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Wind chill factor applied to Patagonian climatology

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> «Les vents que chassent, à travers une échancrure de la Cordillère des Andes, les hautes pressions du Pacifique, s'étranglent et s'accelèrent dans un étroit couloir de cent kilomètres de front, en direction de l'Atlantique, et raclent tout sur leur passage».
>
> Antoine de Saint-Exupéry
> «Un sens à la vie» (1956)

Abstract. The wind cooling effect determines wind chill equivalent-temperatures, which may be rather different to actual temperature. In a windy region such as Patagonia, this difference may reach a magnitude and persistence to become an important bioclimatic element. This paper quantifies the wind cooling effect in Patagonia by the presentation of equivalent isotherms as an adaptation of the usual isotherm maps to the regional bioclimatic environment. It is concluded that due to seasonal variations in wind speed, the annual equivalent temperature range is smaller than the actual temperature range, thus increasing oceanic features, from a thermal viewpoint, of the Patagonian climate.

Key words: Patagonia – Bioclimatology – Wind cooling effect – Maritimity

1 Introduction

Patagonia located in the southernmost extremity of America lies over the latitudes 40° S and 58° S (Fig. 1), wholly in the planetary band where "there is a great prevalence of westerly surface winds, known to the old sailing ships as the Brave West Winds. The strength of these winds in latitudes 40–60° S ... gave rise to the names Roaring forties and Screaming fifties" (Lamb 1972). Being the sole continental mass situated within this zone, it justifies the assertion of Prohaska (1976) included in the World Survey of Climatology (vol 12): "In few parts of the world is the climate of the region and its life so determined by a single meteorological element, as is the climate of Patagonia by the constancy and strength of the wind". Despite this statement, no work has been done concerning wind chill in Patagonia. Although wind strength indications are numerous in Patagonia, such as wind erosion, leeward-sided trees or architectonic details, inclusion of wind chill data in meteorological reports is recent and still relatively scarce.

The influence of wind in the perception of temperature is well known; the first mathematical formulations of the subject were done in 1945 by Siple and Passel; since then, several modifications led to tabulation of wind chill factor and wind speed. In Argentina, Knoche and Borzacov (1947) referred to "effective" or "sensible temperature" as a climatic element. However, the first attempt in assessing and considering wind chill as a bioclimatic factor was performed by Hoffmann and Medina (1971), who, nevertheless recognized that results from Patagonia were unsatisfactory. Hoffmann and Núñez (1981) in their Bioclimatic Map of Argentina, indicate for the whole Patagonian region (except its northeastern extremity and Tierra del Fuego) that the wind makes the different bioclimatic zones go down to a level immediately colder, i.e. a decrease of 3 to 5° S in maximal temperatures. Tuhkanen et al. (1990) consider that "the prevalence of the strong westerly winds in combination with chillness is undoubtedly the most unpleasant feature in the climate of Tierra del Fuego, and at the same time an important plant-ecological factor".

This paper aims to define the influence of the wind in Patagonia as related to wind chill. Like any other results given in isolines, the data are merely indicative average values. The main difficulty found is the sparse database of reliable wind records; because of this and the nature of the wind, it is not possible to give detailed maps of the distribution of equivalent temperatures in Patagonia, but most of the main features are clearly depicted.

Materials and methods

Data of mean seasonal wind speed were taken from the "Atlas del potencial eólico del sur argentino" (Barros 1986), from World Survey of Climatology (Miller 1976; Prohaska 1976) for Chilean sites and from Clark and Wilson (1992) for Stanley (Malvinas Islands). The data were reduced to 1.5 m above ground level in order to obtain bioclimatic representative values. Equation 1 was used in this reduction, where the height of the obstacle was averaged at 0.20 m, according to the grasses covering most of the area. Wherever possible data were compared to those of the Servicio Meteorológico Nacional (SMN 1986) with no significant differences. Some other isolated series published by MESOP-Chubut (Mattio and Schlishting 1984) and the Instituto de la Patagonia, Punta Arenas, Chile (Zamora 1977) were also considered. Temperature data are taken from series 1971–1980 (SMN 1986) for Argentine sites, and from the above-mentioned Chilean sources. The locations of the stations where temperature and wind data were gathered are shown in Fig. 1. The annual mean wind speed and mode values are listed in Table 1.

