Supplementary

Using Satellite Data to Determine Empirical Relationships between Volcanic Ash Source Parameters

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This supplementary section provides a more detailed description of the 14 eruption case studies listed in Table 1 of Zidikheri and Lucas [1]. Reference runs, using hybrid single particle Lagrangian integrated trajectory (HYSPLIT) with a simple source formulation as currently used operationally, were performed for each of the case studies. The resulting ensemble mean mass loads were compared with VOLCAT mass load satellite retrievals [2]. In addition, experimental runs, employing a more complicated source and optimised with respect to the VOLCAT retrievals, using the methodology outlined in Section 2 of Zidikheri and Lucas [1], were performed. The optimisation time windows for each of the case studies are listed in Table 1 of the paper. The results are summarised in Table 2 of this paper and further described below for each of the case studies.

13 February 2014 Kelut Eruption

Kelut (112.31° E, 7.93° S, altitude 1.7 km), a volcano in east Java, Indonesia, erupted at around 1600 UTC on 13 February 2014. The Darwin Volcanic Ash Advisory Centre (VAAC) estimated the height of the plume at 16.7 km, but subsequent imagery obtained from the CALIPSO lidar revealed that the ash column reached as high as 26 km, with the broad umbrella region at around 19 km [3–8]. MTSAT-2 satellite imagery showed the coldest part of the cloud—associated with the umbrella region—detached from the volcano at around 2030 UTC, suggesting an upper estimate of around 4 hours for the strongest phase of the eruption. The bulk of the ash moved to the south west and could be identified in satellite imagery for over 24 hours after eruption. VOLCAT mass load retrievals covering most of the cloud were available between 13/2330–14/0230 UTC and showed maximum mass load levels of 40–120 g m^{-2}. Prior to this, the cloud was too optically thick, and the algorithm did not return any mass load estimates. Dispersion model results reveal that the use of standard source settings in the reference run results in ash mash load distributions that are inconsistent with the satellite retrievals. Whereas in the satellite retrievals the maximum mass loads are associated with the umbrella cloud, which rapidly gets swept to the south-west (Figure S1a), in the reference run the maximum load remains in the vicinity of the volcano (Figure S1b). These differences arise because, in the reference run, the mass is distributed uniformly in the vertical; however, in reality a large portion of the mass ends up in the umbrella cloud. In the experimental run, this is accounted for using a source with variable mass distribution in the vertical and the agreement between the simulated and retrieved patterns is significantly improved (Figure S1c). In addition to discrepancies in the mass load distributions, the absolute values of the mass loads are also significantly overestimated in the reference run, being over an order of magnitude greater in peak values. This problem is ameliorated in the experimental run.

(a) (b) (c)

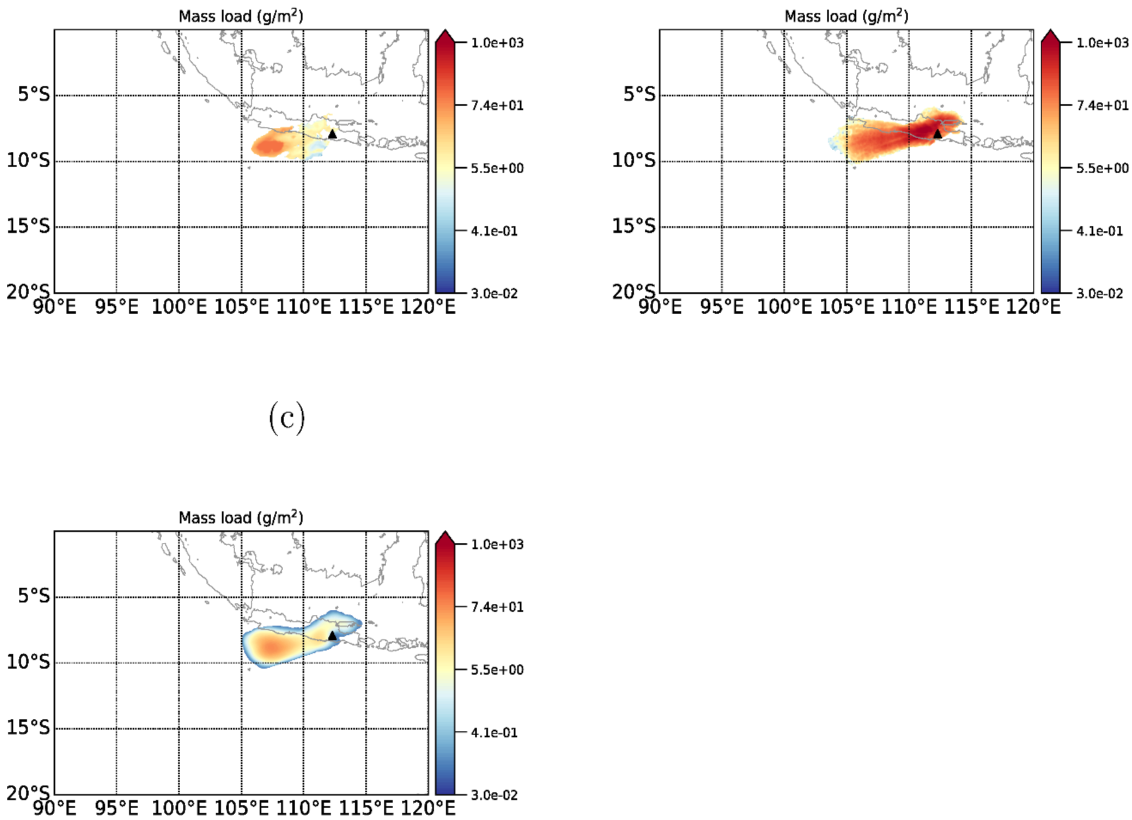

Figure S1. Mass loads (g m^{-2}) in the 13 February 2014 Kelut eruption at 2330 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

<u>30 May 2014 Sangeang Api Eruption—Phase I</u>

Sangeang Api (119.07° E, 8.2° S, altitude 1.9 km), a volcano off the north-east coast of Sumbawa island, Indonesia, erupted at around 0800 UTC on 30 May 2014. The Darwin VAAC reported the height as 15.2 km although pilot reports suggest it could have reached nearly 20 km in altitude. The eruption appeared to be brief (<1 h), but the bulk of the ash moving to the south-east could be identified in satellite imagery for several hours (Figure S2a). There were an optically thinner emissions associated with the eruption seen in satellite imagery that were carried to the east, which dissipated after a few hours. There is some evidence that these emissions could have contained ash as the VOLCAT algorithm detected high-altitude ash (>18 km) to the east of the volcano at 30/1405 UTC, using an available MODIS satellite overpass [6]. Dispersion model results with the standard settings in the reference run reveal that there was too much mass in the vicinity of the volcano as in the 13 February Kelut case (Figure S2b). In addition, again similarly to the 13 February Kelut case, there was overall too much mass being released relative to the satellite retrievals in the reference run, although in this case the discrepancy was not as large. Use of inverse modelling with the improved source settings in the experimental run leads to much better agreement between model and retrievals (Figure S2c).

