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GLOBAL IMPACT DISTRIBUTION OF ASTEROIDS AND AFFECTED POPULATION

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Abstract
Which nations should be concerned about asteroid impacts? 261 impact corridors were calculated based on orbital data and impact probabilities of observed asteroids that could impact the Earth before 2100. The corridors, in the form of impact probability distributions were projected onto the Earth map. The cumulative impact probability distribution was combined with the Earth population producing a risk map to identify nations that should be concerned about the asteroid threat. The 40 nations that experience highest risk were identified. Results show that population size correlates strongly with impact risk and highlight the dilemma of small developing nations: they experience a disproportionally high risk relative to population but do not have the resources to mitigate the threat. The results emphasize the need for international cooperation to address the asteroid threat. Developed nations need to take the lead on asteroid discovery and mitigation on behalf of the rest of the world.

Introduction
An asteroid impacting the Earth is typically not amongst the concerns experienced by people in everyday life. Nonetheless, the asteroid threat is real (Brown et al. 2002) and can have disastrous consequences. Asteroids have hit the Earth since the formation of the solar system and this process continues today. The bolide over Chelyabinsk in February 2013 that injured more than 1500 people demonstrated this palpably (Popova et al. 2013). Only recently have the scientific community and leading nations broadly recognized that the asteroid hazard is a significant threat to our civilization. The establishment of international organizations (UN Office for Outer Space Affairs 2013) to address the threat and commencement of the search for potentially Earth-colliding objects (National Research Council et al. 2010) are a result of this realization. The products of this search are publicly available risk lists maintained by the European and US space agencies, ESA and NASA (Universita Di Pisa & European Space Agency 2014; NASA 2014a). These lists include all known asteroids that have a non-zero chance of impacting the Earth in the next century. However, the impact distribution of these asteroids on the Earth’s surface and whether some nations are more threatened than others is not yet known.

The impact locations of 261 potential impactors, that can collide with the Earth before the year 2100, were calculated and visualized. The considered asteroids had a diameter range of about 30 m – 341 m. For comparison, the Chelyabinsk event was associated with a 19 m sized asteroid (Popova et al. 2013; Borovicka et al. 2013) while the devastating 1908 Tunguska event was likely caused by a 30 m sized object (Boslough & Crawford 2008; Chyba et al. 1993). The nations that experience the highest risk of direct impacts were identified, thus, illustrating the future asteroid impact situation as it is known today.

Method and Validation

Using the information on asteroids provided in the risk lists, the freely available software OrbFit (Milani et al. 1997) was utilized to identify orbit solutions that lie inside the uncertainty region of the asteroid's nominal orbit solution and result in an Earth impact in the future (Milani et al. 2005). The impacting orbit solutions are called virtual impactors (VI). The Asteroid Risk Mitigation Optimization and Research (ARMOR) tool was used subsequently to project the impact probability of these VIs onto the surface of the Earth. ARMOR used the VI orbit solution from OrbFit as initial condition for the trajectory propagation until impact. A solar system model that provided gravitational forces from the Sun, the planets and the Moon (based on the JPL DE430 planetary ephemerides (Folkner et al. 2014)) was employed for the propagation. Typical asteroid propagations spanned 10 days until impact. The asteroid's trajectory was approximated as a three dimensional polynomial in the immediate vicinity of the Earth and it was thus possible to find exact solutions for impact times and locations in analytical form. The impact time determines the sidereal hour angle of the Earth which allows calculation of the impact's latitude and longitude. For each VI all possible impact locations were calculated yielding the impact corridor. Taking into account the width of the asteroid's uncertainty region and the global impact probability, the impact corridor was scaled to represent the impact probability distribution for that VI. The 1-sigma width of the impact probability along the corridor was determined by the Line of Variation (Milani et al. 2005) 1-sigma width. The entire impact probability distribution was scaled to reflect the VI's global impact probability. This method was applied to all VIs and the result is a set of impact corridors, each in the form of a Gaussian distribution. All impact solutions were combined within a global map and the result is shown in Figure 1.