Temperature data were averaged for 3 month values in order to obtain agreement with the wind speed data. Summer value is the mean temperature of the Dec.–Jan.–Feb. trimester and winter value is the mean temperature of the Jun.–Jul.–Aug. trimester. Therefore the annual temperature range calculated from these data is slightly smaller than the temperature ranges usually obtained as the difference between July and January temperatures.

Calculation of wind cooling power was carried out by using Siple and Pasel's formula (Eq. 2), which evaluates wind chill index (WCI) based on temperature and wind speed. As it includes a qua-

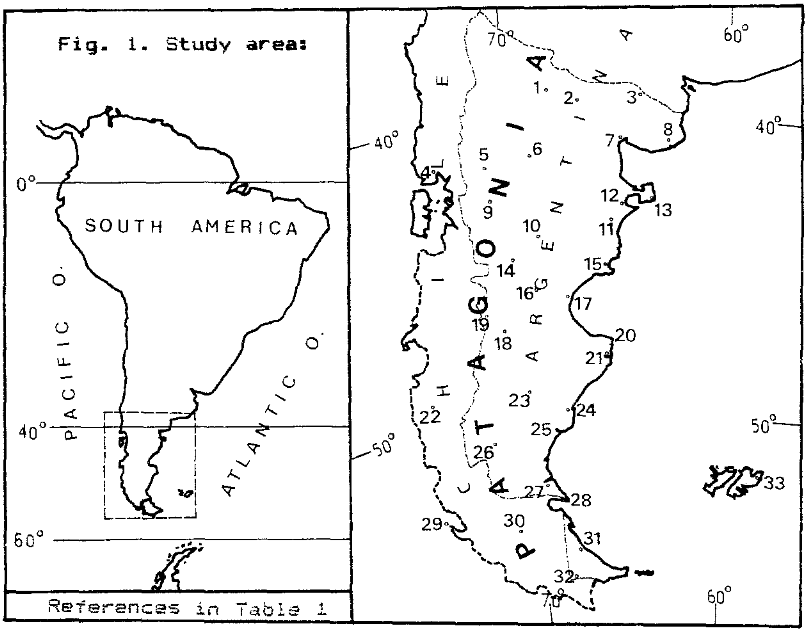

Fig. 1. Location of study area and sites of the meteorological stations for recording of temperature and wind speed data

Table 1. Meteorological stations and wind speed values

No.	Station	Wind speed[a]			No.	Station	Wind speed[a]		
		Mean	Mode	Source[b]			Mean	Mode	Source[b]
1	Neuquen	2.5	1.2	1	17	Comodoro R.	4.9	3.0	1
2	Choele-Choel	2.8	1.5	1	18	Pto. Moreno	6.4	3.1	1
3	Rio Colorado	2.8	1.4	1	19	Media Luna	4.4	2.7	3
4	Pto. Montt	2.1	–	2	20	Cabo Blanco	3.2	–	1
5	Bariloche	4.8	2.9	1	21	Pto. Deseado	3.8	2.8	1
6	Maquinchao	2.2	–	1	22	San Pedro	3.6	–	2
7	San Antonio	2.8	2.0	1	23	Gob. Gregores	4.9	2.7	1
8	Viedma	3.7	–	1	24	San Julian	4.5	2.8	1
9	Esquel	3.8	2.4	1	25	Santa Cruz	4.2	–	1
10	P. de Indios	3.3	1.6	1	26	Calafate	2.2	–	1
11	Trelew	3.7	2.1	1	27	Rio Gallegos	4.1	2.6	1
12	Pto. Madryn	2.4	1.0	1	28	C. Virgenes	3.3	1.8	1
13	Pta. Delgada	2.3	1.1	1	29	Evangelistas	6.2	–	2
14	Gob. Costa	2.8	1.0	1	30	Pta. Arenas	3.5	–	2
15	Camarones	3.8	2.6	1	31	Rio Grande	3.6	2.2	1
16	Sarmiento	4.8	–	3	32	Ushuaia	2.8	1.3	1
					33	Pto. Stanley	3.8	–	4

[a] Annual value in m/s (reduced to 1.5 m above ground level)

