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Mean wind patterns and snow depths in an alpine–subalpine ecosystem as measured by damage to coniferous trees

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Summary

1. Deformations of Engelmann spruce and subalpine fir trees were surveyed for the purpose of determining climatic wind speeds and directions and snow depths in the Glacier Lakes Ecosystem Experiments Site (GLEES) in the Snowy Range of southeastern Wyoming, USA. Tree deformations were recorded at 50- and 100-m grid intervals over areas of *c.* 30 ha and 300 ha, respectively, over the GLEES.

2. The climatic mean wind speed was estimated to be 7·4 m s^{-1}; the mean air flow was predominantly westerly. The snow depths ranged from less than 0·2 m to 5·5 m, depending on topographic features and vegetative architecture.

3. Compared with snow depth surveys, precipitation measurements, and a degree-day snow depth model, the average snow depth estimated by the tree deformation method was 70% of the long-term mean.

4. The tree deformation method was useful for detailed estimates of wind speed, wind direction, and snow depth at a fine scale in complex terrain where meteorological instrumentation and snow survey data are minimal.

Key-words: air flow, complex terrain, *Krummholz*, surface wind, tree deformation, wind speed.

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Introduction

Alpine and subalpine ecosystems in bedrock formations with low acid neutralizing capacities are considered to be particularly sensitive to atmospheric pollutants and to climatic change (Musselman 1994). These high-elevation ecosystems experience a great deal of physical environmental stress, and any additional stress may have a large impact on their growth and/or survival.

Atmospheric deposition is affected by wind speed and intensity of turbulence. Increased turbulence creates regions of enhanced potential for the uptake of atmospheric pollutants by plants. Winds also affect precipitation patterns, snow distribution, snowpack accumulation, and the resultant vegetation types and growth forms. Thus a quantitative knowledge of the regional wind field and snow distribution is basic to understanding the ecological processes.

Measurements of wind speed and wind direction at a small spatial resolution are expensive and difficult at remote, high-elevation sites and would require long-term monitoring to determine averages. Tree damage and deformation caused by prevailing winds has been used as a surrogate to determine mean wind direction and speed. Asymmetrical deformation of trees is related to the mean wind speed and is indicative of the mean wind direction to which the trees have been exposed (Robertson 1987). In effect, the tree deformation integrates long-term wind effects.

Deformation in the winter is caused by ice crystal abrasion and desiccation of leaf bud and foliage tissue exposed above snow surfaces on the windward sides of the trees (Holtmeier 1980; Hadley & Smith 1983, 1986; Daly 1984; Hansen-Bristow 1986). Selective upwind mortality leads to growth and development of branches and foliage primarily on the protected,

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lee side of the tree. Trees are deformed in all seasons by the bending and breaking of twigs because of wind drag (Daly 1984). If the wind speed is sufficiently high, wind drag can also result in the downwind bending of the upper portion of the tree trunk.

The response of trees to the prevailing air flow depends upon the tree species. Robertson (1986) used the degree of asymmetry and directionality of deformation of larch *Larix laricina* to estimate mean annual wind speeds and wind direction in mountainous terrain. He established that microscale variations of air flow were delineated in extensive tree deformation patterns. Engelmann spruce and subalpine fir were used by Holtmeier (1978, 1980, 1981, 1985) to map prevailing wind patterns in the Front Range of the Rocky Mountains. Yoshino (1975) used wind-deformed trees to determine wind speed and wind direction in the Rhone Valley of Switzerland and the mountainous terrain of Japan. He demonstrated that this technique was a powerful tool for studying ecological effects of wind conditions. Using a linear relationship, Yoshino found a Pearson's r^2 of 0·75 between deformation grades and wind speeds.

Trees also react to prevailing winds by lesser tree ring growth on the upwind side, leading to an asymmetric tree ring configuration. The use of a tree ring index has not been found to be as reliable as the deformation of branches and foliage for estimating wind velocities over hilly terrain (Robertson 1986), and requires destructive sampling.

Snow accumulation in windy environments has been difficult to quantify. Because of wind effects, precipitation gauges are not reliable for measuring the amount of snowfall (Martinec & Rango 1986). Snow course* data can be correlated with streamflow, but a high sampling density is required to yield reliable estimates of total water input. Snow core surveys are very labour-intensive and must be carefully designed to produce acceptable results (Elder, Dozier & Michaelsen 1988; Dozier & Bales 1989). Snow deposition and atmospheric chemical deposition are dependent upon topography and wind as well as total precipitation or atmospheric concentration. Snow deposition is redistributed during and after snowstorms, with local winds often changing as storm patterns move over an area. However, since terrain irregularities and prevailing winds are consistent, snow distribution patterns at a given location generally repeat from year to year (Elder, Dozier & Michaelsen 1991). Local snow distribution patterns can be examined by observing how trees respond to snow cover.

The objectives of this study were to determine local wind direction, wind speeds and snow distribution at a high altitude research site with complex terrain, using measurements of tree deformation. The data were used to develop maps of surface wind speed, wind direction and snow depth for use in studies of the response of alpine and subalpine ecosystem to atmospheric deposition and climatic change.