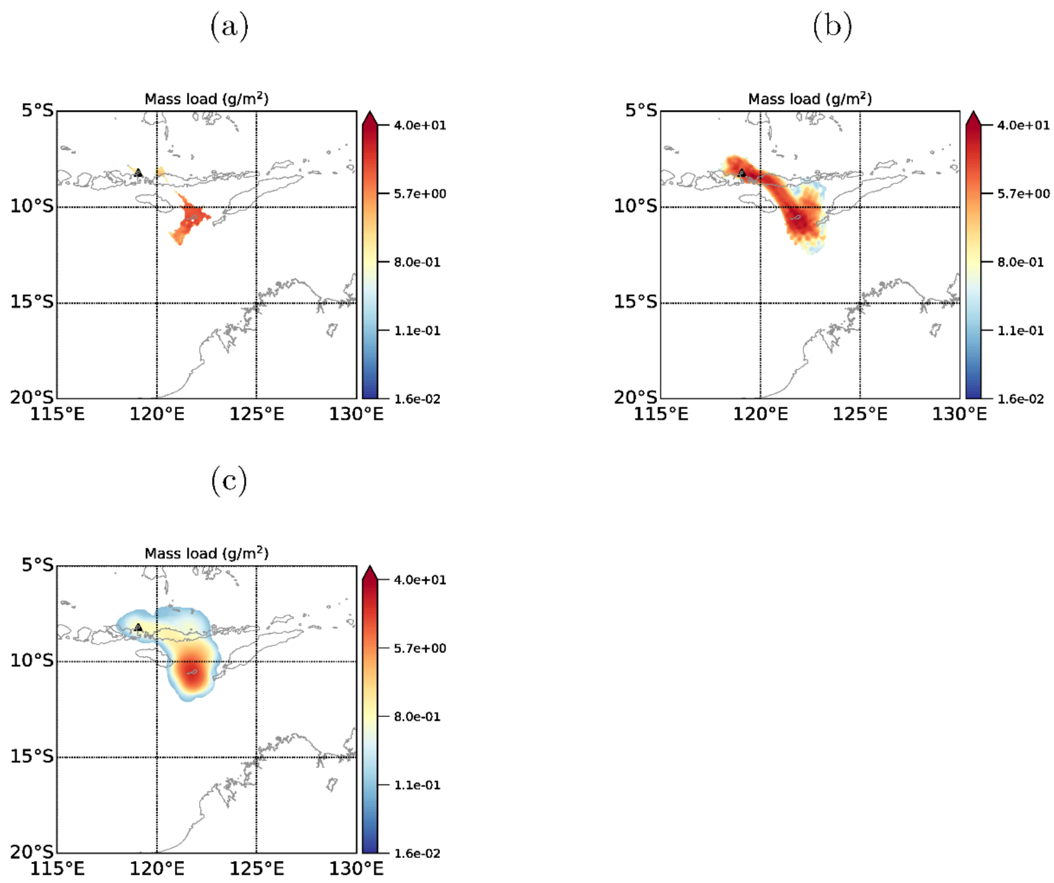

Figure S2. Mass loads (g m^{-2}) in the 30 May 2014 Sangeang Api eruption at 1330 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

30 May 2014 Sangeang Api Eruptions—Phase II

Sangeang Api erupted again at around 1700 UTC, with the Darwin VAAC again assigning a height of 15.2 km to the ash cloud. The brightness temperatures associated with this eruption were higher, suggesting that it was somewhat lower in altitude compared to the stronger first phase. The ash cloud was again carried to the south-east (Figure S3a). HYSPLIT simulations in the reference run (Figure S3b) show, again, that the loads are greatly overestimated by over an order of magnitude when standard source settings are employed. The distribution within the cloud also has slightly too much mass near the source as in the Kelut eruption although the effect is not dramatic in this case. Use of inverse modelling with improved source settings in the experimental run again leads to better agreement between simulations and retrievals (Figure S3c).

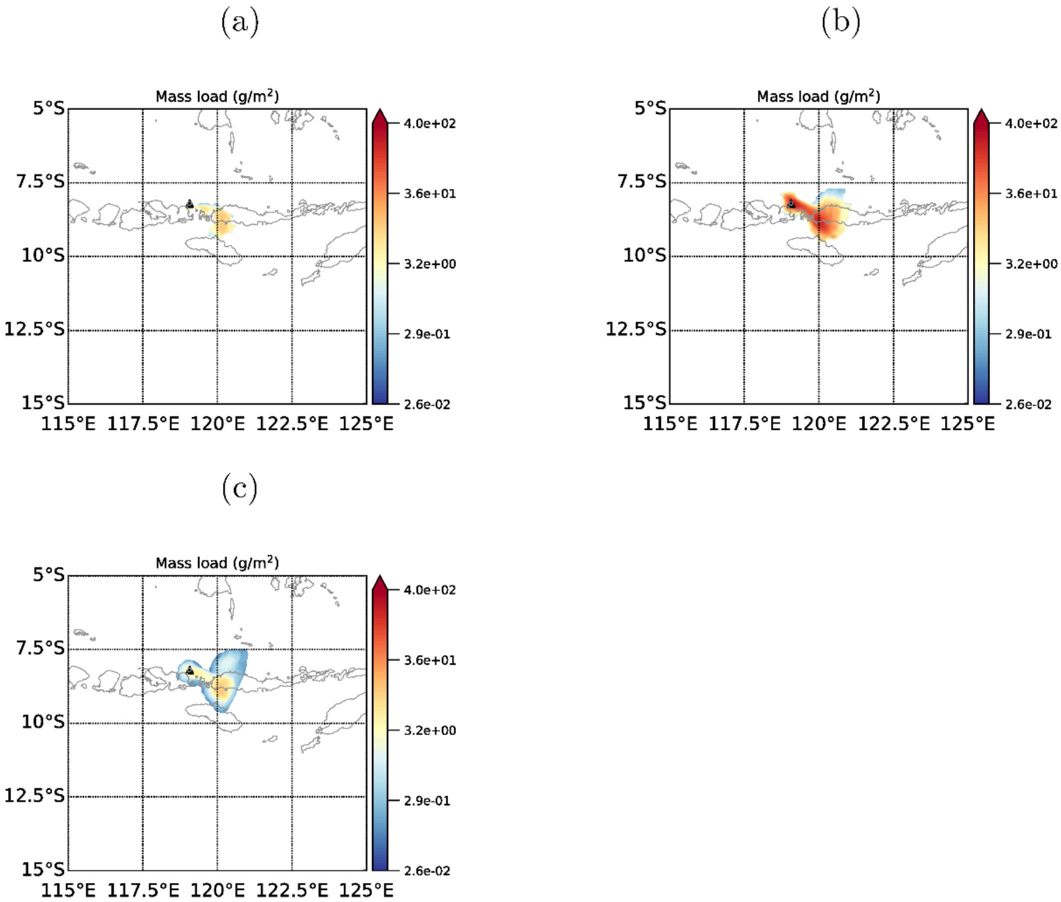

Figure S3. Mass loads (g m^{-2}) in the second phase of the 30 May 2014 Sangeang Api eruption at 1830 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

30 May 2014 Sangeang Api Eruptions—Phase III

Sangeang Api erupted for the third time at around 2000 UTC. The Darwin VAAC again reported the height as 15.2 km although the brightness temperature was somewhat higher than in the 1700 UTC eruption, which suggests a lower altitude. The ash was again carried to the south east and could be tracked for several hours. Mass loads in the reference simulation with standard source settings (Figure S4b) is seen to be higher than corresponding retrievals (Figure S4a) by a factor of at least 30. As in the other case studies, the mass distribution also has too much weight near the volcano. These problems are ameliorated using inverse modelling with improved source settings in the experimental run (Figure S4c).

