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A Cloud Rise Model for Dust and Soot from High Explosive Detonations

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Abstract

Traditionally, the evolution and rise of the dust and soot cloud resulting from high explosive detonations has been divided into two stages, with specific models used for each stage. In this study, based on the assumption that cloud formation progresses smoothly from stage to stage, a simple cloud rise model has been developed based on three sets of field tests of high explosive detonations (25×10^{-3} to 4.5 kg of detasheet and C-4). This model provides a good fit to observations and measurements of clouds from detonations both at ground level and 1 m above the ground. It was also found that the detonation height has a noticeable influence on cloud rise before reaching its effective height, but the influence is minor on the subsequent cloud rise.

Keywords: Cloud rise model, High explosive detonation, Lidar, Atmospheric dispersion model

1 Introduction

It is thought that the debris cloud resulting from the detonation of a high explosive, composed of entrained dirt and soot, develops through four stages. Initially, there is the generation and rapid expansion of the gaseous detonation products, which is followed by further expansion coupled with a buoyancy-driven cloud. In the third stage, cloud elevation continues, due to buoyancy and inertia, and is accompanied by cooling, until the temperature within the cloud approaches external ambient conditions. In the fourth stage, the cloud expands horizontally and vertically as a result of diffusion and turbulence caused by micrometeorological conditions [1]. The atmospheric condition, then, has little influence on the first two stages, while from the third stage onward, the influence of buoyancy and momentum resulting from the detonation starts to weaken, and the surrounding atmospheric conditions begin to dominate. Based on this view of cloud formation, analysis is usually divided into two steps: the first step usually uses a simple model to address the cloud height before it reaches its effective height [1,2]. For the second step, when the surrounding atmosphere begins dominating cloud expansion and rise, general puff or plume models starting from a volume source are used to estimate the cloud top height by estimating the cloud center height and the vertical dispersion.

There are usually two different types of models for predicting cloud rise from high explosive detonations. One predicts cloud height up to the effective cloud height (before the fourth stage) as being a function of explosive mass and dispersion time, and is represented by the Church model [2]. Subsequent cloud rise (fourth stage) is then addressed by general dispersion models. The other type of models is more complicated, and is based on first principles i.e., mass, momentum and energy balances during the detonation and subsequent transport and dispersion, with the cloud top height being estimated based on the location of the cloud center height and vertical dispersion [3–5]. Since the physics of the detonation and cloud dispersion are still ill-defined, assumptions must be made to simplify the problem. These assumptions cannot usually be satisfied, and the application of these models requires information which may not be available. Improper use of these models or incorrect information may result in significant estimation errors.

Yaar and Sharon proposed a simple model for cloud rise before the fourth stage, which provided good predictions of observations of their Green Field (GF) tests, as well as those of the Roller-Coaster series of tests [1]. Since cloud formation usually undergoes a smooth transition from stage to stage, especially over short ranges or dispersion times, it should be possible to extend the cloud rise model of previous stages into the fourth stage of cloud formation by slightly adjusting the fitting parameters without using more complex dispersion models. The development of a simple but comprehensive model extending into the fourth stage of cloud formation is described below.

Data from three series of open surface detonations at Valcartier (October 2005 and February 2007) and Albuquerque (October 2006) have been used in testing available models and for new model development. The new model is compared with other cloud rise models by examining the field observations. We will start with a brief introduction of the field measurements.

2 Experimental

Detonations of detasheet (63 % PETN(explosive), 8 % nitrocellulose, and 29 % ATBC (an organic plasticizer)) and C-4 (91 % RDX (explosive), 1.6 % Motor Oil, 5.3 % Bis(2-ethylhexy) Sebacate (plasticizer), and 2.1 % polyisobutylene (binder)) were conducted at Canadian Forces Base Valcartier, Quebec and at Sandia National Laboratories in Albuquerque, New Mexico between 2005 and 2007 under different atmospheric conditions. Detasheet of 25×10^{-3} and 50×10^{-3} kg, and C-4 of 45×10^{-3}, 2.25 and 4.5 kg were tested on different surfaces (steel, concrete, asphalt, sand, grass and packed ground), with the explosive either in direct contact with the surface or 1 m above it. Previous work had involved detonations at a height of 1 m, so this allowed some comparison between the two bodies of work that are beyond the study reported here. No noticeable difference was detected on the cloud height.

