Response to reviewer 1

We thank the reviewer for their valuable comments (in red).

This paper makes a case that volcanic eruptions may significantly enhance the amount of water vapour in the lower stratosphere. (…) By correlating aerosol extinction measurements with water vapour measurements they conclude that the water source is from the volcano even though the measurements themselves occurred a few months after the eruption.

Puyehue erupted several times with the plume reaching 9 km above the crater on June 13, 2011 (http://volcano.si.edu/showreport.cfm?doi=GVP.WVAR20110608-357150) and circumnavigated the globe twice before the end of June 2011 (see cited Vernier et al., 2013). The ACE measurements of this plume in Fig. 5 start only 18 days after eruption. Nabro finished its major eruptive phase on 14 June 2011 with plume height in excess of 10 km (http://volcano.si.edu/volcano.cfm?vn=221101). ACE measurements following Nabro begin on July 2nd, 2011 (Fig. 10), only 18 days later, which is actually too early in the sense that the plume had not reached all longitudes by this point (Bourassa et al., 2012). As written in the paper, Eyjafjallajokull began its major eruptive phase on April 14th, 2010, but there was a second major eruption on May 5th that reached ~10.0 km (refer to the cited Gudmundsson et al., 2012) and the first ACE high latitude measurement occurs 11 days after this second eruption and sampled the volcanic plume. So in all cases, local ACE measurements first become available roughly two weeks after a major eruption. Despite this good fortune, ACE does not have the spatiotemporal coverage of limb emission sensors.

We have inserted the following sentence near the start of section 3.3:

This was followed by a second eruption on 05 May 2010 that also reached ~10.0 km (Gudmundsson et al., 2012).

For the most part the analysis is straightforward and reasonable but there is an issue that also need to be acknowledged. Referring to the Schwartz et al. GRL, 40 2316-2321, doi:10.1002/grl.50421,2013 paper, it turns out that 2010 and 2011 were years where convective injection of water vapor was quite active and intense, producing events as high as 18 ppmv against a background value of 5 ppmv.

Somehow we missed this paper in our literature search (and hopefully not other relevant ones) and apologize to the reviewer if they were an author of this excellent and highly relevant paper. Schwartz et al. (2013) show that in summer 2010 and 2011, MLS appears to observe water vapour mixing ratios of ≥7 ppm more frequently than other years. This is the only metric used by Schwartz et al to illustrate interannual convective differences. They are omitting the small possibility that Nabro may have contributed to the more frequent extreme water vapour VMRs in 2011 (but not 2010 obviously).

Our analysis of northern mid-latitude water vapour with MAESTRO (which lacks the spatial coverage of MLS) indicates that at altitudes corresponding to 100 and 82.5 hPa, water vapour VMRs are not enhanced when averaging over two summer months (namely July and September 2011, Fig. 10) and we used the same span of years as Schwartz et al. (2004-2012). In fact, at all altitudes in the range 8.5-19.5 km except for the 1 km thick layer centered at 13.5 km, MAESTRO measured normal or below normal water vapour VMR in these two months. It is quite possible that 2011, for example, can have a higher frequency of extreme water vapour VMRs without having a higher central tendency (e.g. median) than other years because the extreme events are too rare to significantly affect the zonal monthly median or even the mean. It is also possible that MAESTRO has a dry bias because we do not observe when optically thick clouds are present. MAESTRO can see through thin cirrus however and so the dry bias is probably largest below 12 km and vanishing up toward 17 km. MLS may also have such a dry bias for clouds with large drops/crystals. In any case, what we present in our manuscript is mostly a statistical analysis. We cannot prove without doubt whether or not the water vapour enhancement in the northern high-latitude lower stratosphere could have occurred without Nabro.

As can be seen in the response to Reviewer 3, we credit Reviewer 1 with providing an alternate process (i.e. summertime deep convection) responsible for the enhancements in water vapour in the northern extratropical tropopause region and we have removed the Nabro section.

Even though the air may be aerosol enriched, by virtue of the two month or so time lag, it is possible if not probable, that the moisture in these air parcels could be enriched by convective events. I think this possibility should be acknowledged.

