THE EFFECTS OF WIND ON FALLING WATERDROPS

by

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A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

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Major Professor

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INTRODUCTION

In recent years man has come to realize the importance of conserving the world's natural resources. With the increasing population and food shortage it is especially important that the land's ability to produce food be preserved. It may be that in the future the strength and survival of a country will depend on its capacity to produce food. Most elements that plants need to grow such as nutrients and water may be supplied artificially, but food can not be produced in quantity without topsoil. When soil is eroded it is carried in the atmosphere or in the water thus contributing to the pollution problems which man has become so aware of in recent years. For these reasons the study of the processes of soil erosion and methods for its prevention or control is important.

The major forces causing soil erosion are wind and water. Quite extensive study has been done on each of these media separately,but even though wind and rain often act together in nature very little is known about their combined effect. This study will help to understand some of the effects of wind on raindrops and perhaps from this, research will be done to help understand the combined effects of wind and rain on soil. If it is known how the forces of wind and rain affect each other and together act on the soil surface in the soil erosion process, land treatments and cultural practices may be developed to more effectively control soil erosion. This in turn will help to retain the land's great ability to produce food. Practices to control or prevent soil erosion will also reduce the amount of soil which is being carried in the atmosphere and surface waters. This study will contribute to the solution of two of this country's greatest problems: retaining the land's ability to produce food and preventing the contamination of the atmosphere and surface waters.

REVIEW OF LITERATURE

Soil Erosion by Rainfall

The mechanics and processes of soil erosion by raindrops have been the subject of much research. The important parameters have been identified and various methods have been used to predict the amount of soil erosion caused by rainfall. (1, 2, 3, 5, 6, 7, 8, 13, 14, 15, 16, 17, 19, 21, 23) Due to the irregularity of natural rains it is difficult to study raindrop soil erosion under natural conditions. For this reason various methods and equipment have been devised to simulate natural rain. (13, 14) These rainfall simulators give more rapid results and allow control of some of the rainfall characteristics and applications.

Some characteristics desirable in rainfall simulators listed by Meyer (14) are (a) drop-size distribution and fall velocities near those of natural rainfall at comparable intensities, (b) intensities in the range of storms producing medium to high rates of runoff and erosion, (c) application area of sufficient size for satisfactory representation of treatments and erosion conditions, (d) uniformity of intensity and drop characteristics throughout the study area, (e) rainfall application nearly continuous throughout the study area, (f) angle of impact not greatly different from vertical for most drops, (g) accurate reproduction of storms, (h) satisfactory operation in winds of appreciable velocity (field-research equipment only), (i) and complete portability (field-research equipment only).

Early research assumed that total amount of rainfall and intensity were the only important parameters in relating simulated rain to natural rain. It was later found that drop size distribution is also important.

Parameters which have been suggested as proportional to rainfall erosion include (a) kinetic energy ($1/2MV^2$) (b) momentum (MV) (c) kinetic energy per unit of drop-impact area ($1/2MV^2/A_d$) (d) momentum per unit of drop-impact area (MV/A_d), and (e) interactions of these variables with rainfall intensity. Since it is not yet known which of these parameters are most important or how soil erosion is related to drop mass, velocity, and intensity; it is necessary that simulated rain have as near as possible the same drop size distribution and drop velocity as natural rain of comparable intensity. (14)

Wischmeier and Smith found that the kinetic energy times maximum 30-minute intensity is a useful parameter in relating soil erosion to rainfall. (23, 22) The kinetic energies of natural rainstorms were measured by determining drop size distribution of the storm and assuming the velocity of fall of the drops was the same as for a drop of that size falling in still air.

Measurement of the Velocity of Falling Waterdrops

Various methods have been used to measure the velocity of falling waterdrops. Meyer (13) listed the following methods which have been used:

(a) Photographing drops during fall

(b) Electronic measurement of time for drop to pass consecutive points

(c) Stopwatch timing

(d) Upward velocity of air stream required to suspend drops

(e) Computation.

The first method, photographing the drops, is probably the most easily adapted to measuring the velocity of drops falling in wind and yet it gives an acceptable degree of accuracy.

In 1941 Laws (10) used the photographic method to do an extensive study of the velocity of waterdrops falling in still air. His photographic equipment consisted of a camera with a revolving disk in front of the lense. The disk had 16 segments cut out of it so that each time a segment passed the lense the film was exposed. The disk was rotated 30 revolutions per second by an electric motor so that the film was exposed 480 times per second. Drops were allowed to fall between the camera and a flood light arrangement so that each time the film was exposed an image of the drop appeared on the film. By knowing the time between exposures and measuring the distance between drop images, the drop velocity could be calculated.

Drop Production

For this study individual waterdrops of known size were required. Drop formers have been constructed from hanging pieces of yarn, graded stainless steel tubing, and glass tubing. Since hanging yarn does not give as uniform drops as steel or glass tubing it was not considered desirable for this study.

Stainless steel drop formers are constructed by soldering short pieces of tubing of various diameters together so that the drop former has a relatively large diameter opening at one end and a small opening at the other end. The water flows from the small end to the large end and the drop forms on the large end, thus the small opening controls the amount of flow and the large opening controls the size of drop. Drops can be formed from approximately 6 mm in diameter down to 3 mm in diameter with these drop formers. (18)

Drop formers are made from glass tubing by heating the glass and drawing it out to a small diameter. The tubing is cut in the drawn out portion thus giving a small diameter hole at the tip. Glass droppers can be constructed to produce drops from 6 mm to 2 mm in diameter.

PURPOSE

The effects of wind on falling waterdrops are of interest under two general conditions:

1. Raindrops falling through the atmosphere are often accompanied by wind. Although wind probably affects many of the parameters associated with soil erosion caused by raindrops, very little is known about these effects and they are not generally considered in rainfall erosion studies. Wind may change size, shape, velocity, path, and angle of impact of raindrops.
2. Spray nozzles used in simulating rainstorms may be operated in the field under windy conditions. Wind may affect the intensity of simulated rain applied to a plot by displacing some of the drops off of the plot. Wind may also affect the same parameters of simulated rain as of natural rain.

The purpose of this study was to investigate the effects of wind on vertical velocity, horizontal velocity, resultant velocity, horizontal acceleration, displacement, shape, and size of falling waterdrops. The results of this study will permit more accurate simulation of natural conditions when studying erosion by wind driven rain and will aid in understanding wind effects on natural raindrops.

