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Spreadsheet Model of COVID-19 Transmission: Evaporation and Dispersion of Respiratory Droplets

Gavin A. Buxton,
Robert Morris University, buxton@rmu.edu

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Abstract

A spreadsheet model of the projectile motion, evaporation and dispersion of respiratory droplets is presented to introduce students to mathematical modeling, computer simulations and important aspects of the science behind the COVID-19 pandemic. The model is simple enough to be implemented by undergraduate biology and health science students, and enables students (and health professionals) to explore the role of droplet size, proximity and environmental conditions on SARS-CoV-2 transmission. It is hoped that this model will help students to better understand the science behind the current pandemic, the practices implemented to mitigate outbreaks, and the seasonality of outbreaks.

1. Introduction

While healthcare worker and first responders are on the frontlines of the COVID-19 pandemic, there are also many scientists and researchers studying the coronavirus and its transmission on an unprecedented scale. In addition, the public has been asked to help contain and mitigate the spread of this disease through social distancing and by wearing face masks. Biology students are obviously curious about the research and science surrounding this pandemic. Incorporating the science behind this current pandemic, and potentially other looming outbreaks, in the classroom can make learning about this important issue more meaningful, and help students connect what they are learning back to the real world. Here, a spreadsheet model of disease transmission and social distancing is detailed that is simple enough to be implemented by undergraduate biology majors, yet captures the necessary science to elucidate the role of social distancing and environmental factors on the transmission of diseases.

SARS-CoV-2, the virus behind the COVID-19 disease, is believed to be transmitted through direct contact [1], and faecal–oral transmission [2] but most probably through respiratory droplets [3]. Pathogens can be exhaled by an infected individual in the form of droplets that can land on surfaces turning them into potentially infectious fomites [4], infect other people in close proximity when directly inhaled, or become airborne and linger in the air for prolonged periods of time [5, 6, 7, 3]. The respiratory fluid droplets, while prevalent when a patient coughs, are also exhaled by asymptomatic individuals when talking and breathing [8]. The droplets initially have a wide range of sizes, which immediately evaporate to form smaller droplet nuclei [5, 6]. Larger droplets have sufficiently high terminal velocities that they fall to the ground within a few seconds, while smaller droplets have a negligible terminal velocity and become airborne, where they can be transported by air currents over great distances for very long times [5, 9, 10, 7]. The cross-over between these two modes of transmission is thought to occur at around 5 μm [9]. While transmission varies with environmental conditions and other factors, respiratory droplets are thought to be the most common form of transmission during outbreaks [11, 10, 12].

Social distancing measures, where everyone is asked to remain 2 m (or 6 feet) or more from others, is considered crucial for mitigating the spread of disease. A drop-off in transmission rate occurs with social distancing, which is often attributed to the larger respiratory droplets falling to the ground over distances of 0.5 to 1.5 m [9, 6]. Socioeconomic and environmental conditions can make social distancing more difficult for some, and one possible explanation for seasonal outbreaks is the increased indoor crowding during colder months [12]. While no seasonality has been established for COVID-19, health officials have predicted that there will be a seasonal decrease in transmission rates and the outbreak will slow down by summer [13]. While, the reasons behind seasonal variations in influenza and other virus outbreaks remain unclear, there are clear indications that temperature and humidity play a large role [14, 15, 16, 17], and this is expected to be the case with the current COVID-19 outbreak [18]. These factors can be explored in a classroom setting through simple computer simulations.

Computer simulations play an increasingly important role in biological and medical research [19], and it is imperative that students become more proficient in computer simulations in order to understand and utilize these tools [20]. Furthermore, it has been found that spreadsheets are the ideal platform for introducing undergraduate biology majors to mathematical modeling and computer simulations [21]. Therefore, a spreadsheet model is presented that predicts the role respiratory droplets play in pathogen transmission. The model is simple enough for undergraduate biology majors, with little prior exposure to computer modeling, and will allow students to elucidate an important aspect of disease transmission that emphasizes the relevance of computer simulations in medical research.

