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Warming and freshwater budget change in the Mediterranean since the 1940s, their possible relation to the greenhouse effect

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Abstract. Temperature and salinity of Mediterranean deep water have been increasing, based on observations extending back to 1959. Over the 1940-1995 period, the corresponding changes in heat and water budgets across the sea surface have been estimated to be 1.74 Wm^{-2} for the greenhouse effect change, 0.5°C and 0.4°C for mean air and sea-surface temperature increases, respectively, and an increase of 0.1 m (or 11%) in the freshwater deficit, which is due partly to human activities and partly to climatic changes.

Introduction

In 1990, it was postulated that heightened greenhouse effect (GHE) had probably contributed to an observed increase in temperature and salinity of the deep waters of the western Mediterranean Sea [*Béthoux et al.*, 1990]. For the period 1959-1997, changes amount to 0.13°C and 0.04 *psu*, respectively [*Béthoux and Gentili*, 1997] (Fig. 1).

According to *Rohling and Bryden* [1992] these changes were assumed to be imported from the eastern basin and man-induced. Temperature and salinity increases effectively occurred in the eastern Mediterranean where they are the main causes of hydrographic events observed in 1993 and 1995 [*Della Vedova et al.*, 1995; *Roether et al.*, 1996]. The characteristics of deep waters are acquired at the surface; resulting from air-sea exchanges and winter formation of dense water in different northern areas of eastern and western basins [e.g. *Lacombe et al.*, 1981; *MEDOC Group*, 1970; *Pollak*, 1951]. Due to evaporation and density increase, resulting from cooling and saltening, surface waters sink and mix with intermediate water to form the dense waters that fill the deep inner basins before flowing out to the Atlantic over the sill of Gibraltar. In the Atlantic, a "Mediterranean" layer participates in the dense water formation in the Norwegian Sea [*Reid*, 1979], a key point for the world ocean circulation, and it was recently assumed that its salinity increase may shift the ocean circulation and cause a glacial age in Canada within the next century [*Johnson*, 1997]. As a consequence of a residence time of about 15 years for the deep waters of the Algero-Provençal basin (western Mediterranean), the deep trends must have been initiated at least as far back as the early 1940s. However, if a residence time of about 100 years for the whole Mediterranean is considered, then the trends currently being measured may be related to surface changes that took place during the previous century.

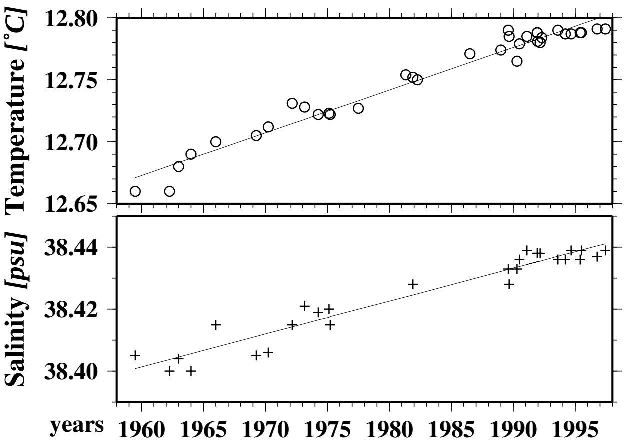

Figure 1. Temperature and salinity trends observed in the deep water of the Algero-Provençal basin over the 1959-1997 period. Each point represents a mean value for data acquired at a depth of between 2000 to a maximum of 2700 m; however, the trends concern the entire deep water from a depth of about 800 m depth. Hydrological stations from 1959 to 1994 are referenced in *Béthoux and Gentili* [1996]; 1995-1997 data were acquired aboard CNRS/Insu ships.