The parameters suggested as important in rainfall erosion all involve products of mass and velocity. In order to study the effects of wind on these parameters the effects of wind on the velocity of drops of known mass must be measured.

The specific objectives were as follows:

1. Measure the effects of wind on velocity and path of falling waterdrops.
2. Calculate the effects of wind on the momentum and kinetic energy of falling waterdrops.
3. Determine the effects of wind on the shape and size of falling waterdrops.
4. Apply the results of these determinations to both natural and simulated rains.

METHODS AND EQUIPMENT

Outline of Investigations

Individual waterdrops of known sizes were formed in a raintower 34 feet above the floor. The drops fell through a wind tunnel which passed through the lower portion of the rain tower. As the drops fell through the wind tunnel multiple exposure photographs were taken of them. The vertical velocity, horizontal velocity, and displacement of the drops were determined from the photographs. The effects of wind on the path, resultant velocity, momentum, kinetic energy, shape, and size of falling waterdrops were determined. These results were applied to both simulated and natural rains.

Equipment

Wind Tunnel-Rain Tower:

A schematic diagram of the wind tunnel-rain tower is shown in Plate I. The wind tunnel is 5 feet wide, 8 feet high, and 100 feet long. Air movement is supplied by a 200,000 cubic feet per minute industrial fan powered by a 100 horsepower internal combustion engine. When the tunnel was constructed it was planned that the wind speed would be controlled by adjusting the pitch of the fan blades. It was found that changing the fan pitch changed the velocity distribution in the tunnel. Wind speed was controlled by adjusting the engine throttle.

When the wind tunnel is operated without the rain tower it is used as a closed circuit tunnel with the air recirculating through a duct on top of the tunnel. To use the tunnel with the rain tower as in this study it is operated as a flow through tunnel. The air is drawn in through an open door and is expelled through another open door downwind of the rain tower.

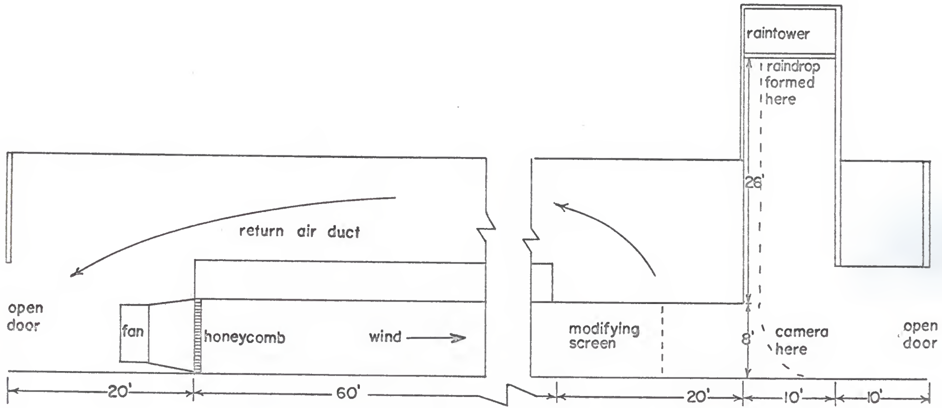
The honeycomb section is constructed from 18-inch pieces of 2-inch steel conduit. This reduces the swirling motion of the air after leaving the fan which results in a relatively one directional flow of air in the tunnel.

It was considered desirable to have a uniform velocity through the cross section of the wind tunnel in the rain tower. Velocity profiles were taken with a moveable pitot tube and inclined alcohol manometer. In order to modify the velocity profiles, pieces of 2-inch chicken wire, 1-inch chicken wire, or 1/2-inch hail screen were placed on a frame which was placed in the tunnel upwind of the raintower. The denser screens were placed over higher velocity areas thus reducing wind velocity in these areas. After many trials and patches of screen the velocity profile was altered to give a relatively uniform profile through the cross section of the tunnel in the raintower. The velocity distributions before and after the screening are shown in Plates II and III.

EXPLANATION OF PLATE I

Schematic diagram of wind tunnel-raintower facility

PLATE I


raintower
raindrop formed here
26'
return air duct
open door
fan
honeycomb
wind
modifying screen
8'
camera here
open door
20'
60'
20'
10'
10'

EXPLANATION OF PLATE II

Velocity distribution in cross section of wind tunnel in raintower before modifying screen was installed.

PLATE II

16.8	16.5	16.4	16.3
16.9	16.6	16.4	16.3
16.6	16·4	16.4	16.6
16.7	16.3	16.4	16.3
16·6	16·4	16.4	16.4
17.1	16.8	16.4	16.4
16.8	16.7	16.3	16.4

EXPLANATION OF PLATE III

Velocity distribution in cross section of wind tunnel in raintower after modifying screen was installed.

PLATE III

16.7	16.9	16.9	16.7
16.9	17.0	17.0	16.9
16.9	17.1	16.9	16.8
16.8	16.9	16.9	16.9
17.1	17.1	16.9	16.9
17.2	17.0	16.9	16.9
16.9	17.0	16.9	17.0

The rain tower has a platform 34 feet above the floor. Rainstorms are simulated in this facility with spray nozzles located directly beneath the platform. Drops released from this elevation attained at least 95% of their terminal velocity before reaching the floor. (10)

One wall of the wind tunnel in the rain tower area is constructed of plexiglass. This allows observation and photographing of events during a simulated wind-rain storm.

Drop Production:

For this study individual drops of known size were required. Due to ease of construction and availability of materials the drop formers were constructed from glass tubing. In order to make a drop former from glass tubing a piece of tubing was placed in the chuck of a drillpress and the drill was slowly turned by hand while a small portion of the length of tubing was heated with a propane torch. When the glass neared the melting point the weight of the glass below the heated portion caused it to stretch out to a very small diameter. The glass was then cut in this drawn out portion thus giving a very small diameter hole in the tip.