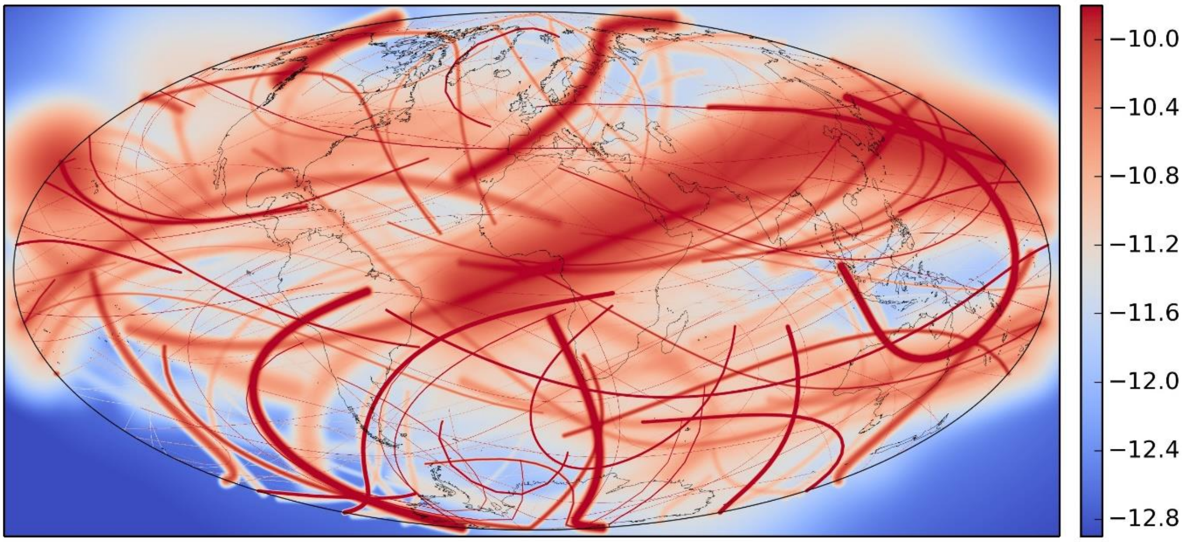

Figure 1: The Earth in the Hammer projection showing the impact probability distributions for 261 VIs. The colour coding represents the impact probability at each location using a logarithmic scale.

Validation of the ARMOR tool was done by employing case studies of asteroid 2011AG5 and 2008TC8. In the case of 2011AG5 successful cross-validation with other predictive software tools was accomplished. Additional details on this case are provided in (Rumpf 2014). Asteroid 2008TC3 was discovered shortly before entering the Earth's atmosphere. Its entry point was predicted and the resulting bolide was observed by eye witnesses, satellite and infra-sound sensors (Chesley et al. 2014). For validation, ARMOR used the nominal orbital solution for 2008TC8 and predicted the atmospheric entry point as well as the ground track (Figure 2). The predicted nominal entry point agreed to within 0.39º longitude and 0.12º latitude at 65.4 km altitude. Furthermore, the shape of the ground track agreed well with the literature. The validation results demonstrated sufficient accuracy of ARMOR for the problems addressed in this paper.