Heat and water budgets

At thermal equilibrium, and characterized by a constant mean annual temperature of sea water, the heat budget of the Mediterranean Sea may be summarized by:

$$Q_s(1-A)+Q_a+Q_e+Q_c+Q_n=0 \qquad (1)$$

where Q_s is the solar heat input, A is the mean albedo, Q_a is the heat gained by marine advection at the strait of Gibraltar, Q_e is the flux of latent heat (evaporation), Q_c the flux of sensible heat and Q_n the net longwave radiation. Advection to the Mediterranean Sea may be written as:

$$Q_a=\rho C_p[V_iT_i-V_oT_o-(E-P-R)T_{e,p,r}] \qquad (2)$$

where ρ represents the mean density of water, C_p is the specific heat, V equals flow, T represents temperature, with i and o subscripts for inflow and outflow, respectively, at the

Strait of Gibraltar, and $T_{e,p,r}$ the mean temperature of evaporated water (E), precipitation (P), and river runoff (R), respectively. A rough estimate of mean $T_{e,p,r}$ can be obtained from mean surface temperature, T_s, which is not very different from either the outflow temperature, T_o, or from the mean inflow temperature T_i. Using values of ρ = 1027 $kg\ m^{-3}$, C_p = 0.95 $cal\ g^{-1}\ °C^{-1}$, T_i = 15.4°C, T_o = 13.4°C and V_i = 1.6 Sv (1 $Sv = 10^6\ m^3\ s^{-1}$), Q_a was calculated to be 5 Wm^{-2} [*Béthoux and Gentili*, 1997]. It is noteworthy that this thermal input, Q_a, is in addition to a solar radiation input of about 200 Wm^{-2}, together with a third and less influential thermal input of earth heat flow across the sea-floor, at about 0.1 Wm^{-2}, neglected in Eq. 1. An increase in water temperature over the 1959-1997 period denotes continuous changes in the different terms of heat budget. Changes in water temperatures permit estimates of changes in marine advection, dQ_a, and in heat content of the water column, dQ_t. If the solar radiation input, Q_s (1-A), is assumed to be constant, marine data permits estimates to be made of changes in atmospheric transfer, as dQ_t- dQ_a = d($Q_e + Q_c + Q_n$). Changes in thermal advection, dQ_a, and in evaporation loss, dQ_e, occur concomitantly with changes in water budget, which may therefore be written as: $V_i - V_o = E - P - R$.

An increase in water salinity denotes a change in evaporation (with links to the Q_e term in the heat budget and changes in water temperature) and/or freshwater input by precipitation and river runoff (with concomitant changes to the resultant $V_i - V_o$ and heat advection Q_a).

Marine data and surface changes

The western basin of the Mediterranean comprises three water masses: a surface layer of about 150 m in depth, a Levantine intermediate water layer (situated between about 150-600 m in depth) issuing from the eastern basin, and deep waters reaching to the seabed (which is at a depth of more than 2800 m in the central part of the Algero-Provençal basin). Over the 1959-1997 period, mean values of trends for temperature and salinity in the deep waters are increases of 3.47 10^{-3} $°C\ yr^{-1}$ and 1.07 10^{-3} $psu\ yr^{-1}$, respectively [*Béthoux and Gentili*, 1997]. Curiously, concomitant changes in temperature and salinity have had no evident effect on water density, which allows the hypothesis of a constant deep outflow over the sill of Gibraltar. According to spatial and temporal changes of water characteristics in the Levantine intermediate waters, estimated trends are less accurate but nevertheless greater than those in the deep water. These are comprised between 6.8 and 9.1 10^{-3} $°C\ yr^{-1}$ for temperature and 1.8 and 1.9 10^{-3} $psu\ yr^{-1}$ for salinity [*Béthoux and Gentili*, 1996; *Sparnocchia et al.*, 1994]. The characteristics of water in the surface layer are strongly influenced both by Atlantic inflow and with changes in water circulation and in year to year variations in local climatology. Despite such variability, a warming phenomenon has been apparent since 1973 for waters of between 0 and 80 m in depth off the Catalan coast (Spain) [*Pascual et al.*, 1995] and since 1977 over the Mediterranean from a synthesis of meteorological data [*Metaxas et al.*, 1991]. Unfortunately, these surface data are not sufficiently robust to allow, in combination with data acquired from deep and intermediate waters, quantification of changes throughout the whole water column. As a rough estimate, *Béthoux et al.* [1990] calculated that dQ_t amounted to 1 Wm^{-2} in the whole water column of the Algero-Provençal basin. Accurate quantification on the scale of the entire sea requires an estimate of changes likely to have occurred in the other inner basins of the Mediterranean, i.e. in the Tyrrhenian Sea and in the eastern basin.

