IAA-PDC-23-07-03
ASTEROID IMPACTS AND CASCADING HAZARDS

Timothy N. Titus(1), **Darrel Robertson** (2), **Joel B. Sankey**(3), **and Larry G. Mastin**(4)
(1)*U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001, 928-556-7201, ttitus@usgs.gov*
(2)*NASA Ames Research Center, 258 Allen Road, Moffett Field, CA 94035, 650-604-1331, darrel.k.robertson@nasa.gov*
(3)*U.S. Geological Survey, Southwest Biological Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001, 928-556-7289, jsankey@usgs.gov*
(4)*U.S. Geological Survey, David A. Johnston Cascades Volcano Observatory, 1300 SE Cardinal Court, Vancouver, WA 98683, (360) 993-8925, lgmastin@usgs.gov*

Keywords: *Hazards, Modeling, Ash3D, Watersheds, Flooding*

Extended Abstract—

Introduction: The initial effects from an asteroid impact are generally well characterized and include thermal radiation and blast waves. If the impactor is sufficiently large, either an earthquake or tsunami can also result, depending on whether the impact occurs over land or water. However, the longer-term effects that also extend beyond the initial affected area are not well characterized. These longer-term regional effects can generally be categorized as either downwind or as downstream [1, 2].

Downwind events are primarily from the plume that forms from either the debris from an air burst and (or) the ejecta from a surface impact. This type of regional effect will disrupt transportation hubs and corridors within a few hours of impact and may have longer term effects on agriculture and human health. We suggest volcanic plumes are an analog for downwind effects. The regional area affected will depend on both the impactor size and the weather patterns at the time of impact [2].

Downstream effects can result in the cascading effects of debris flows and flooding, both of which result from the initial impact damage and weather-triggering events, such as seasonal monsoons. We suggest extreme wildfires that occur in major watersheds are suitable analogs for downstream effects as the wildfire-induced damage also combines with post-fire weather events that result in debris flows and floods [2].

Impact scenarios: Because regional effects not only depend on the size of the impactor, but also on the location and timing of the event, case studies of impact events in various regions should be conducted to better understand how asteroid impact induced cascading hazards may vary. For this study, we use the initial impact effects from an 800-m asteroid strike at two locations: Dallas, TX, USA and Jebba, Nigeria. These two locations are both along the initial risk corridor for the 8th Planetary Defense Conference exercise [2] and provide a contrast in seasonal weather patterns, regional topography, population distributions, and seasonal economic activity (e.g., agriculture). For exercise purposes, the impact occurs on 22 October 2036 at 15:04 UTC. We use the initial damage radii determined for the PDC exercise [3] as determined from the PAIR model (Table 1) [4].

Table 1: Radius of initial impact effects 800m 10 Gigatons (Gt) of TNT [3] using the damage estimated from PAIR [4].

Damage Level	Blast (psi)	Radius (km)	Thermal Severity	Radius (km)
Serious	1	227	2nd degree burns	133
Severe	2	126	3rd degree burns	102
Critical	4	72	Clothing ignites	72
Nonsurvivable	10	39	Structures ignite	61

Methodology: Our approach to estimate the potential downwind and downstream effects from these impact scenarios is to use more common natural disasters as analogs, such as volcanic plumes and wildfires. We use the volcano analog for the downwind debris fall and the wildfire analog to determine downstream effects in the watershed and (or) river basins.

Downwind effects: The process to determine the downwind effects has been simplified. We assume a distribution of debris up to a height of 40 km. We then use the U.S. Geological Survey volcanic ash transport model, Ash3D [5, 6] to estimate the possible downwind distribution based on wind patterns from 20 selected dates over the last two decades. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust).

Downstream effects: The process to determine the downstream effects is complex and requires several simplifying assumptions and published scenarios based on several models, as described in Sankey et al. [7]. The basic premise is that initial damage caused by the thermal radiation and blast will significantly increase precipitation runoff and sediment flux due to changes in the landscape soil and vegetation. The extent to which this occurs is not well established. For simplicity, we use the estimated damage area radii (Table 1) as shown for the PDC23 [3] exercise for both Dallas-Fort Worth and Jebba impact sites, and discuss the implications only based on estimated areas where water from future precipitation events would be expected to flow based on 30-m topography alone [8]. Our model does not solve the shallow-water equations, but instead just traces where the water would flow down-hill. Limited ponding is allowed so water flow does not get trapped in local low spots. A detailed analysis of water volume (e.g., flooding) and sediment flux (including debris flows) is beyond the scope of this study but will be needed to fully characterize the potential impact on these two regions. However, this simplified approach of tracking where the water will likely go does assist in the identification of which communities may be at risk. The number of communities affected is a function of the areal extent of soil damage and vegetation removal.

Results:

Downwind effects – Texas: In late October, the prevailing winds in Texas are generally from west to east, thus blowing the dust in a predictable direction. However, Ash3D simulations for 22 October 2000–2019 shows viable wind directions and dust dispersal (Figs. 1–5). In most cases, a multi-state region would be affected. Due to the time of year, there should be minimal impact on agriculture. The dust will affect respiratory health for both human, pets, and livestock. Ground and air transportation hubs and corridors will be affected due to a lack of visibility, as well as possible damage to internal combustion and jet engines. The hazard continues while the dust remains airborne. Resuspension of the dust could temporally extend the dust hazard in local areas. Due to the variability on weather patterns, downwind hazard warnings may have to wait until relatively accurate forecasts are available, perhaps as late as 10 days prior to the event.

Downwind effects – Nigeria: For Nigeria, the prevailing winds are reversed, blowing from the east to the west. Several nations in sub-Saharan west Africa could be adversely affected as simulated in Figs. 6–9. While the hazards for west Africa are like those in the Texas scenario, the vulnerabilities of the affected communities will be different. For example, are there suitable places for livestock to shelter in place or will large-scale livestock evacuations be needed?

Downwind effects – future efforts: The next step for characterizing downwind events is to model the effects of the dust distribution and deposition on people, both in terms of economic impact and human health. For example, large dust events in Iran are estimated to cost 149 million US dollars per day due to the economic impact of reduced industrial productivity [9].

