EXTENDED DATA

Supplementary Figures

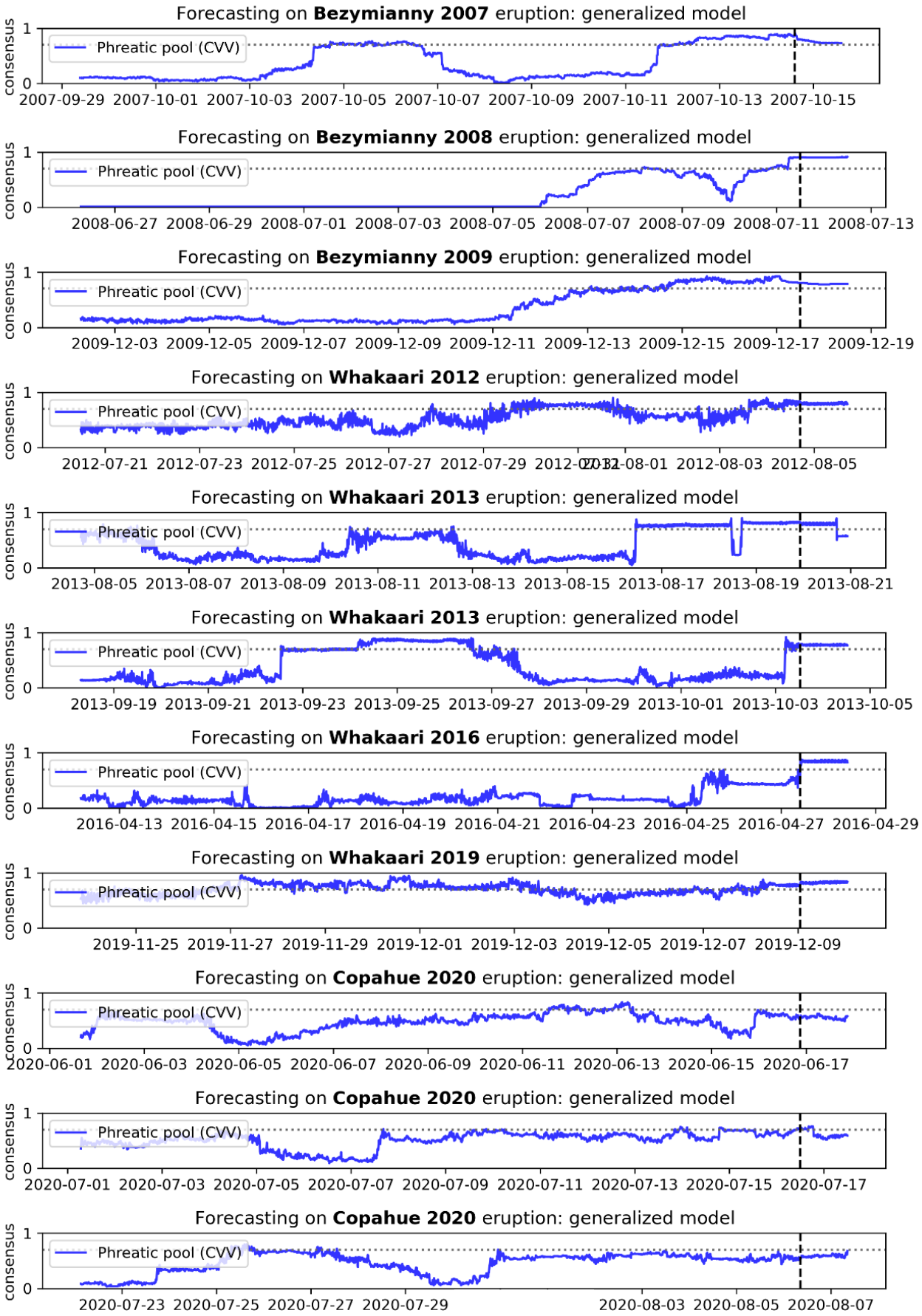


Figure S1. Forecast using phreatic generalized model trained on CVV in Whakaari and Bezymianny (pools are indicated in the legend, eruptions are indicated in the titles, and eruption times by the black dash line). The forecasts correspond to the models tested on eruptions that were not included in the training (out-of-sample). A reference threshold of .7 is indicated with the dash line.

