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L. B. MacHattie

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RAMIFICATIONS OF RELATIVE HUMIDITY IN FORESTRY

by

L.B. MacHattie

Meteorologist, Seconded to Forest Research Division
Department of Northern Affairs & National Resources

An address presented to the Royal Meteorological
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To the aviation forecaster, relative humidity is a rather unpractical function. It is an unwieldy combination of temperature and moisture content. It is difficult enough to handle one variable, temperature, whose diurnal range is so great that it may camouflage a change of air masses, without tying humidity to it. Much better to separate the measure of humidity from temperature and deal with it as dew point, (or mixing ratio).

The average citizen develops a fair understanding of diurnal temperature variation since it affects daily life so closely and can be measured so readily. He realizes that a temperature of say 75°, has little significance unless he knows at what time in the diurnal cycle it occurred. But his understanding of relative humidity has hardly begun; it compares perhaps with a 5-year-old child's sense of temperature. Witness the numerous statements asserting, for instance, that the radio said the temperature was 92° and the humidity 98%.[*] Presumably around breakfast time these people heard a forecast of the maximum temperature and the current relative humidity.

In talking to the public, the press, and radio announcers, I have frequently done my best to discourage them from thinking in terms of relative humidity. (If they must use relative humidity, let them calculate it with respect to saturation vapour pressure at skin temperature rather than air temperature). But dew point is a much better basis for estimating summertime comfort. Dew point is more susceptible to forecasting, and to averaging for climatic purposes. Of what use then is relative humidity?

It is when one considers adsorption that relative humidity is of prime importance. High school chemistry gave me the impression that adsorption has to do with charcoal's marvelous ability to eliminate obnoxious odours. I now find that adsorption is a phenomenon of almost universal occurrence. The first sentence in Gregg's monograph on "Adsorption of Gases by Solids" states, "Wherever we have an interface between a solid and a gas or vapour, the concentration of the gas is higher in the immediate vicinity of the solid than it is in the free space beyond". This excess concentration is adsorption. What concerns us primarily here is adsorption of water vapour by wood. The amount of water vapour adsorbed by wood tends to change in response to atmospheric changes

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[*] The extreme highest dew point values as published in Climatic Summaries are for Malton 80, Ottawa 78, Dorval 74.

in relative humidity. These changes in amount of adsorbed water, change many properties of wood, including its size, strength, electrical conductivity, and inflammability. These changes may be blamed for making drawers stick, opening cracks in floors, weakening structural timbers, detuning pianos, and vice versa -- the piano which goes out of tune in May, may come back in tune in November.

Experimental values of the weight of water vapour adsorbed by wood (5), under different conditions, indicate that the equilibrium moisture content depends primarily on relative humidity, and to a lesser extent, on temperature. Weight of moisture content is usually expressed as a percentage of the dry weight of the wood. The following table shows equilibrium moisture contents for various humidities at two temperatures.

Relative Humidity (per cent)	Moisture Content in Percent of Dry Weight			
	Wood		Air	
	50°F	70°F	40°F	70°F
20	5.4	4.6	.15	.31
40	8.5	7.9	.31	.62
60	12.1	11.4	.46	.93
80	18.2	17.3	.62	1.25

The amounts adsorbed by wood are seen to be quite large. For comparison the percentage weight of water vapour associated with unit dry weight of air, (under the same conditions of temperature and humidity) have been read off a tephigram. At 50°F the water vapour mixed with a pound of air is only 1/30th that adsorbed by a pound of wood, even though the air has 400 times the volume of the wood.

Equilibrium moisture content of wood for 100% relative humidity has not been given because it is a rather indeterminate quantity. One forecaster at the Forest Products Laboratories left a piece of wood soaking in water except for the few minutes each day it took to weigh it. The wood continued to gain weight all summer. Presumably; the process could have gone on indefinitely, until ultimately one might have a solution of wood in water.

The dependence of adsorbed moisture content on relative humidity, rather than vapour pressure or dew point, is evident from a comparison of the amount adsorbed at 70°F with that at 50°F. For a 20° temperature rise at constant relative humidity the vapour pressure doubles, the dew point rises 20°, but the weight of adsorbed moisture changes little. Actually it <u>decreases</u> with a rise in temperature. The amount of the decrease for a 20°F temperature rise is roughly equivalent to that due to a 5% decrease in relative humidity.

