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Synoptic-scale fluctuations of total ozone in the atmosphere

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Abstract. A model, based on ozone-concentration tendency equation, is developed to study synoptic ozone-column variations. The application is referred to a middle-latitude site and to an atmospheric layer extending from the surface up to about 35-km altitude. Photochemical effects at the considered location for synoptic time scales are considered negligible. The data input consists of umkehr ozone profile, total ozone (obtained by Brewer No. 067, located at Rome) and horizontal wind at various levels. Analysis of several cases indicates that meridional advection is the main factor responsible for the observed synoptic-scale ozone fluctuations.

1 Introduction

The importance of synoptic-scale fluctuations in the atmospheric ozone concentration is twofold. First, UV_B irradiance is linked with the day-to-day ozone changes; a 1% decrease in total ozone can cause about 1.5–2% increase in damaging UV dose at ground level (Pyle and Derwent, 1980; Siani, 1995). Second, ozone may be considered a good tracer of stratospheric motions. By analysing O_3 local time changes, a better understanding of the stratosphere dynamics may be achieved. Middle-latitude ozone variability, at time scales of 1–3 days, depends primarily on the transport by atmospheric motions (Dobson and Harrison, 1926; Dobson, 1930). Weather systems at middle and high latitudes affect the stratosphere and the tropopause height, which in turn may influence the ozone-layer thickness. In western Europe an ozone-concentration maximum is often present in the rear side of a cyclone at the passage of a cold front, while a minimum may be found in the south-west sector of a high-pressure area close to the warm front (Götz, 1951).

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The problem of modelling and predicting synoptic-scale ozone changes may be faced by means of statistical schemes taking into account the relationship between O_3 and other meteorological quantities, like temperature and geopotential height (Poulin and Evans, 1994; Vogel *et al.*, 1995). Alternatively, dynamical models, involving trajectory techniques (Götz, 1951) or potential vorticity (Vaughan and Price, 1991), were proposed to interpret and possibly predict day-to-day ozone-column variations. In this paper a preliminary model for the analysis of synoptic-scale ozone-column fluctuations at middle latitudes, based on the O_3 tendency equation, is proposed.

2 The ozone tendency equation

In order to analyse synoptic-scale ozone fluctuations, a scheme, based on the tendency equation and combining the continuity equations for air and ozone, is outlined. The ozone tendency equation may be written:

$$\frac{N_A}{\mu}\left(\frac{\partial \rho_{O_3}}{\partial t} + \vec{V}\cdot(\rho_{O_3}\vec{V_2}) + \rho\frac{\partial(\chi w)}{\partial z}\right) = S - P, \tag{1}$$

where ρ is the air density, ρ_{O_3} is the ozone density, χ is the ozone mass mixing ratio, N_A is the number of Avogadro, $\vec{V_2}$ and w are the horizontal- and vertical-wind velocity, S and P are, respectively, photochemical sources and sinks. Integrating Eq. 1 in a column of unit area, from surface to the top of the atmosphere, we obtain

$$\frac{N_A}{\mu}\left(\int_0^\infty \frac{\partial \rho_{O_3}}{\partial t}dz + \int_0^\infty \vec{V_2}\cdot(\rho_{O_3}\vec{V_2})\,dz + \int_0^\infty \rho\frac{\partial(\chi w)}{\partial z}dz\right) = \tilde{S} - \tilde{P}. \tag{2}$$

Assuming that at middle latitudes synoptic total-ozone variations are mainly due to the atmospheric disturbances between the ground and the first 35 km of height (Holton,

1979) and furthermore neglecting photochemical sources and sinks, Eq. 2 may be written:

$$\frac{\partial O_3}{\partial t} = -\int_0^{Z_{max}} \vec{V}_2 \cdot (\rho_{O_3} \vec{V}_2)\, dz - \int_0^{Z_{max}} \rho \frac{\partial(\chi w)}{\partial z}\, dz, \tag{3}$$

where

$$O_3 = \int_0^{Z_{max}} \rho_{O_3}\, dz \tag{4}$$

is the total ozone. Moreover, if the vertical ozone flux at the top of the column (Z_{max}) is assumed to be zero, Eq. 3 may be expressed as:

$$\frac{\partial O_3}{\partial t} = -\int_0^{Z_{max}} \vec{V}_2 \cdot (\rho_{O_3} \vec{V}_2)\, dz = -\int_0^{Z_{max}} \rho_{O_3} \vec{V} \cdot \vec{V}_2\, dz - \int_0^{Z_{max}} \vec{V}_2 \cdot \vec{V} \rho_{O_3}\, dz. \tag{5}$$