Lidar, short for LIght Detection And Ranging, is a remote sensing technique that is powered by a laser source. A lidar consists of a pulse laser source, a telescope and a fast detector. The telescope is used to collect the light of the laser backscattered by air molecules and aerosols. The time for the light to travel out to the target and back to the lidar is used to determine the range to the target. Measurement of energy at optical or infrared wavelengths permits the determination of measurable scattering, even for very small targets. Even in a "clear" atmosphere, backscatter signals from gases and suspended particles at ranges of several kilometers may readily be detected with lidar of modest performance. A GPS module, built into the lidar, combined with the backscattered signals, is used to determine the location of the aerosols causing the scattering. Consequently, it is possible to measure the position of clouds or aerosols, their motions, and most importantly, their structure (Measures, 1984 [6]). A pulsed lidar provides high power levels during the laser pulse and higher signal-to-noise ratios for the collected radiation, and can be used for long-range measurement. Today, lidars have been extensively used in atmospheric monitoring. More details of lidar operation, lidar signal and application can be found from references [6,7]. An online resource [8] for more basic lidar information is also available.

A scanning lidar system with an Nd:YAG laser source, operating at a wavelength of 532 nm, located about 300 m away from the detonation spot, was used to measure cloud concentration and expansion over time. The laser was pulse-modulated, emitting 10-ns pulses at a repetition frequency of 100 Hz. The beam divergence and receiver field of view were set at 3 and 4 mrad respectively, defining a sampling footprint of 0.9 m at a radial distance of 300 m.

The scanning optics guided the laser pulses along a raster pattern, covering an arc of 66° in 5 s or less. Each lidar emission, called a shot, generated backscattered returns at different distances along the shot. All the shots along one constant elevation formed a sweep. The speed of the scanning optics was set so that 82 shots were taken along each horizontal sweep, and a raster scan (usually consisting of 8 sweeps from lower to higher elevation, see Figure 1) was performed. The lidar scanned a volume spanned by a radial distance of 450 to 750 m, a range of 66° in azimuth, and up to 14° in elevation, as shown in Figure 1. The resolution in azimuth was 0.8°; and the resolution of the scanning lidar in elevation was 2°. The digitization rate of lidar returns was 125 MHz, giving a radial resolution of 1.2 m.

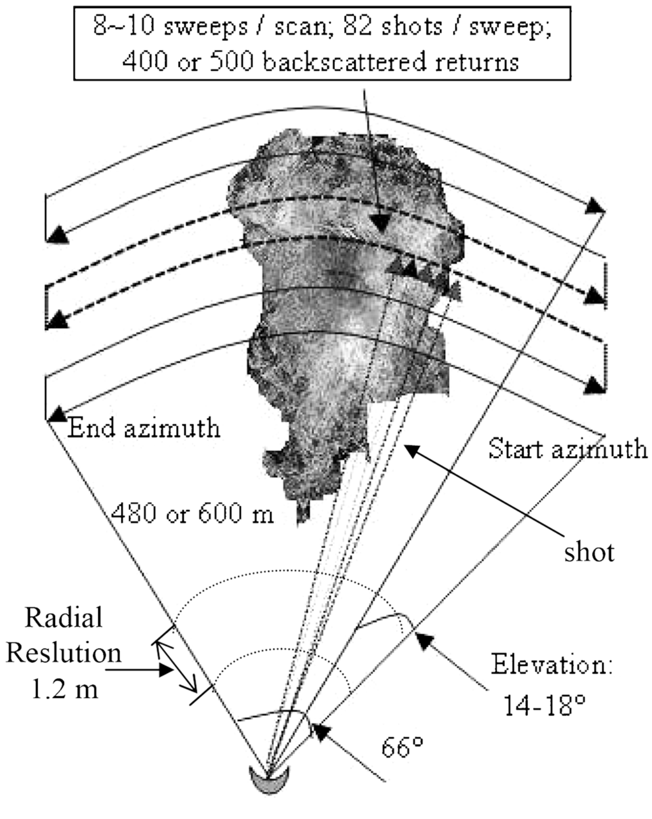

Figure 1. Raster scanning pattern of the lidar.