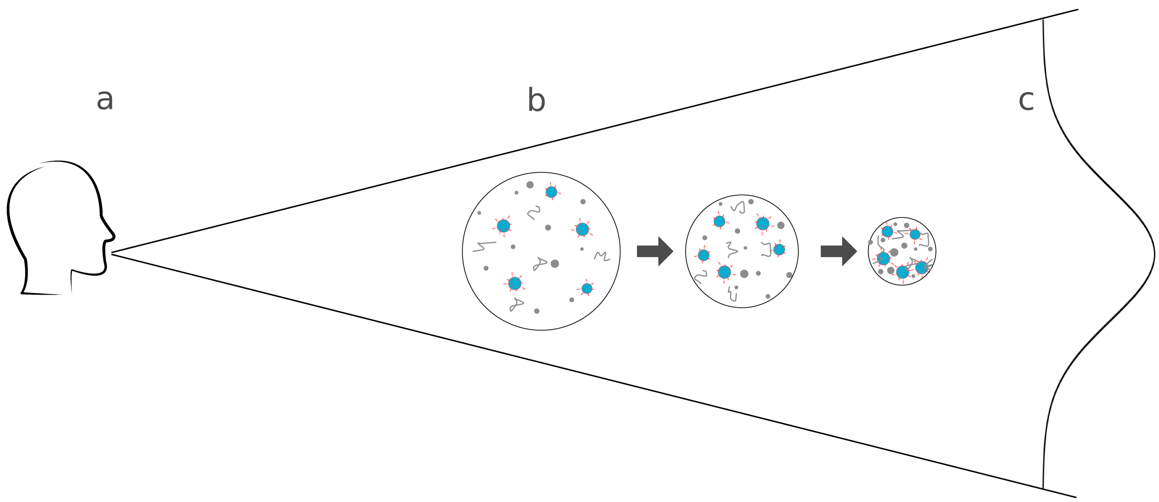

Figure 1. A schematic of the computer model showing a) the emission of respiratory droplets, b) there motion and evaporation, and c) their increasing dispersal with distance.

The computer model is schematically depicted in Figure 1. In Fig. 1a an infected person is depicted breathing or talking, and emitting a large number of respiratory droplets into the air. These droplets are in a variety of sizes, ranging from less than 1 μm up to around 100 μm. As these droplets move through the air, as shown in Fig 1b, they evaporate resulting in a droplet size that reduces with time. These droplets not only contain water, however, but insoluble particulates such as proteins, enzymes, and (potentially) SARS-CoV-2 infectious agents. This limits the size that the droplets will evaporate to. Once most of a droplets water content has evaporated the remaining particle is called the droplet nuclei. In addition, the droplets are also subject to drag forces, as they move through the air, and gravity. These particles are, therefore, carried along by the air currents, and the concentration of droplets disperses in the turbulent eddies that occur in typical air flows. The Gaussian concentration profile of droplets as they diffuse out in directions perpendicular to the direction of air flow is shown in Fig. 1c. In particular, the flow is treated as uniform and the dispersion of breath is captured using a Gaussian puff model; a simple model of pollution dispersion from an instantaneous source (here, a breath) that assumes the pollutants disperse as an expanding Gaussian concentration as they drift in the background air flow. The equations that capture these processes are now detailed.

2. Mathematical Model

There are three aspects to this mathematical model. First, the drag forces and terminal velocity of the droplets have to be described to dictate their settling motion. Second, the evaporation dynamics of the droplets will determine their time-dependent particle size (which feeds back into the terminal velocity equations). Finally, the fluid dynamics have to be described to capture the motion of the droplets in a background air flow.

a. Terminal velocity

The acceleration of a droplet can be described using the following equation

$$\mathbf{a} = \frac{3\rho_a}{4\rho_d d} C_D v^2 \hat{\mathbf{v}} + \frac{\rho_d - \rho_a}{\rho_d}\mathbf{g}$$

where ρ_a is the density of the air, ρ_d is the density of the droplet, d is the diameter of the droplet, C_D is the drag coefficient, the velocity of the droplet relative to the surrounding air is $\mathbf{v}$, and gravitational acceleration is $\mathbf{g}$. Only gravity, buoyancy and drag force are required, while all other forces are negligible [22, 23, 24, 7] given the difference in densities between water and air (the buoyancy force could also be ignored for this reason). Due to their small size, the droplets reach terminal velocity in a very short amount of time. Therefore, the velocity of the particles can be considered the same as the velocity of the air around them, with the addition of a terminal velocity of the form

$$v_y = \sqrt{\frac{4d(\rho_d - \rho_a)g}{3\rho_a C_D}}$$

The drag coefficient depends on the Reynolds number

$$C_D = 24(1 + 0.15 Re_p^{0.687})/Re_p$$

which is given as

$$Re_p = \frac{\rho_a v d}{\mu}$$

where μ is the viscosity of air. For small velocities this is equivalent to Stokes' law. Given the droplet diameter, and the velocity of the surrounding air, the motion of a droplet can be predicted using the above equations.

b. Droplet evaporation

The diameter of a droplet changes as the water evaporates up until a critical time, t_{crit}, when the droplet diameter has reached its minimum, d_{min} [25, 15, 10].

$$d = \begin{cases} d_0\sqrt{1-\beta t} & \text{if } t \leq t_{crit} \\ d_{min} & \text{if } t > t_{crit} \end{cases}$$

where t is time, and β is the evaporation rate given by

$$\beta = \frac{8D(P_{sat} - P_\infty)}{d^2 \rho R_v T}$$

where D is the molecular diffusivity of water vapor, P_{sat} and P_∞ are the saturation and ambient water vapor pressures, R_v is the specific gas constant for water, and T is temperature.

