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Relationships of Soil Acidity and Air Temperature to the Wind and Vegetation at Prudhoe Bay, Alaska.

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ABSTRACT. Investigations in the Prudhoe Bay vicinity suggest that prevailing winds from the east combined with the shape of the coastline and a source of calcareous materials in the Sagavanirktok River delta cause distinct patterns of soil reaction and temperature. Areas downwind from the river have basic soil pH values ranging from 7.1 to 8.4, whereas wet tundra sites outside the path of loess-laden winds have acidic values ranging from 5.3 to 7.0. The winds also affect the local climate by blowing moist cold air and fog further inland in the western part of the Prudhoe Bay oil field. Air temperatures are correlated with distance to the ocean measured in the direction of the prevailing wind vector. The temperature differences also influence the depth of the active layer. The differences in pH and temperatures affect the vegetation of the region. The areas with basic soils show relative abundance of calciphiles, whereas areas with lower pH values have acidiphilous plants. Lower temperatures near the coast affect the distribution of many taxa as well as the phenology and stature of the vegetation.

RÉSUMÉ. Des enquêtes, réalisées dans le voisinage de Prudhoe Bay, font supposer que les vents dominants de l'Est, associés avec la morphologie côtière et une source de matériaux calcaires dans le delta de la rivière Sagavanirktok, provoquent des types particuliers de réaction du sol et de température. Des endroits, à l'abri du vent, dans la rivière montrent des valeurs de pH basiques dans le sol, allant de 7,1 à 8,1, tandis que les endroits à toundras humides, en dehors du passage des vents chargés de loess, ont des valeurs de pH acide allant de 5,3 à 7,0. Les vents affectent aussi le climat local, en soufflant de l'air froid humide et du brouillard vers l'intérieur des terres, dans la partie Ouest du champ d'huile de Prudhoe Bay. La température de l'air est en rapport avec la distance à l'océan; elle était mesurée dans la direction du vent dominant. Les différences de température se reflètent aussi dans l'épaisseur de la tranche de sol actif. Les différences de pH et de température affectent la végétation de la région. Les endroits à sol basique montrent une abondance relative en calciphiles alors que ceux à pH inferieur ont une végétation acidophile. Les températures plus basses de la zone côtière affectent la répartition de beaucoup d'espèces, tout autant que la "phénologie" et la taille de la végétation.
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INTRODUCTION

Along the arctic coast of northern Alaska the winds are consistently from the east to east-northeast. Previous studies by several investigators have shown that these winds result in a variety of effects which have a profound year-round influence on the general ecosystem of the Arctic Coastal Plain. For example, the winds are considered a major cause of the orientation of the thaw lakes which cover a large portion of the coastal plain. These oriented lakes have been described and investigated by several authors (Black and Barksdale, 1949; Hopkins, 1949; Britton, 1967; Rex, 1960; Carson and

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Hussey, 1962; Sellmann *et al.*, 1975; Everett and Parkinson, 1977). Benson *et al.* (1975) and Bilgin (1975) have discussed the effects of the winter winds with respect to the distribution of snow and dust along roads in the Prudhoe Bay region. The winds also affect animal populations, for example caribou seek the cool coastal winds as protection against insects (White *et al.*, 1975). The Inuit have traditionally used wind-caused oriented patterns in the snow called *sastrugi* as an aid in navigation across the flat coastal landscape. This report discusses the wind with regard to its effects on local temperatures and soil pH values in the Prudhoe Bay vicinity and the influence which these factors have on the vegetation of the region.

METHODS

The data cited in this paper have been gathered from 1972-1977 during studies of the vegetation of the Prudhoe Bay region. Soil pH values are for samples from 10 cm depth at 90 permanent study plots. Soil to water ratio for the pH determinations was 1:2.5.

