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Mountain Drag Estimation from the Operational Synoptic Network

Procjena planinskog otpora iz mreže sinoptičkih stanica

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Abstract

This paper presents the time series of the three-hourly average pressure drag vectors per unit volume for the Dinaric Alps computed separately from microbarographic and conventional pressure data. Regardless of magnitude, the pressure drag vectors seem to be aligned almost perpendicularly to the main mountain ridge. The pressure drag maxima during SOP are always connected with the Bora periods and the magnitudes of the drag values indicate that during these events there is a major sink of atmospheric momentum over the Dinaric Alpine region.

The main aim of this paper is to provide a means of drag estimation for period in which no microbarographic data are available. It investigates the correlation between the time series of pressure drag computed from microbarographic and synoptic pressure data. The results suggest the possibility of application of the linear regression method in drag estimation for periods without microbarographic data.

Key words: mountain drag, pressure drag vector, microbarographic data, synoptic network, correlation coefficients, ALPEX-SOP

Sažetak

Prikazani su vremenski nizovi tro-satnih srednjaka vektora planinskog otpora računanih posebno iz mikrobarografskih i redovitih sinoptičkih podataka tlaka zraka. Neovisno o amplitudi, vektor planinskog otpora gotovo je potpuno okomit na planinsku prepreku. Za vrijeme SOP najveći planinski otpor uvijek je bio povezan s periodima puhanja bure, a njegova veličina tada ukazuje da iznad Dinarida postoji značajan ponor atmosferske količine gibanja.

Glavni cilj ovog rada bila je mogućnost procjene planinskog otpora kada ne postoje mikrobarografska mjerenja. Ispitivana je korelacija između vremenskih nizova otpora tlaka dobivenog iz mikrobarografskih i sinoptičkih podataka tlaka zraka. Rezultati ukazuju na mogućnost primjene metode linearne regresije kod procjene otpora tlaka za periode bez mikrobarografskih mjerenja.

Ključne riječi: planinski otpor, vektor otpora tlaka, mikrobarografski podaci, sinoptička mreža stanica, koeficijent korelacije, ALPEX-SOP

1. Introduction

A well known feature of atmospheric flow over orography is the asymmetry of the surface pressure field with high pressure upstream of the mountain and low pressure in the lee. According to Newton's third law, the mountain exerts a force on the flow directed upstream. This phenomenon of mountain drag is a particular case of "form" or "pressure" drag in mechanics of fluids.

Mountain Drag = - Pressure Drag
(in the direction of the airflow)

The determination of the mountain drag force on the atmosphere was among the main objectives of the Alpine Experiment. Several pressure-drag studies (Hafner and Smith, 1985; Davies and Phillips, 1985; Carissimo, Pierrehumbert and Pham, 1988) were undertaken using observational data gathered during the two-month ALPEX project special observation period (March-April, 1982). At that time microbarographic measurements were conducted in the Northern Adriatic and the north-western part of Croatia, as part of a research on the Bora. Tutiš and Ivančan-Picek (1991) have presented the results of computing mountain pressure drag vectors per unit volume on the basis of those high time resolution surface pressure data. As in previous studies if the Alpine region, the drag time series for the Dinaric Alps is strongly correlated with synoptic and subsynoptic events, especially with lee cyclogeneses, frontal passages and Bora occurrence. The pressure drag maxima during SOP are always related to Bora periods. Under weak pressure gradients, however, we find smaller magnitudes and more variation in the orientation of drag vectors.

Regardless of their magnitude, pressure drag vectors seem to be roughly perpendicular to the main mountain ridge, as a direct consequence of an orographically forced overflow. The absolute long term average SOP drag for the Dinaric Alps is relatively small compared to the typical surface friction. But during the periods of maxima (Bora events) the pressure drag becomes comparable to surface friction. In these cases the Dinaric Alps may be compared to the Alpine region as a major sink for the atmospheric momentum. The magnitudes of drag values during Bora events indicate the desirability of representing Dinaric Alpine drag effects in numerical models particularly in the cold season when severe Bora events are frequent.

In this paper conventional pressure data from the synoptic surface network have been used and pressure drag vectors have been computed per unit volume. The results have been compared to those of a previous study (Tutiš and Ivančan-Picek, 1991).

2. The principle of pressure drag evaluation

2.1. The geographical region and the data base

The topography of the Northern Adriatic coastal area, including the inland region as far as Zagreb is shown in Fig. 1. The orientation of the Dinaric Alps is approximately northwest to southeast. The terrain elevation is generally 300 to 500 m. The main mountainous region with elevations up to 1600 m locally extends along the Adriatic coast. This orographic distribution causes particular local phenomena, such as the Bora wind, airflow blocking and frontal deformation.

