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On shear lines in the upper troposphere over Europe

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ABSTRACT

One of the features often associated with the life cycle of large-amplitude disturbances in the upper troposphere is the formation of shear lines. A region noted for this phenomenon is western Europe.

Approximate statistics concerning the occurrence of shear lines over Europe in 1974–1976 are presented. The main emphasis is, however, given to a case study of potential vorticity budget in the region of a shear line which occurred over Europe on November 1–4, 1975. The shear line area is a region of high (potential) vorticity. For the case studied, the total time derivative of potential vorticity indicated, in the area of the shear line, a sink of this quantity with an *e*-folding time of about 1 day. If the potential vorticity is assumed to diffuse mainly vertically, an exchange coefficient of the order of 10 $m^2 s^{-1}$ is needed to explain the sink. This value agrees with that obtained by Shapiro (1980) from the observed vertical fluxes of ozone and some chemical constituents.

1. Introduction

An upper troposphere shear line is a relatively narrow zone across which there is a clear change in the horizontal wind direction, and which is thus a zone of high vorticity. In this respect it is similar to fronts in the lower troposphere. Synoptically, the shear lines are formed when an eastward moving upper-level ridge catches up with slowly moving or stationary ridge downstream and the trough between the ridges is squeezed into a narrow zone. The southern part of a cold trough quite often forms a cut-off low. Common regions of shear line formation are western North America and western Europe.

The first diagnostic studies on shear line formation (Hsieh, 1950; Newton et al., 1951) were made using data from North America, and elucidated the structure of the shear line and the role of stretching in its formation. On the basis of later dynamical and numerical studies (e.g. Lilly, 1973), it has become clear that the basic elements of shear line formation are already included in the dynamics of two-dimensional nondivergent flow. Somewhere between the wave numbers at which forcing and dissipation, respectively, take place, the spectrum of such a flow is characterized by a cascade of enstrophy towards higher wave numbers. Shear lines with their high vorticity and small horizonatal scale (determined by the flow characteristics normal to the line) represent a synoptic outcome of such a cascade.

One question which has so far received little attention is how the shear lines (and fronts) are finally dissipated. Europe has a uniform network of rawinsonde stations which is denser than that of North America, and is therefore better suited for a shear line study. The purpose of the present article is first to present a rough climatology of shear lines over Europe (Section 3). The main body of the paper is, however, devoted to a case study of a dissipating shear line, particularly in terms of potential vorticity (Section 4). Finally, some general comments are given (in Section 5) on the effect of shear lines on larger scale flow.

2. Data and data processing

The 300 mb synoptic maps from the European Meteorological Bulletin (issued by Deutscher Wetterdienst) for the 3-year period 1974–1976 are used

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to determine the rough statistics of shear lines in the upper troposphere over Europe. The case study of potential vorticity development is based on the aerological observations (at 00 and 12 GMT) from 140 aerological stations. Data were interpolated to isentropic surfaces at each station. The horizontal distribution of the zonal and meridional wind components at the $\theta = 330$ K isentropic surface and the pressure thickness of the layer between $\theta = 320$ K and $\theta = 340$ K surfaces were analysed manually for several consecutive observation times. Vorticity and the related quantities were evaluated for the $\theta = 330$ K surface using finite differences ($\Delta\lambda = 4°$, $\Delta\varphi = 2°$). The total time derivative of a particular quantity was calculated for every 12-h period as the sum of local change and horizontal advection of that quantity on the isentropic surface; the mean advection for each period was taken to be the arithmetic mean of the advection evaluated from data for the beginning and end of the period.

3. Shear lines over Europe in 1974–1976

For the purpose of getting approximate statistics of shear line occurrence over Europe, the following *ad hoc* definition of shear line was used when searching through the 300 mb (00 GMT) synoptic maps for the period 1974–1976:

(a) There has to be a line of at least 400 km, on the different sides of which the wind blows from practically opposite directions.

(b) The maximum wind speed in the jet stream associated with the shear line must be at least 23 ms^{-1} (55 knots) and the maximum shear across the line at least 0.7 f (f = Coriolis parameter).

In practice, shear lines were identified as narrow upper troughs in the geopotential field.

There were a total of 85 such shear lines in this sample of 1096 cases (i.e. a shear line in 1/13 of the cases). Fig. 1a shows the frequency of shear lines in different European subareas (a shear line was counted for that subarea in which its main part was located). The frequency is seen to be largest in south-western and southern Europe.

