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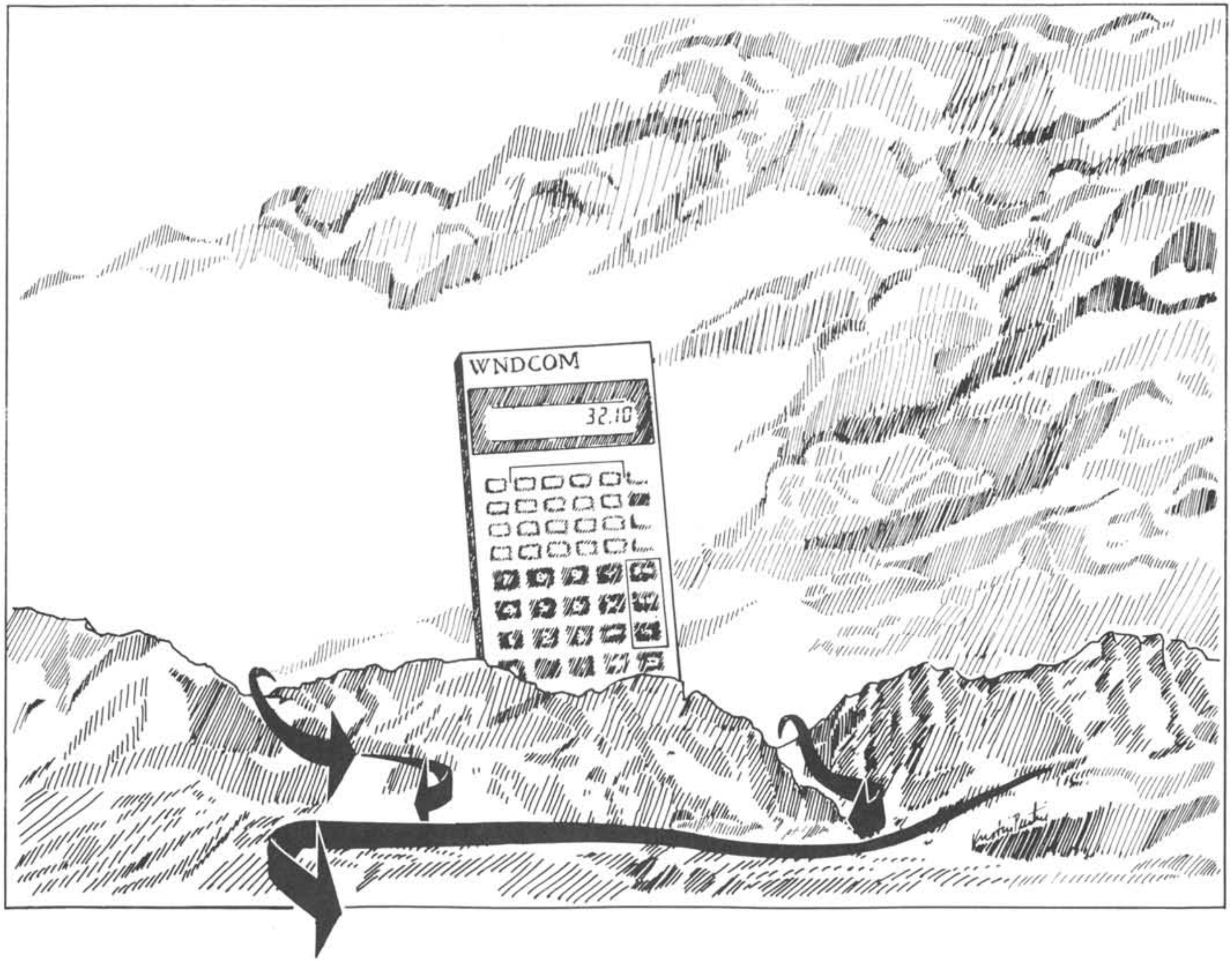
WNDCOM: estimating surface winds in mountainous terrain

Bill C. Ryan



The Author:

BILL C. RYAN, a research meteorologist, is assigned to the Station's forest meteorology research unit, headquartered at the Forest Fire Laboratory, Riverside, Calif. He earned a bachelor's degree in chemistry at the University of Nevada (1950), a master's in meteorology at Texas Agricultural and Mechanical University (1964), and a doctorate in climatology at the University of California, Riverside (1974). He joined the Station staff in 1967.

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WNDCOM is a mathematical model for estimating surface winds in mountainous terrain (Ryan 1977). The model is designed to be used in remote areas where little or no weather data are available. It is based on the premise that wind velocities in mountainous areas are composed of several influencing mechanisms whose effects can be estimated or simulated as individual components and then summed. These wind components include a general surface windflow, which is the wind at the standard 20-foot (approximately 6 m above the surface) level resulting from synoptic scale forcing, the sea breeze, valley wind, and slope wind. The general wind component and the sea breeze component are modified to incorporate the sheltering and diverting effects of the topography. These modified vectors are added to the vectorial sum of the slope wind component and the valley wind component to determine the resultant wind at that point.

Sheltering is the blocking of the wind by terrain features. The model design assumes the sheltering of only the sea breeze and general wind components is significant; that is, the scale of sheltering of the valley and slope wind components is too small to consider. It also assumes that sheltering is a function of the elevation of the location and the elevation angle from the location to the crest of the blocking terrain. Diverting is the changing of direction of the wind by terrain features. As for sheltering, the model design assumes that diverting of only the sea breeze and general wind is significant because the scale of diverting of the valley and slope wind components is too small to consider. The model computes the diverting factor based on the angle at which the wind impinges on the terrain downwind of the location and the elevation angle from the location to the horizon downwind.