The present study has focused on the surface pressure field and associated drag. The data base for this study was gathered

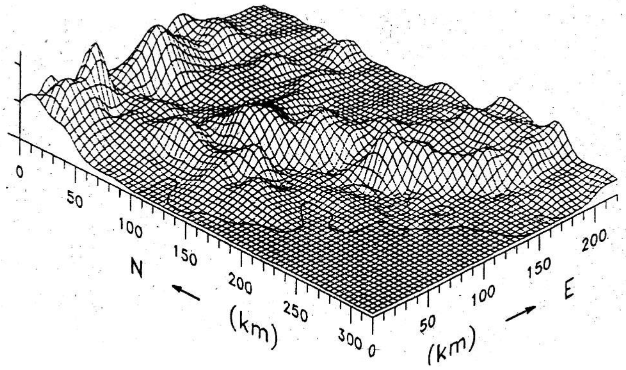


Fig. 1. Topography of the Northern Adriatic area.
Sl. 1. Topografija sjevernog Jadrana.

during the two month (March - April 1982) ALPEX special observation period. An array of 18 microbarographs was disposed (see Fig. 2) from Karlovac to Mali Lošinj to support aerial observations of the Bora (March 6, 7, 22, 25 and April 15). This array was one of three such networks forming the "surface drag" subprogram of the ALPEX project. Aspects of the design strategy of this subprogram have been listed briefly in ALPEX (ICSU/WMO, 1982) and discussed in full detail by Richner (1987). The 10-minute time resolution for pressure measurements has been internationally agreed upon. The criteria for pressure data measurements were set at an absolute accuracy of 0.3 hPa and a relative accuracy of 0.1 hPa. Only in periods with Bora events this absolute criterion was 0.5 hPa because of marked short-term fluctuations. Many of those stations were also equipped for temperature and wind measurements. The data gaps (missing data at single points) were filled using an appropriate spline technique on the time series for the individual stations. The synoptic network in the area is presented in Fig. 2. There are 11 synoptic stations, but unlike the microbarographic ALPEX network, there is a marked lack of data in the mountainous region.

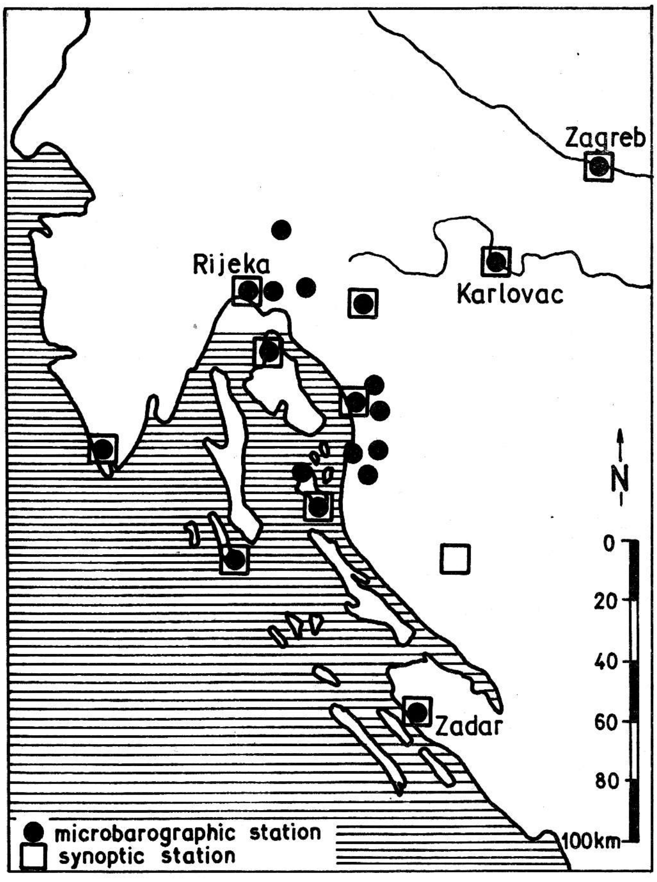


Fig. 2. Location of the microbarograph and synoptic stations.

Sl. 2. Položaj mikrobarografskih i sinoptičkih stanica.

2.2. Method

Following Hafner and Smith (1985), we have taken pressure drag as a two dimensional horizontal vector D_H and computed the total pressure drag per unit volume by applying Archimedes law:

$$D_H/V = -\nabla_H p \qquad (1)$$

where V is the corresponding volume and $\nabla_H p$ is the locally averaged pressure gradient.

Calculations were carried out with microbarographic data and, separately, with conventional synoptic pressure data. In order to determine pressure drag values from Eq. (1) based on microbarographic data, we must first define the volume elements V of the area under consideration. The topography of the Dinaric Alps have been divided into two vertical sections - below 500 m and over 500 m elevation in order to resolve the vertical variation of the horizontal pressure gradient. The station pressure data p_{st} have been reduced to the corresponding intermediate height levels z_i (z_1 = 250 m, z_2 = 850 m) by using a simple reduction formula:

$$p(z_i) = p_{st}\left[T_{st}/(T_{st}+\gamma\ \Delta z)\right]^{g/R\gamma} \qquad (2)$$

where $\Delta z = z_i - z_{st}$, $g = 9.81\ ms^{-2}$ $\gamma = 0.0065\ Km^{-1}$ and $R = 287\ JK^{-1}kg^{-1}$, which is valid in a hydrostatic atmosphere with a constant lapse rate. Mean pressure $\bar{p}_i$ was obtained from p_{st} reduced to z_i, according to the height of the stations. To avoid local fluctuations we have used the appropriate temperature average for z_i instead of the station data. Drag is expressed per unit volume (Nm^{-3}). The drag computation from synoptic pressure data, all data reduced to standard sea level. The standard procedure for calculating $\nabla_H p$ using regression analysis (the least square polynomial approximation) is the equation system:

