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Airflow Patterns in a Small Subalpine Basin

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With 3 Figures

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Summary

A study of mean wind speeds and directions has been completed in the Snowy Range of Southern Wyoming, U.S.A. It was conducted in a subalpine ecosystem at an altitude of 3 200 m to 3 400 m above sea level during the summers of 1988 and 1989. Indexes of deformation and axes of asymmetry due to wind shaping of Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) are related to wind speeds and directions on a 100 m × 100 m grid spacing over the 300 ha research site. Isotach and airflow patterns are drawn to represent climatological near-ground-level winds.

A statistical analysis of the wind data and deformation indexes indicates that the indexes estimated independently by three of the authors were not significantly different at the $F_{0.025}$ level. Two methods of calculating wind speeds were applied. At lower mean wind speeds in Engelmann spruce, results from the Wade-Hewson method were not significantly different from the Griggs-Putnam method at the $F_{0.025}$ level. In slightly higher wind speeds in subalpine fir, the Wade-Hewson method produced significantly lower wind speeds than the Griggs-Putnam method.

1. Introduction

The U.S.D.A. Rocky Mountain Forest and Range Experiment Station maintains the Glacier Lakes Ecosystem Experiments Site (GLEES) for the purpose of studying alpine-subalpine ecosystem responses to atmospheric deposition and global climate change. The site is located about 60 km west of Laramie, Wyoming, in the Snowy Range of the Rocky Mountains.

The habitat at this high elevation site is dominated by spruce, fir, and willow, which exhibit significant wind deformation, as well as meadow and cushion plants. The complex terrain contains lakes with low acid neutralizing capacity, which are sensitive to pollutant deposition. A ridge dominates the northern border of the GLEES, while to the west, separated by small gap, is a second, higher, ridge containing Medicine Bow Peak. Permanent snow fields have formed on the south-southeast aspect of the ridge to the north.

Winds are known to exert major impacts on alpine and subalpine ecosystems, affecting precipitation patterns, snow distribution and accumulation, and the resultant vegetation growth forms. The low-level wind pattern depends on the atmospheric thermal structure, the wind profile, and the terrain features upwind and over the site. However, the acquisition of wind data at remote, high-elevation sites at an approxpriate spatial resolution is expensive and difficult.

2. Tree Deformation and Long-Term Mean Winds

The response of trees to prevailing winds depends on the tree species, the prevailing wind speed and direction, the time of year during which strong winds occur, and the exposure of the tree. This may be evidenced by tree damage caused by ice crystal abrasion, desiccation of leaf bud and foliage tissue on the windward side (Hadley and Smith, 1983; 1986), by bending and breaking of limbs or trunk due to wind drag (Daly, 1984), or by a lesser tree ring growth on the upwind side of the trunk (Robertson, 1986). The asymmetry of the damage, or deformation, indicates the mean wind direction.

Yoshino (1975) used tree deformation to map wind speeds in the upper Rhone Valley of Switzerland. Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) were employed by Holtmeier (1985) to determine prevailing wind patterns and to establish sites for climatological stations along the Front Range of the Colorado Rocky Mountains. Valley wind systems were examined by Ohata and Higuchi (1978) in the very deep Kali Gandaki Valley of Nepal using wind shaping of coniferous and broadleaf trees. They found the strongest valley winds in the upper part where the valley orientation agreed with the prevailing upper level wind direction.

Two years of wind data from a meteorological tower located at the GLEES indicates that over 80% of the winds there blow from a sector between 240 to 300 degrees, with little difference between summer and winter wind directions. Winds are generally stronger in winter than in summer.

The Griggs-Putnam method of deducing wind speeds from deformation indexes has been empirically derived by Robertson (1987) for spruce trees as:

$$V = 0.65\,G + 6.1 \qquad (1)$$

where V is the wind speed in ms^{-1} and G is the index (Fig. 1 a). For fir trees, the relation is:

$$V = 1.2\,G + 2.6. \qquad (2)$$

The Wade and Hewson (1979) method uses the geometry of the tree deformation according to the angle of bending of the trunk in addition to the degree of upwind branch destruction (Fig. 1 b). The relation here is:

$$V = -5.96 + 10\,D - 1.7\,D^2 \qquad (3)$$

where D is the deformation ratio as stated in Fig. 1 b.