It was desirable to have drop sizes similar to those sizes of natural rain. Natural rain drops range in size from approximately 6.0 mm in diameter down to microscopic size particles of water. Generally drops smaller than 0.5 mm are considered insignificant in erosion studies. Drops larger than 7.0 mm will break up when falling through the air because of the low surface tension. Drops smaller than 5.5 mm are quite stable and do not normally break up when falling in air. The minimum drop size formed by allowing the drops to grow on a pointed tip until the force of gravity overcomes the attractive forces between water and tip is approximately 2.0 mm in diameter. Smaller drops have been formed by allowing a stream of saturated air to blow across the drop former and detach drops before they are large enough to be detached by gravity. It was decided that drops for this study should range in size from 2.0 mm to 5.5 mm in diameter.

Drop size produced by a dropper was determined by allowing 100 to 300 drops to fall into a weighing bottle and determining the weight per drop by weighing on a Mettler balance to the nearest 1/1000 gram. Equivalent average diameter of the drops was calculated assuming the drops were uniform sized spheres with density of 1 gram per cubic centimeter.

Drop formers were selected to give 2.2, 3.6, 4.3, and 5.0 mm diameter drops.

A reservoir to supply water to the droppers was made from a one pound coffee can. The top half of the can was cut off and discarded. A 1/4-inch hole was drilled in the center of the bottom and a short piece of copper tubing was soldered into the hole. A dropper was attached to this reservoir with a short piece of rubber tubing between the copper tubing and the dropper. An adjustable hose clamp was placed on the rubber tubing to adjust the flow of the water to the dropper. When photographs were being taken the clamp was adjusted so that a drop was released about once every second.

The drops were allowed to form on the drop former tip and did not fall until their mass was great enough so that the force of gravity overcame the attractive forces between drop and tip. Because of this the pressure head (water level) in the reservoir did not affect the drop size.

Photographic Equipment:

The camera used to photograph the drops was a Polaroid model 150 with

Polaroid type 47 film. This is a black and white film with a very high emulsion speed. The camera was equipped with a close-up lense so that it could be focused on objects 27 inches away from the lense.

The light source was a General Radio Company model 1531-A strobotac which is a repeating electronic stroboscope with an adjustable flash rate of up to 25000 flashes per minute.

Procedure

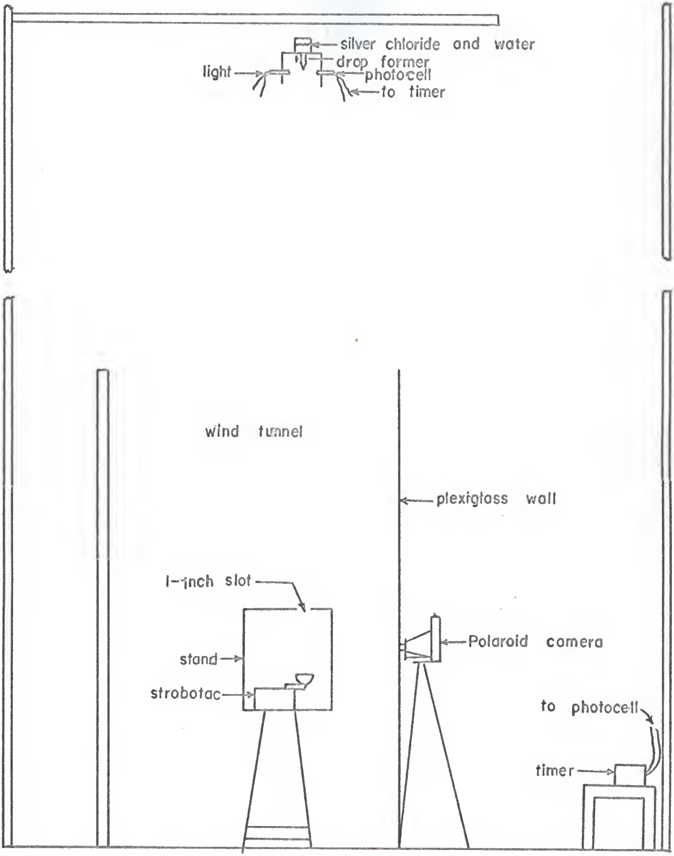
The photographic equipment was arranged as shown in Plate IV. The camera was placed on a tripod outside the wind tunnel. The stroboscope was placed in the wind tunnel on a stand which was constructed from 1/2-inch angle iron. The stand could be adjusted in elevation from 2 to 6 feet. In use the stroboscope was located slightly below the field of view of the camera with the light beam facing the path of the falling waterdrops. This arrangement allowed the light to be close enough to the drops to illuminate them the full length of the photograph and yet not interfere with the wind flow or the drops' fall.

Drops from a single stationary drop former in the rain tower did not all fall in the same place but were spread over an area approximately 4 inches in diameter. If the distance from camera to drop was allowed to vary there would be errors in measuring distances on the photographs due to varying magnification. Because of this problem a framework was built onto the light stand with a 1-inch slot directly above the light. The drops were required to pass through this slot before they entered the view of the camera. This minimized any errors in measurement caused by drops falling different distances from the camera.

EXPLANATION OF PLATE IV

Camera and strobotac arrangement for taking photographs of waterdrops falling through wind tunnel as seen looking downwind.

PLATE IV


silver chloride and water
drop former
light
photocell
to timer
wind tunnel
plexiglass wall
1-inch slot
stand
strobotac
Polaroid camera
to photocell
timer

The velocity profile was determined around the light stand and it was found that the stand altered the air flow considerably. Excess material was eliminated and leading edges were rounded until the stand had very little effect on air flow (Plate V).

