NATURAL HAZARDS
RESEARCH PLATFORM

Contest 2015

Title: Large-scale PDC Hazard Impact Simulations

Leader: A/Prof Gert Lube

Organisation: Massey University

Total funding (GST ex): $289,241 plus GST

Final Report

Key message

All of New Zealand's active volcanoes are capable of producing highly lethal Pyroclastic Density Currents (PDCs). Too dangerous to probe directly, a team of researchers from Massey University, University of Otago, GNS Science, INGV Pisa in Italy, University of Hawaii and Georgia Institute of Technology in the USA synthesized fully-scaled PDCs in large scale experiments. Their work discovered the mechanisms behind the super-mobility of these flows, which they term 'air-lubrication'. They further showed that the enormous damage potential of these hot flows is due to spontaneous oscillations formed inside PDCs, which, somewhat like aftershocks in an earthquake sequence, perpetuate the hazard impact over long durations. The researchers constructed the first international benchmark for computational hazard models to systematically test and validate them, and they developed a series of new models to capture and better forecast the complex future eruption hazards here in New Zealand and overseas. Insights gained from this study will be highly relevant for future hazard assessments at PDC-forming volcanoes and could result in the future development of 'eruption-proof' infrastructure.

Abstract: Pyroclastic density currents (PDCs) are amongst the most frequent and dangerous processes associated with explosive volcanism. Too violent to probe directly, the infamous perils of PDCs, associated with their high velocities and temperatures, variable ash-load and dynamic pressures, can only be indirectly assessed in the eruption aftermath, but a direct view inside these flows to determine how exactly hazard occurs remains missing.

In this research we synthesized the scaled conditions of hot PDCs and their interaction with natural substrates, topographies and model buildings in large-scale experiments. The results of this work allowed for the first characterisation of the internal structure and evolution of dilute PDCs (or pyroclastic surges). These identified the enigmatic process behind the super-mobility of PDCs, discovered the mechanism behind their enormous destructive behaviour and helped develop a model for cumulative dynamic pressure impacts on infrastructure.

The experimental results were also used to create the first international benchmark for computational PDC hazard models. This important exercise undertaken by New Zealand, Italian, American and French scientists highlighted major shortcomings in our current abilities to simulate PDC events for hazard forecasts. Consequent research using both experimental and numerical approaches helped to advance multiphase modelling techniques to account for the complex processes inside PDCs, including the accurate modelling of gas-particle interactions and transport, to understand better the origin and consequences of turbulence in PDCs, as well as their runout and destruction potential over naturally rough surfaces and topography.

Keywords: Volcanic, hazard, pyroclastic density currents, hazard models

Introduction / Background: We are not learning quickly enough about Pyroclastic Density Currents (PDCs) to save lives. These incandescent flows of volcanic particles and gas travel great distances and sweep across landscapes to burn and devastate everything in their path. We aimed to develop a first robust and highly-applicable PDC hazard model for decision makers, hazard planners and governmental agencies that can predict PDC runout and destruction potential over variable landscapes and structures. A tool to robustly forecast the magnitudes and probabilities of PDC impacts is long desired. However, real-world flows persistently defy any internal observations to quantify how vertical stratification develops in PDCs and how this relates to dynamic stresses. We sought to provide these critical measurements by synthesizing the natural conditions of PDC runout over topography in life-scaled experiments; and use these measurements to test and advance the state-of-the-art computational multiphase flow models.

Impact Statement 1

Pyroclastic density current modelling to evaluate their risks and impacts through large-scale simulations

A robust and highly-applicable PDC hazard model is available to decision makers, hazard planners and governmental agencies that can predict PDC runout and destruction potential over variable landscapes and structures. The model has been tested and calibrated against three well-studied PDC-forming eruptions in the North Island of New Zealand and findings presented at the annual Volcanic Advisory Committee Meetings held in Taranaki, Central North Island and Auckland, and similar fora. The model is available to the international community through the VHub cyber infrastructure and has been submitted for publication to an international peer-review journal.

❖ 1.1 Research Aim

Title: Constraining the development of stratification and boundary stresses in volcanic multiphase flows in large-scale PDC experiments

Budget: $144,620 (excluding GST)

Research Aim achieved? Yes

Discussion: A total of 24 large-scale PDC experiments (Table 1) were conducted with systematic natural variations in boundary roughness, temperature, mass flow rate and grain-size. These experiments necessitated the development of new sensor arrays and experimental set-ups (Figure 1) to ensure that continuous fields of temperature, flow density and space and time-variant deposition could be captured accurately. As an additional component to our experiments, we constructed analogues of natural and man-made obstacles (hills, cliff-like wedges, indestructible and destructible scaled model houses) in the paths of the PDCs. To scale the results of our experiments to both the natural

conditions of PDCs in New Zealand, and a possible wide range of topographic conditions at high-risk volcanoes overseas, the range of landscape elements deployed used the mean geometries of volcanic landscapes around Tongariro, White Island, and Tarawera in New Zealand and Merapi in Indonesia. Measuring inside our fully-scaled PDC analogues revealed a number of fundamental and novel findings on the complexity of the internal structure and boundary stresses inside PDCs (published in high-impact journals), including:

