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Vorticity generation and energy budget over central Italy

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ABSTRACT

TEMP data for Milan, Brindisi, Cagliari and Rome from 1961 to 1965 have been processed to study vorticity generation and energy budget over central Italy. Cautious use of the kinematic method has provided satisfactory normal values of divergence. Vorticity generation at 500 mb and temperature changes in the lower half of the atmosphere are confirmed as being weak in the area considered. In January, divergence destroys cyclonic vorticity at 500 mb, and cooling by ascending motion compensates warm advection and diabatic heating in the lower half of the atmosphere, whereas descending motion and warm advection compensate diabatic cooling in the upper half of the atmosphere. Also in January, the dissipation of kinetic energy is found to be negative: there is an input of kinetic energy from smaller perturbations into the mean motion, probably in consequence of local baroclinic developments.

1. Introduction and basic equations

Today a picture of the weather and climate of a region should include some derived quantities, among them divergence, vertical motion and the items of the energy budget. Although the kinematic method is not reliable, when applied to single cases, it can give satisfactory monthly mean values of divergence. By the cautious use of this method, a pilot study has been carried out over central Italy. The sounding data over Milan, Brindisi, Cagliari and Rome at the levels of 900, 700, 500, 300 and 100 mb were analysed twice a day for 5 years. Some monthly normal values of important derived quantities will be shown and discussed in this paper.

Vertical integration of the thermodynamic equation gives

$$g\,\frac{\partial}{\partial t}(I+P) = -\int_0^{p_0} \nabla\cdot c_p T\mathbf{V}\,dp - \int_0^{p_0} \nabla\cdot\phi\mathbf{V}\,dp + \int_0^{p_0} \mathbf{V}\cdot\nabla\phi\,dp + \int_0^{p_0} Q\,dp \qquad (1)$$

where $I + P$ is the total potential energy and Q the rate of heating per unit mass. The total potential energy of an atmospheric column of unit cross-section decreases because of sensible heat and potential energy divergence and the work done by the pressure, and increases because of diabatic heating.

Vertical integration of the kinetic energy equation gives

$$\frac{\partial}{\partial t}\int_0^{p_0} K\,dp = -\int_0^{p_0} \mathbf{V}\cdot\nabla\phi\,dp - \int_0^{p_0} \nabla\cdot K\mathbf{V}\,dp - \int_0^{p_0} D\,dp \qquad (2)$$

where D is the kinetic energy dissipation due to all motions smaller than that explicitly considered. The kinetic energy of an atmospheric column of unit cross-section increases owing to the work done by pressure; it decreases by reason of kinetic energy divergence and by dissipation caused by any kind of perturbations superimposed on the motion considered. Equations (1) and (2) can be found in text books, for instance in Haltiner (1971).

2. Divergence, vertical velocity and vorticity balance

Geopotential heights, winds and temperatures at 100, 300, 500, 700 and 900 mb over Milan, Brindisi, Cagliari and Rome were contemporaneously available 1141 times during the period 1961–1965. These were the only observations chosen as the basic data of the elaborations to obtain reliable averages of divergence and vertical velocity. The triangle Milan, Brindisi, Cagliari is shown in Fig. 1.

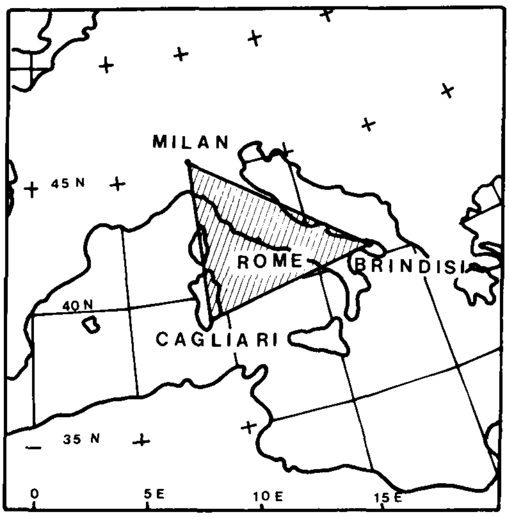

Fig. 1. Triangle Milan, Brindisi, Cagliari.

