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ENHANCEMENT OF PRECIPITATION VIA SEA MIXING

by

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ENHANCEMENT OF PRECIPITATION VIA SEA MIXING

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The sea absorbs some 95% of the incidental solar radiation and practically all of the atmospheric long wave radiation. The outgoing energy consists of latent heat (vapor flux) long wave radiation, and sensible heat fluxes. These fluxes increase with surface temperature. The equilibrium temperature T_e keeps the energy fluxes from the surface at the same level as the incidental fluxes.

In summer the sea temperature is below the equilibrium level and more heat comes into the sea than goes out. The surface temperature depletion depends on the rate of wind mixing. An intensive wind mixing entrains cold water from below which keeps the sea surface at lower temperature and enhances the heat accumulation in and above the seasonal thermocline (Figure 1). In winter the heat storage keeps the sea above the equilibrium temperature and enhances the heat fluxes from the sea to the atmosphere. The winter heat flux from the Mediterranean is about 300 w/m^2, two thirds (200 w/m^2) of which are contributed from the heat storage depletion.

The evaporation rate and heat fluxes from the Eastern Mediterranean (EM) in winter exceeds the summer fluxes (Table 1, Fig. 1). The winter fluxes are enhanced by intrusion of cold continental air masses into the EM. The cold atmosphere enhances heat fluxes and at the same time induces convective instability, which extends above the condensation level. The condensation converts latent heat into a sensible heat, which feeds its energy to the cloud convection. The latent heat dominates the heat fluxes from the EM, and it affects the atmosphere through condensation.

The ten-fold increases of buoyancy convective energy fluxes in storms (Table 1) is mostly related to condensation and cloud formation.

The total flux of kinetic energy is related to the buoyancy flux B as: $b^* = \rho Bh$ (w/m^2).

Eventually this flux of energy is dissipated in the system. Before it dissipates, the energy can be pumped into different scales of atmospheric motions. In a three dimensional isotropic turbulence the energy usually cascades into smaller scales and eventually dissipates in two Kolmogorove microscales.

Levich and Tzvetkove (1982) argued that initial energy input is at the scale of the cumulus clouds, which is few km in size. They assumed that some of the energy cascades into two dimensional (2D) scales. It was shown by Kraichnan (1980) that the 2D turbulence is characterized by two inertial ranges, where enstrophy is propagated unto the small,and energy cascades into the large scale eddies.

Levich and Tzvetkove found that the build up rate of energy in the cyclone is comparable with the conversion rate of heat to convective energy in the clouds.

Tzevtkove and Assaf (1982), examined the variations in heat storage of the sea and the precipitation pattern in Israel. They found a fair correlation (r = 0.56) between the heat storage in early winter and the winter precipitation. A remarkable correlation (r = 0.9) was found between heat storage depletion and winter precipitation. This indicates that, even in years when heat storage characteristics work against atmospheric features or vice versa, the actual heat removed from the sea is proportional to the actual precipitation; for example, in cases where cold winters are associated with small summer heat storage or when warm winters are associated with large heat storage.

Honey and Davis (1976), performed numerical experiments on the seasonal thermocline model. They found that with wind mixing the surface temperature is lower in summer and warmer in the winter by about $0.5^{o}C$.

Table 1 - Characteristics of the physical parameters over the Eastern Mediterranean

	Summer	Winter	Storms
Solar Insulation I (w/m^2)	260	100	50
Heat Storage Variation ΔQ (w/m^2)	180	-180	-500
Mechanical (wind) Mixing Energy M (w/m^2)	3×10^{-3}	5×10^{-3}	5×10^{-2}
Buoyancy Flux in the sea B_s (m^2/sec^3)	-6×10^{-8}	10^{-7}	2.5×10^{-7}
Buoyancy Energy Flux (in the sea) b^*_s (w/m^2)	-3×10^{-3}	10^{-2}	2.5×10^{-2}
Atmospheric Buoyancy Flux B_a (m^2/sec^3)	3×10^{-4}	2×10^{-3}	10^{-2}
Atmospheric Buoyancy Energy Flux b^*_a (w/m^2)	0.3	5	50

Note: The subscripts s and a are used for sea and atmospheric conditions respectively.

