Quantifying stratospheric temperature signals and climate imprints from post-2000 volcanic eruptions

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A R S C l i S y s

Introduction

Volcanic eruptions can substantially influence the climate system through the emission of trace gases, volcanic ash, and aerosol forming substances, such as sulfur dioxide (SO2). In the troposphere, the volcanic ash causes local weather changes. In the stratosphere, sulfate aerosols formed by volcanic SO2 emissions absorb and back-scatter solar and terrestrial radiation, and also enhance chemical reactions, for example ozone depletion. This affects surface temperature as well as stratospheric temperature and dynamics.

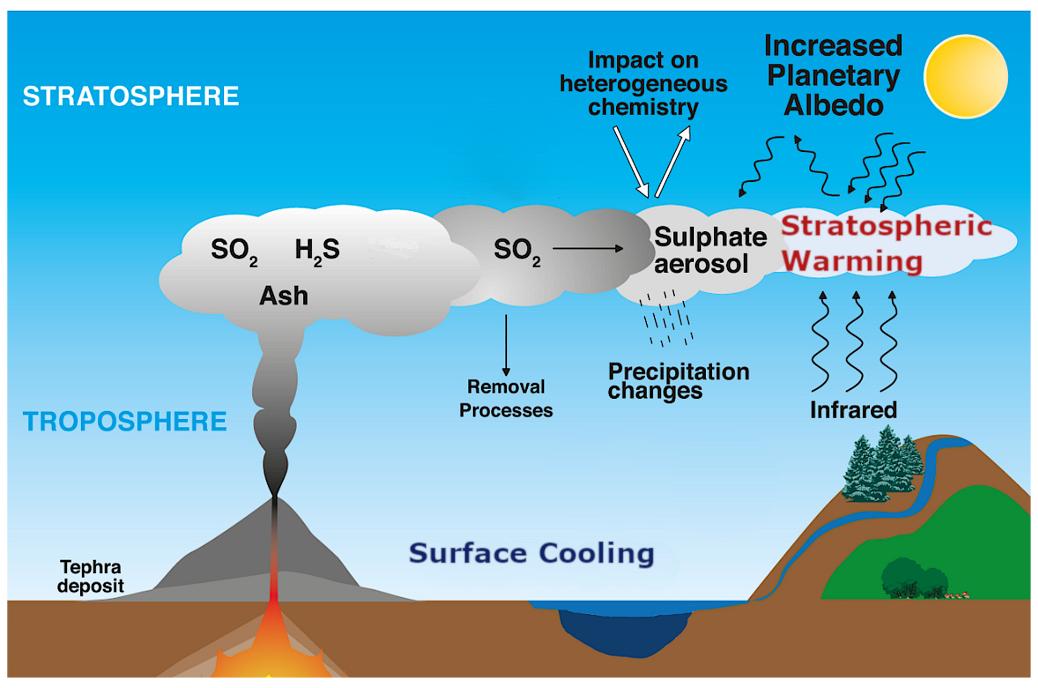

Fig. 1: Schematic illustration of the possible climatic effects following volcanic eruptions. Adapted from Timmreck (2018).

Large volcanic eruptions such as the Pinatubo in 1991 were found to strongly affect tropospheric as well as stratospheric temperature and chemistry. Recently also a series of smaller volcanic eruptions that started in 2002 has been of research interest since those eruptions most likely led to a steady increase in stratospheric Aerosol Optical Depth (AOD) during the last decade (Fig. 2, 3).