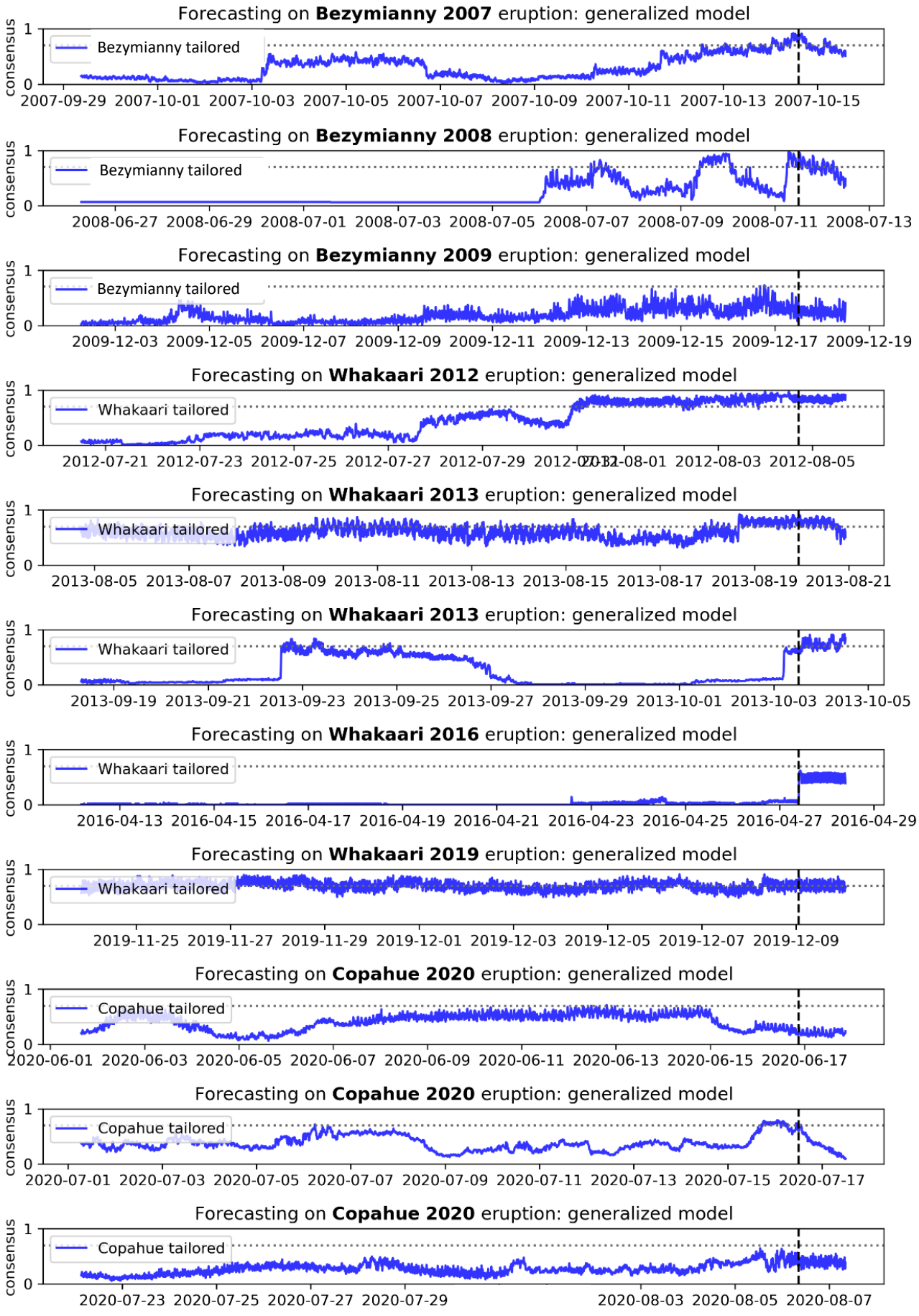


Figure S2. Forecast using tailored models prior to 13 eruptions in Whakaari, Bezymianny and Copahue (pools are indicated in the legend, eruptions are indicated in the titles, and eruption times by the black dash line). The forecasts correspond to the models tested on eruptions that were not included in the training (out-of-sample). A reference threshold of .7 is indicated with the dash line.

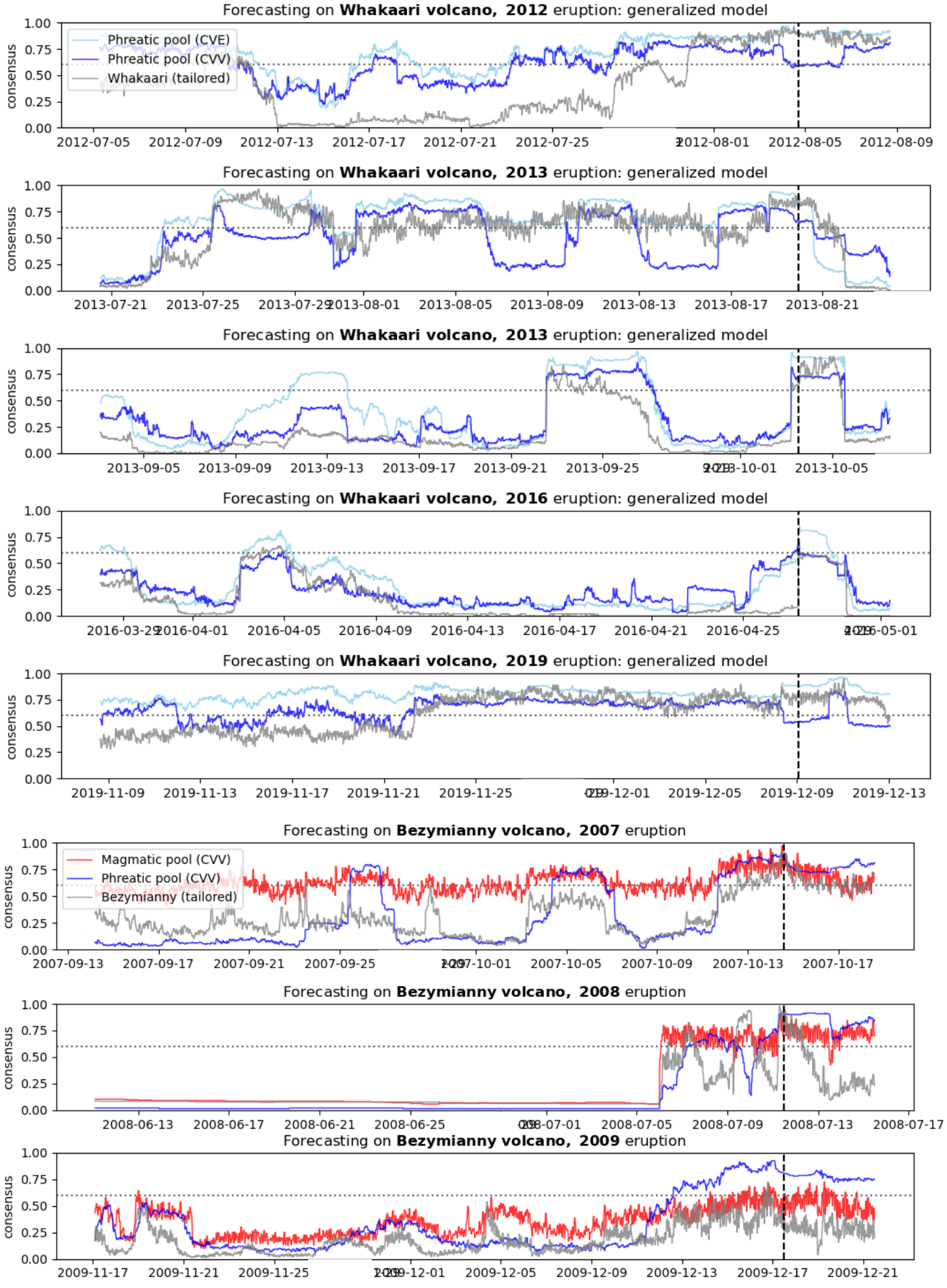
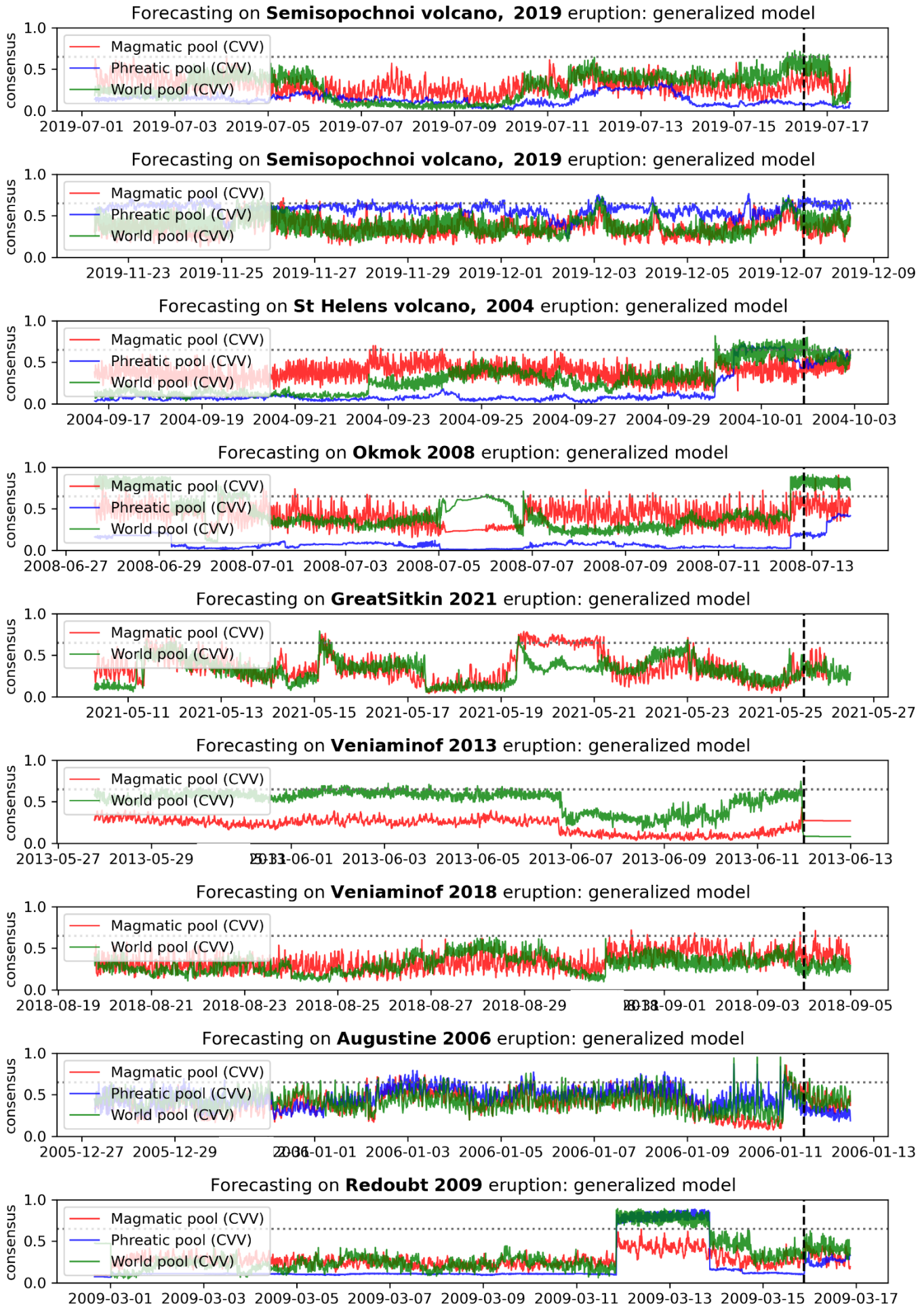