[b] 1, Barros 1986; 2, World Survey of Climatology (Prohaska 1976; Miller 1976); 3, Mattio and Schlishting 1984; 4, Clark and Wilson 1992

Table 2. Comparison of seasonal direct and indirect WCI for Puerto Madryn (series 1982–1989)

	Wind speed (m/s)	Temperature	IWCI	DWCI	IWCI′	Δ(%)	Equivalent temperature (E)(°C)		
							E(DWCI)	E(IWCI′)	Δ° C
Spring (S, O, N)	4.37	12.9	542.4	513.3	517.4	0.8	9.3	9.1	0.2
Summer (D, J, F)	4.92	19.3	379.6	359.9	365.9	1.7	15.9	15.7	0.2
Fall (M, A, M)	4.05	13.0	530.5	506.1	506.3	0.0	9.6	9.6	0.0
Winter (J, J, A)	3.96	6.9	688.8	651.6	653.5	0.3	3.3	3.2	0.1

IWCI, Indirect wind chill index; DWCI, direct wind chill index; IWCI′, corrected indirect wind chill index

dratic term, Eq. 2 is normally considered unsuitable for the calculation of mean WCI from average temperature and wind speed values issued from widely scattered data. Nevertheless Patagonia has a thermal regime described as "definitely maritime" (Walter and Box 1983) and "wind velocities exhibit small but distinct temporary changes" (Prohaska 1976). In order to test the applicability of Eq. 2 to mean values of temperature and wind speed existing in Patagonia, a methodological verification was done.

Balafoutis (1989) asserts that the mean monthly values conceal the real conditions due to a high frequency of calm conditions, which reduces the mean wind speed values. Nevertheless in the study area, the calm frequency is quite low: 16.8% for a mean of 30 stations situated south of latitude 40° S. For this series, mean annual wind speed (1.5 m high) is 3.7 m/s, ranging from 2.1 to 6.4 m/s; however, all the data but two range between 2.1 and 4.8 m/s. On the other hand, the mean monthly temperatures vary between 0 and 22° C.

Regarding these limited conditions of temperature and wind speed found in Patagonia, calculation of 66 WCI values was carried out by employing Eq. 2 within a 0–25° C temperature range and 2–5 m/s wind speed range. With the results a multiple linear regression was performed, and found to fit the straight line defined by equation (3). Although this equation was not employed in this paper for WCI calculation, its linearity justifies working with mean temperature and wind speed data, within the range mentioned above.

Further verification was done employing a quite extensive archive of hourly temperature and mean wind speed data (series 1982–1989) recorded in Puerto Madryn (42° 40′ S; 65° 00′ W) by means of a climatronic of the Centro Nacional Patagónico (National Research Council of Argentina). Hourly WCI values were calculated by means of Siple and Passel's formula, and the 7-year hour-to-hour temperature and wind speed data set. Thus, each hourly (0–24 h) WCI value is the average of about 210 instantaneous WCI values. Separately, the hour-to-hour temperature and wind speed data were averaged in order to obtain hourly (0–24 h) values, based on which a new calculation of hourly WCI values was performed using the same formula.

In that way, two series of 288 hourly WCI values were obtained, the first one by *direct* calculation of instantaneous WCI values (DWCI), and the second one by *indirect* calculation of WCI (IWCI) from the average of temperature (T) and wind speed (W) data, as follows:

$$\begin{array}{llll} T_1; & W_1 & \Rightarrow \mathrm{WCI}_1 & \\ T_2; & W_2 & \Rightarrow \mathrm{WCI}_2 & \\ \cdot & \cdot & & \\ T_n; & W_n & \Rightarrow \mathrm{WCI}_n & \\ \hline \bar{T} & \bar{W} & \mathrm{D\bar{W}\bar{C}I} & \text{direct WCI} \\ \bar{T} * & \bar{W} & \Rightarrow \mathrm{I\bar{W}\bar{C}I} & \text{indirect WCI} \end{array}$$

Using DWCI and IWCI values a regression analysis was made and a straight linear correlation was found ($R^2 = 0.99$). The equation of the fitted line is given as Eq. 4 below. The two-sample analysis showed a significance level of 0.049.