It is important to note that O_3 vertical exchanges between different layers below Z_{max} are not negligible, because the ozone, entering through the column sides at any height, may be distributed vertically along all the column. For the sake of brevity, the first integral on the right side (divergence term) will from now on be indicated as 'D' while the second integral (advection term) will be identified as 'A'. To estimate daily ozone variations by means of the described scheme, it is necessary to know the wind velocity profile, as well as the O_3 vertical distribution together with their horizontal gradients along x and y directions.

3 Model application and results

The model is applied to Rome-station data, considering the atmosphere, from ground to Z_{max} (32 km), divided into eight 4-km-thick layers. The proposed scheme requires the following input:

- *total-ozone values* to compute time derivatives (spectrophotometric O_3 measurements at the Rome station are used);
- *vertical O_3 profile*; in this case data for the Rome station were obtained by means of the Umkehr technique;
- *total-ozone horizontal gradients*; in this application a grid-mesh centred at Rome, with a spacing suitable to characterise the large synoptic scale (400 km) was assumed. Total-ozone fields over Europe were provided by WMO GO_3 OS Ozone Mapping Centre (LAP, Thessaloniki). In the relatively small area being considered, ozone gradients in each layer were computed assuming:

  $$O_{3,i,k} = P_k \cdot O_{3,i},$$

  where O_3 is the total ozone, i indicates the grid point, k is a layer index and P_k is a proper weight derived on the basis of the observed vertical profile ($P_k = O_{3,k}/O_3$);
- *horizontal-velocity gradients in each layer*; all the available observational data, with special attention to the 300-hPa level, are considered; moreover mean profiles of horizontal velocity are used to complete the data set.

Table 1. Values of the correlation coefficients between the time ozone variation and the terms of the horizontal advection along the x and y directions (A_x and A_y, respectively) and of horizontal-velocity divergence (D_x and D_y, respectively); significance level 5%

r_{A_x}	r_{A_y}	r_{D_x}	r_{D_y}
0.3	0.8	− 0.2	0.1

Table 2. A_x and A_y are the horizontal advection along x and y, D_x and D_y are the terms of the horizontal-velocity divergence along x and y, $\Delta O_3/\Delta t$ is the ozone time variation, S is the sum of the four terms representing horizontal advection and divergence. All the quantities are expressed in units of 10^6 molecules $cm^{-3}\,s^{-1}$

Day	$\partial O_3/\partial t$	A_x	A_y	D_x	D_y	S
24/12/92	25.8	32.5	− 0.3	− 2.5	− 0.1	29.6
06/03/93	− 46.3	6.4	− 51.1	− 0.7	2.6	− 42.8
05/12/93	12.9	5.9	− 4.6	16.8	− 2.4	15.7

The present preliminary application is referred to a limited number of cases (22), characterised by either increasing or decreasing total ozone for three consecutive days. Results appear to be quite encouraging and consistent both with experience and physical reasoning. Nevertheless, the statistical significance should be assessed on a larger data base.

In Table 1 the values of the correlation coefficients between the time ozone variation and the terms of the horizontal advection along the x and y direction (A_x and A_y, respectively) and of horizontal-velocity divergence (D_x and D_y, respectively) are reported. The analysis of all collected cases indicates that *horizontal meridional advection* is the most effective factor in determining the observed day-to-day ozone changes. Three cases of particular interest are sorted and discussed. The first is characterised by a marked O_3 horizontal zonal advection which produces a definite positive ozone change; in the second case a negative, rather unusual, meridional O_3 gradient brings about a local ozone decrease the considered side; in the third situation horizontal-velocity convergence in the zonal direction produces a positive ozone change.

In Table 2 an estimate of the various terms, appearing in Eq. 5, is provided. A detailed discussion of each case follows.