Wind divergence has been computed through the relations

$$(\nabla \cdot \mathbf{V})^* = \frac{1}{a \cos \varphi}\left(\frac{\partial}{\partial \varphi} V \cos \varphi + \frac{\partial U}{\partial \lambda}\right) \qquad (3a)$$

$$\nabla \cdot \mathbf{V} = (\nabla \cdot \mathbf{V})^* + \varepsilon \qquad (3b)$$

U and V are assumed to change linearly in the λ, φ plane. The correction ε, defined by (4), has been introduced at each level, to assure vertical compensation of divergence in the layer 50–1000 mb, on the assumption that the compensated divergence vanishes at 50 mb and changes linearly into the layers 50–100 mb, 100–300 mb, 300–500 mb, 500–700 mb and 700–1000 mb.

$$\varepsilon = -[1.25(\nabla \cdot \mathbf{V}_{100})^* + 2.0(\nabla \cdot \mathbf{V}_{300})^* + 2.0(\nabla \cdot \mathbf{V}_{500})^* + 1.75(\nabla \cdot \mathbf{V}_{700})^* + 2.25(\nabla \cdot \mathbf{V}_{900})^*]/9.25 \qquad (4)$$

The vertical velocity has been computed through the continuity equation. ω is put equal to zero at 1000 mb; it vanishes at 50 mb because of the correction ε applied to divergence.

In the following, only the results referring to January, April, July and October will be shown and discussed, in order to save space. In these months ε amounts respectively to 0.72, 0.66, 0.62 and 0.34 10^{-6} s^{-1}, against 2.7, 3.2, 3.5 and 3.1 of the maximum value of $(\nabla \cdot \mathbf{V})^*$ along the vertical. Figs. 2 and 3 show the vertical profile of divergence and vertical velocity. It is remarkable that, as far as monthly averages are concerned, the vertical compensation of wind divergence can be very different from that usually observed in single disturbances, where a level of nondivergence is around 500 mb.

Divergence at 500 mb, and the consequent individual change of vorticity, are strictly connected with the quasi-stationary waves superimposed upon the zonal current. In order to study these waves, the author has devoted a previous paper to vorticity generation at 500 mg over the whole globe (La Valle, 1973). It agrees with the present study in indicating that central Italy is not a major source or sink of vorticity at 500 mb; central Italy is confirmed as a sink of cyclonic vorticity during January.

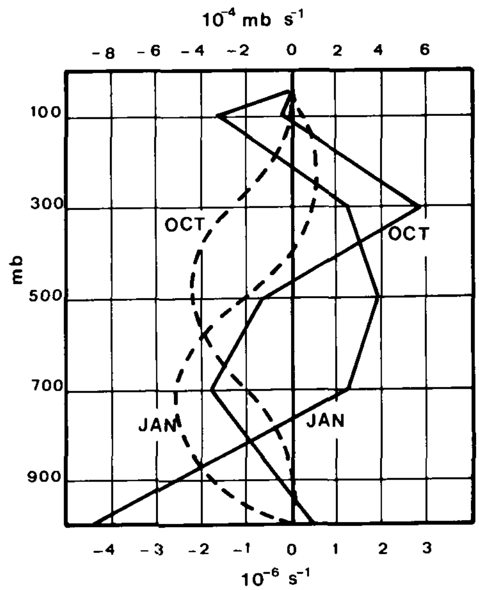

Fig. 2. Vertical profiles of $\nabla \cdot \mathbf{V}$ (full line) and ω (dashed line) for October and January. (Units respectively in 10^{-6} s^{-1} and 10^{-4} mb$\cdot$s^{-1}.)

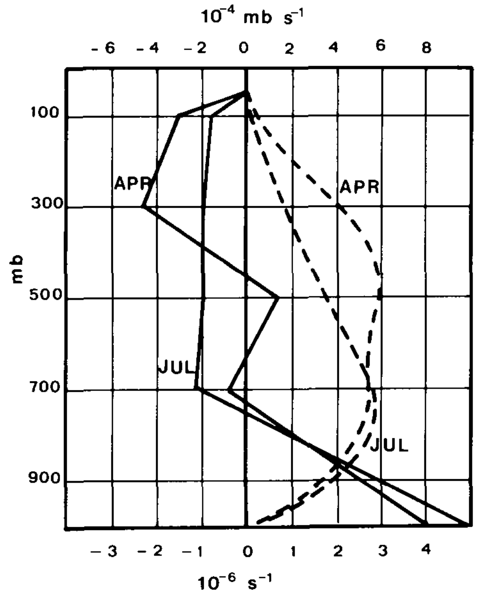

Fig. 3. Vertical profiles of $\nabla \cdot \mathbf{V}$ (full line) and ω (dashed line) for April and July. (Units respectively in 10^{-6} s^{-1} and 10^{-4} mb $\cdot$ s^{-1}.)

The last result seems to contradict the relatively high frequency of cyclogenesis in the Gulf of Genoa during the month of January (Montalto et al., 1967). Some facts must, however, be taken into consideration. First, anticyclones alternate with cyclones every month (Nauchno-issledovatelskii Institut Aeroklimatologii, 1964); second, the lows in the lee of the Alps are often shallow (Buzzi and Rizzi, 1973) and third, a deep cyclone in the lee of the Alps has the genesis and structure of a normal extratropical cyclone, although local geography controls its position and intensity (La Valle, 1964; Danielsen, 1973). It originates when vorticity advection becomes superimposed upon a front, and divergence above is partly compensated by convergence at the ground. Moreover, northerly flow usually converts earth vorticity into relative vorticity. In fact, divergence was found positive at 500 mb in one major cyclogenesis in the Gulf of Genoa which was carefully analysed (Third Group, 1963).