Materials and methods

STUDY SITE DESCRIPTION

A study area has been established in south-eastern Wyoming to examine the effects of atmospheric deposition and climatic change on alpine and subalpine ecosystems (Musselman 1994). The Glacier Lakes Ecosystem Experiments Site (GLEES) is a 600-ha alpine-subalpine catchment at 3400-m elevation in the Medicine Bow National Forest, about 60 km west of Laramie, Wyoming, at 41° 22′ 30″ N, 106° 15′ 30″ W. The site is dominated by Engelmann spruce *Picea engelmannii* (Parry) Engelm., subalpine fir *Abies lasiocarpa* (Hook.) Nutt., willow *Salix* spp. and by extensive meadow and cushion plants. Wind deformation of the tree species is common. The terrain is complex, with abrupt changes in altitude. The soils are thin and undeveloped and the underlying rock is quartzite cut by mafic dykes, leading to soils and lakes with low ability to neutralize acidic input. The site was chosen because the pollution input is presently low, and the ecosystem is considered to be sensitive to any additional stress that might be imposed by climate change and atmospheric pollutant deposition.

The region of study is outlined on the topographic map shown in Fig. 1. The Snowy Range lies at the northern end of the Medicine Bow Mountains. A ridge dominates the northern border of the GLEES, while to the west, separated by a small gap, is situated a second, higher ridge with a nearly north–south orientation. Permanent snowfields have formed on the south–south-east aspect of the ridge bordering the GLEES to the north. The terrain has a large influence on microclimatic conditions, and thus on habitats for vegetation and on plant communities.

Two major climatic variables in the GLEES are surface wind flow and snow distribution. The winds are strong and the climate dry, so that the winds have a major effect on the vegetation through direct mechanical damage, desiccation and abrasion by blowing snow. Snow constitutes more than 80% of the water input to the GLEES and the area is snow-covered from late November to early June.

In the absence of reliable measurements of the amount of snow in a catchment, increased confidence in any single method of estimating snowpack depends on a comparison of different methods. Five methods have been used to determine snow input at the GLEES: (i) the Martinec–Rango (Martinec & Rango 1981, 1986) degree-day method; (ii) point measurements from two precipitation gauges at the GLEES; (iii) snow-core data from a small subcatchment that is a part of the GLEES; (iv) year-to-year comparisons with a nearby Soil Conservation Service snow course;

* Snow course: a series of sampling points at the same site, at which the depth and density of snow are measured.

and (v) a method of determining the mean yearly snowfall from tree morphology discussed here. A detailed comparison of the results from the different methods has been given by Sommerfeld *et al.* (1991).

SAMPLING PROTOCOLS

The GLEES was divided into 100-m grid mapping units in the N-S and E-W directions, and a tree was sampled for deformation measurements near each grid intersection. This grid scale was considered adequate to identify areas of different atmospheric deposition potential for snow and atmospheric pollutants within the study region. For precise location within the GLEES, individual trees to be sampled were identified on stereo pairs of aerial photographs (flown June 16, 1988, scale 1:2400). Trees used for the study were selected on the following bases: (i) full exposure to the prevailing winds; (ii) lack of damage from snow slides, broken trunks or lightning; (iii) whether trees were either Engelmann spruce or subalpine fir; and (iv) similarity in size, shape and health of trees in the immediate vicinity.

DETERMINATION OF MEAN WIND VELOCITIES

Two indices have been used to quantify tree deformation, the Griggs-Putnam and the Wade-Hewson indices. The Griggs-Putnam index (G) requires a visual evaluation of the main axis of crown deformation. G values range from 1 to 8 (Robertson 1987). Figure 2 comprises photographs of trees representing the different degrees of crown asymmetry. For spruce trees, the relation between wind speed and deformation was calculated to be:

$$V = 0{\cdot}65G + 6{\cdot}1 \qquad \text{eqn 1}$$

where V is the climatic wind speed in ms^{-1} (Hewson *et al.* 1979). The relation for fir trees was calculated to be:

$$V = 1{\cdot}2G + 2{\cdot}6. \qquad \text{eqn 2}$$

The Wade & Hewson (1979) index D for computing the climatic wind speed, using the geometry shown in Fig. 3, was:

$$D = \frac{\alpha}{\beta} + \frac{\gamma}{34}. \qquad \text{eqn 3}$$

The wind speed calculation applied the deformation D from eqn 3 to the relation:

$$V = -5{\cdot}96 + 10D - 1{\cdot}7D^2. \qquad \text{eqn 4}$$

Ground photographs were taken of each sample tree at the 126 grid points where trees satisfied the above criteria. Wind direction was determined in the