A 20-box model was used to summarize the main hydrological features in different areas and water masses of the Mediterranean [*Béthoux and Gentili*, 1996, 1997]. The heat and water budgets across the sea surface were constrained in order to simulate most of the geographical variations in temperature and salinity, and to verify a heat inbalance of -5 Wm^{-2} (balanced by thermal advection across the Strait of Gibraltar) and a freshwater deficit ($E - P - R$) of 0.95 $m\ yr^{-1}$. This was assumed to correctly summarize Mediterranean functioning before the 1940s. Thereafter, the 20-box model was used to quantify the effects of continuous changes in heat and water budget across the sea surface on temperature and salinity in western deep water. The observed trend of temperature increase was simulated with changes in the surface heat budget over the entire sea reaching 1.5 Wm^{-2} in 1995. The shifts represented either an increase in heat inputs or a decrease in losses.

Over the 1940-1989 period, no continuous increase in solar radiation was recorded [*Kelly and Wigley*, 1990]. In the Atlantic ocean, anomalies are occurring on decadal scales [e.g. *Hansen and Bezdek*, 1996] but no continuous increase in surface temperature was found. Consequently the change of 1.5 Wm^{-2} in the heat budget may be indicative of a decrease of air-sea heat exchanges. The measured salinity trend was simulated with an increase in water deficit that reached 0.1 $m\ yr^{-1}$ in 1995. Considering that there are increasing trends in both temperature and salinity, the latter cannot be derived solely from an increase in evaporation, the large latent heat flux of evaporation resulting in water temperature decrease. Consequently the two changes are concomitant but more or less independent.

Heat budget and surface temperature increase

From calculated or measured temperature changes in different layers and locations, the change in the heat content of the Mediterranean Sea, dQ_t, amounts to a mean value of 0.65 Wm^{-2} between 1940 and 1995 (derived from 0.70 and 0.53 Wm^{-2} in the eastern and western basin, respectively). Changes in marine advection must be considered given the temporal changes in deep water temperature and salinity as well as changes in water deficit and flows. An almost constant density of western deep-water means a constant deep outflow, V_o, while the temperature of Atlantic inflow, T_i, is assumed constant. Using T_s to approximate $T_{e,p,r}$, temporal changes in marine advection may be written as:

$$\mathrm{d}Q_a/\rho C_p = \mathrm{d}(E-P-R)[T_i - T_s] - V_o \mathrm{d}T_o - \mathrm{d}T_s(E-P-R) \qquad (3)$$

For an initial $E-P-R$ = 2.38 10^{15} $kg\ yr^{-1}$ and a d($E-P-R$) of 4.6 10^{12} $kg\ yr^{-1}$, the 20-box model calculations give mean for T_s, dT_s and dT_o of 13.25°C, 7.34 10^{-3} °C yr^{-1} and 2.9 10^{-3} °$C\ yr^{-1}$, respectively. The calculated temperature change in deep outflow, dT_o, is slightly lower than that measured in the western deep waters, being 3.47 10^{-3} °$C\ yr^{-1}$, due to vertical mixing in the Alboran Sea between the Mediterranean outflow and the Atlantic inflow. The resulting advection change, dQ_a, over the 1940-1995 period amounts to: -0.44 Wm^{-2} in 1995. The shift is linked mainly to the temperature change in deep outflow (second term on the right-hand side of Eq.3). In considering the initial driving force, 1.5 Wm^{-2} in 1995, part of this energy compensates for the advection decrease, dQ_a (-0.44 Wm^{-2}), some of it contributes to an increase in the heat content of the water column, dQ_t = 0.65 Wm^{-2}, while the remainder 0.41 Wm^{-2} corresponds to an increase in heat transferred towards the atmosphere by either evaporation, sensible heat flux or longwave radiation. Inasmuch as there is no evidence of continuous changes in wind speed and/or air humidity, the changes in heat transfers result from dT_s and dT_a. From previous studies of air-sea heat exchanges in the Mediterranean Sea, preliminary estimates of changes in air-sea transfers driven by small changes in air and sea temperature were presented [*Béthoux et al.*, 1990], where: $dQ_e = 32.5(0.77dT_a - dT_s)$; $dQ_c = 16.8(dT_a - dT_s)$; $dQ_n = 0.6dT_s$ (with dT_a and dT_s in °C, and dQ_e, dQ_c and dQ_n being in Wm^{-2}). The sum gives:

$$\mathrm{d}Q_e + \mathrm{d}Q_c + \mathrm{d}Q_n = 41.83\mathrm{d}T_a - 48.70\mathrm{d}T_s \qquad (4)$$

This sum was previously assumed equal to -0.41 Wm^{-2}. With mean dT_s being previously calculated equal to 7.34 10^{-3} °$C\ yr^{-1}$, Eq.4 can be used to calculate the mean change in air temperature, giving dT_a = 8.37 10^{-3} °$C\ yr^{-1}$. This value is situated between the two estimates of global trend calculated from available climatic data over the northern hemisphere since the 1960s: 6 and 10 10^{-3} °$C\ yr^{-1}$ [*Jones*, 1994; *Jones et al.*, 1988]. With known dT_s and dT_a values, different changes in air-sea transfers may be calculated. For instance, the resulting changes in 1995 (when compared with transfers in 1940) for dQ_e, dQ_c and dQ_n are equal to -1.60, +0.95 and +0.24 Wm^{-2}, respectively.

With the previous hypotheses of no change in the solar radiation, nor in the Atlantic advection, the initial driving force of 1.5 Wm^{-2} may correspond to a decrease of net longwave radiation due to the change in atmospheric composition of radiative components. The calculated dQ_n corresponds to a decrease of net longwave radiation due to the evolution of water temperature, probably a feedback from the atmospheric effect. Consequently the total change in net longwave radiation, i.e. the greenhouse effect increase, amounts to 1.5 + 0.24 = 1.74 Wm^{-2} in the Mediterranean area over the 1940-1995 period.

In the previous relationships for dQ_e and dQ_c, numerical factors depend on the drag coefficient (taken equal to 1.7 10^{-3}), the mean wind speed (7.1 $m\ s^{-1}$) and air humidity (77% or 0.77, the dT_a coefficient in dQ_e formula), which somewhat constrains the quantitative results. Nevertheless, drag coefficient and wind speed act both on dQ_e and dQ_c calculations and consequently they have practically no effect on the calculation of dT_a from dT_s (Eq.4). Similarly, a change of +/- 100% of the estimated sum (dQ_e + dQ_c + dQ_n), from a 30% increase of either the external driving force (1.5 Wm^{-2}) or the estimated dQ_t (0.65 Wm^{-2}), gives new estimates of dT_a of 8.19 and 8.46 10^{-3} °$C\ yr^{-1}$, respectively, i.e. rather low changes of -2% and +1%. In order to have both an increase in evaporation (d$Q_e < 0$, salinity increase) and a decrease in sensible heat flux (d$Q_c > 0$, T_s increase), sea surface temperature change dT_s has to be between two limits depending on air temperature change, dT_a, and humidity, H_u : H_ud$T_a <$ d$T_s <$ dT_a. This relationship illustrates that surface temperature change dT_s in the Mediterranean is mainly driven by air temperature change dT_a over the northern hemisphere.