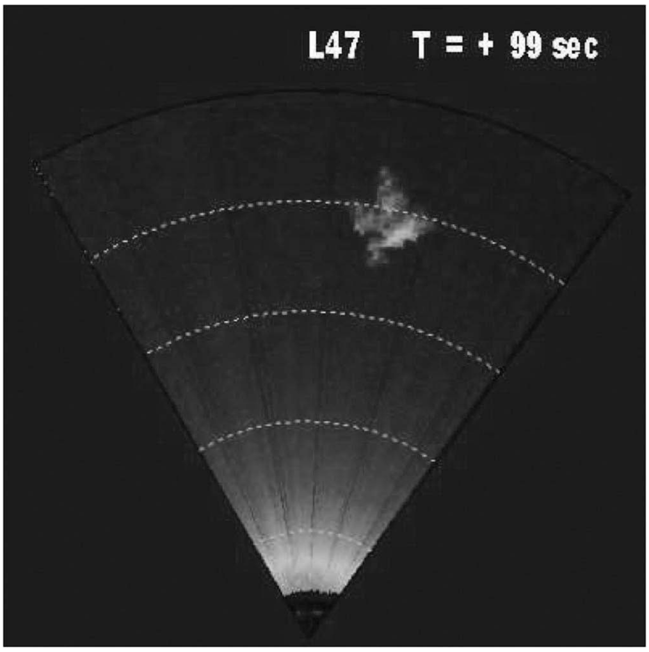

Figure 2. Slice image of a fireball (one sweep).

The lidar started to scan the cloud 3 s after the detonation, and scanned for a period of up to 150 s, depending on atmospheric stability (Figure 2). The lidar was set to scan a fixed volume of space, so the time the cloud was within the field of view was dependent upon the wind speed. Unfortunately, the unstable conditions prevailing during much of the trial periods and concomitant strong winds limited the cloud sampling times.

A weather station was installed near the lidar to measure the temperature, relative humidity at two different heights, wind velocity components, pressure and heat fluxes. The meteorological measurements were recorded at a ground station at a frequency of 25 Hz. The meteorological conditions at each trial period are summarized in Table 1.

The lidar recorded the intensity of the backscattered signal, as well as the position (distance, azimuth, elevation) and time. With this information, cloud top height could be determined as a function of time after detonation, and then used for comparison with existing models or for the development of new models. It should be noted, however, that the cloud heights used in our study were those determined from the backscattered laser signals (values above background) and were undoubtedly at locations where the aerosol concentration was below the visible threshold. Other work used for comparison employed visual means to determine cloud height that were unlikely to have been as sensitive as those determined by the lidar. We suspect that this would result in our measurements indicating cloud heights higher than those determined by visual means.

3 Results and Discussion

The cloud top heights corresponding to the time after detonation of different amounts of explosives at two detonation heights under different stability conditions are shown in Figure 3, where Figure 3a is for very small amounts of explosive (25×10^{-3}, 55×10^{-3} and 150×10^{-3} kg of detasheet, and Figure 3b shows the results of the detonation of C-4 (0.45–4.5 kg). These measurements were made under a variety of atmospheric conditions.

It seems, from Figure 3, that there is no obvious difference in cloud top height for detonations at ground level and 1 m height. However, it can be seen that cloud height is a function of both the explosive amount and dispersion time, i.e., the more explosive and the longer the time, the higher the cloud top.

The influence of atmospheric stability on the detonation-generated cloud height was also examined, with Figure 4 showing results for 0.45 kg of C-4 explosive. Atmospheric stability is characterized by Pasquill stability category [9]. It seems atmospheric stability has little influence on detonation generated cloud height.

The detasheet energy density is about the same as TNT. (See ref. [10], p. 80, Table 3.3), and the energy density of C-4, however, is 1.3 times TNT. The masses of these explosives have been converted to TNT-equivalent masses for comparison with other models based on TNT.