Physically, wind mixing converts kinetic into potential energy by entrainment of dense water from lower layers. The conversion rate of wind into potential energy is exceedingly small: in the open sea, it is of an order of magnitude of few mW m^{-2} (Table 1). This should be compared with a rate of 200 W m^{-2}, which is the rate at which the heat storage is released from the sea to the atmosphere in winter. In other words, the winter heat fluxes which are associated with summer wind mixing are by 5 orders of magnitude larger than the energy flux which generates the mixing itself. This finding led to the idea that artificial sea mixing can be utilized to increase the seasonal heat storage over the EM.

Assaf and Bronicki (1980) explored the technological aspects of artificial sea mixing and consequent increase of heat storage and winter precipitations.

Mixing Energy

Assuming that a devoted person, who reads this paper, decides to do something about the weather and mix the sea in the summer. He rents a boat, a cable and a container, which is open on top and has a hole in the bottom. He lowers the container to the deep layer of the EM where the density is ρ = 1028 kg/m^3 and starts to pull the container upwards (Fig. 2).

As long as the container is submerged in dense water the force exerted on the cable will just balance the extra weight of the walls and the friction which we assume to be negligible.

When the container is lifted to the upper layer, where the density is ρ = 1026 kg/m^2, our man will have to pull the cable at a force of $g\Delta\rho V$,

where : $\Delta\rho$ = 2 kg/m^3 -the density difference

V -the dense water in the container

g -the gravity

The dense water in the container will spread from the hole at the bottom and it will be replaced with light water from above. This will reduce the force exerted by the man to pull the container. We assume that the replacement rate of the dense water will be uniform, so that near the surface all the dense water will be mixed throughout the upper layer and our man will be ready to allow the container to sink for the next mixing cycle.

The average force exerted while the container was lifted is half of the maximum force, i.e. $\frac{g\Delta\rho V}{2}$ and the energy invested by our man in one cycle is:

$$M = \frac{g\Delta\rho V}{2} \cdot h$$

For: $V = 10\ m^3$, $\Delta\rho = 2\ kg/m^3$ and $h = 50\ m$

one obtains: $M = 5000$ Joule

Thus, if our man will make one cycle in 100 seconds, he will experience work at a rate of 50 watts and will mix the sea at a rate of 0.1 m^3/sec.

To increase the volume of the upper layer by 10%, from 50 to 55 m depth, over the entire 600,000 km^2 one needs some three million devoted persons who will work day and night throughout the summer period. It seems difficult to find nowadays so many devoted persons, still we should remember that the power exerted by the three million devoted persons is 150 MW, which is the power of what is considered today a medium to small power turbine.

There are probably more practical means to mix the sea, some of them will be discussed in the next section. Before we go into this, we shall examine the relations between sea mixing and sea temperature.

Surface Temperature and Mixing

Let us approximate the seasonal thermocline as a two layer fluid (Fig. 3). At $T = T_e$ the surface temperature is in equilibrium and the heat balance can be written as:

$$(1) \qquad \rho_a \cdot c_{pa} \cdot c_b \cdot u(1 + R)(T_e - T_a) + IR(T_e) = Q_a$$

where:

a - index air parameters

ρ - density

c_{pa} - specific heat of air
c_b - the bulk exchange coefficient
R - inverse Bowen ratio ($R = \frac{LH}{SH}$)
SH - sensible heat flux
LH - latent heat flux
u - air velocity
Q_a - atmospheric and solar radiation which is absorbed by the sea surface.

Assuming that natural or artificial sea mixing is now turned on; the effect of mixing is displayed by the dashed line in Fig. 2, entrainment will increase the volume and reduce the surface temperature by δT.

