Mountain Drag along the Gotthard Section during ALPEX

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ABSTRACT

An estimate of the time variation of the pressure drag component across the inner portion of the St. Gotthard section of the Alps is derived for the special observational period (March–April 1982) of the ALPEX project. Surface pressure data obtained from a purpose-designed, mesoscale array of microbarograph stations are used, and the results indicate that this drag component amounted to a value per unit area that varied on the order of ±5 Pa with a mean ~0.78 Pa.

It is shown that the phase variations of the time-trace of the drag are directly related to synoptic scale flow developments. However, the magnitude of the drag is substantially influenced by mesoscale effects. Further, an indication is given of the contribution to the drag of the effects of diurnal variation, vertically propagating buoyancy waves, and low-level flow blocking/deflection.

The order of magnitude of these drag values (notwithstanding the potential errors in the estimates) indicates that the Alps exert a substantial influence upon the atmospheric momentum budget of the region.

1. Introduction

It is a recognition of the fundamental importance of the concept of the angular momentum budget of the atmosphere that it has long formed a cornerstone for theoretical (e.g., Jeffreys, 1926, 1933; Lighthill, 1954) and diagnostic (e.g., Starr, 1948; White 1949) studies of the general circulation. The only significant external interaction in this budget arises from the interchange of momentum (i.e., angular momentum) between the atmosphere and the earth–ocean system. This takes place in two distinct ways. There is a drag due purely to a viscous surface stress at the-interface, and there is a pressure drag effect due to horizontal pressure variations in regions (land or sea) of surface unevenness. The pressure drag itself is often viewed as comprised of two types: form drag ($D_f$) and wave drag ($D_w$). In general these two types signify essentially that the primary mode of transport of momentum between the atmospheric source–sink and the terrain is accomplished by,

1) advection of the eddy momentum away with the mean flow and
2) wave-transmission through the flow.

This particular study is concerned with the determination and interpretation of the pressure drag along one special transect—the St. Gotthard Pass—of the European Alps for the two month special observational period (SOP) of the international ALPEX project (see e.g., Kuettnert and O’Neill, 1981). The Alps constitute a major mesoscale orographic feature, yet comparatively little is known about the magnitude of the Alpine pressure drag contribution to the atmospheric momentum budget and the precise mechanisms by which that drag is effected.

Tables 1 and 2 are an attempt to present, in a condensed form, a list of some pertinent drag measurements and a digest of various drag mechanisms. (Succinct discussions of a range of drag mechanisms are to be found in Mason and Sykes, 1978; Smith, 1978; Mason 1979.) It is appropriate to make two general comments regarding the information displayed in the Tables. First, from an observational standpoint, it is to be noted that no definitive measurements of the mesoscale Alpine drag have been undertaken, but the available synoptic scale estimates indicate that an amplitude ~1 Pa per unit area is not unreasonable. It is interesting to record, for benchmark reference purposes, that a downward momentum flux of this magnitude emanating from a 2 km deep tropospheric layer moving at 10 m s$^{-1}$ over the Gotthard region would entirely vacate the momentum of that layer during its passage over the ridge. Second, the direct, but not strictly justifiable, application of the drag assessment formulae listed in Table 2 to the intrinsic orographic configuration (i.e., the characteristic height and width scales, and height variance) of the Alps would endow this mountain range with a large drag-inducing capacity. Thus there is an indication, both from “order of magnitude” observational evidence and from theoretical expectations, that the Alps constitute a potentially significant sink for atmospheric momentum.

These considerations indicate the relevance of, and provide a framework for, the present work. Our study has a two-fold objective. Estimates are sought for the time-variation, during the ALPEX SOP, of the pressure...
### Table 1. Some pertinent atmospheric drag estimates.

<table>
<thead>
<tr>
<th>Nature of terrain</th>
<th>Component measured</th>
<th>Data source</th>
<th>Drag values (Pa)</th>
<th>Remarks</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling hills</td>
<td>wave flux</td>
<td>Airborne measurements</td>
<td>~0.01–0.35</td>
<td>Ensemble of cases</td>
<td>Brown (1983)</td>
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<td></td>
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<tr>
<td>Blue ridge</td>
<td>wave flux</td>
<td>Airborne measurements</td>
<td>~3</td>
<td>Values for drag “events”</td>
<td>Smith (1976)</td>
</tr>
<tr>
<td>(Appalachians)</td>
<td>plus pressure drag</td>
<td>Microbarograph array</td>
<td>~4</td>
<td></td>
<td>Smith (1978)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrenees</td>
<td>wave flux</td>
<td>Airborne measurements</td>
<td>~0.4</td>
<td>Single, strong wave event</td>
<td>Hoinka (1984)</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>European Alps</td>
<td>pressure drag</td>
<td>Synoptic network</td>
<td>~5</td>
<td>Time sequence for ALPEX</td>
<td>Hafner and Smith (1985)</td>
</tr>
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<td></td>
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<tr>
<td>Alpine föhn event</td>
<td>wave flux</td>
<td>Airborne measurements</td>
<td>~0.3</td>
<td>Gross estimate</td>
<td>Hoinka (1985)</td>
</tr>
<tr>
<td></td>
<td>plus pressure drag</td>
<td>Synoptic network</td>
<td>~6.7</td>
<td></td>
<td></td>
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<tr>
<td>Southern Alps</td>
<td>pressure drag</td>
<td>Synoptic network</td>
<td>~1.0–4.0</td>
<td>Monthly mean (typical plus extreme)</td>
<td>Hutchings and Thompson (1962)</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Rocky Mountains</td>
<td>wave flux</td>
<td>Airborne measurements</td>
<td>0.05–0.2</td>
<td>Typical conditions</td>
<td>Lilly et al. (1982)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2–1.2; 4.7</td>
<td>Downslope storms</td>
<td>Lilly (1972, 1978)</td>
</tr>
<tr>
<td>Synoptic/global</td>
<td>pressure drag</td>
<td>Synoptic network</td>
<td>≤0.1</td>
<td>Large-scale zonal component</td>
<td>Wahr and Oort (1984)</td>
</tr>
</tbody>
</table>