Figure S4. Forecast for different models prior to six eruptions considered in the Whakaari and Bezymianny eruptions (pools are indicated in the legend, eruptions are indicated in the titles, and eruption times by the black dash line). The forecasts correspond to the models tested on eruptions that were not included in the training (out-of-sample). This value is arbitrary, and the performance metrics of the models (described in the next figures) are calculated for one hundred thresholds in the range [0, 1].


Forecasting on **Semisopochnoi volcano, 2019** eruption: generalized model
Magmatic pool (CVV)
Phreatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2019-07-01 2019-07-03 2019-07-05 2019-07-07 2019-07-09 2019-07-11 2019-07-13 2019-07-15 2019-07-17
Forecasting on **Semisopochnoi volcano, 2019** eruption: generalized model
Magmatic pool (CVV)
Phreatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2019-11-23 2019-11-25 2019-11-27 2019-11-29 2019-12-01 2019-12-03 2019-12-05 2019-12-07 2019-12-09
Forecasting on **St Helens volcano, 2004** eruption: generalized model
Magmatic pool (CVV)
Phreatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2004-09-17 2004-09-19 2004-09-21 2004-09-23 2004-09-25 2004-09-27 2004-09-29 2004-10-01 2004-10-03
Forecasting on **Okmok 2008** eruption: generalized model
Magmatic pool (CVV)
Phreatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2008-06-27 2008-06-29 2008-07-01 2008-07-03 2008-07-05 2008-07-07 2008-07-09 2008-07-11 2008-07-13
Forecasting on **GreatSitkin 2021** eruption: generalized model
Magmatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2021-05-11 2021-05-13 2021-05-15 2021-05-17 2021-05-19 2021-05-21 2021-05-23 2021-05-25 2021-05-27
Forecasting on **Veniaminof 2013** eruption: generalized model
Magmatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2013-05-27 2013-05-29 2013-06-01 2013-06-03 2013-06-05 2013-06-07 2013-06-09 2013-06-11 2013-06-13
Forecasting on **Veniaminof 2018** eruption: generalized model
Magmatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2018-08-19 2018-08-21 2018-08-23 2018-08-25 2018-08-27 2018-08-29 2018-09-01 2018-09-03 2018-09-05
Forecasting on **Augustine 2006** eruption: generalized model
Magmatic pool (CVV)
Phreatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2005-12-27 2005-12-29 2006-01-01 2006-01-03 2006-01-05 2006-01-07 2006-01-09 2006-01-11 2006-01-13
Forecasting on **Redoubt 2009** eruption: generalized model
Magmatic pool (CVV)
Phreatic pool (CVV)
World pool (CVV)
consensus
1.0
0.5
0.0
2009-03-01 2009-03-03 2009-03-05 2009-03-07 2009-03-09 2009-03-11 2009-03-13 2009-03-15 2009-03-17