Temperature data at Pad F and Drill Site 2 were recorded on 30 day charts in shelters placed on top of white painted oil drums. The temperatures at Deadhorse and the West Dock were recorded on 30 day charts in standard U.S. Weather Bureau shelters. The ARCO airfield temperatures are from hourly observations by airfield personnel of a thermometer placed in a standard shelter. The shelter installation at West Dock and Deadhorse, the changing of charts, and reduction of data were done in cooperation with the U.S. Army Cold Regions Research and Engineering Laboratories, Hanover, N.H.

PHYSIOGRAPHY AND CLIMATE OF THE PRUDHOE BAY REGION

The Prudhoe Bay oil field is located at 70°15' N and 148°30' W, midway between Point Barrow and the Alaskan-Canadian border. Although a part of the Arctic Coastal Plain, the vegetation and soils of the region are quite different from the better known coastal site at Barrow, Alaska (Britton, 1967, compared with Brown *et al.* (ed.), 1975). Much of the difference is due to the presence of two large gravel-laden rivers. The Sagavanirktok River, which is the largest, is located to the east and has been the source of dunes (Fig. 1) and the calcareous loess which covers much of the region. The Sagavanirktok River has its headwaters in the Brooks Range amidst extensive limestone deposits, which are responsible for the base-rich alluvium in its channels. The Kuparuk River is about 25 km west of the Sagavanirktok River. Although it is smaller and has not been a major contributor to the loess deposits in the region, its old terraces and steeply cut channels provide some of the most interesting and varied landforms within the bounds of the oil field. A third and much smaller river is the Putuligayuk, which is located about midway between the other two. It does not have a braided channel, and its headwaters are on the coastal plain. All three rivers carry alkaline gravel alluvium.

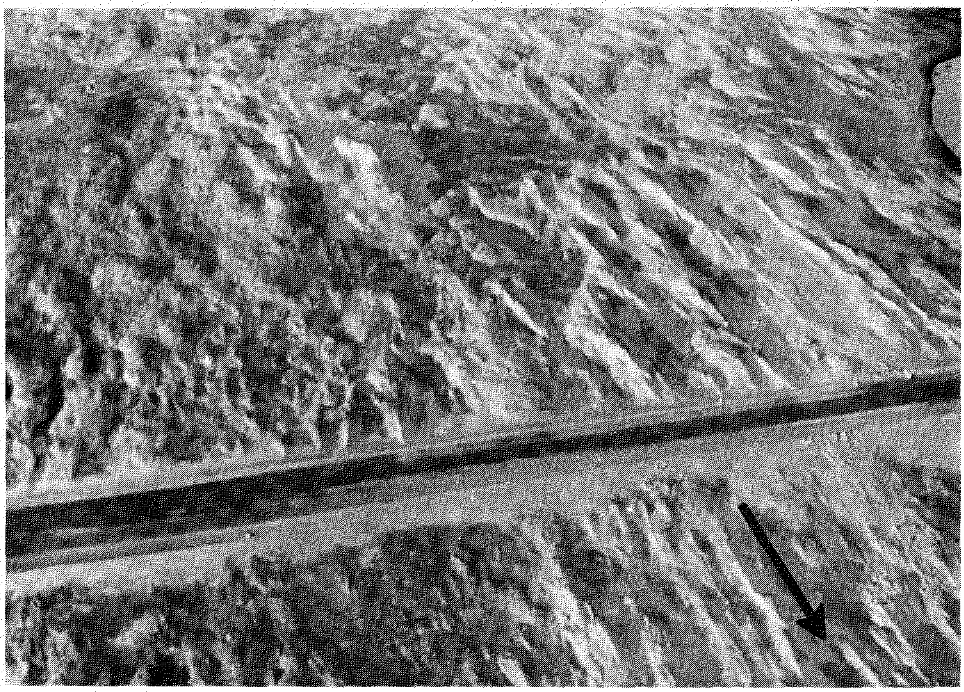

FIG. 1. Sand dunes along a road on the west side of the Sagavanirktok River at Prudhoe Bay. The orientation of the dunes is parallel to the wind direction (arrow).