• A hitherto unrecognised mesoscale turbulence flow regime largely controls the development of stratification and stresses inside PDCs. Published in Nature Geoscience (O1); Appendix I and II.
• The destruction potential of PDCs is largely increased through the upstream propagation of pulses of dynamic pressure inside PDCs. An explanation for these pulses and a new model to account for them was later achieved in combination with experimental and computational data under Research Aim 1.2 (see below). Published in Earth and Planetary Science Letters (O2); Appendix III.
• Entrainment of ambient air into PDCs is highly variable across the PDC surface and controls the development of turbulence. This clarified the importance of correctly capturing turbulent air entrainment into PDCs in computational models. Published in Earth and Planetary Science Letters (O2).
• Transport and sedimentation of particles inside PDCs governs a much broader range than previously thought. Our new model relates these to space- and time-variant changes in the Stokes and Stability numbers, which describe the nature of solid-gas coupling in multiphase flows. However, computational models cannot capture these processes. Further analysis of our experiments revealed that the wide ranges in the Stokes and Stability numbers (showing variable gas-particle coupling as opposed to generally assumed perfect gas-particle coupling in models) do not only exist in relatively concentrated PDCs, but are a general feature of PDCs (see below under Research Aim 1.2). Published in Earth and Planetary Science Letters (O2).
• Our large-scale experiments of PDCs involving scaled destructible model houses revealed that damage occurs sequentially during passage of the current and is not related to a single high dynamic pressure region in the head region of these flows. This finding has important consequences on how field researchers assess and interpret PDC damage in eruption aftermaths.

These outcomes, which have strong implications for hazard assessment procedures and which highlight the importance of the international benchmark for computational PDC models (Research Aim 1.2), were widely picked up by national media in New Zealand and overseas (see below).

List of outputs

Journal Articles

O1. Breard, E., Lube, G., Jones, J., Dufek, J., Cronin, S., Valentine, G., Moebis, A. (2016) Coupling of turbulent and non-turbulent flow regimes within pyroclastic density currents. *Nature Geoscience*, 9, 767-771.

O2. Breard, E.C.P., Lube, G. Inside pyroclastic density currents – uncovering the enigmatic flow structure and transport behaviour in large-scale experiments. *Earth and Planetary Science Letters*, 2017, 458, 22-36.

Coverage of the scientific findings in media articles

Phys.Org: "Mysteries of volcanic avalanches unlocked". Posted on: 6 September 2016

Foreign Affairs New Zealand: "Mysteries of volcanic avalanches unlocked". Posted on: 5 September 2016

Noodls: "Mysteries of volcanic avalanches unlocked". Posted on: 5 September 2016

Nature World News: "Hot discovery! Mystery of Volcanic Avalanche explained for the first time". Posted on: 12 September 2016

Health Medicine: "A look inside volcanic flows". Posted on: 12 September 2016

EurekAlert!: "A look inside volcanic flows". Posted on: 12 September 2016

Science Daily: "A look inside volcanic flows: Research attempts to better understand deadly pyroclastic flows". Poster on: 12 September 2016

Stuff: "What will happen when Taranaki erupts? New 35m volcano simulator reveals secrets inside deadly plumes". Posted on: 4 December 2016.

List of end-users

- CDEM Groups
- Central Plateau Advisory Group
- EQC
- Taranaki Regional Council
- Taranaki Seismic and Volcanic Advisory Group.
- Department of Conservation
- Ngati Rangi and Ngati Tuwharetoa
- Geonet

❖ 1.2 Research Aim

Title: Benchmarking 3D PDC multiphase simulations and deriving a GIS-based hazard tool to compute and visualise PDC runout, velocity, sedimentation and dynamic pressures over digital elevation models

Budget: $144,620 (excluding GST)

Research Aim achieved? Yes, with modifications

Discussion: The foundation for the second research aim was to develop the *first international benchmark for computational PDC models* to validate their performance and ability to forecast PDC hazards. During research visits of AIs Dufek, Esposti-Ongaro and project collaborator Cerminara (INGV, Pisa) to New Zealand, the series of large-scale experiments forming the benchmark (as well as a series of control experiments) were conducted. The resulting datasets include the first complete space- and time-variant evolution of the velocity, density, temperature, grain-size, dynamic pressure, turbulence and sedimentation fields for fully scaled PDC analogues world-wide (Path Step II, milestones 1 and 2).

A test of current PDC computational models against the benchmark was successfully performed with AIs Dufek, Neri, Esposti-Ongaro and project collaborators Breard, Cerminara and Fullard (Path Step III, milestone 1). Importantly, these benchmark tests highlighted strong deficiencies in the accurate capture of shear stresses, velocity and density stratification, development of turbulence and dynamic pressure, sedimentation and entrainment of ambient air in the models (Table 2 summarises the model's performance). With regards to hazard assessment purposes, we highlight the following shortcomings of even the most advanced multiphase models:

• Simulated velocity and density stratifications (controlling dynamic pressure evolution) cannot reproduce the complexity of the benchmark and real-world flows (see Figure 2).
• Models can only accurately capture PDC flow front advance over smooth substrates (see Figure 3).
• Velocities and runout over naturally rough surfaces are severely underestimated. This also applies to flow propagation over successions of hills. However, the model performance improves with increasing flow magnitude, and suggests that current multiphase models are suitable for predicting runout dynamics over complex topography for high VEI PDC-forming eruptions. In preparation for submission as an article to Journal of Geophysical Research (O7).
• In general, models perform poorly in resolving complex flow structures and resultant hazards over topography and buildings. In preparation for submission as an article to Journal of Geophysical Research (O7).

