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Using analysis increments to estimate atmospheric heating rates following volcanic eruptions

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Abstract. By using the analysis increments of the temperatures from atmospheric re-analyses it is possible to roughly estimate the stratospheric radiative heating rates from volcanic eruption. The method is applied to the 30 hPa temperature from the 15 years of the ECMWF-reanalysis. After the influence from the Quasi Biennial Oscillation is subtracted maximum values of the zonal mean radiative heating rates related to El Chichón and Pinatubo volcanic eruptions are estimated to 0.30 K/day and 0.25 K/day, respectively. The estimated heating rates are not solely due to aerosol heating but includes the effects of ozone reduction and geostrophic adjustment as well.

Introduction

Volcanic eruptions can influence the weather and climate on Earth. Sulfur gases from volcanic plumes convert to sulfate aerosols and if they are injected into the stratosphere they can remain there for years. Volcanic sulfate aerosols scatter light in the visible band, reflect and absorb in the near-infrared bands [*Stenchikov et al.*, 1998] and absorb and emit thermal long wave radiation [*Kinne et al.*, 1992]. Some of the short wave solar radiation is scattered and reflected back into space by the aerosols thus reducing the incoming solar radiation resulting in a cooling effect near the surface of the earth. Part of this effect is compensated by increased forward scattered solar radiation. In the stratosphere the absorption of sun light in the near-infrared band [*Stenchikov et al.*, 1998] and absorption of long wave radiation from the surface [*Labitzke et al.*, 1983] leads to a warming. For tropical eruptions, as the lower stratospheric heating is larger in the tropics than at the poles an enhanced pole to equator temperature gradient develops resulting in an enhanced polar vortex and Northern Hemisphere tropospheric winter warming [*Kirchner et al.*, 1999; *Robock and Mao*, 1992].

The direct radiative forcing of prescribed volcanic aerosol concentrations of the stratosphere estimated from observations has been calculated by using Atmospheric General Circulation Models (AGCM) or just radiative transfer models. To perform such calculations accurately the micro-physical properties of the aerosols such as composition and size distribution must be available for different levels. However, even for the latest large eruption of Pinatubo in June 1991, observational data are quite incomplete [*Stenchikov et al.*, 1998]. Moreover, problems in the accuracy of radiative calculations cause additional errors in the forcing calculations.

Here we suggest a new methodology for estimating the atmospheric heating rates in the stratosphere following volcanic eruptions by using the analysis increments of temperatures from a re-analysis. We describe the method and compare the estimated heating rates with the results from radiative transfer models.

Methodology

Analysis increments are the differences between analyses and very short forecasts with the assimilating model. The short forecasts serve as the first guess fields in three dimensional data assimilation used in the reanalysis. Based on these forecasts the analyses constitute in a statistical sense the best spatial fit to the available observations [*Gibson et al.*, 1997]. For the purpose of this paper we are only analyzing slow temporal variations in the analysis increments, i.e. the fast variations due to random observational errors and corresponding short term (basically linear) error growth is not of our interest. The monthly averaged increments considered here are non zero because there are systematic errors in the basic observations and because the model is imperfect. It is a fundamental assumption in the present application, that the observational errors are stationary. On the other hand the model errors in the first guess fields typically include a large systematic component varying with season which is related to systematic initial tendency errors in the basic differential model equations. In addition to the annual cycle there are different types of internal climate variations, related to, e.g., the Quasi Biennial Oscillation (QBO), which may well contribute to the first guess errors if not properly modeled.

Also if a transient atmospheric forcing (related to, e.g., solar activity, volcanic eruptions or atmospheric trace gases) is present but not built into the model, it is reflected in the increments and this is the basis for the present paper. To estimate heating rates we consider the anomalous (i.e. not included in the annual cycle) analysis increments for temperature. To a first approximation these anomalies represent anomalous heating. Note, however, that a certain fraction of real heating will be seen in the increments for the wind field and not in temperature increments. This is because the coupling time between the atmospheric mass and the wind field which is controlled by geostrophic adjustment processes is rather short. This problem becomes progressively more severe as the forecast length increases.