Fig. 1b shows the frequency of the shear lines for the whole European area (seen in Fig. 1a) by month. Main maxima are observed in early spring and late autumn. The spring maximum in the frequency distribution coincides roughly with that of European blocking (Rex, 1950). This is not surprising because formation of both shear lines and blocking highs is a manifestation of large-amplitude nonlinear upper waves.

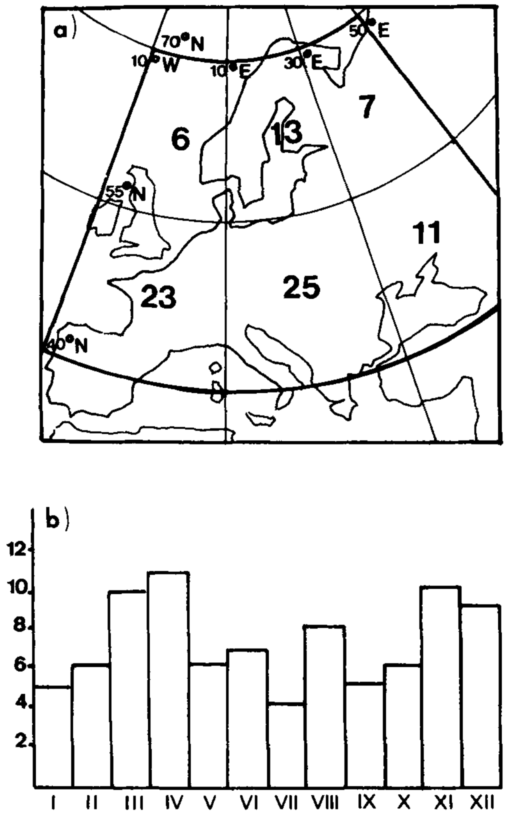


Fig. 1. (a) Number of shear line cases at 300 mb in the different European subareas during 1974–1976. (b) Monthly frequencies of shear line cases at 300 mb in Europe during 1974–1976.

The shear lines usually had a length of about 1000 km and a SW–NE orientation. Values of the horizontal wind shear were usually close to the value of the Coriolis parameter. The temperature at 300 mb west of the shear line was usually some 5 degrees higher than on the eastern side. In such a case we have the situation of warmer air coming from the north and colder air from the south, which statistically contributes to a southward eddy transport of sensible heat at 300 mb (Alestalo and Holopainen, 1980).

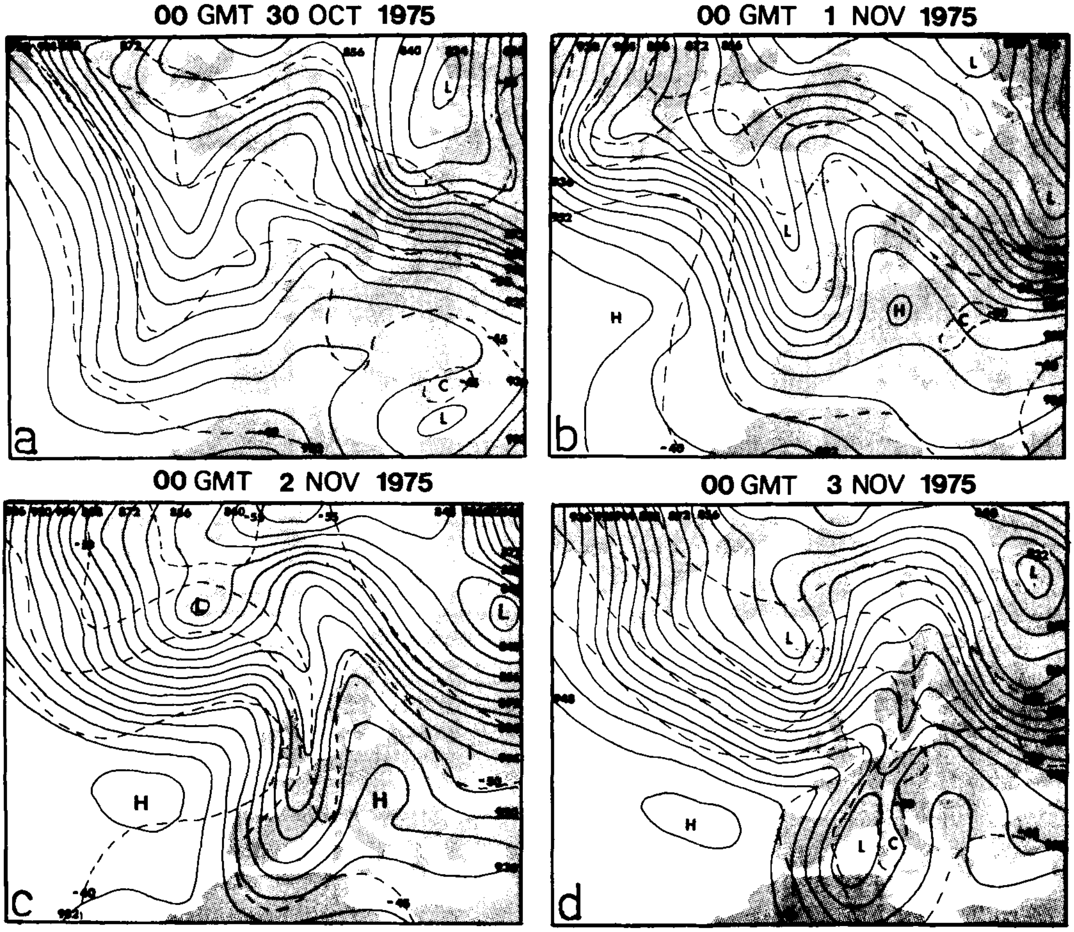
A lot of subjectivity is involved in the definition of the shear line and some ambiguity occurs in its application (e.g. due to relatively large distances between stations, even over Europe). Therefore the frequencies presented in Fig. 1 can be used to obtain only a rough idea of the geographical and seasonal distribution of shear lines over Europe.