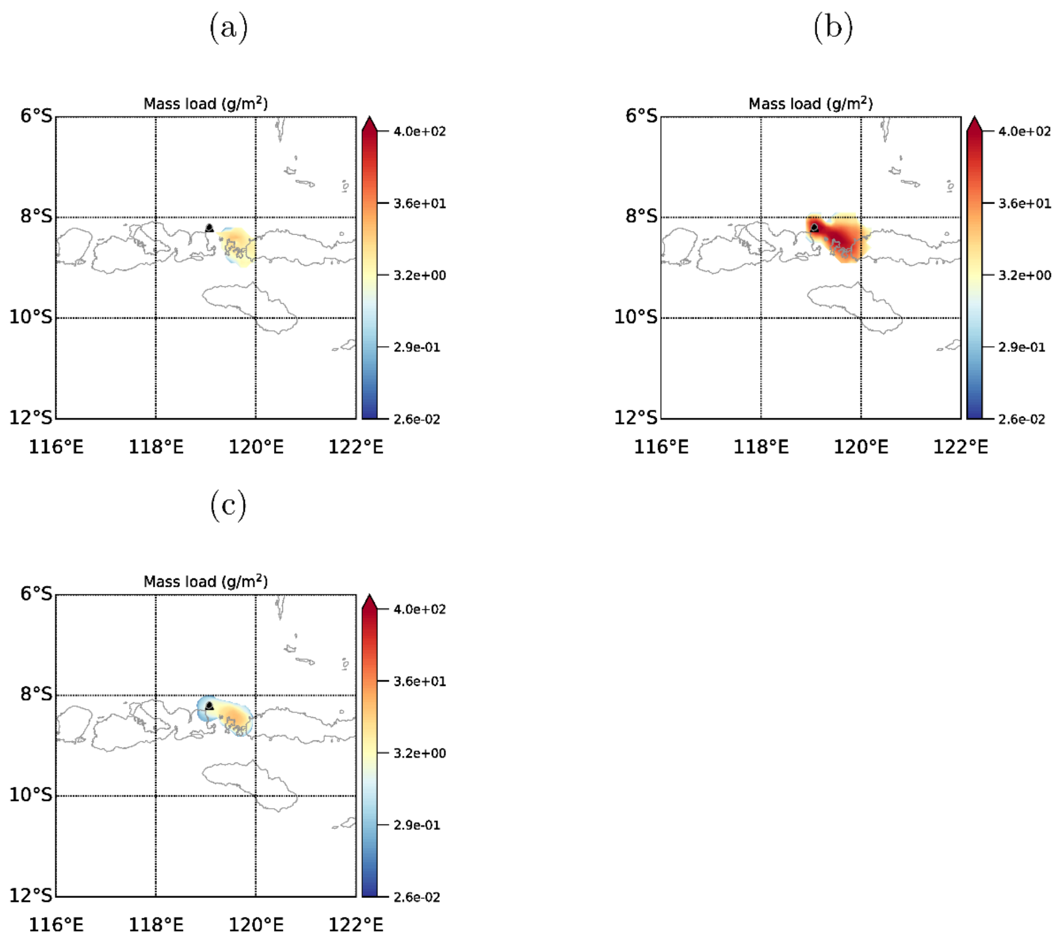

Figure S4. Mass loads (g m^{-2}) in the third phase of the 30 May 2014 Sangeang Api eruption at 2130 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

5 November Rinjani Eruptions—Phase I

Rinjani (116.47° E, 8.42° S, altitude 3.7 km), a volcano in Lombok, Indonesia, experienced a series of eruptions that continued throughout November 2015. In contrast to some of the eruptions described above, these eruptions were at much lower levels, in general less than 6 km in altitude, and continued for several days. The ash cloud was carried to the south-west of the volcano and could be detected by VOLCAT between 0630–1130 UTC on 5 November. The Darwin VAAC reported the height of these emissions as 5.2 km. The retrieved mass loads were in the range of 3–5 g m^{-2}. Because the eruptions were continuous over a period lasting several days, it was difficult to perform simulations initialised from the eruption start time. One difficulty was the length of time it would take to complete the simulations, particularly in the context of multiple trial simulations required by the inverse modelling algorithm. A second, and probably more pertinent, difficulty was the accumulation of modelling errors over time, which would hinder the comparison between model and retrievals. To overcome these difficulties, we initialised the simulations at time $\boldsymbol{t}$, which we treated as an unknown variable to be optimised relative to observations in the inverse modelling framework within a time window of about 24 h prior to the availability of the retrieval data. The effect of this was to limit the lead time (and therefore model errors) to no more than about 24 h. Emissions released earlier would not be modelled, but in practice this does not matter since these emissions would have dissipated into background levels by this time. In the reference run, we arbitrarily set the start of the emissions at 4/1200 UTC while in the experimental run we vary the start time between 4/1200 and 5/0000 UTC. For both reference and experimental runs, the maximum simulated ensemble mean mass loads were found to be about 3 g m^{-2}, in good agreement with retrievals (Figure S5a). However, the spread of ash was significantly greater in the reference simulations due to significant wind field spread among the numerical weather prediction (NWP) ensemble members (Figure S5b). In the experimental simulations (Figure S5c), the ash was more tightly confined in agreement with retrievals because ensemble members that carried the ash in directions inconsistent with the retrievals were rejected by the algorithm.

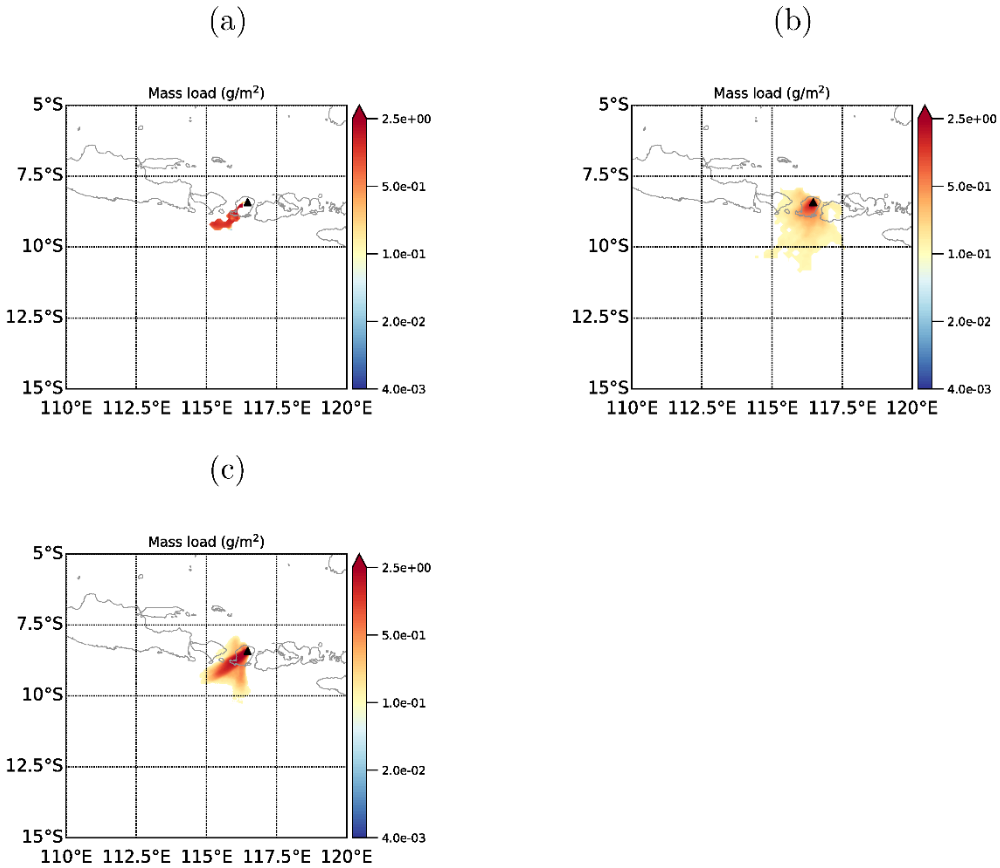

Figure S5. Mass loads (g m^{-2}) at 0630 UTC on 5 November during the November 2015 ongoing Rinjani eruption: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

5 November Rinjani Eruptions—Phase II

The next phase of the November 2015 Rinjani eruptions that we focus on occurred in the time interval 1630–1930 UTC on 5 November. The Darwin VAAC again assigned a height of 5.2 km to these emissions. The ash cloud was seen to be moving to the south during this phase and was detected by VOLCAT. The retrieved maximum mass loads were found to be in the range of 2–3 g m^{-2} (Figure S6a). The same initialisation technique as for the earlier phase was used, with start time being 5/0000 UTC for the reference run and varied between 5/0000 UTC to 5/1200 UTC in the experimental run. Both runs led to maximum simulated mass loads of about 3 g m^{-2} (Figures S6b,c, respectively). The main difference between the two sets of simulations was again the degree of spread between ensemble members, being less in the experimental runs, for reasons similar to those given above.