All components may not be present in some areas. For example, if no water body is near, there will be no sea or lake breeze; if the location is not on a slope, there will be no slope component, etc. Because the model is in modular form, only the pertinent components need to be calculated. Pertinent components can be determined by a simple examination of a topographic map of the area.

Although WNDCOM was designed to be as general as possible, techniques were incorporated to simulate unique characteristics, especially those of the Santa Ana winds of southern California.

This report provides a step-by-step procedure for applying the WNDCOM mathematical model to estimate surface winds in rugged terrain.

SUPPLIES AND DATA NEEDED

Supplies needed in using WNDCOM are a source of topographic data and a calculator or computer. A topographic map of the area at the largest scale available is best; this is often 1:24,000. A raised topographic map is also helpful.

The data and information needed to follow the procedure and do the calculations to estimate the general surface wind are discussed here. The data and information needed to estimate the separate components of the resultant wind are listed in the appropriate sections.

1. Geostrophic-level windspeed V_g and direction θ_g over site. The geostrophic-level wind is needed to estimate general wind, as described in the next section. Geostrophic winds analyzed from pressure gradients, observed by rawinsonde, forecast by the National Weather Service, or interpolated between grid points and between map times can be used. The data from the 850 mbar level are often best, but in plateau areas, the 850 mbar level may not be above the influence of the earth's surface and the 700 mbar level data are preferable. At the geostrophic level, winds are approximately parallel with height contours.

The most suitable method of estimating the geostrophic wind varies with the time and location of the surface wind to be estimated. Frequently, a subjective comparison is necessary to decide which method is best. If the location is distant from a rawinsonde station, from a National Weather Service Limited-area Forecast Model (LFM) grid-point, or from other applicable model grid points, the geostrophic wind found from analysis of pressure gradient is often best. If the time and location of the surface wind are close to the time and location of the observed wind or of forecast grid point data, then use of such data may be best. Interpolation of wind between different points and between different analysis times or prognosis times, may be best under some conditions. If winds are light, and synoptic pressure patterns and observed winds do not seem to be compatible, estimating windspeed and direction over a remote location is often difficult. Fortunately, light upper level winds do not greatly influence surface winds, especially in mountainous areas. In fact, the model assumes no influence when upper-level geostrophic winds are less than 2.5 m/s.

2. Maximum surface temperature (T) for the day at the location. An estimated maximum temperature is needed if the location is influenced by a sea or lake

breeze, and winds during the day are to be estimated. Often no temperature data are available at a specific location or even near a specific location in mountainous areas. As a result, a subjective estimate must be made, based on the maximum temperatures reported in the area from the previous day, current temperatures at the closest reporting stations, and the differences in elevation between the location and these stations.

3. Transmissivity (P). An estimate of transmissivity is needed if the location is on a slope or in a valley or canyon. (Valleys and canyons are not differentiated in these guidelines.) Transmissivity is the ratio of the transmitted radiation to the total incident radiation. Because the transmissivity of the atmosphere is seldom known, rough estimates (such as 0.45 for cloudy skies and 0.9 for bright, clear skies in mountains) must usually be used.

4. Geographic location. The geographic location is needed to determine the general wind, sea breeze, and slope wind. The geographic location includes the latitude (ϕ), longitude (L), and if, appropriate, direction (θ_{sb}) and distance (D_s) to the ocean from the location where the wind is to be estimated.

5. Topographic data. The following necessary topographic data can be obtained from topographic maps, or when possible, by visual survey of the location area.

- Elevation (H). Elevation of the location is needed to estimate general wind, sea breeze, and the sheltering effect.
- Slope (y, percent; S, degrees) of the terrain at location. The slope is used to determine the slope wind component, and is the average slope of a representative area around the location. Approximately a 3-acre area ($\simeq$110 by 110 m) seems to be adequate in most cases.
- Aspect (A) of the terrain at location. The aspect is used to determine the slope wind direction, and is the direction that the slope faces, that is, the horizontal component of the downslope direction. The same area used to determine the slope is used to determine the aspect (in degrees clockwise from north).
- Upvalley direction (θ_c). The upvalley direction is used to estimate the direction of valley windflow. An estimate of upvalley direction must be made for branching or relatively undefined valleys or canyons. The direction is in degrees clockwise from north.
- Elevation angles (Y_i) from the location to the horizon (crest of the terrain) above and surrounding the location. Elevation angles are used to determine the sheltering and diverting effects of the terrain on the general wind and sea breeze, and also to estimate valley wind. A table of 24 average elevation angles, one centered at every 15°, has been assumed in these guidelines. The average elevation angle (in percent slope) from a location to the horizon between 315° (−45°) to <45° azimuth is designated as Y_1; from 330° to <60° is Y_2; etc. Percent slope can be determined by surveying the area from the location, if possible, or by map analysis. The table may be placed in computer storage for easy access.
- Aspects (A_i) of terrain slopes facing the location. Aspects of facing slopes are used to determine the diverting effect of the surrounding terrain. A table of 24 average aspects, one aspect for each 15° of arc, has been assumed in these guidelines. The average aspect of the terrain at −7.5° to <7.5° azimuth is designated as A_1, from 7.5° to <22.5° as A_2, and so on. This table may also be placed in computer storage for easy access.

