Chapter 23

Global distribution of volcanic threat

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23.1 Calculating threat

Within the country profiles (Appendix B) individual volcanoes are ranked by risk; however, it would also be beneficial to understand the total volcanic threat borne by each country.[1] We therefore develop two measures of volcanic threat[2] to enable country ranking. The measures variously combine the number of volcanoes in the country, the size of the total population living within 30 km of volcanoes and the mean hazard score, which is calculated for each country from the relevant volcano hazard scores (VHI). We develop and use a 'Pop30' score, which calculates the number of persons, using Landscan 2011 (Bright et al., 2012) data, within a given country living within 30 km of one or more volcanoes with known or suspected Holocene activity. Note that 30 km is chosen as most fatal incidents that are caused directly by volcanic hazards fall within this distance of volcanoes [see Chapter 4]. VPI_{30}, supplied by VOTW4.0 (Siebert et al., 2010) based on the analysis of Ewert & Harpel (2004) and Siebert et al. (2008), is specific to a volcano and thus cannot be used in place of Pop30 as this would double count persons living within 30 km of neighbouring volcanoes.

We first develop a simple measure of volcanic threat to life country by country based on the number of active volcanoes, an estimate of exposed population and the mean hazard index of the volcanoes. The sum of this measure (Measure 1) for all countries is itself a simple measure of total threat and so the distribution of threat between countries can be evaluated and they can be placed in rank order using a normalised version of Measure 1. However, this measure of threat distribution can be misleading because an individual country may vary considerably in the proportion of its population that is exposed to the volcanic threat. Volcanic threat is very much higher in relation to its economy and population in a small island nation with an active volcano than in larger countries even if they have many volcanoes. Nation states vary greatly in their populations from, for example, China with 1.3 billion people (<1% exposed) to St. Kitts and Nevis in the Caribbean with only 54,000 people (100% exposed). Thus we need a measure of threat that reflects its importance to each country. Here we develop a measure (Measure 2) that rates the importance of volcanic threat in each country based on the proportion of the

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[1] The phrase "country" is used here to denote both countries and some territories, e.g. overseas territories are classed separately to the nation state.

[2] We use threat rather than risk to describe these measures. Threat is defined here as the combination of hazard and exposure. Risk requires assessment of vulnerability, which has many different influences. Some jurisdictions can have high threat but low risk because steps have been taken to reduce the vulnerability (for example through having a well managed and equipped volcano observatory).

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population that is exposed: numbers of volcanoes and the total exposed population are not included in the calculation.

There are some caveats and limitations to our measures. Clearly the measures are not a full evaluation of risk and in particular do not take account of vulnerability. In general populations in high income countries are less vulnerable to loss of life than in low-income countries for a wide variety of reasons. Thus a risk measure might usefully include measures of vulnerability to natural hazards, such as GDP, the Human Development Index (HDI) and the World Risk Index (WRI). For volcanoes these general indicators of vulnerability might not be adequate; for example a measure specific to volcanic hazard should include the existence and resourcing of a volcano observatory. There was not time in this study to explore possible ways that our measures might be combined with vulnerability indicators. If the measures of country volcanic threat were to be combined with vulnerability measures there would be an issue of how to weight the vulnerability indices relative to the hazard and exposure data.

This global assessment of volcanic threat must be understood as a tool for relative ranking based on coarse global data. This approach cannot substitute for focussed local assessments of hazard and risk, as vital information such as topography, which exerts strong controls on hazard emplacement and population exposure, cannot be incorporated into our assessments at present.

23.2 Data completeness

The assessment of threat per country is partially dependent on the hazard classification for the constituent volcanoes. About 20% of the world's volcanoes have been assigned a hazard score, VHI, on the basis of their eruption records [see Chapter 22 and individual country profiles for results]. The use of these classified volcanoes to inform global threat distribution limits the number of countries that can be analysed, with approximately half of the countries having no classified volcanoes.

Hazardous phenomena and eruption size are somewhat associated with volcano morphology, as it is the nature of eruptions which largely determines volcano structure. The volcano type can therefore be used to provide a very approximate indicator of the hazard level at unclassified volcanoes. All volcanoes are grouped into similar types, as indicated by their morphology (the classification of types is adapted from Jenkins et al. (2012), Table 23.1), and the mean hazard scores of the classified volcanoes of each volcano type can be used as proxies for the unclassified volcanoes.