3.1 24 December 1992

A positive time change in the ozone amount (25.8×10^6 molecules $cm^{-3}\,s^{-1}$) is recorded in the period 23–25 December. A negative gradient (west-east direction) in the ozone field is discernible (Fig. 1). The 300-hPa map (Fig. 2) shows a low-pressure area centred over Spain responsible for the eastward export of ozone-rich air. Ozone- and wind-velocity profiles are presented in Fig. 3: wind speed in the x direction is relatively large, indicating the existence of a jet stream at the tropopause level and in

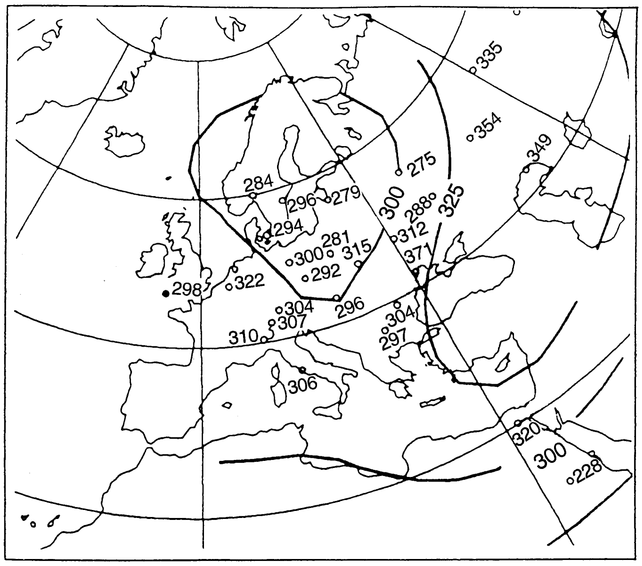

Fig. 1. 24 December 1992; ozone map (Courtesy of LAP Univ. of Thessaloniky, Greece)

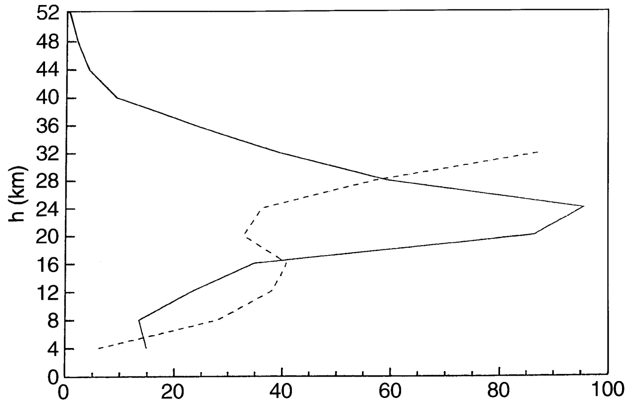

Fig. 3. 24 December 1992; *solid line*: O_3 profile (10^{11} molecules cm^{-3}); *dashed line*: zonal velocity profile ($0.5\ m\ s^{-1}$)

the lower stratosphere, while the meridional component is negligible (this curve is not plotted). Wind- and ozone-fields interaction leads to a marked O_3 horizontal advection along x with a very weak opposed effect of the velocity divergence term; in Fig. 4 the contribution of zonal advection to the ozone time change is shown as a function of height.