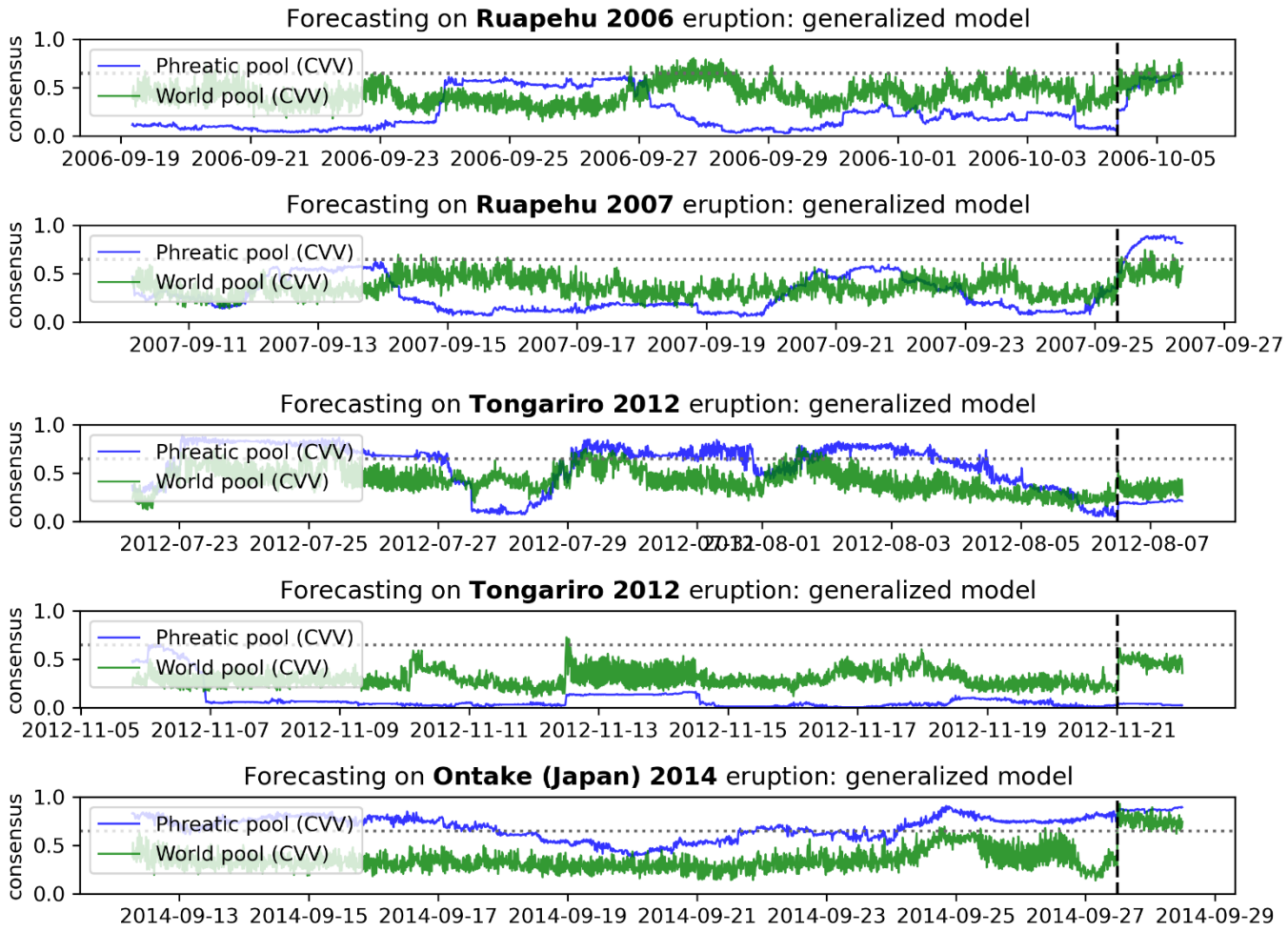


Figure S3. Forecast using generalized models trained on CVV prior to 14 eruptions (pools are indicated in the legend, eruptions are indicated in the titles, and eruption times by the black dash line). The forecasts correspond to the models tested on eruptions that were not included in the training (out-of-sample). A