3.1 Examination of Published Models

Yaar and Sharon describe a few published models of the cloud top height as power-law functions of explosive amount and dispersion time before the cloud formation reaches the fourth stage, having the form:

$$H(w,t) = k \cdot w^a \cdot t^b \tag{1}$$

where H (m), is cloud top height, w (kg) is amount of TNT-equivalent explosive, and t (s) is the time after detonation. Parameters k, a, b need to be determined [1].

Table 1. Weather conditions in each field trial period.

Location	Date	Temp. (°C)	Rel. Humid. (%)	Pressure (kPa)	Wind speed ($m s^{-1}$)	Insolation ($W m^{-2}$)
Valcartier, Quebec	Oct. 18–27, 2005	3.7–8.8	55–91	98–101	0.6–5.5	29–491
Albuquerque, New Mexico	Oct. 23–Nov. 04, 2006	12.9–22	13–46.6	83–84.3	0.1–5.3	53–713
Valcartier, Quebec	Feb. 05–14, 2007	−19–−12	33–59	97–99	1.3–5.1	150–522

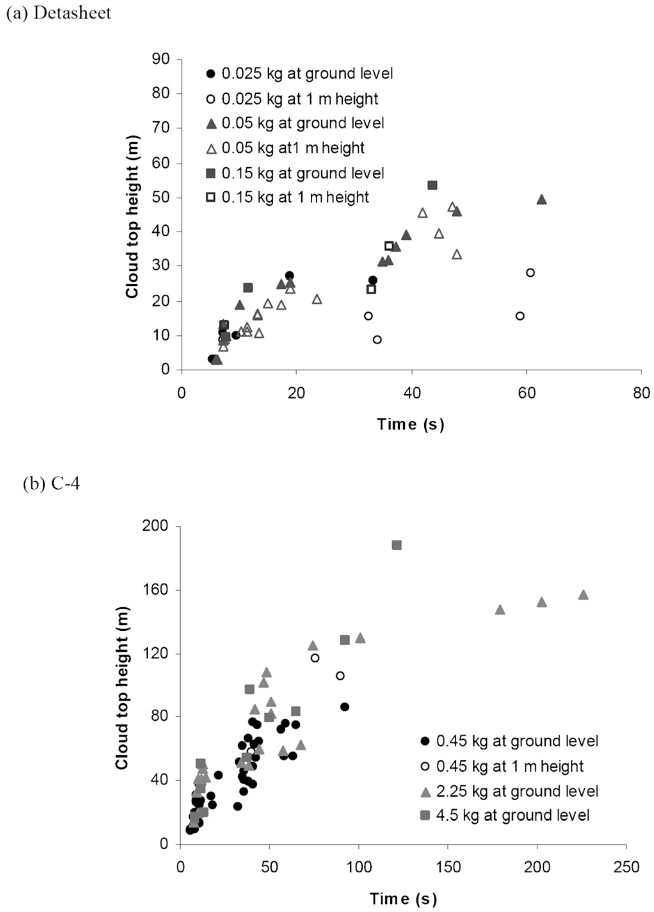

Figure 3. Time and charge mass dependence of the cloud top in the field measurements: (a) detasheet less than 0.45 kg; (b) C-4 (0.45–4.5 kg).

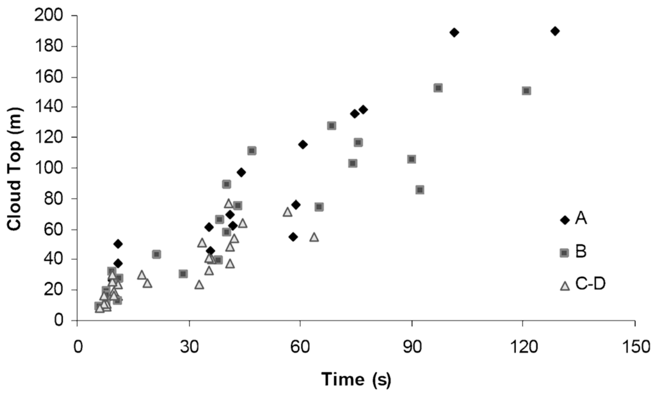

Figure 4. Time and atmospheric (Pasquill) stability dependence of the cloud top in the field measurements as result of 0.45 kg C-4 explosive yields.

