Principles of Energy Balance in Environmental Systems

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Lecture 7

1. Energy balance principles at night: Radiation frost
2. Energy balances principles in the Penman-Monteith equation
3. The simplicity of the Hargraves equation

Frigid index temps not so believable?

By Patricia Swanson
Scripps Howard News Service

How cold is it?

Not as cold as you think if you're basing your view on the wind-chill index, according to Maurice Bluestein, a professor at Indiana University Purdue University-Indianapolis.

Bluestein and others say the index is dramatically flawed and has been since it was developed more than 50 years ago.

The current wind-chill index, which is supposed to measure how cold it feels on bare skin, should be at least 10 degrees higher, said Bluestein.

For instance, he said when the temperature is 10 and the winds are blowing at 10 mph, the true wind chill is just above zero. The current index says it's 9 below zero.

The wind-chill reading on the present index says a temperature of 5 and winds of 15 mph equal a wind chill of minus 25.

Bluestein says it should be "just" minus 14.

"Now that's still pretty cold," he said in a telephone interview. "But it's not as cold as it (the wind-chill index) makes it out to be."

Some scientists, using a slightly different method than do Bluestein and his colleagues, think the difference is even less.

Of course, some people might suggest that the difference between a wind-chill reading of minus 10 and minus 20 isn't enough to be of concern to anyone except weather fanatics. Cold is cold.

But the Indianapolis mechanical engineering professor said the errors in the index cost money and productivity. They also can be dangerous.

He noted that many schools and companies, for instance, close down when the wind-chill index is at a certain figure, thinking the combination would be hazardous to children and employees.

They close "when perhaps they shouldn't be closed," he said. "The students can withstand the actual conditions."

There is also a reverse problem, the professor said.

Say someone is out in what the wind-chill index says is 9 below zero and find they handle it easily. Then comes a day when it really is 9 below zero with no wind and the person suffers cold-related problems.

See CHILL on Page 10

Chill

Continued from Page 1

Bluestein himself became interested in the wind-chill index when Indiana was having a bitter cold outbreak a few years ago. His daughter, who also lives in Indianapolis, was ill and asked him if he would help shovel her driveway since she wanted to go to work in the morning.

"I was out there, waiting for her to get the shovels, and I found it wasn't that bad," he said. "My skin didn't freeze in 15 seconds like they said it would."

He investigated and found the index originally was computed by "a primitive study" of how fast a can of water froze in the Antarctic.

It was done for the military to help determine which kind of clothing service people needed in frigid areas.

But he said you can't extrapolate the water freezing data for human skin. Water and skin have different properties.

Bluestein, author of the sixth edition of "Thermodynamics and Heat Power," used principals of heat transfer to determine how cold it would feel if the wind were hitting people on the face, ears and back of the neck.

His research was predicated on people wearing a hat, gloves and heavy jacket.

Another group, which also used heat transfer principles, thought in cold weather that people would wear earmuffs and mufflers so their method concentrates only on the effect on faces, which they felt were the only part of the body which would be uncovered.

Their index has slightly higher readings.

Bluestein said there "is unanimity in the research community" that the old index is wrong.

He has been appointed to a committee that will submit a proposal for a new index, based on current research, to the National Weather Service.

The group hopes the new charts will be in use within three years.

Computing the wind chill factor

The wind chill is a calculation that describes the combined effect of the wind and cold temperatures on exposed skin.

The wind chill index would be minus 22, for example, if the temperature was 15 degrees and the wind was blowing at 25 mph.