The heat fluxes from the surface (Q_M) will be reduced by:

$$\Delta Q_M = \rho_a \cdot c_{pa} \cdot c_b \cdot u(1 + R) + \frac{\partial(IR)}{\partial T} \quad \delta T \tag{2}$$

Eventually the surface temperature will be stabilized at a new equilibrium T_M, which can be estimated by equating with the cooling rate of the surface due to entrainment of cold water:

$$\rho \cdot c_p \cdot W_e \cdot \Delta T_M = \rho_a \cdot c_{pa} \cdot c_D \cdot u(1 + R) + \frac{\partial(IR)}{\partial T} \quad \delta T \tag{3}$$

where:

W_e - the entrainment velocity
ρ - water density
c_p - specific heat of water
ΔT_M - T_M - T_D
T_D - the deep water temperature
c_D - the bulk coefficient

Equation (3) can be solved for $\delta T/\Delta T_M$

For summer conditions in the Medieterranean we may approximate:

$R = 8$ $\qquad$ $u = 6$ m/sec $\qquad$ $\frac{\partial(IR)}{\partial T} = 5$ W/m^2-^{o}C $\qquad$ $W_e = 5\text{x}10^{-6}$ m/sec

For these parameters we obtain: $\frac{\delta T}{\Delta T_M} = 0.25$

i.e., without mixing, the temperature of the Mediterranean surface will be elevated by $\delta T = 2.5 \quad \Delta T_M = 10^{o}C$ and the accumulated heat during the summer months is estimated as: $\rho \cdot c_p \cdot h \cdot \Delta T_M = 2x10^9$ Joule/m^2 , or: 550 kWh/m^2, this is equivalent for heating at a rate of 200 W/m^2, where:

$h = W_e \cdot t = 50$ m
$\Delta T_M = 10^{o}C$
$t = 10^7$ sec

The mechanical energy which is involved in this mixing process can be approximated as: $ME = g \cdot \rho \cdot \alpha \cdot \Delta T_M \cdot W_e \cdot h/2 = 3.7x10^{-3}$ W/m^2
here: $\alpha = \frac{1}{\rho} \cdot \frac{d}{dT}$ the expansion coefficient of sea water.

Thus natural summer mixing reduces the Mediterranean surface temperature by $2.5^{o}C$ from its equilibrium value. This induces accumulation of heat at a rate of 200 W/m^2 and it consumes only 3.7 mW/m^2 of mechanical energy. Thus one may say that the ratio of heat accumulation rate to mixing rate is given by:

$$\frac{2c_p}{g\alpha h} = 40{,}000$$

where: h - the depth of the mixed layer

Such an efficiency calls for artificial mixing as a practical means to enhance heat storage.

.C Artificial Mixing

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The long surface waves dissipate on the Mediterranean coasts at a rate of 7 kW/m. There are numerous ideas how to convert wave energy to power. One of the ideas, due to the late John Issacs of Scrips Institute, was to introduce deep pipes on floats with one way valve that will allow the water to flow only upward (Fig. 4). These pipes can be converted to effective sea mixers by extending the pipes to the depth of 80 m. and allowing the cold water to be distributed in the upper sea (Fig. 4). A two diameter pipe which floats on 4 m. diameter buoy will induce sea mixing at a rate of 4 kW.

Ten thousands such mixers distributed over an area of 3 x 3 square degrees (330 km x 330 kW) will amplify seasonal heat storage by 10%. As a result

December surface temperature will be elevated by 0.5°C (Haney and Davis, 1976). From Fig. 4 and Fig. 5 of Tzvetkove and Assaf (1982) one may see that this yield excess precipitation of 70 mm in Jerusalem and 30 mm in Amman. Conservatively we assume excess precipitation of 20 mm over an area of 10^5 km^2 or a total of $2x10^9$ m^3 of excess overland precipitation. Each mixer will yield an annual output of 200.000 m^3 of overland precipitation.

The total amount of energy for mixing in an area of 10^5 km^2 will be 10^8 kWh/yr (40 MW for 2500 hours). Thus each m^3 of excess overland precipitation consumes 0.05 kWh of mixing energy.

It is interesting to compare this with the performance of a desalination plant which consumes 10 kWh/m^3. Thus it is possible to consider not only wave mixers but also intensive mixing platforms which pump deep cold water to be mixed with the warm water above.

As the hydraulic head is very small (0.2 m) and the flow rate is large, intensive mixing should be associated with new pumping technology. Air lift pumps seem to be proper means. But one may also consider jet pumps, where a small volume of water will induce larger volume flow rate to be mixed.