Table 23.1 Volcano type classification modified after Jenkins et al. (2012).

Volcano type group	Includes VOTW4.0 volcano types
Caldera(s)	Caldera, Caldera(s), Pyroclastic shield
Large cone(s)	Complex, Compound, Somma, Stratovolcano, Stratovolcano(es), Volcanic Complex
Shield(s)	Shield, Shield(s)
Lava dome(s)	Lava dome, Lava dome(s)
Small cone(s)	Cinder cone, Cinder cones, Cones, Cone, Crater rows, Explosion craters, Fissure vent(s), Lava cone, Maar, Maar(s), Pyroclastic cone(s), Scoria cones, Tuff cones, Tuff rings, Volcanic field
Hydrothermal field	Hydrothermal field, Hydrothermal field(fumarolic)
Submarine	Submarine
Subglacial	Subglacial

Substitution of proxy VHI scores at unclassified volcanoes in practice introduces rather limited uncertainty with most of these volcanoes being scored over a narrow range, with the key drivers of threat ranking being the number of volcanoes and the size of the population within 30 km.

The following measures therefore use a combination of data from classified and unclassified volcanoes. The percentage of volcanoes per country which are classified and on which the ranking is partially controlled by is presented to provide a sense of data quality.

23.3 Volcanic threat to life by country (Measure 1)

A measure of overall threat in a country is obtained using the following equation:

$$Overall\ threat = mean\ VHI\ x\ number\ of\ volcanoes\ x\ Pop30$$

The sum of the resultant scores for all countries with active volcanoes is an indicator of total global volcanic threat. The countries are normalised by this total and ranked as a percentage of the total global threat:

$$\frac{Overall\ threat\ score}{Total\ global\ threat\ score} x\ 100$$

Indonesia scores the highest level of threat and accounts for about two thirds of the total score (Table 23.2) as a consequence of the number of volcanoes (142), extent of population exposure (nearly 69 people million live within 30 km of a Holocene volcano) and the number of Hazard Level II and III volcanoes. The Philippines, which has the second highest rank has just 16% of the score of Indonesia. The Philippines has a similar mean VHI to Indonesia, but has about a third of the number of volcanoes (47) and less than half the exposed population (still over 30 million people). Japan ranks third for overall threat to life, with a comparatively small exposed population of about 9 million, reflecting concentration of the population in Japan in coastal cities and communities. All countries ranked in the top ten for overall volcanic threat have exposed populations of over 4 million.

The global distribution of this volcanic threat is illustrated in Figure 23.1, where the warming of the colours indicates increasing risk rank.

Table 23.2 The top 20 countries with highest overall volcanic threat to life. The percentage classified is the percentage of volcanoes in the country which have a classified VHI. The normalised percentage represents the country's threat as a percentage of the total global threat.

