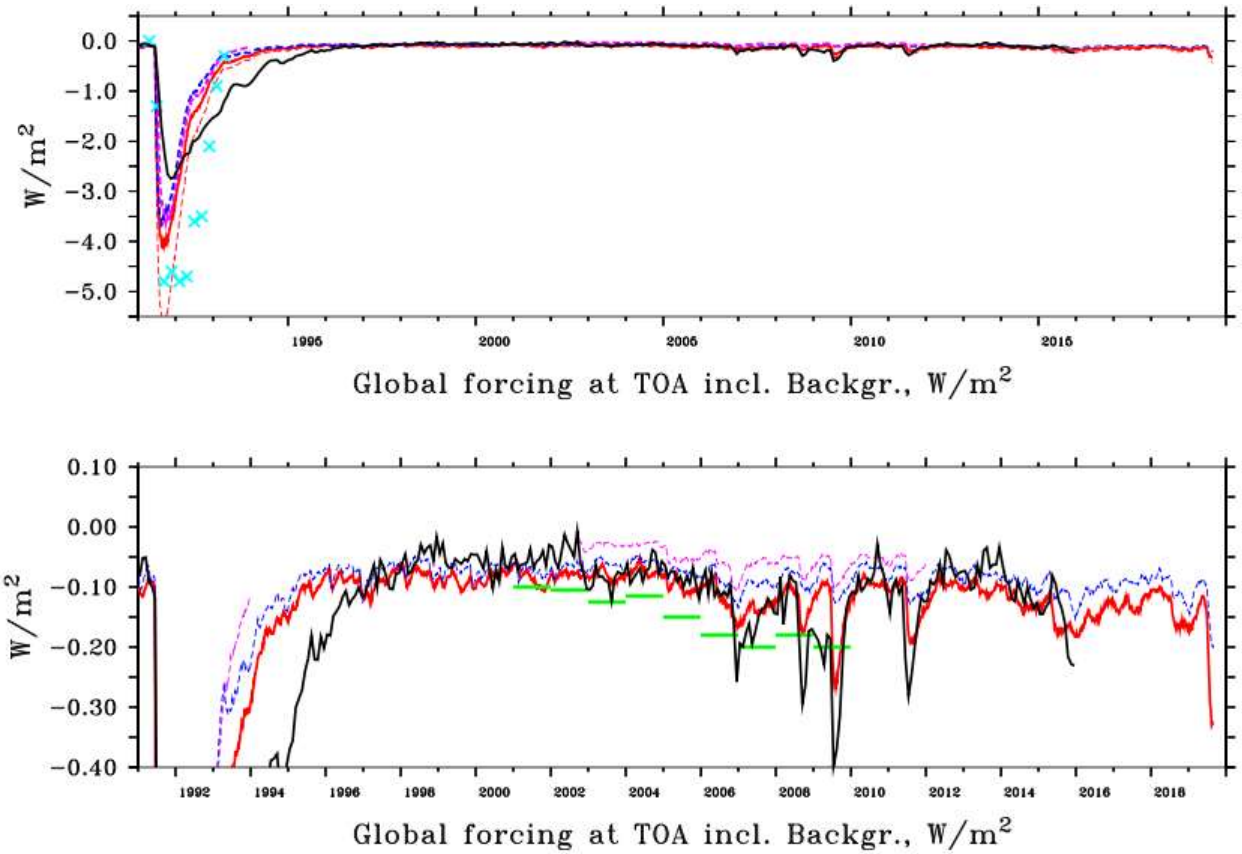

Figure S1: Global radiative forcing by stratospheric aerosol at TOA. As Figure 11 but blue and pink lines show the forcing calculated by previous model versions at TOA.