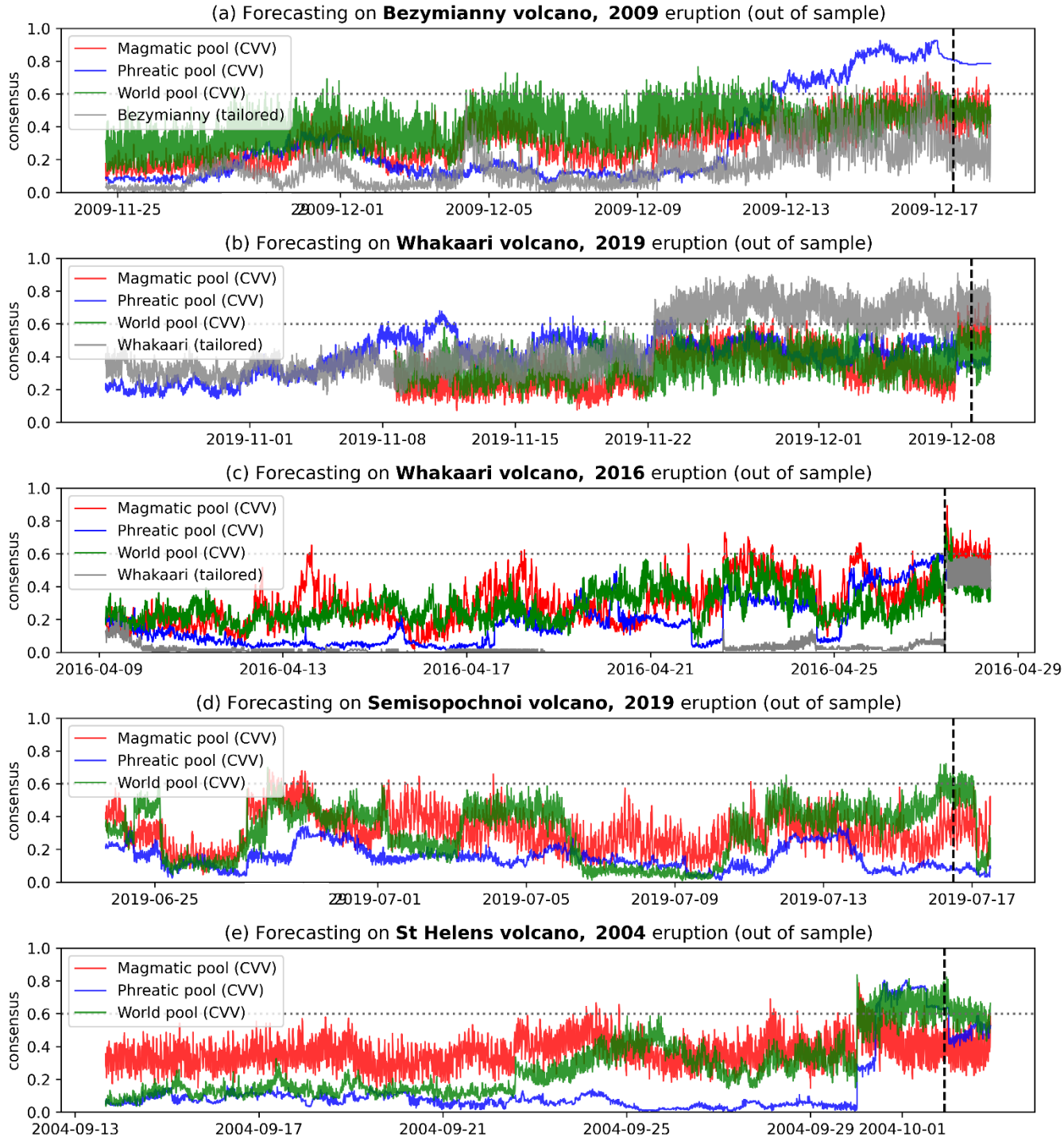


Figure S5. Equivalent to Figure 2 but plotting the full consensus value (without the 2-day rolling 90th percentile for the consensus as in Figure 2). Caption for Figure 2: 'Forecast for different models prior to six eruptions considered in the catalog (pools are indicated in the legend, eruptions are indicated in the titles, and eruption times by the black dash line). The forecasts correspond to the models tested on eruptions that were not included in the training (out-of-sample). A threshold of 0.7 is indicated as a reference (dashed gray line). This value is arbitrary, and the performance metrics of the models (described in the next figures) are calculated for one hundred thresholds in the range [0, 1].'

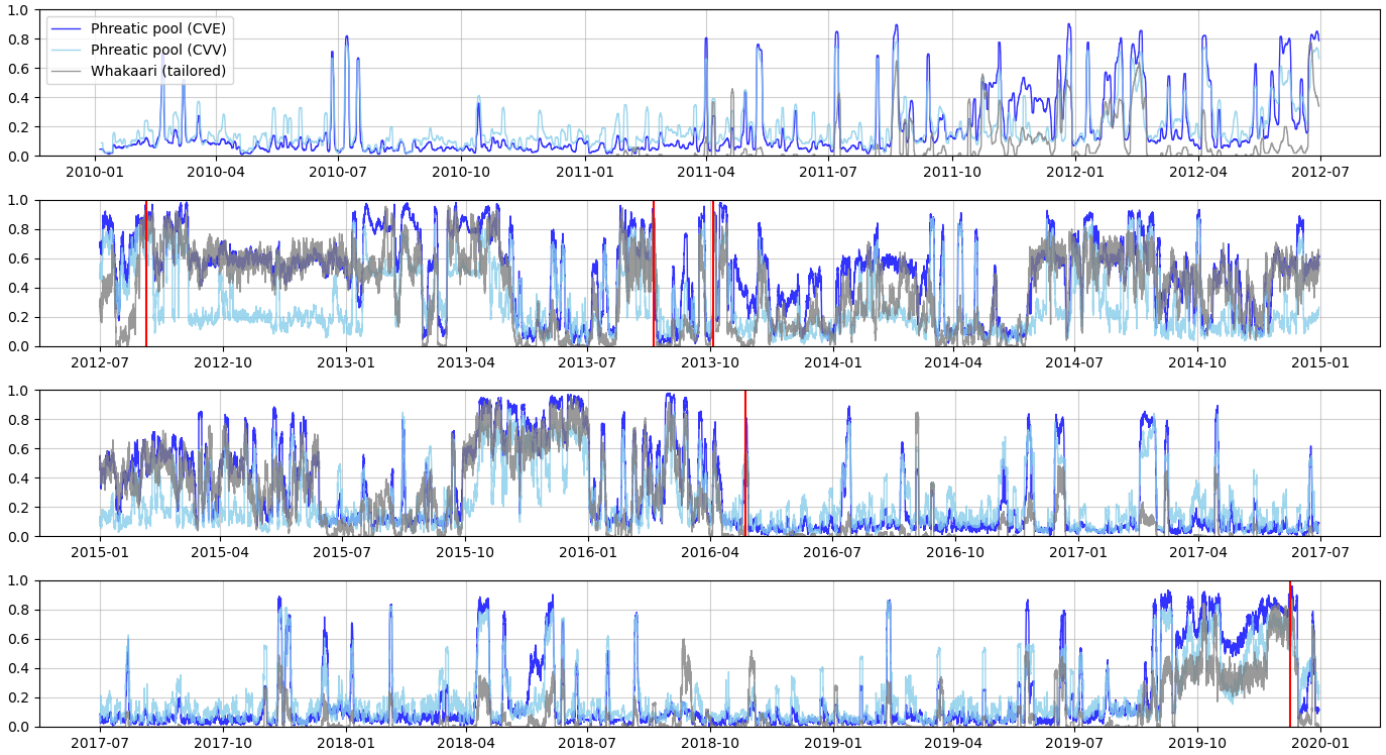


Figure S6. Forecast over the whole Whakaari record. Forecast models are indicated in the legend (eruption times by the red line). The forecasts correspond to the models tested on data that were not included in the training (out-of-sample).