Church's semi-empirical explosive-driven cloud rise model [2] relates the effective height of the detonation generated cloud top, H_e (m), to the amount of explosive used, for large charges of TNT (63.3~1020 kg). Converting weights from pounds into kilograms, it transforms the Church model to:

$$H_e(w) = 86.5 \cdot w^{0.25}. \quad (2)$$

Church's model was based on observations of large amounts of explosives, and two to three minutes after detonation when it was felt that cloud rise would no longer be affected by the detonation, and thus would be independent of time.

Yaar and Sharon [1] calibrated Equation (1) based on two series of explosive trials using varying amounts of explosives (0.25–100 kg of TNT), and found the following model to be a good fit, as long as the time was less than t_m (stabilization time, i.e., time reaching the effective cloud height):

$$H(w,t) = 6.06 \cdot w^{0.265} \cdot t^{0.534}. \quad (3)$$

where

$$\begin{aligned} &1 < t < t_m(w), \\ &\text{and } t_m(w) = (33 \pm 1)\ w^{(0.37 \pm 0.01)} \end{aligned} \quad (4)$$

When $t > t_m$, cloud motion will be the result of atmospheric advection and diffusion only, and no longer related to the momentum and high temperatures generated by the detonation, with general puff dispersion models dealing with volume sources being applicable for the prediction of cloud top height. Here, the estimated vertical dispersion is added to the estimated puff center height to give the cloud top height [3]:

$$H(x) = \begin{cases} H_c(x) + 2.15\ \sigma_z(x); & H_c(x) + 2.15\ \sigma_z(x) < H_m \\ H_m & ; H_c(x) + 2.15\ \sigma_z(x) \geq H_m \end{cases} \quad (5)$$

where $H_c(x)$ is cloud center height at distance x from the source, $\sigma_z(x)$ is the vertical dispersion coefficient at distance x, and H_m is the mixing height. All $H_c(x)$, H_m and $\sigma_z(x)$ values are functions of atmospheric turbulence and stability.

When the dispersion time is far longer than the stabilization time, i.e., $t \gg t_m$, classical semi-empirical dispersion models become appropriate, as beyond this point, turbulence will play a major role in cloud dispersion. The challenge here is that for the simpler models (Gaussian puff and plume), the stability categories used to determine the dispersion coefficients are quite broad, whereas more complex Lagrangian models need significantly more information to calculate turbulence statistics and derive internal parameters. All to say that even these classical approaches are subject to large inherent uncertainties in their predictions. For determining cloud heights at times slightly beyond t_m, ($t \geq t_m$, or for short dispersion times within stage 4), it should be possible to extend the simple cloud rise model into stage 4, as the transition from stage

3 to stage 4 is smooth, with no abrupt change of cloud height being expected.

3.2 Cloud Rise Model Development

The Church model only addresses effective cloud height, while the Yaar and Sharon model addresses cloud top height both before and when at the effective height. The Church model determines cloud height as a function of explosive weight alone, and is appropriate for predicting cloud top heights for large explosive yields. The Yaar and Sharon model, on the other hand, was developed for small-to-medium amounts of explosive charges. We have developed a simple model that covers the first three stages of the cloud formation, and a limited amount into the fourth stage.

Based on the Yaar and Sharon model, the time for a detonation-generated cloud to reach its effective height (for small explosive charges) is very short. It takes only 8.4 s for 25×10^{-3} kg or 60 s for 5 kg of TNT-equivalents after detonation. During our field experiments, we usually started lidar scans 3 s after detonation (before then, the clouds tended to be too optically dense, rendering them opaque to the lidar laser signal) and the scan interval was about 15 s. Therefore, most of the cloud top height observations based on lidar measurements were actually of cloud formations at stage 4.

