THE MEDITERRANEAN SEA AS A HEAT SOURCE FOR THE LARGE-SCALE ATMOSPHERIC MOTIONS

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The fact that the Mediterranean Sea acts as a source of both sensible and latent heat during winter and as a sink during summer has been known for quite a long time. Bunker (1972) estimated the average heat release throughout the winter season 400 cal/cm^2 day. When mistral was blowing the release of sensible heat reached on restricted areas top values exceeding 1000 cal/cm^2 day and the evaopration 1.5 cm/day of water.

On the other hand the winter circulation in the troposphere shows a marked deflection from zonality over the Mediterranean, in particular during winter with prominent meridional circulations (see fig. 1). In terms of surface pressure this perturbation amounts to about 5 mbs of negative anomaly.

The problem of evaluating the dynamical response of the middle latitude atmospheric circulation to the release of heat and moisture from the lower boundary was analyzed for the first time by Smagorinsky (1953). This, as later works on the subject, (Doos, 1962; Egger, 1976), was based on a parameterization of heat sources and sinks that was too coarse to resolve adequately the Mediterranean. Using the same the same kind of quasi-geostrophic linearized approach as Smagorinsky, we studied the perturbation induced on the winter circulation by the Mediterranean as a heat source parameterized on the basis of Bunker's data. Under simplifying, but physical, assumption we find that the Mediterranean might very well force a stationary depression like the one observed during winter.

Thermally forced, stationary disturbances on a barotropic zonal flow.

The horizontal extension of the Mediterranean is about 3500 km in longitude and 1500 km in latitude. Since the vertical scale of motion does not exceed 10 km, the motion is quasi-horizontal and quasi-geostrophic.

If we assume that the fluid is Boussinesq the dynamics of thermal forcing reduces to the two equations (see Charney, 1973):

$$\left\{\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right\} q = \frac{g f_0}{N^2 c_p T_s} \frac{\partial Q}{\partial z} \quad \text{with} \quad q = \left\{\nabla^2 + \frac{f_0^2}{N^2}\frac{\partial^2}{\partial z^2}\right\}\psi + \frac{\partial f_0}{\partial y} y \qquad (1)$$

$$\left\{\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right\} \frac{\partial \psi}{\partial z} + \frac{N^2}{f_0} w = \frac{g Q}{f_0 c_p T_s} \qquad (2)$$

where:

$\mathbf{v}$ is the horizontal velocity vector, ∇ the horizontal gradient operator, g the acceleration of gravity, f_0 the Coriolis parameter, c_p the specific heat at constant pressure, T_s the horizontally averaged air temperature, Q the rate of accession of heat per unit mass, $\psi = (p-p_s)/f_o\rho_s$, where p is pressure, ρ density and the subscript "s" denotes horizontal average at a reference height. Linearization of these equations around a state of uniform, barotropic, zonal flow with mean velocity $\bar{u}$:

$$\psi = -\bar{u}y + \psi' \qquad |\psi'| \ll |\psi| \qquad (3)$$

and use of the thermodynamic equation (2) as boundary condition gives the following linear differential problem for stationary flow:

$$\left\{ \bar{u} \left[\nabla^2 + \frac{f_o^2}{N^2} \frac{\partial^2}{\partial z^2} \right] + \frac{\partial f_o}{\partial y} \right\} \frac{\partial \psi'}{\partial x} = \frac{f_o g}{N^2 c_p T_s} \frac{\partial Q}{\partial z} \qquad (4)$$

$$\bar{u} \frac{\partial}{\partial z} \left(\frac{\partial \psi'}{\partial x} \right) = \frac{g}{f_o c_p T_s} Q \quad \text{at rigid horizontal walls} \quad (5).$$

Sensible heat

We parameterize sensible heat in the simplest form i.e. an exponential distribution of vertical scale H:

$$Q(z) = Q_o e^{-z/H}$$

The linearized problem (4), (5) becomes then for a single horizontal Fourier component $Z(z) = \exp[i(Kx + \lambda y)]$

$$\left[\frac{d^2}{dz^2} - \frac{N^2}{f_0^2}\left(K^2+\ell^2-\beta/\bar{u}\right)\right] Z(z) = -\frac{ig}{K\bar{u}f_0 c_p T_s H} Q_0 e^{-z/H} \qquad (6)$$

$$\frac{dZ}{dz} = -\frac{igQ_0}{f_0 c_p T_s \bar{u} K} \qquad at \quad z=0 \qquad (7)$$

At the upper boundary supposed to be at $z = +\infty$, we apply a radiation condition which is derived from the time dependent equivalent of (6). In fact it can be shown that the negative root of the equation which defines the vertical wavenumber

$$m^2 = \frac{N^2}{f_0^2}\left(K^2+\ell^2-\beta/\bar{u}\right) \qquad (8)$$

gives solutions that are damped exponentially or that are traveling away from the boundary $z = 0$.

The solution of (6), (7) with radiative condition at the upper boundary $z = \infty$ is:

$$Z(z) = -\frac{igQ_0}{K\bar{u}f_0 c_p T_s}\,\frac{1}{1-m^2H^2}\left[mH^2 e^{-mz} + He^{-z/H}\right] \qquad (9)$$

The resonance denominator $1-m^2H^2$ vanishes at a wavenumber:

$$\left(h^2+\ell^2\right)_{res.} = \frac{f_0^2}{N^2H^2} + \frac{\beta}{\bar{u}} \qquad (10)$$

which is of the order of $2.6 \times 10^{-16}\,cm^{-2}$ at the latitude of the Mediterranean (37.5°).