The goodness of fit of WCI values calculated from the average data of temperature and wind speed (IWCI) allowed the calculation of mean monthly and 3-month wind chill values. In Puerto Madryn, seasonal WCI was calculated both directly by averaging hourly wind chill data, and indirectly using mean 3-monthly values of temperature and wind speed. Then, IWCI was transformed to IWCI′ using Eq. 4; the results of this transformation are shown in Table 2. The greater error Δ(1.7%) was considered acceptable in relation to the scale used; moreover the differences lessen when WCI is converted to equivalent temperature (E); with these units, the greater difference found by comparing both methods was 0.2° C. Conversion of WCI to equivalent temperature was done using equation (5), deduced from the table of National Oceanic and Atmospheric Administration (1980).

As may be seen in Table 2, IWCI values are always higher than DWCI values (according to the long 288 data series). That is because in most of Patagonia the mean wind speed is higher than the mode value (Table 1), as can be seen in the Weibull-II distributions presented by Barros (1986). In one sense, this phenomenon is just the opposite to the assertion of Balafoutis (1989) that mean values conceal the real conditions. In Patagonia, the mean wind speed values overestimate the real conditions. Even if the more frequent wind speed values are not high: 2.2 m/s at 1.5 m level (average for the entire region), calm conditions are scarce.

Taking into account the results achieved with the data for Puerto Madryn, the same methodology for the calculation of WCI was employed at all other sites. With the values thus obtained, the different isoline maps were drawn. As has already been stated, these results must be viewed with regard to the limitations inherent in the methodology and in consideration of the dependence on topographic effects of an element such as wind.

Equations used:

(1) (from Sellers 1965, with modification).

$$Wx = Wr\,\frac{\ln(x/z)}{\ln(r/z)}$$

Wx = wind speed at height X (m/s)
Wr = wind speed recorded (at height r)
z = roughness parameter of surface;
the height at which velocity is zero (m)

(2) (Siple and Passel 1945) (from Rosenberg et al. 1983)

$$\mathrm{WCI} = (10\sqrt{W} + 10.45 - W)(33 - T)$$

WCI = cooling power index (kcal/m^2 per h)
W = wind speed (m/s)
T = air temperature (°C)

(3) Multiple linear regression of WCI (from 2 to 5 m/s and 0 to 25° C)

$$\mathrm{WCI} = 40.84\,W - 25.1\,T + 691.6 \qquad R^2 = 0.99$$

WCI = cooling power index (kcal/m^2 per h)
W = wind speed (m/s)
T = air temperature (°C)