The minimum diameter is considered to be 44% of the original diameter, or $d_{min}/d_0 = 0.44$ [26, 10]. However, others have argued for smaller values, or that the minimum diameter might depend on the ambient humidity [6], which could easily be adopted into this spreadsheet model. $R_v = 461.52$ J/(kg K) is the specific gas constant for water and the saturation water vapor pressure in Pascals can be obtained from the Buck equation [27].

$$P_{sat} = 611.21 \exp\left(\left(19.843 - \frac{T}{234.5}\right)\left(\frac{T - 273.15}{T - 16.01}\right)\right)$$

The ambient water vapor pressure in Pascals is given by

$$P_\infty = P_{sat}\frac{RH}{100\%}$$

where RH is the relative humidity and the molecular diffusivity (in m^2/s) of water vapor in air is given by

$$D = 2.16 \times 10^{-5} \left(\frac{T}{273.15} \right)^{1.8}$$

While more complicated models of droplet evaporation exist, that take into consideration temperature variations [28, 29, 30], these are not necessary for respiratory droplets that cool down much faster than they evaporate [10]. In terms of the movement of respiratory droplets, the important aspect of this model is that it captures the decrease in droplet diameter as a function of time. However, note that environmental conditions such as the temperature and humidity can affect droplet evaporation, and the will play a role in COVID-19 transmission through respiratory droplets.

c. Gaussian puff model

The droplets are also carried by air currents, and there has been a large number of computational fluid dynamics (CFD) studies that can capture the complex air flow in hospitals, office buildings, aircraft cabins and other areas of pathogen transmission [31, 7, 32, 33]. In addition, the velocity field associated with coughing can also help propel respiratory droplets [34]. The velocity profiles created as someone coughs and sneezes can propel respiratory droplets on a plume of breath that is projected into the air. Furthermore, the air flow in indoor environments can involve complex recirculations and ventilation systems. Such complicated fluid dynamics, while the focus of other computational studies, is beyond the scope of the current model, and (arguably) the capabilities of typical undergraduate students. However, given the asymptomatic transmission that is believed to occur with COVID-19 [3], it can be assumed that the airflow is steady with negligible perturbations from exhalation. Therefore, as a first approximation it can be assumed that the velocity of the air is horizontal, with turbulent eddies that diffuse the airflow in perpendicular directions. Each breath is captured using a Gaussian puff model that assumes the concentration of the droplets can be described by an ever expanding Gaussian distribution [35].

$$c(x,y,z,t) = \frac{q}{(\sqrt{2\pi}\sigma)^3} \exp\left\{-\frac{1}{2\sigma^2}\left[(x-x_d)^2 + (y)^2 + (z-z_d)^2\right]\right\}$$

where q represents the number of droplets emitted of a given size, σ is the dispersion coefficient (which we assume to be the same in the downwind, crosswind and vertical direction), and x_d and z_d represent the horizontal and vertical position of a droplet, respectively. These positions can be obtained as a function of time from the horizontal air flow and terminal velocity, respectively. The value of the source strength in the current model could be obtained from experimental studies on the number of droplets emitted as a function of droplet size. The distribution of droplets emitted by an infected person can vary significantly between different individuals. Furthermore, the distribution also varies considerably based on the activity of the person (speaking, shouting, coughing, e.g.). The exposure of a person to a concentration of droplets is obviously going to be proportional to the concentration emitted, and while the current model looks at the exposure relative to the source strength (essentially putting the source strength equal to 1), it is easily extendable to account for different size distributions. The dispersion coefficient increases with distance downwind

$$\sigma = ax^b$$

where, for a neutrally stable Gaussian puff model, $a = 0.06$ and $b = 0.92$ [35, 36]. The greater the downwind distance from the source, the greater the dispersion and the lower the concentrations. The dispersion coefficients describe the extent of dispersion as a function of the downwind direction. The dispersion coefficients used here are for neutral conditions (perhaps corresponding with a windy, but overcast and cloudy day); lower wind speeds and higher solar insolation might, for example, double the values used here. The values used in the current model are consistent with Halloran *et al.* 2012 [10]. For simplicity, this model ignores effects such as the reflection of pollutants from surfaces and buoyancy forces, which can be implemented in Gaussian puff models. However, one of the wonderful aspects of teaching research to students is the emphasis that research is a work in progress and such effects could be implemented if desired.

In order to capture the fluid dynamics of more complex air flows (including the effects of confinement, ventilation systems, buoyancy and the velocity of air flow as patients cough, for example) a computational fluid dynamics model would have to be implemented. Such a fluid dynamics model, while difficult, is not beyond the capabilities of spreadsheet modeling (for a spreadsheet implementation of the lattice Boltzmann method see Buxton 2015 [37]). However, this would be time consuming to run as the fluid would have to be updated (using a macro) at each time step and would be more applicable to a model that a student might implement as part of a senior thesis, rather than within a classroom environment. Other simple dispersion models exist. For example, the plume model can be more appropriate for a continuous source of pollutants and has been used for systems involving animals (where the confined animals can be treated as a continuous source of respiratory droplets when averaged over long timescales). Here, however, we consider people that can be more mobile and the dispersion of respiratory droplets from an isolated breath.