The river systems and the many oriented thaw lakes account for most of the topographic variations. Typical relief associated with the drained lake basins is about 2 m. More striking relief is associated with pingos, which occur in some drained lake basins and which may reach heights of 15 m in the Prudhoe Bay area. Some river bluffs near the Kuparuk River also have relief of 15 m. Aside from these features, the coastal plain surface is essentially flat. Most variations in the soils and vegetation are controlled by the ice-wedge polygons which cover most of the terrestrial landscape (Everett and Parkinson, 1977). The relief of polygons is generally less than 0.5 m. The flatness of the landscape is important with reference to the winds since there are no major obstacles to alter wind patterns.

Another aspect of the physiography to be considered in conjunction with the winds is the shape of the coastline (Fig. 2). Prudhoe Bay forms a cup-like impression in the coast near the mouth of the Putuligayuk River. East of the bay, the coastline runs north and east to the delta of the Sagavanirktok River. West of the bay, the coastline runs northward toward Point McIntyre. This exposes inland areas west of the Putuligayuk River to the more direct influence of the fog-laden easterly winds of the Beaufort Sea.

The Prudhoe climate has been discussed by Brown *et al.* (1975) and Everett and Parkinson (1977). The severe temperatures (annual mean −13.6°C) have resulted in permafrost to depths of over 650 m (Gold and Lachenbruch, 1973).

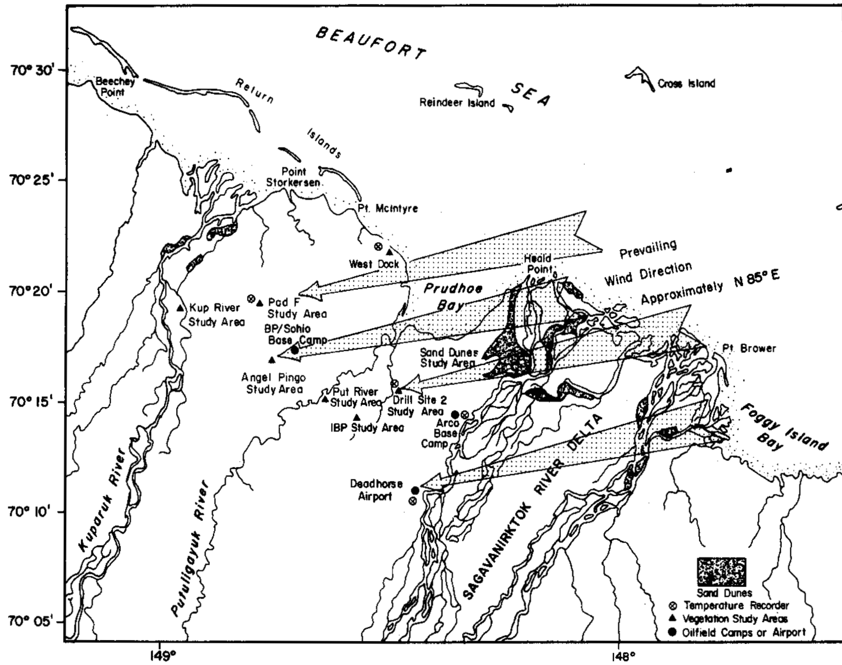

FIG. 2. Direction of the prevailing winds at Prudhoe Bay. The winds affecting the area south of the BP/Sohio Base Camp pass over the delta and sand dunes of the Sagavanirktok River, while areas to the north receive colder winds more directly from the Beaufort Sea. Locations of the main study areas and temperature recorders are also shown.

The climatic summary (Table 1) is based partially on data from Barter Island, which is the closest weather station with available data. Prudhoe Bay and Barter Island have similar weather in most respects. However, Barter Island experiences weather that is somewhat modified by the presence of mountains to the south, resulting in higher wind velocities. Also Barter Island, being closer to the ocean than the ARCO airfield at Prudhoe Bay, experiences more fog and cooler temperatures during the summer.