### Table 2. Resumé of some theoretical and laboratory studies of drag. Here $U_p$, $V_p$ denote, respectively, the geostrophic flow components in the directions normal and tangential to the barrier; $h$, $L$, $d$ refer to the barrier height, scale width and the depth of the resonating layer; while $R_b = U_p/dL$, $F = U_p/Nh$, and $N$ signifies the Brunt-Väisälä frequency. Much of the material summarized here appears in the following references: I Smith (1975); II Batchelor (1967); III Smith (1978); IV Miles and Huppert (1969); V Mason (1979).

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Type of drag</th>
<th>Drag/unit area</th>
<th>Terrain scale (m)</th>
<th>Remarks</th>
<th>Typical values (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary layer turbulence</td>
<td>Form</td>
<td>$\sim \rho_c U_p^2$</td>
<td>$h \leq 10$, $L \leq 10^2$</td>
<td>$c_s \sim 1 \times 10^{-3}$ smooth surface, $\sim 2 \times 10^{-3}$ parkland</td>
<td>I* 0.05 0.2</td>
</tr>
<tr>
<td>Flow separation in “neutral” atmosphere</td>
<td>Form</td>
<td>$\sim \frac{1}{2} \rho_c U_p \left( \frac{h}{L} \right)$</td>
<td>$h \leq 10$, $L \leq 10^2$</td>
<td>$c_s \sim 0.1$ small aspect ratio, $\sim 1$ bluff body</td>
<td>II $\leq 0.5$ for $L \sim 10^2$ m</td>
</tr>
<tr>
<td>Trapped (resonant) buoyancy waves</td>
<td>Wave</td>
<td>$\sim \rho U_p h^2 L d^{-3}$</td>
<td>$L \approx 30 \times 10^3$, $F \leq 1$</td>
<td>Valid for small amplitude</td>
<td>III $\sim 0.5$ for $(h, L) = (50, 2.10^4)$ m</td>
</tr>
<tr>
<td>Untrapped inertia-buoyancy waves</td>
<td>Wave</td>
<td>$\sim \rho U_p h^2 L^{-1}$</td>
<td>$L \sim 1 \times 10^4$, $R_0 \geq 1$, $F \geq 1$</td>
<td>Valid for finite-amplitude barriers</td>
<td>IV $\sim 0.5$ for $(h, L) = (5 \times 10^2$, $5 \times 10^4)$ m</td>
</tr>
<tr>
<td>Upstream blocking</td>
<td>Mixed</td>
<td>$\sim \frac{1}{2} \rho N^2 h^2 L^{-1}$</td>
<td>$F &lt; 1$, $R_0 &lt; 1$, $R_0 \leq 1$</td>
<td>Formula-estimate of static contribution</td>
<td>~0.5 for $h = 10^2$ m $L = 2 \times 10^4$ m</td>
</tr>
<tr>
<td>Coriolis lift</td>
<td>Form</td>
<td>$\sim \frac{1}{2} \rho f V_p h$</td>
<td>$L \geq 10^6$, $R_0 \leq 1$</td>
<td>In situ synoptic scale pressure gradient</td>
<td>~0.5 for $h \sim 10^3$ m</td>
</tr>
<tr>
<td>Pseudo-Ekman layer pumping</td>
<td>Form</td>
<td>$\sim \frac{1}{2} \rho_c N^2 h^2$</td>
<td>$L \geq 10^6$, $R_0 \leq 1$, $F \geq 1$</td>
<td></td>
<td>V $\sim 0.1$ for $h \sim 10^3$ m</td>
</tr>
</tbody>
</table>

* Numerals refer to cited references.
drag across the inner-Alpine region of the Gotthard section. High time resolution data from a mesoscale array of microbarograph stations aligned along this (almost) single-ridge Alpine section are used for this purpose. Thereafter an attempt is made to relate the time-variability of the drag to the synoptic-scale and mesoscale atmospheric flow structure, and hence to the underlying physical processes.

