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Air–Sea Fluxes from Operational Analyses Fields: Intercomparison Between ECMWF and NCEP Analyses Over the Mediterranean Area

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Abstract. Sea surface heat budgets are estimated for the Mediterranean Sea in order to test the air-sea interaction formulae. Sensitivity experiments are carried out in terms of input atmospheric data, height of parameters (surface, 1000 hPa) and bulk formulations.

The *ECMWF* and *NCEP* operational analyses at 1000 hPa are used to compute heat and water fluxes for the period 1987-94 and 1980-88 respectively. For the intercomparison period, January 1987 - December 1988, the ECMWF Re-Analyses surface data are also used. Along with the basic 6-hourly meteorological fields from ECMWF (wind velocity, air temperature, relative humidity and cloud cover), monthly cloud cover fields from COADS and weekly sea surface temperature from Reynolds data are also used.

Surface water budgets (mainly evaporation minus precipitation) have been estimated using the ECMWF precipitation data set.

Our results confirm that the heat budgets estimated from different operational analyses through arbitrary sets of bulk formulae disagree with each other and with observed data. Nevertheless the application of model-specific sets of bulk formulae can give reasonably well calibrated surface heat fluxes from the modeled meteorological fields.

1 Introduction

The Mediterranean Sea is an enclosed basin connected to the Atlantic Ocean by the narrow Strait of Gibraltar, and connected to the Black Sea by the Dardanelles-Marmara Sea-Bosphorus system. It is made-up of two sub-basins, the Western (WM) and the Eastern (EM) Mediterranean, connected through the Strait of Sicily.

In recent years several studies have been carried out to assess the capability of numerical models to simulate the seasonal and interannual variability of the Mediterranean flow field, as well as to reproduce the dynamical processes that characterize the Mediterranean circulation (Roussenov et al., 1995; Zavatarelli and Mellor, 1995; Castellari, 1996). Castellari et al.(1997) used NCEP operational 1000 hPa analyses and studied the sensitivity of the mean heat budget to different sets of bulk formulae. They developed a calibrated set of air-sea physics parameterizations specifically to satisfy the negative Mediterranean basin mean heat budget.

The present paper provides an intercomparison study of the heat budgets of the Mediterranean Sea computed using the *ECMWF* (European Centre for Medium-Range Weather Forecasts, Reading, UK) Operational Analyses and the *NCEP* (National Center for Environmental Predictions, Washington DC, USA) data for the period 1987-94 and 1980-88, respectively. For the intercomparison period, January 1987 to December 1988, additional data are taken from the ECMWF Re-Analyses (*ERA*) in order to test the sensitivity of heat fluxes to the height of the input meteorological fields.

2 Description of Data and Procedures

Basic fields are the zonal and meridional components of the wind velocity (u,v), air temperature (T_a), relative humidity (r), cloud cover (C), and sea surface temperature (T_s).

The first four parameters are available from three different data sets:

▹ the 1000 hPa *NCEP* Operational Analyses, twice daily, for the period January 1980 - December 1988 (Castellari et al., 1990);

▹ the 1000 hPa *ECMWF* Operational Analyses, 6 hourly, for the period January 1987 - December 1994 (Angelucci and Pinardi, 1997);

▹ the surface *ECMWF* Re-Analyses, 6 hourly, for the period January 1987 - December 1993.

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The cloud cover data are available from three data sets:

▷ *ECMWF* Operational Analyses, 6-hourly, for the period January 1987-December 1994;

▷ *COADS* (Slutz et al., 1985) data, monthly averaged, for the period January 1980-December 1988;

▷ *COADS* (da Silva et al., 1995) data, monthly averaged, for the period January 1987- December 1993.

The T_s data are taken from the global weekly Reynolds data set (Reynolds, 1988). All the computations have been performed using a 1° × 1° latitude, longitude grid.

2.1 Heat Flux Computations

The surface heat budget is represented by the net total heat flux at the air-sea interface:

$$Q_T = Q_S - Q_U = Q_S - Q_E - Q_H - Q_B \tag{1}$$

where Q_S is the solar radiation flux, Q_U is the net upward heat flux emitted by the ocean surface. This consists of Q_E, the latent heat flux, Q_H, the sensible heat flux and Q_B, the net outgoing longwave radiation flux. We consider in our estimates that the fluxes Q_E, Q_H and Q_B are positive for energy gained by the atmosphere.

We will briefly describe the physical formulation of each term present in (1).