3. Mean Wind Patterns over the GLEES

Aerial photographs and topographical charts of the GLEES region were overlaid with a 100 m × 100 m grid to facilitate a ground survey of the wind-induced deformation of Engelmann spruce and subalpine fir trees across the site. Observers independently estimated the Griggs-Putnam index, and the tree was photographed. The orientation of the flagging of each tree was determined to obtain the mean wind direction. For each of the 133 trees surveyed, an average of the Griggs-Putnam indexes estimated by three observers was applied to relation (1) and (2), depending on the species, to obtain the wind speed. A statistical analysis of the Wade-Hewson relation, discussed later in this paper, shows that it is

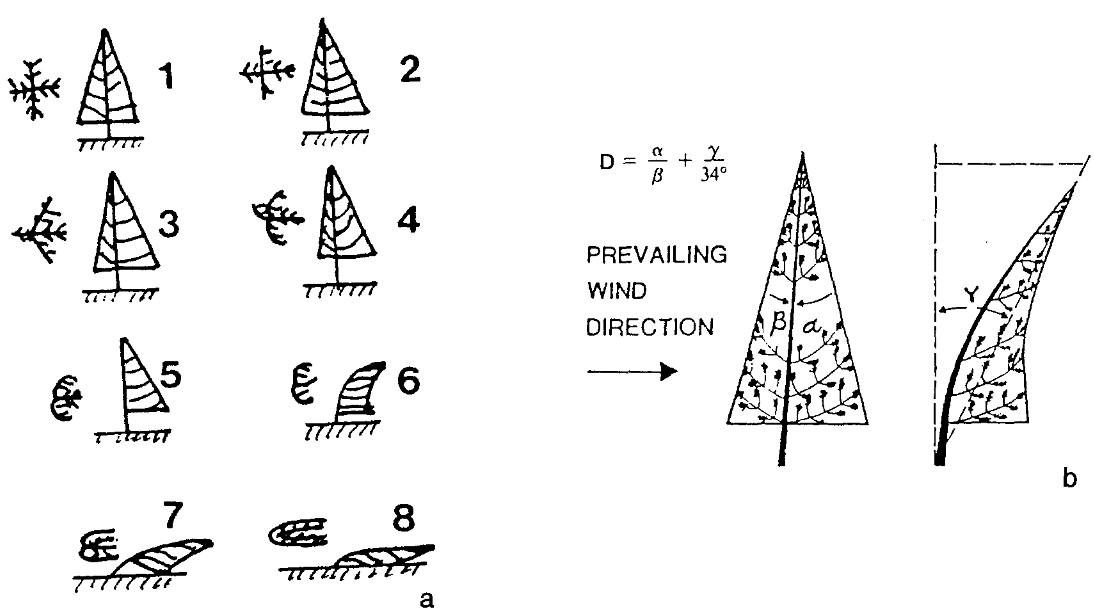

Fig. 1. Tree deformation index. 1 a represents the Griggs-Putnam index for conifers (from Robertson, 1987); 1 b, the Wade-Hewson (1979) deformation ratio for conifers