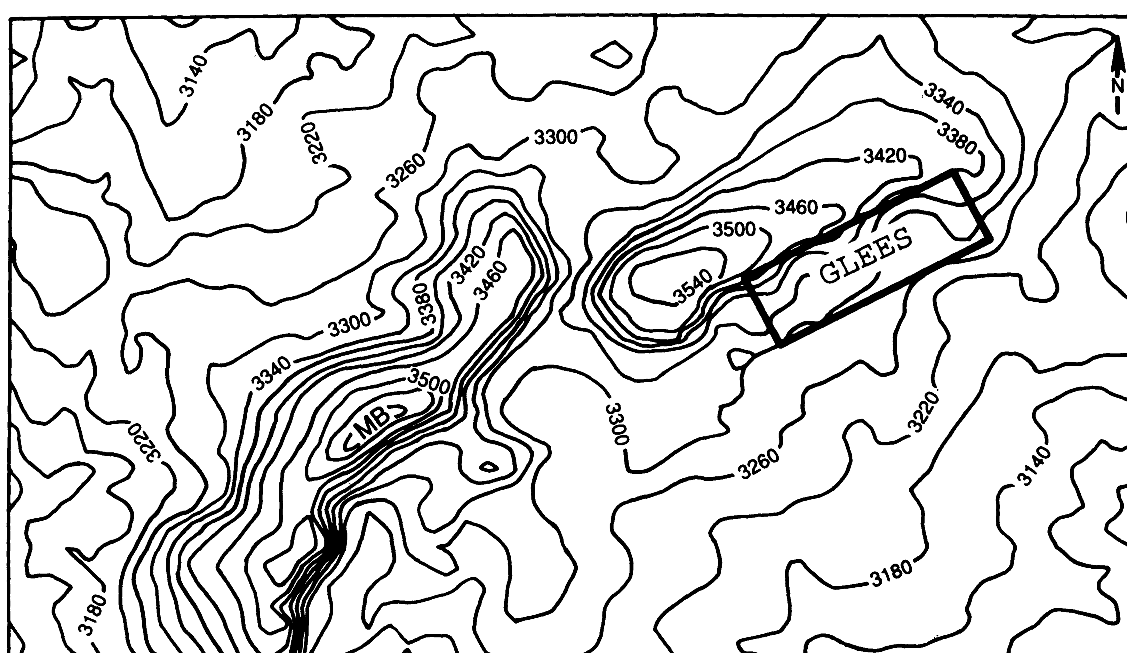

Fig. 1. Computer-derived topographic map of the GLEES and surrounding area. Contour intervals are 40 m. The boundary of the experimental site is outlined in heavy solid lines. Medicine Bow Peak is designated by the letters M B.

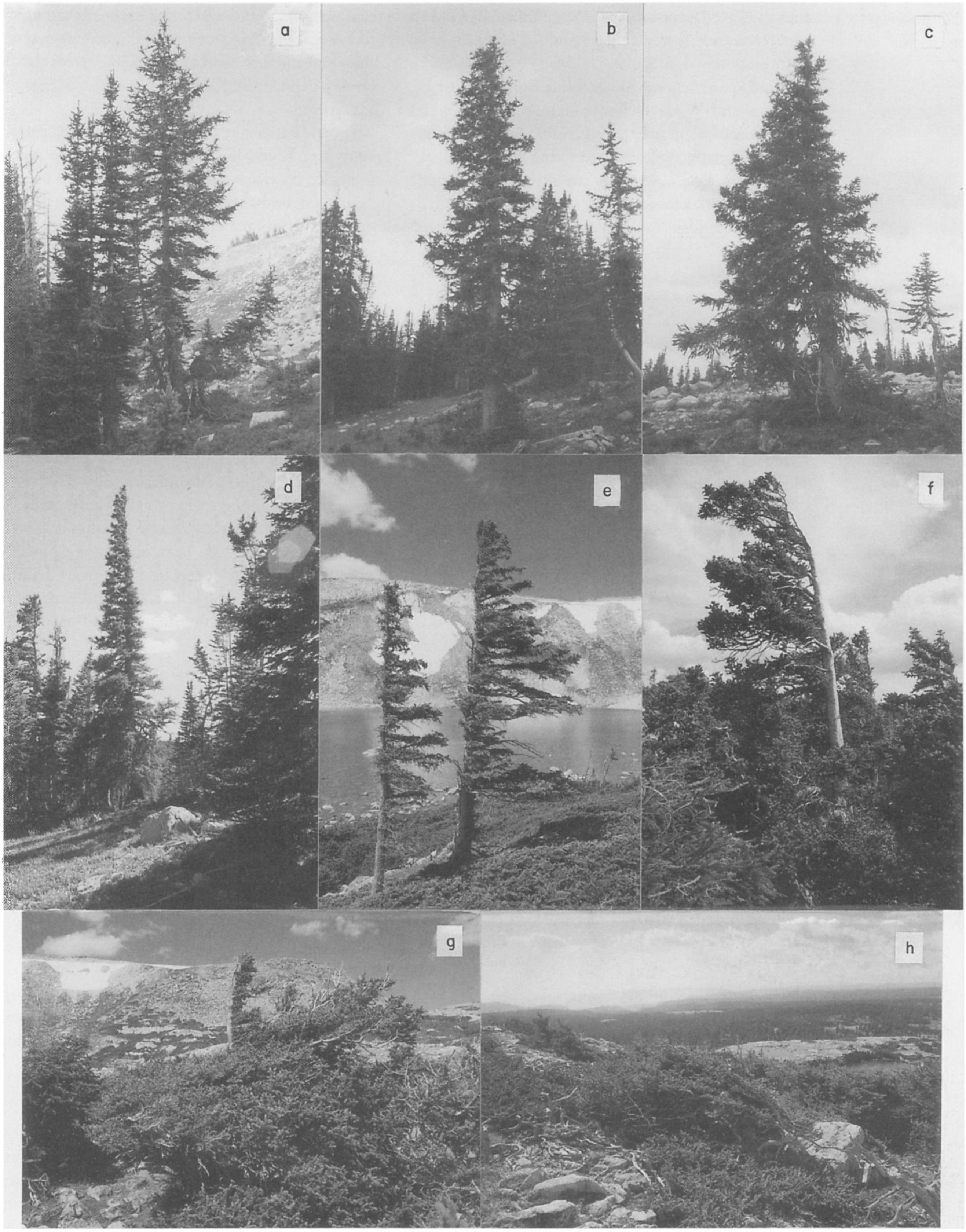

Fig. 2. Examples of the Griggs–Putnam index (G) of wind deformation for conifers taken for this study. $G = 1, 2 \ldots 8$ in a, b, ... h, respectively.

field by measuring the compass direction of the primary orientation of asymmetry or bending at each of these points. The photographs were taken at *c.* 90° to the tree-determined wind direction for evaluating the deformation.

Wind speed was calculated using both the Griggs–Putnam and Wade–Hewson indices. At the aerial photograph points, each of three field observers ranked each tree selected according to the Griggs–Putnam criterion, and the mean of these was applied to calculate the climatic wind speed. When β (eqn 3) was too close to zero, the Wade–Hewson index could not be used.