Downstream effects – Texas: For downstream effects, topography determines where the cascading effects are likely to occur. Texas topography is generally rolling hills and plains that slope towards the Gulf of Mexico. There are several river basins that could be affected by the impactor. Cascading hazards, such as flooding that could be triggered by seasonal rains, could possibly flow all the way to the Gulf, thus potentially affecting communities well outside the initial damage zone, such as Galveston and Houston.

Fig. 10 shows where the water from precipitation will likely flow based on the topography and distance of the rain from the impact site. Because our knowledge of how the soil infiltration and runoff is affected by the intense but short-lived thermal radiation and the effect of the blast wave on vegetation, we allow the radius of precipitation to be a parameter of the model, assuming that inside the radius, precipitation is uniform, and the soil is hydrophobic. However, the results do show which communities outside of the initial damage zone are potentially at risk, including Waco, Houston, Galveston, and possibly Shreveport. The flooding these communities will experience will likely be annually reoccurring – depending on the weather and what mitigation and (or) recovery strategies are implemented. Communities inside the initial damage zone, will likely experience reoccurring enhanced debris flows and flooding, complicating any efforts to rebuild, especially the Dallas-Fort Worth metropolitan area.

Another consideration for this scenario is the possibility of hurricanes. A hurricane storm surge, whether occurring immediately after the asteroid impact event or in the subsequent years, would be the worst-case for the Gulf communities that could simultaneously be hit with flooding from both the storm surge and from downstream flooding from the excess runoff from upriver precipitation.

Downstream effects – Nigeria: The region around Jebba, located in central Nigeria on the Niger River, is mountainous terrain. The analysis of where the precipitation runoff is expected to flow, using the same approach as was used for the Texas impact event, shows that much of the flow, and therefore future flooding, may be restricted to the initial damaged area and the Niger River basin. The communities along the Niger River, which already experience seasonal flooding that annually results in loss of life and economic damage, will be at even greater risk.

An additional factor that could contribute to initial flooding immediately following the impact event is that there is a dam located near the impact site, the Jebba Hydroelectric Power Station. The reservoir has a capacity of 3,900 million cubic meters [10], which could be of concern if the dam were to break.

The initial damage area that extends past the Niger River basin may be less than expected due to the shadowing effect from the mountains. If this is the case, the downstream effects on Lagos, Nigeria, may be significantly reduced. However, Lagos already experiences annual flooding. Any additional flood waters that result from upstream watershed damage could still be overwhelming, especially if the population of Lagos has increased due to an influx of evacuees.

Downstream effects – future efforts: Additional modeling, perhaps using GeoCLAW [11] or the U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) [12], combined with typical precipitation models, is necessary to begin quantifying flooding potential. The use of hillside erosion models, such as Water Erosion Prediction Project (WEPP) [13], is also necessary to evaluate the effects from enhanced erosion and sediment flux. More study is needed on the effects of the thermal radiation on soil hydrophobicity and at what level do these effects become negligible.

Conclusions: When considering regional effects from an asteroid impact, location matters. The results described here were based on generalized output from asteroid impact and air burst hydrocode simulations [4], downwind volcanic ash transport simulations [5, 6], and a simplified downstream water flow model. Assumptions were made to link these models and previously published scenarios together into a coherent narrative. Based on these preliminary results, an 800-m impactor will immediately disrupt transportation networks and cause respiratory health issues for humans and livestock on a regional basis. Downstream effects are likely restricted to the initial damage zones and the communities that lie in river basins affected by the initial damage zones. The comparison between Texas and Nigeria downstream effects demonstrates the importance of including topography in the analysis of regional and cascading hazards. The relative flatness of Texas, combined with multiple major river basins, suggest that a widespread area may be adversely affected, while the mountainous region of Nigeria with a single major river basin, may channel most of the adverse effects away from the more populous parts of the country (e.g., away from Lagos). The greatest unknown is the effect that the initial damage (mainly thermal radiation) will have on the soil conditions (e.g., hydrophobicity). More analysis is needed.

References: [1] Titus, T., Robertson, D., Sankey, J.B. et al., 2021, Planetary Defense Preparedness: Identifying the Potential for Post-asteroid Impact Time Delayed and Geographically Displaced Hazards, Planetary Science and Astrobiology Decadal Survey 2023-2032 white paper e-id. 050; Bulletin of the American Astronomical Society, 53(4), e-id. 050. [2] Titus, T., Robertson, D., Sankey, J.B. et al., 2023, A review of common natural disasters as analogs for asteroid impact effects and cascading hazards. Nat Hazards. https://doi.org/10.1007/s11069-022-05722-z [3] The 2023 PDC Hypothetical Asteroid Impact Scenario, Planetary Defense Conference Exercise - 2023 (nasa.gov). [4] Mathias, D. L., Wheeler, L. F., Dotson, J. L., 2017, Icarus, 289, 106-119. [5] Schwaiger H.F., Denlinger R.P., Mastin L.G., 2012. Ash3d: A finite-volume, conservative numerical model for ash transport and tephra deposition. Journal of Geophysical Research 117(B04204). [6] Mastin L.G., Randall M.J., Schwaiger H.F., Denlinger R.P. (2013) User's guide and reference to Ash3d: A Three-Dimensional Model for Atmospheric Tephra Transport and Deposition. U.S. Geological Survey Open-File Report 2013-1122, 48, http://pubs.usgs.gov/of/2013/1122/. [7] Sankey, J. et al., 2017, Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds, Geophysical Research Letters, 44(17), 8884-8892. [8] USGS EROS, 2018, Digital Elevation - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, doi: 10.5066/F7PR7TFT. [9] Birjandi-Feriz M, Yousefi K., 2017, When the dust settles: productivity and economic losses following dust storms. SSRN. https://doi.org/10.2139/ssrn.3230265 [10] Jebba, Nigeria (power-technology.com), https://www.power-technology.com/marketdata/jebba-nigeria/#:~:text=The%20project%20is%20currently%20owned%20by%20Mainstream%20Energy,hydro%20reservoir%20capacity%20is%203%2C900%20million%20cubic%20meter, extracted 14 March 2023. [11] Berger MJ, George DL, LeVeque RJ, Mandli KM (2011) The GeoClaw software for depth-averaged flows with adaptive refinement. Adv Water Resour 34:1195–1206 [12] Hydrologic Engineering Center's (CEIWR-HEC) River Analysis System (HEC-RAS) https://www.hec.usace.army.mil/software/hec-ras/ [13] Elliot, W.J., Miller, I.S. Glaza, B.D., 2006, Using WEPP Technology to Predict Erosion and Runoff Following Wildfire, 2006 ASABE Annual International Meeting, https://www.fs.usda.gov/rm/pubs_journals/2006/rmrs_2006_elliot_w001.pdf