We acknowledge that during the period of study for Nabro (specifically July-Sept 2011), deep convection was likely the main mechanism for the ACE-observed enhancements in zonal median water vapour in the vicinity of the northern extratropical tropopause. Convective events in Uruguay (Schwartz et al., 2013) during their winter are expected to be rare and this expectation is confirmed by Schwartz et al. Puyehue was the most likely cause of the July-August 2011 enhancements, given the explosivity of its eruption. We do not believe that the reviewer's comment pertains to Eyjfjallajökull since that eruption was in the spring and outside of the summer period in which the anomaly in deep convection was observed.

The Nabro section has been deleted. No change was made to the sections on the other two eruptions.

A water vapor enhancement signature should be evident shortly after an eruption, even if it is injected as ice on particulates because the stratosphere is of very low humidity and sublimation should occur rapidly. I appreciate, that occultation type instruments do not sample well enough to capture a plume early in the eruption cycle. Even instruments like MLS or MIPAS often miss plumes in their early stages, but it would be worth looking at their data to see if enhancements are seen as they should produce bigger signatures and contrasts against background amounts.

The main focus of this paper and the companion paper is to understand water vapour variability on timescales of one month or longer for the high latitude upper troposphere as a function of altitude (5 to ~10 km). This focus is clearer in the revised manuscript with the discussion of stratospheric injection of water vapour now removed and the Nabro section deleted. MLS measurements do not go low enough to cover the entire 5-10 km altitude range. As discussed in response to the next comment, we are not looking for bigger enhancements in individual observations and we are not contrasting against the local background. We are contrasting in time, comparing e.g. the month of September 2011 at northern high latitudes to other Septembers in this same region and looking for “big signatures” on monthly timescales. However, we share the reviewer’s interest in volcanogenic perturbations to stratospheric water vapour, so we looked at MLS water vapour on the day after the Nabro eruption, namely June 14, 2011. We were guided to MLS observations of the Nabro plume by Fig. 1 of the work of Fromm et al. (2013) entitled ‘Comment on "Large volcanic aerosol load in the stratosphere linked to Asian monsoon transport"’ (Science 339: 647, DOI: 10.1126/science.1228605). Figure 1 below shows MLS v4.2 SO_2 at 100 and 68 hPa as a function of latitude for an orbit intercepting the Nabro plume. The highest SO_2 VMR at 100 hPa occurs at a latitude of 26.7°N with the second highest value being in the adjacent limb scan at 25.2°N. At these same adjacent latitudes, MLS v4.2 water vapour from the same orbit is clearly enhanced at both 100 hPa and 121 hPa, but not at 82 hPa (Fig. 2). This indicates that a 2 ppm enhancement in water vapour exists at 100 hPa at a latitude of 26.7°N, but not at altitudes above that. Meanwhile, SO_2 appears to be enhanced at 68 hPa as well, particularly at 25.2°N. The tropopause pressure according to the MLS v4.2 temperature product indicates the tropopause pressure was 100.3 and 99.9 hPa for the two adjacent latitudes of note. This evidence from MLS suggests that a significant amount water vapour was not directly injected into the stratosphere by the Nabro eruption. However, the information presented here does not rule out that water from Nabro could have been directly injected in other phases (e.g. ice). We did not try using MIPAS data given that MLS orbit of observations were very clear about the altitude range and magnitude of the water vapour and SO_2 VMR enhancements on June 14, 2011.

There is no change to the manuscript because the Nabro section has been deleted. The other two studied volcanoes do not appear to be addressed by this comment.