2. The drag derivation: Background and basics

a. The orography

The St. Gotthard region of the Alps is the prime watershed of the Alpine complex. It marks the catchment of four major basins: the Rhone and Vorder-Rhine along a WSW–ENE axis, the Reuss of the Alpine northside, and the Ticino of the Levantinan southside along a NNW–SSE axis (see Fig. 1). It is along this latter axis that one of the three arrays of microbarographs was established during ALPEX. This section provides one of the simplest orographic profiles for a north–south transect of the Alps. Indeed, a relatively smooth, almost direct and single-ridge traverse along this axis can be accomplished from a height of 400 m MSL in the Reuss valley to a similar height in the Levantina.

b. The data base

The data base for this study was gathered during the two-month (March–April 1982) special observational period of the ALPEX campaign of GARP. An array of 27 microbarographs was disposed (see Fig. 2) from Stuttgart in the north across the Black Forest and the Swiss Middleland, along and over the St. Gotthard pass, and down to the Po valley in the south. This array was one of three such networks that comprised the “surface drag” subprogram of the ALPEX project. Aspects of the design strategy of this subprogram involving the issues of data requirements, instrumentation accuracy, the placing and density of the stations, and the calibration, monitoring and performance of the instrumentation are listed briefly in ICSU/WMO (1982a,b) and discussed in full detail by Richner (1985). Of particular note for our present purposes is that the temporal resolution for almost all stations was set at 10 minutes, and the criteria for the pressure data measurements was set at an absolute accuracy of 0.5 mb and a relative accuracy of 0.1 mb. Many of the stations were also equipped for temperature, humidity and wind measurements. Prior to their use in the present study the data were subject to simple quality control checks based upon an analysis of the time series for each individual station, and an inspection of the space–time displays for the whole array.

For the determination of the drag in the inner-Gotthard region, the stations, with altitude (MSL) in parentheses, of most interest are: Zürich–Kloten (435 m); Werd (386 m); Dietwil (433 m); Brunnen (438 m); Atdorf (451 m); Gurtnele (737 m); Gütsch (2288 m); Gomsstock (2949 m); Piotta (1015 m); Giornico (384 m); Lodrino (260 m); and Magadino (200 m). The time
series for these stations, with the exception of the Alpine crest station Gemsstock, is almost complete. The Gemsstock data were excluded from the analysis, and the few data gaps for the remaining stations, (only single data points in the vast majority of cases) were filled using an appropriate spline technique on the time series for the individual stations. This data supplement provides us in effect with a complete series with which to undertake the drag analysis.

Also at our disposal for the interpretation of the drag results are the data from the isolated crest stations of Pilatus (2110 m) and Cimetta (1647 m), and the aeronautical data from the contiguous radiosonde stations Stuttgart, Merenschwand (near Werd), Gütsch, Oberwald (located ~30 km WSW of Gütsch at the head of the Rhone valley) and Milan.

c. The analysis procedure

Estimates of the pressure drag were sought for the segment of the Gotthard region lying 400 m above MSL, from near Werd in the north to near Giornico in the south. An evaluation is required of the integral for the pressure drag per unit length,

\[ D/l = \int_{Z_{MSL}}^{Z_{MSL}} (\Delta p)dz, \]

where \( \Delta p \) is the pressure difference across the mountain at a height \( z \). Thus the pressure values at the microbarograph stations must be utilized to determine \( (\Delta p) \) as a function of \( z \), i.e., \( \Delta p = \Delta p(z) \). In essence this involves a vertical and horizontal spatial interpolation. In view of the large horizontal spatial scales, and comparative data paucity associated with previous studies, it has been usual to adopt schemes that major on the vertical interpolation component (e.g. Wahr and Oort, 1984; Hafner and Smith, 1985). For this study the station array was such as to permit a scheme based more directly upon horizontal interpolation.

The method adopted involved a two-step procedure. First, an idealized, smooth orographic cross section was constructed from the pertinent stations listed in the previous subsection (but with the exclusion of Gemsstock). This was achieved by applying a spline interpolation scheme to the altitude values of these stations. The resulting "artificial" orographic profile, \( \eta = \eta(x) \), is displayed in Fig. 3 alongside some other "real" terrain profiles. A similar interpolation is then performed with the measured values of \( (\ln p) \) at these same stations. This provides an estimate of the horizontal spatial variation of \( (\ln p) \) along the \( \eta \) surface. The resulting two fields, \( \{ \eta = \eta(x), \ln p = \ln p(x) \} \), together yield \( (\Delta p) \) as a function of height \( (z) \). The second step, the evaluation of the integral, is then straightforward.

It is appropriate to make several remarks regarding the adoption of this particular and somewhat unconventional approach:

1) Use of a more realistic orographic profile is clearly possible, but this is hardly justifiable given the station
Fig. 3. Orographic profiles within Switzerland for (a) a transect in the neighbourhood of the microbarograph array, (b) a transect along the meridian through Pilatus, and (c) the artificial terrain obtained by a spline interpolation between the altitude values of the indicated stations. (Orographic data was available every 250 m for profiles "a" and "b").

