The vertical variation of the wind through the friction-layer over the Greenland ice cap

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ABSTRACT

The peculiar wind spirals observed at Station Centrale, Expeditions Polaires Françaises 1949–51, are explained by accounting for the effect of the thermal wind due to the presence of a strong surface inversion over sloped terrain.

During almost two years, September 1949 to August 1951, the meteorologists of the French Polar Expeditions (under the direction of Paul-Emile Victor) carried out soundings of wind and temperature at Station Centrale, 70.9° N. 40.6° W, 2 965 m (Bedel, 1954; Mälzer, 1964), The station, near the location of A. Wegener's "Eismitte" 1930–31, was about 120 km west of, and 200 m lower than, the divide of the inland ice. According to Bedel's topographic map (l.c., fig. 32), the slope of the terrain around Station Centrale is approximately 1/500, with the fall line toward 240°. These features make the station quite comparable to stations on the high plateau of Antarctica (e.g. Plateau Station, Vostok and South Pole), and thus an analysis of the wind in the friction-layer at each of the locations should lead to similar results.

Bedel's evaluation of the wind soundings revealed that the wind in the friction-layer turned to the left with height (i.e., opposite to the sense of the Ekman spiral) when the wind above the friction-layer was from the NE; that it showed little change of direction with upper winds from the E; and turned strongly to the right when the upper wind came from the S or W (see his figs. 22–29).

It is most fortunate that the results of the soundings at Station Centrale, as well as all other meteorological observations, have been published in full detail. This makes it possible to examine whether a recently developed theory of the wind in a strongly baroclinic planetary boundary layer can be used to explain Bedel's findings.

The first step towards such a theory is the following: Wherever a temperature inversion of approximately constant vertical extent lies over sloped terrain, there must be a pronounced horizontal temperature gradient, proportional to the strength of the inversion and the slope of the terrain. Consequently, the change of the wind with height in the lowest few hundred meters of the atmosphere must be affected not only by the Coriolis effect and by eddy diffusion of momentum, but also by the presence of a thermal wind whose direction is parallel to the contour lines of the terrain. This notion was first developed by Dalrymple, Lettau & Wollaston (1963, 1966); its importance for the understanding of the windfield over the Antarctic Plateau and related questions were discussed by Lettau & Schwerdtfeger (1967). The second step in the theory is the idealizing assumption that the vertical temperature profile within the surface inversion-layer and hence the change of the thermal wind with height can be approximated by an exponential function, as the measurements made at the South Pole and Plateau Station suggest (Schwerdtfeger, 1968, 1970). Employing this assumption, Mahrt & Schwerdtfeger (1970) derived the analytical solutions of the equations of motion in a baroclinic friction-layer which lead to strongly distorted Ekman spirals. These theoretical hodographs are in good agreement with the results of slow-rise soundings and micrometeorological tower data of Plateau Station in Antarctica (Schwerdtfeger & Sponholz, 1970; Schwerdtfeger, 1971).

To examine whether the sloped inversion—thermal wind concept also leads to an explanation of Bedel's wind spirals over the Greenland

Table 1. *Frictional deviation* α_0, *diminutionratio of surface wind speed* r_0, *for three groups of upper wind direction; strong surface inversion cases, Station Centrale, Greenland; slope of terrain* $G = 1/500$

D = direction

Group (Fig.)	ΔT (°C)	$\bar{T}_s$ (°C)	$D\bar{c}_s$ (degrees)	h (m)	range $D\bar{c}_r$ (degrees)	$D\bar{c}_h - D\bar{c}_s$ (degrees)	c_s/c_h	α_0 (degrees)	r_0
1	22	−54	079	200	060–080	−15	0.92	50	0.31
				300	040–070	−32	1.00	50	0.35
2	18	−41	090	200	100–120	19	0.99	44	0.42
				300	100–140	22	1.13	46	0.44
3	18	−44	113	200	180–200	72	0.88	49	0.32
				300	190–220	86	0.95	53	0.35