TABLE 1. Mean monthly coastal climatic data applicable to Prudhoe Bay

	J	F	M	A	M	J	J	A	S	O	N	D	M
Temperature (°C)*	-28.8	-31.5	29.6	-19.4	-5.9	3.0	6.7	6.0	-0.3	-11.9	-20.5	-27.5	-13.0
Precipitation (mm)**	10.2	8.9	5.1	4.3	6.4	13.0	22.4	26.7	23.9	21.3	10.2	7.4	13.3
Total Snowfall (cm)**	15.0	8.1	7.4	6.6	7.9	3.8	1.0	4.1	16.3	24.4	14.5	9.7	9.9
Snowcover (cm)**	40.6	43.2	40.6	38.1	12.7	—	—	—	—	20.3	30.1	33.0	32.3
Wind (m/sec.)*	6.3	6.2	6.0	5.4	5.5	5.1	4.7	5.2	5.8	6.4	6.7	6.2	5.8
Prevailing Wind**	W&E	W&E	W&E	E&W	E	ENE	ENE	E	E	E&W	E&W	W&E	ENE

Sources: Battelle, Columbus Laboratories, unpublished data; U.S. Dept. of Commerce, 1970; Brown, Haugen and Parrish, 1975.

* 1970-1973 means, ARCO

**Barter Island, 1949-1974 means (Source Brower *et al.*, 1977).

Annual precipitation is about 150 mm with much of this coming during the summer months. The mean April snow depth is about 40 cm (K. R. Everett, 1977, pers. comm.).

The summer winds at Prudhoe Bay are predominately from the east to east-northeast. This is in contrast to the winter when storm winds often occur from the west (Benson *et al.*, 1975). Moritz (1977) has discussed the summer coastal wind patterns with reference to synoptic-scale weather systems and has indicated the consistent summer wind directions at the coast may be due in part to a sea-breeze effect. Walsh (1977), predicted a sea breeze when the gradient wind is directed offshore at a speed less than about 14.4 km/hr.

THE INFLUENCE OF WIND ON SOIL ACIDITY

In the Prudhoe Bay vicinity there are large areas of wet tundra where the soils have alkaline pH values. Alkaline lowlands have also been noted in several other arctic regions. The upper Firth River valley on the Alaskan-Canadian border (Drew and Shanks, 1965) receives calcareous runoff from a steep limestone outcrop above the river. A similar situation occurs below Sukakpak Mountain near the Dietrich construction camp on the Trans-Alaska pipeline. At Lake Ayan in west-central Siberia, runoff containing gypsum (calcium sulphate) from volcanic rocks creates high pH values in wet *Carex aquatilis* meadows (Webber and Klein, 1977). Sjörs (1959) attributed the extensive calcareous fens in the Hudson Bay lowlands along the Attawapiskat River in Ontario to mineral ions that are somehow acquired from deeper strata and then percolated through the fens. Undoubtedly, conditions similar to those at Attawapiskat River can be found elsewhere in the North American Arctic where there are large expanses of terrain underlain by calcareous deposits. At the sites mentioned above, the soils are able to maintain high pH values because of the flow of mineral-rich water draining across the surface. A complicated mosaic of bogs and fens often results when some sections of the peatland build up organic material until eventually they become raised bogs. Such bogs must rely totally on rainwater for moisture and minerals. The peats in these areas usually consist of *Sphagnum* moss and are acidic due to the accumulation of organic acids. In some situations where wet peats or tundra soils develop on limestone or other calcareous parent material, only the upper soil horizons are acidic. This is true at Cape Thompson, Alaska (Holowaychuk *et al.*, 1966) and the Truelove Lowland, Devon Island (Walker and Peters, 1977). Tedrow (1977) states that surface horizons in tundra soils are often as much as two pH units higher than the C horizon due to leaching and organic accumulation.