Density of the microbarograph network in the inner-region of the Gotthard. A comparison with Fig. 1 and the other profiles in Fig. 3 suggests that the 'constructed' terrain captures only the larger, meso-α/β structure of the Gotthard pass. Indeed the 'constructed' terrain bears a not unreasonable resemblance to the single-ridge, quasi-direct transect referred to earlier. These factors tend to alleviate concern regarding the effect of the inevitable smoothing associated with spline interpolation. In effect we estimate, consistent with the resolution of the available data, the meso α/β drag of an unit strip along the Gotthard.

2) The scheme automatically ensures that the drag value is identically zero under isothermal conditions. Special precautions are required to establish this desirable feature when using other approaches if the station spacing is irregular (see e.g., Wahr and Oort, 1984).

3) The scheme operates exclusively with pressure. Thus the problems associated with pressure reduction to a standard level (Schüepp et al., 1964; WMO, 1984) are avoided. Also circumvented is the attendant need to acquire temperature and humidity measurements and to estimate their vertical and horizontal variation.

4) In essence, the method operates throughout on relative-pressure values. Hence errors in the estimates due to instrumental inaccuracies are only subject to the more favorable relative accuracy criterion of 0.1 mb.
5) The present formulation places $Z_{\text{crest}}$ at the level of Gütsch (2288 m). This level, although higher than the Gotthard pass itself, is somewhat lower than the mean height of the Gotthard ridge in this region. To this extent our drag estimates will be conservative.

6) The restriction of the drag estimate to the domain between Werd and Giornico excludes the additional drag contribution linked to the Alpine region south of Giornico.

7) Some practical aspects of the accuracy and sensitivity of this method are presented in a later section (Sec. 4).

It is also very helpful, for diagnostic purposes, to examine the space–time variation of the temperature and pressure along the Gotthard section. To facilitate this purely interpretative analysis, it is helpful to remove the basically quiescent hydrostatic signal from the data for the mountain stations. The choice of surface potential temperature achieves the desired effect for the thermodynamic variable. Quantitative accuracy is not required in this phase and thus for simplicity an ad hoc scheme was adopted for the pressure reduction. First, the pressure at every station was modified by a reduction factor given by the ratio of the ALPEX-SOP
mean pressure at a standard station (Altdorf) to the same mean at each of the other stations. In the second stage the pressure value at Gütsch is further modified based upon the high correlation between the [Gütsch (2288 m)–Gurtneren (737 m)] and the [Pilatus (2110 m)–Brunnen (438 m)] pressure differences (Fig. 4). Both pairs are neighboring sets of stations; in particular, all four lie on the Alpine northside with Pilatus constituting an isolated peak. Thus this second stage is an empirical adjustment for air mass temperature variations beneath the height of the Gotthard crest on the Alpine northside. It is to be noted that this procedure is employed only for the space–time display of the pressure field and is totally uncoupled from our method for estimating the drag. These space–time sections are reminiscent of Hovmuller diagrams, and proved to be very enlightening diagnostic tools in the drag-interpretation phase of the study. [An atlas of these sections for the whole ALPEX period has been prepared (Phillips, 1984).]

3. Structure of the drag time trace

The time trace of the pressure drag per unit length for the local Gotthard region, computed as outlined in the previous section, is shown for the periods 1–31 March and 1–28 April 1982 in Figs. 5a, b. The pressure drag varies between $\pm 7.5 \times 10^3$ nm$^{-1}$ with a mean of $+0.78 \times 10^3$ nm$^{-1}$. (Positive values signify an atmospheric drag upon the earth toward the south.) These values correspond respectively to a pressure drag per unit area ($D/\Delta$) of the order of $\pm 7.5$ Pa and a mean of 0.78 Pa, since the width of the section is approximately 100 km. For more than 90% of the time the drag per unit area lies between the limits of $\pm 5$ Pa. Recall that
a drag of 5 Pa is sufficient to deplete the momentum of the entire troposphere as it traverses the Alpine ridge. Alternatively, it can be viewed as roughly equivalent to the form drag, per unit width, over-parkland terrain extending over 2,500 km.

In the following subsections we examine the detailed structure of the time variation of the drag.

a. Relationship with synoptic scale flow development

A concise summary of the general weather developments during the ALPEX SOP is given in ICSU/WMO (1982c). Three distinct phases were identified:

- A first period (1–21 March) characterized by a succession of surface frontal systems sweeping southeastward over the Alps, and repeated lee cyclogenesis events on the Alpine southside.
- A second period (22 March–5 April). In the first week of this phase a weak elongated high pressure system enveloped western Europe. The pattern was disrupted by one cold front episode, and thereafter another diffuse high pressure system was established. Prior to the disruption there was quasi-steady easterly low-level flow in the Alpine region, and afterwards the winds shifted southeasterward.
- In the remaining period (6–30 April) the midtropospheric situation over north-central Europe comprised a deep, generally northerly airflow. However, only at the end of this period was there significant penetration of low-level cold air to the Alpine southside.