To determine elevation angles to crests of surrounding terrain and determine aspects of surrounding terrain, follow this procedure: From a hypothetical terrain height contour map (*fig. 1*), calculate elevation angles from an observation point (*fig. 1*). For example, if the horizontal distance from observation point O to point a, directly under point A, at 330° from North on the terrain crest is 10,000 m, and the height from a to A is 160 m. The percent slope, α to point A from point O is

$$100 \times \text{height}/\text{distance} = 100 \times 160/10{,}000 = 1.6 \text{ percent}$$

The percent slope β to point b at 345° from North can be determined similarly. For the average slope, Y_1 to the crest between A and E is

$$Y_1 = (\alpha + \beta + \delta + \gamma + \varepsilon)/5$$

in which δ is the elevation angle to C, γ the angle to D, and ε the angle to E. The average slope Y_2 between point B and F and each the other 22 average slopes to higher terrain surrounding point O can be found by a similar procedure. Examples of aspect angles of terrain surrounding point O are shown in *figure 1B*. Aspect is the direction a slope faces. For example, the aspect A_1 of the terrain is 195°. The aspect of the terrain remains approximately 195° from west of a to J. Thus the aspect used for diverting winds with downwind direction toward the ridge between A and J will be 195°. The ridge changes direction near point J, and the aspect becomes approximately 222° for the next few arcs. Aspects of the terrain in other directions surrounding point O can be found by the same procedure.

Metric units are used for all input and output. All arguments of trigonometric functions are in degrees.

An example of the data input and results of each step of the procedure to estimate the surface wind is entered in parentheses to the right of the blanks shown for each step. The example is for winds at 1600 P.s.t. on August 31, 1974, in Devil Canyon, north of San Bernardino in the San Bernardino Mountains, in southern California.

Depending on conditions and the results of the computations, some parts of the procedures may be omitted. The procedures are written so that the various alternatives can be easily seen. For each step, the symbol for the value referred to is shown, with a blank in which it can be entered.

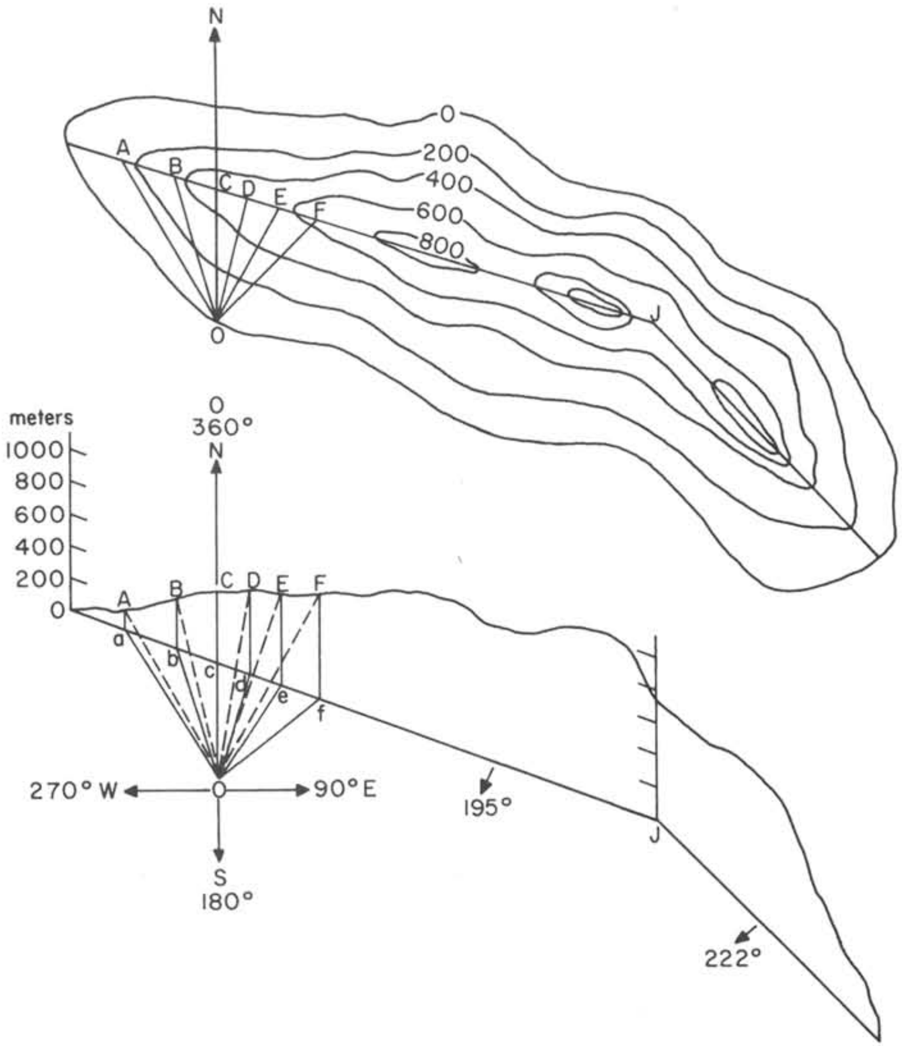

Figure 1—*A*: terrain height contours of an area near observation point 0. Points 0, a, b, c, d, e, and f are in the same plane. *B*: elevation angles, in percent slope, from point 0 to points A, B, C, D, E and F on the crest. Aspect angles of terrain surrounding point 0 are determined from inspection of directions that slopes of surrounding terrain face. From point a to point J, the terrain slope faces toward 195°. Thus the aspect of the surrounding terrain, west of J, is 195°. The aspect southeast of J is 222°.

GENERAL SURFACE WINDFLOW

The general surface wind is the hypothetical wind that would theoretically occur if the terrain were flat, in the open, and not near a large body of water. In this model, the general wind is calculated from the geostrophic level wind modified only by a function that simulates the effect of friction with the earth's surface. The calculated general wind is turned to the left and decreased in speed relative to the geostrophic level wind. The general wind is assumed to be calm if the geostrophic level wind is less than 2.5 m/s.