Adsorbed moisture content of wood is of prime importance to forest protection agencies because of its affect on inflammability. There are many factors affecting the starting and spreading of forest fires including:

prevalence of sources of ignition,
types of forest fuels and their distribution,
slope of ground, wind,
accessibility for fire fighters, etc.,

but fuel moisture content may well be the most important. When fuel moisture content is high, all the other factors may be favourable for fire but even a burning brush pile will not start a forest fire. (Several years ago, the survivors of an air crash between Churchill and Winnipeg, tried to start a forest fire and found it impossible). And when the moisture content is low even a spark from a metal heelplate may start one. (Last July two fires started near Chalk River from sparks from a train brakeshoe).

Early forest fire research sought to put the relationship between moisture content and inflammability on a quantitative basis. The critical fuel as regards forest fires starting and spreading is the litter, or duff layer: the mat of dead material lying on the forest floor. Unless this is dry enough to carry a fire there can be no forest fire, except perhaps on extremely steep slopes. Various experiments were made including dropping of lighted matches on duff layers with different moisture contents.

On a given type of duff it was found that different degrees of inflammability could be distinguished with surprising sharpness. For instance, a small series of tests Gisborne (7) made with 40 matches on white pine duff in Idaho gave the following results. Of 13 matches dropped on duff with 12% moisture content, 5 started fires and 8 did not. With moisture content less than 10% every match ignited the duff, and with moisture content more than 13% none did.

On the basis of intensive research at the Petawawa Forest Experiment Station, 1929-32, J.G. Wright (10) drew the conclusions embodied in the table below.

Duff Inflammability Rating	Ignition Agent	Duff Moisture Content	
		Mixed Pines	Pure Red Pine
Nil	Even one-foot-diameter campfires ineffective	24% and over	35% and over
Low	Campfires usually effective, but not matches	19-23%	30-34%
Moderate	Matches usually effective. Rate of spread and height of flame moderate	16-18%	19-29%
High	Ignition from matches is certain. Fire intensifies at dangerous rate	11-15%	13-18%
Extreme		10% or less	12% or less

The distinction between 'High' and 'Extreme' was based on the difficulty of stamping out a standard test fire with the feet. Under 'Extreme' conditions this could hardly be done.

The long heavy needles of red pine make a thick but very porous duff layer which is more inflammable than that of the other softwood types studied.

Referring back to the table of wood moisture content vs. relative humidity, (which also holds reasonably well for pine duff) we see that duff for mixed pine in equilibrium with 50% or lower relative humidity rates Extreme in inflammability, whereas in equilibrium with relative humidity of more than 80% it can hardly be ignited by matches. Limited laboratory experiments with red and white pine duff to determine how <u>fast</u> they come to equilibrium with a new relative humidity, suggest that 80% of the change occurs in about 3 hours when picking up moisture and about 6 hours when drying. But there are so many factors affecting rate of change of moisture content that these figures should not be assumed to be typical. They simply indicate the importance of diurnal variations in relative humidity.

One important proviso should be appended to the above table of inflammability ratings. They refer to the ease or likelihood of a forest fire developing under the given conditions of duff moisture. But even with moisutre content well over 35%, lightning or a campfire could start a root smouldering. This root might continue to smoulder for weeks, if it is well protected, and then flare up the next dry spell. Theoretically, wood with more than 100% moisture content could keep smouldering; using 5000 cal/gm as the heat of combustion of wood, a quick calculation shows that four-fifths of the heat could escape and there would still be enough left to dry out adjoining fuel and raise it to ignition temperature.

Having determined the importance of the moisture content of the duff layer, the next problem was to find a practical way to measure it, or calculate it.

Three methods have been developed for rating moisture. The most direct is the duff hygrometer (7). The active part of this instrument is a piece of rattan which is inserted horizontally just under the top of the duff. The changes in length of the rattan are registered on a dial calibrated directly in moisture per cent.