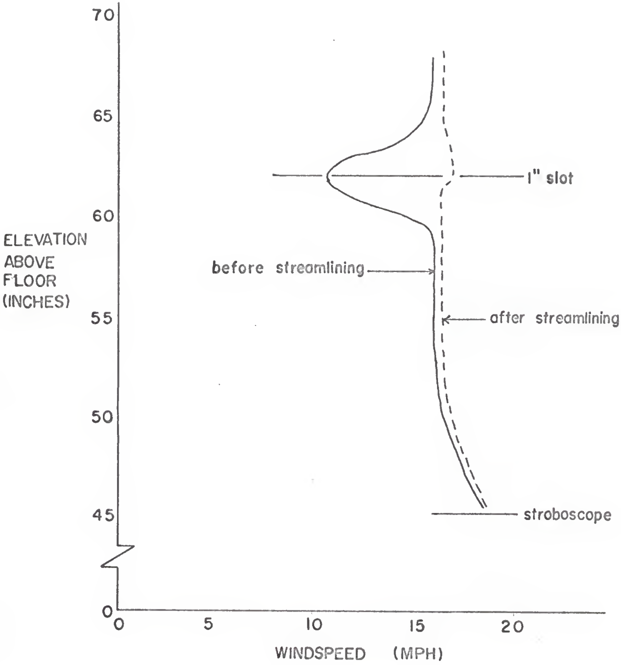
In order to take multiple exposure photographs the camera shutter had to be open and the stroboscope flashing as the drops fell through the camera field of view. Because the stroboscope required a short warm-up period before the flashing rate was accurate one had to operate the unit continuously while photographs were being taken. A signal was needed to indicate when to open the camera shutter as the drops entered the field of view. To accomplish this a dark sensitive photocell and pencil beam light were placed on either side and slightly below the drop former tip. When a drop was released from the dropper it fell through the light beam thus energizing the photocell. The photocell was connected to a timer which was adjusted to emit a click just before the drop fell into view of the camera. When the timer clicked the camera shutter was opened and held open until the drop had fallen out of view. Since the camera shutter had to be held open for relatively long periods of time, there could be no sources of light other than the stroboscope and as little light as possible reflected from objects other than the drops. The wall of the wind tunnel in the background and light stand were painted with nonreflecting black paint. The photographs were taken at night so that light sources other than the stroboscope were eliminated. These precautions allowed multiple exposures of several drops on each picture without overexposing the film.

Some difficulty was encountered in getting enough light reflection from the drops in order for them to appear on the photographs. Most of the light passed through the drops with little reflection to the camera.

EXPLANATION OF PLATE V

Velocity profile near light stand.

PLATE V


70
65
60
55
50
45
0
ELEVATION ABOVE FLOOR (INCHES)
1" slot
before streamlining
after streamlining
stroboscope
0
5
10
15
20
WINDSPEED (MPH)

A solution of 1:100,000 of silver nitrate and sodium chloride with distilled water was used for the drops. This solution results in a colloidal suspension of silver chloride which reflects much more light than distilled water. The silver chloride does not change the physical properties of the water enough to cause errors in measuring velocity. (11)

When the photographs were taken an image of the drop falling through the view of the camera appeared on the photograph each time the stroboscope flashed. The time between flashes was calculated by taking the reciprocal of the flash rate.

To determine the magnification of the photographs, a sheet of 8-inch by 10-inch, 20 squares to the inch, coordinate paper was inserted between two pieces of glass and photographed at the same distance as the drops fell.

A plexiglass ruler was made to measure distances on the photographs. A sewing needle was attached to a ringstand clamp so that it could be adjusted for elevation and position but would not have to move after being adjusted. This was clamped to a ringstand that had a moveable microscope stage attached to its base. A photograph of the coordinate paper was placed on the microscope stage, the needle was lowered to nearly touch the surface, and the number of clicks of the microscope stage required to have one inch on the photograph pass the needle was determined. A one-inch by two-inch piece of plexiglass was then attached to the microscope stage. The needle was lowered to the surface of the plexiglass, and lines corresponding to 1/20 inch on the photograph were scribed on the plexiglass by moving the microscope stage.

A reference was needed on each photograph to measure horizontal displacement and to indicate horizontal and vertical directions. Stainless steel wires were attached to the light-stand so that they appeared as vertical or horizontal lines along the edges and bottom of each photograph. Before a photograph was taken these wires were checked with a level to insure that they were vertical and horizontal. The horizontal distance from the path of drops falling in still air to one of the vertical wires was also measured. These wires were used as references for measurements on the photographs.

Waterdrops were photographed after falling through 2 1/2, 4, 5, 6, and 7 feet in winds of 6.3, 10, 15, and 20 miles per hour. From these photographs, vertical velocity, horizontal velocity, and displacement of the drops were measured. Resultant velocity, drop path, horizontal acceleration, kinetic energy, and momentum were calculated. The effects of wind on drop shape and breakup were observed. Horizontal velocity, vertical velocity, and displacement values reported are averages of 10 to 15 measurements taken from the photographs. Horizontal accelerations were calculated by dividing the change in horizontal velocity between two points by the time it took the drop to travel between these two points. The time was calculated by dividing vertical distance between points by the average vertical velocity for the windspeed-drop size combination. Resultant velocities are the vectorial sum of average vertical and horizontal velocities.

RESULTS

Data

Appendix I gives a summary of all measurements and calculations made.

Data for drops falling through 7 feet of wind are summarized in Table 1. The kinetic energy and momentum values are the ratios of these

Table 1. Summary of drop data after drops had fallen 7 feet in wind.

Windspeed	Drop size	Horizontal velocity	Horizontal acceleration	Vertical velocity	Resultant velocity	Kinetic energy ratio	Momentum ratio
M.P.H.	Mm.	Ft./sec.	Ft./sec.^{2}	Ft./sec.	Ft./sec.	V_r^2/V_o^2	V_r/V_o
0	2.2	0	0	23.75	23.75	1.000	1.000
	3.6	0	0	28.42	28.42	1.000	1.000
	4.3	0	0	29.45	29.45	1.000	1.000
	5.0	0	0	30.40	30.40	1.000	1.000
6.3	2.2	4.37	14.40	23.16	23.57	.985	.992
	3.6	3.76	14.73	27.40	27.70	.950	.975
	4.3	4.14	16.86	28.80	29.10	.976	.988
	5.0	3.62	15.09	29.22	29.44	.938	.969
10.0	2.2	7.24	23.35	22.21	23.36	.967	.984
	3.6	5.45	21.20	26.62	27.16	.914	.956
	4.3	5.39	21.70	27.76	28.28	.922	.960
	5.0	5.08	20.55	28.15	28.60	.885	.941
15.0	2.2	9.65	30.26	21.45	23.52	.981	.990
	3.6	7.79	28.39	25.40	26.57	.874	.935
	4.3	7.45	28.35	26.36	27.39	.865	.930
	5.0	7.49	28.88	27.07	28.09	.854	.924
20.0	2.2	13.22	39.58	20.63	24.50	1.064	1.032
	3.6	12.95	43.87	23.09	26.47	.867	.931
	4.3	11.87	41.43	24.41	27.14	.849	.922
	5.0	11.79	41.42	24.54	27.23	.802	.896

parameters in wind to their respective values in still air. Because the drop masses were not changed by the wind, change in kinetic energy and momentum is proportional to change in velocity squared and velocity, respectively.

