FORECASTING SUN VERSUS SHADE IN COMPLEX TERRAIN FOR THE 2010 WINTER OLYMPIC AND PARALYMPIC GAMES

by Rosie Howard and Roland Stull

Patchy shading of ski runs by mountains and trees can alter snow-surface texture and friction so strongly as to affect the outcome of races.

MOTIVATION. Solar radiation can affect the surface of a snowpack within seconds, increasing the temperature, modifying the liquid water content within the first few centimeters of depth, and affecting snowpack metamorphism (specifically grain size, bonding between grains, and hardness of snowpack) (Bethke et al. 2005). Past work on the shadowing of sunlight in complex terrain (Fig. 1) focused on natural snow surfaces relevant for avalanche study (Gray et al. 1999; McClung and Schaerer 2006; Sawyer 1959). However, sunlight shadowing also affects the groomed snow surfaces used for ski racing in terms of race ski chosen, waxing, course preparation, and even television broadcasting (positioning of cameras, etc.). Ski-snow friction depends upon many processes, including dry friction, wet (lubricated) friction, snow compaction, impact resistance, capillary adhesion, electrical charging, abrasion, and contamination with dirt particles (Colbeck 1988, 1992; Federolf et al. 2008; Glenne 1987). Meteorological variables that indirectly affect friction are humidity, air temperature, snow temperature, and solar radiation. Friction between snow and skis is also somewhat dependent on the prevailing crystal type, temperature, and liquid water content of the snow (Colbeck 1988), all of which are influenced by solar radiation. Fauve et al. (2005) state that solar radiation can significantly affect the results of ski races.

The coefficient of friction between skis and snow is strongly dependent on the snow temperature (Buhl et al. 2001), which in turn strongly depends on ▶

Fig. 1. Photograph at Blackcomb Mountain, Spearhead Range, showing mountain terrain blocking direct solar radiation from reaching portions of a snow surface (photo credit: Jenny Haywood).

solar and infrared (IR) radiation. Solar radiation heats the ski base directly and uniformly. Some of the photons that enter the snowpack are scattered back out. Net IR radiation from a ski piste (a compacted and groomed ski trail) is usually upward toward space (day and night, sunny and shady). When this occurs, especially in cloudless conditions, it is an unrelenting cooling process. The net heat balance at the snow surface can cause as much as a 4°C variation between sunny and shady conditions, as has been observed in controlled testing (Colbeck 1994). It is therefore not surprising that the desired ski and wax preparation for shaded snow is not the same for snow receiving direct or strong diffuse solar radiation. So, knowledge ahead of time of when and where the sun will hit the race course (RC) turns out to be important. For example, the morning of a ski race, testing may be on shaded snow; however, the sun could hit the piste in places later during the race. According to Colbeck (1994), the amount of solar radiation should be considered when choosing ski wax and structure.

Solar radiation is also important to consider when choosing the color of a ski base (Colbeck and Perovich 2004), since heat produced by solar radiation on a black ski base could be more than the heat produced by friction, at lower speeds. Ski runs made well after sunset showed that even small amounts of diffuse sunlight on a cloudy day provided a reduced but significant source of energy to affect skis (Colbeck and Perovich 2004).

The behavior of snowboards on snow has been informally observed during competitions and training leading up to the 2010 Vancouver Winter Olympic and Paralympic Games ("Olympics"). Joncas (2010, personal communication) reported that when the snow surface is initially warm and soft with large granules [implying snow metamorphism is occurring or has occurred (McClung and Schaerer 2006)] and then the same snow surface transitions into the shade, it becomes "like sandpaper" and can be abrasive after several snowboard runs. For these conditions it was necessary to change the type of wax, and more work was required to rewax the snowboards between each run. Both of these factors can have a large impact on the outcome of competitions.

As described, the condition of the snow surface, in particular whether it is in direct sun or shaded, is of interest for a variety of skiing applications. This paper presents a method that was developed to forecast sun versus shade along ski pistes. The method has been applied during the Olympics to help ski technicians, coaches, and athletes be better prepared. For reference, the 2010 Olympic venues are located in southwest coastal British Columbia (BC), Canada (see Fig. 2).