The Wade–Hewson method was applied to photographs of 93 trees from the 129 that were sampled at the GLEES; trees at 36 grid points were not measured because bending angles could not be determined from the photographs. Photographs of the trees were overlaid with an orthogonal grid to measure the angles required for application of eqn 3. In this analysis, we found that the limit of asymmetry (α/β: Fig. 3) was closer to 3 than to the 5 recommended by Wade & Hewson (1979). Tree deformation data were used to create charts of air flow and wind speeds, which should assist in later studies of atmospheric deposition.

DETERMINATION OF MEAN SNOW DEPTHS

Two different types of tree damage, by winds and by brown felt blight *Herpotrichia juniperi* (Duby) Petrak, were used to estimate snow depths at the GLEES. Snow distribution is influenced by vegetation patterns: in particular *Krummholz* mats and forest clumps affect snow drift patterns. In turn, redistribution of snow by wind will affect the shape of conifers, with the resultant tree structure ranging from undeformed and erect to *Krummholz* mat. In many mountainous areas, snow depth close to the maximum may occur as early as January (Schild & Gliott 1981), with additional snowfall settling and compacting the snow. Lower tree branches embedded in the snow remain sheltered and symmetrical during most of the winter, while above the snow the trees are exposed to the prevailing wind, to desiccation and to ice abrasion. The height at which these effects are apparent on the trees is often clearly defined, and can be measured within a few centimeters.

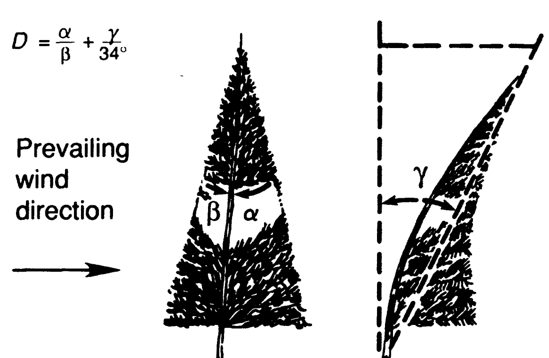

Fig. 3. The Wade–Hewson deformation ratio for conifers (from Wade & Hewson 1979). α/β represents the ratio of the downwind–upwind asymmetry of the branch deformation. γ indicates the bending of the trunk in degrees, due to static pressure on the canopy. (Adapted from Wade & Hewson 1979.)

Brown felt blight develops under deep, persistent snow, and results in the death of the tree needles. It is indicated by areas of dead, fungus-covered needles or defoliated branches near the base of the tree. The extent of development of the blight, and consequently the severity of the damage, is dependent upon the duration of the snow cover. The top of the dead area occurs near the level of maximum persistent snow depth, but it is often not so sharply defined as the wind-induced tree deformation above the snow. The deformation and the blight-indicator heights on trees tend to merge over long periods of time for long-lived trees, since years of low snowfall will lower the ice abrasion and tree deformation height, while years of high snowfall will move the blight defoliation line upward on the trees. The index of snow depth derived from tree morphology will probably indicate the long-term minimum of each year's maximum snowpack because, early in each year and in years with low snowfall, abrasion, desiccation and death will occur at a lower height on the tree. Thus, the mean depth determined from tree deformation will be lower than the true mean.

We measured the heights at which wind deformation began or brown felt blight damage ended on Engelmann spruce and subalpine fir trees to prepare charts of mean snow depths over the GLEES. The heights were measured on trees at or near the 100-m grid points, where possible, to estimate the long-term mean snow depth for the site. Isopleths of snow depth at intervals of 0·5 m were constructed from these measurements. These isopleths were overlaid on the aerial photographs as a method of correcting the isopleth orientation. The aerial photographs clearly indicated remaining drifted, deeper snow part way through the snowmelt season, and thus assisted in determining the exact location and orientation of the areas of deepest snowpack. Ambiguities in isopleth location were resolved using the aerial photographs but in no case was the information on tree damage violated by these adjustments.

STATISTICAL ANALYSIS

The grid resolution required to establish the minimum data density appropriate for the GLEES snowpack determination was statistically evaluated by comparing isopleth patterns from 50-m, 100-m, and 200-m grids. The sampling at 50-m grid spacing was performed on a 30-ha catchment of East Glacier Lake along the eastern edge of the GLEES. This resulted in only minor modifications of the snow depth isopleth pattern (not shown here). The 200-m grid sampling was accomplished over the entire GLEES by the simple expedient of using every second snow measurement in each direction over the original 100-m grid. The effects of spatial resolution on estimated mean snow depths over the GLEES, and in the smaller East Glacier Lake watershed, were evaluated statistically using a two-sample Student's *t*-test.

Results

MEAN WIND DIRECTIONS

The regional airflow in the Medicine Bow Mountains is from the west-northwest. This study shows that in the GLEES the surface wind flow across the GLEES is predominantly westerly (Fig. 4), indicating strong topographic channelling because of the abrupt rise in topography caused by the escarpment along the northern border. Smaller scale responses to topographic features can also be seen at the site. In the south-central region, some upwind divergence and downwind convergence was observed as air flowed around a small promontory (A in Fig. 4). At the north-eastern corner (B), some convergence of the flow indicates channelling along a small valley, and to the south of that (C) the flow diverged before it passed over a low ridge. Areas of convergence are areas where wind speed is expected to increase. Conversely, areas of divergence should experience lower wind speeds.