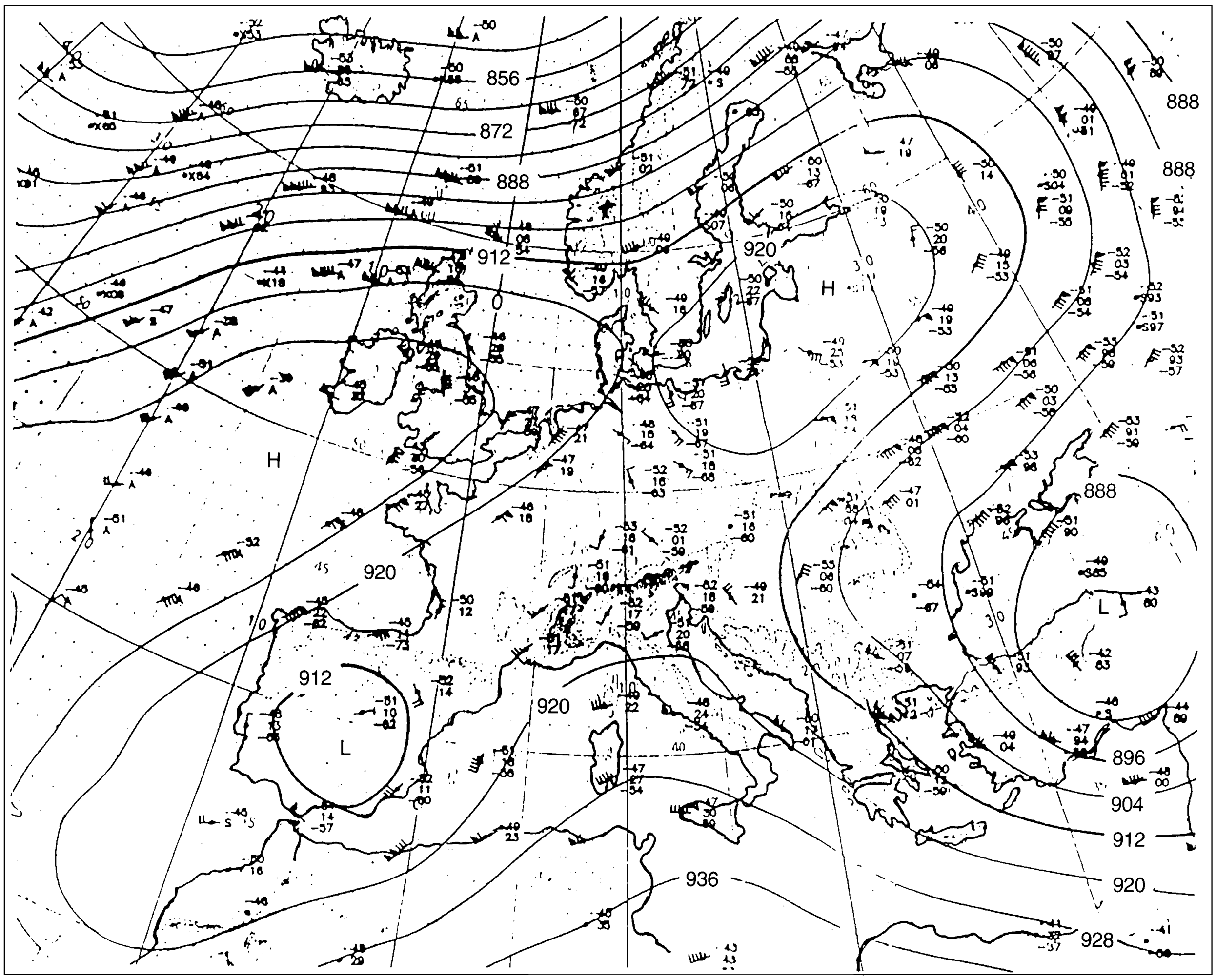

Fig. 2. 24 December 1992; 300-hPa map (Courtesy of European Meteorological Bulletin, Germany)

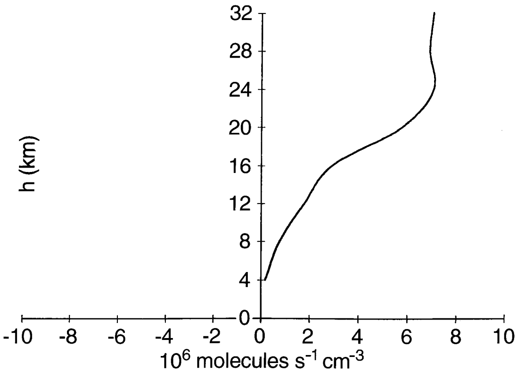

Fig. 4. 24 December 1992; contribution of zonal advection to the local variation of the ozone concentration as a function of height

3.2 6 March 1993

The negative horizontal advection along the *y* direction (northward) seems to be the cause of the decreasing O_3 (-46.3×10^6 molecules $cm^{-3}\,s^{-1}$). As a matter of fact, a strongly negative meridional gradient of ozone is clearly visible in the map (Fig. 5). The 300-hPa field (Fig. 6) is