Name	Start date	VEI	SO_2 mass	SO_2 altitude (max.)	Latitude	Country
Ruang (Ru)	09-25-2002	4	80 kt	22 km	2.3°N	Indonesia
Reventador	11-03-2002	4	84 kt	17 km	0.077°S	Ecuador
Manam (Ma)	10-24-2004	4	152 kt[b]	24 km[b]	4.08°S	Papua New Guinea
Rabaul (Tavurvur) (Ta)	08-11-2006	4	300 kt	18 km	4.271°S	Papua New Guinea
Chaitén	05-02-2008	4	14 kt	17 km	42.833°S	Chile
Okmok	07-12-2008	4	150 kt	15 km	53.43°N	United States (Alaska)
Kasatochi (Ka)	08-07-2008	4	2000 kt	15 km	52.177°N	United States (Alaska)
Sarychev Peak (Sp)	06-11-2009	4	1200 kt	17 km	48.092°N	Russia
Eyjafjallajokull	03-20-2010	4	466 kt	9 km	63.633°N	Iceland
Merapi (Me)	10-26-2010	4	300 kt	17 km	7.54°S	Indonesia
Grimsvötn	05-21-2011	4	300 kt	12 km	64.416°N	Iceland
Puyehue-Cordón Caulle	06-04-2011	5	200 kt	14 km	40.59°S	Chile
Nabro (Na)	06-13-2011	4	3650 kt	18 km	13.37°N	Eritrea
Tolbachik	11-27-2012	4	200 kt	10 km	55.832°N	Russia
Sinabung	09-15-2013	4	20 kt	7 km	3.17°N	Indonesia
Kelut (Ke)	02-13-2014	4	200 kt	19 km	7.93°S	Indonesia
Calbuco (Ca)	04-22-2015	4	400 kt	20 km	41.33°S	Chile
Wolf	05-25-2015	4	200 kt	7 km	0.02°N	Ecuador

[a]Data from the Global Volcanism Program (2013); [b]main emission event during the eruption.

Fig. 2: Eruptions between 2002 and 2017 with a minimum Volcanic Explosivity Index (VEI) of 4. (Global Volcanism Program, 2018).

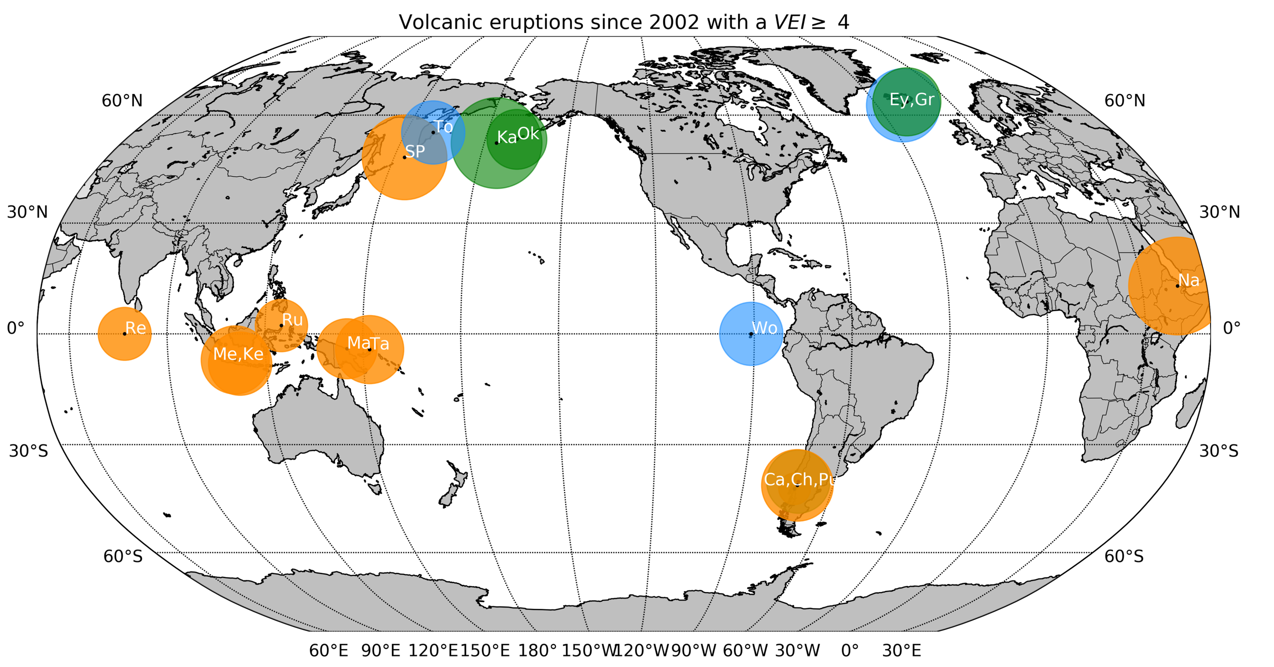

Fig. 3: Eruption locations. The size of the circular areas indicates the emitted SO2 mass (logarithmic scale). Colors indicate the emission altitude (blue ≤ 10 km, green ≤ 15 km, orange > 15 km. (Global Volcanism Program, 2018).