4. A case study

4.1. *Synoptic description*

The shear line which occurred over the eastern North Atlantic and over Europe between October 30 and November 5 in 1975 was chosen for a detailed study. Fig. 2 shows the life history of the shear line (i.e. narrow upper trough) at 300 mb. The map for 00 GMT on October 30 (Fig. 2a) shows an upper trough approaching Europe. West of this trough a rapid development of a ridge is taking place (Fig. 2b). This ridge is moving eastwards with a higher phase velocity than the trough and the ridge downstream, with the result that the trough is "squeezed" between the two ridges and forms a shear line in the wind field. Later on (Fig. 2d) a cut-off low is formed in the southern part of the trough. By November 5 (not shown) the shear line had almost totally disappeared.

Fig. 3 shows the synoptic analyses at some selected pressure levels for 00 GMT on November 2. The pattern of the isobaric height and tem-



00 GMT 30 OCT 1975

00 GMT 1 NOV 1975

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00 GMT 3 NOV 1975

Fig. 2. Analyses of geopotential height (solid lines, unit: 10 gpm) and temperature (dashed lines, unit: °C) at 300 mb for: (a) 00 GMT, October 30, 1975; (b) 00 GMT, November 1, 1975; (c) 00 GMT, November 2, 1975; (d) 00 GMT, November 3, 1975.