At 500 mb the vertical transport of vorticity is positive in every month: $-\omega \partial \zeta / \gamma p = 0.57$, 0.32, 0.33 and 0.07 10^{-10} s^{-2} respectively in January, April, July and October. Gazzola and Mosco (1967) have found a substantial deficit in the vorticity balance in the layer 850–500 mb over northern and central Italy during some major cyclogeneses in the lee of the Alps. That could be explained by vertical transport due to deep convection, as in the tropics (Reed and Johnson, 1974). In most of the troposphere, ascending motion is found during October and January, and descending motion during April and July. This agrees with the monthly normal precipitation observed at Rome (Mennella, 1967, p. 513). Vertical velocity over central Italy and the average vertical velocity at the same latitude, as estimated by Oort and Rasmusson (1971), present a completely different annual change. Moreover the former has a much larger magnitude than the latter. This means that vertical velocity and weather over Italy depend much more on large-scale quasi-stationary waves and local motions than on the annual shift of the average meridional circulation.

3. Thermal balance

Table 1 shows the diabatic heating distribution obtained as residual of the thermodynamic equation. Most of the heating at 500 and 700 mb in January and October is certainly due to latent heat release (Clapp, 1961). The radiative cooling at 300 mb is greater than that found by other authors over comparable areas, see Katayama (1967), Dopplick (1972) and Hantel (1976). It could be explained by a large amount of high and medium cloudiness.

Table 1. *Q/c_p: diabatic heating in layers of 200 mb. (Units in °C/day)*

mb	January	April	July	October
100	−1.7	−2.0	−0.1	0.3
300	−2.5	−4.7	−0.1	0.7
500	0.4	−1.3	0.3	1.6
700	1.3	−2.0	−1.5	0.2
900	−0.2	−1.0	−1.1	−0.9

The vertical profiles of Q/c_p, $-\mathbf{V} \cdot \nabla T$, $\partial T/\partial t$ and $\omega(\Gamma - \gamma)$ are connected, through the continuity equation, with the vertical distribution of $\nabla \cdot \mathbf{V}$, which explains vorticity production and quasi-stationary waves. Γ and γ are the lapse rate of temperature, respectively dry adiabatic and actual.

Fig. 4 shows the January profile of these quantities. In the lower half of the atmosphere,

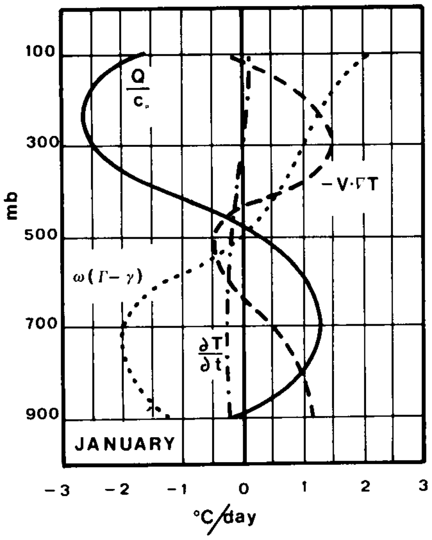

Fig. 4. Thermal balance. Vertical profiles of Q/c_p (full line), $-\mathbf{V}\cdot\Delta T$ (dashed line), $\omega\ (\Gamma-\gamma)$ (dotted line) and $\partial T/\partial t$ (dashed and dotted line): January (Units in °C/day.)

warm advection and diabatic heating are compensated by ascending motion. In the upper half of the atmosphere descending motion and warm advection compensate diabatic cooling. The hemispheric distributions of Q/c_p and $-\mathbf{V}\cdot\Delta T$, mean during January 1958 at $0.75p_s$ (La Valle, 1977), agree with the present study in indicating that diabatic heating and temperature advection in the lower half of the atmosphere are relatively small over Italy.

4. Kinetic and potential energy balance

Table 2 shows the dissipation of kinetic energy. $M_{200\,\mathrm{mb}}$ is the mass of an atmospheric column of 200 mb and unit cross-section. During April and October (especially during April) friction and perturbations superimposed on the mean motion dissipate kinetic energy. In January the local perturbations supply kinetic energy to the mean motion. In fact, the strong winter contrast between the warm Tyrrhenian Sea and the cold Po Valley (Mennella, 1967) is expected to generate local baroclinic development. According to Kung (1970), the work done by the pressure is negative at the intermediate latitudes of North America in medium and high troposphere and low stratosphere during the winter season. That agrees qualitatively with the negative dissipation found by the writer in January.