Since duff moisture content varies with weather conditions, considerable research was aimed towards rating duff moisture on the basis of weather observations (2).

In practice the duff hygrometer does not appear to be used much. The standard stick method is most widely used on this continent. In the Western States and British Columbia, ½-inch diameter cylinders of fir or pine are used, several of them being dowelled together to make up a dry weight of 100 grams. In the Eastern States a faster reacting wood is preferred -- 1/8-inch-thick basswood venetian blind slats are used.

The third method, based on weather observations, has been developed by the Federal Fire Protection Section, and is in use in all but two of the forested provinces of Canada. In this system the fuel moisture content is not calculated explicitly; the weather data which indicates duff moisture is combined with other data to give a direct rating of Fire Danger. On the basis of rain gauge data and daily noon readings of air temperature, relative humidity and wind, Fire Danger is rated with fair accuracy. This is indicated by the following forest fire data from New Brunswick.

An analysis was made of all forest fires during the period 1938-46, caused by man or dry lightning within 25 miles of any of the 30 odd forest weather stations -- there were 966 such fires.

The average rate of occurrence of fires for each of the five classes of danger rating was:

Nil danger, one fire every 270 days
Low danger, one fire every 5 days
Moderate danger, one fire every day
High danger, 2 fires every day
Extreme danger, 5 fires every day

The following table shows the percentage of the time that the danger rating fell in the different classes, the percentage of the total number of fires that started while the danger was rated in a given class, and the percentage area burned by danger classes.

Danger Classes	Proportions Expressed in Per Cent		
	Time	Number	Area Burned
Nil and Low	56%	10%	Less than 1/10%
Moderate	28	31	2
High and Extreme	16	59	98

Consideration of these figures shows that the most efficient fire detection and suppression procedure would not keep the same number of men on duty all the time. Rather it would allow most of them to perform other work, e.g. road and telephone maintenance, during the 50 per cent or so of the time the danger rating is "Nil" or "Low"; and when the danger is "High" or "Extreme" not only would all the regulars be on fire duty, but as many additional men seconded from other jobs as possible. This is the most important use of Fire Danger Ratings; to be an objective guide in the deployment of men and equipment.

While this system of rating fire danger on the basis, primarily, of a single noon weather observation, works well through most of Canada, it has not been satisfactory in the Rocky Mountain sections of Alberta. Whereas the system implicitly assumes that the relative humidity rises close to 100% at night, with resultant regain of moisture by forest fuels, in the mountains, nights during which the relative humidity remains below 80% occur frequently enough to upset the ratings. It was primarily to investigate this effect that a meteorologist was seconded to the Forest Research Division in December, 1951.

The close relation between adsorbed moisture content and atmospheric relative humidity suggests extensive measurements of relative humidity in any investigation of variations in duff moisture content. It is surprising how readily, in biological research work, the assumption may be made that relative humidity should always be measured the way the

Meteorological Service measures it, in a screen four feet above ground; and if the property in question doesn't correlate with screen humidity, then it is assumed to be unrelated to relative humidity. In some measurements in Idaho, Hayes (9) found that on south slopes "the same minimum duff moisture was recorded, within limits of instrumental variation, on all clear days from May to August. Some days the air temperature would be 70°F and relative humidity 30%; on other days the temperature was over 95°F and relative humidity under 15%". (The difference in adsorbed moisture content corresponding to the difference between 30% and 15% relative humidity is 2½%). Since this litter was exposed to considerable sunshine, the effective relative humidity to which it was exposed must have been much different from the screen humidity.

When studying the effect of sunshine on the surface temperature of lodgepole pine cones in Alberta, D.I. Crossley found that with air temperature about 80°F the surface temperature of a cone exposed to sunshine would rise to 110°F in less than 20 minutes. If the screen relative humidity was 40%, the relative humidity of the air layer adjacent to the cone would be something less than 20%.

Wood moisture content is drastically affected not only by incoming solar radiation (3) but also by outgoing radiation. At the Bent Creek Experimental Forest near Asheville, North Carolina, Byram (4) made a study of surface duff temperatures in comparison with 5-foot air temperatures on north and south slopes at sites about 1500 feet above the valley floor.