$$p_i - \bar{p} = b_1 \varphi + b_2 \lambda \qquad (3)$$

where $b_1 = \frac{\delta p}{\delta y}$, $b_2 = \frac{\delta p}{\delta x}$. The coordinate system has horizontal axes pointing east (λ) and north (φ), while the vertical axis is pressure p. The solution of system (3) gives the eastward (b_2) and northward (b_1) components of the drag vector D_H/V. While drag calculation based on regular synoptic and special microbarigraphic data is basically the same, we have also calculated drag per unit volume only from pressure (reduced to sea level) differences at stations Zagreb (Maksimir) and Senj (the aerial distance is approximatelly 130 km). The main aim of these parallel drag calculations is to make possible drag estimation for periods in which microbarographic data are not available. For the purpose of comparing all three ways of computing drag, our further discussion deals with values projected to an azymuth of 45° (the azymuth of the Zagreb-Senj line).

3. Results

The time series of the three-hourly average pressure drag vectors per unit volume for the Dinaric Alps, computed as described in the previous section separately from microbarographic and synoptic pressure data, is shown in Figs. 4 and 5 for the entire ALPEX SOP for March and April 1982. As presented in Tutiš and Ivančan-Picek (1991), the absolute average SOP drag for the Dinaric Alps is $6.1 \cdot 10^{-4}$ Nm^{-3} and the absolute maximum is $2.3 \cdot 10^{-3}$ Nm^{-3}, reached during the Bora period on 14 April (when the daily average pressure difference

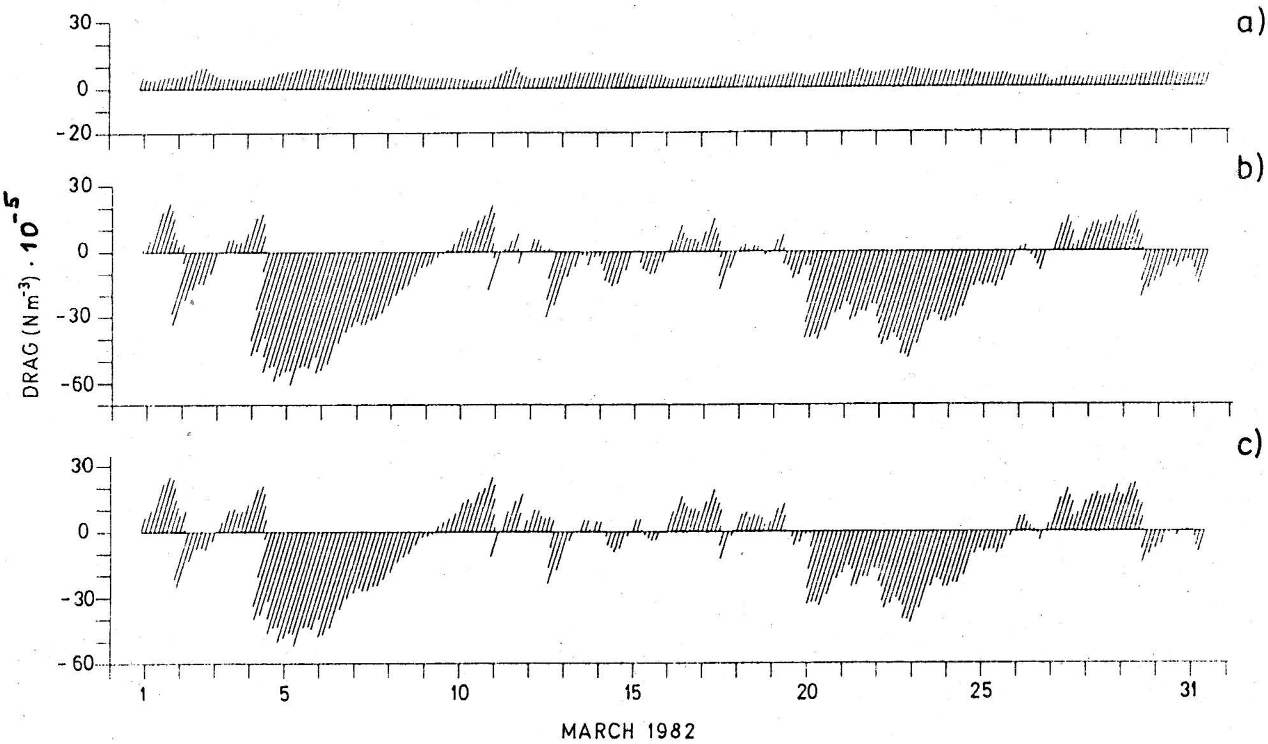


Fig. 3. Time trace of pressure drag vectors per unit volume for the Dinaric Alps, March 1982
a) high section (above 500 m) b) low section (0 - 500 m)
c) vertical sum of the two sections (a) and (b) (from Tutiš and Ivančan-Picek, 1991)