The possibility of fundamental weaknesses in existing computational PDC models was anticipated and discussed in the project proposal (Path Steps III and V, Mitigation Risks). However, our quantification of the extent of the current shortcomings is an important fundamental result of this work. This resulted in a re-defined focus of the latter stages of our research (Path Steps IV and V) to advance our fundamental understanding of the evolving PDC flow structure and resulting hazards and how to capture these in advanced models. The resulting research can be split into two parts: firstly combined experimental and computational investigations to comprehensively understand the complex PDC flow structure and resulting hazards; and secondly, using the benchmark data to develop and test new computational models that can capture these processes. Highlights of research results under the first point include:

• We discovered the enigmatic process that controls the super-mobility of PDCs, which we term ‘air-lubrication’. In our experiments we measured a low-friction air-cushion that is self-generated in these flows and perpetuates their motion. Submitted as article to Nature Geoscience (O5)

• We developed a new rheology model that mathematically describes the resulting flow behaviour, which we showed be a variety of pore-pressure feedbacks that also occur in water-particle flows. Submitted as article to Nature Geoscience (O5)

• We discovered that pyroclastic surges spontaneously generate oscillations of their velocity and density fields (see Figure 4), which explains the generation and perpetuation of high-magnitude dynamic pressure pulses. We developed a novel turbulence intensity analysis model for unsteady, fully turbulent multiphase flows, which shows that low-frequency oscillations are due to the formation of large-scale eddies. This new model allows forecasting of the number and timing of the highly dangerous pressure pulses. In preparation for submission as an article to Nature Communications (O6).

• Importantly for hazard assessment strategies, this new model explains the enormous destruction of infrastructure through the passage of PDCs. Contrary to previous theories, dilute PDCs are not characterised by a single dynamic pressure peak in the rear of the head. Instead boundary stresses and turbulence dictate a succession of dynamic pressure pulses associated with the down-flow passage of the largest eddies inside the current. This is somewhat analogous to the accumulated hazard impact to infrastructure during seismic events with strong aftershock sequences. As a result, PDC destruction of infrastructure accumulates during successive pressure peak arrivals to weaken and subsequently cause failure of building elements and entire houses. The model further explains the generation of pressures in excess of tens of kilopascal, and the accumulation of an effective pressure often in excess of a hundred kilopascal, which coincides with current estimates from field data. We tested this model to simulate the dynamic pressure accumulation for the cases of the 2010 Merapi and 2012 Te Maari eruptions and confirmed the field data of infrastructure damage. We also suggest that future uptake and continuation of this research on PDC simulations over model infrastructure are likely to resolve new building designs towards higher resilience in high-risk areas here and overseas. In preparation for submission as an article to Nature Communications (O6).

• We found a fundamental link between the complex PDC flow structure and the resultant deposit structure. This link is due to high-frequency oscillations in the lower flow boundary layer of PDCs where mesoscale clusters form and segregate into sedimentation instabilities (See Figures 4 and 5). In preparation for submission as an article to Nature Communications (O6).

• In our search for the reasons why current PDC computational models fail to reproduce the flow front kinematics, runout behaviour and interaction with naturally rough surfaces, we developed a new model to describe the vertical stratifications in velocity and particle concentration that account for turbulence intensity and replace the empirical formulations of Graf and Altinakar (1996). In preparation for submission as an article to Journal of Geophysical Research (O7).

Highlights of the research results under the second point are:

• We developed a new Lagrangian-Eulerian multiphase model to capture the formation of mesoscale clusters in PDCs. The model was validated against our experimental data. The work also showed why PDCs group into low-density and high-density end-members of transport. Published as article in Geophysical Research Letters (O3).
• We developed a new high-resolution discrete-element model (MFIX-DEM) capable of simulating four-way gas-particle coupling, which allowed us to model the existence of air-lubrication for a wide range of natural PDC conditions. Submitted as an article to Nature Geoscience (O5).
• We further used this new model to constrain the effective particle diameter to be used to capture essential gas-particle feedback mechanisms of PDCs in multiphase simulations. Submitted as an article to the Journal of Geophysical Research (O4). This work will also be presented to the international audience during the next Cities on Volcanoes Conference in Naples.

Results of our work under Research Aim 1.2 have been presented at three different meetings to national stakeholders (see below) and also resulted in four solicited presentations to the international community at meetings of IAVCEI and IUGG (see below). Media interest in the hazard research and model development resulted in three science documentaries, two of which have been screened in New Zealand and overseas and one will appear in New Zealand and Australian TV programmes in late 2018 (see below).

List of outputs

Journal articles

O3. Breard, E. C. P., Dufek, J. & Lube, G. Enhanced mobility in concentrated pyroclastic density currents: an examination of a self-fluidization mechanism. *Geophysical Research Letters* **45**, 654-664 (2018).

O4. Breard, E.C.P., Jones, J.R., Fullard, L., Lube, G., Davies, C. & Dufek, J. The permeability of volcanic mixtures – implications for pyroclastic currents. *Journal of Geophysical Research* (under review).

O5. Lube, G., Breard, E.C.P., Jones, J., Fullard, L., Dufek, J., Wang, T. & Cronin, S.C.J. The air-lubrication of pyroclastic flows. (Submitted to Nature Geoscience).

O6. Brosch, E., Lube, G., Cerminara, M., Breard, E.C.P., Esposti-Ongaro, T., Jones, J. Spontaneous oscillations in pyroclastic surges controls their hazard and sedimentation dynamics. (In preparation for submission to Nature Communications).