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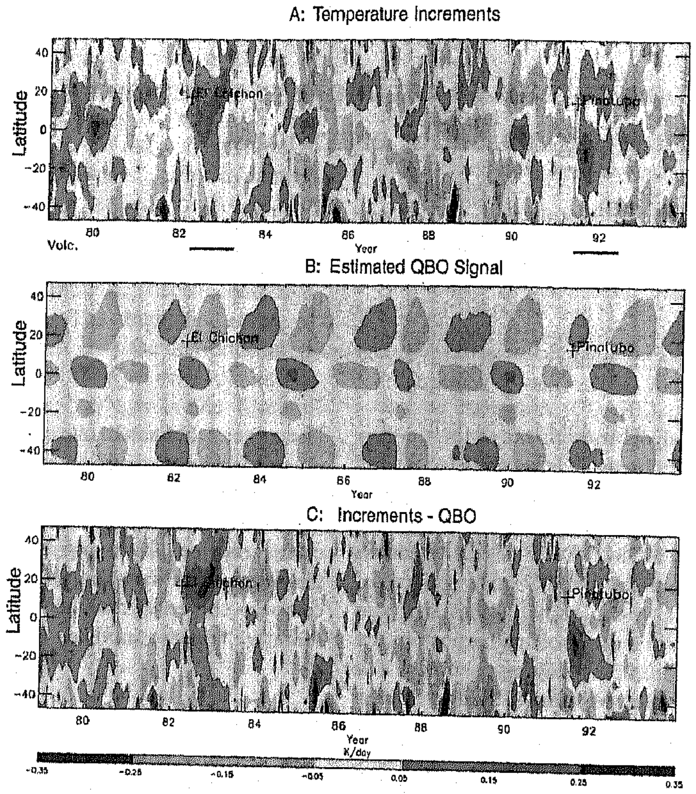
A: Temperature Increments

B: Estimated QBO Signal

C: Increments - QBO

Figure 1. Zonal averages-time diagrams for a) The 30 hPa temperature increments. The line beneath the diagram indicates the periods that were excluded during calculation of SVD. b) The estimated QBO signal of the increments calculated by using the first two patterns for the increments and the coefficients for the zonal winds. c) The increments with the estimated QBO signal removed. The color scale (in K/day) applies to all three diagrams.

The potential use of analysis increments to detect external forcing was first shown by *Alpert et al.*, (1998) in a study of lower tropospheric dust over the eastern tropical Atlantic.

Data

We used the ECMWF Re-Analysis (ERA-15) daily analysis of the 30 hPa temperature at 12 UTC [*Gibson et al.*, 1997]. The assimilating model for ERA-15 is in T-106 resolution with 31 vertical levels, 10 hPa and 30 hPa being the two uppermost levels.

The zonal, 3-month mean of temperature bias in the tropics at 30 hPa are between -2.4 and -0.6 K (91-day running mean of daily mean bias of layer mean temperatures: first-guess minus radiosonde) [*Uppala*, 1997]. The 30 hPa level was chosen as the heating rates are highest at this pressure level according to *Stenchikov et al.*, (1998).

We used the temperatures at 12 UTC together with the 24-hour forecast of the same parameter from the previous day. The reason for using analysis and forecast only once a day is that more observations are assimilated in the analysis at 12 UTC, thus making the analysis more accurate. Furthermore, a 24-hour increment minimizes the risk of verifying a forecast based on one type of observations with an analysis based on another. Strictly speaking, the 24-hour increment is not a real analysis increment, as the data-assimilation cycle for ERA is 6 hours.

Our study is based on monthly means of the 24-hour increments and the climatologic model error was removed for each grid point and month, i.e. the 15 year average increments were subtracted prior to the analysis carried out in the following. Between 50°N and 50°S the amplitudes of the subtracted seasonal cycle varies between 0.1 K/day and 0.6 K/day.

Results

The time variation of the zonal means of estimated heating rates are shown in Fig. 1a. As the data contain significant noise at high latitudes only data between 50°N and 50°S were used. The noise is related to less good performance of the assimilating model a high latitudes in the stratosphere [*Uppala*, 1997]. The influences from the two major volcanic eruptions in the ERA period, El Chichón and Pinatubo are easily seen.