Sl. 3. Vremenska promjena vektora otpora tlaka po jedinici volumena za područje Dinarida, ožujak 1982
a) viši sloj (iznad 500 m) b) niži sloj (0 - 500 m)
c) vertikalni zbroj oba sloja a) i b). (iz Tutiš i Ivančan-Picek, 1991)

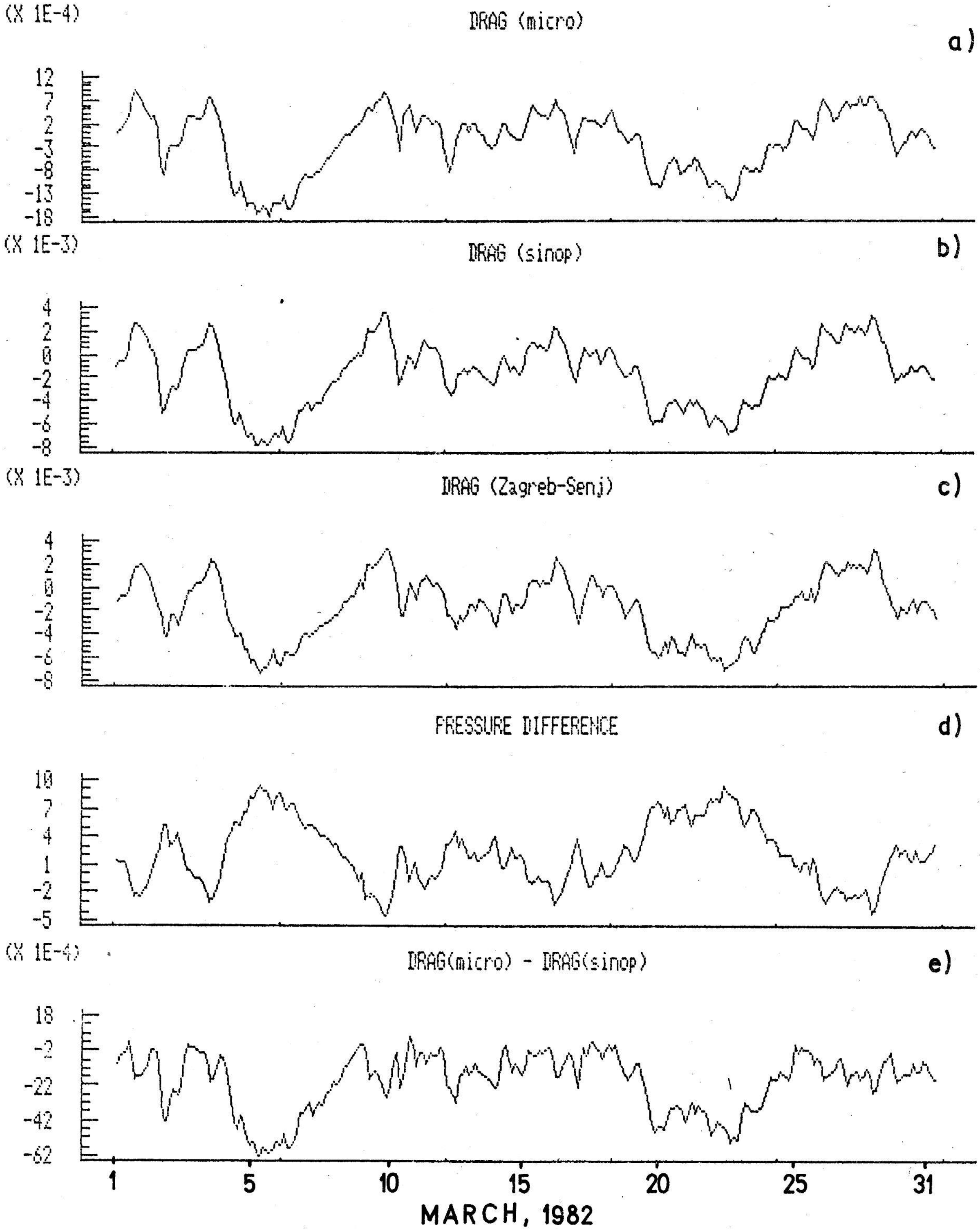


Fig. 4. Time trace
a) of pressure drag per unit volume calculated from microbarographic data (Nm^{-3})
b) of pressure drag per unit volume calculated from synoptic data (Nm^{-3})
c) of pressure drag per unit volume calculated from pressure differences at stations Zagreb and Senj (Nm^{-3})
d) of pressure differences between Zagreb and Senj (hPa)
e) of the differences between a) and b) (Nm^{-3}) for the Dinaric Alps, March 1982

Sl. 4. Vremenska promjena
a) otpora tlaka po jedinici volumena računanog iz mikrobarografskih podataka (Nm^{-3})
b) otpora tlaka po jedinici volumena dobivenog iz sinoptičkih podataka (Nm^{-3})
c) otpora tlaka po jedinici volumena dobivenog iz razlike tlaka u Zagrabu i Senju (Nm^{-3})
d) razlike tlaka izmedju Zagreba i Senja (hPa)
e) razlike izmedju a) i b) (Nm^{-3}) za područje Dinarida, ožujak 1982