Wind speed (MPH)	Actual air temperature (°F)														
	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35
	Equivalent Chill Temperature														
5	33	27	21	16	12	7	0	-5	-10	-15	-21	-26	-31	-36	-42
10	22	16	10	3	-3	-9	-15	-22	-27	-34	-40	-46	-52	-58	-64
15	16	9	2	-5	-11	-18	-25	-31	-38	-45	-51	-58	-65	-72	-78
20	12	4	-3	-10	-17	-24	-31	-39	-46	-53	-60	-67	-74	-81	-88
25	8	1	-7	-15	-22	-29	-36	-44	-51	-59	-66	-74	-81	-88	-96
30	6	-2	-10	-18	-25	-33	-41	-49	-56	-64	-71	-79	-86	-93	-101
35	4	-4	-12	-20	-27	-35	-43	-52	-58	-67	-74	-82	-89	-97	-105
40	3	-5	-13	-21	-29	-37	-45	-53	-60	-69	-76	-84	-92	-100	-107
45	2	-6	-14	-22	-30	-38	-46	-54	-62	-70	-78	-85	-93	-102	-109

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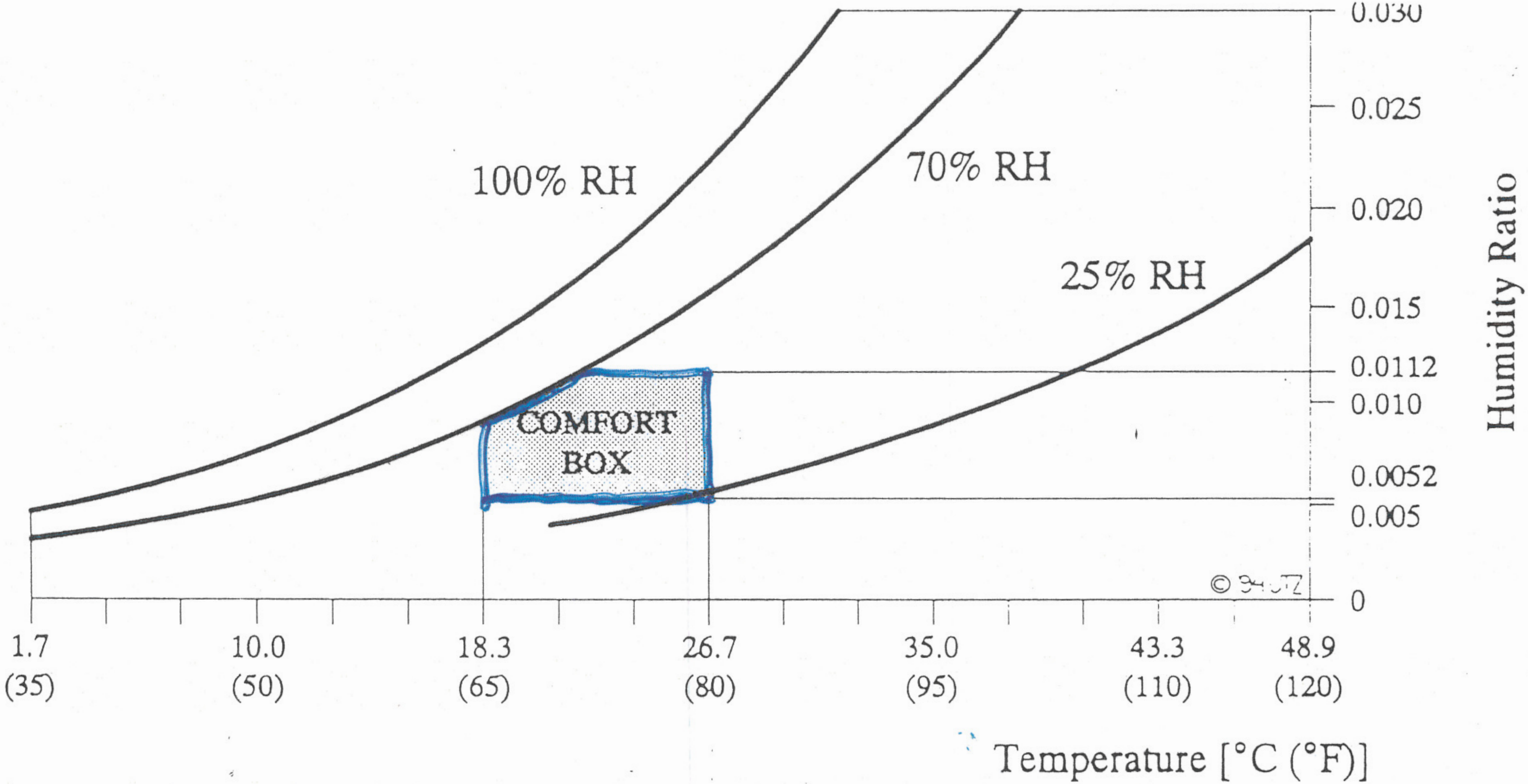
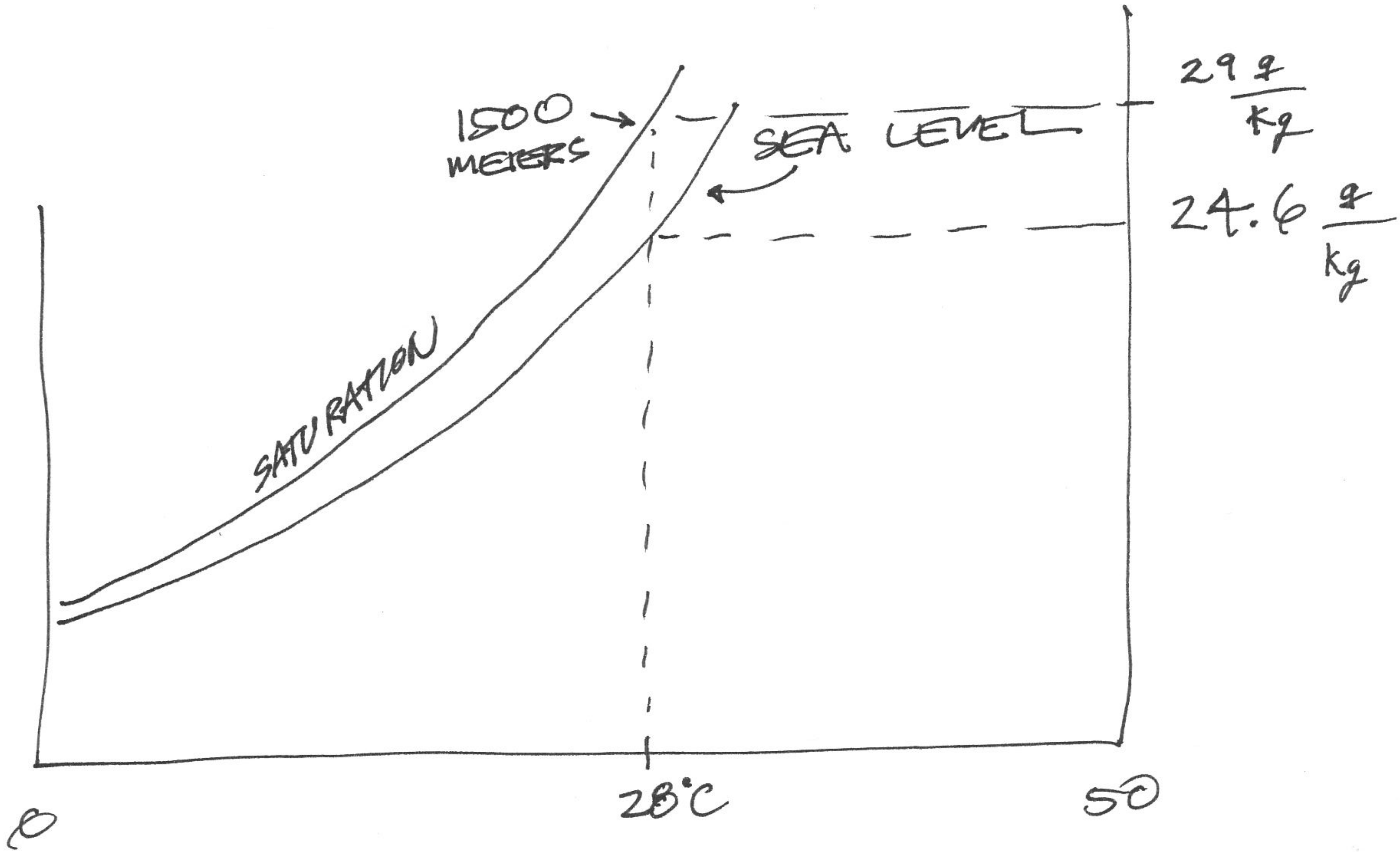