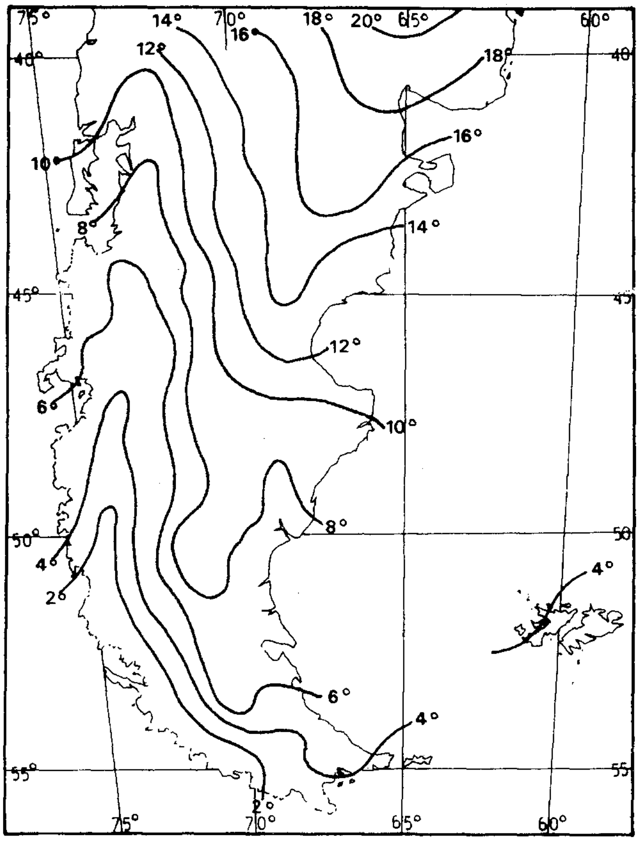

Fig. 2. Summer equivalent-isotherms

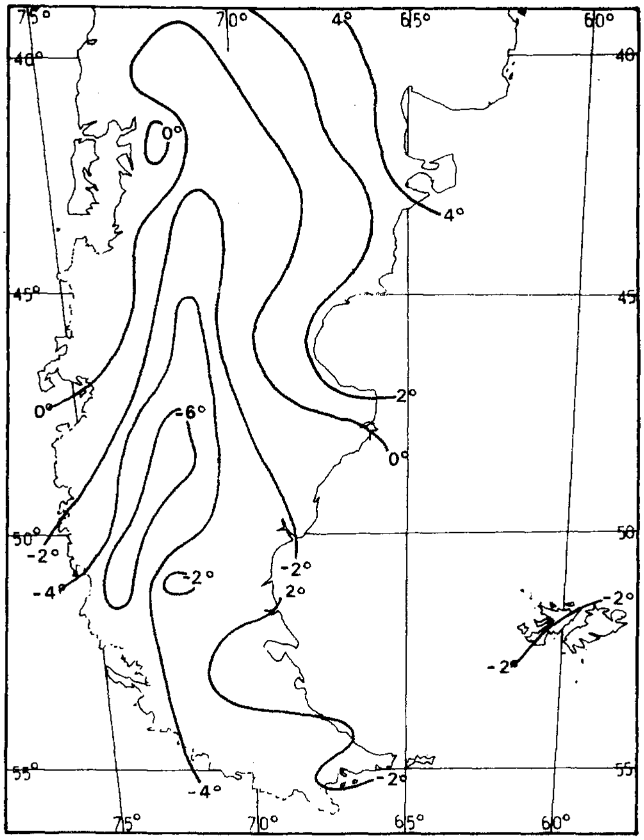

Fig. 3. Winter equivalent-isotherms

(4) Corrected indirect WCI (IWCI′)

$IWCI' = 0.93\,IWCI + 12.93 \qquad R^2 = 0.991$

(5) Conversion of WCI to equivalent temperature (deduced from NOAA 1980)

$E = -0.0432\,WCI + 31.46$

E = equivalent-temperature (°C)
WCI = cooling power index (kcal/m^2 per h)

[to convert kcal/m^2 per h to W/m^2 (S.I.) multiply by 1.16]

Results and discussion

In all Patagonia eastward to the Andes Cordilleras, wind speed is higher in summer than in winter, varying from 4.4 to 3.5 m/s, for a mean of 20 extra-Cordilleran sites. Because of this, the wind cooling effect is also greater in summer (4.7 versus 3.6° C; mean of 20 sites). For this reason, the Patagonian climate is perceived as being even cooler than it is. Summer and winter equivalent-isotherms are shown respectively in Figs. 2 and 3. The difference among these equivalent-isotherms and the homologous actual isotherms, i.e. summer and winter wind cooling, is shown in Figs. 4 and 5.

A comparison of Figs. 4 and 5 allows some distinction between summer and winter cooling, although the shape of the isolines is, in both cases, quite similar. Curve expansion is maximal over a zonal band between 45 and 50° S, in agreement with the assertion: "... the zone in which wind speed is highest ... is a band over 49° S" (Barros 1986). The lowest cooling effects are found in both extremities of the region: northeast and Tierra del Fuego, coincidentally with the bioclimatic map of Hoffmann and Núñez (1981), although disregarding the fact that annual mean wind chill in these areas may reach 3° C.

Although in both extreme seasons the isolines are similarly shaped, summer values are higher everywhere eastward to the cordilleras and the area enclosed by homologous isolines increases noticeably. Even in summer, there is an 8° C cooling secondary maximum, centered eastward from the Andes, between 45 and 47° S. Throughout the year, the highest cooling effect is found along the Pacific coast of the Magellanic archipelago, between 50 and 52° S. This area is considered by Tuhkanen (1987) as the world's extreme case of oceanity in a temperate climate. Further east, the cooling effect lessens markedly due to the sheltering effect that decreases with distance from the Andes (Tuhkanen et al. 1990).