| % classified	Rank	Country	Normalised %	% classified	Rank	Country	Normalised %
40	1	Indonesia	66.0	18	11	Papua New Guinea	0.4
17	2	Philippines	10.6	37	12	Nicaragua	0.4
38	3	Japan	6.9	33	13	Colombia	0.4
10	4	Mexico	3.9	0	14	Turkey	0.4
2	5	Ethiopia	3.9	50	15	Costa Rica	0.3
17	6	Guatemala	1.5	0	16	Taiwan	0.2
31	7	Ecuador	1.1	8	17	Yemen	0.2
43	8	Italy	0.9	14	18	Chile	0.2
14	9	El Salvador	0.8	29	19	New Zealand	0.2
5	10	Kenya	0.4	0	20	China	0.2
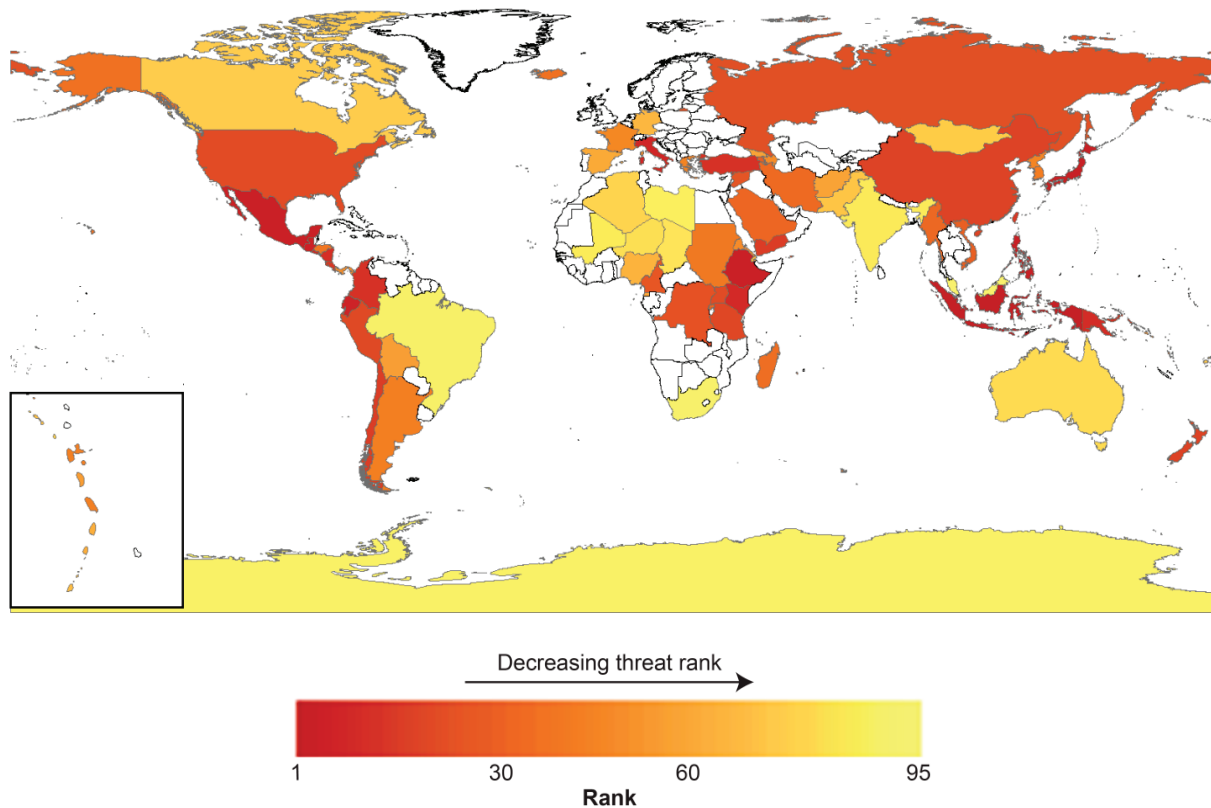
Figure 23.1 Global distribution of volcanic threat to life. Inset map shows the West Indies.

23.3.1 Distribution of volcanic threat and fatalities

Auker et al. (2013) undertook an analysis of fatality distributions, and found that Indonesia, Melanesia and the Philippines have had the highest number of fatalities (with the largest ten disasters removed). The regions considered in Table 23.3 are amended from the standard regions of VOTW4.0, to correspond with those used in Auker et al. (2013) incorporating the volcanic threat data for only those countries in which fatalities are recorded. Indonesia's history of fatal incidents corresponds well with the overall volcanic threat, and indeed ten regions only change in rank by a maximum of two positions, indicating a reasonable correlation between the overall threat and occurrence of fatalities.

Table 23.3 Regional ranking of volcanic fatalities (from Auker et al. (2013) and the threat measure.*The regions used here comprise only the countries or territories named, allowing for comparison of ranks with the fatality data. The percentage of fatalities per region with the largest ten disasters removed is shown (Auker et al., 2013).

Overall threat rank	Region* (Country)	Fatalities rank	% of fatalities
1	Indonesia (Indonesia)	1 (=)	38
2	Philippines and China (Philippines, SE China)	3 (-1)	10
3	Japan (Japan)	6 (-3)	8
4	Mexico and Central America (Costa Rica, El Salvador, Guatemala, Mexico, Nicaragua)	4 (0)	10
5	Africa and Red Sea (Cameroon, DRC, Ethiopia, Tanzania)	9 (-4)	3
6	South America (Chile, Colombia, Ecuador, Peru)	7 (-1)	5
7	Mediterranean (Italy, Greece, Turkey)	5 (+2)	9
8	Melanesia (Papua New Guinea, Solomon Islands, Vanuatu)	2 (+6)	11
9	New Zealand to Fiji (New Zealand, Tonga)	11 (-2)	0.53
10	North America (Alaska, Canada, USA-contiguous states)	12 (-2)	0.11
11	Atlantic Ocean (Azores, Canary Islands, Cape Verde)	10 (+1)	0.90
12	Kuril Islands and Kamchatka (Russia)	14 (-2)	0.07
13	Indian Ocean (Comoros, French territories)	15 (-2)	0.05
14	Iceland (Iceland)	16 (-2)	0.02
15	West Indies (Martinique and Guadeloupe, Montserrat, St. Vincent and the Grenadines)	8 (+7)	4
16	Hawaii (Hawaii)	13 (+3)	