O7. Lube, G., Cerminara, M., Brosch, E., Breard, E.C.P., Esposti-Ongaro, T., Jones, J. The characteristics and consequences of turbulence in dilute pyroclastic density currents. (In preparation for submission to Journal of Geophysical Research).

Conference presentations

Brosch, E., Lube, G., Cerminara, M., Breard, E., Esposti-Ongaro, T. Death by a thousand perils – spontaneous oscillations in pyroclastic surges control their hazard impact and sedimentation. Cities on Volcanoes conference (2018). Conference talk.

Lube, G., Cerminara, M., Brosch, E., Breard, E., Esposti-Ongaro, T., Jones, J. The characteristics and consequences of turbulence in dilute pyroclastic density currents. Cities on Volcanoes conference (2018). Poster presentation.

Brosch, E., Lube, G., Breard, E.C.P., Kreutz, K., Jones, J., Esposti-Ongaro, T. First views inside pyroclastic surges reveal new mechanisms behind their thermal and dynamic pressure hazard potentials. GSNZ 2017, Auckland, New Zealand (2017).

Bread, E., Lube, G., Dufek, J., Brosch, E., Jones, J., Esposti-Ongaro, T., Fullard, L. Constructing a benchmark for pyroclastic density currents. IAVCEI General Assembly (2017). Solicited talk.

Lube, G., Breard, E., A recipe for disasters – Unleashing the infernal forces of pyroclastic flows. IAVCEI General Assembly (2017). Solicited talk.

Brosch, E., Lube, G., Breard, E., Kreutz, K., Jones, J., Esposti-Ongaro, T., Synthesizing hot pyroclastic surges to link flow dynamics and deposit characteristics. IAVCEI General Assembly (2017). Poster presentation.

Lube, G., Breard, E., Jones, J., Fullard, L., Cronin, S. The air-cushioning of pyroclastic flows. IUGG General Assembly (2015). Solicited talk.

Lube, G., Breard, E., Cronin, S., Jones, J. Inside pyroclastic flows – Large-scale simulations of pyroclastic density currents at PELE volcano, New Zealand. IUGG General Assembly (2015). Solicited talk.

Presentation to stakeholders

Lube, G. Testing and advancing models for pyroclastic density currents. Central Plateau Volcanic Advisory Group meeting presentation to MCDEM, EQC, MetService, Geonet, Army, Police, Regional Councils. Ohakune 2018.

Lube, G. Benchmarking and validating computational PDC models for New Zealand. Hui involving Ngati Rangi, Ngati Tuwharetoa and Department of Conservation. Turangi 2017.

Lube, G. Recipe for disasters – How to synthesize pyroclastic flows to derive at hazard models. Presentation to DEVORA representatives, UoA and Auckland University of Technology researchers during Earth Science Seminar. Auckland 2017.

Coverage of the scientific findings in media articles

Science documentary “Beneath New Zealand II” Prime, NZ on Air, Australian Broadcasting Corporation (to be screened in NZ in late 2018).

Science documentary “Beneath New Zealand” Prime, NZ on Air, Australian Broadcasting Corporation (2016).

Discovery channel News Story “Hot Discovery! Mystery of Volcanic Avalanche explained for the first time’ (2016).

List of end-users

- CDEM Groups
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- EQC
- Taranaki Regional Council
- Taranaki Seismic and Volcanic Advisory Group.
- Department of Conservation
- Ngati Rangi and Ngati Tuwharetoa
- Geonet

Conclusions & Recommendations: This research project has successfully made the first steps towards resolving the enigmatic internal structure and boundary stresses of dilute pyroclastic density currents through systematic series of large-scale experiments with variable flow conditions and over naturally-scaled topography and buildings; it has defined the first international benchmark for computational PDC hazard models and tested the ability of current PDC models to forecast hazards; it resulted in the development and testing of new PDC models that can simulate the flow phenomena discovered here, including the process of air-lubrication that explains the super-mobility of PDCs, and the spontaneous oscillation inside PDCs that explains the origin of the enormous destruction potential of the currents. The results of this research have been published in high-impact peer-review journals, such as Nature Geoscience and Earth and Planetary Science Letters, and have been communicated to national stakeholders and the international research community.

An important outcome of the benchmark testing of existing PDC models is that even the most advanced computational models currently fail to reproduce the internal flow dynamics to an extent that allows accurate forecasting of flow runout, flow velocity evolution and development of destructive dynamic pressures in dilute PDCs over naturally variable topography. A notable exception is the case of very high magnitude PDC-forming eruptions where bulk energy scales dominate over flow-internal variations. This result is alarming with regards to the application of advanced (and even more so simpler 1D and 2D) models for hazard assessments in New Zealand and overseas. For this reason, our research deviated from the original plan to simplify computationally expensive multiphase models to fast and inexpensive solvers. Instead, we developed new advanced models, analytical solutions and model additions to the existing MFIX and KFIX multiphase codes to reduce the current weaknesses of PDC models.

Our work strongly recommends the continuation of a transparent international benchmarking exercise of PDC hazard models, as initiated in this research. In fact, we have demonstrated clearly in this study that the combination of large-scale experiments and numerical models is highly effective for understanding fundamental gaps in model performance, and for subsequently developing more advanced and robust numerical codes.

Our results towards explaining the dynamics of PDC interactions with infrastructure provide field volcanologists and hazard scientists with a new paradigm for mapping and quantifying PDC destruction in the aftermath of an eruption. In combination with our new surge-oscillation model it will be possible to accurately estimate the number and magnitudes of dynamic pressure pulses in PDCs from New Zealand's active volcanoes. We suggest that this type of hazard assessment can result in future research investigating the feasibility of designing PDC-proof infrastructure in high-risk areas.