The duff temperatures were measured with the thermometer bulb covered by one leaf. The results for a cloudless period near the end of November are summarized below. The figures were read off a graph to an accuracy of about ± 2°F.

North Slope			South Slope		
Hours	Duff	Air	Air	Duff	Hours
00-08	20-23°F	30-34°F	32-35°F	19-23°F	00-08
12-18	27-33°F	35-46°F	46-52°F	80-100°F	11-14

The north slope site was so chosen that it received no direct sunshine. The high surface temperature during sunshine on the south slope might be expected, however the large daytime difference between surface and air on the north slope was somewhat surprising. The duff averaged about 11°F colder, and at times was 15°F colder than the 5-foot air temperature. The similarity between north and south night time temperatures indicates that the daytime difference was not due to underlying soil differences, but to terrestrial radiation.

Another study of Byram's (3) shows the effect of wind combined with sunshine on rate of drying.

Wind is generally considered a drying element, presumably because the wind dissipates the zone of high humidity which tends to build up around each evaporating surface. After a rain, a windy day is expected to dry forests much faster than a still day.

It came as a surprise then when moisture indicator sticks which were exposed to receive some sunshine were found to be heavier on a windy, sunny, afternoon than on a calm sunny afternoon. Wind and sun separately were drying agents, but the two together had less drying action than sun alone. Although wind decreased the ambient relative humidity in the general neighbourhood of the stick, it also decreased the surface temperature of the stick to such an extent that the effective relative humidity in the air skin immediately adjacent to the stick was raised. The adsorbed moisture content then rose in response. While the change in relative humidity of the air layer around the stick appears to be the chief effect, a large temperature drop would in itself have an appreciable effect in increasing moisture content.

To get more exact values for the effect of different wind speeds on sunny days, Byram constructed a radiation chamber in which an artificial sun of electric light bulbs shone on forest fuels over which air was drawn at various speeds by exhaust fans. Using natural hardwood leaf litter, he measured fuel-air temperature differences. With 1.2 cal/cm.^{2} per min. radiation, the temperature differences were: 44°F with no wind, 24°F with 2 mph, and 16°F with 4 mph. With half that intensity of radiation the temperature differences were also halved.

Now consider the heat evolved when water vapour is adsorbed. Since the density of adsorbed water vapour is similar to liquid water, this heat should be comparable to the latent heat of condensation. Except that in so far as the bonding between adsorbent and the adsorbed molecules is greater than between ordinary liquid water molecules, the heat of adsorption should be correspondingly greater than the latent heat of condensation. The amount of this excess calculated from data of Stamm and Loughborough for Sitka wood ranges from 10 calories per gram with relative humidity around 93%, to 88 at 42%, and 246 calories per gram at 1% relative humidity.

It will be understood that this heat of adsorption is considerable. For instance when 100 gms. of spruce is moved for 20% relative humidity to 40%, its equilibrium moisture content increases by some 3 grams and in the process approximately $3(580+100) = 2000$ calories of heat must be dissipated.

For lack of suitable experimental data for wood, an example from textile research is quoted here to indicate the effect of this heat of adsorption on the rate at which an adsorbing substance changes its moisture content. A.B.D. Cassie (6) and co-workers of the Wool Industries Research Association reported several decisive experiments on wool fibres. It is known that when wool (or wood) in equilibrium with one relative humidity is suddenly exposed to a higher relative humidity, it takes a considerable time to complete even 80% of the change in adsorbed moisture. There are three possible time consuming processes involved:

i) diffusion of water vapour to the fibre
ii) movement of water molecules into the fibre
iii) dissipation of the heat of adsorption

To simplify the situation Cassie eliminated the first of these by operating in an atmosphere of pure water vapour -- all the air was evacuated from the apparatus, then enough water evaporated in it to give the desired vapour pressure. Thus water vapour would move toward the wool, to replace molecules adsorbed, by a mass movement in response to total pressure instead of by a slow diffusion of individual water molecules impeded by air molecules.