Data and Method

To analyze the spatiotemporal imprint of volcanoes on stratospheric temperature we apply a multiple linear regression analysis using highly resolved GloSSAC aerosol data (Thomason, 2017) and variability indices derived from RO measurements.

From the original aerosol concentration we subtract the provided background aerosol concentration to create deseasonalized aerosol anomalies. The aerosol concentration divided by the background concentration is illustrated in Fig. 4 and clearly shows a volcanic pattern of aerosols which are lofted into the middle stratosphere over time by the tropical upwelling.

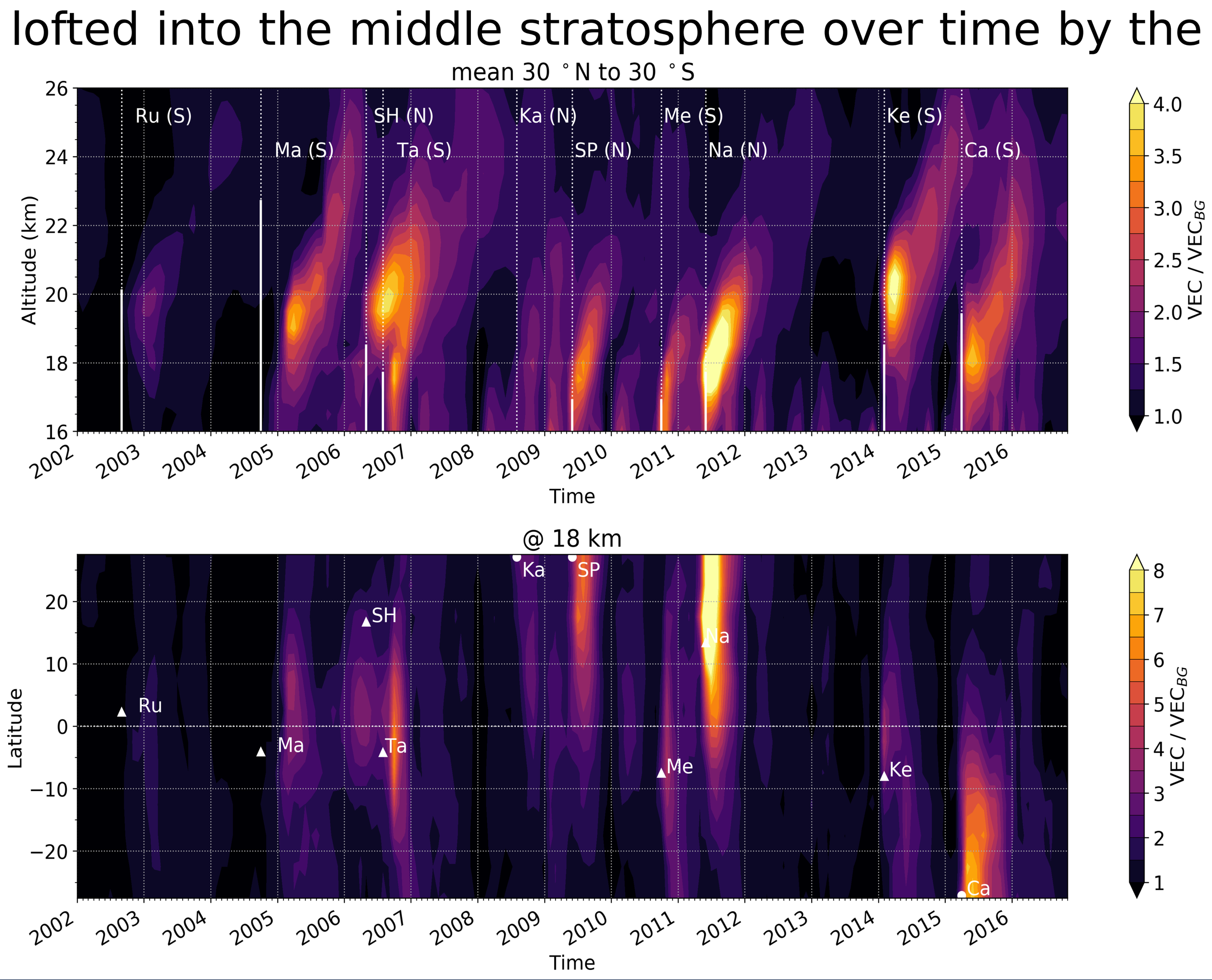

Fig. 4: Altitude time pattern of the aerosol concentration (top) as well as the latitude time pattern of the aerosol concentration at 18 km (bottom).