To determine whether a point on the Earth's surface is in the sun or shade on a cloudless day, the following should be calculated: local elevation and azimuth angles of the sun, and elevation and azimuth angles of the visible horizon, defined by shadow-casting obstacles, such as mountains, trees, and structures.

METHOD. Previous methods for calculating solar radiation and effects on mountainous terrain include using digital elevation models, as have been applied in numerical weather prediction and hydrology (Müller and Scherer 2005; Zanotti et al. 2004). These methods are usually computationally expensive and relatively complex, and they usually include only the effects of the topography, as described in digital elevation models. However, for the outdoor Olympics venues, the race pistes were bordered by tall (order of 20 m) evergreen trees that also caused significant shading. To quantify the combined influences of trees and topography, a field survey was conducted the year before the Olympic competition.

As a result of this surveying procedure, the surrounding topography, trees, buildings, and other local/nonlocal obstacles large enough to cast a shadow (apart from clouds) were taken into account. Such surveying was necessary because the highest-resolution (on the order of meters) digital elevation data available to nonmilitary users can still not resolve all the smaller objects, such as trees, and may be out of date. Surveying can be done in a timely manner to account for recent tree growth or removal in the months before a ski competition. For optimum accuracy, surveys must be carried out on days when the local horizon is not obstructed with clouds. Entirely cloud-free days are best.

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/2011BAMS-D-11-00017.1

In final form 4 May 2011

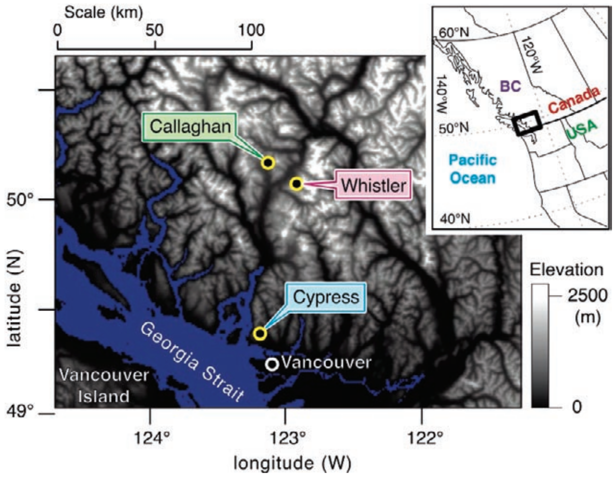

FIG. 2. Image showing complex terrain of southwest British Columbia and three 2010 Winter Olympic and Paralympic Games venues: Callaghan Valley, Whistler Mountain, and Cypress Mountain. Created from U.S. Geological Survey (USGS) 30 arc-second digital elevation data.

A theodolite (Pentax, GT-4B) was used to make these local horizon surveys at a series of points along each Olympic ski and snowboard race course at Callaghan, Cypress, and Whistler. Points were chosen somewhat arbitrarily, but with some guidance from race staff, at an approximate interval of 150 m. Although this interval was not small enough to provide complete coverage, it was sufficient to provide representative information to ski technicians, coaches, and other race officials. Thirty-five points were surveyed at Whistler, 60 at Callaghan, and 38 at Cypress.

At each point, the theodolite was erected and leveled with built-in bubble levels, and the zero-azimuth set to magnetic north using the built-in compass. The latitude and longitude of each point was noted using a GPS unit. Local horizon elevation angles were measured for every 5° azimuth, where the horizon elevation angle is the angle above horizontal at which the top of any local or nonlocal object (tree, mountain, etc.) was observed. Only the sky is higher than this point. Azimuth angles were later converted to a true north coordinate system by adding the local magnetic variation angle of 17.9°E (NRC 2010).