Figures:

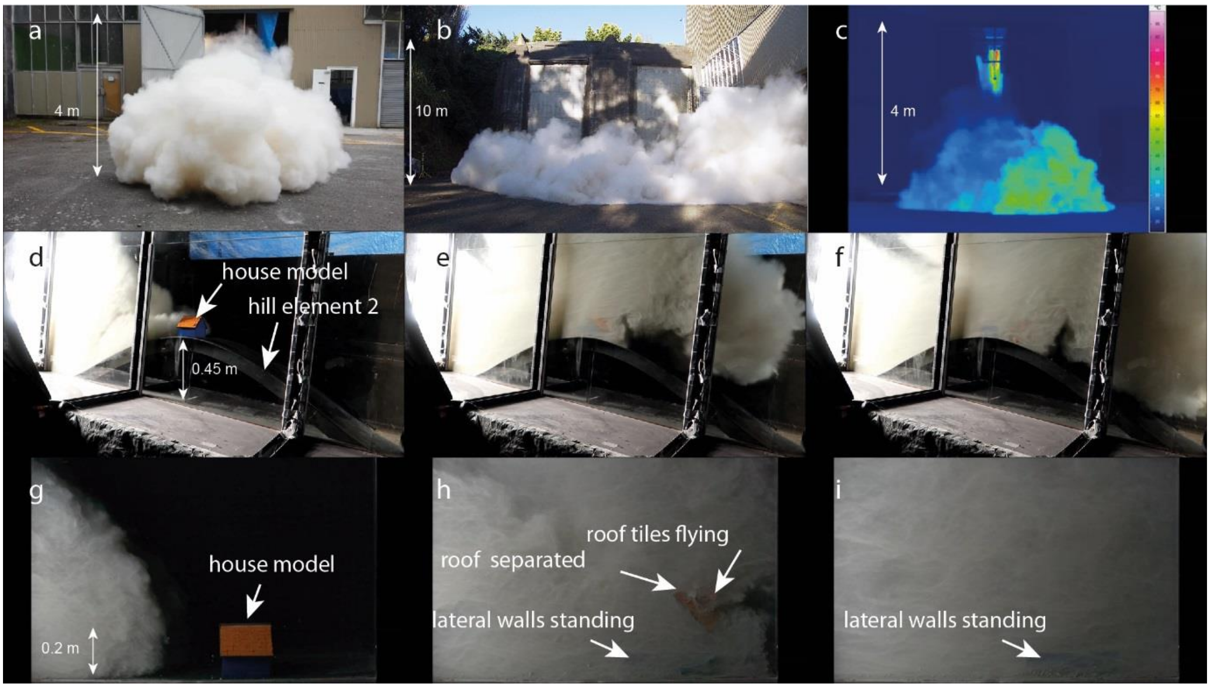

Figure 1. Synthesizing PDCs in large-scale experiments. **a.** Advancing PDC over erodible intermediate roughness substrate. **b.** Side-view of advancing PDC with separating phoenix-cloud. **c.** Still-image of thermal infrared video sequence to measure PDC surface temperature. **d-f.** PDC propagation over hill element and destructible model house. **g-i.** High-speed video sequence of sequential destruction of instrumented model house during PDC propagation over non-erodible fine substrate.