A summary of the statistical analysis of the data is given in Table 2. Analyses of variance were calculated for horizontal velocity and vertical velocity. Prediction equations were derived for horizontal velocity and drift as functions of drop size, windspeed, and distance drop has fallen in wind.

Table 3. Drop breakup data for 4.3 mm. drops

Windspeed	Breakup
M.P.H.	Percent
18.6	0
20.6	5
21.9	19
22.6	19
24.7	43

Discussion

Photographs of drops falling in still air showed that after a drop is released from the dropper it vibrates from prolate to oblate until it finally reaches a stable shape and terminal velocity (4). Drops falling at terminal velocity in still air are flattened on the bottom, spread sideways, and rounded on the top (4). Drop vibrations similar to those for drops falling in still air were observed for drops falling in the wind tunnel. The sudden change in forces on the drop as it enters the wind tunnel apparently increases and changes its vibrating characteristics. If the drops could fall in steady wind long enough, these vibrations would

Table 2. Summary of statistical analyses.

Analysis of variance

Variable	Variance ratio for horizontal velocity	Variance ratio for vertical velocity
Drop size (D)	161.5*	80.9*
Windspeed (W)	6355.2*	36.3*
Distance (H)	1239.6*	.61 NS
W x D	20.6*	.91 NS
D x H	8.8*	.04 NS
W x H	51.9*	.17 NS
W x D x H	3.6*	.05 NS

* Significant at 99 percent level
NS Nonsignificant

Regression analysis

(1) $\text{Drift} = -10.524 - 1.081D + .915U + 2.298H.$ $R = .85.$

(2) $\text{Drift} = .1915U^{.95}H^{1.07}/D^{.33}$

($\log \text{drift} = 1.6530 + .951\log U + 1.071\log H - .331\log D.$ $R = .88$)

Drift - (in.)
D - drop diameter (mm.)
U - horizontal windspeed (m.p.h.)
H - distance drop has fallen with wind acting on it (ft.)

(3) $V_H = -3.4383 - .3816D + .5096U + .8633H.$ $R = .96.$

(4) $V_H = .1791U^{1.03}H^{.73}/D^{.23}$

($\log V_H = -1.7199 + 1.031\log U + .731\log H - .231\log D.$ $R = .97$)

V_H = horizontal velocity (ft./sec.)

probably dampen out and the drops would reach a stable shape and steady velocity. Drop shapes ranged from nearly spherical with a flattened area between bottom and upwind side to "flying saucers" with flat side at an angle between bottom and upwind side (Plate VI).

Blanchard (4) found that drops smaller than 4.6 mm. in diameter are quite stable. Drop breakup data from this study show that very few 4.3 mm. drops broke up while entering the wind tunnel when windspeed was below 20 miles per hour (Table 3). When windspeed was increased above 20 miles per hour, drop breakup increased greatly. This indicates that larger drop sizes which are normally quite stable may break up when subjected to high winds.

Values calculated for horizontal acceleration were inconsistent. The time elapsed while a drop falls 1 foot is approximately 1/30 second. An error in velocity measurement of only 0.25 ft./sec. would result in a 7.5 ft./sec.^{2} error in acceleration. If horizontal acceleration could have been calculated accurately, the forces exerted on the drop by wind could be determined.

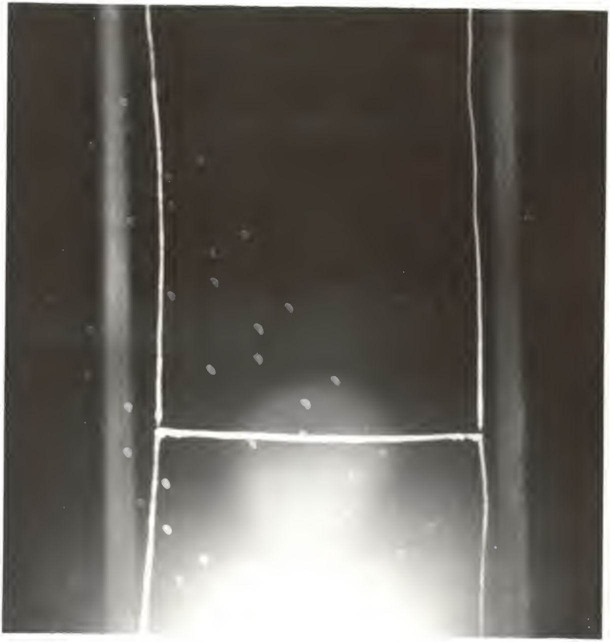
Equations (1) and (2) predict the drift of drops falling in wind. Although equation (2) fits the measured data quite well it is quite different from the drift equation derived in a similar experiment (20). ($\text{Drift}=0.0198H^{1.83}V^{1.21}/D^{0.69}$). The differences are probably due to the fact that Umback measured drift for fall distances of 0 to 12 feet whereas the greatest fall distance in this study was 7 feet. Plate VII compares these two equations with some drift measurements. The differences in these equations indicated that they cannot be extended much beyond the limits of the data measured without introducing serious errors.

The analysis of variance on horizontal velocity shows that drop size,

EXPLANATION OF PLATE VI

Photographs showing drop shape of 5.0 mm drops falling in 20 m.p.h. wind. Wind direction is left to right.