Here, we are interested in the concentration of the puff that interacts with a person a distance of L away from the source, and at a height Δh below the source.

$$c(L, \Delta h, t) = \frac{q}{(\sqrt{2\pi}\sigma)^3} \exp\left\{-\frac{1}{2\sigma^2}\left[(L - x_d)^2 + (z_d - \Delta h)^2\right]\right\}$$

The dose of respiratory droplets that the person has been exposed to up to the time, t, is the concentration of the puff integrated over the time that the puff travels past the person

$$Dose(L, \Delta h, t) = \int_0^t c(L, \Delta h, \acute{t})\, d\acute{t}$$

In particular, as the Gaussian puff of droplet concentrations pass the location of the second person then the concentration that the second person is exposed to is calculated as the integration of the concentration at the location of the second person with respect to time. For simplicity, this exposure is considered at a point in space, a given distance away and and a given height below the site of droplet emission. In this manner the exposure of a person to COVID-19 pathogens inside respiratory droplets can be obtained as a function of the initial droplet size, the ambient temperature and humidity, and background air flow. In addition students can explore the introduction of buoyancy in the Gaussian puff model, varying the minimum diameter of the droplets (and potential humidity-dependence), or capture the dose over an area rather than just at a point. Therefore, this model could be used both in a classroom as an introduction to mathematical modeling and spreadsheet simulations, or as a spring board for a more complicated student research project.

3. Implementation

Undergraduate biology students are not typically exposed to computer programming in their course of study, and so including spreadsheets into their curriculum offers a wonderful environment to both introduce students to computer models and for students to obtain increased spreadsheet proficiency.

A layout of the spreadsheet model is depicted in Figure 2, and a copy of the spreadsheet is included as supplementary material. Constants used in the model are contained at the top of the spreadsheet, although it is worth noting that some of these constants are determined through calculation. Cells that contain constants at the top of the spreadsheet are shaded pink if they contain universal constants, or calculations from other variables. Where applicable the units of the constants are also included in adjacent cells.

	A	B	C	D	E	F	G	H	I	J
1										
2										
3		d_0	1.00E-05	m		rho_p	1000	kg/m3		
4		T	293.15	K		rho	1.21	kg/m3		
5		RH	60	%		g	9.81	m/s2		
6		vx	1	m/s		viscosity	1.81E-05	Pa s		
7										
8										
9		d_min	4.4E-06	m		dt	5.00E-03	s		
10		P_sat	2338.3399785	Pa		L	2	m		
11		P_infinity	1403.0039871	Pa		height diff.	0	m		
12		D	2.452977E-05	m^2/s						Dose
13		Rv	461.52	J/(kg K)		a	0.06			12.349810075
14		beta_min	13.566587132	s^-1		b	0.92			
15		beta_max	70.075346755	s^-1						
16										
17	t	d	beta	vz	Re	CD	xd	zd	sigma	Dose
18	0	1.00E-05	13.566587132	0.0009584469	0.0006407297	37493.253315	0	0	1.00E-05	0
19	0.005	9.65488E-06	14.553815138	0.0016674206	0.0010762145	22330.95933	0.005	-8.3371E-06	0.0004583568	0
20	0.01	9.243711E-06	15.877346839	0.0021140622	0.0013063841	18400.091629	0.01	-1.89074E-05	0.0008672639	0
21	0.015	8.728343E-06	17.807663997	0.0022631024	0.0013205134	18203.424261	0.015	-3.02229E-05	0.0012593754	0
22	0.02	8.024006E-06	21.071144279	0.002181561	0.0011702143	20538.84503	0.02	-4.11307E-05	0.0016409632	0
23	0.025	6.879109E-06	28.668583736	0.0019016315	0.0008745111	27476.527897	0.025	-5.06389E-05	0.0020149119	0
24	0.03	4.4E-06	70.075346755	0.0013149029	0.0003867703	62094.442074	0.03	-5.72134E-05	0.0023828835	0
25	0.035	4.4E-06	70.075346755	0.0008746781	0.000257281	93331.063274	0.035	-6.15868E-05	0.0027459578	0
26	0.04	4.4E-06	70.075346755	0.0007134467	0.0002098558	114415.23936	0.04	-6.5154E-05	0.0031048916	0
27	0.045	4.4E-06	70.075346755	0.0006443661	0.0001895362	126677.54058	0.045	-6.83759E-05	0.0034602443	0
28	0.05	4.4E-06	70.075346755	0.0006123854	0.0001801293	133291.14374	0.05	-7.14378E-05	0.0038124456	0
29	0.055	4.4E-06	70.075346755	0.0005969995	0.0001756036	136725.37081	0.055	-7.44228E-05	0.0041618356	0
30	0.06	4.4E-06	70.075346755	0.0005894542	0.0001733842	138475.04898	0.06	-7.73701E-05	0.0045086903	0
31	0.065	4.4E-06	70.075346755	0.0005857184	0.0001722853	139358.02929	0.065	-8.02986E-05	0.0048532374	0
32	0.07	4.4E-06	70.075346755	0.0005838599	0.0001717387	139801.50989	0.07	-8.32179E-05	0.0051956687	0
33	0.075	4.4E-06	70.075346755	0.0005829331	0.0001714661	140023.71981	0.075	-8.61326E-05	0.005536147	0

Figure 2. A screenshot of the spreadsheet model displaying the layout of the calculations.