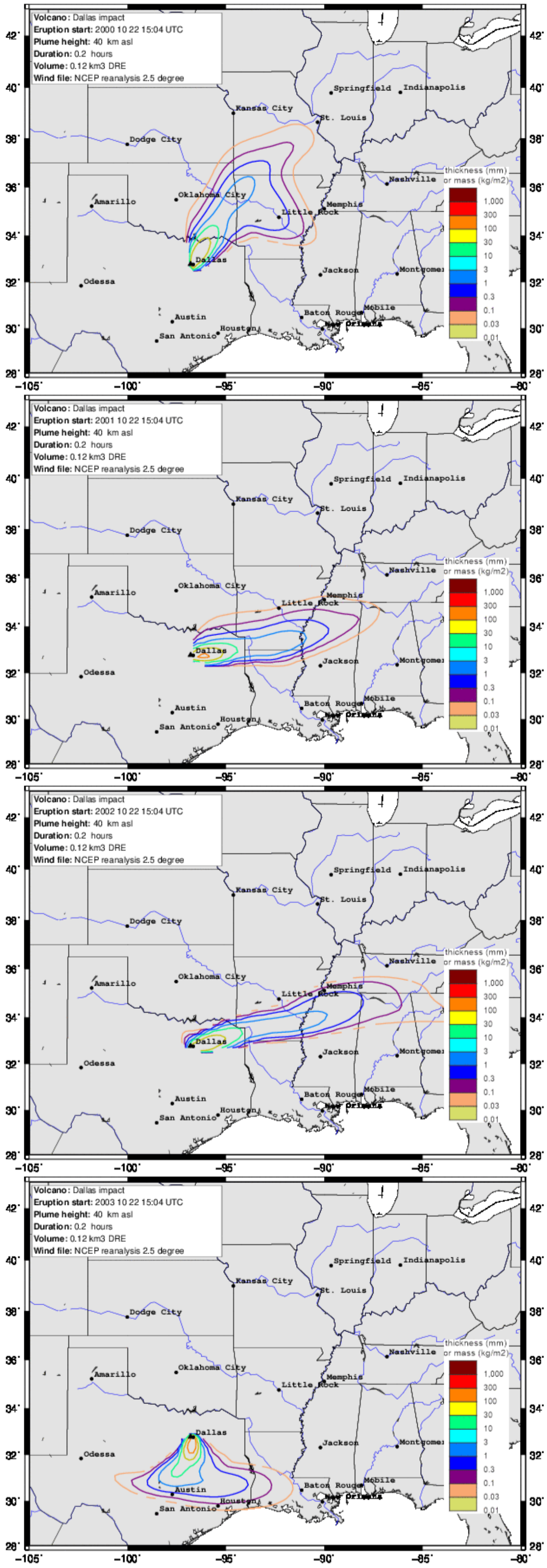

Figure 1: Ash3D dust distribution results for the Texas impact simulation, Oct 22, 2000–2003, at 15:04 UTC. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust). The winds cause the dispersion to occur over many states.

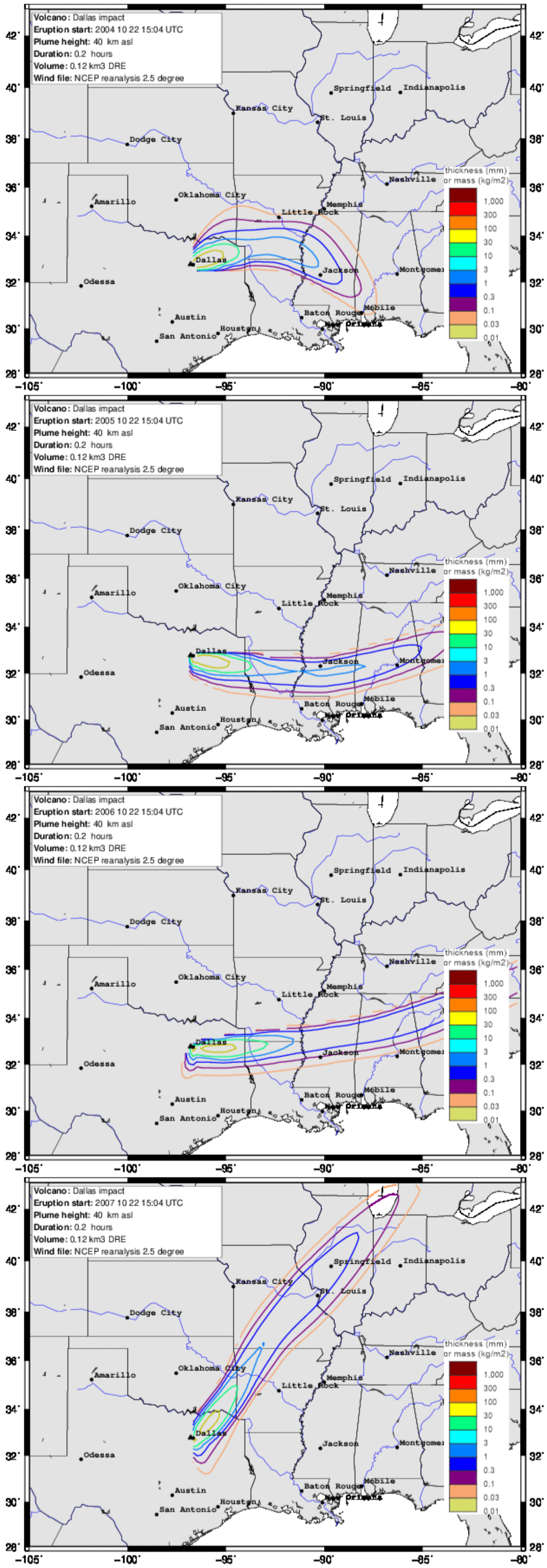

Figure 2: Ash3D dust distribution results for the Texas impact simulation, Oct 22, 2004–2007, at 15:04 UTC. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust). The winds cause the dispersion to occur over many states.