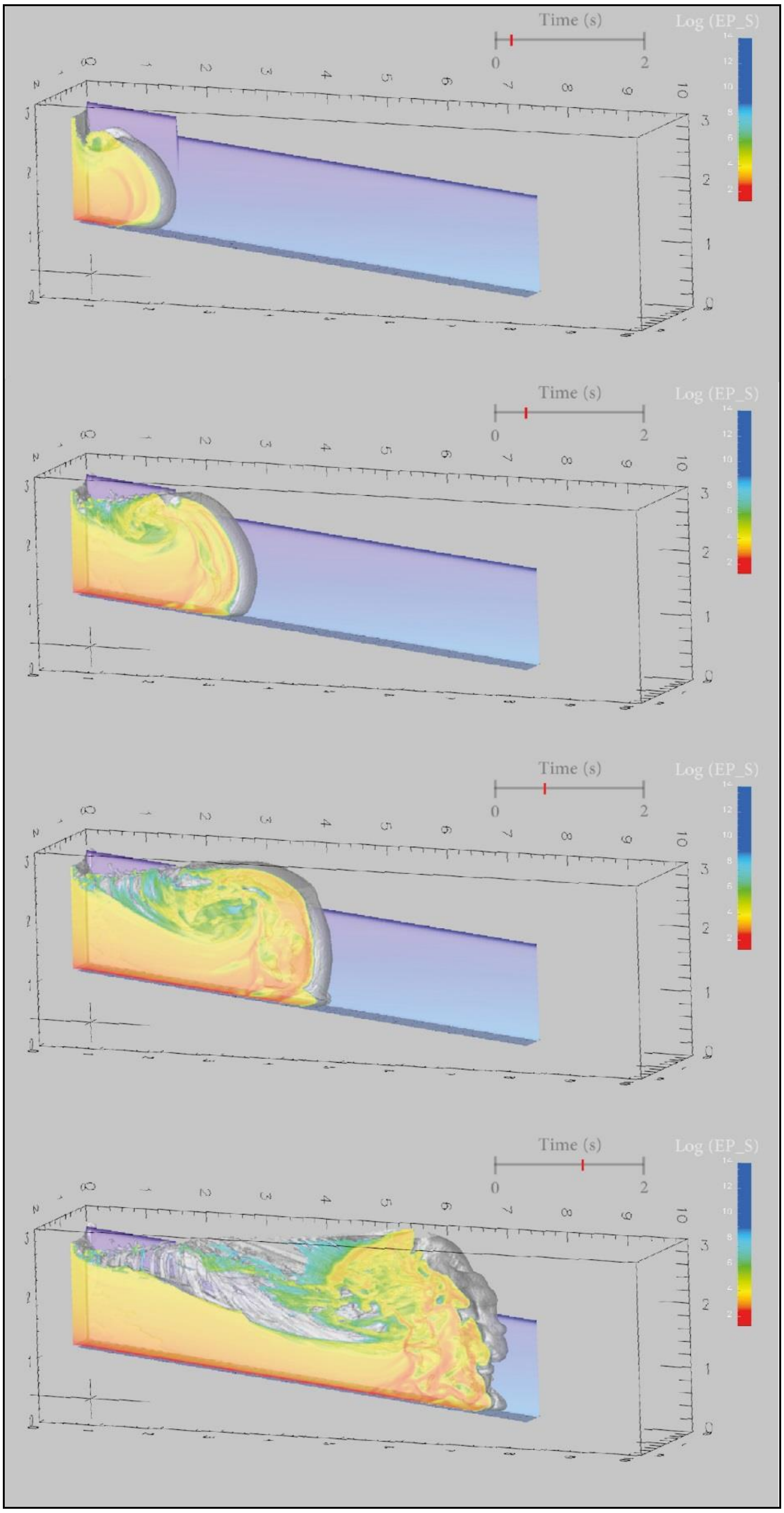

Figure 2. MFIX 3D multiphase simulation of the international PDC benchmark at different times. Contours show particle concentration in a log scale. Note the development of normal density stratification, the development of significant turbulence in the head and wake regions of the PDC, and the absence of high turbulence in the PDC body in contrast to the benchmark.

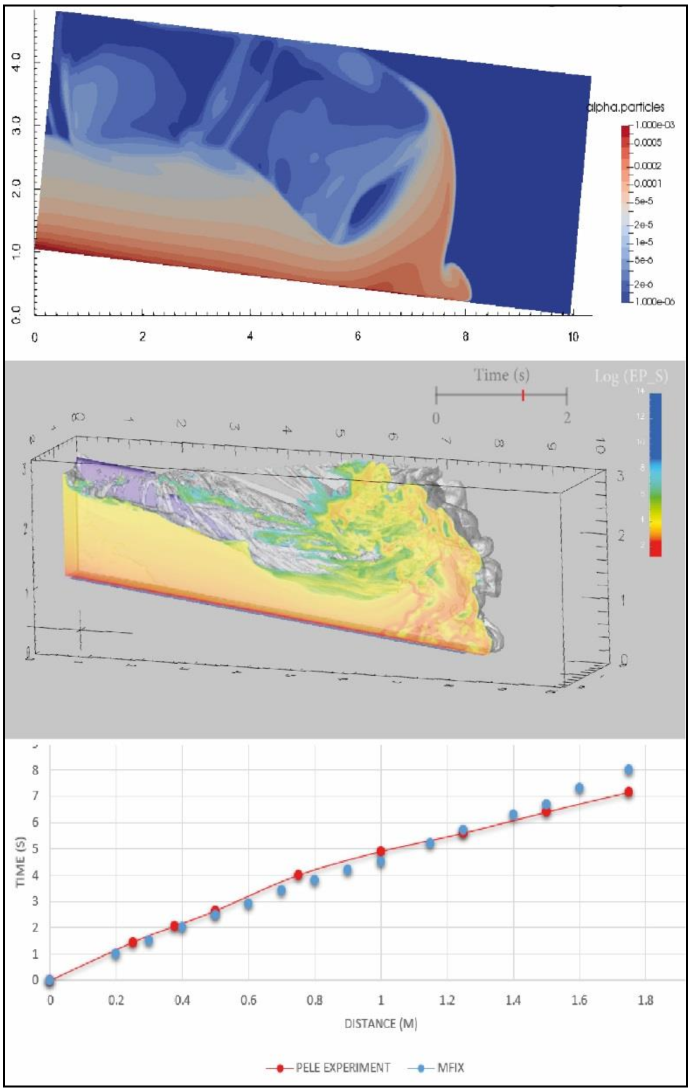

Figure 3. Performance and comparison of fully 3D multiphase simulations against the benchmark. **Top.** Snapshot of KFIX simulation. Note the development of vertical stratification and large-scale turbulence, but the absence of the crucial fine-scale turbulence structure and sediment transport. **Middle.** Snapshot of MFIX simulation. Note the relative natural development of vertical stratification and turbulence structure for the strongly entraining head of the PDC. **Bottom.** Comparison of the flow front kinematics of fully 3D multiphase models (blue symbols) and the benchmark (red symbols). Note the close match of experimental benchmark and numerical solution.