ice cap, the theory has now been applied to some of his data. Only the wind soundings of days which had an inversion of 15°C or more and a surface temperature of −40°C or lower have been analyzed. Since there can be random errors in individual soundings, and since the wind above the friction-layer can differ considerably from the ideal state of geostrophic equilibrium, several soundings have been grouped according to the wind direction at the 200 m level. This height may be considered as the top of the friction-layer in the case of extremely stable air-masses with correspondingly small values of the eddy diffusivity (on the order of 10^3 cm^2/sec). For three categories of the 200 m wind direction (060–080°, 100–120°, and 180–200°) five soundings satisfying the selection-criteria were available. The resultant wind (vector average) was computed for 100 m levels between the surface and 500 m. The constancy of these wind vectors was between 0.92 and 0.99, which indicates that the characteristic features of the individual wind profiles was not lost in the averaging.

Figs. 1, 2, and 3 show the essential results of this study. The magnitude of the thermal wind c_T has been computed by the formula (Dalrymple et al., 1966)

$$c_T = \frac{g}{f} G \frac{\overline{\Delta T}}{\bar{T}}$$

where g is the gravity acceleration, f the Coriolis parameter, G the slope of the terrain and presumably of the inversion layer, $\overline{\Delta T}$ the average strength of the inversion in the respective category, and $\bar{T}$ the average mean temperature of the inversion layer. The direction of the inversion-induced thermal wind is given by the contour lines of the terrain, from 330° according to Bedel's fig. 32 (1954). The geostrophic wind *at the surface level*, c_{gs}, is then obtained by subtracting the the thermal wind from the upper wind,

$$c_{gs} = c_{gh} - c_T$$

as it is shown by the dashed line in the three graphs. The angle of frictional deviation of the wind is:

$$\alpha_0 = \text{angle } c_{gs} - \text{angle } c_s$$

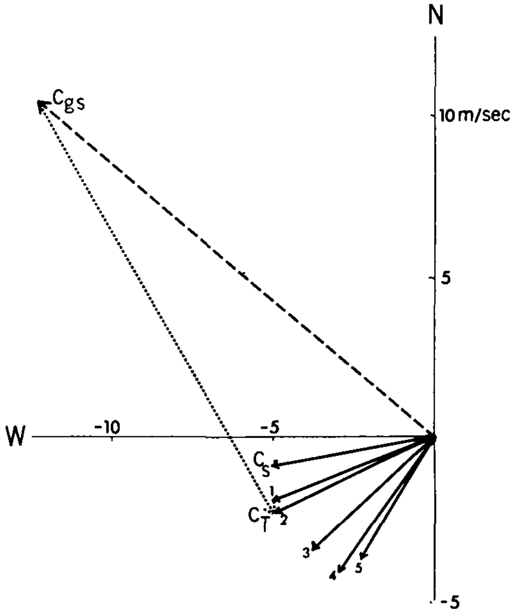

Fig. 1. Wind in the friction-layer at Station Centrale, when a strong surface inversion exists and the upper wind blows from NE. —, Resultant wind vector for 5 days, at surface and at 100 (1) to 500 (5) m above ground; – – – –, geostrophic wind at surface level; . . . . ., inversion-induced thermal wind.

and the ratio of frictional diminution of wind speed is

$$r_0 = c_s/c_{gs}$$

These parameters are summarized in Table 1, together with another set of values assuming the height of the friction layer to be 300 m instead of 200 m. The differences are not significant.

The most interesting graph is that of Fig. 1 in which the wind turns against the sense of the Ekman spiral. The geostrophic wind at the surface level, c_{gs}, is from the SE and the surface wind c_s about 50° to the left. With an approximately exponential temperature profile, the increase of the temperature is strongest near the surface. Hence the thermal wind decreases markedly in the lowest 100 m layer, and the geostrophic wind at the 100 m level (not shown in the graph) must be between E and ENE, as the frictional deviation at this level is small already.