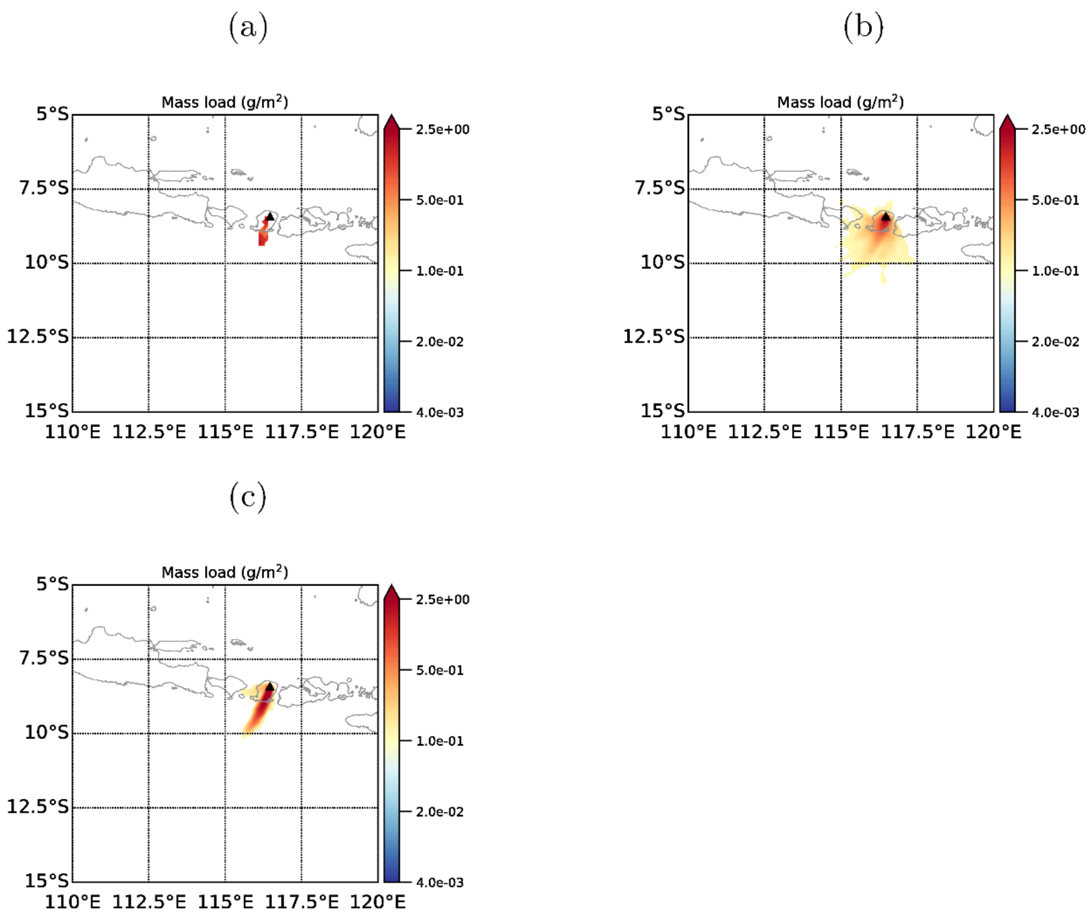

Figure S6. Mass loads (g m^{-2}) at 1630 UTC on 5 November during the November 2015 ongoing Rinjani eruption: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

<u>31 July 2015 Manam Eruption</u>

Manam (145.04° E, 4.08° S, altitude 1.8 km), a volcano in Papua New Guinea, erupted at around 0130 UTC on 31 July 2015. The plume reached a height of about 20 km, according to the Darwin VAAC. The eruption was brief, and the ash cloud was carried to the south-west. The cloud was detected by the VOLCAT software and mass load retrievals were produced (Error! Reference source not found.a). The cloud dissipated relatively quickly and could not be discerned in satellite imagery after a period of about 24 hours, although VOLCAT detections (and corresponding retrievals) had ceased by about 0500 UTC. The retrieved mass load is unlikely to be accurate due to presumed presence of large amounts of ice in the cloud. The rapid dissipation of the cloud also suggests much lower ash load levels. Reference simulations with standard settings (Error! Reference source not found.b) reveal similar problems to the Kelut and Sangeang Api I cases, namely too much mass remaining near the source and overall too much mass being released. In this case, the discrepancies are at least a factor of 30, with mass loads reaching as high as 3000–7000 g m^{-2} in the model. Using inverse modelling with improved source settings in the experimental runs (Error! Reference source not found.c), the mass distribution and total mass released are in much better agreement with the retrievals (although even these values, reaching about 200 g m^{-2}, are probably overestimates due to the limitations of the retrieval scheme).

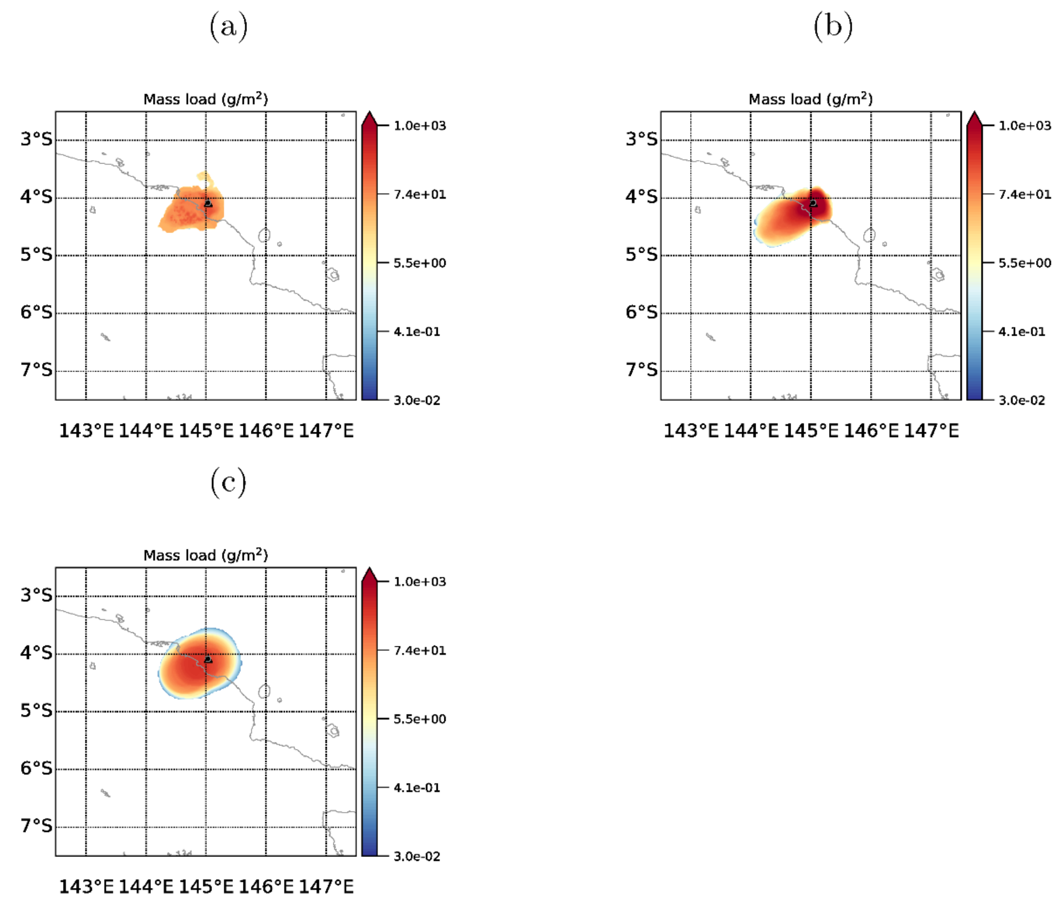

Figure S7. Mass loads (g m^{-2}) in the 31 July 2015 Manam eruption at 0230 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

4–6 January Soputan Eruptions—Phase I

Soputan (124.74° E, 1.11° N, altitude 1.8 km), a volcano in Sulawesi, Indonesia, experienced a series of eruptions in the period 4–6 January 2016. Here we focus on the eruption that occurred at around 2240 UTC on 4 January. This was reported by the Darwin VAAC to have reached 12.8 km in height. The ash cloud was detected by VOLCAT and was seen to comprise at least two branches, with one branch moving to the south and the other branch to the west (Error! Reference source not found.a). VOLCAT detections and retrievals ceased after about 5/0050, but the cloud was still clearly visible on satellite imagery until well after 5/0200 UTC. Reference simulations with standard source settings were observed to overestimate retrieved mass loads by almost two orders of magnitude in this case (Error! Reference source not found.). A systematic discrepancy in the spatial distribution of the mass load was not as apparent here. Use of inverse modelling with improved source settings in the experimental runs led to better agreement between simulations and retrievals as far as the magnitudes of the mass loads were concerned (Error! Reference source not found.c).