At Prudhoe Bay the mineral input is via aeolian materials; the soil profiles therefore have high pH values in all horizons. This was noted by Everett and Parkinson (1977) at Prudhoe Bay, and by Drew (1957, cited in Tedrow, 1977) in areas further south along the Sagavanirktok River. In the eastern part of the Prudhoe Bay region there is a large expanse of terrain where the soils are alkaline on all microsites. Near Drill Site 2 (Fig. 2) the soil pH values range only between 7.4 and 7.8. This is for 20 samples from widely diverse microsites including the side of a dry pingo, moist upland tundra, snowbanks, polygon rims, low polygon centers, small ponds, and the margins of larger lakes. The highest pH values in the Prudhoe Bay region are found in the vicinity of the sand dunes just west of the Sagavanirktok River. The dunes themselves have pH values ranging from 8.1 to 8.4, and wet peats in the immediate vicinity of the dunes have values consistently above 7.6. Toward the west, the mean pH values tend to decrease as shown in Figure 3. The range of pH values, however, increases toward the west. This is reflected in the standard deviations shown in Figure 3. Toward the west the decreased input of alkaline loess allows the wet sites to become more acid, whereas the dry sites are consistently alkaline throughout the entire region due to the influence of calcareous parent material. Parkinson (1977) discussed the pH gradient across the region and showed an inverse relationship between the calcium carbonate equivalents and the percentage of organic carbon. Wet sites in the western portion of the region have higher percentages of organic carbon and lower percentages of carbonates.

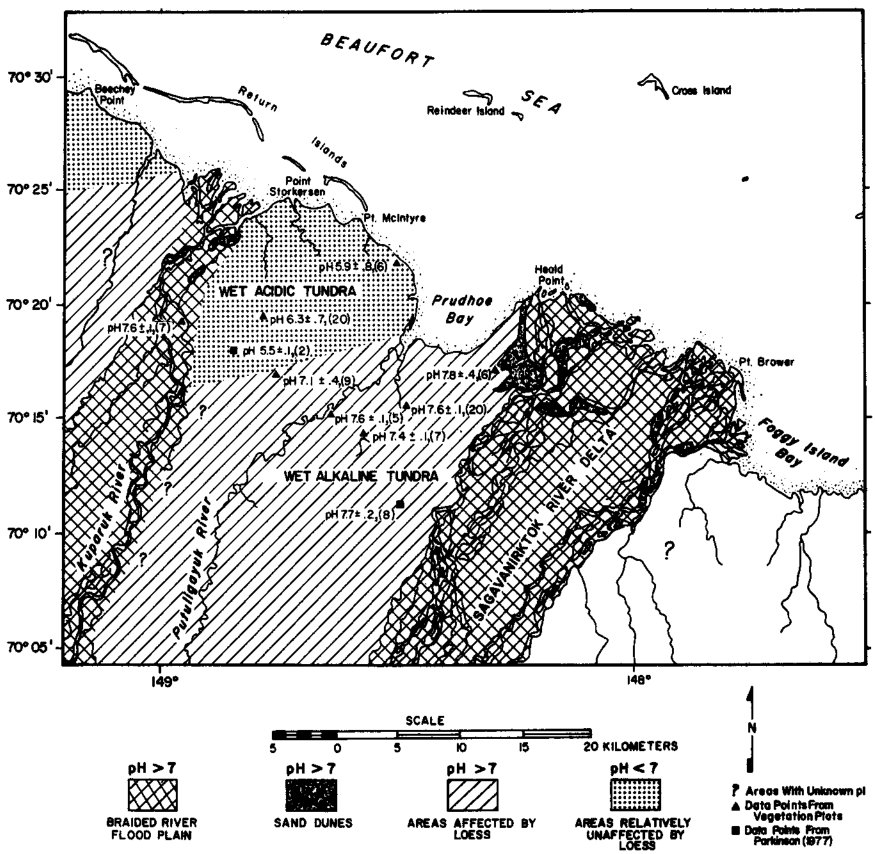

FIG. 3. Map showing the mean pH values for the top 10 cm of soil at the major study areas. The boundary between the wet acidic tundra and the wet calcareous tundra is drawn parallel to the wind direction and extends from the northernmost reaches of the Sagavanirktok River delta. Values are expressed as mean ± standard deviation, (no. of samples).