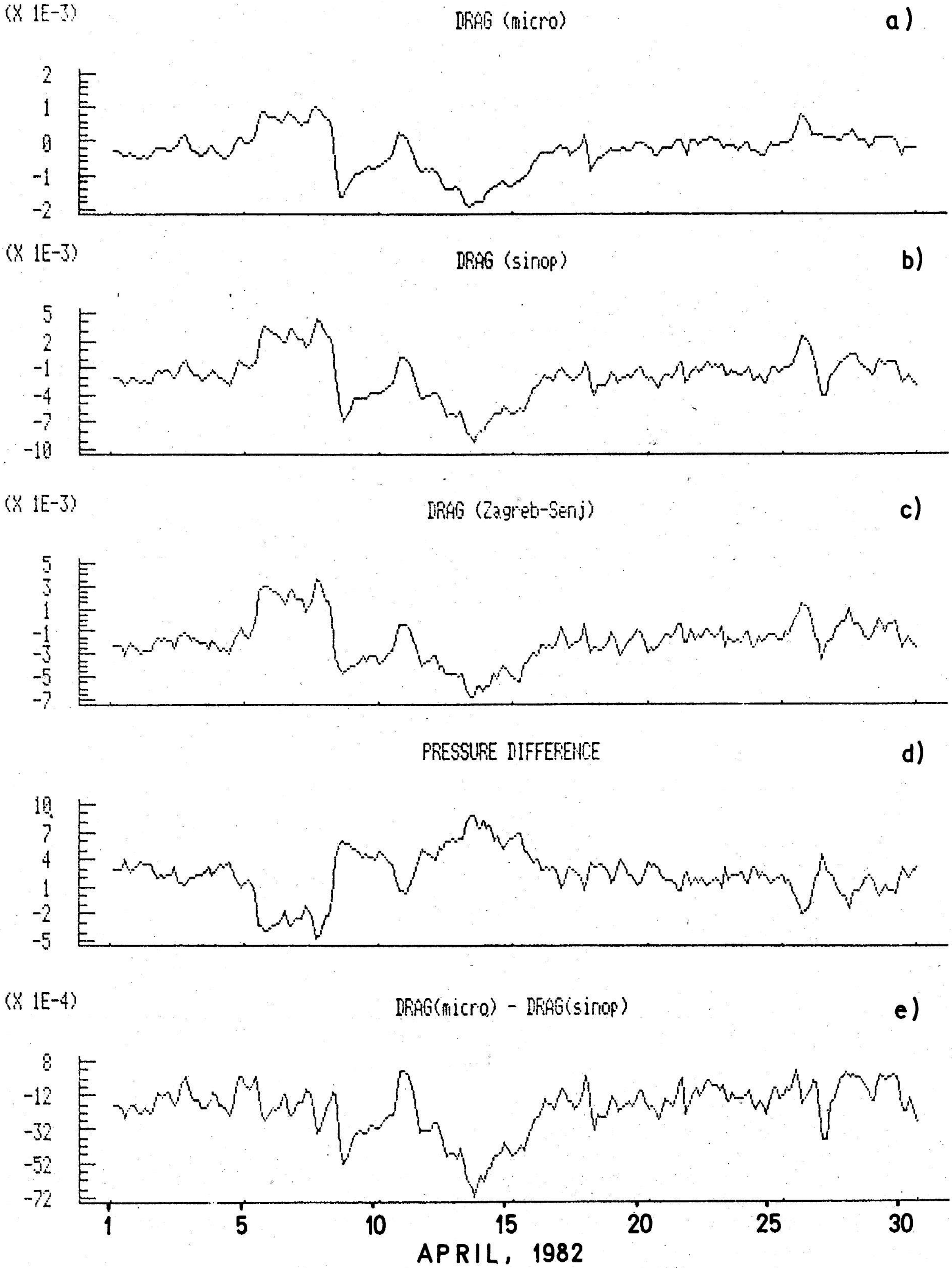


Fig. 5. Same as Fig. 4, for April 1982
Sl. 5. Isto kao Sl. 4, za travanj 1982

between Zagreb and Senj was 8 hPa). The drag vector is in most cases perpendicular to the main mountain ridge (the azymuth is usually about 77° as presented in Fig. 3).

During most of the ALPEX SOP the weather patterns were quite variable. Tutiš and Ivančan-Picek (1991) present detailed summaries of the weather events in March and April 1982 in the Dinaric Alps region and show that there is a strong correlation between drag variations and the occurrence of synoptic events.

The pressure drag maxima during SOP are always connected with the Bora periods and with the largest pressure differences between the upstream and downstream regions (Fig. 4 and 5). The strongest Bora, with maximum gusts greater than 30 ms^{-1} (Omišalj- 35.2 ms^{-1} on 5 March at 22 UTC; Senj- 31.8 ms^{-1} on 6 March at 12 UTC), was registered on the Northern Adriatic on 5-7 March 1982 (Bajić, 1988). On 6 March, total drag recorded one of the largest values during the SOP (from microbarographic data $-1.7 \cdot 10^{-3}$ Nm^{-3} and from synoptic data $-7.8 \cdot 10^{-3}$ Nm^{-3}). On 6 March the Bora was stronger than on 7 March and there was a smaller magnitudes to the drag vectors. The largest pressure difference (8.9 hPa) between Zagreb, on the windward side, and Senj, in the lee side occurred during the strongest Bora.