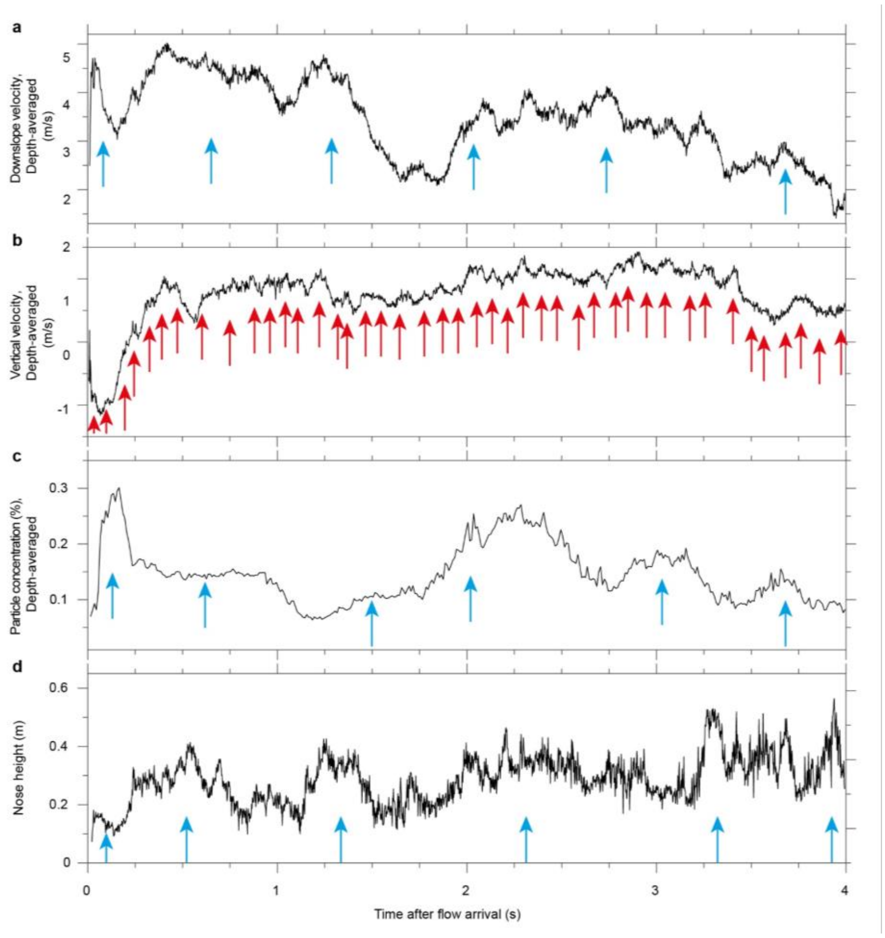

Figure 4. Spontaneous oscillation in pyroclastic surges. Time-series data of characteristic time and length-scales of PDCs. **a.** depth-averaged downstream velocity; **b.** depth-averaged vertical velocity (downward is positive); c. depth-averaged particle volumetric concentration; and d. height of maximum velocity. PDCs self-generate strong low-frequency downstream (blue arrows) and high-frequency (red arrows) downwards-propagating wave-like oscillations of their velocity and concentration fields.