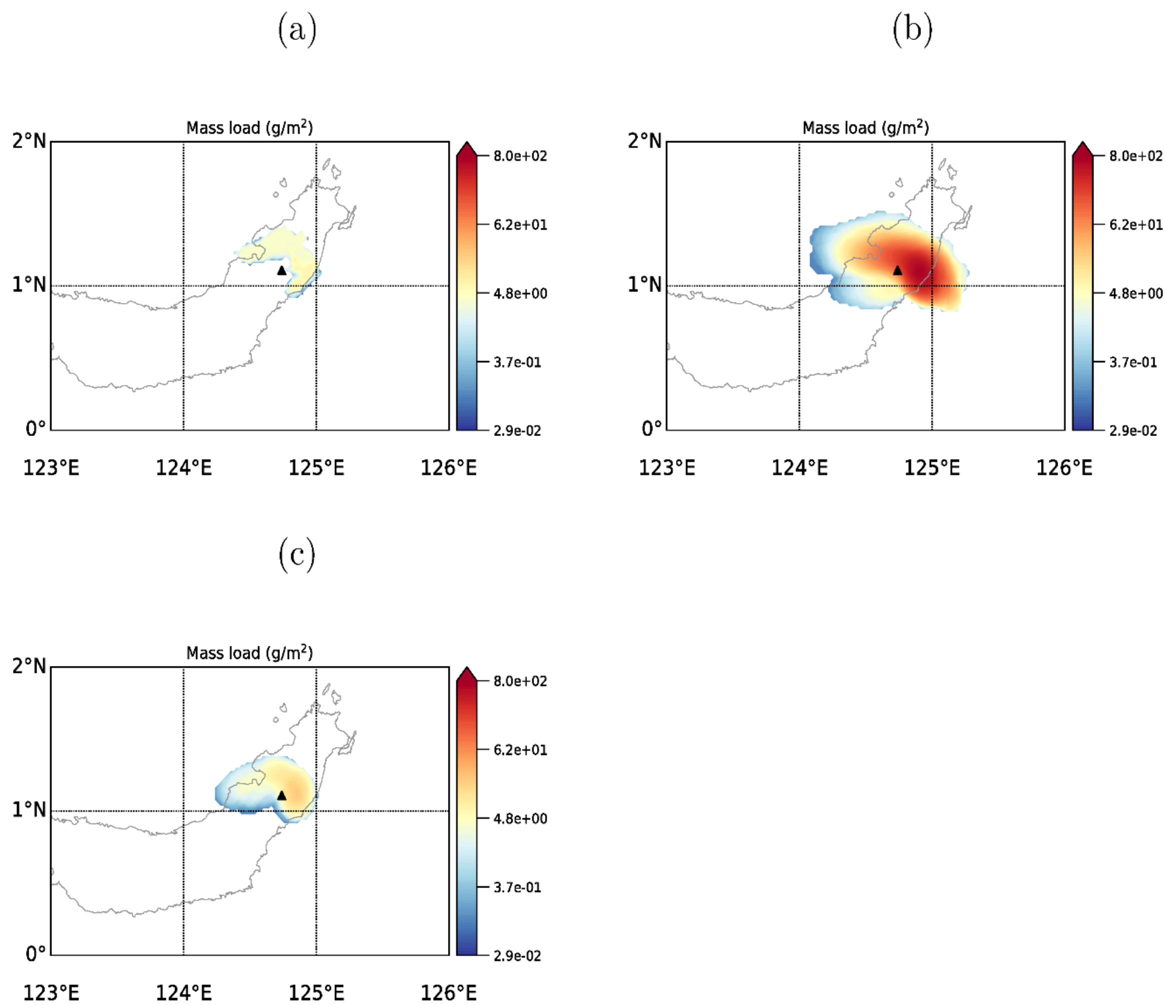

Figure S8. Mass loads (g m^{-2}) in the 4-6 January 2016 Soputan eruptions at 0030 UTC on 5 January: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

<u>4–6 January Soputan Eruptions—Phase II</u>

Here we focus on another phase of the 4–6 January 2015 Soputan eruptions—this one occurring at approximately 0640 UTC on 5 January. The eruption was shortlived, and the emissions reached about 12.5 km in altitude, according to the Darwin VAAC. There were VOLCAT detections and retrievals until about 0740 UTC, showing the cloud moving to the west of the volcano (Error! Reference source not found.a). After this time there were other detections and retrievals near the volcano, but it is difficult to definitively associate these detections and retrievals with the eruption at 0640 UTC. Reference simulations with standard source settings are again higher than the retrieved mass load by over two orders of magnitude (Error! Reference source not found.). Mass loads obtained from using inverse modelling with improved source settings in the experimental run are in better agreement with retrievals (Error! Reference source not found.c).

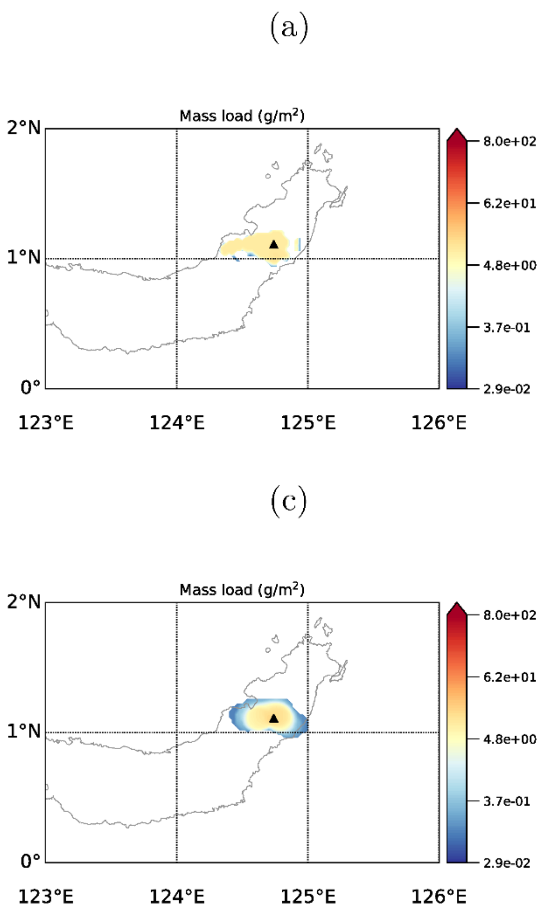

Figure S9. Mass loads (g m^{-2}) in the 4–6 January 2016 Soputan eruptions at 0710 UTC on 5 January: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

<u>1 August 2016 Rinjani Eruption</u>

Rinjani erupted again at approximately 0400 UTC on 1 August 2016. In contrast to the earlier, November 2015, eruptions, this eruption lofted ash to a somewhat higher altitude and was relatively shortlived (<2 h). The Darwin VAAC initially reported a height of 9.8 km based on pilot reports although subsequent advisories reported an altitude of only 6.1 km based on satellite brightness temperatures. VOLCAT retrievals were available soon after, and these showed the ash cloud moving south of the volcano (Error! Reference source not found.a). The retrievals lasted until about 0630–0700 UTC, after which the retrieval pattern became more fragmented, possibly due to dissipation of the ash or to presence of meteorological clouds, or both. Retrieved maximum mass loads were in the range 4–7 km. HYSPLIT simulations with standard source settings in the reference run resulted in mass loads in the range 1–3 g m^{-2} (Error! Reference source not found.b). Use of inverse modelling with improved source settings in the experimental run improved the agreement between retrievals and simulations (Error! Reference source not found.c).