At time $t = 0$ the initial variables are calculated (row 18) assuming that the particle is released at $x = 0$ and $z = 0$, with a diameter set equal to the initial diameter d_0. Initially, the velocity is assumed to be the terminal velocity due to Stokes' law (ignoring the effects of drag). At the next time step the time is incremented, and the new diameter is calculated (ensuring the size does not go below d_{min}) using the evaporation rate at the previous iteration; the evaporation rate, in column C, increases as the diameter decreases. The terminal velocity is calculated using the current diameter but the drag coefficient from the previous iteration, and then used to both calculated an updated drag coefficient and to update the position of the droplet in the z-direction. The droplet position in the x-direction simply depends on the velocity and time. The time step used in the current model is 0.005 s. Note that the accuracy of the model will increase as the time step is reduced, and will become unstable at larger time steps; something that students might be encouraged to explore. The droplet position is used as an average location in the Gaussian puff model, to predict the dispersal of the concentration of droplets as they travel downwind. These concentrations at the location of another person (at a distance of x away and with a height differential of Δh) are numerically integrated in column J. In particular, there might be a significant difference in height between an adult and a child, that would be expected to significantly increase transmission rates. Decreasing Δh in the model would capture this effect. The calculations at subsequent times are obtained from copying row 19 (the first time step) to subsequent rows (representing later times). Cell J13 shows the accumulated dose that the person has been exposed after the puff of droplets has passed by.

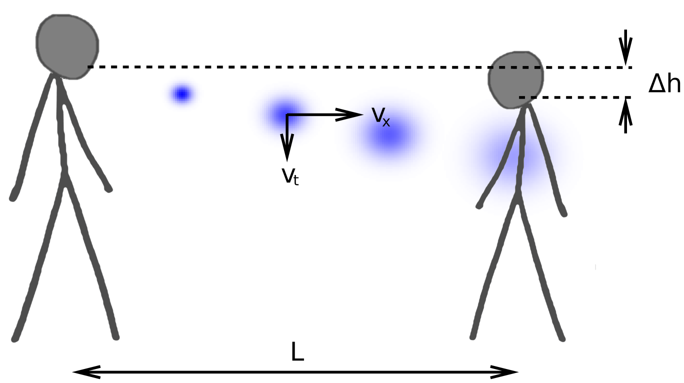

Figure 3. Two people standing a distance x away. The person on the left produces a "puff" of breath that propagates downwind and disperses before reaching another person on the right.

A typical simulation is shown schematically in Figure 3. A person at $x = 0$ emits a breath containing droplets that are assumed to travel with the air flow across to another person, a distance of x away. The respiratory droplets fall with a terminal velocity v_t and travel downwind with a velocity v_x, while the concentration of droplets is assumed to disperse according to the Gaussian puff model. Upon reaching the second individual the spreadsheet integrates the concentration of droplets at the height of the second person's mouth over time. The height of the second person is not necessarily the same as the first person.

The spreadsheet contains two additional sheets. The second sheet takes the location and size of a Gaussian puff at a given time from the first sheet and calculates the spatial distribution of the Gaussian puff. The third takes the parameters from the first sheet and calculates the relative dose of droplets for ten different initial droplet sizes. This produces a plot, similar to those presented here in Fig. 4, Fig. 5 and Fig 7., of the relative dose of droplets as a function of initial droplet size. If provided with the spreadsheet (included in the supplementary materials) then students will be able to immediately see the effects of changing variables in the first sheet.

The size of the droplets, and the minimum size of the droplet nuclei that the droplets evaporate to, can be varied in the model (cells C3 and C9), but it should be noted that experimentally there is a wide variation in reported values [6]. Most studies consider virus viability over hours, rather than the seconds considered here, and so it is reasonable to assume that no loss of viral activity occurs during the simulation [38]. That said, the amount of virus contained within the droplets may vary depending on the size of the droplets. On the one hand, small droplets have small volumes and are expected to carry small viral loads [11], but a greater number of exhaled droplets at smaller sizes [8] can still result in appreciable viral exposure [39]. Furthermore, where the droplets (or droplet nuclei) deposit in the respiratory tract will depend on their size [40]. Small droplets are more likely to be carried by the air flow deeper into the lower pulmonary region, while larger droplets are more likely to impact onto the surfaces of the upper airways [9]. Smaller numbers of pathogens are also generally required to infect the lower respiratory tract, resulting in more severe infections [40]. The effects of particle size, therefore, is crucial in this model and also impacts the precautions that healthcare professionals might have to take (special ventilation in patient rooms and full personal protective equipment, versus wearing surgical masks when in close proximity) [41]. Of course, one of the aspects that is thought to dictate increased transmission rates in the winter is the close proximity of people indoors. The air flow in an indoor environment will be much more complicated than considered in this model. However, the effects of unfiltered ventilation systems and closed environments might be expected to increase exposure to smaller respiratory droplets as the air is continually recirculated.