Under strong north to east windflow (>11 m/s from 360° clockwise through 110°) in southern California the model couples the geostrophic level wind more closely to the general wind. This feature of the model is empirically derived from observations in southern California and has not been tested under foehn conditions in other areas.

Information Needed

- Geostrophic level wind observed, interpolated, or forecast over site
  a. Direction, θ_g (degrees clockwise from north)
  b. Speed, V_g (m/s)
- Latitude of site, ϕ (degrees)
- Time of day, t (l.s.t., in hours and tenths of hours after midnight; e.g., 9:30 p.m. = 21.5)
- Aspects of surrounding terrain and elevation angles to horizon of surrounding terrain.

Procedures

These procedures lead to values for the general surface wind direction (θ_{20}) and speed (V_{20}).

1. Enter geostrophic-level wind; observed, interpolated or forecast over site.
   Direction (degrees clockwise from north) θ_g = ______(225)
   Speed (m/s) V_g = ______(7.2)

2. Determine if general winds will be calm.
   Alternatives:
   A. If speed $V_g < 2.5$ m/s, then $V_{20} = 0$ and go to section on Sea Breeze (calm general winds are assumed).
   B. Proceed with remaining steps.
3. Enter time of day (l.s.t.) $t =$ ______(16.0)
   and latitude of site (degrees and tenths) $\phi =$ ______(34.2)
4. Determine control constants M and V_g'. (If location is not in southern California but foehn winds occur, alternative C may need modification.)
   Alternatives:
   A. If in southern California and $\theta_g \leq 110$, $M = 0.67$ and $V_g' = V_g + 8$ (m/s). $M =$ ______(0.42)
   B. If in southern California and $\theta_g > 110$, $M = 0.42$ and $V_g' = V_g$ (m/s). $V_g' =$ ______(7.2)
   C. If not in southern California, $M = 0.42$ and $V_g' = V_g$ (m/s).
5. Enter or calculate diurnal variation control parameter.
   Alternatives:
   A. Under very strong geostrophic level wind conditions, that is, if $V_g' > 26$, $C_a = 0$; go to step 6.
   B. Under moderate conditions, if $V_g' \leq 11$, $C_a = 1$; go to step 6.
   C. Under strong wind conditions, if $11 < V_g' \leq 26$, $C_a = 1 - \sin(6.24\, V_g' - 72.2)$ $C_a =$ ______(1.0)
6. Calculate coupling control parameter:
   $B = M + 0.35\, C_a \sin(15t + 251)$
   $+ 0.02\, C_a \sin(30t + 238)$ $B =$ ______(0.68346)
7. Calculate wind components at standard surface level: Component in direction (θ_g) of geostrophic wind,
   $u' = V_g - V_g \exp(-B) \cos(57B)$ (m/s). $u' =$ ______(4.3733)
   Component positive 90° to left of u',
   $v' = V_g \exp(-B) \sin(57B)$ (m/s). $v' =$ ______(2.2855)
8. Calculate wind at standard surface level before sheltering and diverting.
   Direction:
   In Northern Hemisphere,
   $\theta_{20} = \theta_g - \arctan|v'/u'|$;
   if $\theta_{20} \leq 0$, $\theta_{20} = \theta_{20} + 360$. $\theta_{20} =$ ______(197.41)
   In Southern Hemisphere,
   $\theta_{20} = \theta_g + \arctan|v'/u'|$;
   if $\theta_{20} > 360$, $\theta_{20} = \theta_{20} - 360$.
   Speed (m/s): $V_{20} = [(u')^2 + (v')^2]^{1/2}$ $V_{20} =$ ______(4.935)

The following steps lead to estimates of the sheltered general wind.

9. Calculate the number i of the arc of azimuth in the upwind direction:
   $i = \text{INT}[(\theta_{20} + 22.5)/15]$ $i =$ ______(14)
   (INT means "truncate to integer")
   Note: if $i \geq 25$, $i = 1$.
10. Enter elevation angle to horizon upwind (percent slope). $y_i =$ ______(6)
11. Determine if sheltering is significant.
    Alternatives:
    A. If $Y_i \leq 3$ percent, go to step 16.
    B. Proceed with remaining steps.
12. Enter elevation of site (meters). $H =$ ______(685)
13. Determine effect of elevation of location on sheltering. It may require modification for strong winds in other areas.
    Alternatives:
    A. If location is not in southern California, or if $\theta_{20} > 120$, or $V_{20} \leq 3.2$ m/s, then $E_p = 1$. Go to step 14.
    B. If in southern California and if $H < 1240$ m, $E_p = 1 - 0.0008\, H$. Go to step 14.
    C. If $H \geq 1240$ m, go to step 16. $E_p =$ ______(1.0)
14. Calculate sheltering factor:
    $F_{Gs} = \arctan(0.17\, Y_i)/100$ $F_{Gs} =$ ______(0.456)
15. Calculate sheltered general windspeed (m/s): $V_{20} =$ ______(2.69)
    $V_{20} = V_{20} - E_p \cdot F_{Gs} \cdot V_{20}$

The following steps lead to estimates of the diverted general wind.