Figure 6 is an attempt to summarize, in a diagrammatic form, aspects of the foregoing train of weather events, and their influence on some of the weather elements in the inner region of the Gotthard section. One recurring feature is worthy of particular note: The weather sequence demarked by the heavy sloping lines serves to highlight an oft-repeated sequence of events, viz. a cold front approaching from the northeast accompanied by mild south–Föhn conditions, followed by the frontal passage, lee cyclogenesis and frequently...
FIG. 7. Schematic of two recurring signatures in the time trace of the drag: (a) the variations accompanying a cold front passage, and (b) the signal during quasi-steady or weak synoptic situations.

FIG. 8. Juxtaposition of the pressure drag variations (solid line) for 15–28 March with (a) the corresponding horizontal pressure difference (mb, scale on right) at 400 m between Stuttgart and Milan (dashed line), and (b) with the in situ, synoptic scale, pseudo-pressure drag (dashed line) derived from the same radiosonde data. (Units as for Figs. 5.)
persistent (≥2 days) mild north−föhn conditions. This sequence is typified by the period 3−6 March.

Useful qualitative understanding of the drag variations can be gained by directly relating characteristic features of the traces of Figs. 6a, b with the co-temporal synoptic scale phenomena. One distinctive recurrent signature of the drag trace is displayed schematically in Fig. 7a. Not unreasonable analogues of this signature occurred during the aforementioned cold frontal episodes of 1−3, 3−7, 10−12, 12−14, 14−19, 19−21, 30−31 March; 8−10, 22−23, 23−24, 26−27 April.

A second distinctive signature is shown in Fig. 7b. This feature is evident during prolonged periods when the low-level gradient of the synoptic scale pressure field is weak and/or quasi-steady (e.g., 24−27 March, 19−21 April). The signature is essentially a diurnal signal superimposed upon a slowly varying mean. This second pattern is presumably a local Alpine induced effect, and it is examined in more detail in the next subsection.

These two signatures, particularly the synoptically forced frontal signature, account for a substantial part of the variance in the drag estimates. It is therefore of interest to inquire what percentage of the drag variation is explicable purely in terms of the larger-scale synoptic flow field. The strong correlation between the local Gotthard region drag and the larger scale synoptic flow field is strikingly illustrated in Fig. 8a, where the time trace of the horizontal pressure difference at 400 m between Stuttgart and Milan (derived from the radiosonde data) is plotted alongside the trace of the Gotthard pressure drag for the 15−28 March period. The correlation evident in this figure is maintained throughout the two-month period. In opposition, Fig. 8b contrasts for the same time period the actual estimated drag with a pseudo-drag representing the in situ synoptic scale contribution. The latter drag is obtained by projecting the horizontal pressure difference between Stuttgart and Milan onto our simplified Gotthard topography, assuming a linear variation of the pressure in the horizontal. It is evident from Fig. 8b that, although the phase of the drag is linked to the in situ north−south synoptic pressure field, the amplitude of the drag is determined principally by mesoscale effects. This point is further emphasised by the relative amplitudes of the three pressure gradient fields displayed in Fig. 9. These three, north−south pressure gradients at a height of 400 m MSL represent, respectively, the inner-Gotthard region of Werd/Merenschwand-Gior nico, the northern Alpine-removed region of Stuttgart-Merenschwand and the southern region between Gior nico-Milan. Inspection of these time-trace profiles indicates that neither the amplitude nor phase of the pressure gradients for the two outer regions are a satisfactory guide to the values for the inner region. The inference is that mesoscale effects induced in the immediate vicinity of the ridge, or conceivably the advection of mesoscale flow systems toward the ridge, strongly modify the synoptic scale north−south horizontal pressure gradient and concomitantly provide the

Fig. 9. Time trace for the 15−28 March period of the horizontal pressure gradient at a height of 400 m between Stuttgart-Merenschwand (long dashed line), Merenschwand/Werd-Giornico (solid line) and Giornico-Milan (short dashed-line); units (Pa km⁻¹).
Fig. 10. The diurnal cycle in the \(\overline{(D/\Delta)}\) pressure drag values (see text for definition).

A measure of the climatological mean, for the two month ALPEX period, of the diurnal variation of the drag was obtained by averaging the 10 minute drag data for the 24 hour cycle over the whole ALPEX period of 61 days, e.g., for the midnight data,

\[
\overline{(D/l)}_{l-00} = \frac{1}{61} \sum_{i=1}^{61} (D/l)_{i-00}.
\]

The 24 hour cycle of \((D/\Delta)\) is shown in Fig. 10. It has an amplitude \(~\sim 0.5\) Pa (c.f., full drag variation \(\approx \pm 5\) Pa). It attains its maximum and minimum values at around 1500 hours and midnight respectively. This phase and amplitude of the diurnal variation accounts for some of the smaller amplitude variations in \((D/\Delta)\) that occur not only during quiescent synoptic periods but also even during periods of intense synoptic activity. One example of the latter is the 9–10 April period (see Fig. 5b).