Figure 3 shows a region that is outside the influence of the loess. This area is labelled "wet acidic tundra." It is acidic because the winds which reach this area have come directly from the ocean and have not picked up calcareous silts and sands from the Sagavanirktok River region. The boundary between the "wet acidic tundra" and the "wet alkaline tundra" was determined by drawing a line from the northernmost tip of the Sagavanirktok River delta parallel to the direction of the wind. The orientation of the sand dunes at the mouth of the Sagavanirktok River and the short axis of the oriented thaw lakes in the region indicate that the wind direction is N85°E. Areas north of the boundary have acidic soils in moist to very wet microsites whereas sites to the south have alkaline soils. There are exceptions to this. At the Angel Pingo site (Fig. 2) the pH values in wet locations are very close to 7.0. This may be the approximate westward limit of basic soils in wet areas. The map shows question marks in the area west of the Angel Pingo site denoting the possibility of a western boundary for the area of wet alkaline tundra. The map (Fig. 3) also has a loess boundary west of the Kuparuk River. This boundary is drawn with reservations because the Kuparuk River is much smaller than the Sagavanirktok River, and the dunes and the gravel channel of the Kuparuk River, which would be the primary sources of loess, are much smaller than those associated with the Sagavanirktok River.

THE INFLUENCE OF WIND ON LOCAL TEMPERATURES

At Prudhoe Bay and all along the arctic coast there is a steep temperature gradient due to the proximity of the frozen Beaufort Sea. This gradient has been studied by Johnson and Kelley (1966), Clebsch and Shanks (1968), and Brown *et al.* (1975). The effects of the gradient on the vegetation are particularly striking. The summer temperatures near the coast are rarely much above freezing, and slight differences in the annual number of degree days above freezing can have an important effect on plant growth and the species which are found in a given area. This has been discussed in detail by Young (1971) who has divided the Arctic into floristic zones where the number of species that one can expect to find in a given area can be fairly well predicted by the summer temperature regime.

Within the Prudhoe Bay oil field there is considerable local variation in summer temperatures. There is a stronger coastal influence in the western part of the region, that can be understood by reference to Figure 2 which shows that the area west of the Putuligayuk River is more directly influenced by the cold winds from the Beaufort Sea. During the 1977 field season surprisingly shallow depth of thaw was noticed at the coast and in the Pad F vicinity. The thaw at Pad F in late July was only 26 ± .50 (standard error) cm which compared to 22 ± .53 cm at the coast and values above 33 cm for three other inland stations within the Prudhoe Bay region. Table 2 shows a similar pattern in 1977. Another indicator of the coastal influence is fog, which is often encountered west of the British Petroleum/Sohio (BP/Sohio) base camp when much of the rest of the road network is in sunshine. The fog also affects the temperature by decreasing the incident solar radiation.

Temperature data from five Prudhoe sites for July, 1977, indicate that the temperatures are correlated with the distance to the coast measured along the vector of the prevailing wind direction (Table 2). Near the coast the temperature gradient is very steep with higher temperatures occurring inland. The thaw measurements (Table 2) show a similar trend. The thaw values,

TABLE 2. Mean July temperature 1976 and 1977 and the distance to the coast measured via the shortest route and via the direction of the prevailing wind vector (N85°E) for five sites at Prudhoe Bay, Alaska. (Unpublished temperature data from USA/CRREL, 1978.)