16. Calculate the number i of the arc of the azimuth in the downwind direction:
    $i = \text{INT}[(\theta_{20} + 202.5)/15]$.
    Note: if $i \geq 25$, $i = i - 24$. $i =$ ______(2)
17. Enter elevation angle to horizon downwind (percent slope).
    Alternatives:
    A. If $Y_i \leq 15$ percent, go to section on Sea Breeze. $Y_i =$ ______(37)

B. Proceed with remaining steps.

18. Enter aspect of terrain downwind (degrees clockwise from north). A_i = ______(270)
19. Calculate diverting factor:
    $F_{Gd} = -0.225\ Y_i \sin[2(A_i - \theta_{20})]$ F_{Gd} = ______(-4.753)
20. Calculate diverted wind direction:
    $\theta_{20} = \theta_{20} + F_{Gd}$ (degrees) θ_{20} = ______(192.66)

SEA BREEZE

The sea breeze (V_{sb}) is the daytime wind component caused by the difference in temperature between air over land and air over an adjacent water body. The model includes steps to estimate the temperature of the Pacific Coast ocean surface if the temperature is not known or cannot be estimated more accurately. If general wind is estimated to be greater than 10 m/s and between 360° and 110°, then the model assumes there is no sea breeze. This is a feature of the model incorporated to account for the unique influence of the Santa Ana winds in California. No significant nighttime land breeze is assumed by the model. (This model feature may not be realistic near bodies of water other than the Pacific Ocean. Little or no nighttime land breeze is typical of the West Coast of the United States but not of coasts bordered by warmer water.)

Information Needed

- Day of the year, D (1–366)
- Estimate or forecast of maximum or 1500 l.s.t. temperature for day at location, T (°C)
- Latitude of location, ϕ (degrees and tenths of degrees)
- Estimate or measurement of ocean surface temperature, T_s (°C)
- Distance to ocean D_s (km)
- Direction to ocean, θ_{sb} (degrees clockwise from north)
- Time of day, t (hours and tenths of hours after midnight)
- Aspects of surrouding terrain and elevation angles to horizon of surrounding terrain.

Procedures

These procedures lead to values for the sea breeze direction (θ_{sb}) and speed (V_{sb}).

1. Enter general wind at location.
   Direction (degrees clockwise from north) θ_{20} = ______(197)
   Speed (m/s) V_{20} = ______(4.94)
2. Determine if general wind is too strong to allow sea breeze.
   Alternatives:
   A. In areas such as southern California, where strong northeast offshore flow occurs, if $\theta_{20} \leq 110°$ and $V_{20} > 10$ m/s, assume that there is no sea breeze: $V_{sb} = 0$.
   Go to section on Slope Wind.
   B. Proceed with remaining steps.
3. Enter distance of location from ocean (km). D_s = ______(112.7)
4. Enter direction to ocean from location (degrees clockwise from north). θ_{sb} = ______(240)
5. Enter forecast or estimated 1500 l.s.t. temperature for day at location (°C). T = ______(36.2)
6. Determine coastal-water temperature (°C).
   Alternatives:
   A. Enter ocean temperature, T_s, if measured within the last two weeks, then go to step 10.
   B. If no measured temperature is available, obtain estimate of T_s near the coasts of California, Oregon, and Washington by the following procedures. Equations for T_s will need modification for other areas.
7. Enter day of year (1–366) D = ______(243)
   and latitude of location (degrees and tenths). ϕ = ______(34.2)
8. Compute mean minimum annual temperature of water off coast at latitude ϕ (°C):
   $T_\phi = 26.4 - 0.37\ \phi$. T_ϕ = ______(13.75)
9. Compute temperature on day, D:
   $T_s = T_\phi + 4.5 \sin|0.5(D - 18.5)|$ T_s = ______(17.91)
10. Determine if sea breeze will occur.
    Alternatives:
    A. If $T_s \geq T$, $V_{sb} = 0$.
    Go to section on Slope Wind.
    B. Proceed with remaining steps.

11. Calculate sea breeze for day at location (m/s):
$\beta_0 = [(-2.97D_s)10^{-4} + 0.14][T - T_s]$ $\beta_0 =$ ______(1.95)
12. Calculate other coefficients needed to find sea breeze strength at specific times of day:
$\beta_1 = [(-3.31D_s)10^{-4} + 0.19][T - T_s]$ $\beta_1 =$ ______(2.79)
$\beta_2 = [(1.85D_s)10^{-4} + 0.026][T - T_s]$ $\beta_2 =$ ______(0.86)
13. Enter time of day (hours and tenths of hours since midnight, l.s.t.; e.g., 9:30 p.m. = 21.5). t = ______(16.0)
14. Calculate sea breeze speed.
Alternatives:
A. If $V_{20} \leq 3.3$ m/s,
$V_{sb} = \beta_0 + \beta_1 \sin(15t + 231) + \beta_2 \sin(30t + 28)$
B. If in southern California and if $V_{20} \leq 3.3$ m/s or $\theta_{20} > 110°$, then
$V_{sb} = \beta_0 + \beta_1 \sin(15t + 231) + \beta_2 \sin(30t + 28)$. $V_{sb} =$ ______(5.01)
C. If in southern California and if $V_{20} > 3.3$ m/s and $\theta_{20} > 110°$, then $V'_{sb} = \beta_0 + \beta_1 \sin(15t + 231) + \beta_2 \sin(30t + 28)$, and
$V_{sb} = V'_{sb} - V'_{sb} \sin(13.5 V_{20} - 45)$
D. If not in southern California and $V_{20} > 3.3$ m/s, modification of alternative C is probably necessary.