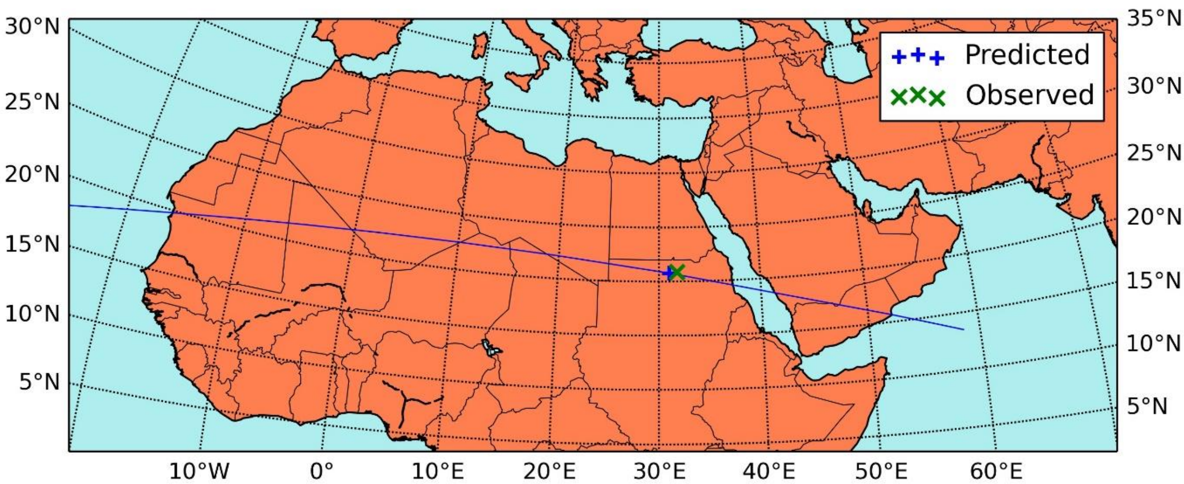

Figure 2: Observed and predicted entry point for asteroid 2008TC3. The blue plus sign marks the point of the nominal entry solution while the green cross gives the solution of the observed entry point at the same altitude of 65.4 km.

Results and Discussion

It is apparent in Figure 1 that much of the Earth is potentially exposed to an asteroid impact. Hence, the asteroid threat is an inherently global issue and should be addressed as such. However, based on the observed asteroids, some regions are more likely to be affected than others and the risk to populations across the globe varies accordingly.

The risk, as used here, is equivalent to impact probability (see Figure 1) weighted by population data to identify regions of increased concern to the direct asteroid impact hazard. The definition is suitable as a comparative measure for asteroid impact risk but not to estimate expected losses because physical impact effects are not included. Considering that the size range of the asteroids warrants the assumption of a ground impact or a significant ground effect in the case of a bolide (the most common impact event), the definition is valid in connecting asteroid impact probabilities with populations because populations will be affected by these impacts. It shows which nations should be most concerned about the threat of a direct asteroid impact. To estimate the percentage of the global risk that each nation carries, risk values were normalized with respect to the global risk. The normalized risk in each map cell (ca 5 km by 5 km) is:

$$\text{normalized risk}_c = \sum_i \frac{P_{i,c} N_c}{\sum_c P_{i,c} N_c}$$

where subscript c denotes a map cell, subscript i denotes a VI, P is the impact probability and N is the population. Figure 3 shows the global normalized risk distribution.