Table 2. *D: dissipation of kinetic energy in layers of 200 mb.* (*Units in* (*kly/year*)/$M_{200\,\mathrm{mb}}$)

mb	January	April	July	October
100	2	5	−1	3
300	−2	5	0	−1
500	−3	1	1	1
700	0	1	0	1
900	1	1	1	−0

Fig. 5 shows the balance of the kinetic energy, mean in the 4 months considered, at each level. At the level of the jet stream, kinetic energy increases

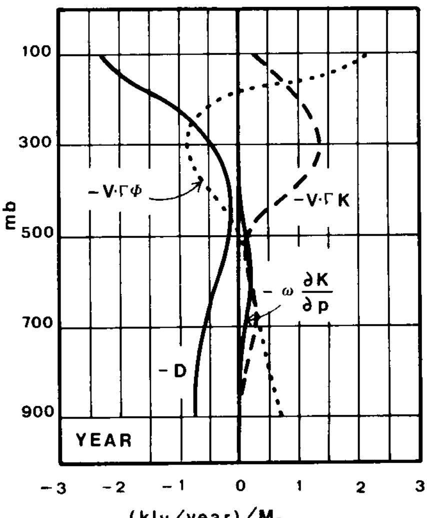

Fig. 5. Kinetic energy balance. Vertical profiles of $-D$ (full line), $-\mathbf{V}\cdot\nabla K$ (dashed line), $-\mathbf{V}\cdot\nabla\phi$ (dotted line), $-\omega\partial K/\partial p$ (full line): year. (Units in (kly/year)/$M_{200\,\mathrm{mb}}$.)

by advection; the surplus is partly dissipated and partly transformed into potential energy by work against pressure. The kinetic energy dissipation is positive everywhere, with a main maximum in the stratosphere and a secondary one in the planetary boundary layer. About 4.14 kly/year, equal to 5.38 W/m^2, are dissipated in the entire column. These results agree fairly well with those obtained by Kung over North America (Kung, 1966), apart from the position of the two maxima, which is reversed.

Table 3. *Budget of total potential energy and kinetic energy of an atmospheric column of unit cross-section: year.* (*Units in kly/year*)

$\frac{1}{g}\int_0^{1000} dp$	January	April	July	October
$-\nabla\cdot c_p T\mathbf{V}$	166	−241	−271	181
$-\nabla\cdot\phi\mathbf{V}$	−131	456	321	−222
Q	−49	−197	−46	33
$\frac{\partial}{\partial t} c_p T$	−8	5	6	−13
$\mathbf{V}\cdot\nabla\phi$	7	−13	2	−5
$-\mathbf{V}\cdot\nabla\phi$	−7	13	−2	5
$-\nabla\cdot K\mathbf{V}$	5	1	4	−1
$-D$	1	−13	−2	−3
$\frac{\partial}{\partial t} K$	0	0	−0	0

Table 3 indicates the mean value of every item of the energy budgets (eqs. (1) and (2)). The maxima terms are sensible heat convergence and potential energy convergence. As the former is positive when the motion is upward and the latter is positive when the motion is downward, they tend to compensate.

5. Conclusions

The literature contains some excellent analyses of vorticity and/or energy budgets over large areas. The present work shows that automatic processing of selected data makes it possible to study the climatology of triangles of contiguous radiosonde stations. The following conclusion is reached: the soundings accumulated up to date contain a huge bulk of information not yet turned to account. The work required to exploit this mine of information is very tedious; nevertheless it should be undertaken in view of the contribution it would make to our knowledge of the phenomena that rule long-term wheather change and climate modification.

6. Acknowledgements

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ГЕНЕРАЦИЯ ЗАВИХРЕННОСТИ И БЮДЖЕТ ЭНЕРГИИ НАД ЦЕНТРАЛЬНОЙ ИТАЛИЕЙ

Для изучения генерации завихренности и бюджета энергии над Центральной Италией были проанализированы данные TEMP для Милана, Бриндизи, Кальяри и Рима с 1961 по 1965 гг. Осторожное использование кинематического метода дало удовлетворительные нормальные величины дивергенции. Подтверждено, что в рассматриваемой области генерация завихренности на поверхности 500 мб и изменения температуры в нижней половине атмосферы были слабыми. В январе дивергенция разрушает циклоническую завихренность на 500 мб, а охлаждение восходящими движениями компенсирует адвекцию тепла и неадиабатический нагрев в нижней половине атмосферы, в то время как нисходящие движения и адвекция тепла компенсируют неадиабатическое охлаждение в верхней половине атмосферы. Подобным же образом найдено для января, что диссипация кинетической энергии отрицательна: имеется приток кинетической энергии от меньших возмущений к среднему потоку, вероятно, вследствие развития локальных бароклинных возмущений.