The following steps lead to an estimate of the sheltered sea breeze.
14. Calculate the number i of the arc of azimuth in the upwind direction:
$i = \mathrm{INT}[(\theta_{sb} + 22.5)/15]$ i = ______(17)
(INT means "truncate to integer")
Note: if $i \geq 25$, $i = 1$.
15. Enter elevation angle to horizon upwind (percent slope). $Y_i =$ ______(18)
16. Determine if sheltering slope is significant.
Alternatives:
A. If $Y_i \leq 3$ percent, go to step 21.
B. Proceed with remaining steps.
17. Enter elevation of site (meters). H = ______(685)
18. Enter effect of elevation of location on sheltering. (This step recognizes Santa Ana conditions in southern California. It may require modification for strong winds in other areas.)
Alternatives:
A. If location is not in southern California, or if $\theta_{20} > 120$ or $V_{20} \geq 3.2$ m/s, then $E_p = 1$.
Go to step 19.
B. If in southern California and if $H < 1240$ m, $E_p = 1 - 0.0008\,H$.
Go to step 19.
C. If $H \geq 1240$ m, go to step 21. $E_p =$ ______(1.0)
19. Calculate sheltering factor:
$F_{sd} = \arctan(0.17\,Y_i)/100$ $F_{sd} =$ ______(0.72)
20. Calculate sheltered sea breeze speed (m/s):
$V_{sb} = V_{sb} - E_p \cdot F_{sd} \cdot V_{sb}$ $V_{sb} =$ ______(1.41)

The following steps lead to a value for the direction of the diverted sea breeze.
21. Calculate the number i of the arc in the downwind direction:
$i = \mathrm{INT}[(\theta_{sb} + 202.5)/15]$.
Note: if $i \geq 25$, $i = i - 24$. i = ______(5)
22. Enter elevation angle to horizon downwind (per cent slope). $Y_i =$ ______(30)
Alternatives:
A. If $Y_i \leq 15$ percent, go to section on Slope Wind.
B. Proceed with remaining steps.
23. Enter aspect of terrain downwind (degrees clockwise from north). $A_i =$ ______(270)
24. Calculate diverting factor:
$F_{sd} = -0.225\,Y_i \sin[2(A_i - \theta_{sb})]$ $F_{sd} =$ ______(-5.85)
25. Calculate diverted wind direction:
$\theta_{sb} = \theta_{sb} + F_{sd}$ (degrees) $\theta_{sb} =$ ______(234.15)
(If $\theta_{sb} > 360°$, $\theta_{sb} = \theta_{sb} - 360°$)

SLOPE WIND

Slope wind is the wind component caused by heating or cooling of air next to a slope. This temperature change causes a temperature gradient perpendicular to the slope, and air flow with a component parallel to the slope—upslope during the day, and downslope at night. The model simulates the nighttime drainage flow as a function of sky cover, slope, and time since sunset. It simulates upslope flow as a function of calculated solar radiation on the surface slope and time since sunrise. Sheltering and interference effects of vegetation are not explicitly considered.

Information Needed

- Average slope, y, of approximately 3-acre area surrounding location (percent)
- Difference in time, Δt_z, between G.m.t. and l.s.t.
- Latitude of location, ϕ (degrees and tenths of degrees from equator)
- Longitude of location, L (degrees and tenths of degrees from prime meridian)
- Day of the year, D (1–366)
- Elevation angles, Y_r, and Y_s to horizon surrounding location (percent slope)
- Elevation, H, of location (m)
- Estimate of transmissivity or cloud cover, P
- Average aspect, A, of approximately 3-acre area surrounding location (degrees clockwise from north)
- Time of day, t (hours and tenths of hours after midnight, l.s.t.).

Procedures

These procedures lead to values for direction (θ_s) and speed (V_s) of drainage or upslope winds.

1. Enter average slope of surrounding 3-acre area (percent). y = ______(12.5)
   Calculate slope of surrounding 3-acre area (degrees):
   $S = \arctan (y/100)$. S = ______(7.13)
   Note: If $S < 3°$, then $V_s = 0$;
   go to section on Valley Wind.
2. Enter day of the year (1–366), D = ______(243)
   elevation of the site (meters), H = ______(685)
   latitude of the site (degrees and decimal degrees), ϕ = ______(34.2)
   longitude of the site; west longitude +, east longitude − (degrees and decimal degrees), L = ______(117.3)
   time difference (hours), Δt_z = G.m.t. − l.s.t., Δt_z = ______(8)
   average aspect of approximately 3 acres surrounding site (degrees clockwise from north), A = ______(180)
   and time of day (hours and tenths of hours, l.s.t.; e.g., 8:30 p.m. = 20.5). t = ______(16.0)
3. Calculate approximate arc of azimuth between 90° (east) and azimuth of sun at sunrise or between 270° (west) and azimuth of sun at sunset at solstice (degrees):
   $\alpha = 21.6 + 1.4 \exp (\phi/19)$ α = ______(30.07)
4. Calculate azimuth of sun (degrees clockwise from north).
   A. At sunrise:
   $A_r = 90 + \alpha \cos (0.986\ D + 7.9)$. A_r = ______(78.49)
   B. At sunset:
   $A_s = 270 - \alpha \cos (0.986\ D + 7.9)$. A_s = ______(281.51)
5. Calculate the number of the arc.
   A. At sunrise:
   $r = \mathrm{INT}\ [(A_r + 22.5)/15]$. r = ______(6)
   If $r \geq 25$, $r = 1$.
   B. At sunset:
   $s = \mathrm{INT}\ [(A_s + 22.5)/15]$. s = ______(20)
   If $s \geq 25$, $s = 1$.
6. Calculate elevation angle to horizon at azimuth of sun.
   A. At sunrise:
   Y_r (percent) Y_r = ______(31)
   $S_r = \arctan (Y_r/100)$ (degrees) S_r = ______(17.2)
   B. At sunset:
   Y_s (percent) Y_s = ______(40)
   $S_s = \arctan (Y_s/100)$ (degrees) S_s = ______(21.8)
7. Calculate correction for elevation of site (degrees).
   If $H \leq 100$, let $R = 0$ and go to 8.
   $R = \arccos [(6.37 \cdot 10^6)/(6.37 \cdot 10^6 + 1.32H)]$ R = ______(0.97)
8. Calculate declination of the sun (degrees north or south of Celestial equator).
   A. In Northern Hemisphere:
   $d = 23.45 \sin [0.973(D - 81.5)]$ d = ______(9.11)
   B. In Southern Hemisphere:
   $d = -23.45 \sin [0.973\ (D - 81.5)]$
9. Calculate hour angle of sun (degrees from meridian; − east, + west).
   A. At sunrise:
   $h_r = -\arccos ([-\sin (0.8 + R - S_r) - \sin \phi \sin d]/[\cos \phi \cos d])$ h_r = ______(−77.44)