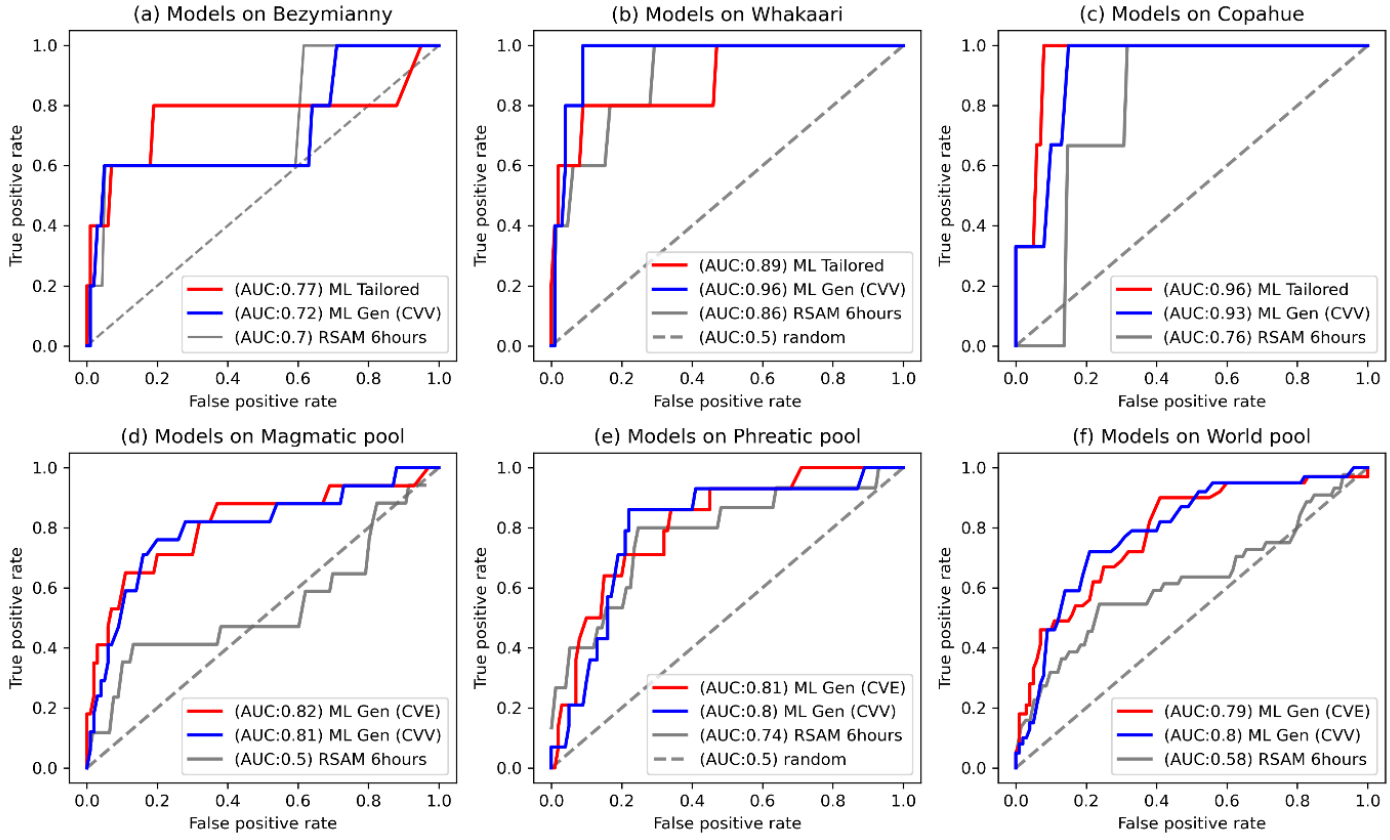


Figure S7. ROC curves (Receiver Operating Characteristic) and AUC (Area Under the Curve) that illustrates and compare the performance of different forecasting models train on machine learning (ML), and a simplified forecaster based on real time seismic amplitude measurements (RSAM) using thresholds (see Methods). Three RSAM version correspond to a 6 hours rolling median (2-day and 10 minutes, which correspond to the instantaneous values given our data streams sample rate, were tested and the one with best performance is shown). Subplots (a) to (c) compare performance over tailored forecasters for Bezymianny, Whakaari and Copahue. Subplots (d) to (f) compare performance over generalized forecasters for the magmatic pool, the phreatic pool, and the world pool. The diagonal line represents a random model, and the AUC in the legends indicates the area under the curve. Each point on the ROC curve corresponds to a threshold and provides information about the corresponding true positive rate (sensitivity, Y-axis) and false positive rate (1-specificity, X-axis). Performance of a random classifier, one that assigns labels to data points randomly, is indicated by the diagonal dash line and corresponding 0.5 AUC.