The typical implementation of this model in a classroom setting might consist of around 30 minutes of introduction and discussion. Then I would have students break into small groups (or individually, if they prefer) to implement the model on their own computers. I would circulate around the room and correct mistakes and help students debug their code, until all students have working models. This might take an hour or an hour and a half, given the complexity of the model and the experience of the students. I personally teach a class on computational biology, that meets weekly for four hours, and so would then have the students spend a couple of hours exploring the model and creating a preliminary result from the model. I certainly believe the complexity of this model, and the expected student interest, might warrant an additional class period for students to further explore the model. However, the time spent implementing and exploring this model will obviously depend on the class, and instructor preferences.

We can now turn our attention to the exposure of an individual to droplets of a particular diameter, as a function of different parameters in the model. The following parameters are considered: droplet size, the ambient temperature, the relative humidity and the separation distance.

4. Results

The dose is plotted relative to the dose of smaller droplets at a distance of 2 m as a function of droplet size. The dose of droplets multiplied by the volume of the droplets is depicted in the inset, as it is assumed the number of pathogens within a droplet varies with volume. However, this does not take into the consideration the number of particles emitted. Figure 4 shows the effect of varying ambient temperature. In warmer environments the evaporation of the droplets occurs faster and the smaller droplet nuclei are carried by the airflow to greater horizontal distances. Therefore, the exposure is greater for larger droplets in warmer environments, that in cooler environments would remain larger and settle faster.

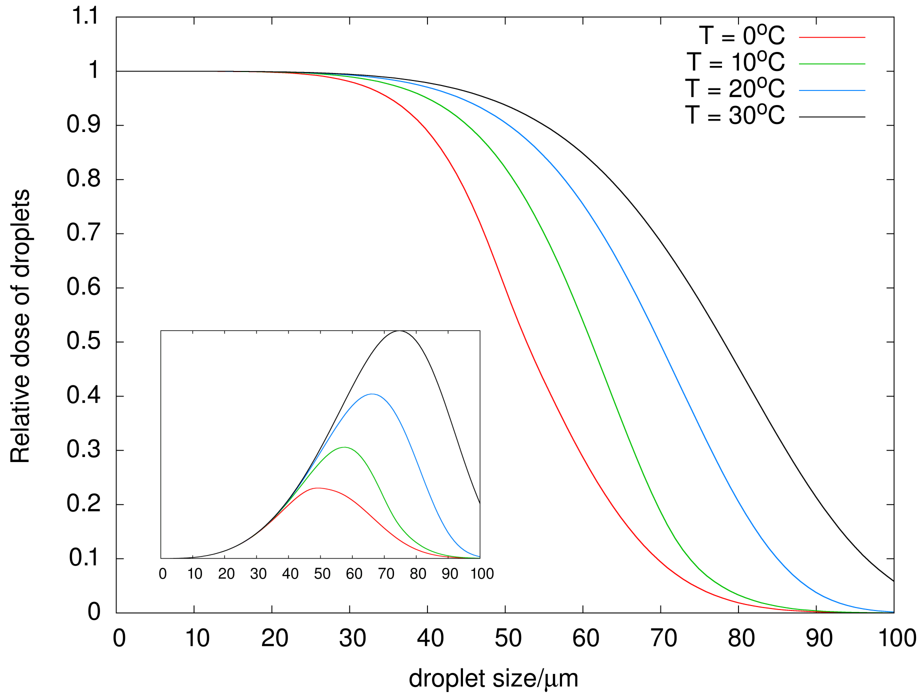

Figure 4. The relative concentration of droplets reaching a person that is 2 m away as a function of droplet size is shown for various ambient temperatures. To better compare probabilities of transmission the concentrations multiplied by droplet volume are shown in the inset.

Seasonal variations of viral outbreaks correspond with variations in temperatures. However, it is unknown how temperature generally affects viral viability, certainly over the timescales considered here, or how temperature might affect COVID-19 outbreaks [13, 18]. It has also been suggested that ambient temperature might have a greater affect on immune response than the transmission of a virus.

The inset of Figure 4 depicts the dose for a given droplet size multiplied by the volume of the droplets. As the temperature increases the number of viral particles that the second person is exposed to increases, and the peak size of droplets that transmit the virus will increase. Recall, however, that larger particles are more likely to be deposited in the upper respiratory tract where more virus particles are thought to be required to cause infection.

Furthermore, these results don't take into the consideration the distribution of droplet sizes emitted by the infected person.