The correlation between overall threat and regional distribution of fatalities where the largest ten disasters are included is less clear, with just five regions being of similar rank (within 2 positions). These high fatality events can significantly alter the regional ranking, and are shown by Auker et al. (2013) to dominate the fatalities record in several regions, obscuring the record of smaller events.

23.4 Proportional threat – Measure 2

The calculation of volcanic threat in Measure 1 considers the total number of people exposed and the number of volcanoes within a country. We have developed a second measure that is independent of country size but indicates how important volcanic risk is to each country. The following measure (Measure 2) is used:

$$Proportional\ threat = \frac{Pop30}{TPop}\ x\ Mean\ VHI$$

The countries in which volcanic threat is highly significant in terms of the proportion of population exposed are small-area nations. The top 20 countries or territories ranked most highly using this measure are dominantly countries of Central and South America and small island nations or territories. All islands of the West Indies, with the exception of the Dutch Antilles, are ranked in the top 20, as most have comparatively high mean hazard scores and significant proportions of their populations living within 30 km of a volcano. The Dutch Antilles ranks at position 24, with several non-volcanic islands located in the southern Caribbean Sea off the coast of Venezuela.

Table 23.4 The top 20 countries or territories ranked by an index of proportional threat: the product of the proportion of the population exposed per country and the mean VHI.

% Classified	Rank	Country	% Classified	Rank	Country
100	1	UK- Montserrat	17	11	Guatemala
100	2	St. Vincent & Grenadines	0	12	Sao Tome & Principe
100	3	France – West Indies	33	13	Canary Islands
0	4	St. Kitts & Nevis	50	14	Grenada
0	5	Dominica	43	15	Vanuatu
29	6	Azores	37	16	Nicaragua
0	7	St. Lucia	0	17	Samoa
0	8	UK – Atlantic	0	18	American Samoa
14	9	El Salvador	0	19	Armenia
50	10	Costa Rica	17	20	Philippines

There are some strong caveats about the rankings in Table 23.4 and the information should not be over-interpreted. As emphasised earlier the assessment is quite crude and takes no account of important local factors, including the detailed distribution of populations and, the specifics of the particular volcano in a small island state. Here it is even more important not to conflate the

threat measure with risk. Many of the jurisdictions in Table 23.4 are small territories with only one volcano and so a complete assessment of risk and ranking against other jurisdictions would need to take account of many local factors that affect vulnerability. In some jurisdictions the threat can be ranked high but the risk is in fact low and vice versa; the relationship between threat and risk is now explained.

Montserrat appears at the top of the list but such a ranking would be highly misleading if the measure were used to imply high risk. The Soufriere Hills Volcano, Montserrat, has a well-established volcano observatory and the population has been relocated to the north of the island, which is now at very low risk because of the intervening topography. Thus, even though the population all live within 30 km, vulnerability and hence risk is actually very low. The volcanic threat though on Montserrat remains high, and continues to prevent re-population of areas where most people lived before the eruption, requiring the continued vigilance of a well-founded Observatory.

Indonesia and the Philippines ranked most highly for threat by Measure 1, but these countries drop in rank to 23 and 20 respectively when using Measure 2. Measure 2 cannot be used to infer either how risk is distributed globally or to rank in terms of risk, but highlights small nations with high exposure to volcanic hazards in relation to their size (Figure 23.2).