The next highest total drag value was achieved on 14 April (from microbarographic data $-1.9 \cdot 10^{-3}$ Nm^{-3} and from synoptic data $-9.0 \cdot 10^{-3}$ Nm^{-3}), when a maximum gust of 44 ms^{-1} was observed on Krk's Bridge connecting the island of Krk to the mainland. The Bora period on 12-18 April was characterised by the longest duration among all ALPEX SOP bora cases (138 hrs in Senj) (Vučetić, 1988).

On 9 April the Bora on the Northern Adriatic was associated with the most pronounced cold air outbreak during SOP and was classified as a "frontal bora type" (Jurčec, 1988). It was the most pronounced frontal system in April in at least 10 years 1973-1982. In 24 hours (8 April, 12 UTC - 9 April, 12 UTC) the pressure drag vector changed from $1.0 \cdot 10^{-3}$ to $-1.6 \cdot 10^{-3}$ Nm^{-3} (microbarographic data), and from $4.5 \cdot 10^{-3}$ to $-6.8 \cdot 10^{-3}$ Nm^{-3} (synoptic data).

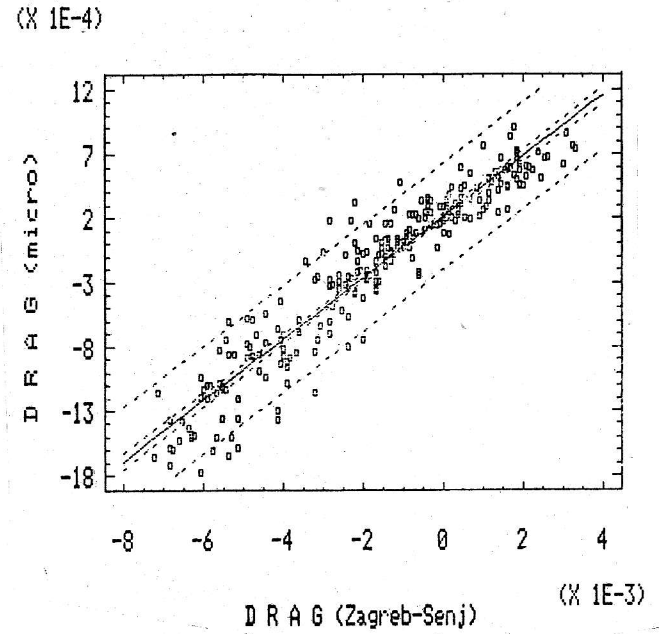
Quasi-steady or weak synoptic situations were observed in late March and early April, when the weather was influenced by a Central-European anticyclone. As expected, under weak pressure gradients we found smaller magnitudes of drag vectors than in other periods with pronounced synoptic activity

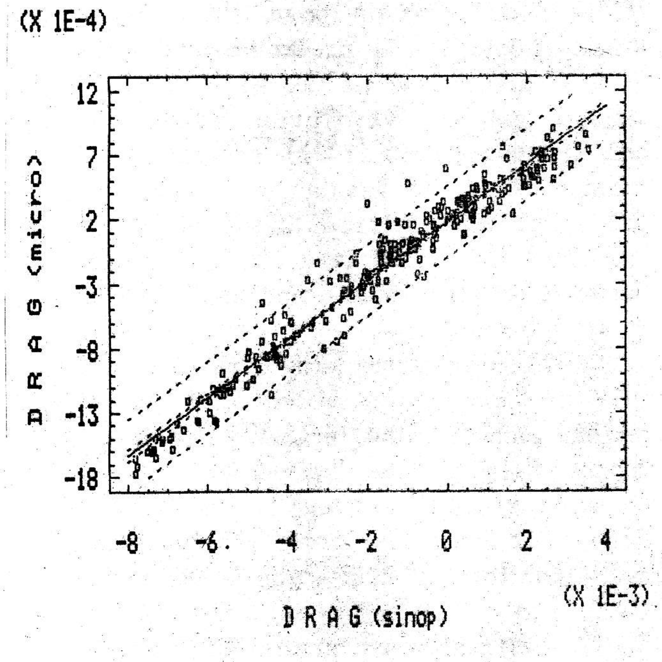
Tab. 1. The correlation coefficient k between the time series of pressure drag computed from microbarographic data (MIKD) and synoptic data (SIND), of pressure differences Zagreb (Maksimir)-Senj (DPZS) and of pressure drag obtained only from pressure differences Zagreb-Senj (NPDZS).

Tab. 1. Koeficijent korelacije k između vremenskih nizova otpora tlaka računanog iz mikrobarografskih podataka (MIKD) i iz sinoptičkih podataka (SIND), zatim razlike tlaka Zagreb (Maksimir) - Senj (DPZS) i otpora tlaka dobivenog samo iz razlike tlaka Zagreb-Senj (NPDZS).