B. At sunset:

h_s = arc cos ([-sin (0.8 + R - S_s) - sin ϕ sin d]/[cos ϕ cos d]) h_s = ______(71.91)

10. Calculate correction to obtain l.s.t. (decimal hours):

$\Delta t_g = \Delta t_z - L/15$ Δt_g = ______(0.18)

11. Calculate equation-of-time, Q (in decimal hours):

$Q = [0.7 \sin(-0.986\, D) + \sin(-1.97\, D - 15.78)]/6$ Q = ______(-0.02)

12. Times of sunrise and sunset (hours and decimal hours after midnight, l.s.t.).

A. At sunrise:

$t_r = (h_r + 180)/15 - \Delta t_g - Q$ t_r = ______(6.68)

B. At sunset:

$t_s = (h_s + 180)/15 - \Delta t_g - Q$ t_s = ______(16.63)

13. Transmissivity: If data to estimate transmissivity are not available, let

P = 0.45 if sky cover is broken or overcast,

P = 0.9 if clear or scattered. P = ______(0.9)

14. Determine slope wind direction. The model simulates upslope wind from 1 hour after sunrise until sunset and drainage winds the rest of the day.

Alternatives:

A. If time $t \leq t_r + 1$ and $t > t_s$, then determine drainage flow direction:

$\theta_s = A + 180$. If $\theta_s > 360$, $\theta_s = \theta_s - 360$

B. If time $t > t_r + 1$, and $t \leq t_s$, then determine upslope wind direction: θ_s = ______(180)

$\theta_s = A$.

15. Determine slope windspeed.

Alternatives:

A. If time $t > t_s$, then determine drainage wind before midnight.

(1) Calculate time interval

$\Delta t = t - (t_s - 2)$

(2) Calculate variable C_p

$C_p' = [1.5 (\tan^2 S) \cdot \Delta t]$

If $C_p' > 5$, $C_p = 0$.

If $C_p' \leq 5$, $C_p = \exp(-C_p')$.

(3) Calculate drainage windspeed:

$V_s = 1.50\, P\, (1 - C_p)/\tan S$

B. If time $t \leq t_r + 1$, then determine drainage wind after midnight.

(1) Calculate time interval

$\Delta t = 24 - (t_s - 2) + t$

(2) Calculate variable C_p

$C_p' = [1.5 (\tan^2 S) \cdot \Delta t]$.

If $C_p' > 5$, $C_p = 0$.

If $C_p' \leq 5$, $C_p = -\exp(-C_p')$.

(3) Calculate drainage windspeed:

$V_s = 1.50\, P(1 - C_p)/\tan S$

C. If $(t_r + 1) < t \leq t_s$, then determine upslope wind (upslope wind is simulated between 1 hour after sunrise until sunset).

(1) Calculate time interval:

$\Delta t = (t - t_r)$. Δt = ______(9.32)

(2) Calculate variable C_p: C_p' = ______(0.22)

$C_p' = [1.5 (\tan^2 S) \cdot \Delta t]$.

If $C_p' > 5$, then $C_p = 0$, or C_p = ______(0.804)

if $C_p' \leq 5$, then $C_p = \exp(-C_p')$.

(3) Calculate the hour angle of the sun at time t (degrees from meridian, - east, + west):

$h = 15 (t + Q + \Delta t_g) - 180$ h = ______(62.43)

(4) Calculate the altitude of the sun (degrees above horizontal:

C = arcsin (cos d cos h cos ϕ + sin ϕ sin d) C = ______(27.84)

(5) Calculate the azimuth angle Z of the sun at time t (degrees from north):

sin Z″ = (-cos d sin h)/cos C sin Z″ = ______(-0.9898)

If sin Z″ > 1, let sin Z″ = 1.

If sin Z″ < -1, let sin Z″ = -1,

Z″ = arcsin Z″. Z″ = ______(-81.81)

(6) Determine correct quadrant.

(a) C′ = arcsin [cos d cos (h - 0.1) cos ϕ + sin ϕ sin d] C′ = ______(27.92)

(b) sin Z′ = -cos d sin (h - 0.1)/cos C′ sin Z′ = ______(-0.9897)

(c) If sin Z′ > sin Z″; Z = 180 - Z″ and go to (7). Z = ______(261.8)

(d) If sin Z″ ≤ 0; Z = Z″ + 360; go to (7).

(e) Z = Z″

(7) Compute the angle at which the sun's radiation strikes the slope at time t (degrees above parallel to slope).