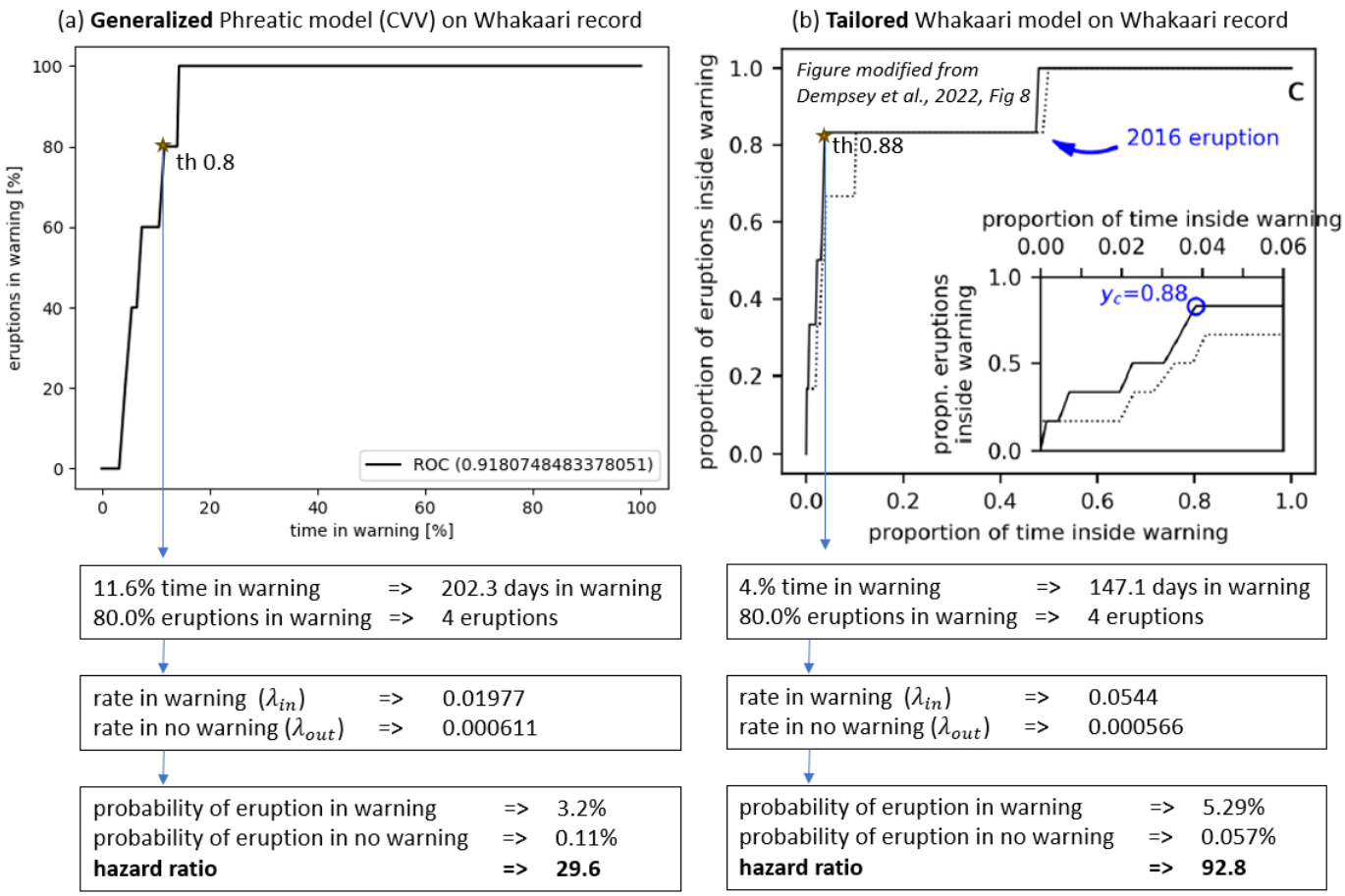


Figure S8. Conditional probabilities and hazard rate estimated for (a) generalized Phreatic model and (b) tailored Whakaari model, both tested on the Whakaari record (10 years) (see Methods for details).

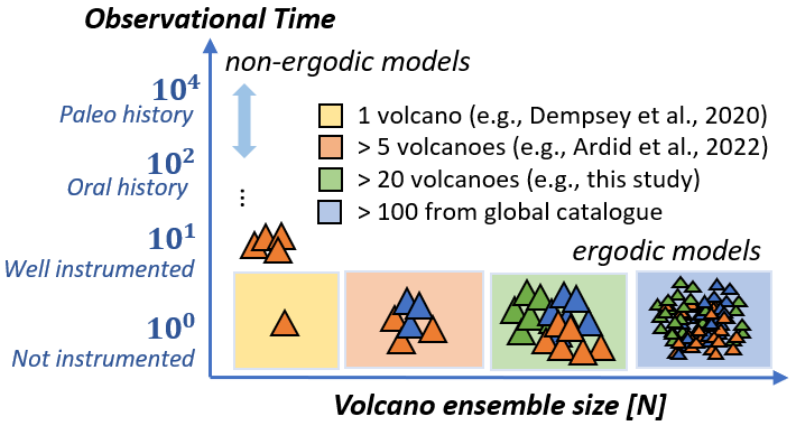


Figure S9. Diagram shows the ensemble size of volcanoes used in global forecasting models of volcanic activity. Ergodic models states that observations drawn from a large enough ensemble of volcanoes contain enough information to approximate future behavior at a target volcano outside the subset. However, volcanic systems are not perfectly ergodic, meaning that past observations from one volcano may not be sufficient to predict future behavior at another volcano. To address this limitation, non-ergodic models have been developed that explicitly account for the unique characteristics of each volcano.

Figure from: *Dempsey, D. E., Kempa-Liehr, A. W., Ardid, A, ... & Cronin, S. J. (2022). Evaluation of short-term probabilistic eruption forecasting at Whakaari, New Zealand. Bulletin of Volcanology, 84(10), 91.*