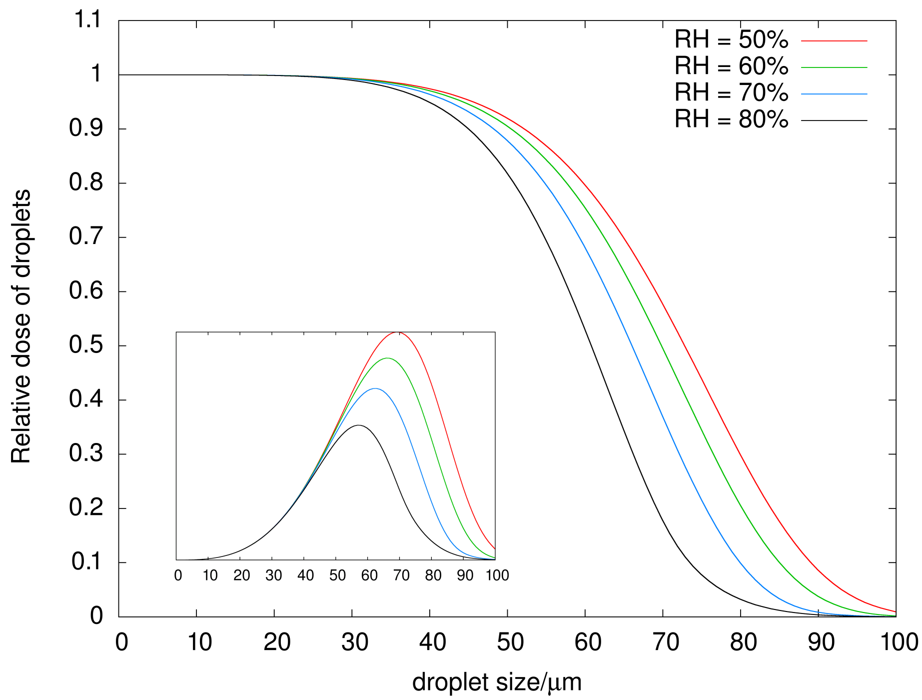

Figure 5. The relative concentration of droplets reaching a person that is 2 m away as a function of droplet size is shown for various percentages of relative humidity. To better compare probabilities of transmission the concentrations multiplied by droplet volume are shown in the inset.

Figure 5 depicts the effect of humidity on the transmission of respiratory droplets. Increasing the relative humidity decreases the evaporation rate and this causes the droplets to remain larger longer. For smaller droplets the evaporation occurs quickly, and so the effects of humidity are negligible, and for larger particles (greater than $100\,\mu$m) the droplets will reach the floor before they have evaporated. For intermediate particle sizes, however, the effects of humidity are more pronounced. Slowing the evaporation of droplets between $50\,\mu$m and $100\,\mu$m means these droplets have larger terminal velocities and settle faster [6, 7].

Humidity is thought to play an important role in the seasonaility of virus outbreaks [15, 42], although it remains to be seen if the same occurs for COVID-19 [13]. The effects of humidity on virus viability is complicated [43, 16], and while increasing humidity may decrease viability [14, 44], this would be expected to occur over days rather than seconds [43]. Therefore, the effects of humidity on droplet transmission shown in this model are likely to explain the effects of humidity on the seasonality of viral outbreaks, making it likely that the transmission of COVID-19 will decrease with increasing humidity.

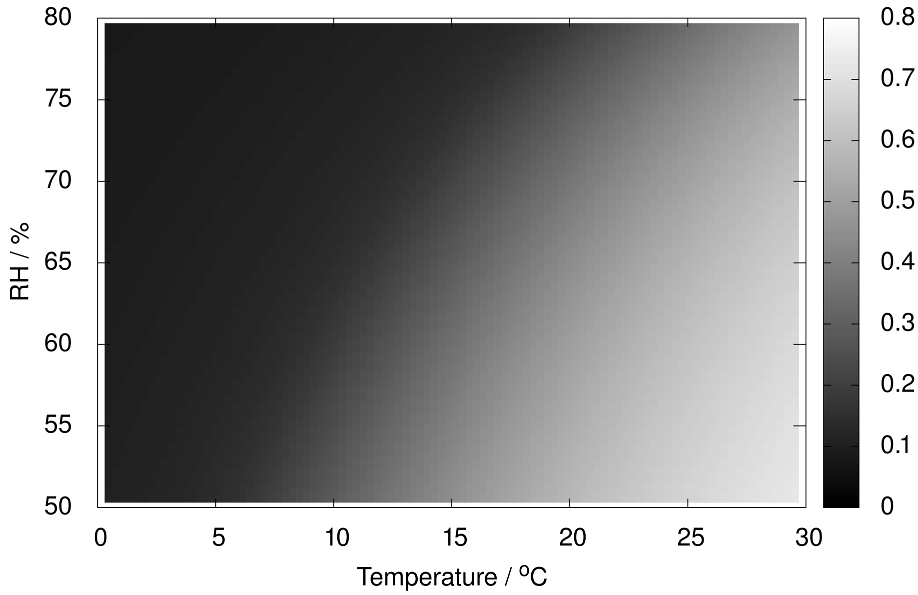

Figure 6. The relative concentration of droplets reaching a person that is 2 m away, as a function of both ambient temperature and relative humidity, is shown for droplets with an initial size of 70 μm.