MEAN WIND SPEEDS

The mean values obtained by using the Griggs–Putnam index were similar to those using the Wade–Hewson index. Therefore, an average of the two methods was used for a selected tree when both could be applied to a grid point. The isotach (isopleth of wind speed) pattern (Fig. 5) indicates variation in wind speeds as the air flowed over the rugged terrain of the GLEES. Exposed, higher terrain was characterized by high wind speeds, while lower sites generally showed lower wind speeds. In some sheltered areas, tall spruce trees protruded upward into higher speed flows, showing wind deformation on their tips above the surrounding forest. A zone of lower wind speeds near the eastern border of the GLEES agrees with the divergent airflow shown in Fig. 4 (C). This zone is a region of increased tree density as the air approaches from the direction of the Glacier Lakes.

The mean wind speed over the GLEES was calculated to be 7·4 m s^{-1}, on the basis of results of the tree deformation study, with considerable variation generally related to interaction of the airflow with terrain features upwind and within the site. A 3-year mean annual wind speed of 7·8 m s^{-1} was recorded at

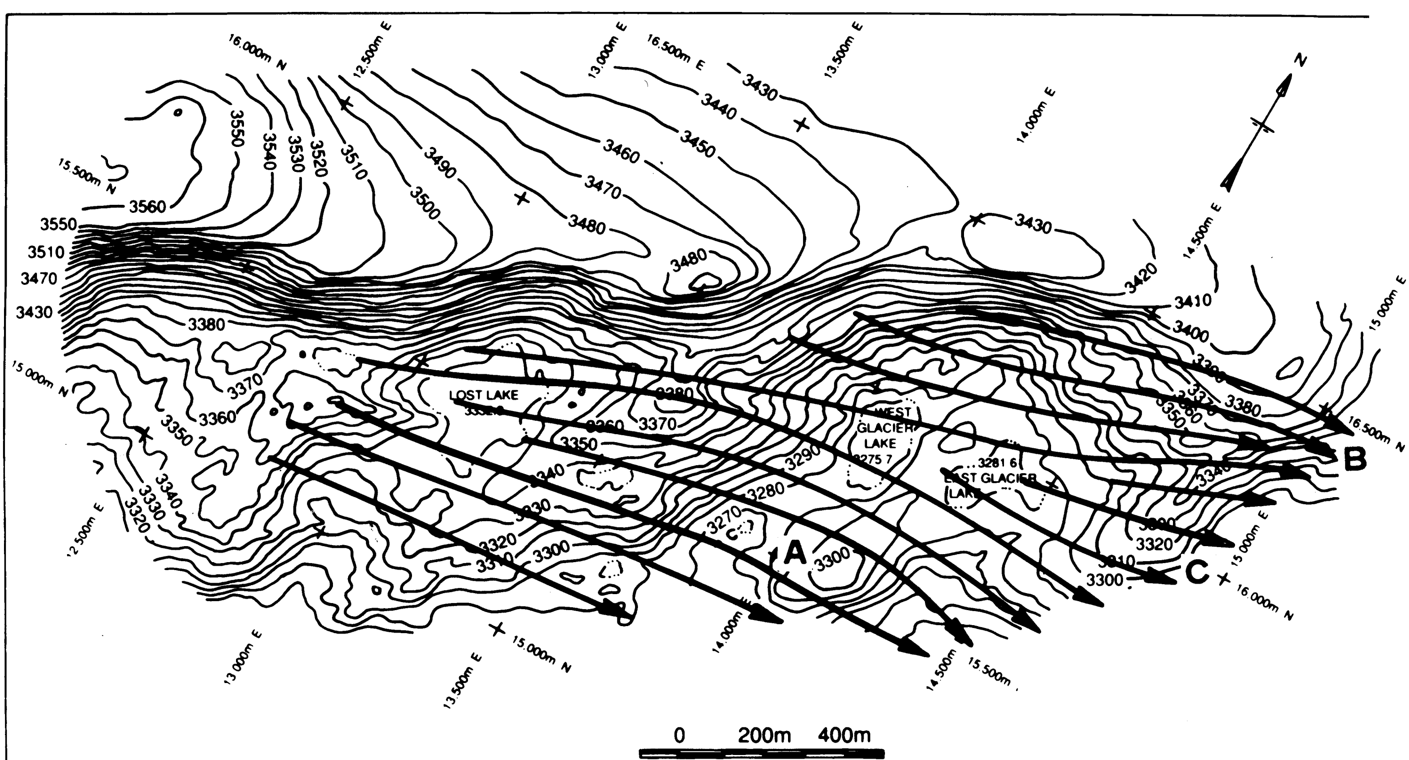

Fig. 4. Airflow pattern near the surface of the experimental site, as derived from the asymmetric deformation of Engelmann spruce and subalpine fir trees. Heavy lines with arrow tips indicate direction of airflow. Finer lines are altitude contours at 10-m intervals. Areas of divergence upwind and convergence downwind around a small promontory (A) were observed. Other areas of convergence (B) and divergence (C) are indicated.

17 m above ground on a meteorological tower (Fig. 5, T). located at the GLEES. At the same site a wind speed of 8·0 m s^{-1} was derived from tree deformation.

MEAN SNOW DEPTHS

Isopleths of snow depth (Fig. 6) show large variations across the GLEES. Generally, shallow accumulations of snow were found over and downwind of the lakes and over exposed ridges and hills, where wind speeds were high. Snow depths ranged from less than 0·2 m to 5·3 m, with a mean depth of 1·8 m for the whole of the GLEES, and 2·0 m for the East Glacier Lake catchment, as determined from the 100-m measurement grid.