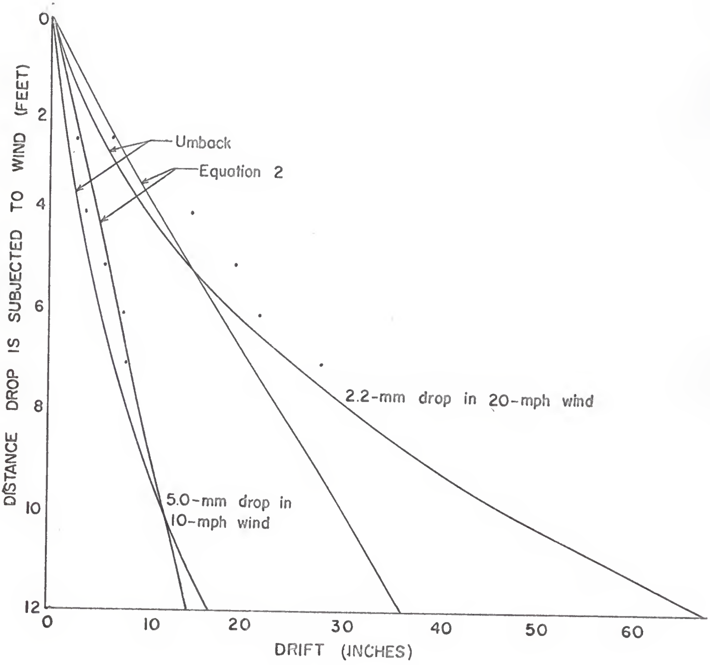
PLATE VI



EXPLANATION OF PLATE VII

Comparison of Umback's equation (20), equation 2, and observed data for drift.

PLATE VII


0
2
4
6
8
10
12
DISTANCE DROP IS SUBJECTED TO WIND (FEET)
0
10
20
30
40
50
60
DRIFT (INCHES)
Umback
Equation 2
2.2-mm drop in 20-mph wind
5.0-mm drop in 10-mph wind

windspeed, distance, and all interactions were highly significant. Because of the significant interactions, the effects of one variable depends on the values of all other variables.

A raindrop falling in wind gradually gains horizontal velocity until it approaches the horizontal velocity of the wind. As the horizontal drop velocity approaches the wind velcoity the drag force on the drop would decrease and thus horizontal acceleration would decrease. Because of the changing acceleration it would be expected that the equation predicting horizontal velocity is probably curvilinear. Equation (3) fitted the measured data nearly as well as equation (4). Since the drops in this study fell through only 8 feet of wind these prediction equations are fitted to only a short portion of a curve. If greater fall distances could have been used the resulting equation probably would have been different and the linear equation would not have fit the data as well.

The highest horizontal velocity measured in this study was 13.22 feet per second (9 miles per hour) for the 2.2 mm. drop in a 20 mile per hour wind. Consequently, the drops did not approach their maximum velocity in the time required to fall through the wind tunnel. Plate VIII indicates that the horizontal velocity of the 2.2 mm. drop falling in 20 miles per hour wind would reach the windspeed after falling approximately 12 feet. This distance is probably underestimated due to the limitations of the prediction equation.

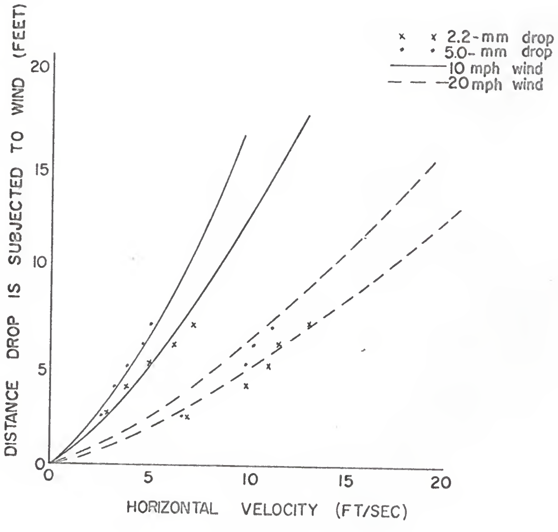
The vertical velocity of the drops falling in the wind tunnel decreased as the windspeed was increased (Plate IX). Because the drops approached terminal velocity in still air before entering the wind tunnel, they were flattened on the bottom and rounded on the top as they entered the air-stream. Because of this shape, lift forces on the drop were generated as

EXPLANATION OF PLATE VIII

Relationship between horizontal velocity and distance of fall.

Equation 4 and observed data.

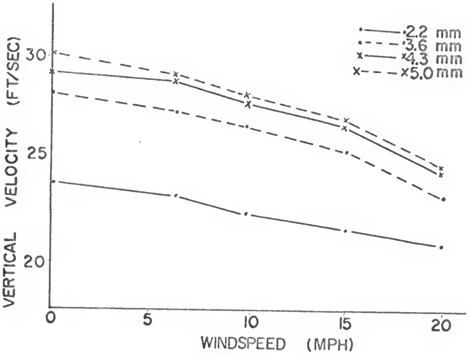
PLATE VIII


× 2.2-mm drop
• 5.0- mm drop
10 mph wind
20 mph wind
DISTANCE DROP IS SUBJECTED TO WIND (FEET)
0
5
10
15
20
HORIZONTAL VELOCITY (FT/SEC)
0
5
10
15
20

EXPLANATION OF PLATE IX

Windspeed versus vertical velocity.

PLATE IX



2.2 mm
3.6 mm
4.3 mm
5.0 mm
VERTICAL VELOCITY (FT/SEC)
30
25
20
0
5
10
15
20
WINDSPEED (MPH)

they entered the airstream due to the Bernoulli effect. Static pressure was found to be greater in the wind tunnel than in the still air above the tunnel. Therefore, the drops were falling from a lower to higher pressure area. The decrease in vertical velocity was probably due to both lift and pressure gradient.

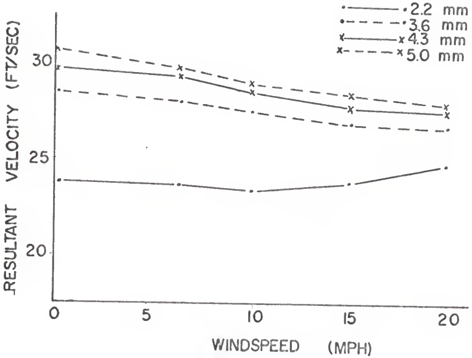
The decrease in vertical drop velocity in wind was sufficient to lower the resultant velocity below that in still air in all but one case (Plate X). The exception was 2.2 mm. drops being acted on by 20 miles per hour wind. Since kinetic energy and momentum depend on resultant velocity the ratios of the values of these parameters in wind with their respective values in still air are less than one. The 5.0 mm. drop acted on by 20 miles per hour wind had the smallest kinetic energy and momentum ratios. Using equation (4) to preduct horizontal velocity and assuming vertical velocity does not decrease with an increase in fall distance the 5.0 mm. drop after falling 13.5 feet in 20 miles per hour wind would have kinetic energy and momentum ratios of greater than one. If the drops could have fallen in wind long enough for their horizontal velocity to approach that of the wind their resultant velocity would have been increased by wind in all cases. Umback found that "... the larger drops showed no effect of the vectorial addition of gravitational force and wind force in determining drop velocity." (20) In his study Umback measured resultant velocity rather than the vertical and horizontal components.