Figure 6 presents overlaps of both the temperature annual range and the equivalent-temperature annual range. The dashed area enclosed between two homologous isolines indicates a rise of oceanity within a thermal setting. It can be observed that such an increase is greater along a meridian axis (69 to 71° W), midway from one ocean to another. For this reason wind speed variations (i.e. wind chill variation) between summer and winter

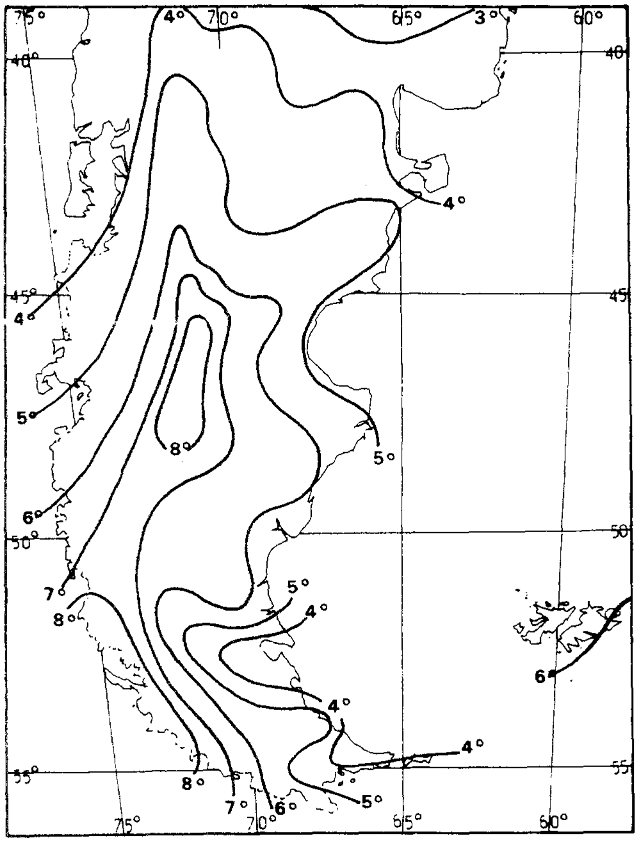

Fig. 4. Wind cooling effect (Summer)

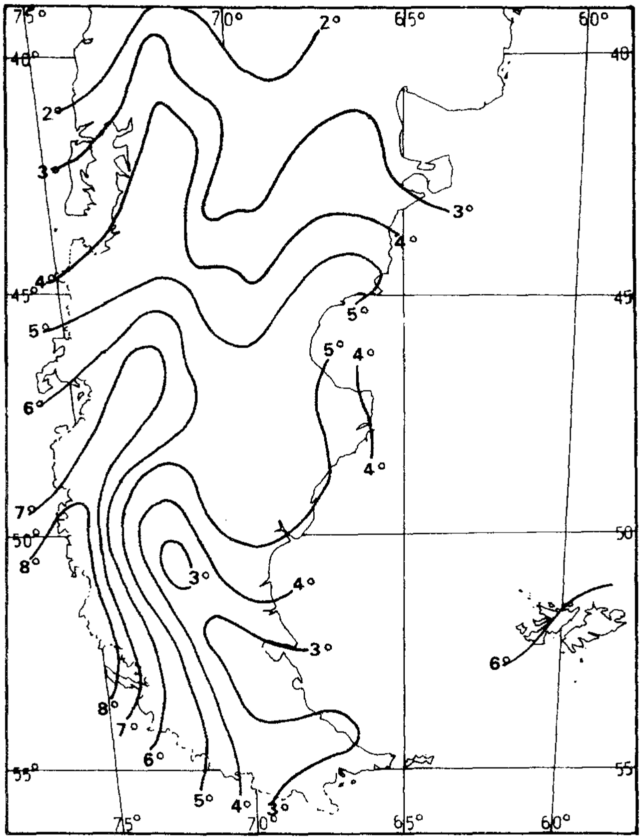

Fig. 5. Wind cooling effect (Winter)

Table 3. Mean wind speed (m/s) at 1.5 m above ground level: average of 9 coastal sites and 7 inland sites (series 1978–1985)

Area	Summer	Winter	Year	Variation
East coast	4.6	4.1	4.3	12%
Inland	4.1	2.8	3.5	46%
Whole extra-Andean region	4.4	3.5	3.9	26%

are greater inland than on the coast, as shown in Table 3. Beyond the four isolines drawn in Fig. 6, the phenomenon must be understood as a continuum, which tends to efface the differences among seasons and between coast and inland.