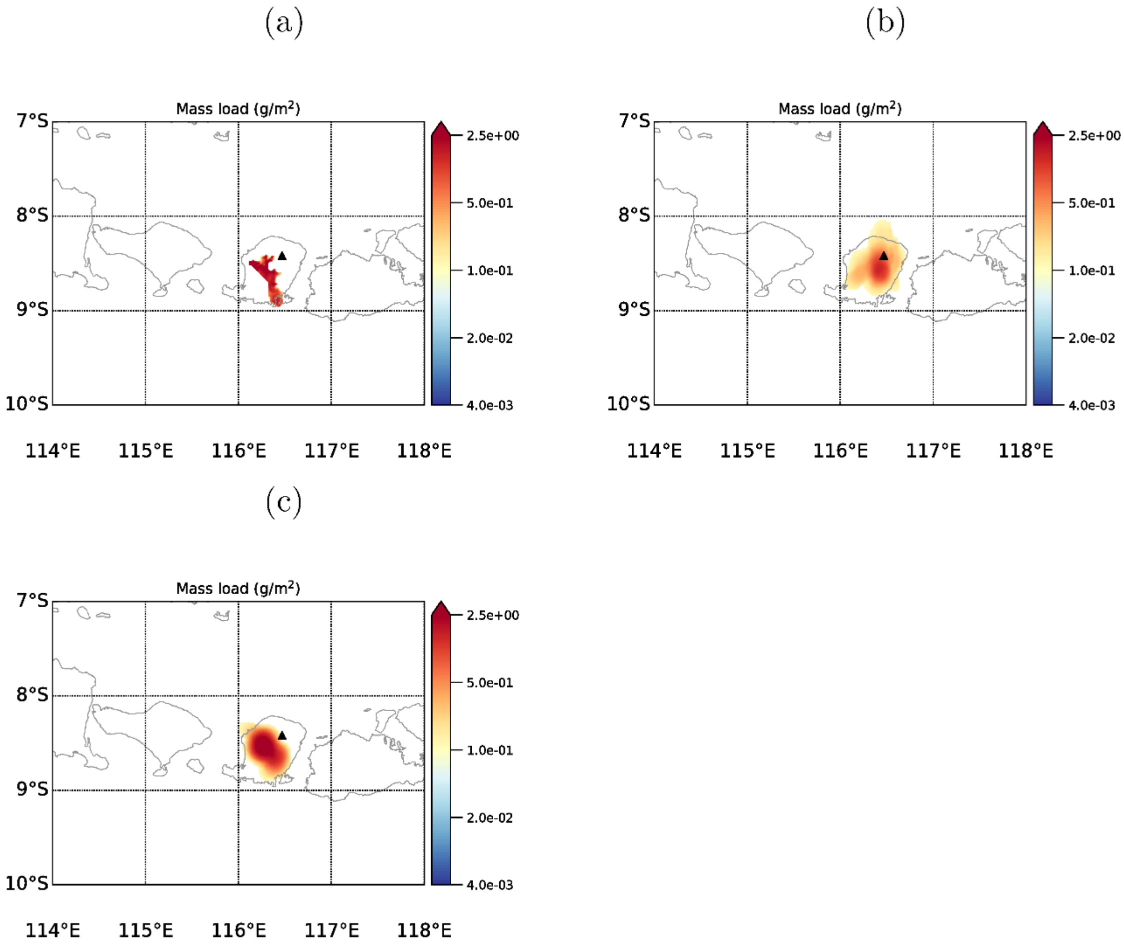

Figure S10. Mass loads (g m^{-2}) in the 1 August 2016 Rinjani eruption at 0600 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

<u>20 October 2017 Tinakula Eruption</u>

Tinakula (165.80° E, 10.39° S, altitude 0.8 km), a volcano on a 3.5 km-wide island on the north-west end of the Santa Cruz Islands, Solomon Islands, erupted at about 1910–1920 UTC on 20 October 2017. This is the only volcano that we consider that is not within the Darwin VAAC domain; it instead falls under the responsibility of the Wellington VAAC. The Wellington VAAC reported a height of 10.7 km, although this is almost certainly a significant underestimate. Some of the brightness temperatures were below 200 K, which correspond to tropopause temperatures; in addition, a warmer spot, indicating stratospheric intrusion, was identified. There were no VOLCAT retrievals during this phase of the eruption. The cloud could, however, be easily tracked due to its anomalous growth pattern relative to surrounding meteorological clouds, and the bulk of the ash appeared to be moving in the north-east direction. In addition, there was a distinctive positive brightness temperature difference at the edges of the clouds, which made it easier to delineate from surrounding meteorological clouds. The volcano erupted again at around 2330–2340 UTC. As during the first phase, the eruption could be tracked well by the anomalous growth and positive brightness temperature difference in satellite imagery. The brightness temperatures again indicate that the ash intruded the stratosphere. There were VOLCAT detections and corresponding retrievals this time that were triggered by the anomalous cloud growth algorithm within VOLCAT (Error! Reference source not found.a). As in the 31 July 2015 Manam eruption, the strong positive brightness temperature difference signal suggests the presence of large amounts of ice in the cloud and therefore the VOLCAT mass load values may not accurately describe the amount of ash in the cloud. HYSPLIT simulations with the standard source setting in the reference run (Error! Reference source not found.b) reveal much higher mass loads (generally >1000 g m^{-2}) than in the retrievals, which is a phenomenon also seen in other eruptions of this magnitude as described above. The discrepancy in the spatial mass load distribution, seen in the other eruption case studies, is not as apparent here, however. Use of inverse modelling with improved source settings in the experimental run (Error! Reference source not found.c) leads to better agreement between the model simulations and retrievals although as in the 31 July 2015 Manam eruption the retrievals are probably overestimates since the ash cloud is seen to dissipate quite quickly.