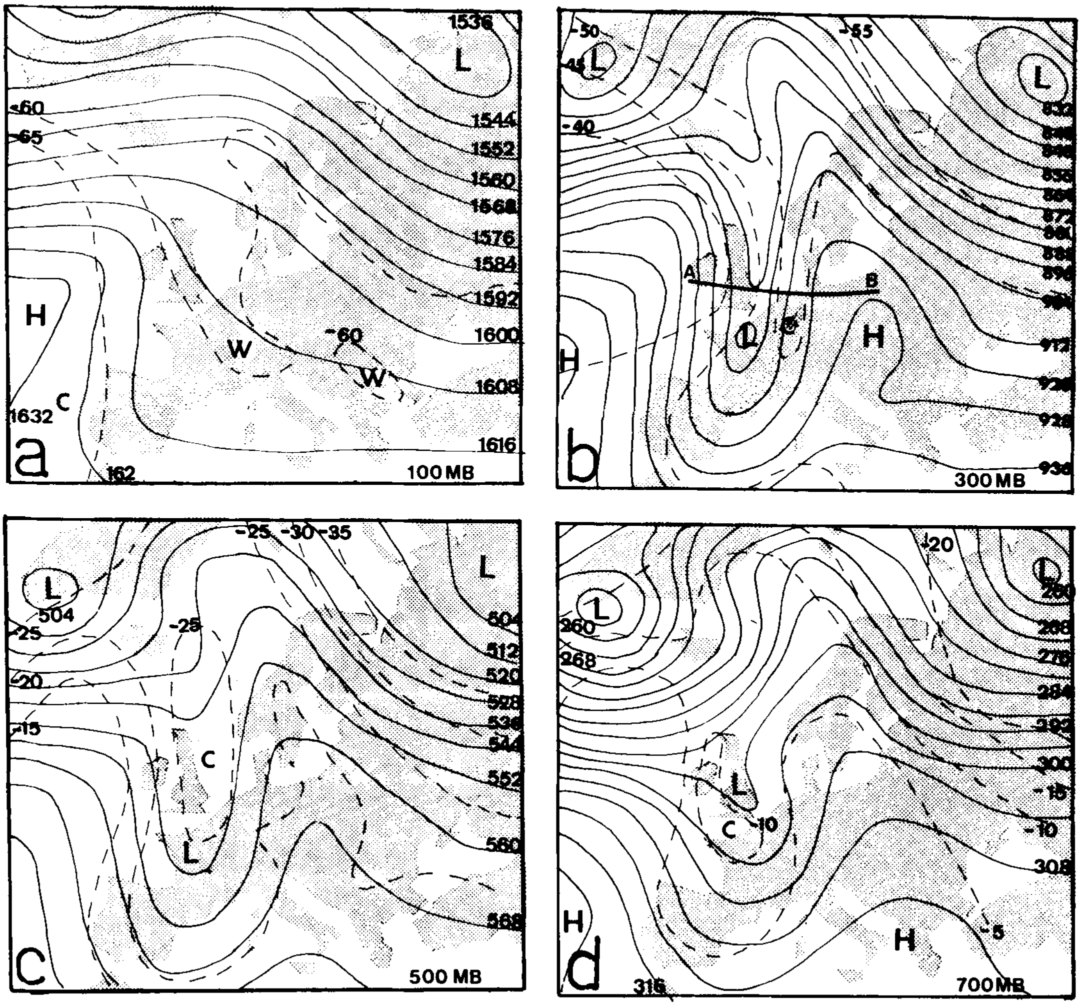

Fig. 3. Analyses of geopotential height (solid lines, unit: 10 gpm) and temperature (dashed lines, unit: °C) 00 GMT, November 2, 1975: (a) at 100 mb; (b) at 300 mb; (c) at 500 mb; (d) at 700 mb. (The analyses are redrawn from the European Meteorological Bulletin issued by Deutscher Wetterdienst.)

perature in the region of the shear line shows the structure of a narrow trough, which is seen to be most distinct at 300 mb. At 100 mb the phenomenon is visible only in the temperature field. This is normally true also for the lower troposphere, although in the particular case of Fig. 3 it can also be seen in the height field at the 700 mb level.

The "line structure" is best seen in the pattern of wind data. A vertical cross-section, perpendicular to the shear line, for 00 GMT on November 2 is shown in Fig. 4. The wind component parallel to the shear line was used to calculate the distribution of potential vorticity seen in the cross-section. Its distribution shows a case of stratospheric air seemingly being intruded into the upper troposphere: these kinds of intrusions in the case of upper level fronts have, on the basis of observations from North America, been documented by several authors (e.g. Reed, 1955; Staley, 1960; Danielsen, 1968; Reiter, 1973; Shapiro, 1980).

Basically, the cross-section around the shear line region has the same thermal characteristics (e.g. cold upper troposphere and warm lower