Falling waterdrops attain a steady vertical velocity when the vertical drag forces equal the force of gravity (5). Drag forces on a drop depend on its shape. Since waterdrops falling in wind have their flat side tilted toward the upwind side rather than on the bottom as in still air the terminal vertical velocities of drops falling in wind are probably at

EXPLANATION OF PLATE X

Windspeed versus resultant velocity.

PLATE X


2.2 mm
3.6 mm
4.3 mm
5.0 mm
RESULTANT VELOCITY (FT/SEC)
30
25
20
0
5
10
15
20
WINDSPEED (MPH)

least as great as the terminal velocity of corresponding drop sizes in still air. Since natural rain falls through wind for thousands of feet the drops probably reach a terminal vertical velocity and horizontal velocity near that of the wind. In view of this it seems reasonable to assume that the resultant velocity of raindrops in wind is the vectorial sum of the drops' terminal velocity in still air and the average horizontal wind velocity (7).

The vertical and resultant velocities measured in this study were affected by the laboratory facility and cannot be directly applied to other rain simulating facilities. These data will be useful in estimating kinetic energy and momentum of rainstorms simulated with this facility.

The prediction equation for horizontal velocity may be used to calculate the effects of wind on kinetic energy of other rain simulators. If vertical velocity is not changed by wind, as would probably be the case for a field simulator, the resultant velocity can be calculated by the vectorial sum of vertical velocity in still air and predicted horizontal velocity using equation (4). Table 4 is a summary of calculations for a nozzle operating at an elevation of 8 feet in a wind of 10 miles per hour. It was found that the 10 miles per hour wind increased the kinetic energy of this simulated rain by 13 percent.

CONCLUSIONS

1. Vertical velocity of the waterdrops falling in the wind tunnel decreased as windspeed increased.

2. The decrease in vertical velocity was sufficient to lower the resultant velocity below that in still air.

3. Drop vibrations similar to those for drops falling in still air

were observed for drops falling in wind.

4. Larger drop sizes which are normally quite stable may break up when subjected to high winds.

5. The prediction equation for horizontal velocity may be used to calculate the effects of wind on kinetic energy of field simulated rains.

6. Resultant velocity of natural raindrops falling in wind can be estimated by the vectorial sum of the drops' terminal velocity in still air and the average horizontal wind velocity.

Table 4. Characteristics of Spraying Systems Co. 80100 Veejet, operating at 6 p.s.i., data from center of pattern; nozzle velocity 22.3 ft./sec.

Drop size group**	Percent by weight**	Accumu-lative percent*	1/2 mass per acre-inch**	Velocity at 8 feet in still air**	Velocity at 8 feet with wind	V^2 at 8 feet in still air **	V^2 at 8 feet w/wind	KE at 8 feet in still air**	KE at 8 feet with wind
Mm.	%	%	lb.	ft/sec	ft/sec	$(ft/sec)^2$	$(ft/sec)^2$	ft-lb/ac in	ft-lb/ac in
3.5+	4.5	4.5	158.5	25.8	26.6	665.6	707.6	105,498	112,155
3.0-3.5	11.5	16.0	405.0	25.1	26.0	630.0	676.0	255,150	273,780
2.5-3.0	18.0	34.0	634.0	24.3	25.3	590.5	640.1	374,377	405,823
2.0-2.5	22.5	56.5	792.5	22.8	23.9	519.8	571.2	411,942	452,676
1.5-2.0	19.5	76.0	686.8	19.9	21.33	396.0	455.0	271,973	312,494
1.0-1.5	14.0	90.0	493.1	15.9	18.0	252.8	324.0	124,656	159,764
0.5-1.0	10.0	100.0	352.2	10.1	13.7	102.0	187.7	35,924	66,108
								1,579,520	1,782,800***

* Tabulated by Umback (20)
** Tabulated by Meyer (13)
*** 13 percent increase in K.E. due to 10 mile per hour wind

SUGGESTIONS FOR FURTHER RESEARCH

1. Since it was found that the laboratory facility affected the velocity of the falling waterdrops, it is suggested that measurements of the effects of wind of raindrops be measured under natural conditions. This study may have to be continued for several years in order to get measurements from storms under various conditions of rain and wind.

2. Since the basic reason for determining the effects of wind on raindrops is to determine their combined effects on soil erosion it is suggested that studies be conducted to determine how their forces act and interact in the soil erosion process.

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Dr. G. H. Larson for his counsel and guidance during the preparation of this manuscript.

To the Agricultural Research Service, Soil and Water Conservation Research Division, U. S. Department of Agriculture, in whose employ the author served during the planning and conduct of the study, go sincere thanks for able assistance in resolving many problems, as well as for financial support.

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APPENDIX

Velocity, Acceleration, and Displacement Measurements

Table 5. Summary of velocity, acceleration, and displacement measurements.

Drop size	Wind speed	Distance	Horiz. vel.	Horiz. acc.	Vert. vel.	Resultant vel.	Displacement
			ft	ft/sec^2	ft/sec^2	ft/sec^2	in
2.2mm	6.3mph	2.5 ft	2.01	18.55	22.99	23.07	4.61
		4	2.93	14.15	23.41	23.60	3.50
		5	3.71	18.00	22.90	23.20	6.20
		6	3.82	2.54	22.90	23.22	6.50
		7	4.37	12.69	23.16	23.57	5.66
	10.0mph	2.5	2.80	25.28	22.71	22.88	4.02
		4	3.82	15.35	23.12	22.44	4.76
		5	4.99	26.41	22.41	22.96	5.76
		6	6.40	31.83	22.41	23.31	6.64
		7	7.24	18.96	22.21	23.36	8.68
	15.0mph	2.5	4.47	39.25	22.32	22.76	1.48
		4	6.77	33.66	22.46	23.46	6.05
		5	8.03	27.66	21.76	23.19	9.53
		6	8.89	21.95	21.78	23.52	15.12
		7	9.65	16.69	21.45	23.52	15.05
	20.0mph	2.5	6.97	58.43	21.40	22.50	5.96
		4	10.01	42.47	21.02	23.28	14.18
		5	11.15	23.89	20.55	23.38	18.83
		6	11.52	7.75	21.19	24.12	21.14
		7	13.22	35.63	20.63	24.50	27.50

Table 5. (cont.)