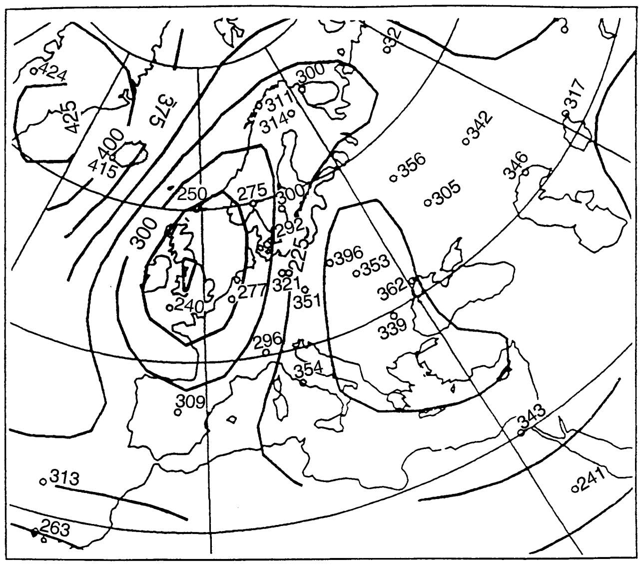

Fig. 5. 6 March 1993; ozone map (Courtesy of LAP Univ. of Thessaloniky, Greece)

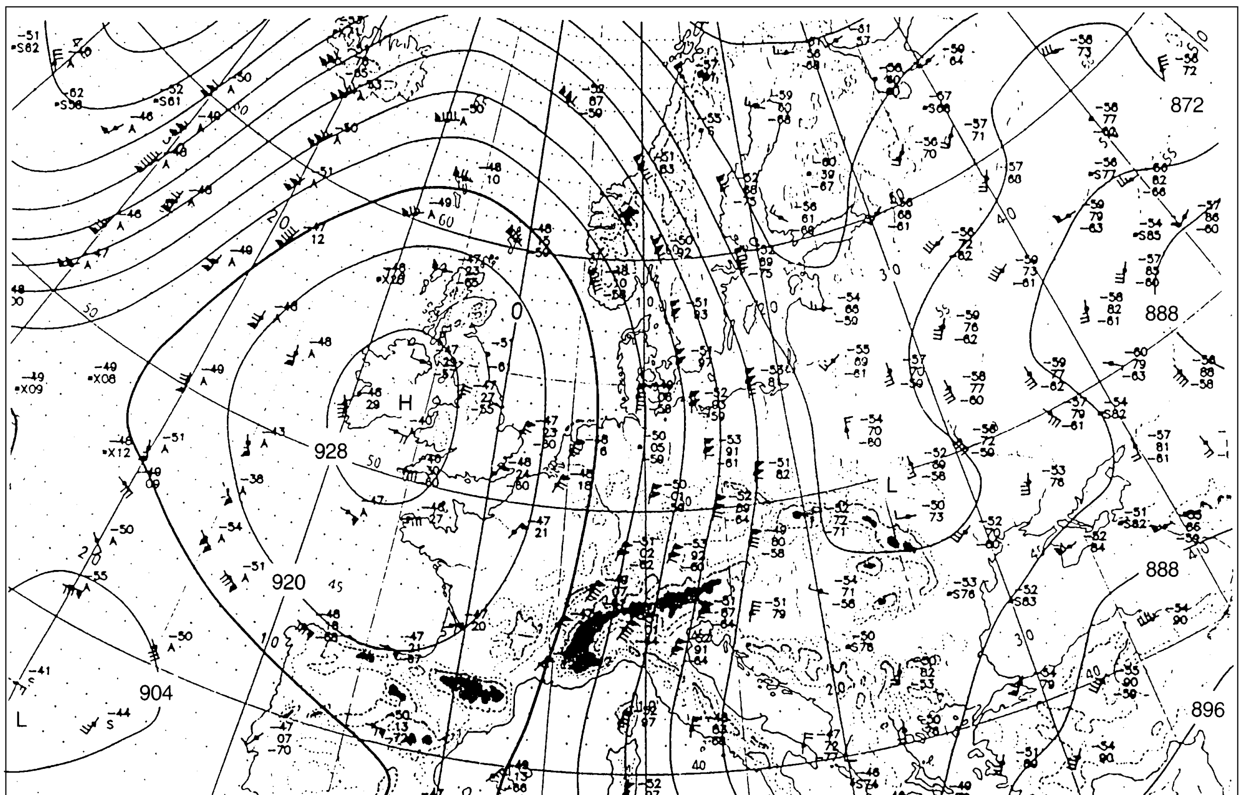

Fig. 6. 6 March 1993: 300-hPa map (Courtesy of European Meteorological Bulletin, Germany)