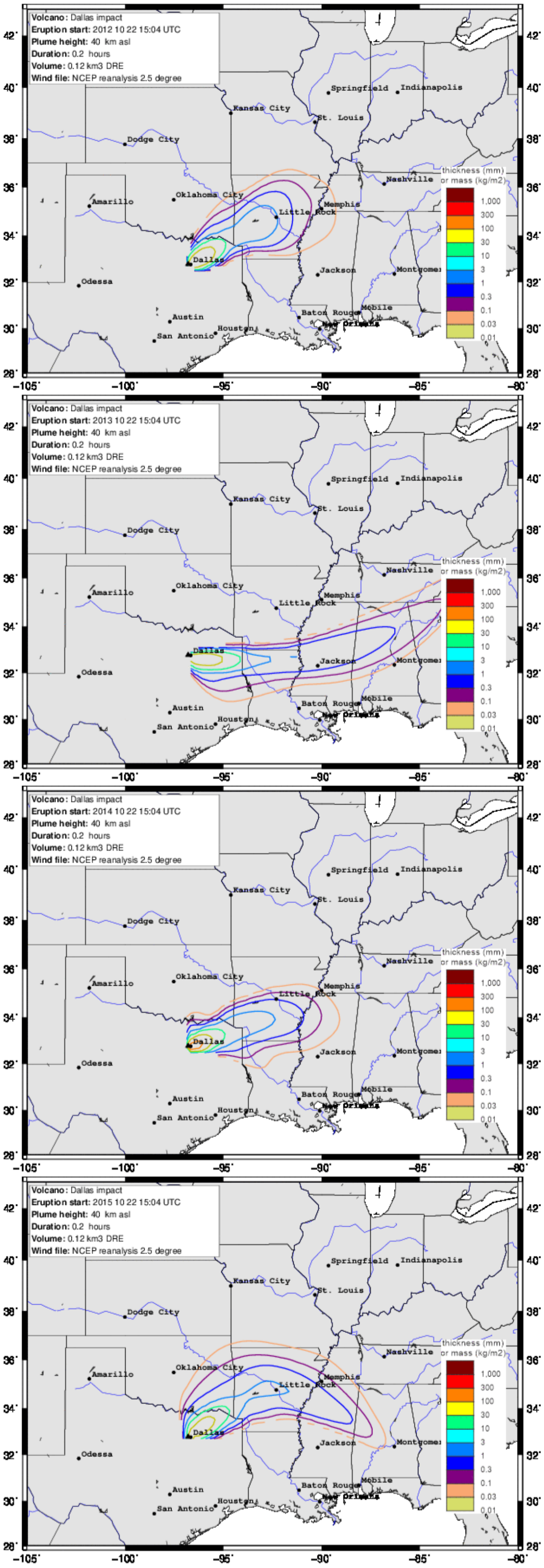

Figure 3: Ash3D dust distribution results for the Texas impact simulation, Oct 22, 2008–2011, at 15:04 UTC. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust). The winds cause the dispersion to occur over many states.

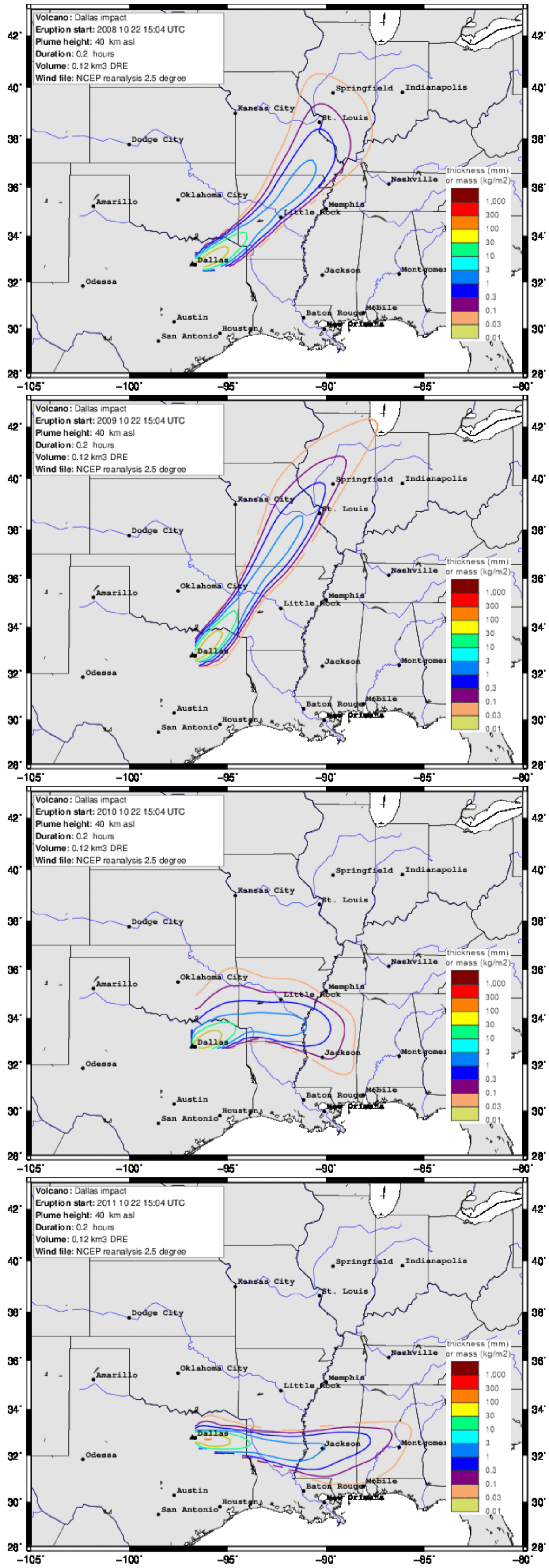

Figure 4: Ash3D dust distribution results for the Texas impact simulation, Oct 22, 2012–2015, at 15:04 UTC. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust). The winds cause the dispersion to occur over many states.