3. The effect of the output temporal resolution on stratospheric AOD and radiative forcing

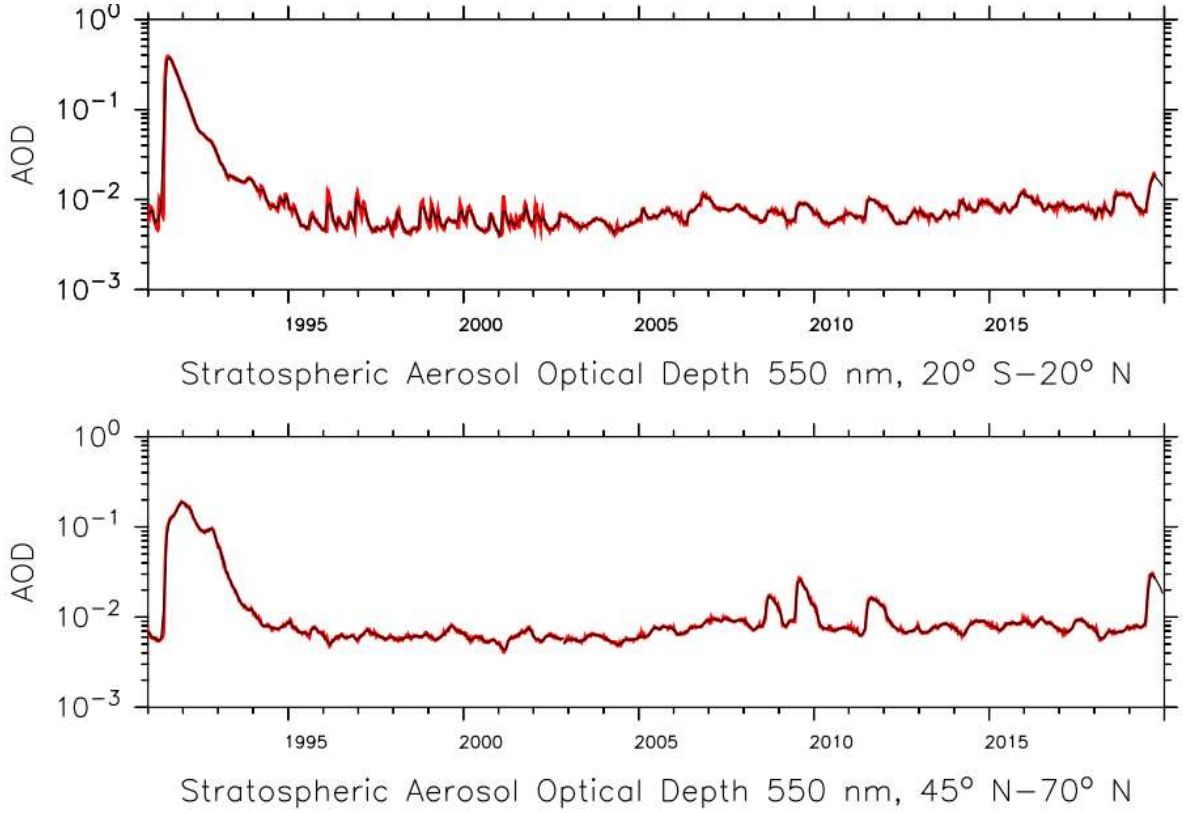

Figure S2: Stratospheric aerosol optical depth at 550nm simulated by EMAC: red 5-day averages as in Fig. 9, black monthly averages.

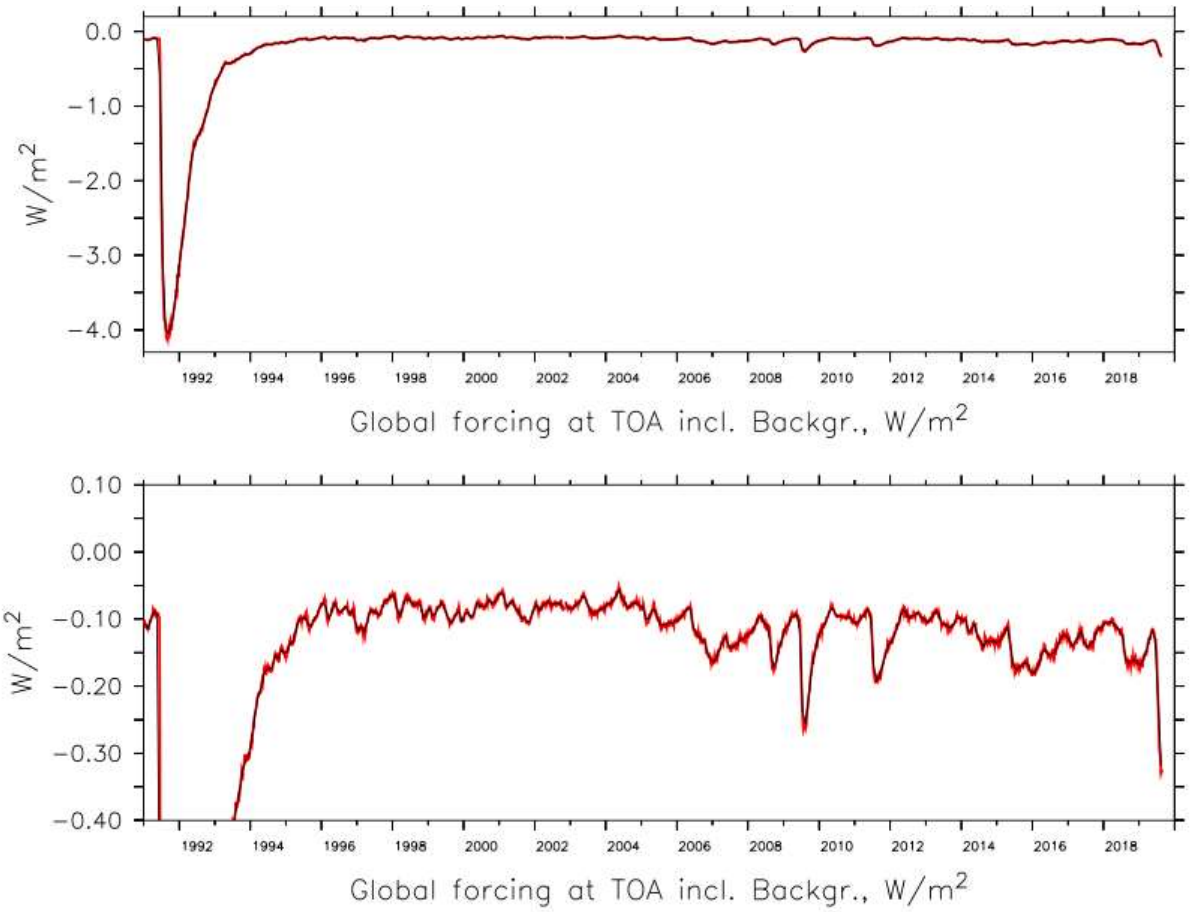

Figure S3: Global radiative forcing by stratospheric aerosol at TOA simulated by EMAC, red 5-day averages, black monthly averages.