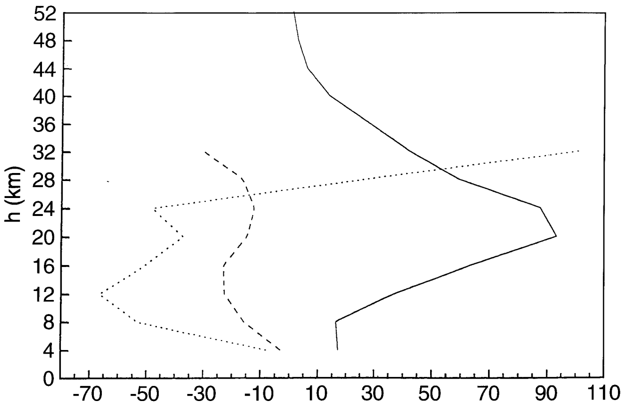

Fig. 7. 6 March 1993; *solid line*: O_3 profile (10^{11} molecules cm^{-3}); *dashed line*: zonal velocity profile (0.5 m s^{-1}); *dotted line*: meridional velocity profile (0.5 m s^{-1})

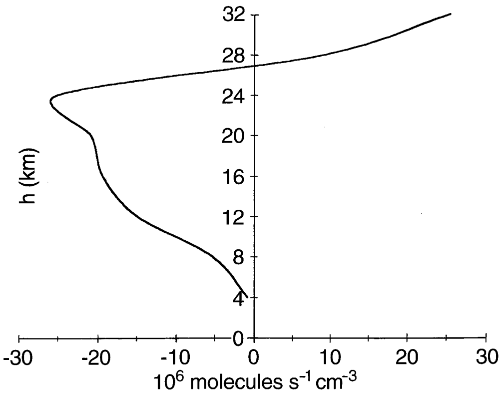

Fig. 8. 6 March 1993; contribution of meridional advection to the local variation of the ozone concentration as a function of height

characterised by a definite high-pressure area, affecting western Europe. Fairly vigorous northerly components in the troposphere and in the stratosphere up to 24 km are the dominating feature (Fig. 7). In this case, the horizontal-ozone gradients being reversed with respect to the most common situation, north-south flux of ozone-poor air is experienced. The negative contribution of meridional advection to the ozone time change is rapidly increasing with height up to a maximum at about 23 km (Fig. 8).

3.3 5 December 1993

A positive time change in the ozone concentration (12.9×10^6 molecules cm^{-3} s^{-1}) is recorded. Horizontal-velocity convergence along x determines the positive ozone variation, while horizontal advection along x and y, positive and negative, respectively, compensate each other; in fact the ozone map (Fig. 9) indicates negative meridional and zonal O_3 gradients in the area under consideration.

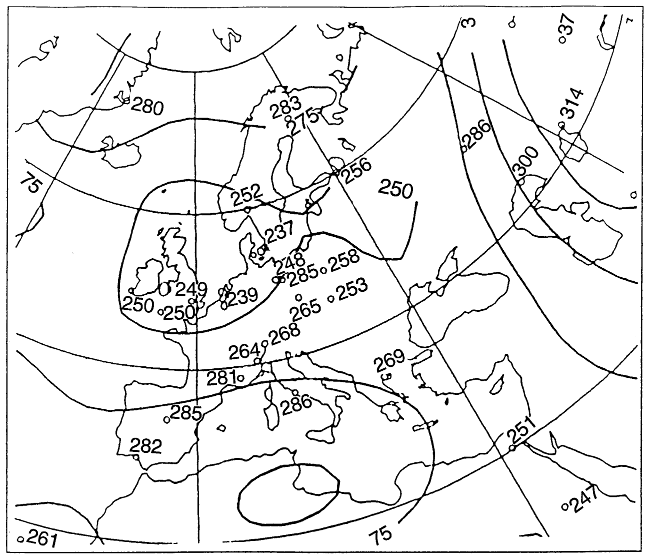

Fig. 9. 5 December 1993: ozone map (Courtesy of LAP Univ. of Thessaloniky, Greece)