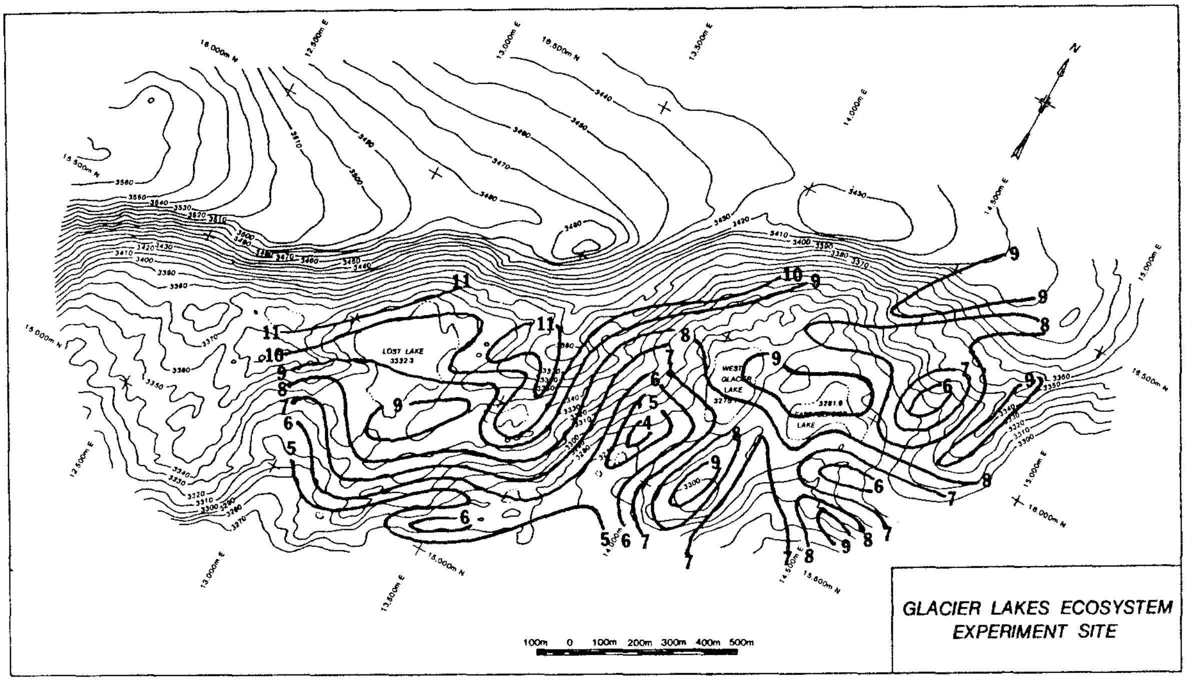

Fig. 2. Isotachs (heavy lines) of mean winds over the GLEES in $m\,s^{-1}$. The topography is presented at 10 m intervals

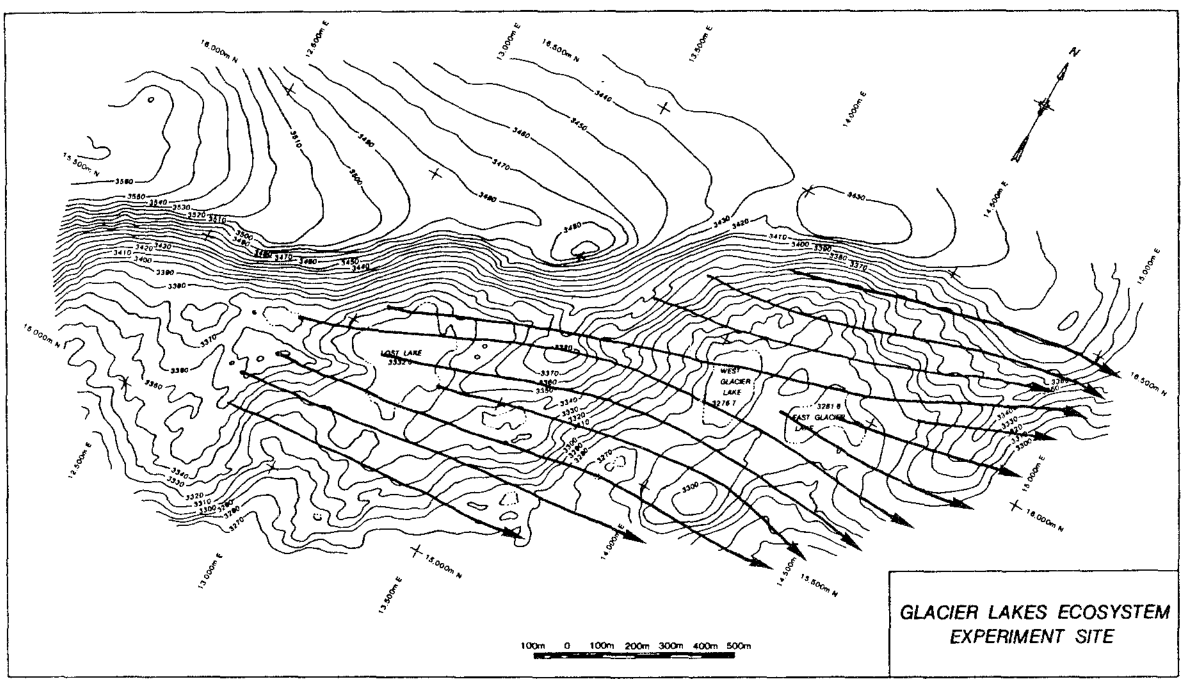

Fig. 3. Streamflow from mean wind directions deduced from tree flagging

not suitable for application to the subalpine fir trees surveyed here. Therefore, only the Griggs-Putnam relation was used to calculate wind speeds for subalpine fir, while speeds derived from the Wade-Hewson relation were averaged with those from the Griggs- Putnam relation to obtain speeds for Engelmann spruce.

The isotach analysis given in Fig. 2 shows the spatial distribution of mean wind speeds across the GLEES. The wind speeds appear to depend mostly on terrain features on the scale of hundreds of meters. The highest wind speeds occur where higher terrain is better exposed to the upper level winds. This also occurs where the wind encounters a relatively unobstructed fetch across the Glacier Lakes. The northern border of the GLEES also exhibits high wind speeds, probably due to some channeling of the winds south of the sharp rise in terrain to the north. This portion of the GLEES is typically sparsely covered with Krummholz spruce, subalpine fir, and willow. A low-speed area occurs just east of East Glacier Lake, where a stand of taller spruce is found immediately upwind of the small ridge at the extreme eastern border of the GLEES.