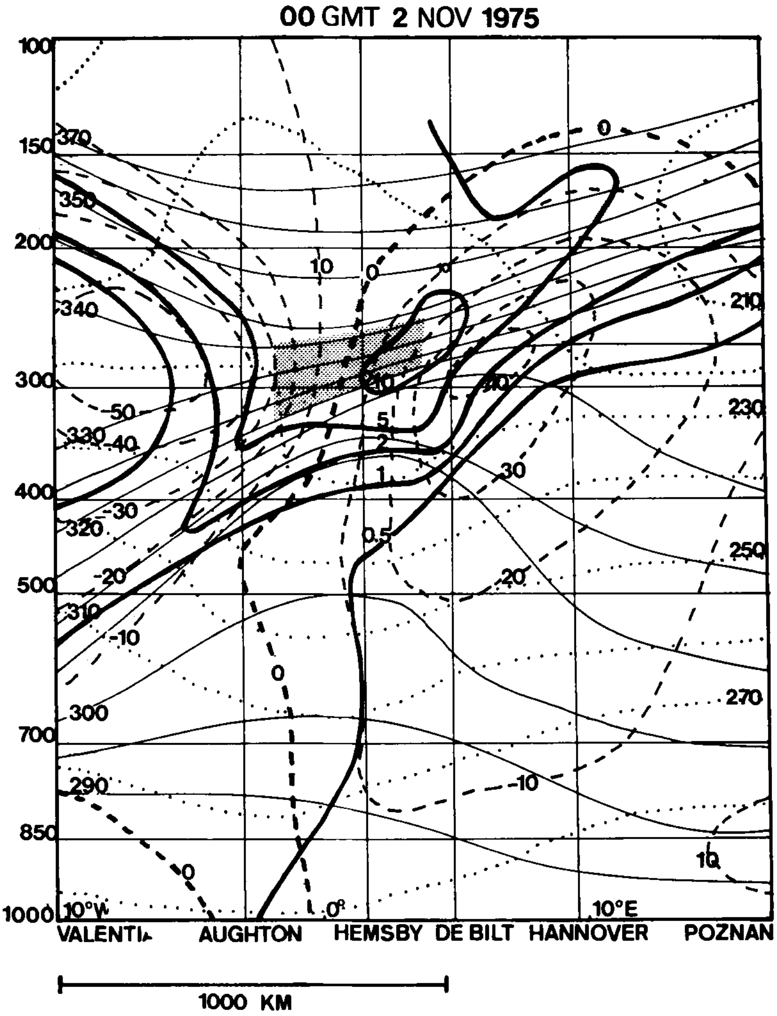

Fig. 4. Vertical cross section of potential temperature (thin solid lines), temperature (dotted lines), meridional wind component (dashed lines) and potential vorticity (thick solid lines) along the line A–B in Fig. 3b 00 GMT, November 2, 1975. Units for (potential) temperature: K, for wind: m s^{-1}, for potential vorticity: 10^{-7} K Pa^{-1} s^{-1}

stratosphere) as those observed in most synoptic scale upper troughs in the middle latitudes. The only unique feature with the shear line is its scale: the distance between the maxima of northerlies and southerlies, which is normally several thousands of kilometres in the upper waves, can be seen to be about 1000 km in Fig. 4. In the data-sparse areas such shear lines cannot be properly depicted with the aid of ordinary observations and are thus partially subgrid scale phenomena.

The distribution of relative vorticity ζ_θ (the subscript θ indicates that the horizontal derivatives involved are evaluated at an isentropic surface), static stability $(-\partial\theta/\partial p)$ and potential vorticity $P = -(\partial\theta/\partial p)\,(\zeta_\theta + f)$ at the $\theta = 330$ K isentropic surface are shown in Fig. 5. The shear line is seen to be not only a region of high relative vorticity but also of relatively high static stability and, hence, of high potential vorticity. The time sequence in Fig. 5 indicates (when considered together with Fig. 2) a gradual decrease in the potential vorticity as the shear line disappears.