	1982	
k	MARCH	APRIL
MIKD - SIND	0.976	0.970
MIKD - DPZS	- 0.945	- 0.946
MIKD - NPDZS	0.945	0.946

Our purpose was to investigate the correlation between the time series of pressure drag computed from microbarographic and conventional synoptic pressure data (Figs. 6 and 7). Correlation coefficients have been also calculated between the pressure drag computed from microbarographic data and the drag per unit volume obtained from Zagreb-Senj pressure differences. The correlation coefficients k are presented in Tab. 1. The value of k in all cases exceeds 0.9. The results show that pressure drag is highly correlated with the pressure differences between upstream and downstream areas. The results suggest the possibility of application of the linear regression method in drag estimation for periods for which microbarographic data are not available.





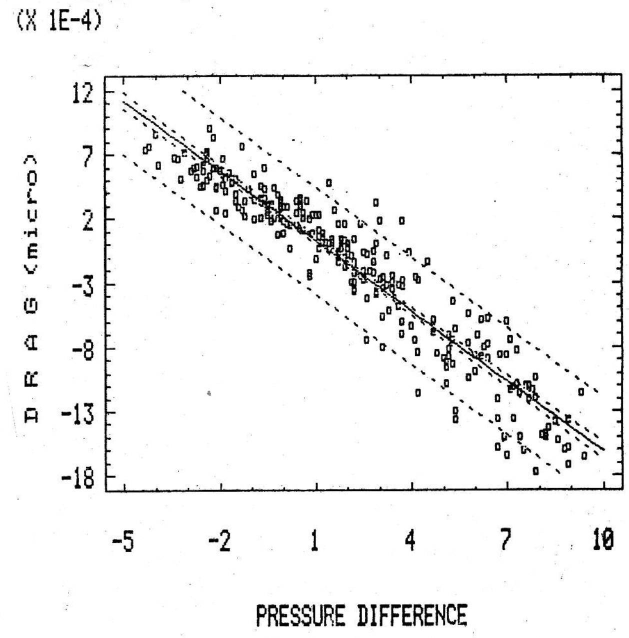


Fig. 6. Pressure drag per unit volume derived from microbarographic data displayed as a function of
a) pressure drag obtained from synoptic data
b) pressure drag obtained only from pressure differences between Zagreb and Senj
c) the pressure differences between Zagreb and Senj for March 1982.

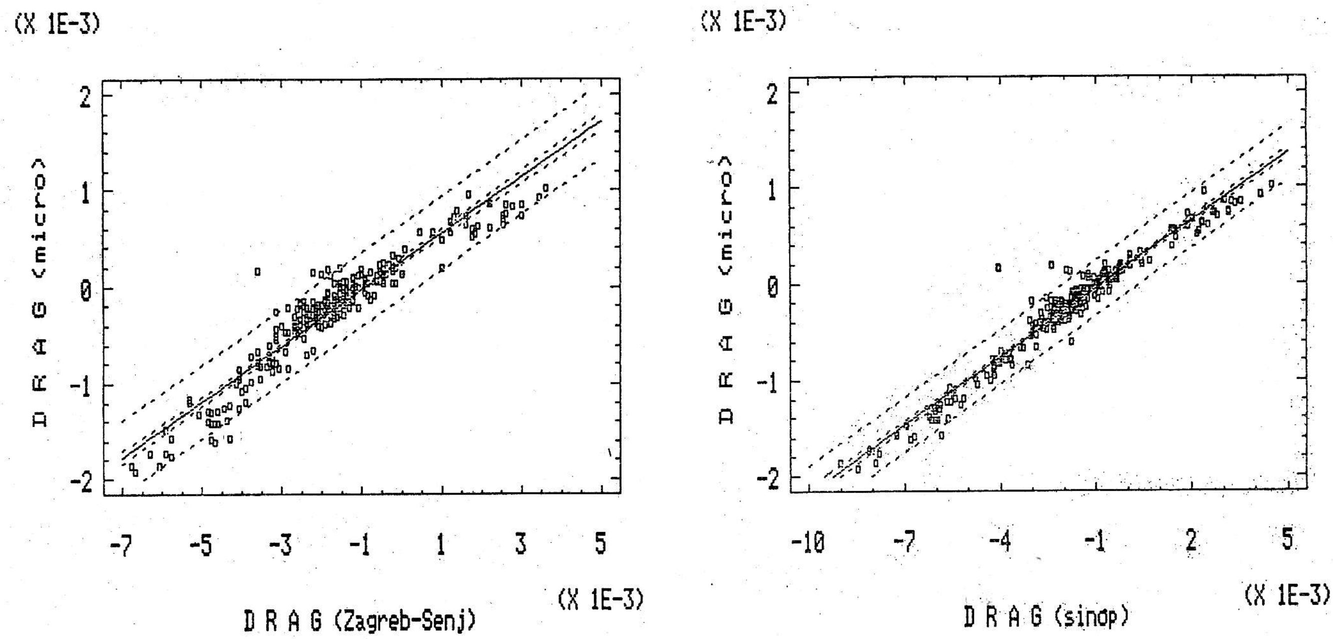
Sl. 6. Otpor tlaka po jedinici volumena dobiven iz mikrobarografskih podataka prikazan kao funkcija
a) otpora tlaka računanog iz sinoptičkih podataka
b) otpora tlaka dobivenog samo iz razlike tlaka izmedju Zagreba i Senja
c) razlike tlaka između Zagreba i Senja za ožujak 1982.