For the small eruptions in the study period, temperature signals are hard to detect because they are masked by natural variability. We therefore take advantage of the RO-based temperature variability indices introduced by Wilhelmsen et al. (2018) which leave very small temperature residuals by construction. These variability indices do not only include QBO or ENSO, but also aerosol-induced temperature changes. Additionally the aerosol anomalies include QBO variability. This results in collinearity between the regressors in the regression analysis.

To avoid collinearity, we remove in a first step the QBO signal from the aerosol index (Fig. 5), and in a second step the resulting QBO-free volcanic aerosol signal from the variability indices.

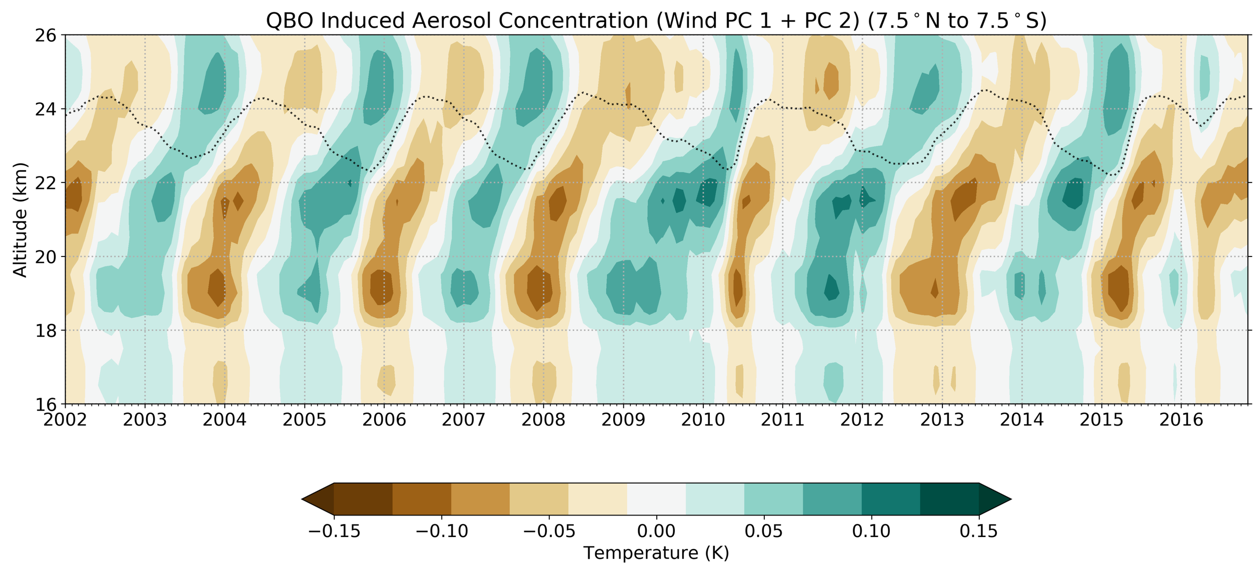

Fig. 5: QBO signal in the aerosol concentration which is removed from the aerosol anomalies. The dashed line represents the QBO wind anomalies at 30 hPa.