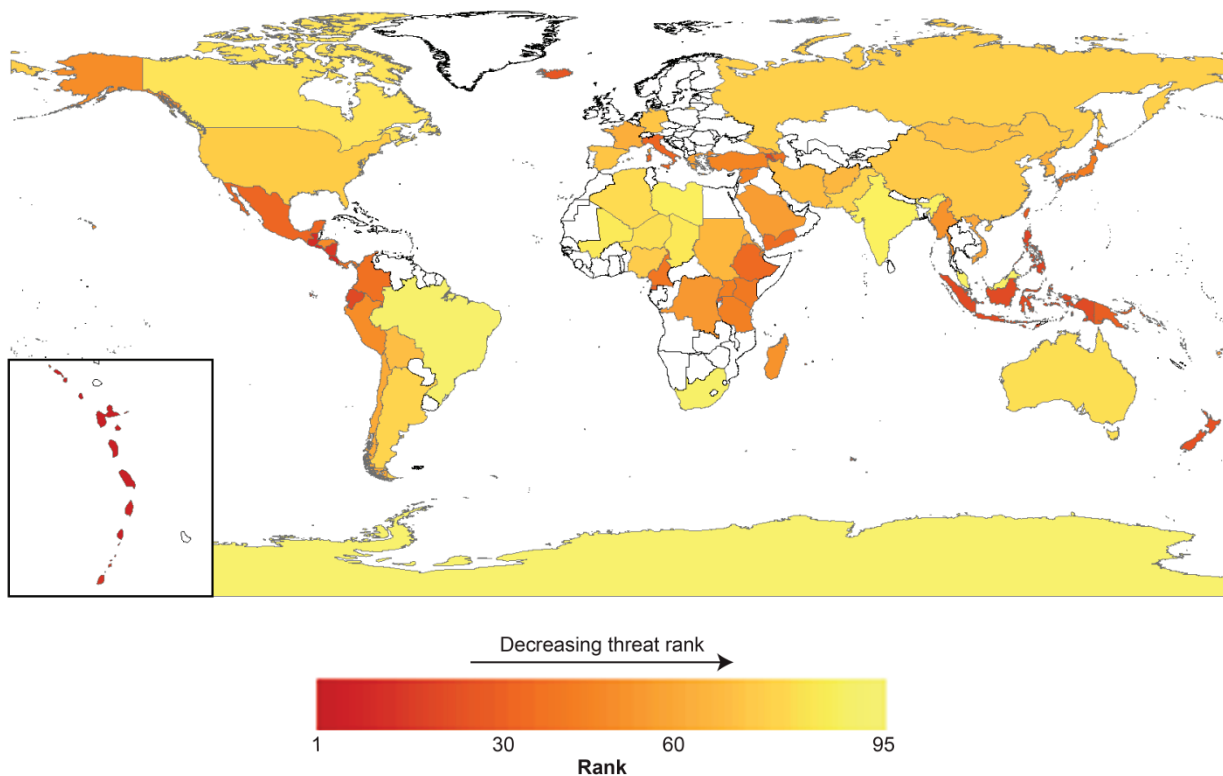Figure 23.2 Global distribution of proportional risk. Inset map shows the West Indies.

23.4.1 Regional distribution of proportional threat

Many of the highest ranking regions for proportional threat comprise multiple small island groups: notably the small island nations and territories in the West Indies, the island groups of the Canaries, the Azores and Cape Verde in the Atlantic, and those of Fiji, Samoa and Tonga in

New Zealand to Fiji (Table 23.5). Not all of the highest ranked regions comprise small island groups. Mexico and Central America ranks highly, comprising multiple nations in which high proportions of the population are exposed. Africa and the Red Sea region also ranks highly, comprising countries that range in size from small (e.g. Sao Tome and Principe, 964 km² area (United Nations Statistics Division, 2014)) to large (e.g. Algeria, 2,381,741 km² (United Nations Statistics Division, 2014)) resulting in a range of exposed populations from less than 1% of the country's total to 97%. It is those small nations which control this region's ranking.

Table 23.5 Proportional threat as ranked by region. Note the Kuril Islands region is not included due to the absence of population data. The percentage shows the percentage risk of the top ranked region: e.g. Indonesia has about 3% of the proportional risk of the West Indies.

Proportional threat rank	Region	% of top region	Proportional threat rank	Region	% of top region
1	West Indies	100	10	Philippines & SE Asia	4
2	Mexico & Central America	35	11	Indonesia	3
3	Atlantic Ocean	32	12	Japan, Taiwan, Marianas	3
4	Africa & Red Sea	17	13	Iceland & Arctic	2
5	New Zealand to Fiji	14	14	Alaska	<1
6	Melanesia & Australia	9	15	Hawaii & Pacific	<1
7	Mediterranean & West Asia	9	16	Kamchatka & Mainland Asia	<1
8	Middle East & Indian Ocean	8	17	Canada & Western USA	<1
9	South America	5	18	Antarctica	-

23.5 Discussion

There are numerous methods available for the classification and determination of global volcanic threat. Here we only consider threat to life. The two ranking systems adopted here are shown in Table 23.6 in full.