4. Conclusion

The present study has focused on the surface pressure field and associated drag.

In the Dinaric Alps region, 18 microbarographs were distributed from Karlovac to Mali Lošinj during the ALPEX SOP. This paper presents the results of computing the mountain pressure drag vectors per unit volume on the basis of those surface pressure data. It also includes computation of pressure drag from regular pressure data from the synoptic surface network (11 stations). The main aim of these parallel drag calculations is to make possible the drag estimation for periods when microbarographic data are not available.

Tutiš and Ivančan-Picek (1991) pre-



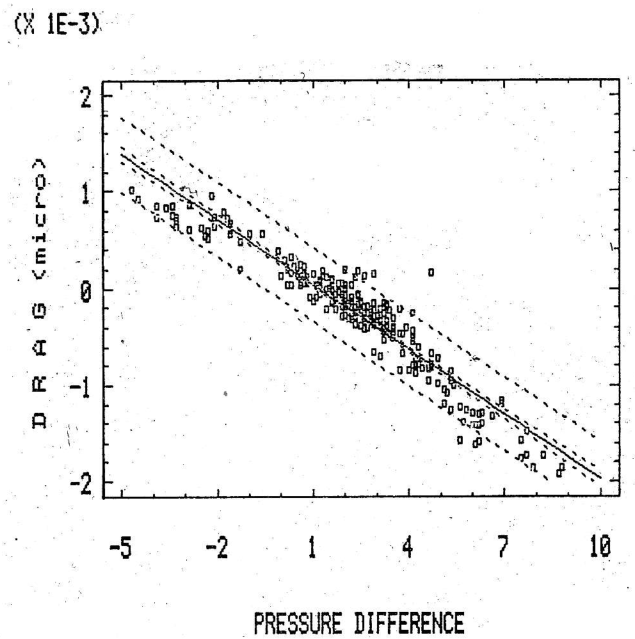


Fig. 7. Same as Fig. 6, for April 1982
Sl. 7. Isto kao Sl. 6, za travanj 1982.

sent detailed summaries of the weather events in March and April 1982 in the Dinaric Alps region and show that there is a strong correlation between drag variations and the occurence of synoptic events. The pressure drag maxima during SOP are always related to Bora periods. Under weak pressure gradients, however, smaller magnitudes are found and more variation in the orientation of the drag vectors. During SOP there was no typical pronounced upper-level southwesterly prefrontal flow which could also possibly produce stronger pressure drag.

This is an investigation of the correlation between the time series of pressure drag computed from microbarographic and conventional synoptic pressure data. The value of the correlation coefficients k in all cases exeeds 0.9. The pressure drag values during SOP computed from synoptic pressure data are somewhat high in comparison with pressure drag derived from microbarographic data. This is due to a sparse synoptic network. There are not enough synoptic stations at higher altitudes and all pressure data are reduced to standard sea level. The results suggest the possibility of application of the linear regression method in drag estimation for periods when microbarographic data are not available.

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Kratak sadržaj

Prikazani su vremenski nizovi trisatnih srednjaka vektora otpora tlaka po jedinici volumena za područje Dinarida. Otpor tlaka računan je na osnovu mikrobarografskih mjerenja iz perioda SOP i regularnih sinoptičkih podataka tlaka zraka. Otpor tlaka promatran je kao dvo-dimenzionalni vektor i računan je ukupni otpor po jedinici volumena primjenom Arhimedova zakona. Kao što je pokazano kod Tutiš i Ivančan-Picek (1991) apsolutni srednjak otpora tlaka u periodu SOP za Dinaride je $6.1 \cdot 10^{-4}$ Nm^{-3}, a apsolutni maksimum iznosi $2.3 \cdot 10^{-3}$ Nm^{-3} (14 April). Maksimalne vrijednosti otpora uvijek se podudaraju s periodima pojave bure. Tada otpor tlaka postaje usporediv s prizemnim trenjem, a Dinarsko gorje može se usporediti s Alpama kao važnog ponora atmosferske količine gibanja. Nažalost, za vrijeme SOP nije bilo klasičnog predfron-

talnog jugozapadnog visinskog strujanja, koje bi vjerojatno isto dovelo do velikog otpora tlaka. Općenito, vremenski nizovi otpora tlaka pokazuju visoku koreliranost s gibanjima na sinoptičkoj i mezo-skali (zavjetrene ciklogeneze, fronte, bura).

Cilj ovog rada bio je paralelno računanje otpora u periodu SOP iz mikrobarografskih i sinoptičkih podataka tlaka i temperature zraka, radi mogućnosti njegove procjene kada ne raspolažemo s mikrobarografskim mjerenjima. Dobiveni koeficijenti korelacije u svim slučajevima premašuju 0.9. Za vrijeme SOP dobiveni otpor iz sinoptičkih podataka tlaka zraka nešto je veći od onog računanog iz mikrobarografskih mjerenja. Razlog tome je dosta gruba sinoptička mreža stanica i njihov nedostatak na većim visinama od 500 m, tako da su svi podaci tlaka reducirani na standardni morski nivo. Ipak, dobiveni rezultati sugeriraju mogućnost primjene metode linearne regresije za procjenu otpora tlaka i onda kad nemamo mikrobarografska mjerenja.