It should be noted that one may pump cold water to be mixed with warmer water or warmer water may be pumped to deeper levels to be mixed with cold water below. We envision that each platform will induce mixing at a rate of, say, 4 MW, i.e., it will pump some 2000 m^3/sec across an hydraulic head of 0.2 m. The pipe will be between 50 m to 100 m long and 15 m diameter. Each platform will hold 3 such pipes that will inject the water as plumes with 1 m diameter or so.

The actual mixing will be developed as an entrainment into these plumes. Ten platforms with a total power generation of 10 MW and mixing generation rate of 4 MW each (i.e. 40% pumping efficiency) which will function during 3000 hours a year will be needed to enhance overland precipitation by $2x10^9$ m^3, i.e. 0.15 kWh/m^3 overland precipitation.

A detailed engineering study will be needed to evaluate the most economical means for sea mixing. Personally, I believe that a wave mixer will win the bid.

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Figure Legend

Fig. 1.: Schematics of the heat fluxes.

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- I - In-going (solar and atmosphere fluxes)
- q' - Out-going heat from the sea surface without sea mixing (q'=I)
- q - The out-going heat from the sea with summer mixing.
- T_e - The equilibrium temperature.

Fig. 2.: The effort associated with sea mixing.

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- A: As long as the container is within the dense water, the effort is negligible.
- B: Large effort is needed to raise the dense water within the light water above.

Fig. 3.: Schematic of two layer one dimension sea mixing.

Fig. 4.: One version of wave mixer.

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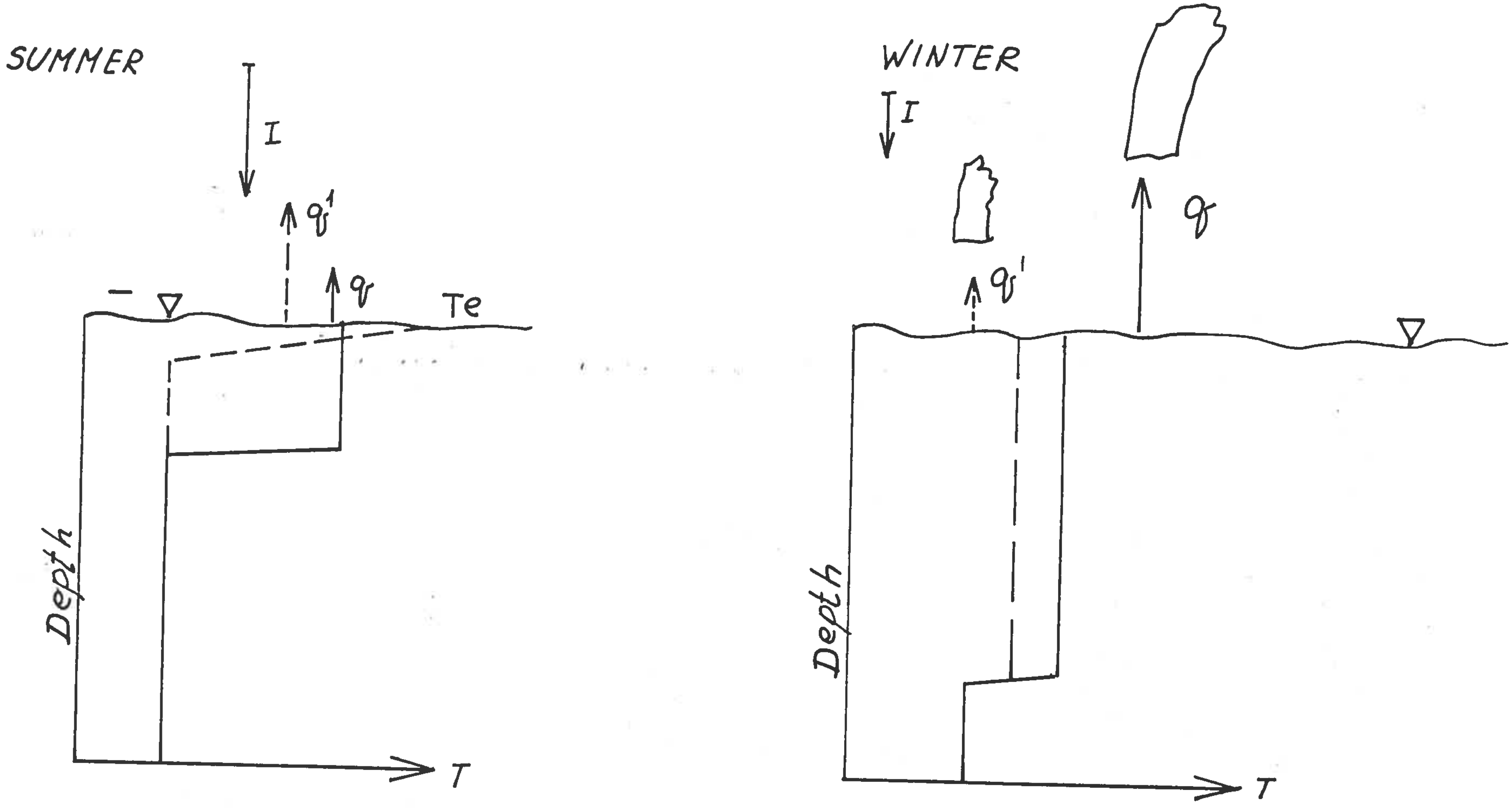