The seed of the explanation for this effect can be deduced from Fig. 11. Here a space–time section is shown of the adjusted surface-pressure field derived from the microbarograph network data. The display covers the region from Hechingen in the north to Lugano in the south for the period around 15 April. A semidiurnal variation (amplitude \(~\sim 0.5\) mb) is evident in the northernmost region, a diurnal variation (amplitude \(~\sim 1\) mb) on the Alpine southside and a combination of the two variations on the northern Alpine slopes.

An alternative estimate of these values can be obtained by computing an ALPEX climatological mean of the diurnal \((\bar{p}^D)\) and semidiurnal \((\bar{p}^{SD})\) variation of the pressure fields at each of the microbarograph stations, using the following formulae:

\[
\bar{p}^D_{l-00} = \frac{1}{61} \sum_{i=1}^{61} (p|_{i-00}),
\]

and

\[
\bar{p}^{SD}_{l-00} = \frac{1}{122} \sum_{i=1}^{61} (p|_{i-00} + p|_{i-12}).
\]

Fig. 11. Space–time section of the adjusted surface pressure field between Hechingen on the northern side of the Black Forest to Lugano in southern Switzerland for 15 April 1982 (isolines every 0.5 mb).
Figure 12 displays these variations for a key sample of stations. The results indicate a semidiurnal oscillation whose amplitude shows no perceptible change with latitude but decreases from ~0.6 mb at 400 m to ~0.3 mb at 2950 m. On the other hand the diurnal variation has an amplitude ~0.2 mb on the northern pre-Alpine region and values ≥1 mb in the Levantina. [The amplitude and phase of these variations at Zürich are in reasonable accord with those reported by Haurwitz and Cowley (1975) based upon statistical analysis of 49 years of data].

To interpret these results we note that the upper reaches (i.e., at elevations above 440 m) of the Reuss and Ticino stations are geometrically similar, albeit orientated in different directions. The latter valley is, however, far more constricted at altitudes lower than 440 m. This factor can limit the nighttime drainage of cold air from the upper reaches and hence induce the observed latitudinal variation of the diurnal pressure cycle and the related diurnal cycle in the drag. It is thus conceivable that this diurnal effect would be reduced if the section for the drag computation was extended southward onto the Italian plain region in the neighborhood of Milan.

c. Buoyancy waves

The definitive quantitative determination of the drag contribution of meso-β scale buoyancy waves requires measurements made from north–south aircraft traverses of the Alps in the mid- and upper troposphere. Such measurements were undertaken during the SOP (ICSU/WMO, 1982b). These measurements, when they become available, coupled with the estimates of the present study, will help establish the ratio of form- and wave-drag contributions in the Alpine region.

Here we are restricted to making some indirect inferences. Theoretical considerations (see Table 2) suggest that for certain ideal flow systems the wave momentum flux associated with untrapped vertically propagating buoyancy waves is proportional to \(NU\), where now \(U\) is the incident flow component normal to the mountain ridge. In Fig. 13 the value of this product at a height of 3000 m, is computed from the radiosonde data of Merenschwand (for northerly flow) and Milan (for southerly flow) for the whole SOP period. A high elevation, 3000 m, was chosen for the evaluation to reduce, at least partially, the impact that low-level blocking would have upon the magnitude of \(NU\). However, the possible existence of variable depths and extent of upstream blocked air precludes a meaningful direct comparison of the time trace of \(NU\) with the derived values of the pressure drag. This limitation follows from noting that the drag formulation for untrapped buoyancy waves varies with both the height (see Table 2) and the shape of the mountain ridge. In effect, blocking would modify the “effective” mountain profile encountered by the incident far-upstream flow.

This caveat necessarily limits the usefulness of comparing the variations of \(NU\) in Fig. 13 with the time trace of the drag (Fig. 5). Visual inspection of these figures reveals a good qualitative similarity of the profiles during the first (1–21 March) of the three ALPEX weather phases referred to earlier. However, it has already been noted that the drag during this period is strongly correlated with the advection of fronts into the Alpine domain and hence the buoyancy wave effect would simply modulate this signal. In contradistinction it is of interest to note that a prolonged period of large positive drag values between 9–14 April, associated with a high–low dipole across the Gotthard (reminiscent of a buoyancy wave signature at the surface) does not have a comparable signature in Fig. 13. This is an indication that the ageostrophic, essentially north–south flow was weak in this system. Indeed, toward the end of the period strong low-level easterlies were recorded at Payerne and Merenschwand, and the resulting drag mechanism must relate to a rotationally influenced meso-α and synoptic-scale effect.