A typical horizontal wavenumber of the Mediterranean is $k^2 + \ell^2 = 4.3 \times 10^{-16} cm^{-2}$. The resonance might therefore be relevant. Apart from the resonance factor, an order of magnitude of the perturbation in pressure at the ground is given by

$$p - p_s \simeq \frac{\rho_s g H}{K \bar{u} c_p T_s} Q_0 \simeq 3 mb \tag{11}$$

Latent heat

The heat source corresponding to the release of latent heat is better represented as a sine function of wavelength 2L, $Q = Q_L \sin(\pi z/L)$ in a confined system between two walls at $z = 0$ and $z = L$.

The equivalent of the equation (6) is then:

$$\left(\frac{d^2}{dz^2} - m^2\right) Z(z) = \frac{i g \pi}{K \bar{u} \rho_0 c_p T_s L} Q_L \cos \frac{\pi z}{L} \tag{12}$$

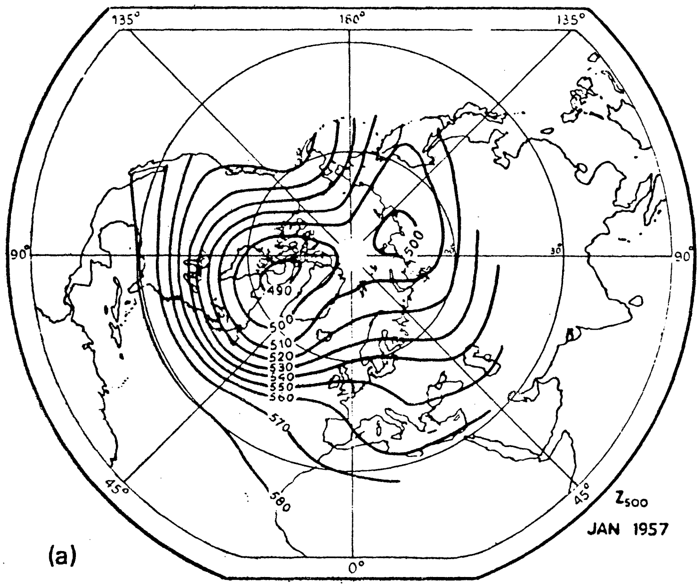
and the boundary conditions:

$$\frac{dZ}{dz} = 0 \qquad at \quad z = 0, L \tag{13}$$

The solution of this problem reduces to the non-homogeneous part:

$$Z(z) = \frac{-i g L \pi Q_L}{K \bar{u} \rho_0 c_p T_s} \frac{1}{\pi^2 + m^2 L^2} \cos \frac{\pi z}{L} \tag{14}$$

Since m^2 is positive in the range of parameters typical of



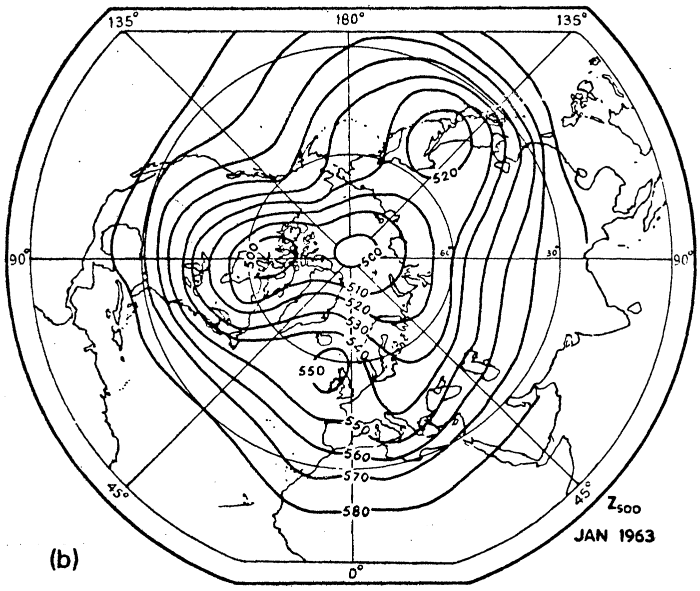


Fig. 1 Average height of the 500 mb pressure level in dekametres in January:

(*a*) 1957: Example of a strong zonal wind circulation.

(*b*) 1963: Example of a weak zonal wind circulation with large amplitude waves and prominent meridional currents.

the Mediterranean, there is no resonance in this case.

The order of magnitude of the perturbation in pressure at the ground including the resonant term, of order 10, $\pi^2 + m^2L^2$ is:

$$p - p_s \simeq \frac{\rho_s g L \pi}{K \bar{u} c_p T_s} \frac{Q_L}{\pi^2 + m^2 L^2} \simeq 3\,mb \tag{15}$$

Conclusions

Our calculations, even if far from conclusive, show that the problem of thermal forcing by the Mediterranean should be investigated further. This not only for what concerns the local dynamics (the pressure perturbation that we find at the ground is quite relevant), but also the impact on the general circulation of the atmosphere: the problems of cyclogenesis in the Mediterranean and Atlantic blocking, are intimately connected and presumably related to the simultaneous action of mountains and heat sources. Future development should be in the direction of including time-dependence and nonlinearity in the theory.

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