The total solar radiation reaching the ocean surface under clear sky is:

$$Q_{TOT} = Q_{DIR} + Q_{DIFF} \tag{2}$$

where

$$Q_{DIR} = Q_0 \tau^{\sec z} \tag{3}$$

is the component of solar radiation reaching the ocean surface attenuated by an atmospheric transmission coefficient ($\tau = 0.7$), Q_0 is the solar radiation reaching the top of the atmosphere, and

$$Q_{DIFF} = \frac{[(1 - A_a)Q_0 - Q_{DIR}]}{2} \tag{4}$$

is the downward diffuse radiation with clear sky ($A_a = 0.09$ is the water vapor plus ozone absorption) (Rosati and Miyakoda , 1988; Castellari et al., 1997).

We use an empirical relation derived by Reed (1977) for the solar radiation flux at the ocean surface:

$$Q_s = Q_{TOT}(1 - 0.62C + 0.0019\beta)(1 - \alpha) \tag{5}$$

where C is the fractional cloud cover (tenths), β is the solar noon altitude in degrees, and α is the ocean surface albedo. This relation for Q_S is correct for $C \geq 0.3$; otherwise, $Q_S = Q_{TOT}$, as suggested by Reed (1977).

Q_E represents the heat released from the ocean to the atmosphere through evaporation and it plays an important role in the water mass formation processes in the ocean. Q_H represents the heat absorbed or emitted from the sea to the atmosphere mainly by turbulent motions, conduction, convection and advection of water vapor or rain.

These fluxes are parameterized through bulk formulae as:

$$Q_E = \rho_a L_E C_E |\vec{V}| [(e_{sat}(T_s) - r e_{sat}(T_a)] \frac{0.622}{p_a} \tag{6}$$

$$Q_H = \rho_a C_p C_H |\vec{V}| (T_s - T_a) \tag{7}$$

where $\rho_a = \rho_a(p_a, T_a, r)$ is the density of moist air, C_p is the specific heat capacity, C_H, C_E are the turbulent exchange coefficients, L_E is the latent heat of vaporization, $|\vec{V}|$ is the wind magnitude and p_a is the surface air pressure. Several parameterizations schemes are present in the literature (Bunker et al., 1982; May, 1986; Gilman and Garrett, 1994) to describe the variability of C_H, C_E with respect to $|\vec{V}|$, T_s, T_a and the virtual temperature T_v.

Here we use two different schemes for C_H and C_E, the Kondo scheme (*K*) and the Smith scheme (*S*). In the Kondo (1975) scheme, the transfer coefficients are estimated in terms of $T_s - T_a$ and $|\vec{V}|$ at a single level (10m) and are nonlinearly modulated from an index of atmospheric stability. More recently Smith (1989) developed tables for C_E as a function of wind speed and $T_s - T_v$ at 10m over the sea surface. In the Smith scheme, $C_H = C_E/1.2$. In Castellari et al. (1997) the Kondo scheme was found to give reasonable results with the NCEP 1000 hPa data. On the other hand, the Smith scheme was used by Gilman and Garrett (1994) in their analysis of the Mediterranean heat budget with the COADS data.

For the net outgoing longwave radiation, the May formula is adopted (May, 1986):

$$\begin{aligned} Q_B \;=\; & [\sigma T_a^4 (0.4 - 0.05 e_a^{1/2}) + \\ & + 4\sigma T_a^3 (T_s - T_a)](1 - 0.75 C^{3.4}) \end{aligned} \tag{8}$$

where σ is the Stefan-Boltzman constant, $e_a = r e_{sat}(T_a)$ is the atmospheric vapor pressure and $e_{sat}(T_a)$ is the saturation vapor pressure relative to T_a. This formula gave the best results in Castellari et al. (1997).

The monthly heat budgets have been computed by averaging in time the fluxes estimated every 6 hours. The experiment name (see Table 1) indicates both the atmospheric data set used (*N*12 for *NCEP* twice daily, *E*6 for *ECMWF* 6 hourly, *RE6* for *ERA* 6 hourly), and the latent and sensible heat fluxes schemes (*K* for Kondo and *S* for Smith). For experiment *N12_K* and *N12_S*, we have taken the results from Castellari et al. (1997). For all the experiments we have used the COADS clouds, except for experiment *EC6_S*, where the ECMWF 6-hourly clouds have been used.

Table 1. 1987-88 annual surface average values of each component of the heat budget from the different experiments and the da Silva et al. (1995) results. Units are $\frac{W}{m^2}$.