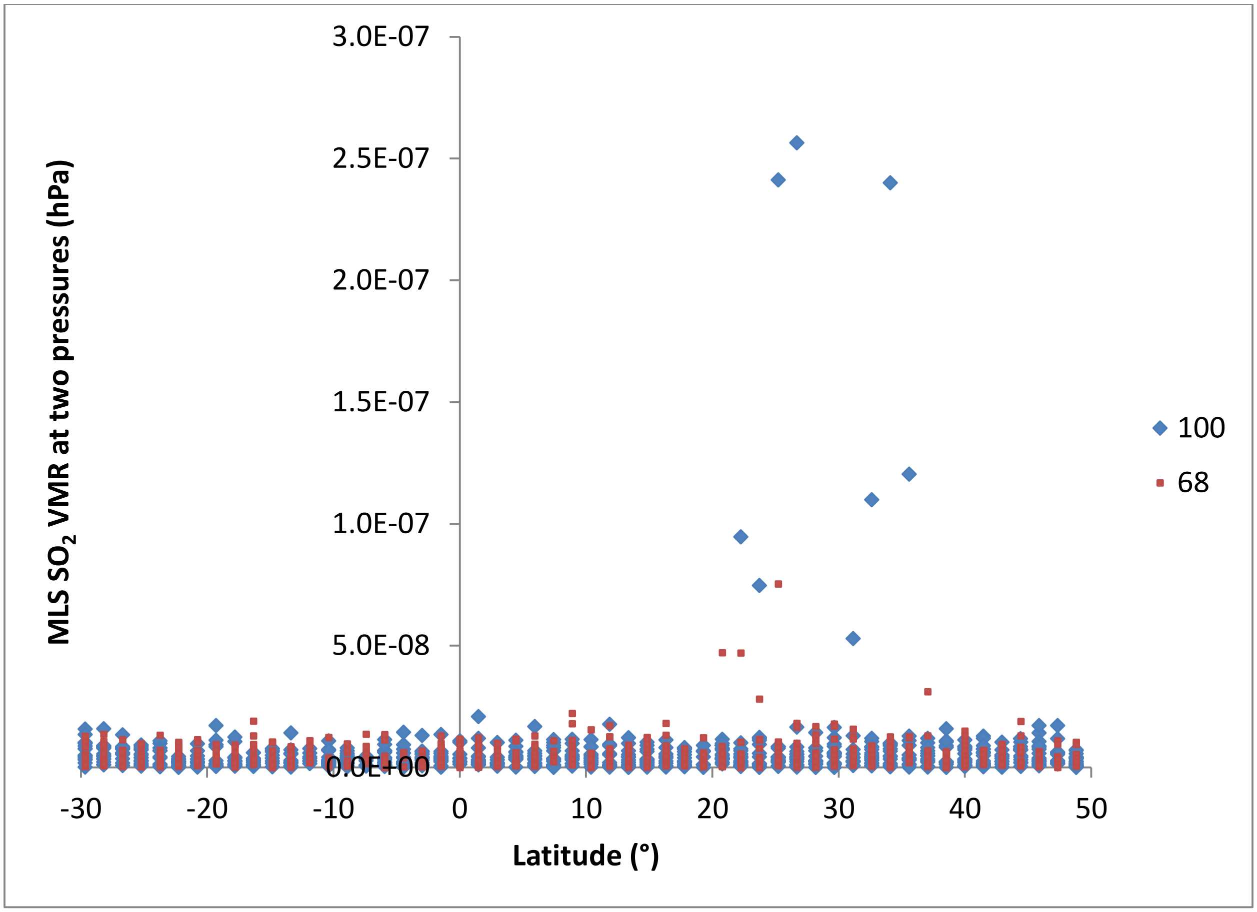

Figure 1 – MLS SO_2 VMR at two pressures (hPa) at low latitudes for an orbit intercepting the Nabro plume on June 14, 2011.