A quarter gram of wool was used -- the average fibre diameter was .021 mm. A piece of platinum wire 16 cm. in length was intertwined with the wool and wound into a loose bundle which was suspended from a spiral spring. Changes in adsorbed moisture were measured by observing the extension of the spiral spring with a travelling microscope. A duplicate run was then made with the ends of the platinum wire connected for use as a resistance thermometer so that the variation of temperature with time could be noted, and correlated with the previously observed variation of adsorption with time.

The graph of variation of adsorption with time gave a smooth curve ascending very steeply at first and gradually flattening off. This gives little indication of which process, ii) or iii), was the slow one.

The graph of temperature against time is illuminating. The temperature rose very steeply from 25°C to over 65°C then fell, fairly rapidly at first, gradually flattening. The first temperature measurement made was 30 seconds after admission of the water vapour. It showed 65°C.

Consideration of this temperature curve leads to the conclusion that the time taken for water molecules to move from the surrounding vapour film to their adsorbed positions in the wool fibre is negligible; that practically the whole delay is due to the time required for dissipation of the heat of adsorption.

What apparently happens is that at first water molecules adsorb at a very rapid rate, their heat of adsorption raising the temperature of the wool, till a point is reached where the amount adsorbed at the moment is in equilibrium with that value of relative humidity calculated from the surrounding vapour pressure and the saturation vapour pressure at the temperature of the wool fibre. This may be clearer if we use some sample figures. In this experiment, initial temperature of the wool and surroundings was 25°C; then vapour pressure of 30.8 mbs. was admitted. This corresponds to 97.4% relative humidity at 25°C. For this humidity the equilibrium moisture content of wool is about 30 per cent of the dry weight of the wool.

Consider the situation after the wool moisture has risen to 3%, i.e. one tenth of equilibrium value. Heat of adsorption is about 750 cal/gm, and the specific heat of wool 0.3 cal/gm per °C. If all the heat went to raising the temperature of the wool the temperature rise would be $\frac{750}{0.3} \times \frac{3}{100} = 75^{\circ}C$. Since the initial temperature was 25°C this would be the boiling point of water and saturation vapour pressure would be 1013 mbs. The effective relative humidity would be $\frac{30.8 \text{ mbs.}}{1013 \text{ mbs.}} = 3.5\%$. Since equilibrium moisture content of wool in 3.5% relative humidity is less than 3 per cent, the adsorbed moisture content could not have risen to 3 per cent until the wool fibre had cooled off somewhat.

An immediate adsorption of about 2.3% moisture gives a temperature rise sufficient to establish a momentary equilibrium between effective ambient relative humidity and adsorbed moisture content. Thereafter the rate of adsorption depends on the rate of cooling. The time involved in this initial adsorption of 2.3 per cent is unknown, but should be considerably less than 15 seconds. A theoretical calculation suggests a fraction of a second. Cassie comments at the end of his article to the effect that the investigators who have been deducing things about the surface structure of fibre colloids from studying rate of moisture pick-up curves are wasting their time.

Other experiments performed with air-water vapour mixtures instead of pure water vapour atmosphere show the same general results with both increasing and decreasing humidity and when using cotton in place of wool. An initial rapid temperature change effectively brings the relative humidity into equilibrium with the current moisture content of the fibre; thereafter moisture content changes are dependent on fibre temperature approaching water vapour temperature.

Since Cassie's results applied to cotton, (as well as wool), since cotton is largely cellulose, and since the hygroscopic part of wool is cellulose, these results should have a close bearing on the rate of change of moisture content of the duff layer in a forest.

These experiments may also have a bearing on the design of humidity instruments. If the active element of an instrument to measure relative humidity adsorbs much moisture, the lag in response may be chiefly thermal in nature. It is noted that the adsorption properties of hair are practically the same as of wool.

Now let us consider another relative humidity situation. A large proportion of Canada's forested area is interspersed with numerous lakes. It is generally assumed that the relative humidity is higher downwind from the lake than upwind. When the lake surface temperature is as high or higher than the atmospheric dew point, this should be so. But during the spring season, which is especially important for tree growth and is often a period of high fire hazard, lake temperatures will frequently be lower than atmospheric dew point; this may result in condensation. As the air comes off the lake its relative humidity would be high, but on a sunny afternoon one would expect it to rapidly regain its original temperature, due to the low level inversion. The result might well be a lower relative humidity on the downwind side of the lake than on the upwind side. In this case the effect of the lake is to further <u>dry</u> the downwind forest at the time of day when the fire hazard is a maximum. In practice this effect <u>may</u> be small enough that it may be neglected, but it is mentioned as an interesting paradox.