The peculiar convergent pattern of the wind velocity south of Rome is due to a low pressure centred over the Gulf of Sirte, very close to the coast of Africa, as may be seen on the 300-hPa map (Fig. 10). The existence of strong northerly currents is shown clearly in Fig. 11, while the contribution of horizontal-velocity convergence is shown in Fig. 12.

4 Possible further development

The described scheme provides a methodology to interpret ozone changes having a characteristic duration of 1–3 days, and suggests a possible way to develop a tool for predicting ozone changes. As a matter of fact, total-ozone fluctuations appear to be clearly related to large-scale circulation patterns in the upper troposphere. Nevertheless, it has to be stressed that results appear to be valuable only when one of the factors involved, either advection or divergence, plays a dominating role, leading to significant ozone time changes. When a larger set of data is available, it should be possible to provide a reliable indication of the actual ozone tendency. The availability of predicted fields by global general circulation models is promising for projecting the interpretation 2 or 3 days in advance.

A further application of the proposed model, in the process of implementation, consists in experimenting the possibility of using synoptic ozone fluctuations to derive information about the vertical motion profile in the stratosphere.

5 Conclusions

The correlation between ozone time changes and horizontal meridional transport is in agreement with the

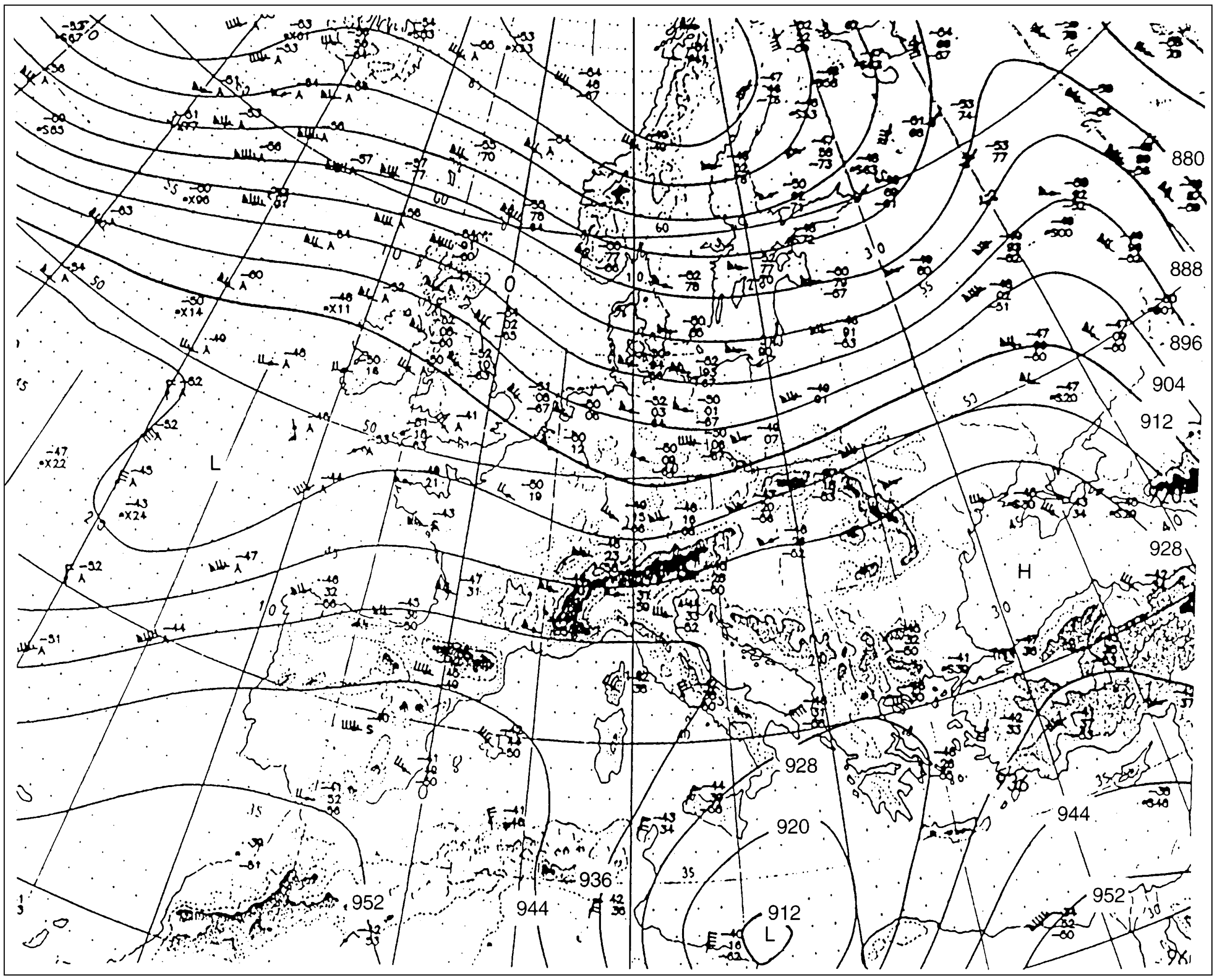

Fig. 10. 5 December 1993; 300-hPa map (Courtesy of European Meteorological Bulletin, Germany)

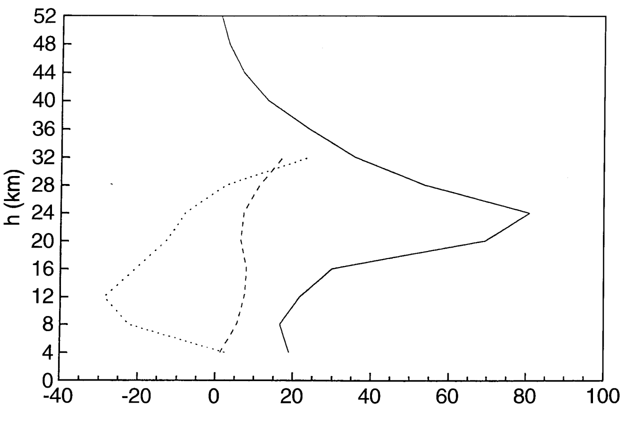

Fig. 11. 5 December 1993; *solid line*: O_3 profile (10^{11} molecules cm^{-3}); *dashed line*: zonal velocity profile (0.5 m s^{-1}); *dotted line*: meridional velocity profile (0.5 m s^{-1})

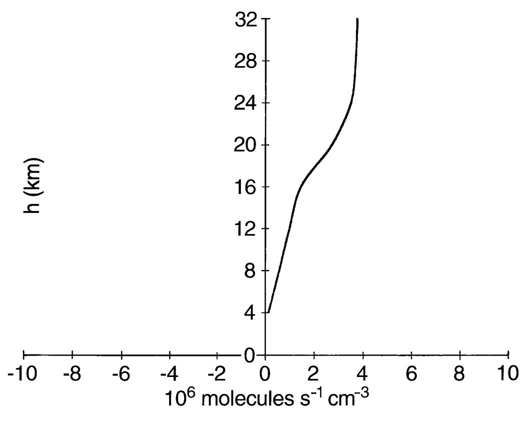

Fig. 12. 5 December 1993; contribution of horizontal-velocity divergence to the local variation of the ozone concentration as a function of height

literature, indicating horizontal advection and vertical motion in the lower stratosphere, due to the atmospheric disturbances, as the cause of the total-ozone variations.

The dominance of the advection term along the *y* direction in the ozone tendency equation shows that the synoptic ozone fluctuations are prevailingly related to the existence of south-north gradients of this trace gas.

A decrease in the total ozone is experienced when a large blocking high-pressure centre is located about 1000–2000 km upstream of the considered area. The ozone increase is very likely to occur when a cold low, extending up to the tropopause, is present upstream of the point of interest. Occasionally, large-scale velocity convergence or divergence, discernible in the flow patterns, may be an important cause of ozone variations.

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