The final regression model then includes the QBO-free aerosol anomalies as well as the aerosol-free variability indices derived from the temperature anomalies after subtracting the estimated volcanic temperature signal.

Results

We found robust warming signals in the lower stratosphere up to 20 km from the inspected explosive volcanoes. The strongest imprints were found for Tavurvur, Merapi, Nabro and Calbuco.

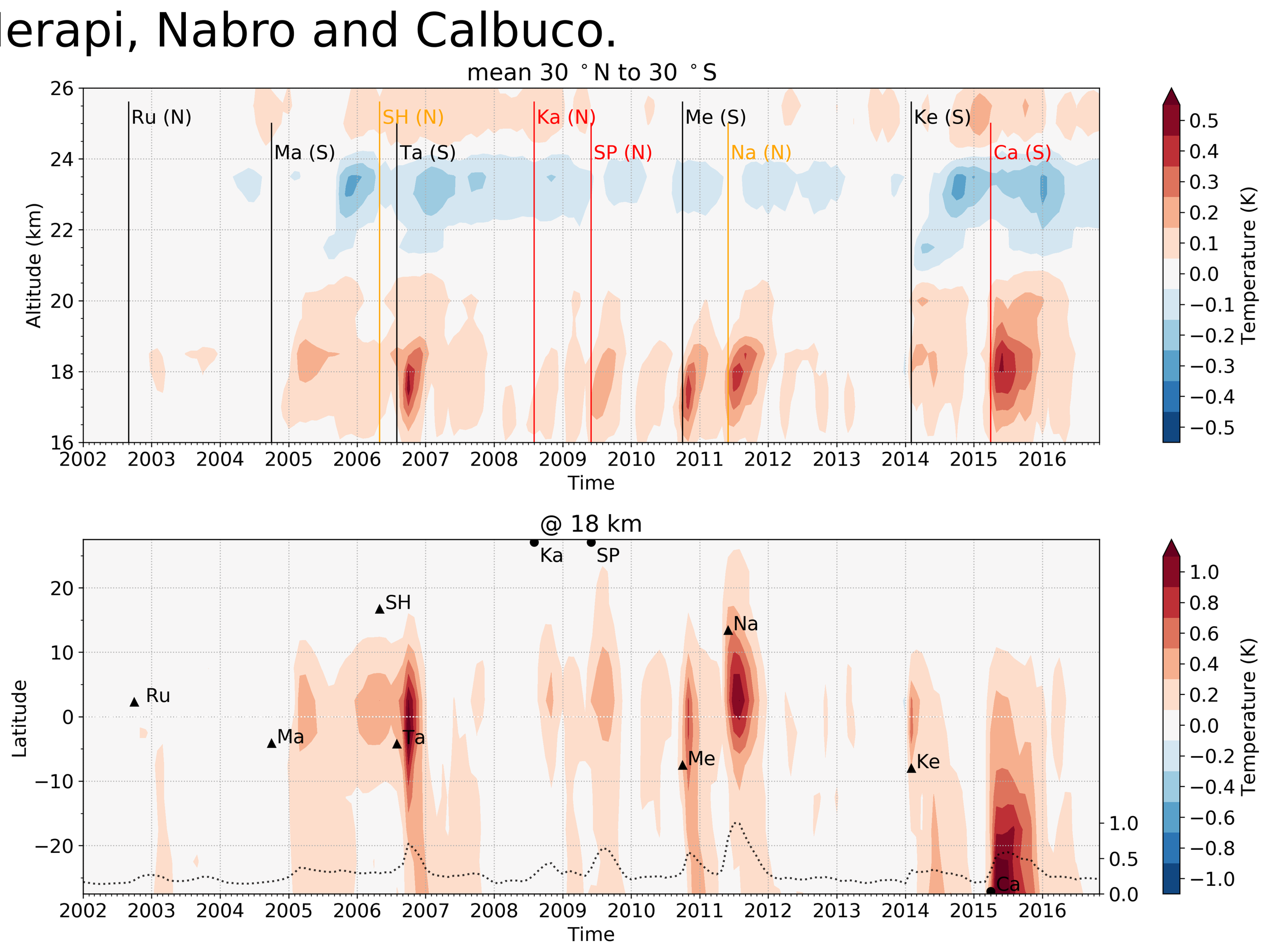

Fig. 6: Altitude time cross section of the volcanic aerosol reconstructed temperature (top) as well as the latitude time cross section at 18 km (bottom). The dashed line represents the normalized Volume Extinction Coefficient (VEC) for the 18 km altitude level.