Drop size	Wind-speed	Distance	Horiz. vel.	Horiz. acc.	Vert. vel.	Resultant vel.	Displace-ment
3.6mm	6.3mph	2.5	1.70	18.65	27.56	27.61	5.33
		4	2.38	12.43	27.50	27.60	4.04
		5	3.02	17.55	27.22	27.39	3.62
		6	4.05	28.25	27.44	27.74	4.08
		7	3.76	-7.95	27.40	27.70	4.84
	10	2.5	2.21	24.07	27.55	27.64	3.76
		4	2.86	11.80	27.55	27.70	5.82
		5	3.93	29.13	27.00	27.28	4.80
		6	4.36	11.71	27.40	27.74	6.42
		7	5.45	29.67	26.62	27.17	7.92
	15	2.5	3.95	40.31	25.53	25.83	2.84
		4	5.18	20.92	25.67	26.19	5.81
		5	6.09	23.22	25.57	26.29	7.86
		6	7.63	39.29	25.40	26.52	10.82
		7	7.79	4.08	25.40	26.57	13.72
	20	2.5	6.83	64.79	24.50	25.43	3.92
		4	9.32	39.37	23.53	25.31	9.54
		5	10.51	28.22	23.94	26.16	13.36
		6	19.89	9.01	23.51	25.91	16.50
		7	12.95	48.85	23.09	26.47	24.05

Table 5. (cont.)

Drop size	Wind-speed	Distance	Horiz. vel.	Horiz. acc.	Vert. vel.	Resultant vel.	Displacement
4.3mm	6.3mph	2.5	1.87	21.33	29.00	29.06	4.48
		4	2.29	6.08	28.53	28.72	3.99
		5	2.76	13.40	27.94	28.08	3.02
		6	3.55	22.53	28.30	28.52	2.97
		7	4.14	16.82	28.80	29.10	4.65
	10	2.5	2.36	26.60	28.64	28.74	3.20
		4	2.87	9.58	28.33	28.47	5.57
		5	3.83	27.05	28.17	28.43	4.86
		6	4.22	10.99	28.01	28.33	6.01
		7	5.39	32.97	27.76	28.28	7.95
	15	2.5	3.12	33.24	26.64	26.82	5.28
		4	3.94	14.56	26.57	26.86	5.20
		5	5.71	47.15	26.83	26.83	7.90
		6	6.73	27.17	26.78	27.61	9.68
		7	7.45	19.18	26.36	27.31	11.45
	20	2.5	6.76	66.06	25.29	26.18	4.73
		4	8.73	32.09	24.32	25.84	9.45
		5	9.90	25.59	24.43	26.36	13.17
		6	12.67	67.68	23.71	26.88	19.04
		7	11.87	19.55	24.41	27.14	21.48
	25	2.5	9.71	87.47	23.13	25.08	8.26
		4	13.72	60.20	22.24	26.13	15.77
		5	16.09	53.37	22.32	27.52	25.31
		6	16.86	17.34	22.43	28.06	34.66
		7	17.81	21.39	22.48	28.68	40.08

Table 5. (cont.)

Drop size	Wind-speed	Distance	Horiz. vel.	Horiz. acc.	Vert. vel.	Resultant vel.	Displace-ment
5.0mm	6.3mph	2.5	2.03	23.70	29.67	29.74	
		4	2.27	4.67	29.22	29.31	
		5	2.90	18.39	28.90	28.99	
		6	3.81	26.56	28.93	29.18	
		7	3.62	-5.55	29.22	29.44	
	10	2.5	2.52	28.54	28.47	28.58	
		4	3.23	13.40	28.30	28.48	
		5	3.89	18.69	28.28	28.55	
		6	4.77	24.92	28.38	28.78	
		7	5.08	8.78	28.15	28.60	
	15	2.5	3.92	42.31	26.84	27.13	
		4	6.32	43.18	27.06	27.79	
		5	5.89	-11.60	26.95	27.59	
		6	7.63	46.96	27.01	28.07	
		7	7.49	-3.78	27.07	28.09	
	20	2.5	6.67	65.62	25.20	26.07	
		4	9.01	38.37	24.29	25.91	
		5	9.99	24.10	24.06	26.05	
		6	10.36	9.10	24.88	26.95	
		7	11.79	35.17	24.54	27.23	

THE EFFECTS OF WIND ON FALLING WATERDROPS

by

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
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1969

Effects of wind on the fall velocity and shape of waterdrops were studied and evaluated in terms of their influence on the waterdrop parameters used in rainfall erosion studies. Waterdrops 2.2, 3.6, 4.3, and 5.0 mm. in diameter were dropped 26 feet from a raintower into an 8-foot wind tunnel. Mean windspeeds of 6.3, 10, 15, and 20 miles per hour were studied. Multiple-exposure photographs were taken on the drops. Horizontal and vertical velocities and horizontal displacemnt of the drops were measured from the photographs, and kinetic energy and momentum of the waterdrops were calculated. Prediction equations were developed for horizontal velocity and displacement of drops falling in the wind tunnel.

Vertical drop velocity decreased as wind velocity increased. The decrease was sufficient to reduce the resultant velocity in wind below that in still air. Consequently, kinetic energy and momentum of drops were lower in wind than in still air for the conditions studied. The observed decrease in kinetic energy and momentum exhibited by the drops in wind may be due to the physical arrangement of the experimental raintower-wind tunnel structure and may not apply to natural rain.

Although some of the parameters measured were affected by the laboratory facility, conclusions can be drawn about the effects of wind on both natural and simulated rain. The resultant velocity of natural raindrops falling in wind is the vectorial sum of the terminal drop velocity in still air and the average horizontal windspeed. The prediction equations developed for displacement and horizontal velocity can be applied to rain simulated with other facilities. The effects of wind on kinetic energy of field simulated rain can be estimated using the prediction equation for horizontal velocity and assuming wind does not affect