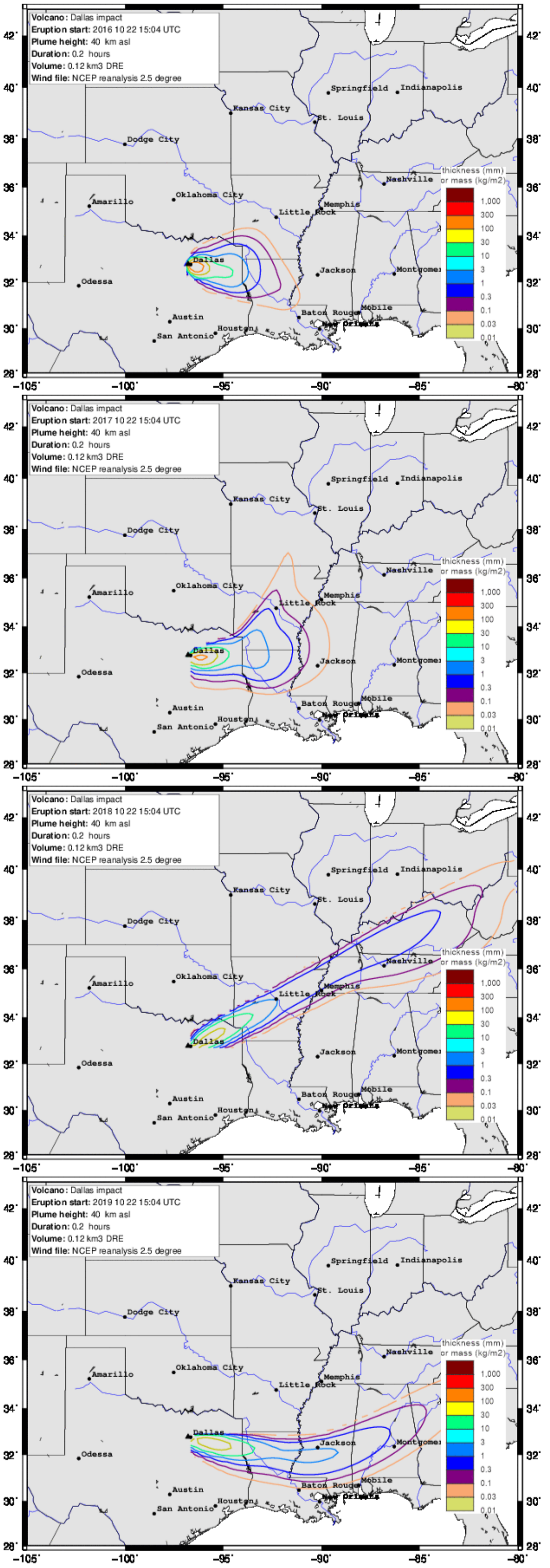

Figure 5: Ash3D dust distribution results for the Texas impact simulation Oct 22, 2016–2019, at 15:04 UTC. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust). The winds cause the dispersion to occur over many states.

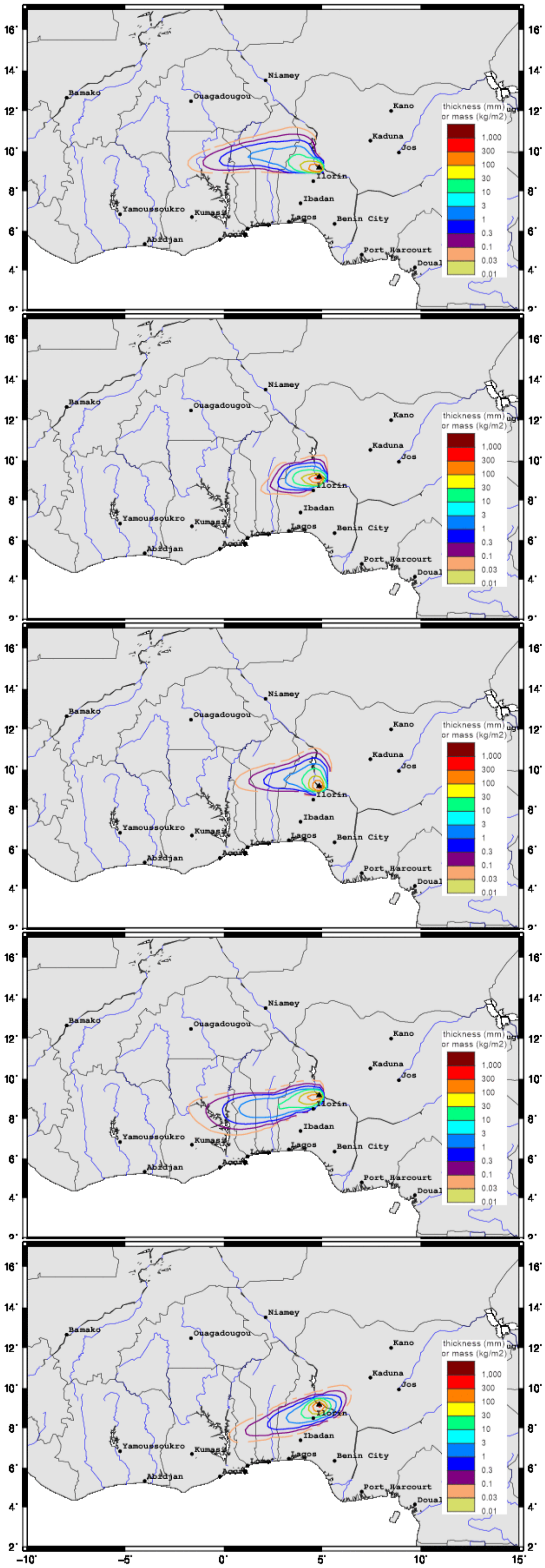

Figure 6: Ash3D dust distribution results for the Nigeria impact simulation, Oct 22, 2000–2004, at 15:04 UTC, from top to bottom, respectively. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust).