In general terms, the behavior of the wind in the friction-layer to be expected in the presence of a strong surface inversion over sloped terrain can be described in the following way: (*a*) the wind turns with height counterclockwise (northern hemisphere) when the magnitude and direction of the upper wind and the thermal wind are such that the *geostrophic* surface wind points to the right of the upper wind by more than α_0, less than $180° - \alpha_0$; (*b*) for a given speed of the upper wind, the strongest surface wind occurs when the upper wind blows parallel to the contour lines of the terrain, opposite to the thermal wind induced by the sloped inversion. In the case of Station Centrale, that would be from 150°.

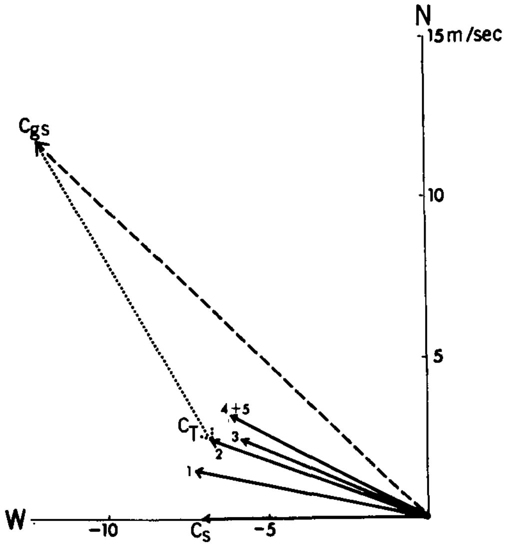

Fig. 2. Same as Fig. 1, with upper wind from ESE.

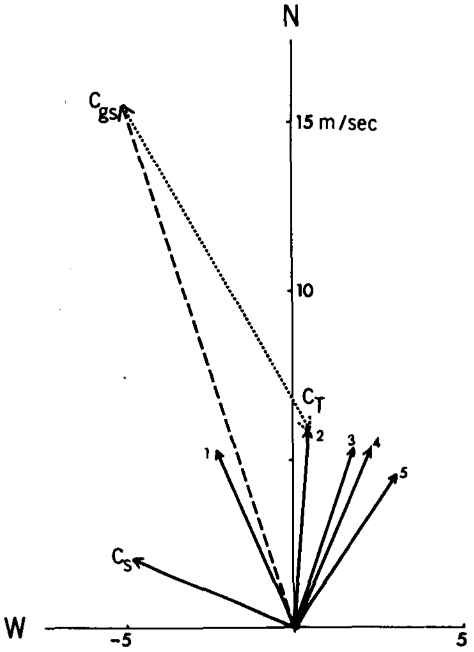

Fig. 3. Same as Fig. 1, with upper wind from SSW.

As most of the temperature increase in typical polar surface inversions is found in the lowest 200 m, the thermal wind *above* 200 m (or in some cases perhaps above 300 m) is assumed not to be related to the inversion. It rather is understood as representing the general horizontal temperature gradient in the atmospheric layer above the inversion. In the groups shown in Figs. 1 and 3 it corresponds to a gradient of about 3°C/100 km, toward the NNE.

Since the same principle of interpretation applies to the cases with the upper wind from the ESE (Fig. 2) and from the SSW (Fig. 3), a detailed discussion is not needed. However, it is important to note that for the three different directional groups shown in Table 1 the values for α_0 and r_0 indicate reasonable consistency. In contrast, the difference in direction of the upper wind and the surface wind varies from small negative to large positive values. The inversion-wind concept also explains why the direction of the surface wind is not independent of the direction of the upper wind; see column $D\bar{c}_s$ in Table 1. The earlier concept of the so-called "gravity wind" affected by the Coriolis force left this relationship unexplained.