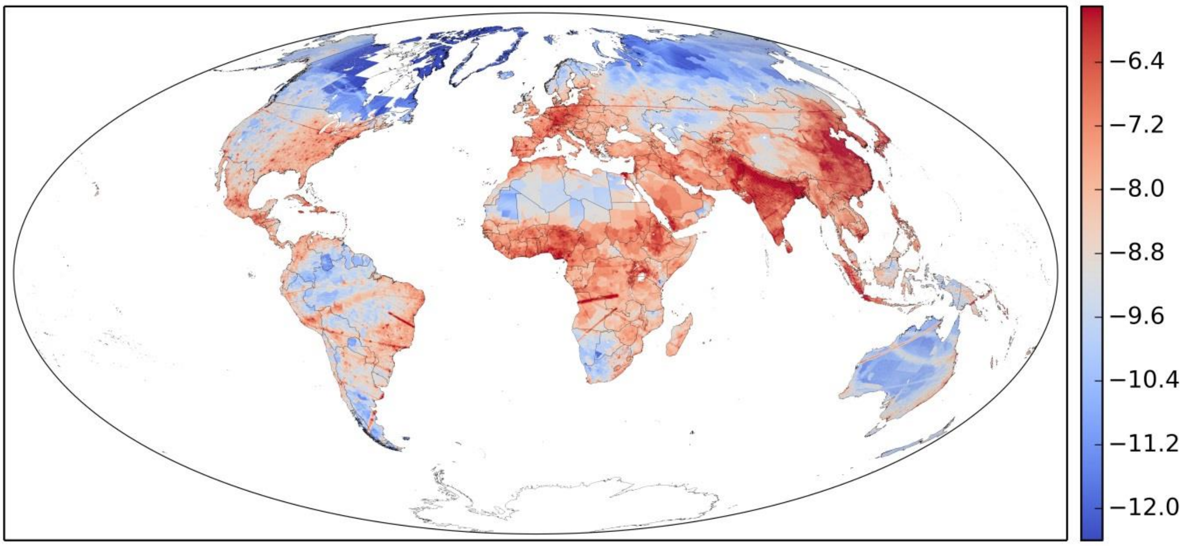

Figure 3: The asteroid risk map is a combination of impact probability and world population data. The colour in each region indicates the risk level for that population. Risk is normalized with respect to global risk and is colour coded using a logarithmic scale.

The impact probability map shown in Figure 1 suggests a uniform distribution of the potential impact locations of asteroids and recorded bolide data support this assessment (NASA 2014b). Given the definition of risk, a uniform impact probability distribution would produce a risk map resembling a typical global population distribution map (Figure S5). However, individual VIs with high impact probabilities have the potential to skew the risk distribution towards their ground tracks. In fact, Figure 3 features numerous high risk ground tracks which increase the local risk even in less populated regions, for example, in continental South America and across southern Africa. Clearly, the risk distribution identified here, based on observed asteroids, goes beyond the general assumption that impacts are distributed uniformly. What may be learned from these results?

Of all 206 countries, Figure 4 lists the 40 countries at greatest risk from these 261 VIs, in descending order, with population data for comparison. The risk and population values are normalized with respect to the global risk and population to allow comparison between the two curves showing their strong correlation. Population is a good proxy for risk with a correlation coefficient of 0.953.

However, there are some outliers in Figure 4 where the orange population curve falls below the blue risk curve. The risk for these nations is higher than expected based on their populations. The countries that show a risk that is disproportionally high relative to population are: Dominican Republic, Angola, Guatemala, Taiwan, Papua New Guinea and Honduras. A shared characteristic of these nations is that they are small- to mid-sized compared to the international community. This condition allows a high impact probability VI to cover the entire territory and, thus, severely raise the national risk.