Conversely on the Pacific coast as mentioned above, winter wind speed and therefore also wind chill is higher; thus there is a slight increase in the equivalent-temperature annual range. In spite of an apparent decrease in maritimity, the climate remains highly oceanic because the annual temperature range is narrow ("super-oceanic"; Tuhkanen 1987). In this area, the isolines of the equivalent-temperature range are situated southward to those of the temperature range. Figure 7 shows isolines assessing the differences between the actual annual temperature range and the equivalent-temperature range, i.e. the apparent decrease of continentality. Highest values are found in central Patagonia, in the crossing of the

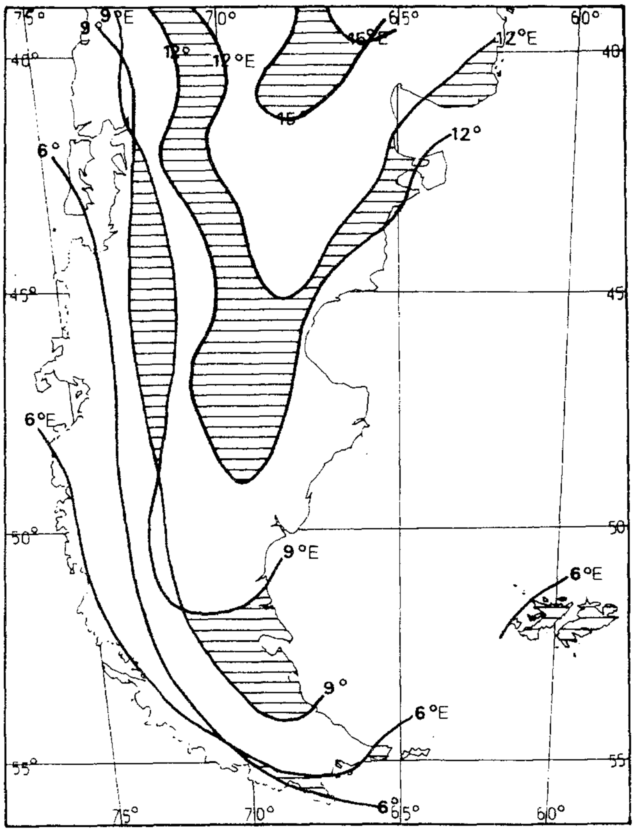

Fig. 6. Annual range of temperature and equivalent-temperature (E)

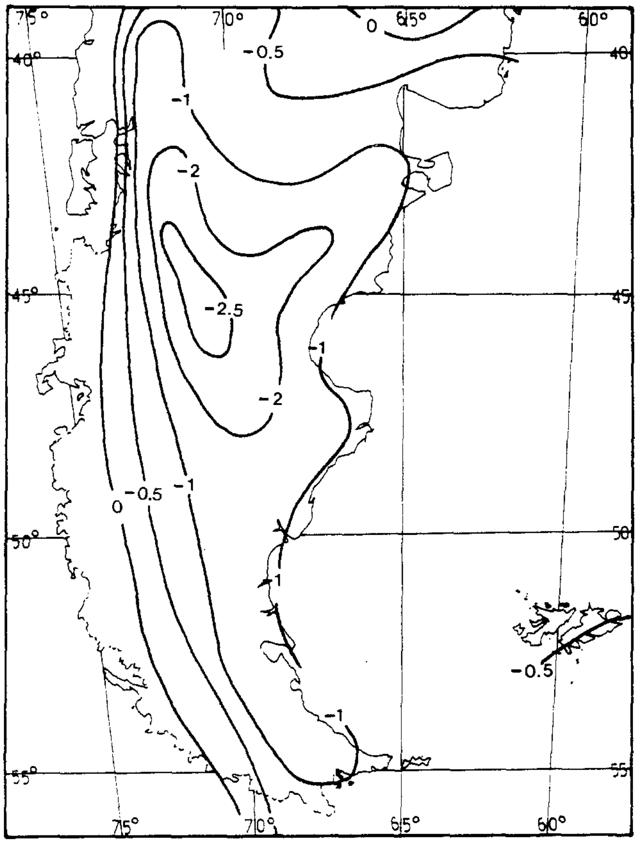

Fig. 7. Decreasing of continentality due to wind cooling effect

band of higher wind speed (45 and 47° S), and the meridian axis (69 to 71° W), in which interseasonal wind speed variation is wider.