In the middle stratosphere small cooling signals for the investigated volcanic eruptions were found. A suggested explanation is an indirect aerosol effect on ozone due to an enhanced upwelling of ozone-poor air after the eruption.

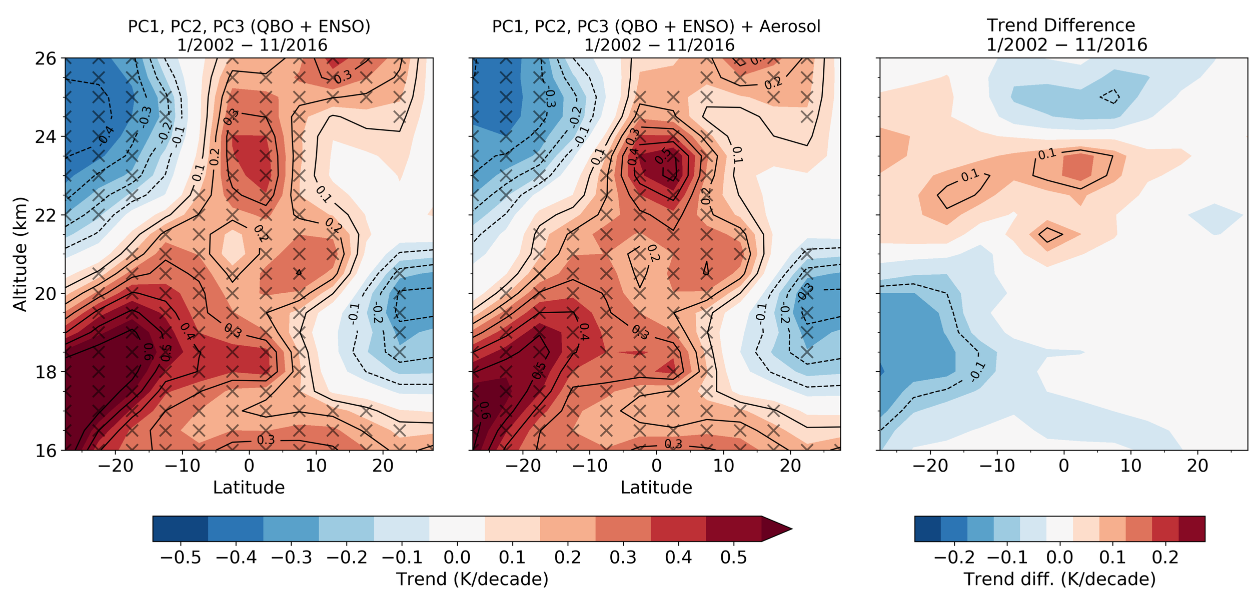

Fig. 7: Altitude-latitude cross section of the linear trend for the time series from 2002 to 2016 considering only natural variability indices (left), and natural variability indices together with the volcanic aerosols (center); trend difference (right).

Compared to major variability modes such as the QBO, the overall variability due to post-2000 volcanic eruptions was found to be small. However, they are of importance for short term trend analysis. For the investigated time series we found that the impact on linear trends can be up to 20%, depending on altitude and latitude.

Conclusions

The results show that detailed knowledge of the vertical structure of volcanic temperature changes from minor eruptions such as Nabro or Calbuco is crucial for comprehensive trend analysis, as their influence varies for different altitudes and latitudes. This work has been submitted to GRL.

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WEGC RO OPSv5.6 data are available via https://doi.org/10.25364/WEGC/OPS5.6:2019.1.