The Yaar and Sharon model has shown that Equation (1) can be a proper model in estimating the effective cloud top height when appropriate values for coefficients k, a, b are used. Consequently, based on the data collected from our field experiments, parameters for a model with the form of Equation (1), as well as other forms, were adjusted to minimize the least square errors between the predicted and the observed cloud heights. Parameters showing best fit are used and the corresponding model is:

$$h(w,t) = 7.4 \cdot w^{0.18} \cdot t^{0.55}. \qquad (6)$$

Based on Eqs. (3) and (4), stabilization time t_m and effective heights from the Yaar and Sharon model at t_m are calculated and shown in Table 2. The Church model predictions are also shown in the same table. The recommendation for the Church model application to the cloud height was for 2 minutes after detonation for all explosive yields of 50 kg to 200 tons. Here, we also assume Church's prediction is applicable for small explosive yields at 2 min after detonation. Predictions from all three models (Yaar and Sharon, Church and our model) are compared with field measurements and are shown in Figure 5.

It was found that predictions of cloud top height from our model were always greater than corresponding predictions from the Yaar and Sharon model. Further, for 2 min after detonation, Church model predictions were slightly higher than Yaar and Sharon model predictions, but still very close. Consequently, one could say that Yaar and Sharon provide a more generalized Church model for small explosive yields. When our model was compared with Yaar and Sharon's for $t \leq t_m$, it could be seen that our predictions were about 33 % higher than those from Yaar and Sharon model for 0.6 kg explosive yields, and about 10 % higher for 6 kg yields. In other words, the differences between these two models decrease when explosive amounts increase. When compared to field measurements, as noted above, both model predictions are close, when $t \leq t_m$.

For $t > t_m$, Church model predictions are always slightly higher than extrapolations from the Yaar and Sharon model, but lower than predictions from our model (which remain the closest to our field measurements). However, the greater the amount of explosive charges used, the less is the difference between the two extremes of our model and that of Yaar and Sharon.

4 Conclusion

To date, models developed to predict the height of the debris and soot cloud resulting from the detonation of high explosive charges have treated the phenomenon in two distinct regimes, i.e., before and after cloud formation reaches stage 4. The model for cloud rise before stage 4 is usually a function of explosive amount and dispersion time only, and models for cloud rise after stage 4 are functions of turbulence and other atmospheric parameters only. However, this study has shown that it is possible to develop a simple model covering the first three stages and part of the fourth stage, to give a good estimation on cloud rise without considering the atmospheric stability explicitly (since stability has been observed to have little influence on detonation-generated cloud heights within short times after detonation, e.g., less than 120 s.

This model was formulated based on lidar scanning results of detonation tests performed using 25×10^{-3} to 454×10^{-3} kg of detasheet or C-4 at ground level on different surfaces and under different stability conditions, and

Table 2. Effective cloud top height and corresponding time.

Amount of explosive	TNT Equivalent (kg)	t_m (s)	h_e (m) Yaar and Sharon	h_e (m) Church
25×10^{-3} kg detasheet	0.025	8.4	7.1	34.4
50×10^{-3} kg detasheet	0.05	10.9	9.8	40.9
45.4×10^{-2} kg C-4	0.59	27.1	30.7	75.8
2.27 kg C-4	2.95	49.2	64.7	113.4
4.54 kg C-4	5.90	63.6	89.1	134.8