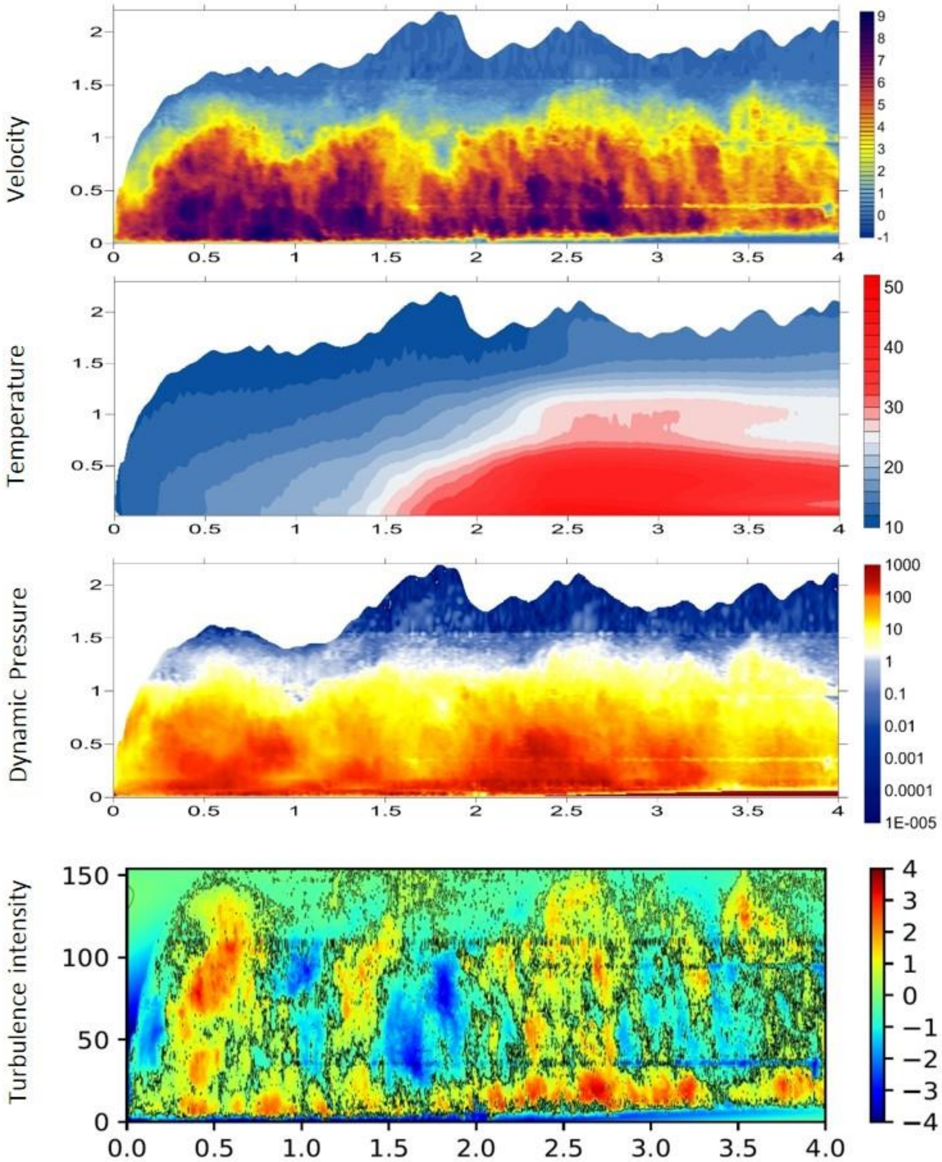

Figure 5. Contour plots of the PDC perils in time and space. Top. Velocity magnitude; note the low-frequency oscillations due to the downstream propagation of the largest eddies, and the high-frequency oscillations in the boundary layer due to mesoscale cluster instabilities inducing sedimentation waves. Second down. Thermal evolution showing the bi-partite PDC structure with a cold first half of the flow that has cooled by entrainment of ambient air and the second half carrying the majority of thermal energy in the flow body. Third down. Dynamic pressure evolution. Note the succession of low-frequency pulses of very high dynamic pressure. These scale to pressures of 10s to 100s of kPa in real-world flows capable of knocking-down strong buildings. Bottom. Turbulence intensity evolution. Note the separation of small high-frequency eddies in the boundary layer (inner layer) and large low-frequency eddies in the turbulent jet region (outer layer).

Tables:

Experiment	**Mass**	**Temperature**	**Fines content**	**Topography**
(name)	(kg)	(°C)	(Wt. %)	
PDC1	1000	ambient	15	Fine, coarse
PDC2	1000	30	15	Fine, coarse
PDC3	1000	120	15	Fine, coarse
PDC4	1000	120	15	Fine, coarse
PDC5	1000	240	15	Fine, coarse
PDC6	1000	30	5	Fine, coarse
PDC7	1000	30	10	Fine, coarse
PDC8	1000	30	20	Fine, coarse
Surge1	125	120	15	Fine
Surge2	125	120	15	Intermediate
Surge3	125	120	15	Coarse
Surge4	125	120	15	Intermediate, hill 1
Surge5	125	120	15	Intermediate, hill2
Surge6	125	120	15	Intermediate, wedge 1
Surge7	125	120	15	Intermediate, house indestructible
Surge8	125	120	15	Intermediate, houses destructible
Surge9	125	120	15	Intermediate, houses destructible
Surge10	300	120	15	Intermediate, houses destructible
Surge11	125	120	15	Fine, non-erodible, benchmark 1
Surge12	125	120	15	Intermediate, benchmark 2
Surge13	125	ambient	15	Intermediate, benchmark 3
Surge 14	125	120	15	Intermediate, benchmark 2 (control)

Table 1. Summary of the conditions of the 24 large-scale experiments conducted in the PERILS project. The starting and boundary conditions were chosen to allow correct dynamic and kinematic scaling to real-world flows, and to incorporate the flow scales of the targeted New Zealand analogue eruptions (i.e. Te Maari 2012, White Island 2012 and 2014, Tarawera 1886). Systematic series of experiments were conducted to constrain natural variations in boundary roughness, temperature, mass flow rate, temperature, as well as the occurrence of natural and man-made obstacles (hills, cliff-like wedges, indestructible and destructible scaled model houses).

Model	Captures runout distance correctly	Captures velocity evolution	Captures turbulence structure	Captures dynamic pressure evolution
Existing models tested during PERILS project				
1-D models	no	no	no	no
2-D models	partially	no	no	no
3-D KFIX	mostly	no	yes (but incorrect)	yes (but incorrect)
3-D MFIX	mostly	no	yes (but incorrect)	yes (but incorrect)
Newly developed models during PERILS project				
3-D MFIX-DEM	yes, but only dense part	yes, but only dense part	not intended	not intended
New 2-D Analytical	not intended	yes	yes	no(t) yet

Table 2. Summary of performance of existing PDC models with regards to essential hazard assessment requirements. Note that only 3D multiphase models and new advanced models capture the runout kinematics correctly and that even the most advanced multiphase models (MFIX and KFIX), while simulating the internal velocity, dynamic pressure and turbulence structure, currently fail to reproduce essential elements of the international PDC benchmark developed in the PERILS project.

Appendices

Appendix I

Breard, E., Lube, G., Jones, J., Dufek, J., Cronin, S., Valentine, G., Moebis, A. (2016) Coupling of turbulent and non-turbulent flow regimes within pyroclastic density currents*. Nature Geoscience*, 9, 767-771.

Appendix II

Breard, E., Lube, G., Jones, J., Dufek, J., Cronin, S., Valentine, G., Moebis, A. (2016) Coupling of turbulent and non-turbulent flow regimes within pyroclastic density currents*. Nature Geoscience*, 9, 767-771. Supplementary Material

Appendix III

Breard, E.C.P., Lube, G. Inside pyroclastic density currents – uncovering the enigmatic flow structure and transport behaviour in large-scale experiments. *Earth and Planetary Science Letters*, 2017, 458, 22-36.