In studying and discussing processes of adsorption and transpiration it helps to think of relative humidity as a suction, the suction depending on the amount by which the relative humidity is less than 100%. This might be called "humidity deficit". One might claim for this concept the same degree of validity as for that convenient fiction "centrifugal force". Anyway, using this concept, equilibrium in adsorbed moisture content is simply a balance of forces; humidity deficit versus adsorptive attraction. When the relative humidity is near 100%, the humidity deficit is low and from a saturated piece of wood it can pull off only the very loosely adsorbed molecules from the outer layers. As the relative humidity lowers, more tightly adsorbed molecules can be pulled off.

One may go further and put this humidity deficit in quantitative terms. Consider a vertical capillary tube with one end in a reservoir of water. If the diameter of the capillary is 3 mm. the water will rise 1 cm up the tube. With progressively smaller diameters the rise is progressively greater as shown in the following table.

Capillary Diameter mm.	Capillary Rise cm.	Relative Humidity %
3.0	1	99.99+
.3	10	99.99+
03	100	99.99
.003	1000	99.93
3X10-4	10^4	99.2
3X10-5	10^5	92.6
3X10-6	10^6	55.4

With smaller and smaller capillaries the degree of curvature of the meniscus gets greater and the equilibrium vapour pressure above it proportionally less. We can then make a table relating relative humidity to height of capillary rise, and since a 1000 cm. head of water is equivalent to <u>one</u> atmosphere of pressure we can convert height of capillary rise into pressure expressed in atmospheres, thus being able to convert relative humidity to pressure units.

A physical argument for the validity of this conversion of relative humidity to pressure units might run as follows:

The capillary rise in a tube of 3.10^{-4} mm. diameter is 10,000 cm and the equilibrium relative humidity above the meniscus is 99.2%. Now suppose the actual relative humidity is 99.1%, then evaporation will proceed and the result will be a flow of water up the tube. If relative humidity is 99.3% condensation will take place and there will be a flow of water down the tube. Therefore the equilibrium relative humidity must represent a suction equal to the pressure required to raise a column of water 10,000 cm high. It will be seen that relative humidities less than 50% are equivalent to pressures upwards of 1000 atmospheres.

This presumably is what raises water up to the crowns of trees. Trees have been known to reach heights of about 450 feet. To supply water to this height requires a pull of at least 15 atmospheres. The water in the trunk near the top must be under negative pressure of at least 15 atmospheres -- i.e. it is actually under tension. As a physicist it startled me to be told by a forester that water has tensile strength. I thought it was generally understood that when the pressure over liquid water decreased below the saturation vapour pressure that the liquid simply turned into vapour. But on consulting with a physical chemist at N.R.C., I found matters were not at all that simple. Apparently, in the absence of nuclei, vapourization is as difficult as condensation. In laboratory experiments, especially purified water has been subjected to stresses up to 65 atmospheres before vapourizing, and on theoretical grounds it is thought the tensile strength of pure water is about 300 atmospheres.

In closing I would like to just mention another adsorption problem -- soil water. The water in the soil layers where trees usually have their roots is more or less adsorbed. To obtain water, tree roots must be able to overcome the adsorptive bonding. When the soil is dried to the point where the roots can no longer obtain water for growth and photosynthesis, trees and plants wilt (some visibly, some imperceptibly). The interesting thing is that all plants wilt at the same degree of soil dryness -- and that this degree of dryness is in equilibrium with an atmospheric relative humidity of more than 98%.

If we postulate a site where the relative humidity always remained at 95%, the deadwoody material on the ground would be so wet that a forest fire would be impossible, and the soil would be so dry that it would be barren. Any inherent contradiction in postulating a duff layer on a barren site may be blamed on my two years in Ireland.

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