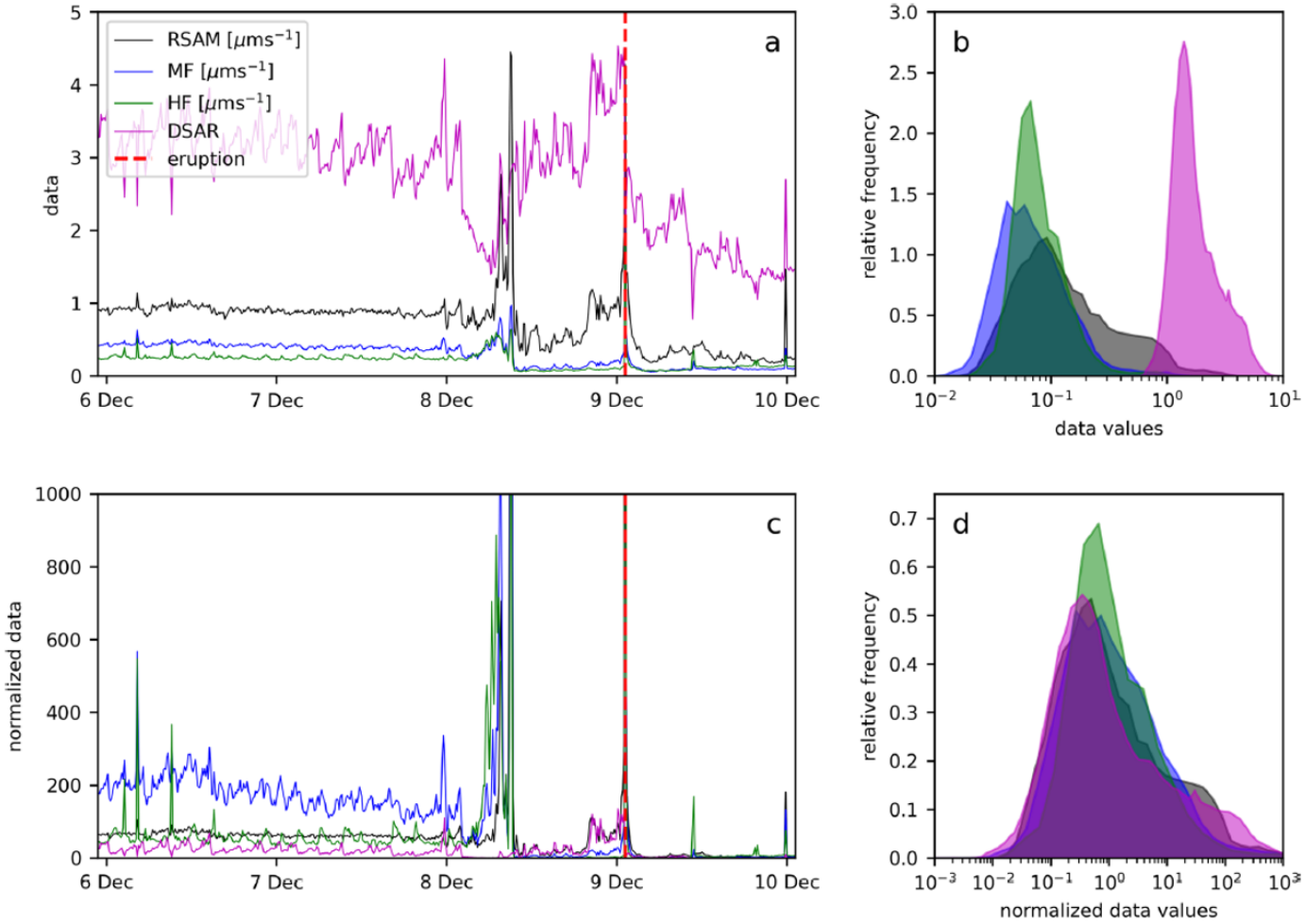


Figure S10. The figure is extracted from Dempsey et al., 2022, and it illustrates the effects of z-score normalization on the 10 years of Whakaari record across the four data streams RSAM, MF, HF, and DSAR. (a) Data normalization of input: Time series data before and after the 2019 eruption (indicated by the red dashed line): RSAM (black), MF (blue), HF (green), DSAR (magenta). (b) Distribution histograms displaying all data values throughout the 10.5-year study period. (c) Time series data normalized across the same time span as in (a). (d) Distribution histograms of data post z-score normalization.

Supplementary Tables

(a) AUC	Whak.	Bezy.	Cop.	Magma.	Phrea.	World	Mean
ML tailored	0.89	0.77	0.96				0.87
ML Gen CVV	0.96	0.75	0.93	0.81	0.80	0.80	0.84
RSAM 6h	0.86	0.70	0.76	0.50	0.74	0.58	0.69

(b) AOC	Whakaari	Bezymianny	Copahue	Magmatic	Phreatic	World	Mean
ML tailored	0.11	0.23	0.04				0.13
ML Gen CVV	0.04	0.25	0.07	0.19	0.20	0.20	0.16
RSAM 6h	0.14	0.30	0.24	0.50	0.26	0.42	0.31

Table S1. AUC and AOC values for the forecasting models depicted in Figure 3 (ML: Machine Learning; RSAM: Real Time Seismic Amplitude Measurement for 6 hours average). Forecaster models include tailored models for Whakaari (Whak.), Bezymianny (Bezy.), Copahue (Cop.), as well as Generalized Magmatic (Magma.), Phreatic (Phrea.), and World pools. The "Mean" column is the average AUC across all models for each row.

Volcano	*Country*	*Station*	*Network*	*# erup.*	*Type of erup.*	*Eruptions year*	*Record years*
Pavlof	Alaska, USA	PVV 4 km	AV	3	Magmatic	14, 14,16	2 .5
Veniaminof	Alaska, USA	VNSS 5.3 km	AV	2	Magmatic	13,18	4
Bezymianny	Kamchatka, Russia	BELO 1 km	YC	3	Magmatic	07,07,07	1
Whakaari	New Zealand	WIZ 500 m	NZ	5	Phreatic	12,13,13, 16,19	11
Tongariro	New Zealand	KRVZ 2 km	NZ	2	Phreatic	12,12	14
Ruapehu	New Zealand	FWVZ 2.5 km	NZ	3	Phreatic	06,07	14
Redoubt	Alaska, USA	REF 2.5 km	AV	1	Magmatic	09	.3
Augustine	Alaska, USA	AUH 1 km	AV	1	Magmatic	06	1
Great Sitkin	Alaska, USA	GSTR 4.5 km	AV	3	Magmatic	21	2
Semisipochnpo	Alaska, USA	CETU 7 km	AV	2	Magmatic	19 (2)	.5
Okmok	Alaska, USA	OKWR 5 km	AV	1	Magmatic	08	1
St Helens	USA	SHW 1 km	AV	1	Magmatic	04	1
Telica	Nicaragua	TBTN 0.5 km	6D	3	Magmatic	11,12,13	2
Poas	Costa Rica	CRPO 0.3 km	OV	56			1
Turrialba	Costa Rica	VTUN 0.2 km	OV	2		14,15	1.5
Rincon de la Vieja	Costa Rica	VRLE 2 km	OV	3		14,15,17	3
Montserrat	UK	MBGH 3.6 km	NA	2		04,05	2
Eyjafjallajökull	Iceland	GOD 7.4 km	NA	1	Magmatic	10	.2
Holuhraun	Iceland	VONK 50 km	NA	1	Magmatic	14	.5
Ontake	Japan	ONTA 2 km	NA	1	Phreatic	14	1.5
Cordon Caulle	Chile	PHU	TC	1		11	1
Kawah Ijen	Indonesia	POS 1 km	ID	1	Phreatic	13	.5
Copahue	Chile/ Argentina	COP		3	Phreatic	20 (3)	.8
Piton de Fournaise	France	BOR 0.2 km	PF	16			

Table S2. Basic information on volcanoes included in this study indicating the country, the station and network used and its distance to the crater, the number of eruptions recorded, the type and year of eruptions, the length of the seismic record analysed, and the % of continuous data on the record.