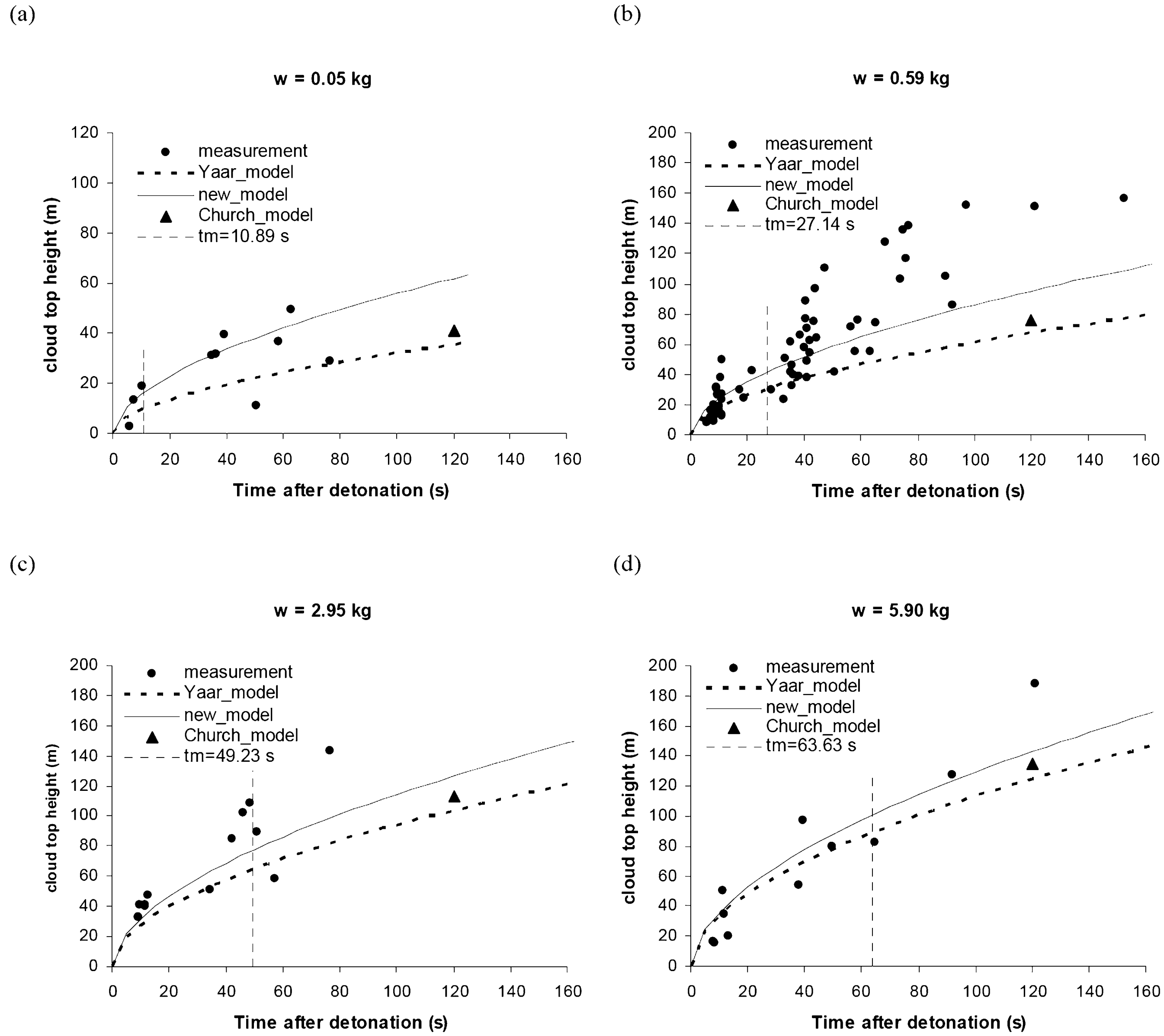

Figure 5. Models comparison with field measurement on cloud top height within 2 minutes after detonation of small amount of TNT equivalent (0.05 kg to 5.9 kg). Yaar model means Yaar and Sharon model.

the amounts of different explosive charges used being considered as TNT-equivalents, based on their energy density. There is not much difference between our model and that of Yaar and Sharon, when predictions are compared with field measurements, within the stabilization time specified by the Yaar and Sharon model. The major difference between these two models is with predictions for times beyond t_m for very small explosive yields (less than 0.45 kg), as our model predictions for 2 min after detonation cloud be twice those of the Yaar and Sharon model. The more explosive used, the less the difference between the two models.

Church's model predictions are very close to Yaar and Sharon model predictions at 2 minutes, so it is possible that the Church model could also be used for smaller explosive yields, although it has not been validated for less than 0.45 kg of TNT equivalent.