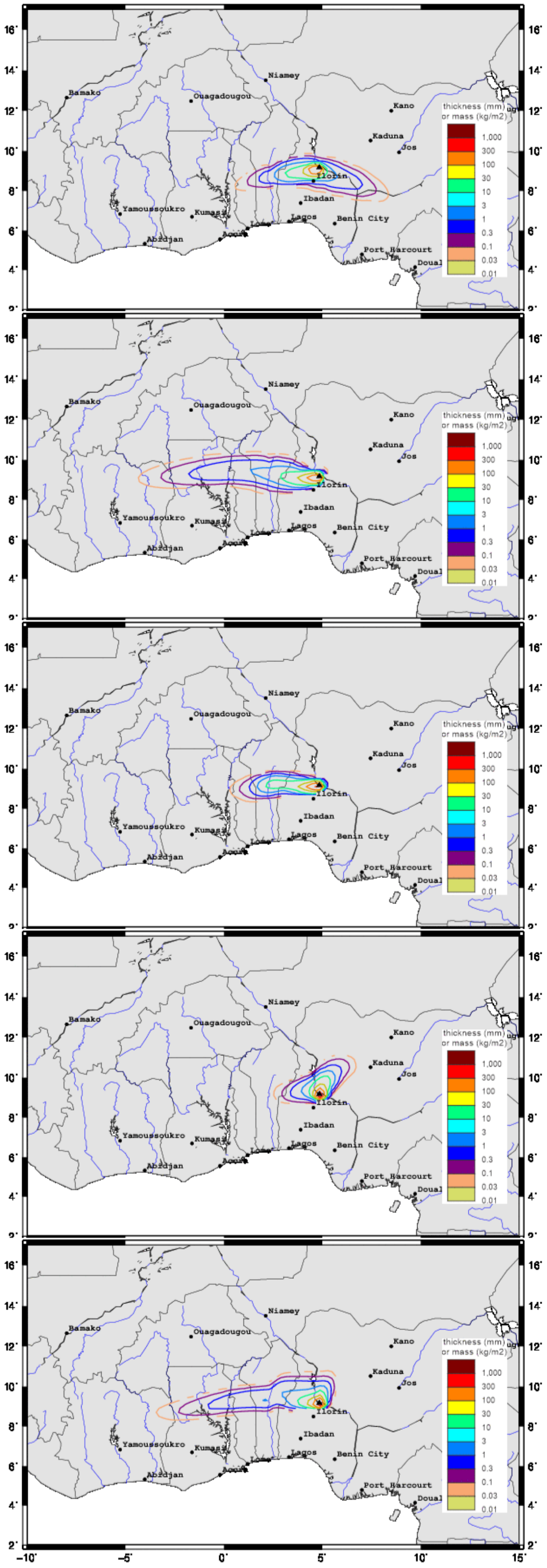

Figure 7: Ash3D dust distribution results for the Nigeria impact simulation, Oct 22, 2005–2009, at 15:04 UTC, from top to bottom, respectively. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust).

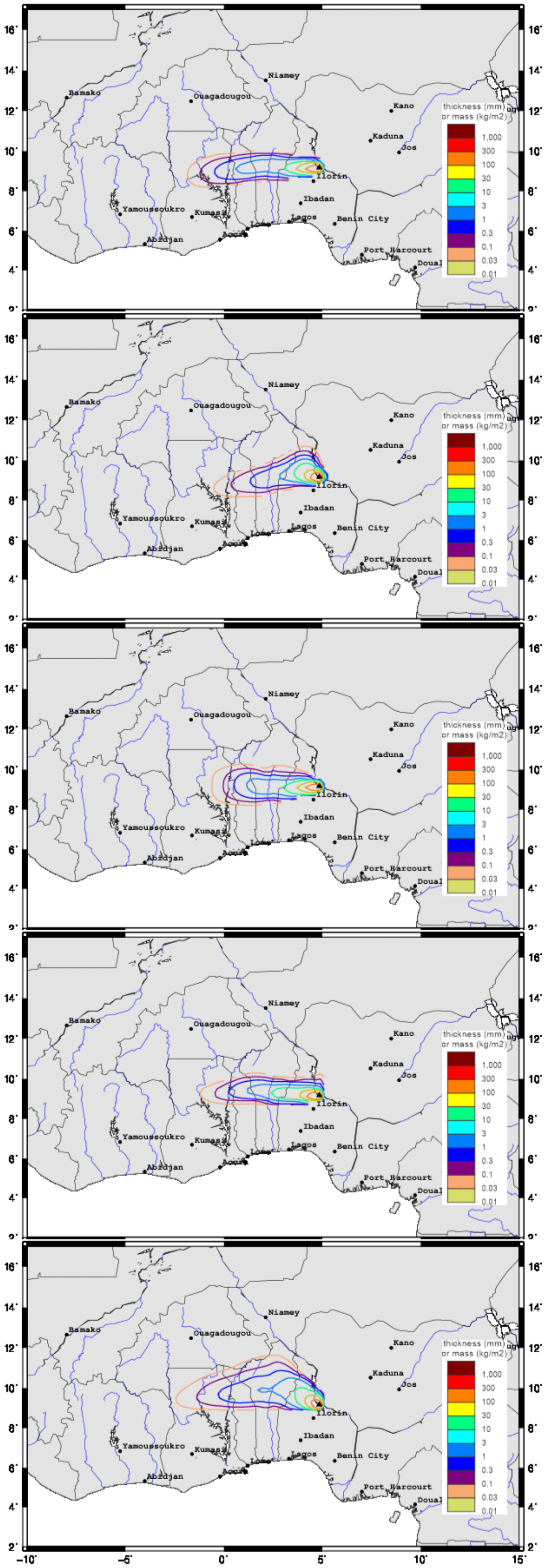

Figure 8: Ash3D dust distribution results for the Nigeria impact simulation, Oct 22, 2010–2014, at 15:04 UTC, from top to bottom, respectively. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust).