The direction of the surface mean winds was plotted at the location of each tree studied. Figure 3 gives the windflow pattern which results from the analysis of these data. In general, this shows a broad westerly flow over the site, but with some response to the terrain. In the south-central part of the GLEES, one observes some upwind divergence and downwind convergence due to flow around a small promontory. Near the eastern border, some divergence occurs where the wind speed is reduced. The reader will note that while the airflow shows only small changes in direction over the site, considerable detail is observed in the isotach pattern. This is thought to result in part from high turbulent intensities in the lower atmosphere such as were observed during balloon flights at all times of the day, causing strong downward fluxes of momentum into the lower atmosphere over the site.

4. Statistical Analysis of Calculated Wind Speeds

A statistical analysis of the significance of the mean wind speed computed from the Wade-Hewson and Griggs-Putnam methods and of the observer rating of the indexes used in the Griggs-Putnam method makes use of F-values calculated from the data compared with F-values from appropriate statistical tables (Roscoe, 1975). The results given in Table 1 indicate that there is no significant difference in the mean winds computed by the Wade-Hewson method as compared to the Griggs-Putnam method for Engelmann spruce trees at the GLEES.

However, as shown in Table 2, a significant difference is found between the two methods when applied to subalpine fir tree wind deformation. The subalpine fir are usually found at the higher elevations at the GLEES, where wind speeds are generally higher than at lower elevations.

Observer differences in estimating the tree deformation index, according to the F-values presented in Table 3, are not significant for the GLEES studies. Each observer made visual comparison with the sketches shown in Fig. 1 for each

Table 1. *Comparison Between Wade-Hewson ($W-H$) and Griggs-Putnam ($G-P$) Methods of Computing Mean Wind Speeds: Engelmann Spruce*

Method	Degrees of freedom	Mean wind speed ($m\,s^{-1}$)	Variance	F-Value
$W-H$	64	7.1	3.24	
$G-P$	64	6.8	3.36	
F, calculated				1.04
$F_{0.025}$, tables				1.67
$F_{0.050}$, tables				1.53

Table 2. *Same as Table 1, Except for Subalpine Fir*

Method	Degrees of freedom	Mean wind speed ($m\,s^{-1}$)	Variance	F-value
$W-H$	29	7.9	1.22	
$G-P$	29	8.6	0.55	
F, calculated				2.23
$F_{0.025}$, tables				2.13
$F_{0.050}$, tables				1.88

Table 3. *Comparison of Tree Deformation Indexes for the $G-P$ Method by Three Observer Pairs*

Observers	Degrees of freedom	Mean index	Variance	F-value
B. C.		4.14	3.20	
R. M.		4.24	2.76	
G. W.		4.17	3.07	
B. D.: R. M.	116			1.16
B. C.: G. W.	116			1.05
R. M.: G. W.	116			1.11
$F_{0.025}$, tables				1.45
$F_{0.050}$, tables				1.37

tree examined. The majority of the indexes were in the 4 to 6 range, where differences in tree deformation are more evident that in the 1 to 3 range.

5. Discussion

An evaluation of the wind deformation of Engelmann spruce and subalpine fir at a subalpine site has enabled the drafting of climatological streamlines and isotach patterns over the 300 ha region. Since the data were derived at a 100 m × 100 m grid spacing, considerable detail in the isotach pattern resulted. High wind speeds were generally found over exposed, higher, terrain features and along the northern boundary, where a bluff hill channels the airflow.

In some sheltered regions with dense spruce stands it was difficult to find single trees with sufficient exposure to apply the deformation index methods. Occasionally a single tree could be observed extending upward above the general canopy height. Where such trees protruded into the airflow above, an index value could have been estimated for the top few meters for the application of the G − P relationship. However, for this study only trees with good exposure over the entire tree were used so that the climatological winds shown in Figs. 1 and 2 can be said to represent near-ground airflows.

A statistical analysis of the relationship from which wind speeds were calculated from tree deformation indicates that the Wade-Hewson and Griggs-Putnam methods were not significantly different for Engelmann spruce at the $F_{0.025}$ or $F_{0.050}$ levels, but were different for subalpine fir at the same test levels. A comparison between pairs of observers estimating deformation indexes for both species of trees indicates no differences at the $F_{0.025}$ or $F_{0.050}$ test levels.

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