Figure IV.3: Temperature and Humidity Ranges for the U.S. Space Station [48]



1500 METERS
SEA LEVEL
SATURATION
29 g/kg
24.6 g/kg
0
28°C
50

The panel of experts recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration and advised on procedures for calculation of the various parameters. By defining the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered, the FAO Penman-Monteith method was developed. The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data worldwide.

From the original Penman-Monteith equation (Equation 3) and the equations of the aerodynamic (Equation 4) and surface resistance (Equation 5), the FAO Penman-Monteith method to estimate ET_o can be derived (Box 6):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \qquad (6)$$

where

ET_o	reference evapotranspiration [mm day^{-1}],
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}],
G	soil heat flux density [MJ m^{-2} day^{-1}],
T	mean daily air temperature at 2 m height [°C],
u_2	wind speed at 2 m height [m s^{-1}],
e_s	saturation vapour pressure [kPa],
e_a	actual vapour pressure [kPa],
e_s-e_a	saturation vapour pressure deficit [kPa],
Δ	slope vapour pressure curve [kPa $°C^{-1}$],
γ	psychrometric constant [kPa $°C^{-1}$].

FIGURE 10
Illustration of the effect of wind speed on evapotranspiration in hot-dry and humid-warm weather conditions

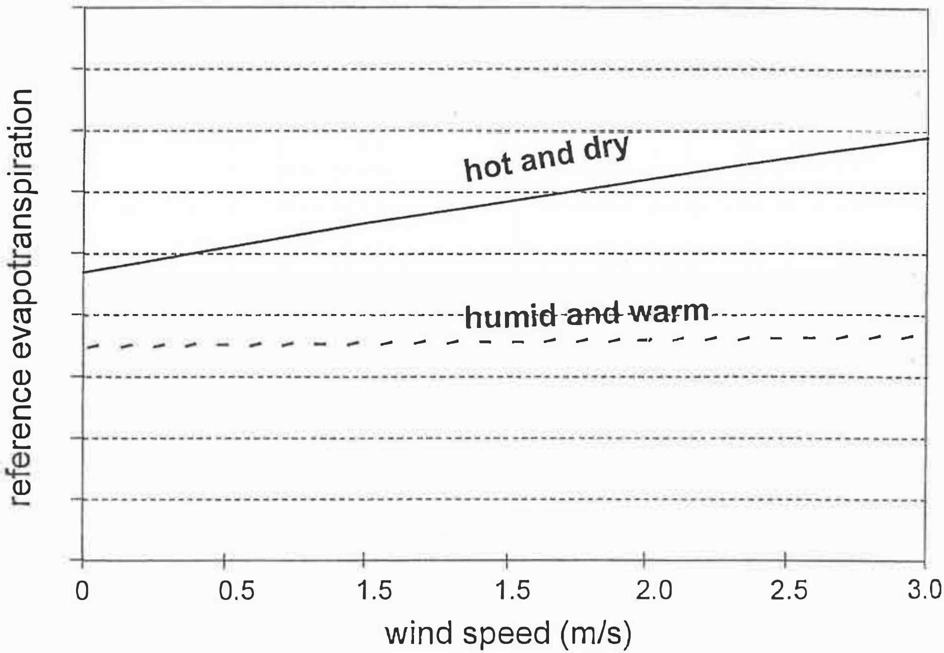


FIGURE 5
Schematic presentation of the diurnal variation of the components of the energy balance above a well-watered transpiring surface on a cloudless day