It is felt that the difference between our model and that of Yaar and Sharon is mainly due to the fact that they were developed from cloud data measured using different technologies. Further, although Church model predictions deviated significantly from our measurements for extremely low explosive yields, e.g., below 0.45 kg., due perhaps to the increased sensitivity of lidar measurements compared to visible-light video cameras. Our model, on the other hand, was based on small explosive yields (less than 10 kg TNT equivalent) only, so its application to large explosive yields has yet to be validated.

We also tried our model with HE data reported in reference [2], for large explosive yields. We compared our model predictions with Yaar and Sharon's model and Church's model for TNT yields from 63.5 to 725 kg (140 to 1600 lbs). Our model under-estimated the cloud top. Since the Yaar and Sharon model was based on explosive yields in this same range of explosive amounts and these data were collected using the same measuring technology, it is not surprising that their predictions were close to each other. Our model was based on cloud data from very small yields (less than 10 kg), so extrapolations beyond this range would be of questionable validity. That notwithstanding, we found that predictions from our model, as well as from those of Yaar and Sharon and Church, match for explosive yields of up to 50 kg TNT equivalent, within differences of less than 10%. For explosive yields greater than this, our model predictions will be lower than those from either of the other two models, e.g., our model underpredicts by 25% for an explosive yield of 725 kg.

5 Future Work

One of the weaknesses in our model, which applies equally to the other models referred to above, is the paucity of data. In fact, data collection is challenging, at best. If we have the opportunity, we will attempt to expand our range of data, both in terms of measuring cloud heights and cloud development for larger charges and under a wider variety of atmospheric and micrometeorological conditions. More data would also enhance validating our model, as we would be able to compare predictions with measurements not previously used in model development. A further investigation would be to develop a calibration factor that would correlate our laser-based measurements with cloud heights derived from optical/visual media, e.g., film. We would then be able to better compare models and measurements based on the two detection methodologies. All this said, we still feel that our model best represents the data we obtained and provides the simplest, most direct and most accurate predictions of the cloud height of soot and debris resulting from the detonation of small charges of high explosives, at or near ground level, during the first three stages of cloud development and into the fourth stage.

Acknowledgments

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References

[1] I. Yaar, A. Sharon, Calibration of a Cloud Rise Model for a RDD Scenario from Prevention, Detection and Response to Nuclear and Radiological Threats, in (Eds.: S. Apikyan, D. Diamond, R. Way) *Proceedings of the NATO Advanced Research Workshop on Prevention, Detection and Response to Nuclear and Radiological Threat* (PDR-2006), 25–29 September 2006, Springer, Netherlands, **2008**, p. 193.

[2] H. W. Church, *Cloud Rise from High Explosive Detonations*, Report SC-RR-68-903, **1969**. Sandia Laboratories, Albuquerque (now Sandia National Laboratories, Sandia), USA.

[3] J. R. Bjorklund, J. F. Bowers, G. C. Dodd, J. M. White, *Open Burn/Open Detonation Dispersion Model (OBODM) User's Guide*, Report DPG-TR-96-008b, April **1998**, West Desert Test Center, U.S. Army Dugway Proving Ground, Dugway, USA.

[4] E. J. Kansa, *A Time-dependent Buoyant Puff Model for Explosive Sources*, Report UCRL-ID-128733, **1997**, Lawrence Livermore National Laboratory, Livermore, USA.

[5] B. A. Boughton, J. M. DeLaurentis, An Integral Model of Plume Rise from High Explosive Detonations, *24. National Heat Transfer Conference and Exhibition*, 9 Aug **1987**, Pittsburgh, USA.

[6] R. M. Measures, *Laser Remote Sensing: Fundamentals and Applications*. John Wiley & Sons, New York, **1984**.

[7] B. T. N. Evans, *Lidar Signal Interpretation and Processing with Consideration for Military Obscurants*, Report DREV R-4477/88, Valcartier, Canada, **1988**.

[8] http://home.iitk.ac.in/~blohani/LiDAR_Tutorial/Airborne_AltimetricLidar_Tutorial.htm.

[9] F. Pasquill, F. B. Smith, *Atmospheric Diffusion*, 3rd ed. Halsted Press, New York, USA, **1983**.

[10] M. L. Wilkins, *Computer Simulation of Dynamic Phenomena*, Springer, New York, **1999**.