	Mean July Temperature		Mean Thaw July 25, 1977	Distance to the Coast	
Site	1976	1977	($X \pm$ S.E., N = 100)	Via Shortest Route	Via Wind Direction
West Dock	4.1°C	2.6°C	21.2 ± .55 cm	.5 km	.8 km
Pad F	5.4	4.2	26.9 ± .59	6.8	10.0
ARCO	6.8	5.5	N.D.	5.6	20.7
Drill Site 2	N.D.	4.2	29.3 ± .61	4.4	18.3
Deadhorse	7.3	8.0	29.9 ± .71	12.0	25.0

however, can only be used to roughly compare the temperature regimes at the four sites because of different relative amounts of organic matter in the soils. Soils to the east have higher components of mineral matter due to the influence of loess and could consequently be expected to have relatively deeper thaw. R. K. Haugen and P. Keleman (pers. comm. 1978) have shown that temperatures at sites as far inland as Umiat are also closely correlated to the distance to the coast measured in the direction of the N85°E wind vector. They have shown that the July 1977 temperatures at 11 North Slope stations are correlated according to the regression equation:

$$\text{Estimated 1977 July Mean Temperature} = 2.5 \times (\text{Distance to coast along N85°E vector})^{0.26}$$

In this equation $R^2 = 0.92$, standard error of estimate = 0.89°C. All the Prudhoe Bay sites except Deadhorse lie very close to the line for this equation. Haugen and Keleman (pers. comm. 1978) feel that the Deadhorse temperatures are somewhat anomalous due to a gravel airport runway which lies immediately upwind from the thermograph.

VEGETATION RESPONSES TO THE DIFFERENCES IN SOIL ACIDITY AND TEMPERATURE

The vegetation in the region has been studied by numerous botanists. Nieland and Hok (1975) and Webber and Walker (1975) have partially characterized the vegetation communities. A fuller description of the region is forthcoming in a comprehensive treatment of the soils, landforms, and vegetation (Walker *et al.*, in press). Several taxonomists have also visited the region and made important observations regarding the local flora (Rastorfer *et al.*, 1973; Murray and Muray, 1975; Murray, in press; Steere 1976). The very calcareous nature of much of the wet tundra landscape has been noted by several authors (Bilgin, 1975; Everett and Parkinson, 1977; Parkinson, 1977;

Murray, in press; Steere, in press). In wet areas at Prudhoe Bay there is often a surface deposit of carbonates that covers most of the mosses and litter materials. Small ponds and water-filled thermokarst pits often have such thick deposits that the growth of sedges and mosses is severely hampered or prevented. There is an abundance of plants which show preference for calcium-rich environments. For example, *Dryas integrifolia* M. Vahl and *Saxifraga oppositifolia* L., two plants considered to be calciphiles over much of their range of distribution (Sørenson, 1941; Porsild, 1957; Bamberg and Major, 1968), are ubiquitous on all moist and dry microsites in the region of alkaline tundra at Prudhoe Bay. Steere (in press) has commented on the abundance of calciphilous mosses such as *Scorpidium scorpioides* (Hedw.) Limpr., *Drepanocladus lycopodioides* (Brid.) Warnst., and *Catascopium nigritum* (Hedw.) Brid. He also noted the absence of *Sphagnum* and several other common acidiphilous tundra mosses.

Several plants show obvious differences in their abundance in the regions of alkaline and acidic tundra. A few examples are listed in Table 3. Not all the

TABLE 3. List of several species showing preference for either the region of alkaline tundra or the region of acidic tundra.

	Preference	
Species*	Wet Acidic Tundra	Wet Alkaline Tundra
Vascular plants:		
Carex rariflora (Wahlenb.) J. E. Sm.	X	
Carex subspathacea Wormskj.	X	
Salix planifolia Pursh ssp. *pulchra* (Cham.) Argus	X	
Saxifraga foliolosa R. Br. var. *foliolosa*	X	
Vaccinium vitis-idaea L. ssp. *minus* (Lodd.) Hulten	X	
Carex atrofusca Schkuhr.		X
Casiope tetragona (L.) D. Don ssp. *tetragona*		X
Chrysanthemum integrifolia Richards		X
Dryas integrifolia M. Vahl.		X
Equisetum variegatum Schleich.		X
Polygonum viviparum L.		X
Salix lanata (L.) ssp. *richardsonii* (Hook.) Skvortsov		X
Saxifraga oppositifolia L.		X
Bryophytes:		
Dicranum elongatum Schleich. *ex* Schwaegr.	X	
Pogonatum alpinum (Hedw.) Roehl. var. *Septentrionale* (Brid.) Brid.	X	
Ptilidium ciliare (L.) Hampe	X	
Catoscopium nigritum (Hedw.) Brid.		X
Cinclidium latifolium Lindb.		X
Drepanocladus lycopodioides (Brid.) Warnst. var. *brevifolius* (Lindb.) Moenk.		X
Meesia triquera (Richt.) Angstr.		X
Scorpidium scorpioides (Schimp.) Limpr.		X
Lichen:		
Ochrolechia frigida (Sw.) Lynge form *telephoroides* (Th. Fr.) Lynge	X	