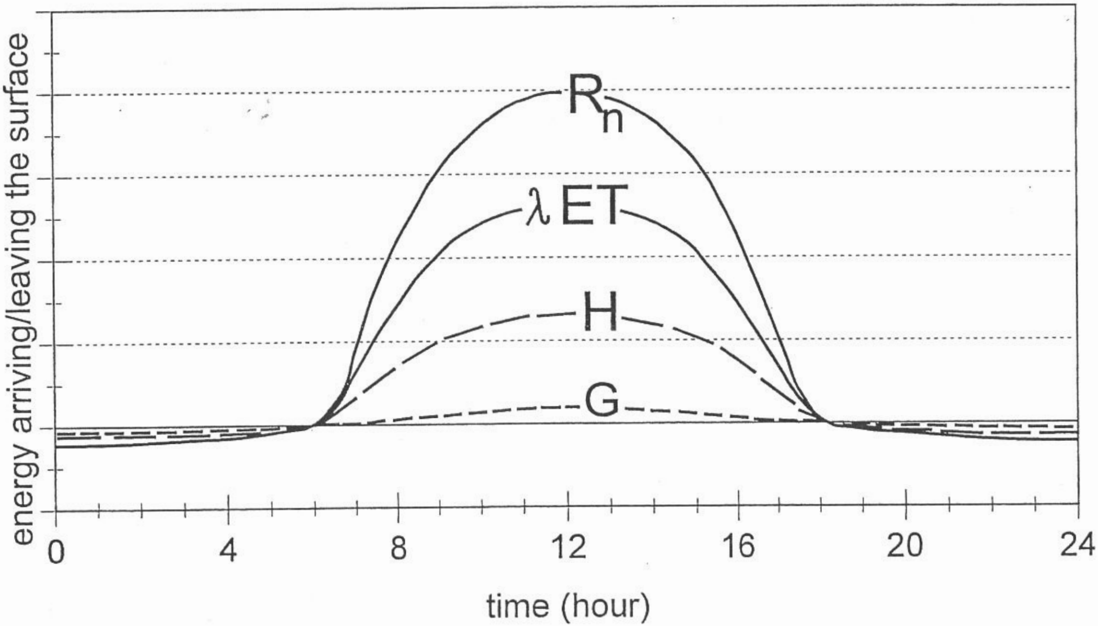
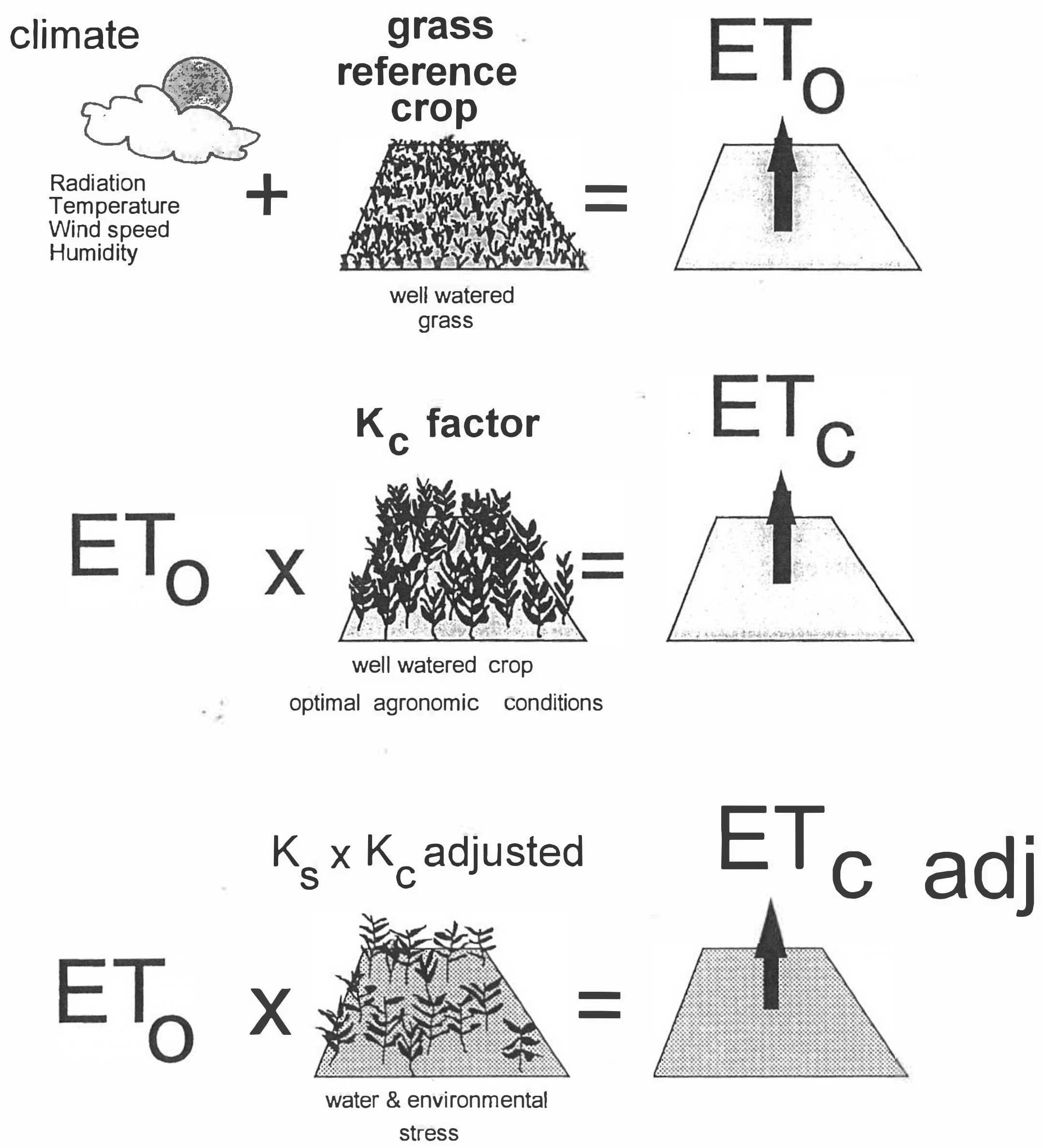