In the absence of aircraft data some interesting ancillary evidence of the existence and vertical structure of buoyancy waves above the St. Gotthard crest can
be gleaned using the radiosonde data from the contiguous location of the Gütsch and Oberwald stations astride the crest. In Fig. 14 the vertical structure of the potential temperature field is displayed for the cases of strong southerly (28 March) and strong northerly (27 April) flow. In both cases there is evidence of large isentrope displacements at ~4–5 km with a nodal point at ~7 km. Other features of these two cases will be referred to in the next section.

The information presented in this subsection suggests that untrapped buoyancy waves might be sporadically significant contributors to the drag—this will need to be verified by aircraft measurements—but that other flow systems also play an important part.

d. Blocking and deflection

Scale analysis considerations and appropriate model studies suggest (e.g., Pierrehumbert, 1985) that the character of uniform (\(U\) and \(N\) constant) incident steady flow over an infinite or elongated ridge is governed by the values of the Rossby and Froude numbers,

\[ R_0 = U/L \quad \text{and} \quad F = U/NH, \]

where \(U\), \(N\), \(L\) and \(H\) denote, respectively, the incident velocity, the Brunt-Väisälä frequency, and the horizontal and vertical scale of the ridge. In the parameter space of \((R_0, F)\), it can be shown that upstream blocking of the flow is expected if,

\[ F \leq 1, \quad R_0 \geq 1, \]

\[ F/R_0 \leq 1, \quad R_0 \leq 1. \]

Estimates based upon the Merenschwand radiosonde data indicate that \(F \leq 1/2\), and usually \(F \leq 10^{-1}\) in the lower troposphere during periods with a northerly wind component. Moreover, for the same periods, \(R_0 \gg 1\) for the Gotthard region. On this basis the northern Alpine foreland should frequently be characterized by upstream blocking of the flow or low-level deflection of the flow around the Alps. Moist convective processes can provide two disparate effects: the existence and release of conditional instability on the upslope will, in effect, reduce \(N\) and increase \(F\), while evaporative downdrafts can produce the opposite effect. The detection and analysis of this blocking/deflection effect was one of the primary goals of the ALPEx program. Preliminary analysis of aircraft data has shown evi-
idence of deflection of the low-level cold frontal air of 2 March around the ridge (Kuettnner, 1982). Also in quasi-steady northerly flow (29 April) a shear layer has been detected at the level of the Alpine crest in the air some distance (~100 km) upstream of the Alps (Pierrehumbert, 1985). In principle the depiction of isentropes in a north-south section across the Gotthard during quasi-steady synoptic stations of northerly or southerly flow can provide some evidence of the extent of the blocking. Analyses of this kind were undertaken (Davies et al., 1984) using the Stuttgart, Merenschwand, Gütsch, Oberwald and Milan sonde data and the surface array of stations for the protracted periods of northerly flow (1200 GMT 27 April 1982) and southerly flow (1200 GMT 28 March 1982). In both cases there is clear evidence of upstream deflected/blocked flow almost up to the crest of the Gotthard. In the context of the present study this mesoscale blocking of a layer of colder air on the upstream side of the Gotthard region would generate a substantial pressure drag, ~3 Pa, during such flow episodes. This value is comparable to that observed during these particular periods.

The progression of a cold front toward the main Alpine ridge also potentially constitutes an example of a transient development of a blocking event. An examination of the space–time sections of the surface potential temperature indicates that such fronts are invariably either retarded or distorted by the Alps. Such a section is shown in Fig. 15 for the strong cold front that approached the Alps early on 24 April. The leading edge of the surface front (θ ~ 284°) crests the ridge but the rear portion is confined to the north slope. Inspection of Fig. 6 shows that most passages of cold fronts are preceded by mild south föhn conditions and succeeded by mild north föhn conditions. Our definition of these conditions (see legend of Fig. 6) is consistent in each case with a measure of upstream blocking. These south and north föhn episodes are linked respectively (cf. Figs. 5 and 6) with substantial, and often persistent, negative and positive values of the pressure drag.

In view of the foregoing it is reasonable to conjecture that this form of blocking was a prevalent (and perhaps predominant) drag mechanism during the SOP. Note however, that there can be a coexistence of upstream blocking and vertically propagating buoyancy waves (e.g., the two cases of 28 March and 27 April). It can be argued that the low-level upstream blocking modifies the "effective" mountain profile to a ramp configuration with a sharp downslope, and this in turn enhances the amplitude of the buoyancy waves.

Fig. 14. The vertical structure of the potential temperature field at Gütsch and Oberwald during the quasi-steady period of (a) northerly flow (1200 GMT 27 April) and (b) southerly flow (1200 GMT 28 March).
4. Sensitivity studies of the drag estimates

The density and distribution of the microbarograph network, along with the data quality, will influence the accuracy of the inferred pressure drag values. In view of the arrangement of stations along the inner Gotthard region, the rudimentary analysis procedure outlined earlier was adopted for the computation of the drag. Here we comment in turn upon the sensitivity of the derived estimates to various factors.