In addition to the volcanic signals there is a clear pattern of oscillations in the zonal mean increments. For a given time it has a north-south three pole structure centered around the Equator and a period exceeding two years. As this signal varies closely in phase with the tropical stratospheric winds, we ascribe this structure to the QBO. The reason why the QBO temperature signal shows up in the increments can be explained as follows: firstly the model that is used in the assimilation of the ERA is not good enough to simulate the evolution of the QBO due to the inadequate spatial resolution. Secondly, the QBO winds redistribute the ozone. As the ozone absorbs ultra violet radiation from the sun, this will alter the heating rates in the stratosphere [*Lait et al.*, 1989; *Randel and Cobb*, 1994].

The QBO signal of temperature anomalies can be subtracted using singular value decomposition (SVD) by finding patterns in the temperature and in the tropical stratospheric winds that have maximum covariance [*Randel and Wu*, 1996]. Here we use a slightly different method on the increments.

The QBO was represented by zonal stratospheric winds in the tropics (data from Singapore at levels between 70 and 10 hPa) [*Naujokat*, 1986, updated] with the seasonal cycle removed. The patterns of temperature increments and zonal winds with maximum covariance were found using SVD. To avoid the influence from the volcanic eruptions the data from one year following the eruptions (April 1982–March 1983 and June 1991–May 1992) were excluded when the maximum covariance patterns were found.

The QBO signal in the temperature increments was next calculated by matrix multiplication of the two leading patterns of the increments with the scaled expansion coefficients of the zonal winds. By using the coefficients for the zonal winds the QBO is better resolved where it is masked by the volcanic eruptions. The estimated QBO signal is shown in Fig.1b, and in Fig.1c the estimated QBO signal is removed from the increments. Both volcanic eruptions are now more clearly visible in the data.

It is important to note that the present method detects temperature changes originating from processes that are not included in the assimilating model. Apart from the volcanic aerosol heating this includes cooling due to reduced ozone concentration. *Kinne et al.*, (1992) found that increased temperatures enhance upward motion and thereby reduce the ozone concentrations. They found that the maximum reduction and therefore the maximum cooling effect occurred nearly half a year after the eruption of Pinatubo.

Ozone reduction due to heterogeneous reactions on the sulfuric acid aerosol can also contribute to lower heating rates [*Brasseur and Granier*, 1992; *Kinne et al.*, 1992; *Kirchner et al.*, 1999]. The ozone reduction can last up to 2 years after the eruption [*Angel*, 1997*a*].

Figure 2 zooms into the heating rates right after the two volcanic eruptions. Despite the fact that Pinatubo ejected about twice as much SO_2 into the stratosphere as did El Chichón [*Brasseur and Granier*, 1992] the maximum heating rates following the two volcanic eruptions are nearly similar. This is, however, in qualitative agreement with the maximum temperature anomalies at 30 hPa which have been estimated to 2.4 ± 0.6°C and 2.5 ± 0.6°C for El Chichón and Pinatubo, respectively [*Angel*, 1997*b*]. Due to increased concentration of anthropogenic chlorine in the stratosphere ozone reduction caused by heterogeneous reactions is larger for Pinatubo than for El Chichón [*Angel*, 1997*a*]. This could explain why the heating rates following Pinatubo are not larger than those following El Chichón.

The heating rates of El Chichón have a maximum of 0.30 K/day which is located close to the latitude position of the volcano. We have found no other work where the heating rates of the atmosphere following the El Chichón eruption are calculated.

The Pinatubo eruption shows a maximum heating rate of 0.25 K/day. *Stenchikov et al.*, (1998) and *Kinne et al.*, (1992) both found values at 0.3 K/day. The heating is strongest south of Pinatubo between 5°N and 30°S in accordance with the work by *Stenchikov et al.*, (1998). The excessive heating rates of the Pinatubo eruption are only present for one year. This is in contrast to the work by *Stenchikov et al.*, (1998) where heating rates were found to be 0.1 K/day at April 1993, nearly two years after the eruption.