EFFECTS OF MEASUREMENT DENSITY ON SNOW DEPTH CALCULATIONS

Measurements of the height on trees where snow damage was caused by wind damage and by brown felt blight were completed at 100-m intervals across the GLEES and at 50-m intervals over a small catchment within the GLEES. Using a measured snow density of 454 kg m^{-3} that occurred near maximum accumulation, Sommerfeld, Musselman & Wooldridge (1990) calculated a mean accumulation of 0·83 m water for 1·8 m of snow depth. An Alter-shielded precipitation gauge located at the Snowy Range National Atmospheric Deposition Program (NADP) site near West Glacier Lake showed that 0·82 m equivalent depth of water accumulated from November 1987 to April 1988, after which there was little snow fall. The Martinec–Rango (Martinec & Rango 1986) method yielded a water accumulation of 1·1 m for the 1987–88 winter snowpack (Sommerfeld *et al.* 1990). The US Soil Conservation Service (SCS) snow course data for 1987–88 showed an accumulation of 91% of normal at a site just beyond the southeast corner of the GLEES. A calibration of the Martinec–Rango estimate in 1989–90 indicated that it is expected to lie within $\pm$ 5% of the true value. The accuracy of the SCS estimate is often taken as $\pm$ 10%. From these results, it appears that the heights at which tree damage caused by wind begins, or at which snow blight damage ends, indicate a mean snow depth which is 70% of other measures of mean snow depth.

A statistical test for the significance of differences of means of the snow depths derived from tree morphology indicators was completed for two sets of data populations: (i) for the whole of the GLEES, at 200-m resolution vs. 100-m resolution; and (ii) for the East Glacier Lakes watershed, at 100-m resolution vs. 50-m resolution. The 100-m resolution data were removed from the 50-m set for the purposes of this test. The results are given in Table 1.

From these calculations, it appears that within 95% confidence intervals there is no significant difference between the mean snow depths derived from a 200-m grid resolution and from a 100-m resolution for the

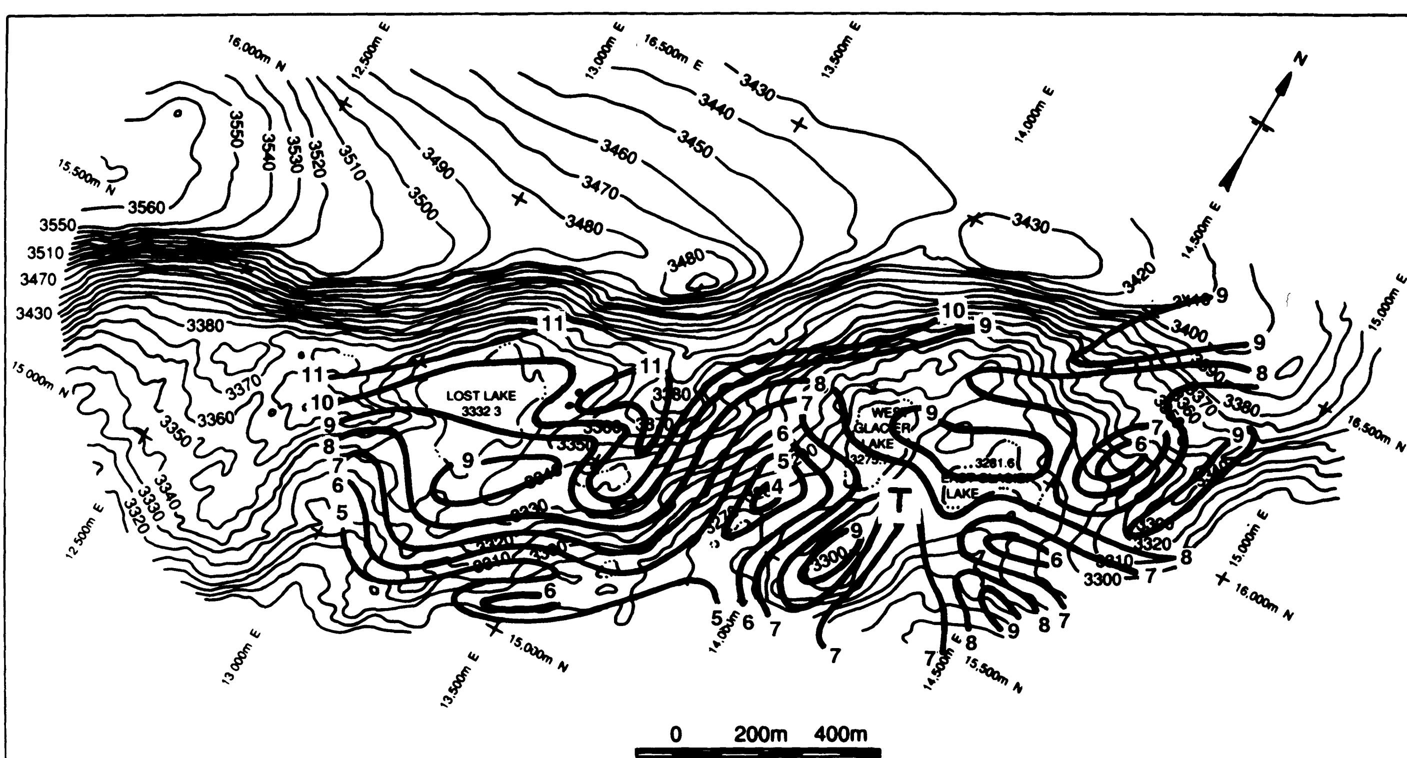

Fig. 5. Isotach pattern (heavy lines) of wind speed (m s^{-1}) near the surface of the experimental site, as derived from asymmetric deformation of Engelmann spruce and subalpine fir trees. Finer lines are altitude contours at 10-m intervals. The GLEES meteorological tower was located at T in the lower right portion of the map.