If in Southern Hemisphere, let $A = (180 - A)$.
If $A \leq 0$; $A = A + 360$.
$\sin \mu = \sin C \cos S$
$+ \cos C \sin S \cos (Z - A)$ $\sin \mu =$ ______(0.479)
(8) Compute insolation on slope (Wm^{-2}):
$I = 1350\ P^{1/\sin C} \sin \mu$ $I =$ ______(516)
If $I < 0$; $I = 0$.
(9) Compute upslope windspeed (m/s): $V_s =$ ______(1.16)
$V_s = I\ (1 - C_p)/(697 \tan S)$

VALLEY WIND

The valley (or canyon) wind is the component caused by the temperature gradient that tends to develop between valleys and the plain outside. Solar heating tends to cause higher temperatures in the valley and windflow into the valley during the day. In the evening, air in the valley tends to become cooler than the air over the plain and flow out of the valley develops. (The upvalley flow is what has sometimes been called "mountain wind".)

Information Needed

- Upvalley direction, θ_c (degrees clockwise from north)
- Elevation angles, Y_l and Y_r, to crest of walls of valley or canyon (percent slope)
- Day of year, D (1-366)
- Time of day, t (hours and tenths of hours after midnight, l.s.t.).

Procedures

1. Enter upvalley direction (degrees clockwise from north). $\theta_c =$ ______(30)
   Alternatives:
   A. If index of valleyness is known, go to C (4) and enter.
   B. If elevation angles to the valley or canyon ridges are known, go to C (4) and compute index of valleyness.
   C. Compute elevation angles and index of valleyness.
   (1) Compute number of the arc to one side of canyon:
   $l = \mathrm{INT}[(\theta_c + 292.5)/15]$. $l =$ ______(21)
   If $l \geq 25$, $l = l - 24$.
   (2) Compute number of arc to other side of canyon:
   $r = \mathrm{INT}\ [(\theta_c + 112.5)/15]$. $r =$ ______(9)
   If $r \geq 25$, $r = r - 24$.
   (3) Enter elevation angle Y_l to top of one side of canyon or valley and elevation angle Y_r to top of other side of canyon or valley (percent slope). $Y_l =$ ______(44) $Y_r =$ ______(32)
   If Y_l or $Y_r < 12.5$ percent, then $V_v = 0$, and go to section on Resultant Wind.
   (4) Enter or compute index of valleyness:
   $I_v = (Y_l + Y_r)/250$. $I_v =$ ______(0.30)
   If $I_v \leq 0.8$, let $I_v = 0.8$.
3. Enter day of year, D (1-366). $D =$ ______(243)
4. Enter time of day (hours and decimal hours since midnight, l.s.t.) $t =$ ______(16.0)
5. Enter transmissivity.
   If data to estimate transmissivity P are not available, let
   $P = 0.45$ if sky cover is broken to overcast,
   $P = 0.90$ if clear or scattered. $P =$ ______(0.9)
6. Compute mean valley windspeed for day of the year (m/s):
   $\overline{V_v} = 0.40 + 0.45 \sin (0.986D - 79.88)$ $\overline{V_v} =$ ______(0.56)
7. Compute valley windspeed at time t (m/s):
   $V_v = [\,\overline{V_v} + 3.4 \sin (15t + 244)$
   $+ 0.76 \sin (30t + 51)] \cdot P \cdot I_v$
   A negative value of V_v indicates downvalley flow, a positive value, upvalley flow. $V_v =$ ______(0.96)
8. Compute valley wind direction (degrees clockwise from north).

If $V_v > 0$, $\theta_v = \theta_c + 180$.
If $V_v < 0$, $\theta_v = \theta_c$.
If $\theta_v > 360$, $\theta_v = \theta_c - 180$. θ_v = ______(210)

RESULTANT WIND

The resultant wind is the vectorial sum of the individual wind components simulated by the model. These procedures lead to a value for the resultant wind.

1. Compute east-west component (m/s):
   $u = - V_{20} \sin \theta_{20} - V_{sb} \sin \theta_{sb} - V_s \sin \theta_s - V_v \sin \theta_v$ u = ______(2.21)
2. Compute north-south component (m/s):
   $v = - V_{20} \cos \theta_{20} - V_{sb} \cos \theta_{sb} - V_s \cos \theta_s - V_v \cos \theta_v$ v = ______(5.44)
3. Compute resultant direction.
   Alternatives:
   A. If $v = 0$ and $u > 0$, $\theta = 90°$. θ = ______(202)
   B. If $v = 0$ and $u < 0$, $\theta = 270°$.
   C. If $v < 0$, and $u \leq 0$, then $\theta = \arctan (u/v)$.
   D. If $v < 0$ and $u > 0$, then $\theta = \arctan (u/v) + 360$.
   E. If $v > 0$, $\theta = \arctan (u/v) + 180$.
4. Resultant speed (m/s)
   $V = (u^2 + v^2)^{1/2}$ V = ______(5.87)

REFERENCE

Ryan, Bill C. **A mathematical model for diagnosis and prediction of surface winds in mountainous terrain.** J. Appl. Meteorol. 16:571-584; 1977 June.

Ryan, Bill C. **WNDCOM: estimating surface winds in mountainous terrain.** Gen. Tech. Rep. PSW-73. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 10 p.

WNDCOM is a mathematical model for estimating surface winds in mountainous terrain. By following the procedures described, the sheltering and diverting effect of terrain, the individual components of the windflow, and the surface wind in remote mountainous areas can be estimated. Components include the contribution from the synoptic scale pressure gradient, the sea breeze, the slope wind, and the valley wind. For each component, a brief description, the data and information needed for estimation, and step-by-step procedures are provided.

Retrieval Terms: surface wind, mountain wind, wind model, mathematical model, southern California

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