FIGURE 4
Reference (ET_o), crop evapotranspiration under standard (ET_c) and non-standard conditions ($ET_{c\ adj}$)



Evapotranspiration (ET) is a term used to describe the combined loss of water due to evaporation from soil surfaces and transpiration from plants. It is critically important to estimate the amount of evapotranspiration because it determines the cycles of water movement between the soil and the atmosphere. The most reliable estimates of **ET** come from research studies with plants in large containers called lysimeters. It is not possible to directly determine ET from climate data, unlike other properties such as temperature. However, it is possible to estimate ET to within 5 to 10% by using equations that predict it from climate data.

If soil moisture is not limiting, we know that ET increases in hot, windy, sunny, low humidity conditions. If the surface is composed of short, healthy vegetation that completely covers the ground and is well supplied with water the ET value will be mainly determined by the weather conditions. An equation was developed from general scientific principles to calculate the ET value for such a virtual surface, which is called the **Potential ET**. It is **not** the same as the actual ET. It is the largest value of ET that could exist under the climate conditions at the time. For specific crops and certain other vegetated surfaces, many studies have been conducted to find empirical or approximate relationships between actual and reference ET. The actual ET is determined by calculating the reference ET and multiplying it by a value called the **crop coefficient**.

More than 20 equations have been developed to estimate reference ET from weather data. The most exact equation is based on biophysical principles and requires weather data that includes at least hourly averages of solar radiation, temperature, humidity and wind. This is called the **Penman-Monteith equation**. Not all climate stations, however, record all of the necessary measurements. Fortunately, there is a well known equation for reference ET that only requires temperature, which is measured at all climate stations.