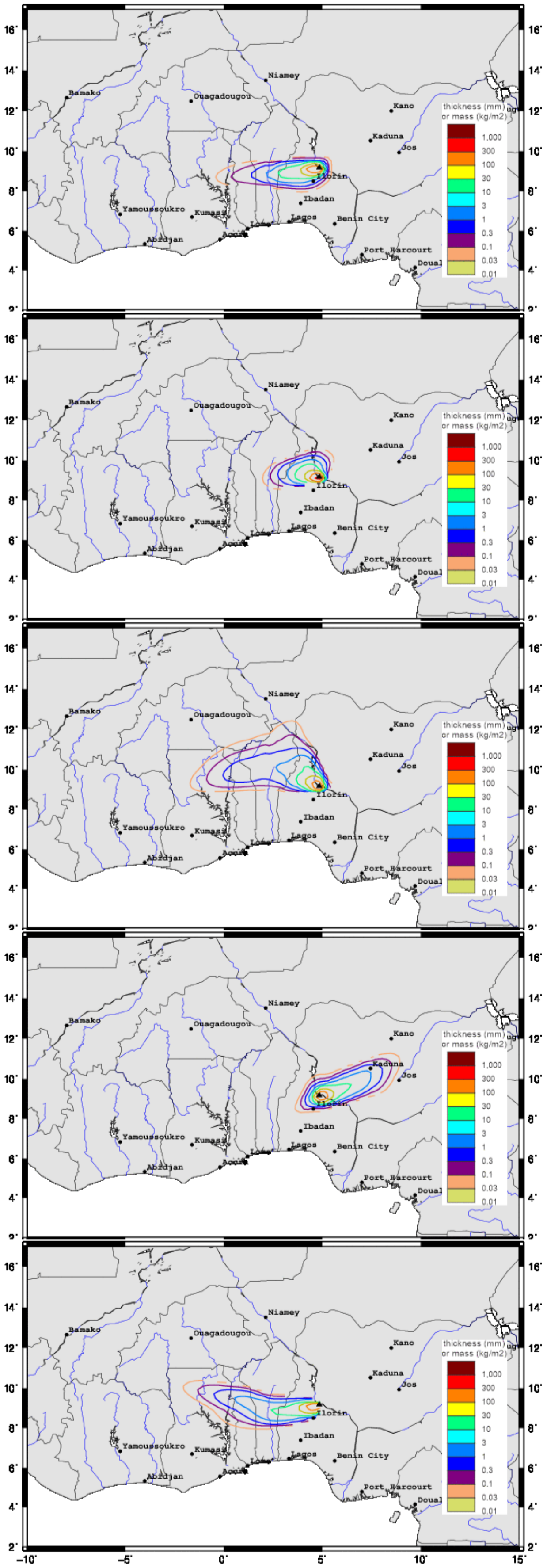

Figure 9: Ash3D dust distribution results for the Nigeria impact simulation, Oct 22, 2015–2019, at 15:04 UTC, from top to bottom, respectively. Fig. 1 has plume assumptions. Debris from the asteroid was assumed to disperse from an elevation 40 km above sea level in the atmosphere and follow the ambient wind field while falling. The size distribution of debris was assumed to be like that of volcanic tephra used in tephra dispersal simulations [6]. The duration of the event is modeled to last 0.2 hours and release 0.12 km^3 of dense rock equivalent (DRE) of ash (or dust).