The local horizon data were input into a program that calculates the geometry of the sun and Earth for every half-hour, for any dates chosen. Horizon elevation angles were compared with the sun elevation angles for each azimuth and time of day, and a binary flag signifying sun or shade was determined for each location. Figure 3 illustrates the calculated track of the sun relative to the surveyed obstacles for "point 2" on the Cypress Mountain ski/snowboarder cross course.

Equations. Geometric equations and constants for the sun and Earth used for the calculations were taken from Stull (2000). These equations are for the solar declination angle and the local elevation and azimuth angle of the sun relative to true north for each location surveyed.

Solar declination δ_s is given by

$$\delta_s = \Phi_r \times \cos\left[\frac{C \times (d - d_r)}{d_y}\right],$$

where Φ_r = 23.45° is the tilt of the Earth's axis, C = 360°, d is Julian day, d_r is Julian day of the summer solstice, and d_y = 365 is the number of days per year.

The local elevation angle Ψ of the sun is

$$\sin(\Psi) = \sin(\phi) \times \sin(\delta_s) - \cos(\phi) \times \cos(\delta_s) \times \cos\left[\frac{C \times t_{UTC}}{t_d} - \lambda_e\right],$$

where ϕ is latitude at the survey point, t_{UTC} is time of day in UTC, t_d = 24 h is length of day (in the same time units as t_{UTC}), and λ_e is longitude.

Finally, the local azimuth angle of the sun α relative to true north is

$$\cos(\alpha) = \frac{\sin(\delta_s) - \sin(\phi) \times \cos(\zeta)}{\cos(\phi) \times \sin(\zeta)},$$

where $\zeta = C/4 - \Phi_r$ is the zenith angle of the sun. These are the equations that were used to calculate the curves in Fig. 3.

Following these calculations, all that remains is for the measured horizon elevation angles to be compared to the elevation angles of the sun for the same azimuth angles for each location surveyed.

Assumptions. In using these relatively simple equations, several assumptions are made (Stull 2000) including the following:

i. The solar declination angle here assumes the Earth's orbit around the sun is circular. The actual orbit is slightly elliptical, with eccentricity e = 0.0167.
ii. The sun is assumed to have an infinitesimal radius rather than finite, corresponding to an angle of α = 0.267° as viewed from Earth.
iii. Light refraction through the atmosphere is neglected, where refraction allows the top of the sun to be seen even when it is β = 0.567° below an unobstructed horizon.

These last two points mean that the actual sunrise (sunset) may occur sooner (later) than the output of this program indicates, when the sun has an elevation angle of $-(\alpha + \beta) = -0.834°$. For Whistler Mountain, the maximum timing error is 6 min 51 s. This is negligible, since the final time resolution users were interested in was 30 min.

Additional error comes from the difference between snow depth at the theodolite survey time and snow depth at the sun-versus-shade forecast time (ΔSD), which affects the distance between the snow surface and treetop. The distance between the ground/snow surface and the theodolite's angle axes (pivot point, 1.65 m on average) adds to or decreases this error depending on whether ΔSD is negative or positive, respectively. The greatest snow depth on the groomed pistes was about three meters during the Olympics, giving an absolute error of 3 ± 1.65 m, which is small (but not negligible) compared to the typical tree height of 20 m. If ΔSD = 1.65 m, then this error is zero.

Data and implementation. The three outdoor venues for which sun/shadow calculations were made were as follows:

i. Callaghan Valley, Whistler Olympic Park: Nordic skiing venue
ii. Whistler Mountain: Alpine skiing venue
iii. Cypress: Freestyle skiing venue

Sun angles and the sun-versus-shade flag were calculated in advance for the 133 survey points. Output was calculated in half-hourly intervals for every day from November 2009 to April 2010. These dates were chosen to include the Olympic and Paralympic Winter Games (12–28 February 2010 and 13–21 March 2010, respectively) as well as prior training and testing dates. Output was an array for each survey-point location giving the day of year, time (UTC), sun elevation angle (degrees), net solar radiation at the top of the atmosphere (W m^{-2}), and shade/no-shade flag (binary: shade = 0, sun = 1). The time resolution can be chosen, and in this case the users requested 30 min. Results were provided to the Canadian Olympic and Paralympic teams and the Vancouver Olympic Committee (VANOC).