Fig. 1

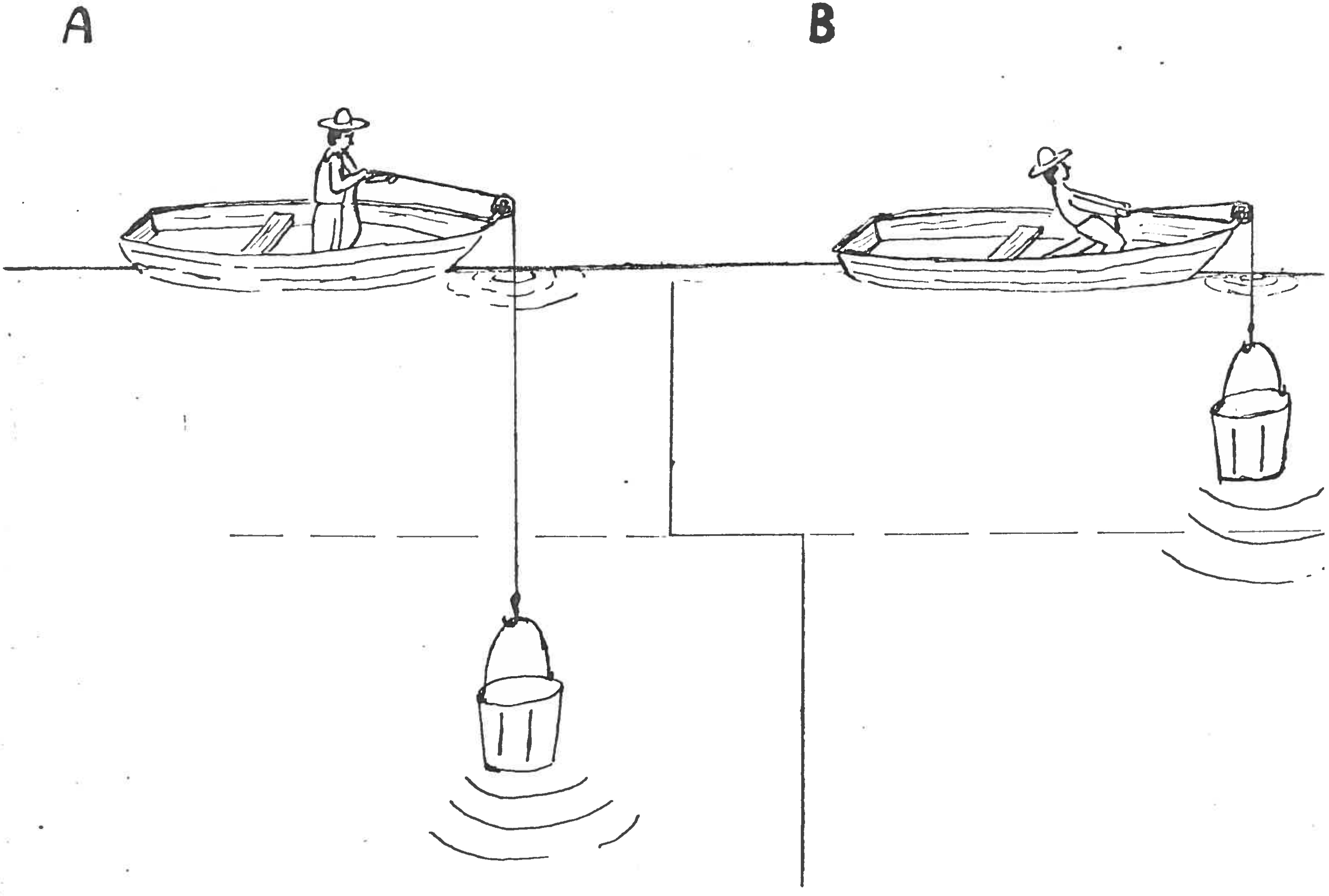

Fig. 2