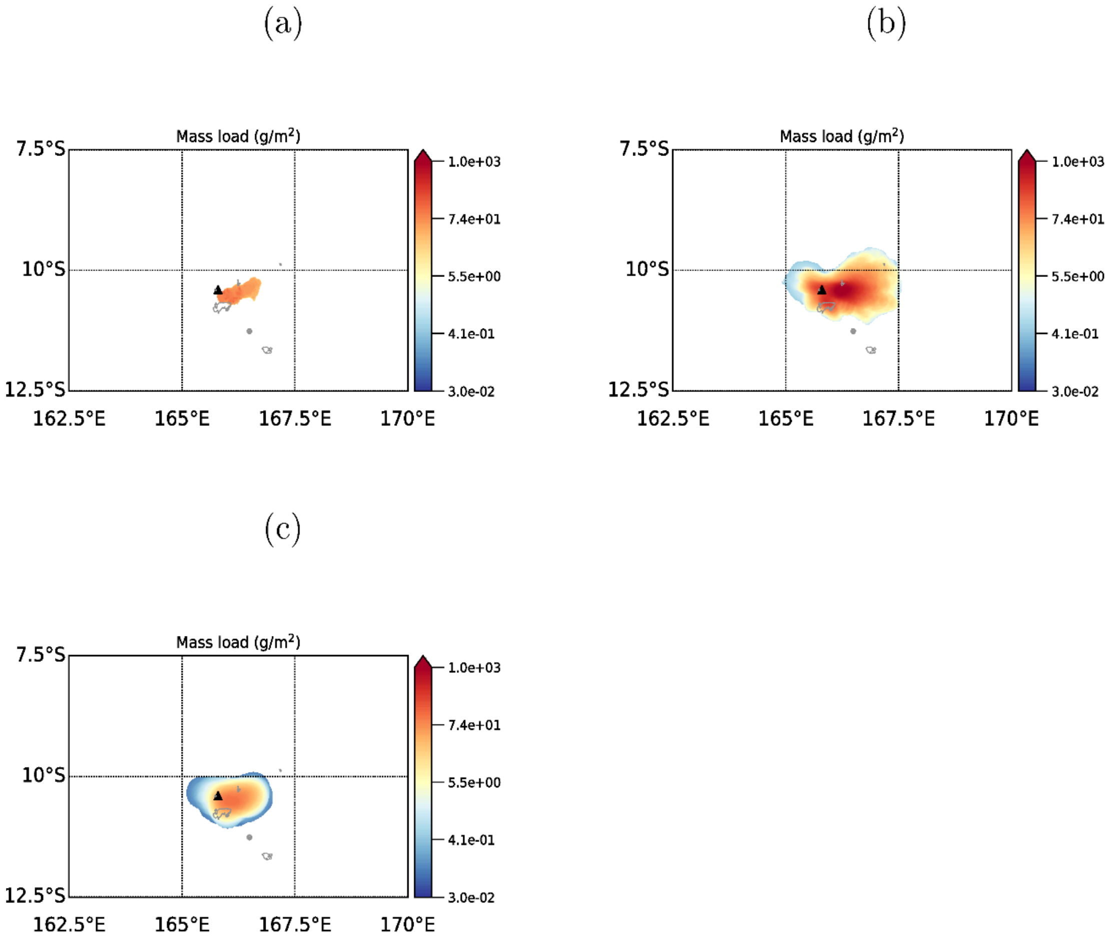

Figure S11. Mass loads (g m^{-2}) in the 20 October 2017 Tinakula eruption at 0130 UTC on 21 October: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

<u>11 May 2018 Merapi Eruption</u>

Merapi (110.44° E, 7.54° S, altitude 3.0 km) is an extremely active volcano located in Java, Indonesia. It erupted suddenly at around 0030 UTC on 11 May 2018. The Darwin VAAC initially reported the height of the eruption as 15.2 km. This is almost certainly a gross overestimate. Models initialised with ash at these levels show ash being transported faster and much further than seen in satellite imagery. Brightness temperature analysis of satellite imagery suggests maximum heights of about 8 km. As well as problems with the estimation of the cloud height, the dispersion model fails to capture the splitting of the ash cloud into a southern and southern-eastern branch seen in satellite imagery. VOLCAT retrievals show mass load values generally below 5 g m^{-2} soon after the eruption (Error! Reference source not found.a), consistent with a lower-level eruption. Using standard source settings in the reference runs results in simulated maximum mass loads of around 70–90 g m^{-2} (Error! Reference source not found.b). With the use of inverse modelling and improved source settings in the experimental run, the simulations are in closer agreement with retrievals (Error! Reference source not found.c).

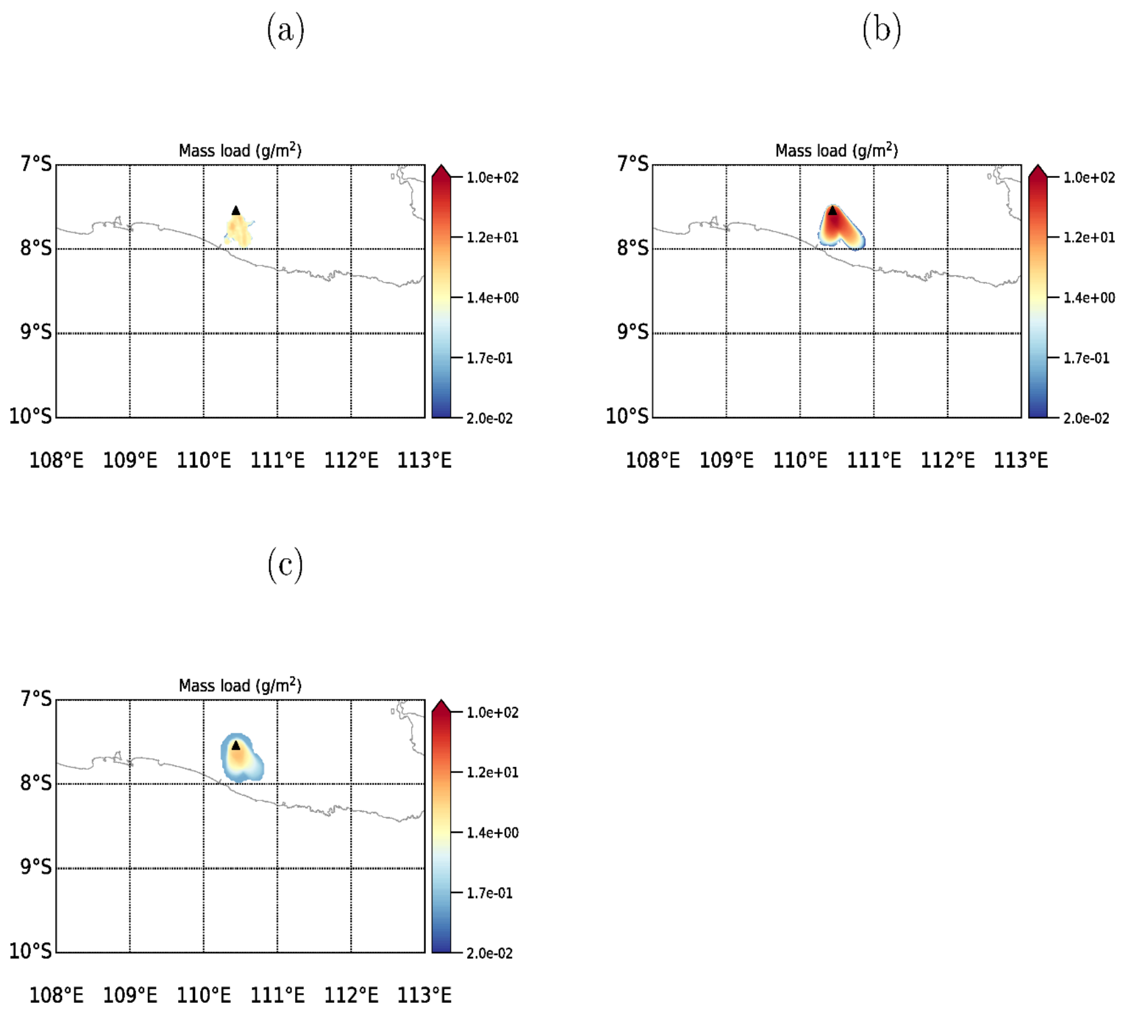

Figure S12. Mass loads (g m^{-2}) in the 11 May 2018 Merapi eruption at 0230 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

8 December 2018 Manam Eruption (Manam II)

Another high-level eruption of Manam occurred at approximately 0300 UTC on 8 December 2018. The Darwin VAAC reported the eruption height as 13.7 km. The eruption continued for a period of about 3 hours. Ash mass load retrievals from VOLCAT were generated and indicated ash mass loads greater than 20 g m^{-2}, consistent with a high-level eruption (Error! Reference source not found.a). The retrievals were available for a period of about 5 hours after the start of the eruption. Reference simulations utilising standard source settings carried the ash bulk of the ash to the east, consistent with observations, but the forecasted mass loads were overestimated by a factor of at least 20 (Error! Reference source not found.b). Discrepancies in mass load distributions are not as clear here. Use of inverse modelling with improved source settings in the experimental run leads to improved agreement with retrievals (Error! Reference source not found.c).