Output. Data from an Olympic intensive observation period (IOP) included the measurement of downwelling surface shortwave (SW) radiation by a CNR1 net radiometer (manufactured by Kipp & Zonen). The day 19 February 2009 was identified as having a clear sky from hourly manual observations taken between 1000 and 1500 PST (PST = UTC – 8 h). SW data from the CNR1 were sampled at a frequency of 2 s and averaged and recorded by a CR3000 datalogger (manufactured by Campbell Scientific) every 10 s. A theodolite survey was conducted directly beneath the CNR1, which was suspended over the Whistler race course at the observation station (Whistler RC, latitude = 50.1°N, longitude = 123.0°W).

For comparison, the sun-versus-shade program was run for this day and location with a time resolution of 10 s. The calculated (top of atmosphere) and measured downwelling surface SW radiation are compared in Fig. 4.

The large increase in measured SW radiation occurring close to 1035 PST implies that the sun first appeared above the local mountains and trees around this time.

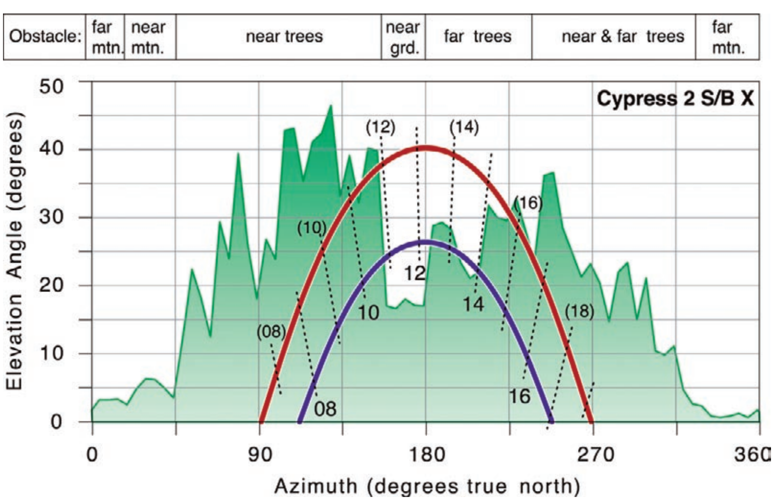

Fig. 3. Solar elevation angle (thick curves) and obstacle elevation angles (shaded region) for "point 2" on the ski/boarder cross course at Cypress. The purple curve is for the start date of the Olympics (12 Feb 2010), and the thin dotted lines are isochrones labeled at the bottom in Pacific standard time (h). The red curve is for the end date of the Paralympics (21 Mar 2010), and the isochrones are labeled above the curve in Pacific daylight time (numbers in parentheses). The black dotted isochrone lines are shown for every hour but are labeled only at every other line; for example, the dotted line labeled 10 standard time also corresponds (unlabeled) to (11) daylight time. For the hours when the curves and the shaded region are not overlapping, point 2 is in sunlight on cloud-free days. Here mtn. = mountain and grd. = ground.