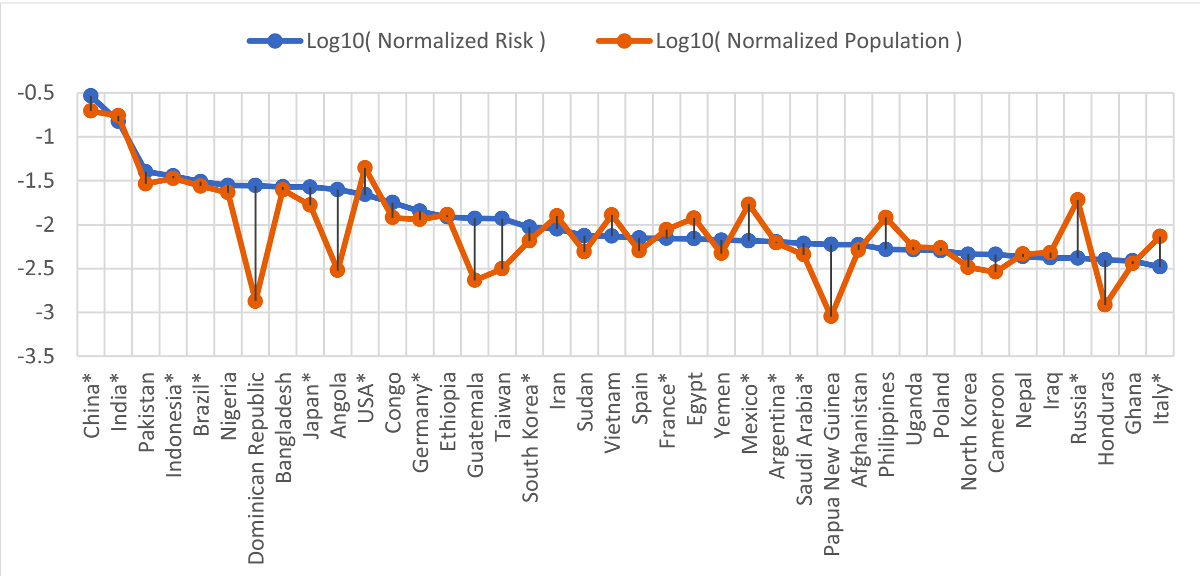

Figure 4: Listing of first 40 countries according to their risk in descending order. The normalized risk and population are presented for each country (G20 members are annotated with asterisks). Normalization was achieved by dividing the risk and population values by the global risk and population. The data are presented using a logarithmic scale. Risk and population data have a correlation coefficient of 0.953. The risk for a country is disproportionally high when the blue line is above the orange line.

Furthermore, these nations (with the exception of Taiwan) are considered to be developing nations. None of them have the technological capabilities or the resources for an adequate response to the asteroid threat. Yet, these nations are likely to suffer more than others if impacted by an asteroid. This dilemma suggests a moral obligation of developed nations to lead the effort on asteroid threat mitigation on behalf of the entire world. In fact, the United Nations have recognized the need for a coordinated response to the asteroid hazard (UN et al. 2013).

Developed countries should lead and increase efforts to detect asteroids and develop deflection technologies because they have the resources to accomplish this task. Member nations of the G20 are representatives of this category and are highlighted with an asterisk in Figure 4. Indeed, a good example of international cooperation to discover new asteroids and warn of potential asteroid impacts is the International Asteroid Warning Network (IAWN) (Camacho 2014). In addition, the formation of the Space Missions Planning and Advisory Group (SMPAG) (Drolshagen 2014) represents another international effort to consolidate multinational resources for an asteroid deflection mission. International cooperation is also important to share the 1-10 B$ cost for a complete deflection effort (NASA 2006). However, not all nations that show high risk in figure 3 are involved in these organizations. For example, China has the highest risk and is not yet a member of IAWN; India has the second highest risk and is not yet represented in IAWN or SMPAG.

Because of the dilemma faced by developing nations, international organizations such as IAWN and SMPAG need to be prepared to respond to an imminent threat even if none of their member states are at risk. Furthermore, they need to encourage collaboration with developing nations to help prepare them for such a disaster.

For all countries, especially the developing ones, efficient preparation for a potential impact means increasing public awareness and including the asteroid hazard in natural disaster response planning. Disaster response planning should address direct impact effects such as blast waves, hot thermal radiation and seismic shocks. For example, the Chelyabinsk bolide generated a shockwave that shattered windows and the glass shards injured people standing nearby. A pre-disaster plan that warns people to seek shelter and to avoid windows at the time of atmospheric passage would be an effective way to protect the population in the case of a bolide airblast close to an urban area.