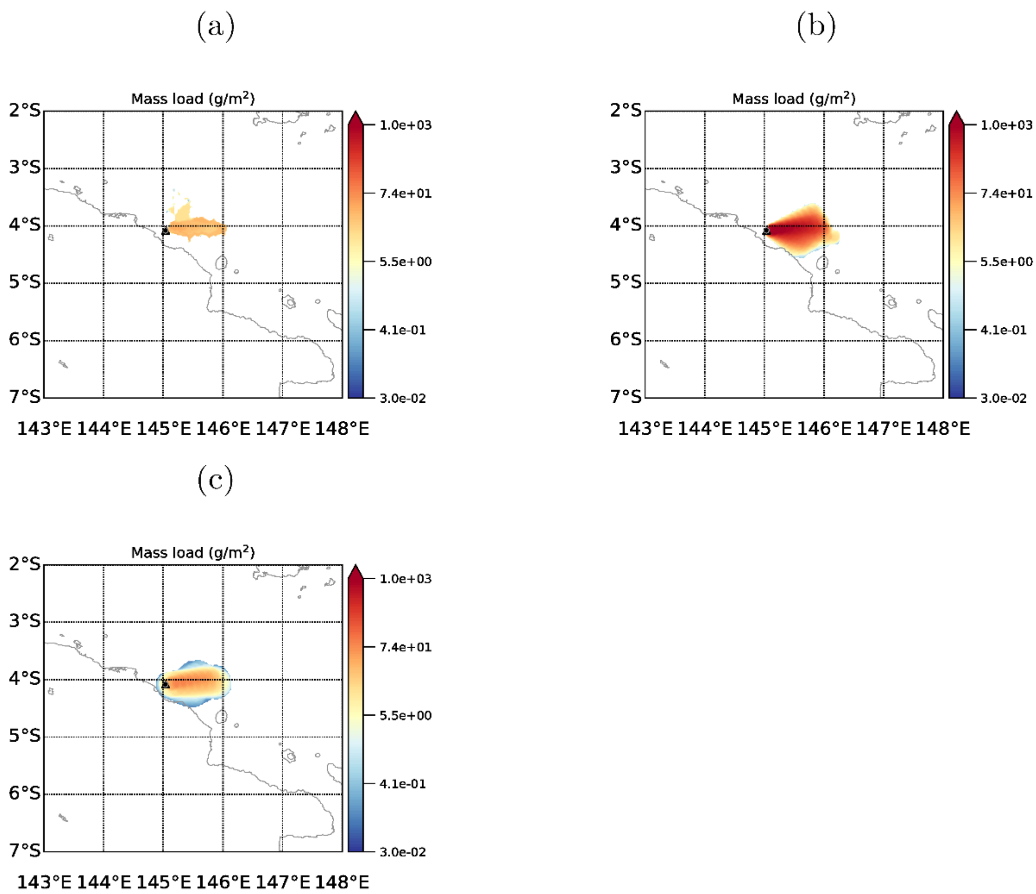

Figure S13. Mass loads (g m^{-2}) in the 8 December 2018 Manam eruption at 0530 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

24 May 2019 Agung eruption

Agung (115.51° E, 8.34° S, altitude 3.1 km), a volcano located in Bali, Indonesia, erupted briefly at about 1130 UTC on 24 May 2019. The Darwin VAAC reported the eruption height as 4.6 km. VOLCAT retrievals show ash with maximum mass load levels in the range of 1–6 g m^{-2}, consistent with a low-level eruption, moving to the south-west of the volcano (Error! Reference source not found.a). Reference simulations with standard source settings employing this eruption height carried the ash in a direction consistent with observations, but maximum mass loads were forecasted to be only in the range of 0.1–0.2 g m^{-2}. Inverse modelling yielded an eruption height of 7 km, which is somewhat higher than the VAAC report of 4.9 km. Brightness temperature analysis suggested a cloud top height of about 6–7 km, consistent with inverse modelling results. Reference simulations using an eruption height of 7 km yielded maximum mass load in the range of 6–15 g m^{-2} (Error! Reference source not found.b). Simulated mass loads utilising improved source settings and inverse modelling in the experimental runs were in better agreement with retrievals (Error! Reference source not found.c).

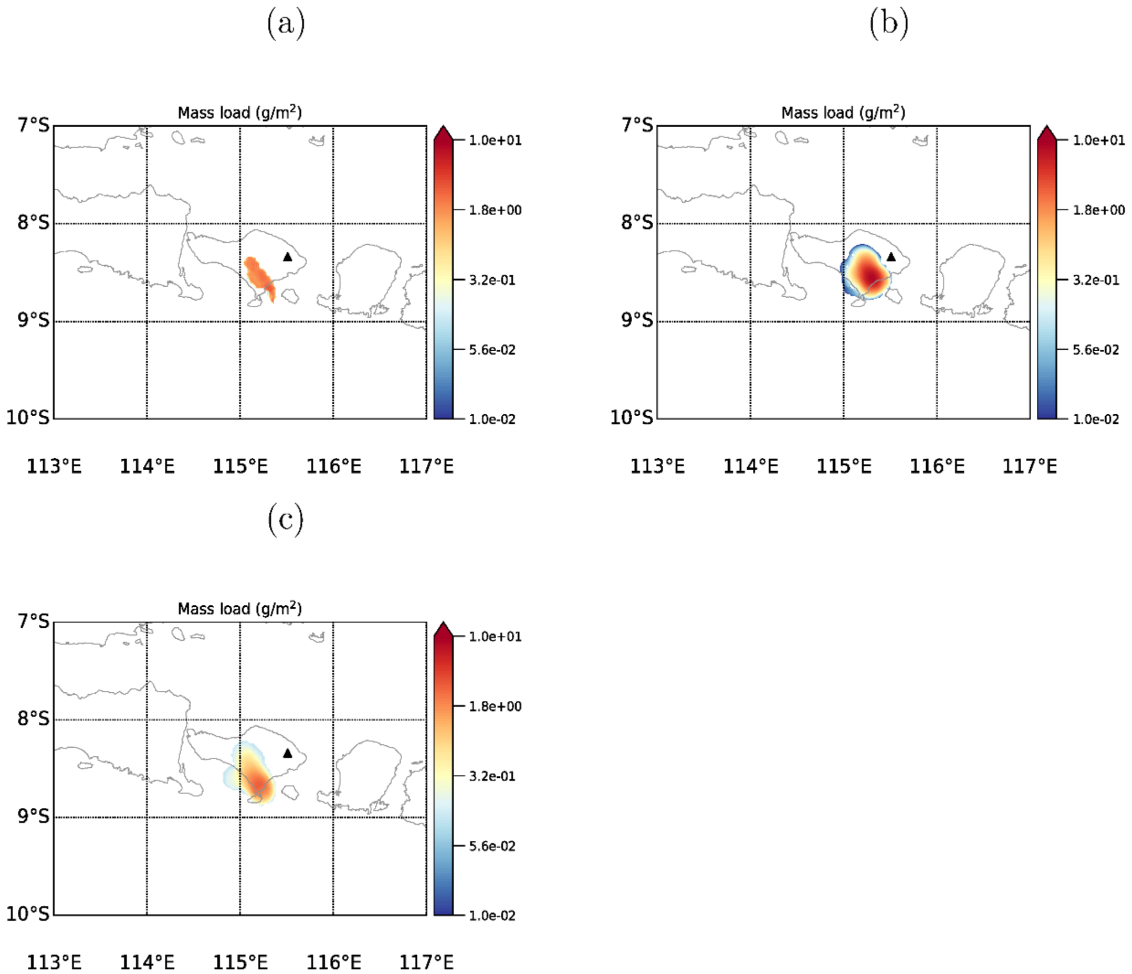

Figure S14. Mass loads (g m^{-2}) in the 24 May 2019 Agung eruption at 1330 UTC: (**a**) VOLCAT retrieval, (**b**) reference run, and (**c**) experimental run based on inverse modelling.

Reference

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