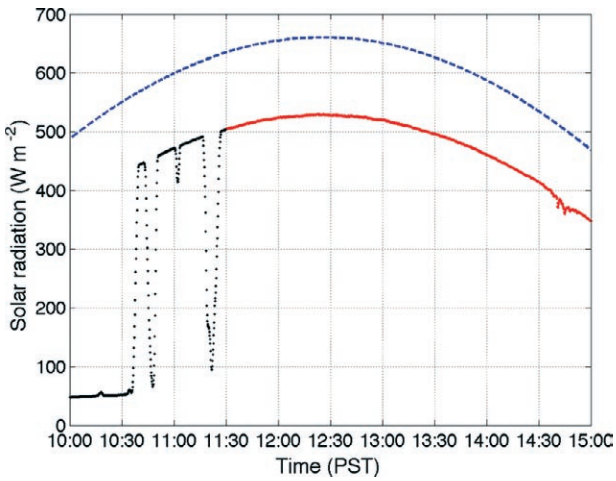

FIG. 4. Downwelling SW radiation for observation site on Whistler Mountain, BC, for 19 Feb 2009. The bottom line (with dots) shows measured downwelling SW radiation (W m^{-2}). Black data points are measured downwelling SW radiation for times when the model predicted the location to be in the shade. The red data points are measured downwelling SW radiation for times when the model predicted the location to be in the sun. The thin blue dashed line shows the theoretical maximum top-of-atmosphere downwelling SW radiation as predicted by the model (W m^{-2}).

Subsequent fluctuations diverging from the smooth curve expected for downwelling SW can be accounted for by the irregular horizon caused by local trees of various heights, as shown in Fig. 5. The model predicts sunrise at almost exactly 1130 PST, demonstrating that the azimuthal resolution of the theodolite measurements (5°) is not high enough for this time resolution (10 s). For trees 30 m away from the observer, with an azimuthal resolution of 5°, the treetops would need to be spaced more than about 2.6 m apart to be "seen" by the model. However, for this application in this location, the azimuthal resolution is adequate since the time resolution for the user was 30 min.

A further reason for the discrepancy is that the measurement height for radiation (somewhere between 6 and 9 m above the local ground level, depending on the snow depth at the time of the theodolite survey) and for the horizon elevation angles (1.6 m between the snow-surface and theodolite's angle axes, measured at the time of the theodolite survey) are different. In other words, the radiation data used to verify this model would have ideally been measured at the same height as the horizon elevation angles. This could explain why the model did not "see" the sun at 1100 PST.

The race course at this location was similar in width (order of 30 m) to most other locations surveyed on Whistler Mountain. The Callaghan race courses were roughly half the width of Whistler's, according to the theodolite surveyor, while Cypress's were about the same as Whistler's. So, for Callaghan, trees closer together than 2.6 m were seen for the same azimuthal resolution of 5°.

APPLICATION OF RESULTS AND FURTHER WORK. A graphical user interface (GUI) was designed to display the sun-versus-shade data via the Internet. Background images using recent high-resolution aerial photographs of each venue were chosen to show the least amount of real shadows on the race courses as possible, as seen by aircraft or satellite at the time of the image capture. These images were mapped onto digital elevation data to present a 3D view of the scene to the user. Actual race lines were drawn on these background images for clarity. Although most of the survey points were on the race lines, certain points on the actual race lines were inaccessible at the time of surveying, so points close by were used instead. Finally, the output images were

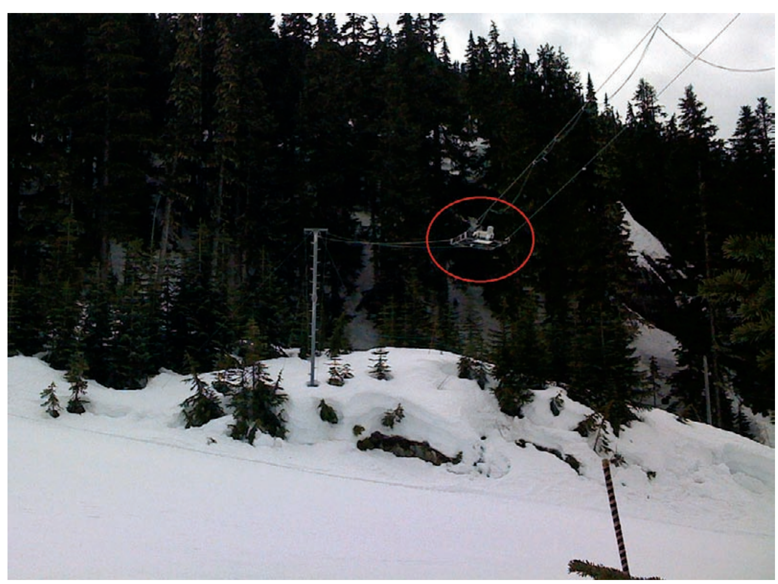

FIG. 5. Photograph at the Whistler RC IOP site showing the CNRI instrument platform (circled) and local trees that cause intermittent shading of a point below the instrument platform on a clear-sky day. The photographer is looking south-southeast across the piste (photo credit: Rosie Howard).

made available on a Web site accessible to the users.