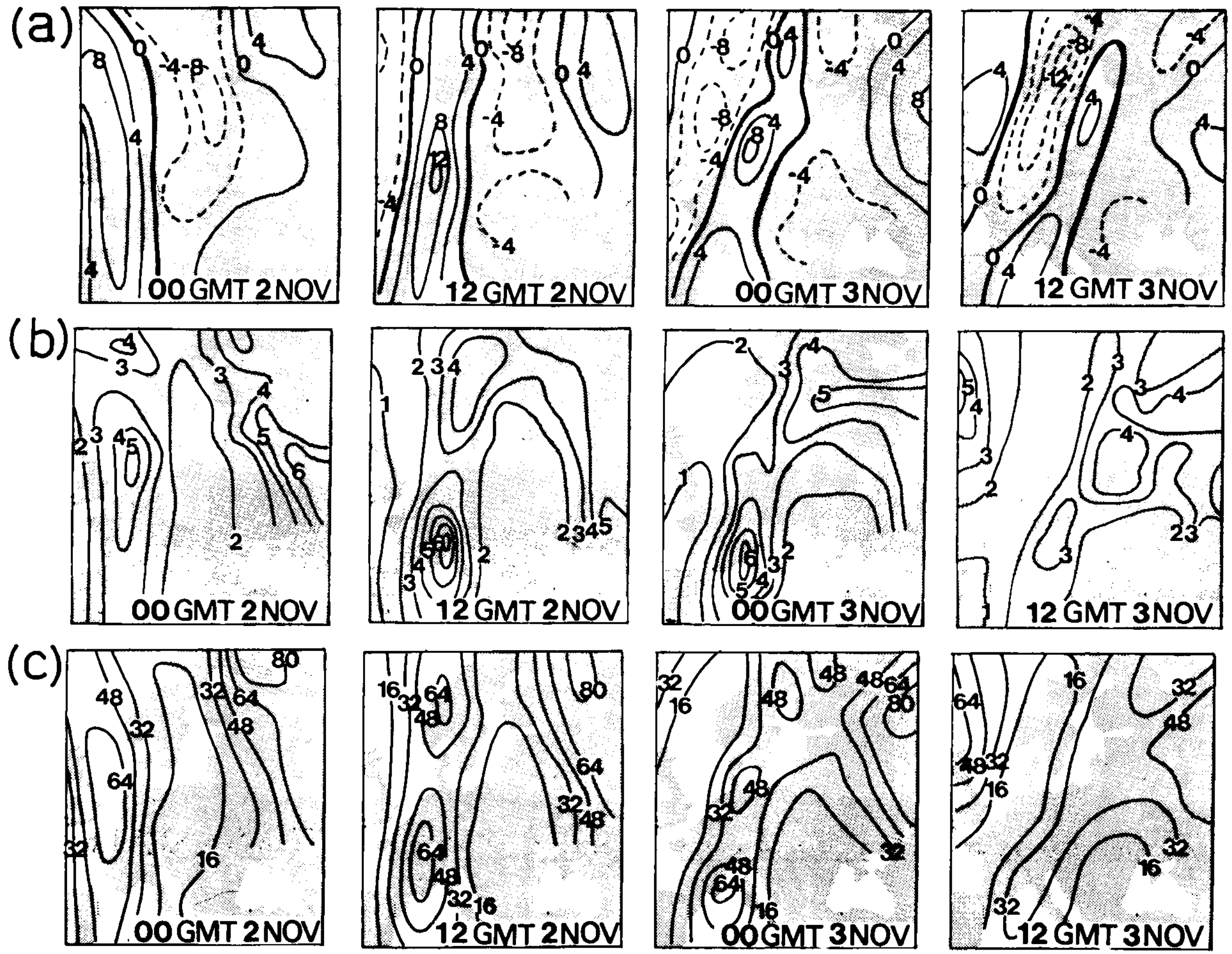

Fig. 5. Geographical distribution over Europe of: (a) the relative vorticity (in 10^{-5} s^{-1}); (b) the static stability $-\partial\theta/\partial p$ (in 10^{-3} K Pa^{-1}); (c) the potential vorticity $P = -(\partial\theta/\partial p)\ (\zeta_\theta + f)$ (in 10^{-8} K Pa^{-1} s^{-1}) on the $\theta = 330$ K isentropic surface for consecutive synoptic times between 00 GMT November 2 and 12 GMT November 3, 1975. The location of the shear line (narrow upper trough) is approximately that of maximum of relative vorticity.

4.2. *Budget of potential vorticity*

The rate of change of potential vorticity P (see Staley, 1960; Gidel and Shapiro, 1979) can be written as

$$\frac{d_\theta P}{dt} = S_p \qquad (1)$$

where

$$S_p = -\frac{\partial\theta}{\partial p}\,\mathbb{k}\cdot\nabla_\theta \times \mathbb{F} + \frac{\partial\theta}{\partial\theta}\left(\mathbb{k}\cdot\frac{\partial \mathbb{V}}{\partial\theta}\times\nabla_\theta\frac{d\theta}{dt}\right) - (f+\zeta_\theta)\frac{\partial}{\partial p}\left(\frac{d\theta}{dt}\right) - \frac{d\theta}{dt}\frac{\partial P}{\partial\theta} \qquad (2)$$

S_p represents the source of P, and d_θ/dt is the total time derivative on an isentropic surface:

$$\frac{d_\theta}{dt} = \left(\frac{\partial}{\partial t}\right)_\theta + \mathbb{V}\cdot\nabla_\theta \qquad (3)$$

(For notation used in (2) see Gidel and Shapiro, 1979.) In adiabatic ($d\theta/dt = 0$), frictionless ($\mathbb{F} = 0$) flow $S_p = 0$ and P is conserved. In the upper troposphere and in the stratosphere these conditions are usually met and the potential vorticity can in principle be used as an air tracer in the same way as ozone (e.g. Reiter, 1973).