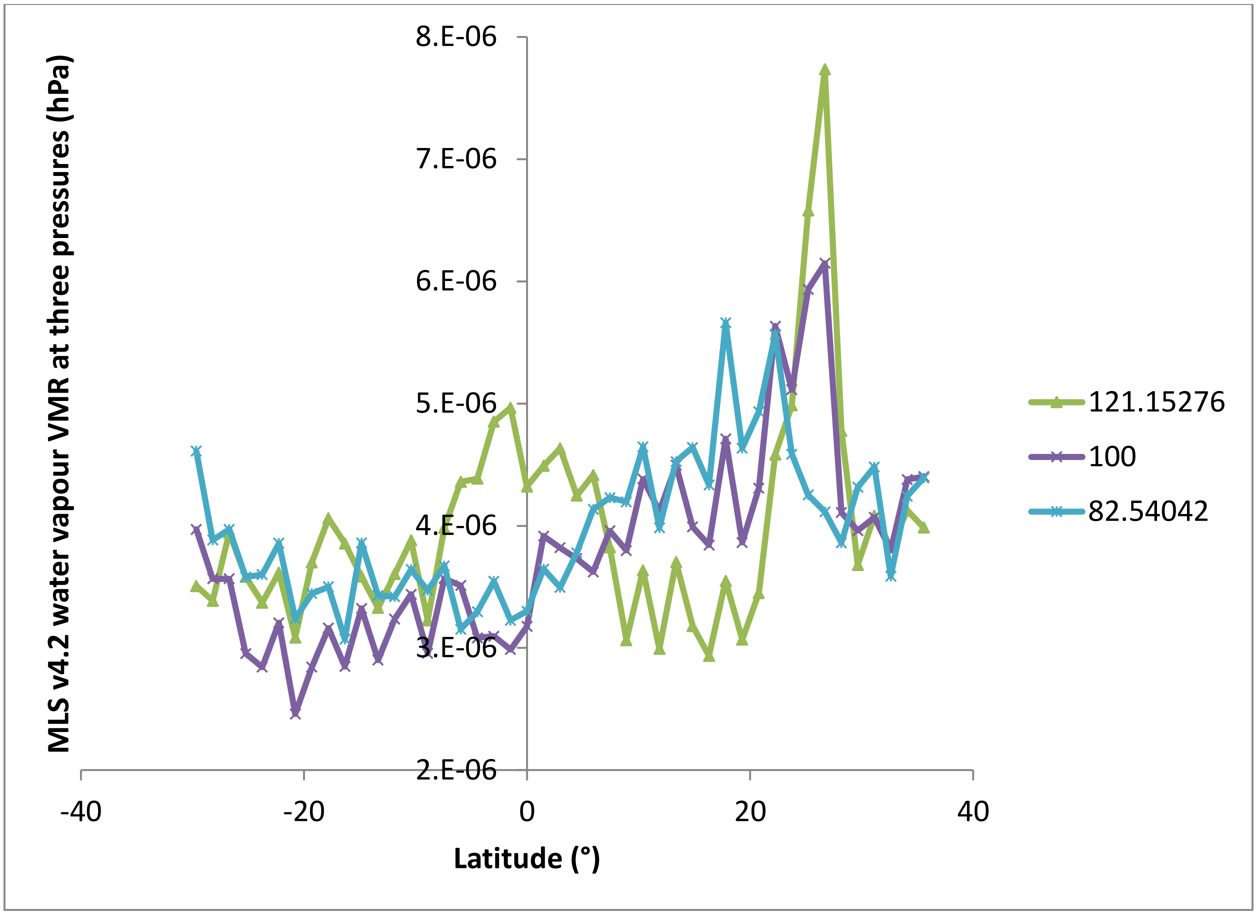

Figure 2. MLS water vapour VMR at three pressures (hPa) at low latitudes for an orbit intercepting the Nabro plume on June 14, 2011.

A case in point being in the Discussion (page 25885, line 10) that Kasatochi produced little impact on stratospheric water. MLS did observe enhancements in H_2O from this eruption (see Schwartz, 2013 for reference); hence, the other volcanoes should produce even bigger signatures near eruption if they are able to influence the stratospheric water vapour budget as claimed.

We did not claim that Puyehue and Eyjfjallajökull influenced the stratospheric water vapour budget. Nabro was a tropical volcano and the tropopause is very high in the vicinity of the eruption leading to larger background volume mixing ratios at ~13.5 km, the altitude of the ACE-observed water vapour enhancement at mid-latitudes in July and September 2011 (Fig. 10). The reviewer's comment implies that in order to influence the stratospheric budget, volcanoes must produce big water vapour 'signatures' near the eruption. Our original paper hinted at a second mechanism that again does not require direct stratospheric injection that ironically is the main focus of Schwartz et al. (2013): the monsoon (specifically the Asian one). In the revised manuscript, after a more probing and latitudinally resolved analysis (including examination of individual profiles), we no longer claim that Nabro influenced the stratospheric water budget.

A last point, even the southern hemisphere is also affected by mid-latitude convection events like those in the north (usually occurring over Uruguay) but they are not as frequent or intense.

Mid-latitude convective events are expected to be less frequent and less intense in winter (e.g. July 2011), when Puyehue water emissions were detected in the upper troposphere. For Puyehue, we find water vapour enhancements at 6.5 to 9.5 km. Thus, the convective events at 100 hPa (~16 km) illustrated in Schwartz et al. are not very relevant. The spatial pattern of water vapour at 6.5 km could be much different.

At p25884L25, we have rewritten the original sentence as follows:

Volcanic UTWV enhancements in the extratropics during the cold season are more readily detected in monthly zonal median data because of the low background VMR of water vapour in this region and season, owing to the lack of deep convection.

Minor correction, page 25875 line 14 should 2002 be 1992?

Thanks to the reviewer for noticing this strange mistake. It has been corrected.

Page 25879 line 7-8, you talk about Austral summer and also July / August. This is Austral Winter.

We thank the reviewer for catching this. This has been corrected (twice).