Of course, from a statistical point of view the three groups of five soundings each are very small samples. It is, therefore, reassuring to note that the results are supported by those obtained from much larger numbers of soundings over the Antarctic Plateau (Schwerdtfeger & Mahrt, 1968). It is difficult to say what other factors may cause the remaining discrepancies, which are larger for soundings with weaker inversions. Loewe (1935) has argued that the slope of the top of the inversion-layer may differ significantly from the slope of the terrain. This would make the determination of the inversion-induced thermal wind more uncertain, because no adequate observations of the true slope of the inversion height are available. Another source of errors may be the assumption that the vector average of a small number of wind observations above the inversion-layer represents a geostrophic wind. In the theoretical approach, finally, the assumption of constant eddy diffusivity still is a serious shortcoming, particularly when various soundings with different surface wind speeds are combined to produce a representative vector average. Nevertheless, it appears that the peculiar features of the wind profiles over Greenland's inland ice can be explained by the inversion-wind concept.

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REFERENCES

Bedel, B. 1954. Les observations météorologiques de la station Française du Groenland; conditions atmosphériques en altitude. *Expéditions Polaires Françaises, Missions Paul-Emile Victor, Resultats Scientifiques, No. N V*, Paris, 119 pp.

Dalrymple, P., Lettau, H. & Wollaston, S. 1963. South Pole micrometeorology program, data analysis. *Quartermaster Res. Eng. Center, Earth Sci. Div., Tech. Report ES-7*, 93 pp. Also published 1966, in M. J. Rubin (Editor), Studies in Antarctic Meteorology. *American Geophys. Union, Antarctic Research Series 9*, 13–58.

Lettau, H. & Schwerdtfeger, W. 1967. Dynamics of the surface-wind regime over the interior of Antarctica. *Antarctic Journal of the U.S. 2* (5), 155–158.

Loewe, F. 1935. Das Klima des Grönländischen Inlandeises. In Koeppen–Geiger, *Handbuch der Klimatologie*, 2 K, 67–101.

Mahrt, L. & Schwerdtfeger, W. 1970. Ekman spirals for exponential thermal wind. *Boundary-Layer Meteorology 1* (2), 137–145.

Mälzer, H. 1964. Das Nivellement über das Grönländische Inlandeis. *Meddelelser om Grønland 173* (7), 122 pp.

Schwerdtfeger, W. 1968. New data on the winter radiation balance at the South Pole. *Antarctic Journal of the U.S. 3* (5), 193–194.

Schwerdtfeger, W. 1970. Die Temperaturinversion über dem Antarktischen Plateau und die Struktur ihres Windfeldes. *Meteorologische Rundschau 23* (6), 164–171.

Schwerdtfeger, W. 1971. Remarkable wind shifts and a speed maximum a few meters above the surface of the Antarctic Plateau. *Antarctic Journal of the U.S. 6* (5), in print.

Schwerdtfeger, W. & Mahrt, L. 1970. The relation between the Antarctic temperature inversion in the surface-layer and its wind regime. *Proceedings of the international Symposium on Antarctic Glaciological Exploration (ISAGE)*, September 1968, ICSU, SCAR, and IASH, Publ. No. 86, 308–315.

Schwerdtfeger, W. & Sponholz, M. 1970. Theory and observations of the wind in the friction layer over the Antarctic Plateau. *Antarctic Journal of the U.S. 5* (5), 175–176.

О ВЕРТИКАЛЬНОМ ИЗМЕНЕНИИ ВЕТРА В СЛОЕ ТРЕНИЯ НАД ЛЕДЯНЫМ КУПОЛОМ ГРЕНЛАНДИИ

Особого вида спирали ветра, наблюдавшиеся над станцией Центральной во время французской полярной экспедиции 1949–51 гг., объясняются при учете эффекта термического ветра, возникающего благодаря присутствию сильной инверсии у поверхности над склоном.