In the region of a shear line, however, large down-gradient vertical fluxes of any quasi-conservative quantities are likely to occur in connection with clear air turbulence and the associated meso-scale circulations; direct measurements of the fluxes of potential temperature, ozone and some chemical constituents have been recently reported by Shapiro (1980). In such a case the source term S_p in (1) should be given by

$$S_p = -\frac{\partial F}{\partial z} \qquad (4)$$

(see eq. (4) in Shapiro, 1980), where F is the vertical (subgrid scale) flux of potential vorticity. If we further assume that the flux is down-gradient

$$F = -K_p\frac{\partial P}{\partial z} \qquad (5)$$

and that the exchange coefficient K_p is a constant, we have

$$S_p = K_p\frac{\partial^2 P}{\partial z^2} \qquad (6)$$

Using (3) the fields of $d_\theta P/dt$ at the $\theta = 330$ K surface were evaluated for different 12-h periods between 00 GMT November 2 and 12 GMT on November 3, 1975. The results (Fig. 6) show a decrease in potential vorticity with a typical value of $d_\theta P/dt = -4 \times 10^{-12}$ K Pa^{-1} s^{-2} in the region of the shear line. Because the typical value of P at the shear line (Fig. 5c) is 4×10^{-7} K Pa^{-1} s^{-1}, the e-folding time of the decay process is 10^5 s $\approx$ 1 day.

It is now of interest to infer from (6) what kind of

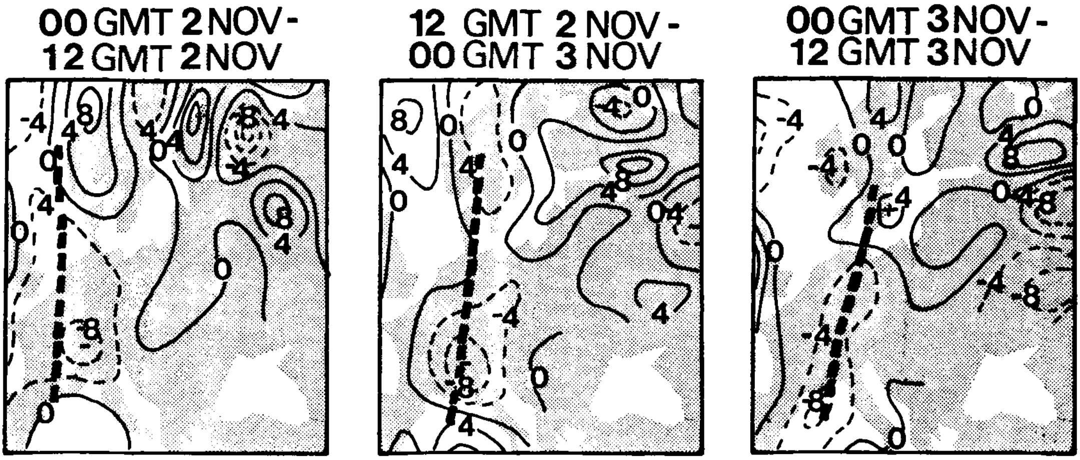

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Fig. 6. The total time derivative of potential vorticity $P = -(\partial\theta/\partial\theta\,(\zeta_\theta + f)$ (in 10^{-12} K Pa^{-1} s^{-2}) on the isentropic surface $\theta = 330$ K as a function of time. The approximate position of the shear line is indicated by the thick dashed line.

vertical exchange coefficient K_p is needed in order to give the observed value of $d_\theta P/dt$ for S_p. From the data on which Fig. 4 is based we calculate -5×10^{-13} K Pa^{-1} s^{-1} m^{-2} as the approximate average value of $\partial^2 P/\partial z^2$ in the shear region (shaded area in Fig. 4), which together with $d_\theta P/dt$ given above imply $K_p \approx 10$ m^2 s^{-1}. This is of the same order of magnitude as reported by Shapiro (1980) on the basis of direct measurements of vertical flux of ozone and particles in the case of an upper level front and the associated jet stream.