There is a band of zero heating rates at the latitude and time of the volcanic eruption moving down to the equator in January 1992. The reason for this is unclear but *Stenchikov et al.*, (1998) found a local minimum of heating rates above 30 hPa at 10°N in August 1991 and at equator in January 1992 (their Fig. 10d and 10h). Generally the estimated heating rates using the present method are up to 0.15 K/day lower than the heating rates found by *Stenchikov et al.*, (1998).

The main source of errors in the present method is the atmospheric 24-hour respond to the temperature forcing. Preliminary tests with the global atmospheric model ARPEGE [*Déqué et al.*, 1994] suggest that up to one third of the forcing in the stratosphere dissipates to other latitudes as well as to the wind field, meaning that the present method tends to underestimate the radiative forcing by up to one third. *Stenchikov et al.*, (1998) estimated their errors of calculated radiative forcing following the Pinatubo eruption to be 5% for the radiative scheme and 20% for the uncertainties in the aerosol observations. Given these errors the estimated heating rates from the present method agrees satisfactory with the results from *Stenchikov et al.*, (1998).

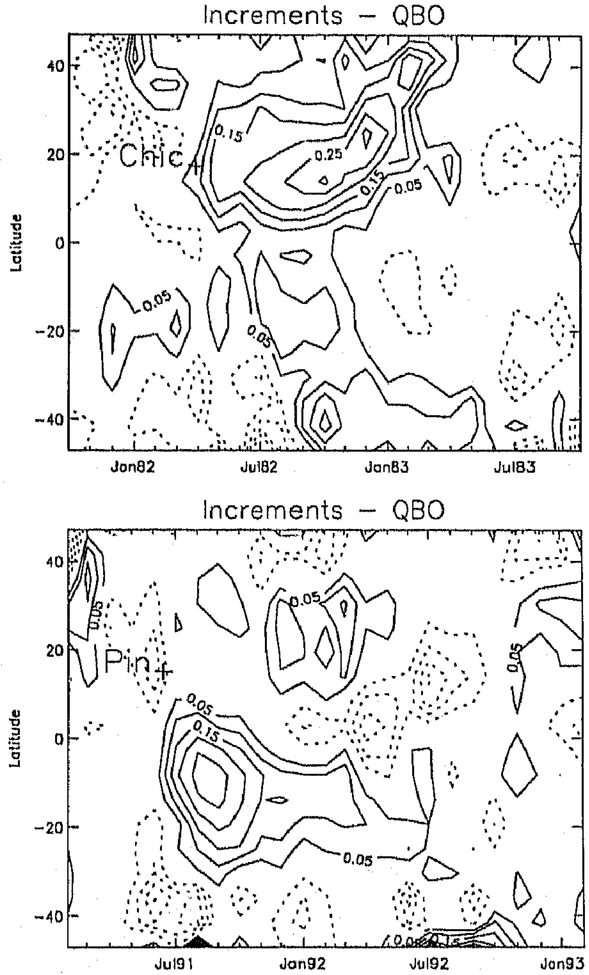

Figure 2. Same as Fig. 1c for the periods following a) El Chichón and b) Pinatubo eruptions. The contour interval is 0.05 K/day. (No contour for 0.0 K/day) Negative contours are dashed.

Discussion and Conclusion

In this pilot study we have shown that the incremental errors of the stratospheric temperature can be applied to crudely estimate the heating rates following large volcanic eruptions. The estimated heating rate of 0.25 K/day, which also includes the effect of ozone reduction, following the Pinatubo eruption is fairly close to results from AGCMs and radiative transfer models.

Because of the geostrophic adjustment problems, it is anticipated that it is needed to use other measures than increments to estimate more accurately the anomalous forcing. One possibility to be investigated in a subsequent paper is to perform a re-assimilation of ERA into a climate model (e.g., *Jeuken et al.,* 1996).

This method might furthermore be used also to separate the different forcing from volcanic eruptions, such as radiative forcing due to volcanic aerosol and ozone changes.

The estimates of initial tendency or forcing errors are expected to improve significantly when the planned 40 years of re-analysis from ECMWF (ERA-40) is available. First the much longer time series will give a better estimate of the QBO signal in the temperature. Secondly, the model is expected to improve in simulating the QBO due to a much higher vertical resolution in the stratosphere. Third, ozone will be a prognostic variable in the assimilating model.

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