Figure 6 shows a snapshot of the finished display for Whistler Mountain. The image shows predictions of the sun on pistes at specified locations, given the month, day, and time chosen by the user. Predictions are valid only for clear-sky conditions or for days when bright diffuse sunlight is present [e.g., thin cloud layer(s)]. The GUI allows the user to select the venue (Callaghan/Cypress/Whistler), month (November/December 2009, January/February/March/April 2010), day, and time to see the shading on a race course.

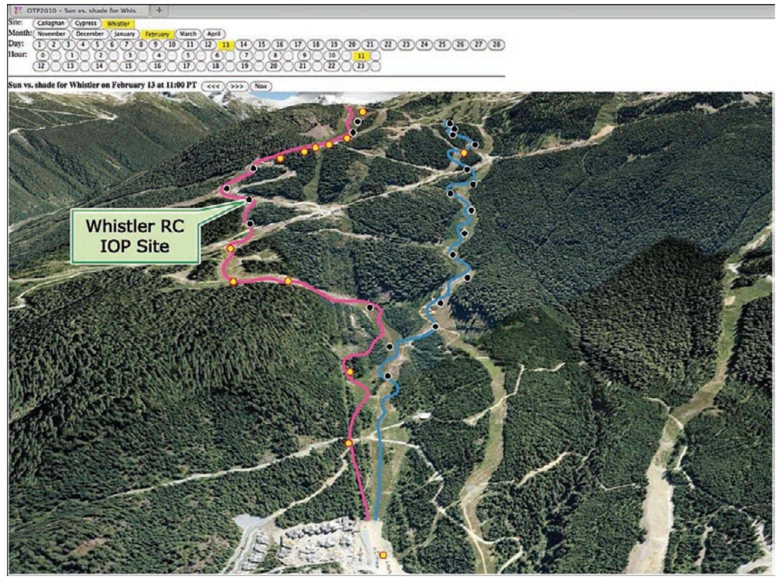

Fig. 6. Sun-vs.-shade screenshot for Whistler Mountain, set to 1100 PST 13 Feb 2010. The black dots show locations that are in shade, and the yellow dots show locations that are in sun at this time. The pink line is the men's downhill course, and the blue line is the women's downhill course. The Whistler RC IOP site is highlighted (source: Weather Forecast Research Team 2010).

Ski technicians, coaches, and other race officials accessed the Web site on a daily basis prior to and during the Olympics. Course preparation and sports managers were interested, particularly given the occurrence of moderate-to-strong El Niño conditions (NOAA 2010) with an intense Aleutian low and associated southerly winds bringing warm air northward along the North American west coast (Crawford 2010). There were at least six consecutive mostly sunny days during the Olympics (17–22 February 2010) and four days during the Paralympics (17–20 March 2010) that could possibly be attributed to this El Niño event. Regardless, all the mostly sunny days had race events at all the Olympic venues for which the sun-versus-shade information was used and found valuable.

If sun-versus-shade calculations are made at any venues in the future, we recommend the following:

- The azimuthal and spatial resolution of theodolite measurements should be increased to allow for higher time resolution and to "fill in" gaps along the race courses. Sufficient time must be allowed to conduct the theodolite surveys, which take about two hours per site, including theodolite setup, calibration, observing and recording the horizon data, packing up, and hiking to the next location.
- For greater model accuracy, a correction can be made to include the radius of the sun rather than assuming it is infinitesimal, as well accounting for the height of the theodolite axes from the ground/snow surface.
- Further research can be applied to combine the sun-versus-shade output with numerical weather prediction output to determine, for example, the maximum temperatures or temperature change expected based upon the maximum direct solar radiation.