*Nomenclature according to Hulten (1968), Crum *et al.* (1973) and Hale and Culberson (1970).

plants in the table are responding to variation in hydrogen ion concentrations. Some could very reasonably be responding to other factors such as temperature or variations in salt and nutrient concentrations (e.g., *Carex subspathacea*). The vegetational differences between the two regions are, nonetheless, distinct.

The temperature regimes have a particularly important effect on the vegetation. Table 4 shows the thaw degree-days for July and August at the

TABLE 4. Thaw degree days at five Prudhoe Bay temperature stations. Data are from Haugen and Keleman (1978, pers. comm.).

		Thaw Degree Days*		
Station	Year	July	August	Σ
West Dock	1976	128	131	259
	1977	93	138	231
Pad F	1976	167	127	294
	1977	131	200	331
Drill Site 2	1977	135	221	356
ARCO	1976	211	204	415
	1977	171	254	425
Deadhorse	1977	237	305	542

*Thaw degree days is the sum of all mean daily temperatures above 0°C.

five Prudhoe Bay temperature stations. The rather remarkable differences in the amount of available summer warmth are reflected in the phenology of the plants. Early season development is much delayed at the coast compared to the other stations. In 1975 the first flowering of *Pedicularis lanata* Cham. and Schlecht. ssp. *lanata* and *Saxifraga oppositifolia* were observed to occur several days later at the coast than at any of the other sites. The growth forms of plants are also affected by the temperature regimes. Many herbaceous species are noticeably shorter at the coast than they are a few kilometers inland, and all the willow species at the coast are prostrate. Inland, within the oilfield boundaries, *Salix lanata* ssp. *richardsonii* sometimes reaches heights exceeding 25 cm, but such stature usually occurs only with the protection of deeper snow along some of the tundra streams. Further south, at Franklin Bluffs, which is 71 km from the coast via the shortest route and 125 km via the wind direction, there are several species of erect willows which reach heights of over 2 m in protected sites.

Many other site factors besides pH and temperature are also influenced by the winds. Variation in the percentages of organic carbon and several soil nutrients can be attributed to the direct effects of loess deposition, and these in turn affect an array of other factors such as depth of thaw, water availability, and cation availability. A great deal of soil and vegetation data has been gathered along the loess-temperature gradient, and the indirect ordinations of this data (sensu Whittaker, 1967) will provide further insights to this complex situation.

SUMMARY

Investigations of the vegetation, soil, and climatic characteristics in the Prudhoe Bay region indicate that the winds play an important role with respect to local variations of these characteristics. Thaw depth and temperature data from several sites show that there are major differences in the amount of warmth available to the plants in different parts of the region. The temperatures are correlated with the distance to the coast along the wind vector. The wind is also responsible for the transport of calcareous sands and silts from the braided channel of the Sagavanirktok River over a large area downwind from the river. This loess soil has high pH values (7.1 to 7.8) in moist to very wet microsites, whereas areas which are relatively unaffected by loess have acidic pH values (5.3 to 7.0) in similar wet microsites. A region of wet acidic tundra which lies north of a more extensive region of wet alkaline tundra. There are very noticeable differences in the composition of plant communities in these two regions.

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