Freshwater budget and salinity increase

Due to a strong evaporation (continental climate) and to reduced precipitation and river runoff, the freshwater deficit was estimated to 95 $cm\ yr^{-1}$ in 1940 [*Béthoux and Gentili*, 1997]. The increased latent heat flux (1.6 Wm^{-2} in 1995) corresponds to a surplus of water loss by evaporation of 2 *cm*, which may explain, in part, the increased salinity of Mediterranean waters. Known changes in freshwater input are decreases in the outflow of the Nile river since the closing of High Dam in 1964 [*Wadie*, 1984], and the Ebro river since the 1960s [*Martin and Milliman*, 1997], about 2 10^3 $m^3\ s^{-1}$ and 1 10^3 $m^3\ s^{-1}$, respectively. These two man-made changes correspond to a diminished layer of freshwater input at the sea surface of about 3.6 $cm\ yr^{-1}$. Another anthropogenic cause of salinity increase may be an increasing flow of saline water from the Red Sea into the Mediterranean. At its opening in 1869, the cross-sectional area of the Suez Canal was 304 m^2, compared to 3600 m^2 in 1981, after different deepenings and widenings [*Halim*, 1990]. The changes favour the natural inflow of Red Sea water towards the Mediterranean Sea. With a rough estimate of a mean current of about 0.25 $m\ s^{-1}$ in the Suez Canal, this salinity input may be equivalent to the effect of an evaporation increase of about 1.3 *cm* over the entire sea.

The other probable change in freshwater budget corresponds to a decrease in precipitation, observed around the western basin since at least the 1940s and also reported from some observations in the eastern basin [*Bradley et al.*, 1987]. From calculated evaporation increase, known river runoff decreases and simulated freshwater deficit change, the estimated precipitation decrease in 1995 amount either to 4.4 *cm* or to 3.1 *cm*, if the estimated effect from Suez Canal inflow is taken into account. These values correspond to a 14% or a 10% decrease of precipitation over the whole sea; the previous estimate from records from the north-western basin suggested a 11% decrease [*Béthoux and Gentili*, 1996]. Regional changes of river runoff (Nile and Ebro rivers) and the link with the Red Sea may correspond to an increase of the freshwater deficit of about 4.9 *cm* in 1995, i.e. about 50% of the estimated change from salinity increase. Increase in evaporation and decrease in precipitation, due to global climate and probably to GHE change, may correspond to the remaining 50% salinity change.

Conclusion

The GHE change was probably initiated at the end of the preindustrial period (around 1750) such that, since the early 20th century, surface temperatures of oceans and lands have reflected the global warming trend [*Jones*, 1994; *Jones et al.*, 1988]. A radiative forcing of 2.45 Wm^{-2} was calculated for year 1992 [*IPCC*, 1995] from alterations in the atmospheric concentration of radiative components. Most of the estimated change apparently dates from the 1940s, but until now no direct proof has been provided. Our calculated change in radiative forcing of 1.74 Wm^{-2} between 1940 and 1995 over the Mediterranean area is comparable to that estimated from the curve of change with time over the northern hemisphere [*IPCC*, 1995], about 1.7 Wm^{-2} during the same period. Consequently, we believe that the trend of increasing temperature observed in the Mediterranean constitutes the first measured effect of the GHE change. Furthermore, the effect is quantifiable as well as its consequences on air temperature and freshwater budget in the Mediterranean area, where recurrent droughts and freshwater availability are already a problem. Improvement of results requires more marine and climatic data and a special attention to different simplifying hypotheses used in this first attempt. Nevertheless, the calculated changes in heat and freshwater budgets, i.e a 2.5% decrease of the longwave radiation and 10% change in freshwater budget, appear sufficient [*Béthoux and Gentili*, 1997] to explain the dramatic change in water mass formation and distribution in the eastern Mediterranean [*Della Vedova et al.*, 1995; *Roether et al.*, 1996]. Once again, the Mediterranean appears as a scaled down model for the study of ocean circulation and environment - air - sea interaction, and the monitoring of climatic and environmental evolutions, changes with consequences for the Mediterranean ecosystem, marine circulation and the global change [*Johnson*, 1997].

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