ACKNOWLEDGMENTS. Thank you to Daniel Casanova for completing all 133 theodolite surveys. The help and financial support of Dr. Todd Allinger, Own the Podium 2010, and the Vancouver Olympic Committee is greatly appreciated. Also, thank you to Dr. Henryk Modzelewski, George Hicks, May Wong, Thomas Nipen, and Bruce Thomson of the Weather Forecast Research team, University of British Columbia, Canada, for their input and assistance.

REFERENCES

Bethke, S., M. Fauve, C. Fierz, M. Lehning, O. Martius, H. Rhyner, and W. Ammann, 2005: Predicting snow conditions for the optimization of race piste preparation. *Science and Skiing III,* E. Müller et al., Eds., Meyer & Meyer Sport, 395–400.

Buhl, D., M. Fauve, and H. Rhyner, 2001: The kinetic friction of polyethylen on snow: The influence of the snow temperature and the load. *Cold Reg. Sci. Technol.* **33,** 133–140.

Colbeck, S. C., 1988: The kinetic friction of snow. *J. Glaciol.,* **34,** 78–86.

——, 1992: *Review of the Processes That Control Snow Friction. CRREL Monogr.,* No. 92-2, U.S. Army Cold Regions Research and Engineering Laboratory, 40 pp.

——, 1994: Bottom temperatures of skating skis on snow. *Med. Sci. Sports Exercise,* **26,** 258–262.

——, and D. K. Perovich, 2004: Temperature effects of black versus white polyethylene bases for snow skis. *Cold Reg. Sci. Technol.,* **39,** 33–38.

Crawford, B., 2010: The northwest Pacific during the winter of 2009/2010. *CMOS Bull. SCMO,* **38,** 125–127.

Fauve, M., D. Buhl, H. Rhyner, M. Schneebeli, and W. Ammann, 2005: Influence of snow and weather characteristics on the gliding properties of skis. *Science and Skiing III,* E. Müller et al., Eds., Meyer & Meyer Sport, 401–410.

Federolf, P., P. Scheiber, E. Rauscher, H. Schwameder, A. Lüthi, H. Rhyner, and E. Müller, 2008: Impact of skier actions on the gliding times in alpine skiing. *Scand. J. of Med. Sci. Sports,* **18,** 790–797.

Glenne, B., 1987: Sliding friction and boundary lubrication of snow. *J. Tribol.,* **109,** 614–617.

Gray, J. M. N. T., M. Wieland, and K. Hutter, 1999: Gravity-driven free surface flow of granular avalanches over complex basal topography. *Proc. Roy. Soc. London,* **A455,** 1841–1874.

Mass, C., 2008: *The Weather of the Pacific Northwest.* University of Washington Press, 280 pp.

McClung, D., and P. Schaerer, 2006: *The Avalanche Handbook.* 3rd ed. The Mountaineers Books, 342 pp.

Müller, M. D., and D. Scherer, 2005: A grid- and subgrid-scale radiation parameterization of topographic effects for mesoscale weather forecast models. *Mon. Wea. Rev.,* **133,** 1431–1442.

NOAA, cited 2010: Cold and warm episodes by season. [Available online at www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.]

NRC, cited 2010: Geological survey of Canada: Geomagnetism. [Available online at http://geomag.nrcan.gc.ca/apps/mdcal-eng.php.]

Sawyer, J. S., 1959: The introduction of the effects of topography into methods of numerical forecasting. *Quart. J. Roy. Meteor. Soc.,* **85,** 31–43.

Stull, R. B., 2000: *Meteorology for Scientists and Engineers.* 2nd ed. Brooks/Cole, 502 pp.

Weather Forecast Research Team, cited 2010: Sun vs. shade for Whistler on January 1 at 0:00 PT. [Available online at https://weather.eos.ubc.ca/otp2010/sunshadedir/sunshade.php?.]

Zanotti, F., S. Endrizzi, G. Bertoldi, and R. Rigon, 2004: The GEOTOP snow module. *Hydrol. Processes,* **18,** 3667–3679.