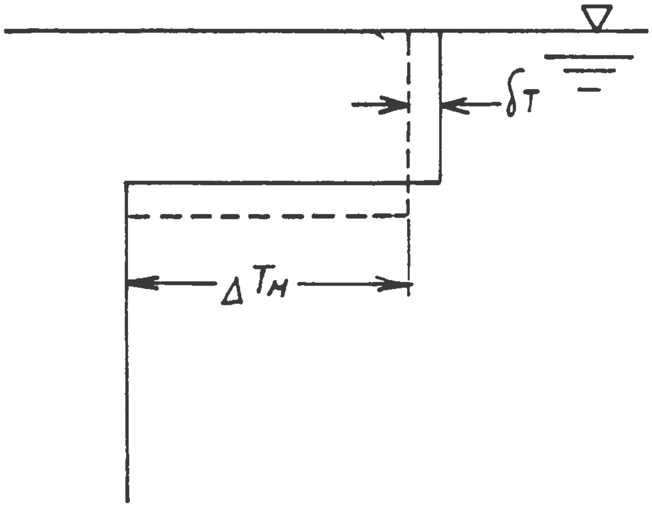

Fig. 3

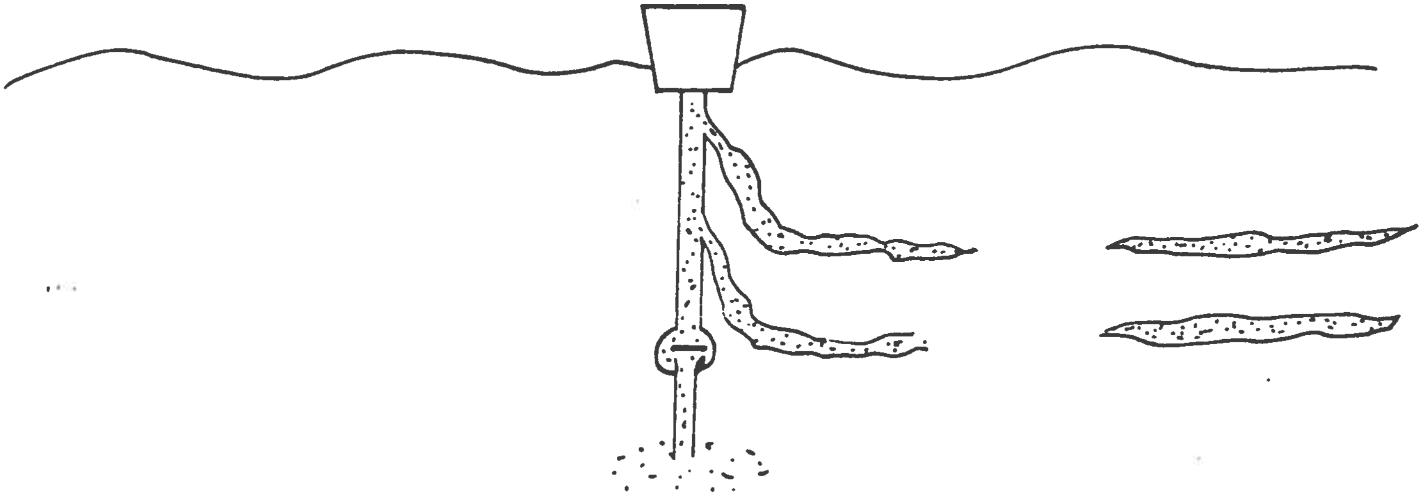

Fig. 4