Figure 6 depicts the effects of changing the temperature and humidity. The relative dose of droplets is plotted as a function of temperature and humidity (same range as in Figures 4 and 5). The droplet size is 70 μm and the increase in exposure for higher temperatures and lower humidity can be clearly observed. This size particles were chosen because they are predicted to be the most affected by temperature and humidity in the systems considered here.

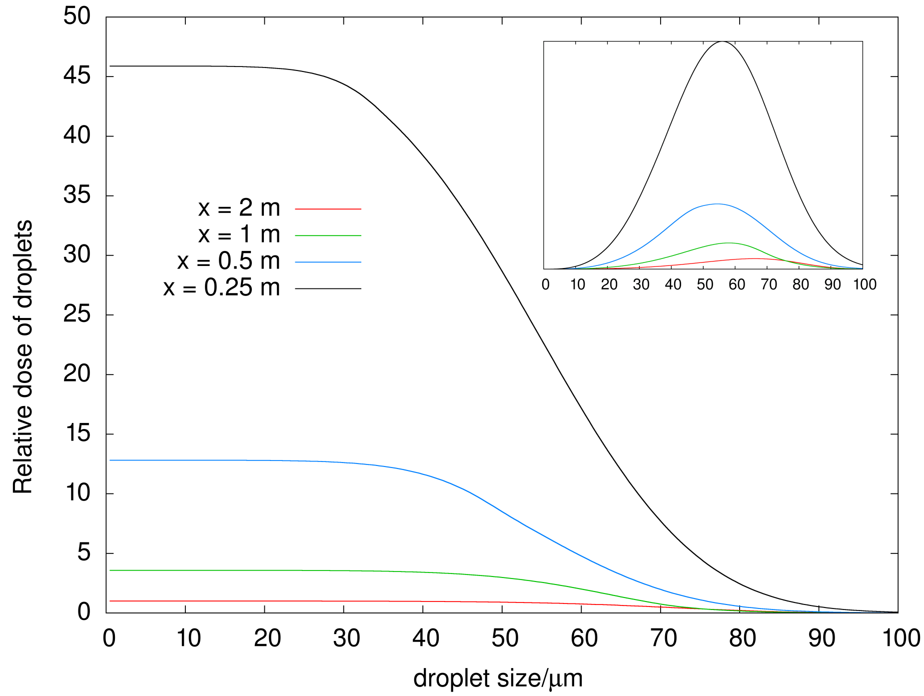

Figure 7. The relative concentration of droplets reaching a person that is 2 m, 1 m, 0.5 m and 0.25 m away as a function of droplet size. To better compare probabilities of transmission the concentrations multiplied by droplet volume are shown in the inset.

The dose of droplets that a person might be exposed to for different separation distances, between the infected person and the exposed person, is depicted in Figure 7. As expected, the closer a person comes to an infected person the greater the concentration of droplets that the person will be exposed to. This is especially true for smaller droplets, but all droplets disperse as they travel downwind. Therefore, being closer to the source of the emission means the droplets have not dispersed as much, and the concentration remains higher as the Gaussian puff in the model passes the location of the exposed person. In a confined space the airflow will circulate, and smaller particles can remain in the air, potentially infecting the exposed person, for a long time. Here, these effects are not considered and once the droplets move past the exposed person then the exposure is over (which might more accurately represent outdoor exposure). For larger droplets, those greater than $100\,\mu$m, the exposure is limited by the sudden drop of the droplets to the ground. Even for short distances these droplets are unlikely to cause primary infection. However, for intermediate particles (say between $30\,\mu$m and $80\,\mu$m) the exposure rapidly increases, especially when considering the dose of droplets multiplied by the volume of the droplets (Fig. 7 inset). Decreasing the distance from 2 m to 1.25 m, is predicted to increase ones exposure to the viral particles in these intermediate droplets by a factor of 26.

5. Conclusions

A new spreadsheet model of the evaporation and dispersion of respiratory droplets is presented. This model is simple enough for use in an undergraduate biology course. Not only will this expose students to computer models, and more advanced uses of spreadsheets, but the application of computer models to the COVID-19 pandemic may significantly improve student interest and learning.

The model is shown both to capture the behavior of droplets and to easily allow students to vary the size of the droplets, the ambient temperature, the relative humidity and to explore the effects of social distancing. Furthermore, the model could easily be extended (for example, as part of an undergraduate research project) to account for any potential humidity-dependence on droplet nuclei sizes, the effects of face masks (both on particle filtering and air velocity), or to include the distribution of droplet sizes emitted by an infected person; which could be especially crucial in the role of superspreaders, who are disproportionately responsible for outbreaks of airborne infectious disease [8]

It is hoped that through education, students can appreciate the science behind the current pandemic and the practices implemented to mitigate outbreaks. In particular, the spreadsheet model directly leads to students exploring the science behind social distancing and seasonality of outbreaks. Two areas of research that are at the forefront of the current COVID-19 pandemic.

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