The Hargreaves equation is used here to estimate reference ET or ET_o, because it generally produces the best ET_o estimates. The equation has the form:

$$ET_o = 0.0023\,(T_{mean} + 17.8)\,(T_{max} - T_{min})^{0.5}\,R_a$$

where 'ET_o' is the reference evapotranspiration in millimeters per day. 'T_{max}' and 'T_{min}' are, respectively, the daily maximum and minimum temperatures in degrees Celsius.'T_{mean}' is the daily mean temperature in degrees Celsius which is found by summing the T_{max} and T_{min} together and dividing by two. 'R_a' is the extraterrestrial radiation. The R_a value is a function of location (latitude) and day of year. It is used to estimate the theoretical amount of solar radiation incident upon a particular location, and converted to a value of the amount of water that could be evaporated from this energy, in mm per day. The amount of actual solar radiation can be implied by the Hargreaves equation because of the way it utilizes temperature data. The daily temperature range (i.e. T_{max}-T_{min}) is related to can the cloudiness and humidity at a given location. For example, when the conditions are cloudy the daily temperature range is generally small. Likewise, the temperature range tends to be small when humidity values are high. As a note of caution, the Hargreaves equation has a tendency to under-predict under high wind conditions (greater than 6 – 7 miles per hour) and to over-predict under conditions of high relative humidity. Occasionally, during the winter months, the calculated T_{mean} value for a given day can be less than -17.8°C. When this occurs, the Hargreaves ET_o equation yields a negative value. Negative ET_o values under these conditions have no physical meaning and should be set to zero. Generally, this is not a problem because ET_o values were designed to be used during the warmer months when plant growth is active and ET_o values will be positive. [note: it would be useful to provide a numerical example, using typical summer data, showing how the Hargreaves provides a typical ET value.

Once an ET_o value is determined, the appropriate coefficient or **crop coefficient** must be found to obtain an actual ET. This requires finding a published value for the crop of interest, and multiplying it by the ET_o value. Crop coefficients are available for a variety of crops and vary according to plant type and the stage of plant growth. Appendix III contains a table of crop coefficients for use with different types of crops and their associated stages of development. There is usually considerably more error associated with the estimate of the crop coefficient than with the estimation of ETo.

TABLE 1. The Beaufort Scale

Beaufort No.	Description	Wind-speed equivalent at a standard height of 10 m above open flat ground: Knots	m/s	Km/h	Miles/h	Specifications for estimating speed over land
0	Calm	<1	0– 0·2	<1	<1	Calm: smoke rises vertically
1	Light air	1– 3	0·3– 1·5	1– 5	1– 3	Direction of wind shown by smoke-drift but not by wind vanes
2	Light breeze	4– 6	1·6– 3·3	6– 11	4– 7	Wind felt on face; leaves rustle; ordinary vanes moved by wind
3	Gentle breeze	7–10	3·4– 5·4	12– 19	8–12	Leaves and small twigs in constant motion; wind extends light flag
4	Moderate breeze	11–16	5·5– 7·9	20– 28	13–18	Raises dust and loose paper, small branches are moved
5	Fresh breeze	17–21	8·0–10·7	29– 38	19–24	Small trees in leaf begin to sway, crested wavelets form on inland waters
6	Strong breeze	22–27	10·8–13·8	39– 49	25–31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty
7	Near gale	28–33	13·9–17·1	50– 61	32–38	Whole trees in motion; inconvenience felt when walking against the wind
8	Gale	34–40	17·2–20·7	62– 74	39–46	Breaks twigs off trees: generally impedes progress
9	Strong gale	41–47	20·8–24·4	75– 88	47–54	Slight structural damage occurs (chimney-pots and slates removed)
10	Storm	48–55	24·5–28·4	89–102	55–63	Seldom experienced inland; trees uprooted; considerable structural damage occurs
11	Violent storm	56–63	28·5–32·6	103–117	64–72	Very rarely experienced; accompanied by widespread damage
12	Hurricane	64 and over	32·7 and over	118 and over	73 and over	