Conclusion

In Patagonia, high mean wind speed determines a noticeable cooling effect. Considering the region as a whole, wind chill reduces by 4.2° C the perception of mean annual temperatures. Due to higher wind speed during the summer the wind cooling effect is greater in this season and, thus, there is an apparent decrease in the annual range of sensible temperature; the climate is perceived as being coller and still more oceanic than it actually is. The equivalent isotherm maps presented might be considered as an improvement of the usual isotherms maps, for a bioclimatic environment strongly conditioned by wind. A new bioclimatic classification could be achieved if the thermal index were rebuilt using equivalent temperatures.

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References

Balafoutis C (1989) Diurnal variation of wind chill at Thessaloniki, Greece. Int J Biometeorol 33:272–281

Barros V (1986) Atlas del potencial eólico del sur argentino, 2nd edn. Centro Regional de Energía Eólica and Centro Nacional Patagónico. Consejo de Planeamiento y Desarrollo (COPLADE). Rawson, Chubut, Argentina

Clark R, Wilson P (1992) Occurrence and significance of ventifacts in the Falkland Islands, South Atlantic. Geogr Ann [A]. Phys Geogr 74:35–46

Hoffmann J, Medina L (1971) Ensayo de una clasificación bioclimática en la Republica Argentina. Rev Meteorol 2:150–168

Hoffmann J, Núñez E (1981) Mapa bioclimático de la República Argentina. Servicio Meteorológico Nacional

Knoche W, Borzacov V (1947) Clima de la República Argentina. In: Geografia de la Rep. Argentina, VI, Buenos Aires

Lamb H (1972) Climate: present, past and future, vol 1. Fundamentals and climate now. Methuen, London

Mattio H, Schlishting R (1984) Red hidrológica provincial. Información básica 1981–83. Dirección general de Estudios y Proyectos. Ministerio de Economía, Servicios y Obras Públicas (MESOP). Rawson, Chubut, Argentina

Miller A (1976) The climate of Chile. In: Schwertfeger W (ed) Climates of Central and South America. World survey of climatology, vol 12. Elsevier, Amsterdam, pp 113–145

National Oceanic and Atmospheric Administration (1980) Heed the wind chill factor. NOAA News 5:4, 5

Prohaska F (1976) The climate of Argentina, Paraguay and Uruguay. In: Schwertfeger W (ed) Climates of Central and South America. World Survey of Climatology, vol 12. Elsevier, Amsterdam, pp 13–112

Rosenberg N, Blad B, Verma S (1983) Microclimate: the biological environment. Wiley, New York

Sellers W (1965) Physical climatology. University of Chicago Press, Chicago

Servicio Meteorológico Nacional (1986) Estadisticas meteorológicas 1971–80. Publication 36, Servicio Meteorológico Nacional de la República Argentina, Buenos Aires

Siple P, Passel C (1945) Measurements of dry atmospheric cooling in sub-freezing temperatures. Proc Am Phil Soc 89:177–199

Tuhkanen S (1987) The phytogeographical position of the Faeroe Islands: problems associated with highly oceanic areas. Ann Bot Fenn 24:111–135

Tuhkanen S, et al. (1990) Tierra del Fuego as a target for biogeographical research in the past and present. Anales del Instituto de la Patagonia. Serie Ciencias Naturales, vol 19-2, pp 5–107. University of Magallanes, Punta Arenas, Chile

Walter H, Box E (1983) Climate of Patagonia. In: West N (ed) Ecosystems of the world, 5. Temperate deserts and semi-deserts. Elsevier, Amsterdam, pp 433–436

Zamora E (1977) Resumen meteorológico 1972–77. Estación Schythe. Anales del Instituto de la Patagonia. Serie Ciencias Naturales, vol 8, pp 391–399. Universidad de Magallanes, Punta Arenas, Chile