a. The analysis procedure

An alternative (and simpler) analysis procedure was also implemented. It consisted of a piecewise linear orographic profile formed by joining the neighboring stations with line segments; pressure differences were formed by direct interpolation of ln p with height. The resulting differences in the drag estimates were insignificant. However, it is to be noted that this comparison would not of itself reveal a systematic bias arising from the asymmetry with respect to height of the locations of the stations.

b. The accuracy of the pressure data

To examine the sensitivity to data errors, the full time trace of the drag and its diurnal variation was evaluated with the original analysis procedure but now with a time invariant pressure perturbation of 0.2 mb imposed at a given station. This computation was performed successively for perturbations at each of the five key stations of Altdorf, Gurtrel, Gütsch, Piotta and Giornico. There was comparatively little variability of the difference within the diurnal cycle. Based on these computations the departure from the ALPEX-mean drag of 0.78 Pa was respectively +0.01, +0.20, +0.19, −0.16, and −0.09 Pa. Again a comparison of the original and new time traces during periods of rapid and large change in the pressure drag, e.g., 3−4 and 10−11 March, yielded comparable (~0.2 Pa) deviations.

c. The density of the network

One aspect of the sensitivity to station density was examined by computing the entire drag time trace with Altdorf, Gurtrel, Piotta and Giornico treated in turn as “missing data” stations. The magnitude of the departures from the ALPEX-mean value of the drag were respectively −0.04, −0.52, +1.19, and −0.07 Pa, with corresponding standard deviations of 0.04, 0.61, 0.37, and 0.11 Pa. These results indicate that the station density, as opposed to inaccurate data, is the limiting factor in our drag estimation.

The strong dependence of the drag values upon the data from the slope stations of Gurtrel and Piotta is not unexpected. However, the magnitude and asymmetry of the results for these stations warrants further consideration. This asymmetry in the ALPEX-mean values is not merely a statistical residual but is also evident in periods of strong northerly and southerly flows, during frontal passages, and in the diurnal variation.

The effect is apparent and typified in Fig. 16 which shows, for the period of rapid and large change between
10–11 March, the original time trace of the drag alongside the traces derived without the Gurtnellren data and without the Piotta data. A reduction in the absolute value of the pressure drag for the latter two traces can readily be related to the smoothing of the field of pressure difference due to the reduced (and now inadequate) network of stations. However, in addition to a reduction observed when the data from an upstream slope station are withheld, there is also a substantial increase in the absolute value accompanying the omission of the data from the downstream station. The accentuation of the pressure difference can arise in our analysis technique if there is substantial mesoscale asymmetry in the absolute magnitude of the pressure gradients on either side of the crest. There is some evidence of this in the space–time sections of the adjusted surface pressure fields and potential temperature fields. Indeed, such a pattern would be expected during the passage of a front and in upstream blocking situations.

The differences portrayed in Fig. 16 are illustrative of the lack of redundancy in the station array, but are clearly not the error bands for the derived drag estimate. It is conceivable that the data from the mountain top stations of Pilatus, Gemstock and Cinetta could be incorporated to refine the drag estimate. On the other hand we note that, for routine estimates of the drag, a subset of the stations used in our analysis, viz. the ANETZ network of the Swiss Meteorological Service, are in day-to-day operation and yield drag estimates not substantially different from those of the network used here but with Gurttelnren excluded.

5. Further remarks

In this study we have confined our attention to the pressure drag component across, and in the immediate neighborhood of, the St. Gotthard section of the Alps. The derived estimates are the first obtained using an array of microbarograph stations aligned across such a major (~2,500 m high) mesoscale (~50 km) mountain range. The magnitude of the drag values, although subject to significant errors, indicate that the Alpine region is a major sink for atmospheric momentum. Mesoscale pressure gradients are shown to contribute substantially to the variability and mean value of the drag in the Gotthard section. It follows that attempts to infer the net pressure drag using only synoptic data will lead to an underestimate.

The present study should be viewed in the broader context of the net pressure drag acting on the entire Alpine range and the general issue of the momentum budget of the atmosphere. Thus it would be useful to extend the present study to the whole Alpine region and update the results of Hafner and Smith (1985) by incorporating additional recording stations to capture more of the mesoscale structure.

It is interesting to note from a geophysical standpoint that fluctuations in the axial and equatorial components of the atmosphere's angular momentum have been shown (Hide et al., 1980; Barnes et al., 1983) to exhibit, on time scales of the order of weeks and months, a reasonable correspondence respectively, with equal and opposite fluctuations in the axial angular momentum of the earth's solid mantle, and with the movement of the earth's rotation pole. It is the latter effect that would be primarily influenced by the Gottthard pressure drag.

A more pressing issue from an atmospheric standpoint is the relevance of the present study to the problem of the parameterization of mesoscale orographic effects in numerical weather prediction models. The magnitude of the drag values reported here clearly indicates the desirability of representing Alpine drag effects. Moreover, the interpretation of the time-trace of the drag suggests that such a parameterization will need to be a suitable combination of an enhanced, nontrivial surface drag formulation to represent small scale and blocking effects, coupled with a free atmosphere momentum dissipation to represent the buoyancy wave contribution.

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