The asteroid lists maintained by ESA and NASA change over time with the discovery of new high impact probability asteroids and the exclusion of asteroids that were previously considered with a high impact probability. New observations will also adjust the impact probability of asteroids already present in the lists and, thus, the risk landscape will change. Only about 1% of all Near Earth Asteroids have been observed (16). The majority, especially in the sub-km size regime, have yet to be discovered. Consequently, the results shown here represent only a snapshot in time of knowledge of the asteroid hazard. However, the conclusions drawn based on this snapshot data will likely hold true in the future even if the risk landscape changes. For example, some small to mid-sized developing nations will continue to be at a disproportionally high risk due to individual high impact probability asteroids. Thus, these nations should increase their resilience and developed nations should be prepared to respond to the threat on their behalf.

Asteroid impact and consequence modelling can be very complex. Aspects that were not included here are physical impact effects as well as the future evolution of population and infrastructure. These processes have large uncertainties associated with them given their complexity and the considered timeframe of 85 years. Inclusion of these aspects would transfer their uncertainties into the results producing ambiguity. Instead, the work is based on today's certain knowledge of observed asteroids and their impact probabilities, their future trajectories and the current population situation. This method allows gaining insight into today's asteroid risk distribution without relying on uncertain data. The asteroid impact distribution, as it presents itself today, is important to inform and support the international community because the time to address the asteroid threat is now.

Conclusions

This article presented the asteroid impact distribution on Earth until 2100 as it is currently known. The work encourages nations to include the asteroid threat in their natural disaster response planning and to increase public awareness of this hazard. The nations that currently experience the highest risk of a direct asteroid impact and the nations that exhibit a disproportionally high risk, relative to their population, were identified. The latter are exclusively nations that would not be able to respond adequately to an imminent threat. This dilemma was previously unreported and emphasizes the importance of international cooperation and the responsibility of developed nations to assume a leading role in establishing a response to the asteroid threat.

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Supplementary Material

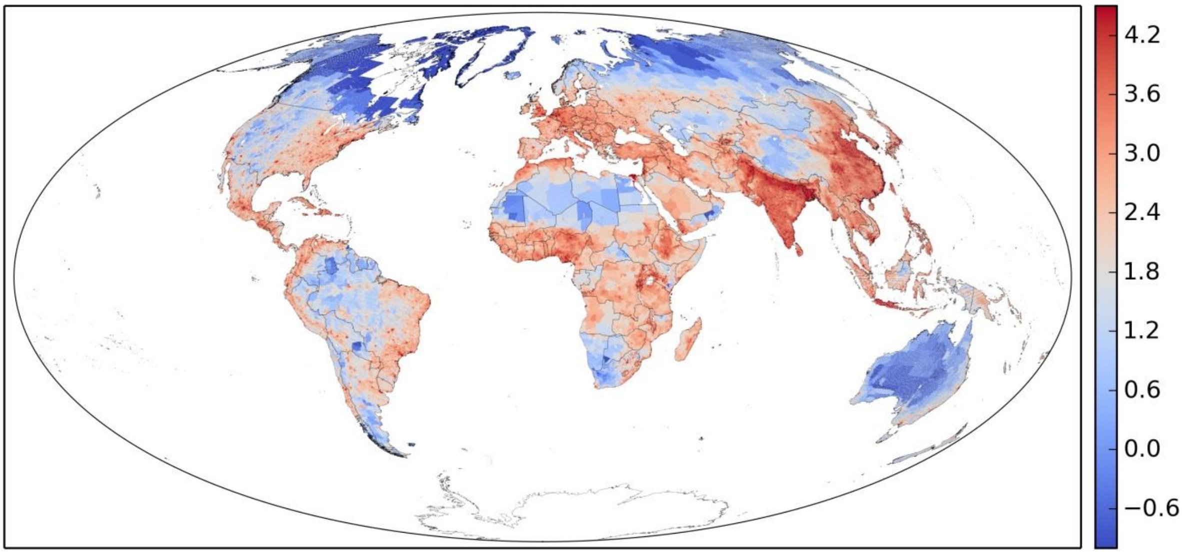

Figure S5: World population map for 2015 in the Hammer projection. The data are colour coded using a logarithmic scale.