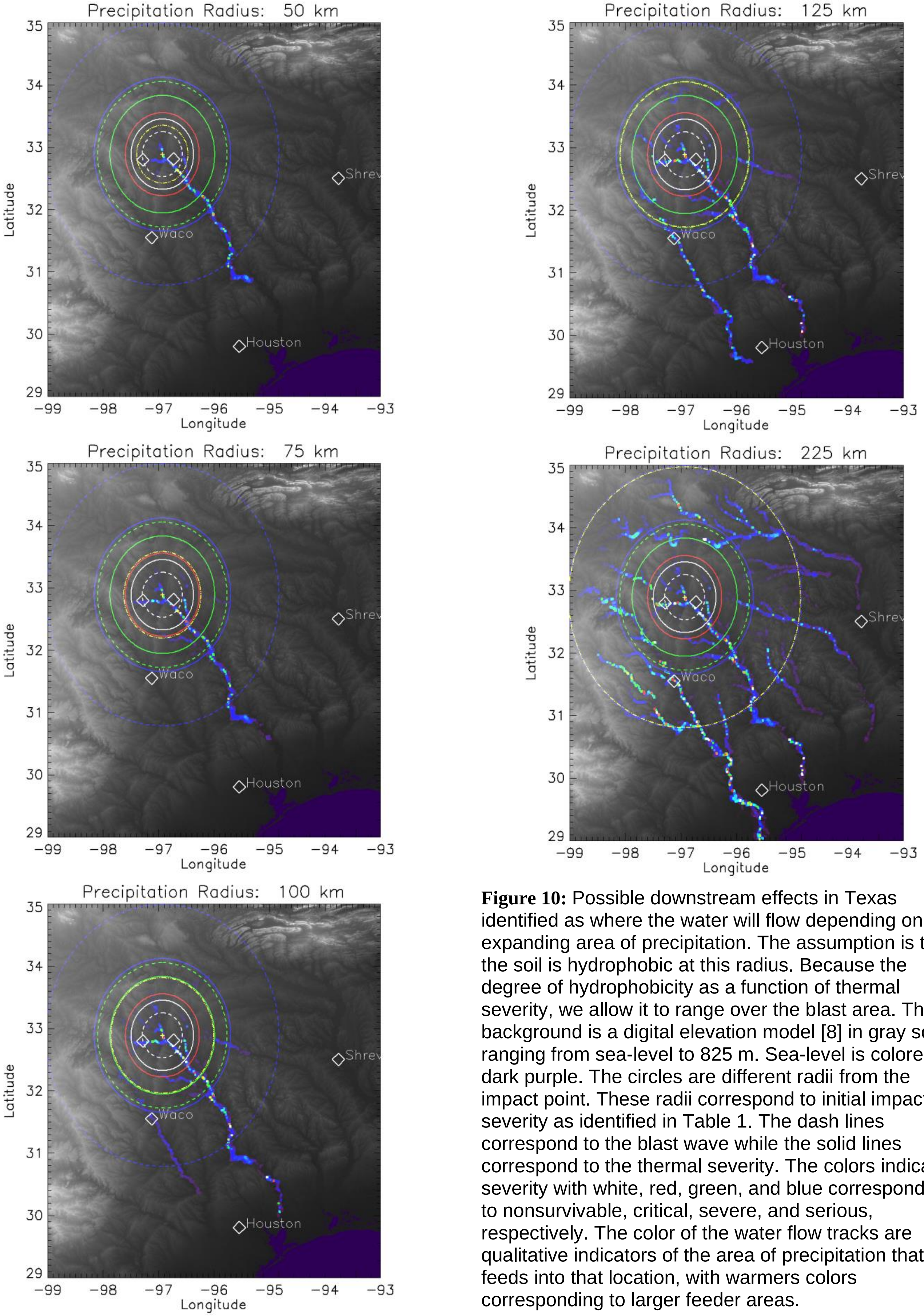

Figure 10: Possible downstream effects in Texas identified as where the water will flow depending on an expanding area of precipitation. The assumption is that the soil is hydrophobic at this radius. Because the degree of hydrophobicity as a function of thermal severity, we allow it to range over the blast area. The background is a digital elevation model [8] in gray scale, ranging from sea-level to 825 m. Sea-level is colored dark purple. The circles are different radii from the impact point. These radii correspond to initial impact severity as identified in Table 1. The dash lines correspond to the blast wave while the solid lines correspond to the thermal severity. The colors indicate severity with white, red, green, and blue corresponding to nonsurvivable, critical, severe, and serious, respectively. The color of the water flow tracks are qualitative indicators of the area of precipitation that feeds into that location, with warmers colors corresponding to larger feeder areas.

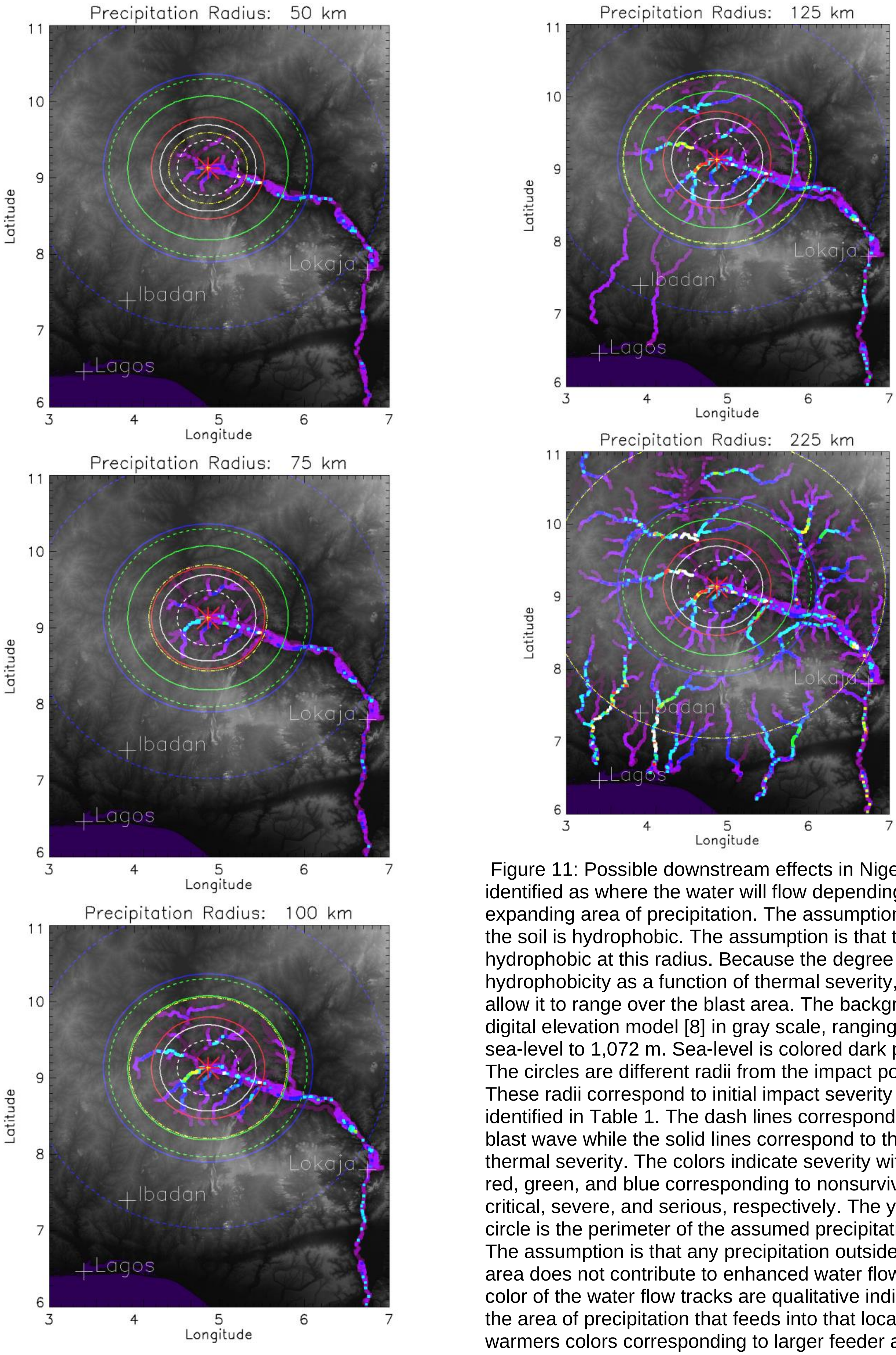

Figure 11: Possible downstream effects in Nigeria identified as where the water will flow depending on an expanding area of precipitation. The assumption is that the soil is hydrophobic. The assumption is that the soil is hydrophobic at this radius. Because the degree of hydrophobicity as a function of thermal severity, we allow it to range over the blast area. The background is a digital elevation model [8] in gray scale, ranging from sea-level to 1,072 m. Sea-level is colored dark purple. The circles are different radii from the impact point. These radii correspond to initial impact severity as identified in Table 1. The dash lines correspond to the blast wave while the solid lines correspond to the thermal severity. The colors indicate severity with white, red, green, and blue corresponding to nonsurvivable, critical, severe, and serious, respectively. The yellow circle is the perimeter of the assumed precipitation area. The assumption is that any precipitation outside of this area does not contribute to enhanced water flow. The color of the water flow tracks are qualitative indicators of the area of precipitation that feeds into that location, with warmers colors corresponding to larger feeder areas.