5. Discussion

Shear lines in the upper troposhere are concentrations of high (potential) vorticity and represent a product of the cascade, extensively discussed in the literature in recent years, of (potential) enstrophy towards smaller scales. The dissipation of these potential vorticity concentrations is most likely due to subsynoptic processes. Overall there has to be a balance between the rate (measured in synoptic scale terms) at which these concentrations are generated, and the rate at which they are dissipated by processes on subsynoptic scales. The fact that the time scale obtained in this study for the rate of decay of potential vorticity concentration in a shear line agrees with what Shapiro (1980) obtained on the basis of measurements on subsynoptic scales, is just one demonstration of this basic balance.

Many questions related to the shear lines (and fronts) remain to be answered. For example, is it only the vertical subgrid scale fluxes that are important in the dissipation of the shear lines (and fronts), or does, for example, lateral mixing also play some significant role? How does this dissipation influence the large-scale fields of temperature and momentum?

In the framework of a numerical model Gidel and Shapiro (1980) have conducted an interesting experiment to answer the second question. In a model, however, the results depend upon the parameterization schemes used to represent the subgrid scale processes, and these schemes may not be entirely realistic. An attempt similar to that by Staley (1960) was made here to partition $d_\theta P/dt$ seen in Fig. 6 into contributions from heating and friction. The crucial term needed for this kind of partitioning is the horizontal divergence $\nabla_\theta \cdot \mathbb{V}$. Due to inaccuracies in its determination the results (not shown) were inconclusive.

A fundamental problem in connection with the above-mentioned scale interaction problem is that the "synoptic" and "subsynoptic" processes are not distinctly different by scale. For example, the measurements by Kennedy and Shapiro (1978, 1980) and Shapiro (1980) show that in the cases of upper fronts (and the associated clear air turbulence) the vertical flux of momentum, heat, ozone, etc., takes place most efficiently at wavelengths 10–50 km, which are not far from synoptic scales. In such a case the source term (due to all unresolved scales) in the equation of the large-scale budget of a quantity q has to be written in the form

$$S_{\hat q} = -\nabla \cdot (\widehat{q\mathbb{V}} - \hat{q}\hat{\mathbb{V}}) \tag{7}$$

where ($\widehat{\quad}$) denotes the smoothing applied to the total flow in the process by which the large-scale flow is specified (Holopainen and Nurmi, 1979, 1980) and $\mathbb{V}$ is the 3-dimensional velocity. There is no guarantee that the flux $\widehat{q\mathbb{V}} - \hat{q}\hat{\mathbb{V}}$ (and thus also $S_{\hat q}$) can be parameterized in any easy way in terms of resolved-scale variables.

6. Acknowledgements

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ЛИНИИ СДВИГА И ИХ РОЛЬ В БЮДЖЕТЕ ПОТЕНЦИАЛЬНОЙ ЗАВИХРЕННОСТИ: ИССЛЕДОВАНИЕ КОНКРЕТНОГО СЛУЧАЯ НАД ЕВРОПОЙ

Одной из особенностей, часто связываемой с циклом жизни возмущений большой амплитуды в верхней тропосфере, является формирование линий сдвига. Областью, известной по частоте этого явления, служит Западная Европа. Представлена приближенная статистика по повторяемости линий сдвига над Европой в 1974–1976г.г. Однако основное внимание уделяется изучению бюджета потенциальной завихренности в области линии сдвига для конкретного случая, происходившего над Европой с 1 по 4 ноября 1975 г.

Область линии сдвига является районом высокой (потенциальной) завихренности. Для изучаемого случая полная производная по времени от потенциальной завихренности указывает на существование в облести лимии сдвига стока зтой величины со временем изменения в *e* раз иорядка 1 суток. Если предположить, что иотенциальная завихренность диффундирует в основном по вертикали, то необходим козффициент обмена порядка 10 $м^2$ $с^{-1}$, чтобы обьяснить зтот сток. Эта величина согласуется с той, что была получена Шапиро (1980) из наблюдаемых вертикальных потоков озона и некоторых химических примесей.