Table 1. Snow depths derived from tree morphology indicators, as related to sampling density

Area	Degrees of freedom	Variance (s^2)	Mean depth (m)	*F* value	
				Calculated	$P = 0{\cdot}025$
All of the GLEES					
200-m grid	32	0·92	1·95	1·45	1·83
100-m grid	124	1·35	1·83		
East Glacier Lake catchment					
100-m grid	23	2·00	2·18	1·78	2·06
50-m grid	65	1·12	2·09		

300-ha area of the GLEES, or between those derived from a 100-m grid resolution as compared with a 50-m resolution for the 30-ha East Glacier Lake catchment.

Discussion and conclusions

The survey of the degree and direction of asymmetric deformation of Engelmann spruce and subalpine fir provide data for analyses of surface wind patterns and wind speeds over a subalpine-alpine ecosystem in the Rocky Mountains of south-eastern Wyoming. The analyses indicate the effects of topographic features in producing divergence–convergence patterns and channelling of the air flow. Wind speeds near the surface vary sharply across complex terrain, with strong winds over promontories and ridges and much reduced wind speeds where trees are sheltered by higher terrain. Separate analyses of the wind direction and the wind speed produced consistent results. High wind speeds on exposed sites indicate convergence; while low wind speeds in sheltered valleys indicate divergence. The agreement between the measured long-term mean wind velocity at an anemometer location and that determined from the tree deformation is excellent. The Griggs–Putman index is quicker and easier to use in the field, and provides estimates of wind speed that agree closely with those calculated using the Wade–Hewson index.

Measurements of the height of wind deformation and damage from snow blight are useful as indicators

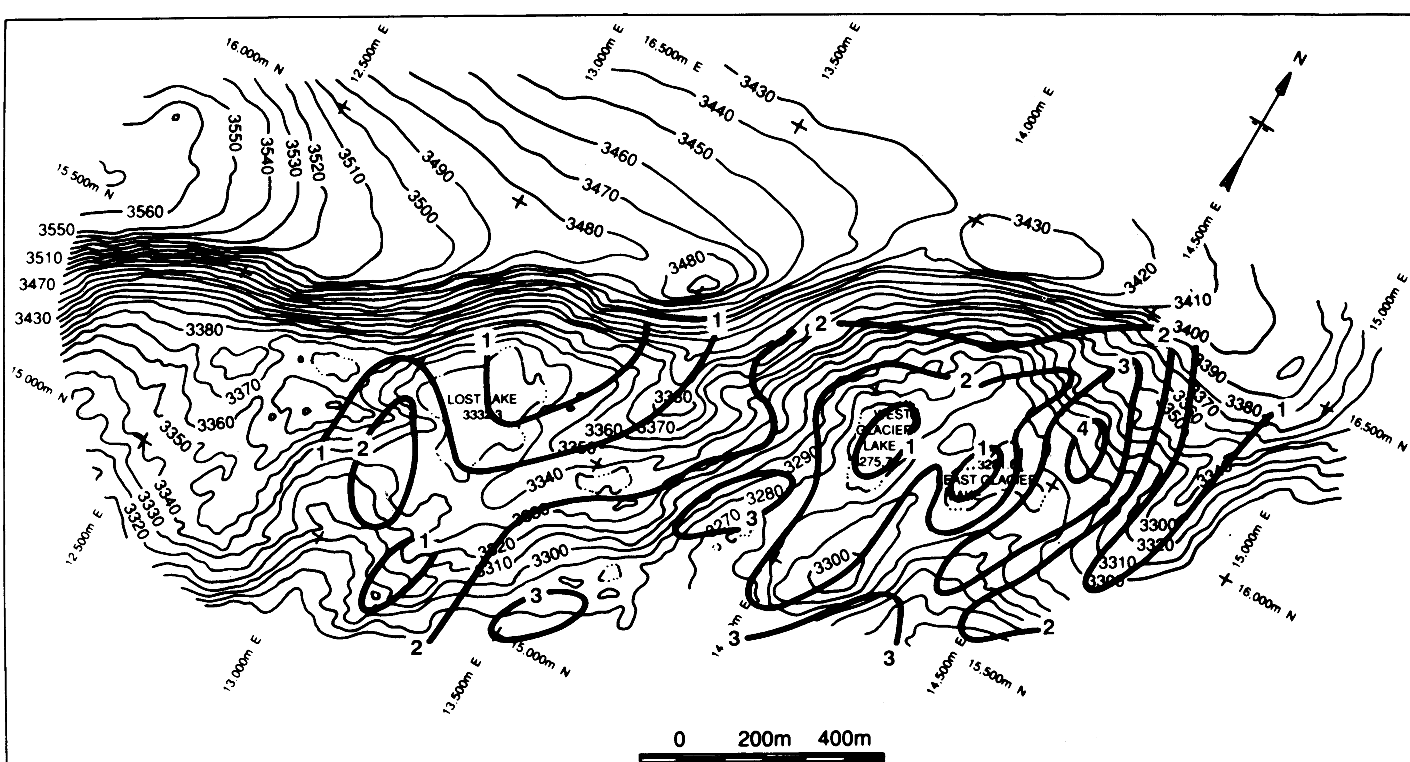

Fig. 6. Climatological maximum snow depth isopleths (heavy lines) for the experimental site, in increments of 1·0 m, as indicated by snow protection and brown blight felt blight infection of conifers. Finer lines indicate snow-free ground altitude contours at 10-m intervals.

of the maximum seasonal snow depth. The data suggest that the snow depth estimated by these methods will be significantly less than the long-term mean snow depth. In this study, the snow depth determined from tree deformation was about 70% of the long-term mean depth.