Measure 1 allows the identification of those countries with the highest overall level of threat to life due to a combination of large numbers of people living within 30 km of an active volcano, large numbers of volcanoes and high hazard scores. Indonesia by far has the highest level of volcanic threat worldwide, with about 30% of the population living close to volcanoes. To better understand the importance of volcanic risk to individual countries, the calculation of the proportional threat is independent of the country size and number of volcanoes (Measure 2). This highlights those countries where large portions of their population live within close proximity of volcanoes – chiefly small island nations and territories where the population and volcanoes share small areas.

The differences in threat rank illustrate how whilst many countries could be expected to suffer large losses in absolute terms as shown by a high rank using Measure 1, it is the small island nations where the relative social and economic losses could be much larger (Measure 2).

Table 23.6 All countries or territories ranked in order of overall risk to life (Measure 1). Ranking through Measure 2, proportional threat, is also shown. The percentage of volcanoes per country which are classified is shown.

Country	% of volcanoes in country with classified VHI	Measure 1: Overall threat to life rank	Measure 2: Proportional threat rank
Indonesia	40	1	23
Philippines	17	2	20
Japan	38	3	43
Mexico	10	4	34
Ethiopia	2	5	36
Guatemala	17	6	11
Ecuador	31	7	22
Italy	43	8	33
El Salvador	14	9	9
Kenya	5	10	42
Papua New Guinea	18	11	31
Nicaragua	37	12	16
Colombia	33	13	39
Turkey	0	14	47
Costa Rica	50	15	10
Taiwan	0	16	29
Yemen	8	17	37
Chile	14	18	62
New Zealand	29	19	26
China	0	20	74
Tanzania	10	21	45
Peru	24	22	50
Uganda	0	23	44
USA Contiguous States	19	24	75
Russia	12	25	77
DR Congo	33	26	55
Syria	0	27	46
Cameroon	20	28	41
Spain: Canary Islands	33	29	13
Portugal: Azores	29	30	6
Vietnam	0	31	61
Armenia	0	32	19
Rwanda	0	33	30
Saudi Arabia	0	34	57
Burma (Myanmar)	0	35	53
Iran	0	36	69
Madagascar	0	37	54
France: Indian Ocean	11	38	27
Iceland	50	39	28
USA: Alaska	24	40	51

Vanuatu	43	41	15
Honduras	0	42	49
Sudan	20	43	67
South Korea	0	44	66
Argentina	10	45	78
France: West Indies	100	46	3
Greece	40	47	60
North Korea	0	48	65
France: Mainland	0	49	64
Eritrea	0	50	63
Azerbaijan	0	51	38
Panama	0	52	40
Solomon Islands	25	53	35
Comoros	50	54	21
USA: Hawaii	27	55	52
Cape Verde	33	56	25
Dominica	0	57	5
Bolivia	0	58	70
Afghanistan	0	59	68
Georgia	0	60	58
Equatorial Guinea	0	61	32
Spain: Mainland	0	62	72
Samoa	0	63	17
Saint Vincent & the Grenadines	100	64	2
Saint Lucia	0	65	7
Nigeria	0	66	76
Djibouti	0	67	48
Germany	0	68	73
USA: American Samoa	0	69	18
Grenada	50	70	14
Saint Kitts and Nevis	0	71	4
Sao Tome and Principe	0	72	12
Pakistan	0	73	79
Fiji	33	74	56
Mongolia	0	75	71
Canada	0	76	84
Tonga	33	77	59
Algeria	0	78	81
UK: West Indies	100	79	1
Netherlands	0	80	24
Australia	67	81	82
UK: Atlantic	0	82	8
Niger	0	83	83
Chad	0	84	85
France: Pacific Ocean	13	85	80
India	33	86	89
Mali	0	87	86
Libya	0	88	88
USA: Marianas Islands	14	89	87
Norway	33	90	90
South Africa	0	91	91

Malaysia	0	92	92
Brazil	0	93	93
Antarctica	13	-	-
Kuril Islands	27	-	-

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