The results of the study of 50-m vs. 100-m on a grid scale on the 30-ha watershed and 100-m vs. 200-m on a grid scale on the 300-ha GLEES indicates that the larger scale grid sampling was adequate. Using the smaller-scale grid did not give a significantly different value for the mean snow depth.

Results of the tree study indicate that asymmetric tree deformation and snow blight damage on Engelmann spruce and subalpine fir trees are useful indicators for estimating wind direction (Fig. 4), wind speed (Fig. 5), and snow pack depths (Fig. 6) at the GLEES. The maps can be used to determine sites at the GLEES where atmospheric deposition might be expected to be greater and to provide the basis for models of such deposition. The maps also provide data that can be related to floristics and habitat patterns at the GLEES.

The methods described here may be useful at other remote sites with complex terrain where meteorological equipment is not available for fine-scale resolution mapping of wind fields. The snow depth mapping can be conducted during summer when conditions are more favorable for collection of such data. Such information can be used in studies of atmospheric deposition effects on high altitude ecosystems.

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References

Daly, C. (1984) Snow distribution patterns in the alpine *Krummholz* zone. *Progress in Physical Geography*, **8**, 157–175.

Dozier, J. & Bales, R.C. (1989) Recent snow-property research in the western US. *46th Eastern Snow Conference, Quebec, Canada, 8–9 June 1989*.

Elder, K., Dozier, J. & Michaelsen, J. (1988) Spatial variation of snow distribution in an alpine watershed. Abstract of presentation to the *American Geophysical Union Fall Annual Meeting, San Francisco, 6–11 December 1988*, **69**, 1198.

Elder, K., Dozier, J. & Michaelsen, J. (1991) Snow accumulation and distribution in an alpine watershed. *Water Resources Research*, **27**, 1541–1552.

Hadley, J.L. & Smith, W.K. (1983) Influence of wind exposure on needle desiccation and mortality for timberline conifers in Wyoming, U.S.A. *Arctic and Alpine Research*, **15**, 127–135.

Hadley, J.L. & Smith, W.K. (1986) Wind effects on needles of timberline conifers: seasonal influence on mortality. *Ecology*, **67**, 12–19.

Hansen-Bristow, K. (1986) Influence of increasing elevation on growth characteristics at timberline. *Canadian Journal of Botany*, **64**, 2517–2523.

Hewson, E.W., Wade, J.E. & Baker, R. (1979) Vegetation as an indicator of high wind velocity. *Annual Progress Report, Oregon State University*, Department of Energy Contract No. EY-76-F06-2227, 2–6.

Holtmeier, L.K. (1978) Die bodennahen Winde in dem Hochlagen der Indian Peaks section (Colorado Front Range). *Munstersche geographische Arbeiten*, **3**, 47.

Holtmeier, L.K. (1980) Influence of wind on tree physiognomy at the upper timberline in the Colorado Front Range. *New Zealand Forest Service, Forest Research Institute Technical Paper*, No. 70, 247–261.

Holtmeier, L.K. (1981) What does the term '*Krummholz*' really mean? Observations with special reference to the Alps and the Colorado Front Range. *Mountain Research and Development*, **1**, 253–260.

Holtmeier, L.K. (1985) Climatic stress influencing the physiognomy of trees at the polar and mountain timberline. *Berichten der eidgenössische Anstalt für das forstliche Versuchswesen*, **270**, 31–40.

Martinec, J. & Rango, A. (1981) Areal distributions of snow water equivalent evaluated by snow cover monitoring, *Water Resources Research*, **17**, 1480–1488.

Martinec, J. & Rango, A. (1986) Parameter values for snowmelt runoff modelling. *Journal of Hydrology (Amsterdam)*, **84**, 197–219.

Musselman, R.C. (1994) The Glacier Lakes Ecosystem Experiments Site. *US Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report* RM-249, Fort Collins.

Robertson, A. (1986) Estimating mean windflow in hilly terrain from tamarack (*Larix laricina* (Duroi K. Koch) deformation. *International Journal of Biometeorology*, **30**, 333–349.

Robertson, A. (1987) The use of trees to study wind. *Arboricultural Journal*, **11**, 127–143.

Schild, M. & Gliott, L.S. (1981) Schnee- und Lawinenverhaltnisse im schweizerischen Alpengebiet. *Schnee und Lawinen in den Schweizer Alpen Winter 1979/80*, No. 44, 42–92.

Sommerfeld, R., Musselman, R. & Wooldridge, G. (1990) Comparison of estimates of snow input with a small alpine catchment. *Journal of Hydrology (Amsterdam)*, **120**, 295–307.

Sommerfeld, R.A., Musselman, R.C., Wooldridge, G.L. & Conrad, M.A. (1991) The performance of a simple degree day estimate of snow accumulation to an alpine watershed. *Snow, Hydrology and Forests in High Alpine Areas* (eds H. Bergman, H. Land, W. Frey, D. Issler & B. Salm). Proceedings of the IAHS Symposium, Vienna, August 1991. International Association of Hydrological Sciences Publication Number 205. IAHS Press, Wallingford.

Wade, J.E. & E.W. Hewson (1979) Trees as a local climatic wind indicator. *Journal of Applied Meteorology*, **18**, 1182–1187.

Yoshino, M.M. (1975) *Climate in a Small Area: an Introduction to Local Meteorology*. University of Tokyo Press, Tokyo.

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