Yr 1987	Qs	Qe	Qh	Qb	Qu	Qt
N12_K	203	113	12	65	190	13
N12_S	203	86	11	65	162	41
E6_K	207	152	22	88	262	-55
E6_S	207	111	16	87	214	-7
EC6_S	228	111	16	88	215	13
RE6_K	207	91	14	81	186	21
RE6_S	207	61	10	81	152	55
COADS	188	85	10	61	156	32
Yr 1988	**Qs**	**Qe**	**Qh**	**Qb**	**Qu**	**Qt**
N12_K	203	104	9	67	180	23
N12_S	203	79	8	67	154	49
E6_K	206	152	20	86	258	-52
E6_S	206	112	14	86	212	-6
EC6_S	226	112	14	86	212	14
RE6_K	206	91	13	80	184	22
RE6_S	206	60	9	80	149	57
COADS	188	89	10	61	160	28

3 Discussion and Results

In general, in the Mediterranean the long-term mean heat budget should satisfy two conditions:

1) the mean heat budget should be about $-7 \pm 3\frac{W}{m^2}$ (Bethoux, 1979) or $-5.2 \pm 1\frac{W}{m^2}$ (Macdonald et al., 1994) to balance the annual mean gain of heat through the Strait of Gibraltar;

2) the evaporation rate should be within the range $1.32 - 1.57\frac{m}{y}$ (Castellari et al., 1997) in order to maintain a reasonable water budget. The corresponding latent heat flux range is $103 - 122\frac{W}{m^2}$.

However, this work is concerned with the analysis of the heat budget for only two years, 1987 and 1988, which are considered extremely warm years (Castellari et al., 1990) and too short to satisfy the two conditions described above. Then, for these two years, we decided to compare our results to the fluxes from COADS (da Silva et al., 1995) estimated by using only observational data.

Table 1 presents the annual surface integrals over the Mediterranean area of each term of (1), for the different experiments performed, and the da Silva et al. (1995) estimates for years 1987 and 1988. It is important to notice that these heat fluxes from COADS observational data are also estimated through a certain set of bulk formulations.

Three are the experiments using the Kondo scheme. In *N12_K* and *E6_K* this scheme is utilized in combination with 1000 hPa data, but results obtained through the latter give a latent heat flux (and consequently the evaporation rate) too large, breaking the water budget constraint. On the other hand, when surface data are used (*RE6_K*), the latent heat is too low compared to the range values given above, due to the lower wind amplitude at 10m. If we focus the attention on experiments *N12_K* and *RE6_K*, the difference in Q_B is to some extent balanced by the difference in Q_E, in such a way that the heat budget is comparable in the two experiments. For both experiments, a positive net heat flux is achieved, mainly due to positive temperature anomalies in these years.

On the other hand, the Smith scheme combined with *ECMWF* data (*E6_S*) maintains reasonable values for the latent heat fluxes, while with NCEP (*N12_S*) and ERA data (*RE6_S*) Q_E is much lower.

It is important to remark that the Smith scheme leads in general to an underestimation of Q_E and Q_H (Gulev, 1995).

About Q_S, in Table 1 we observe a discrepancy between the values in the *N12* (Castellari et al., 1997) and *E6, RE6* experiments, due to the fact that they use the cloud cover fields from Slutz et al. (1985) and da Silva et al. (1995), respectively. Furthermore, these values for Q_S show some inconsistences with respect to the estimates of da Silva et al. (1995), probably linked to some corrections applied by the latter in the astronomical terms of (5), despite the fact that the same Reed formulation is used.

In Table 1, the largest difference is between both the N12 and E6 experiments, the latter giving a negative heat budget for 1987 and 1988. This is in contrast with all the other computations and we are forced to think that, for the ECMWF data set, the choice of 1000 hPa data is problematic. The experiment *EC6_S*, which uses a self-consistent data set, gives a positive heat budget in good agreement with the *N12_K* result. However, the Q_S obtained from *EC6_S* seems too large, due to the fact that the cloud cover values from ECMWF operational analyses are too low. This confirms their known unreliability (ECMWF, 1994).

To evaluate which is the best experiment, we consider the comparison of our results to the estimates of da Silva et al. (1995), which we have taken as reference. For the years 1987 and 1988 (see Table 1), *RE6_K* gives annual means of latent and net heat fluxes close to the ones by da Silva et al. (1995). On the basis of this comparison, we decided to consider *RE6_K* our best experiment.

In Fig.1, we show the winter (top), spring (middle) and summer (bottom) climatological Q_T fields, obtained with *RE6_K* for the period 1987-93. The winter map (Fig.1,a) presents high losses of heat, mainly in the regions where water mass formation processes occur, such as in the Northern Adriatic (NA), the Liguro-Provencal (LP) and Levantine-Aegean (LA) regions. The largest heat losses of the whole basin are found in the NA and Northern LA areas where Eastern deep waters and Levantine Intermediate waters are formed, respectively.

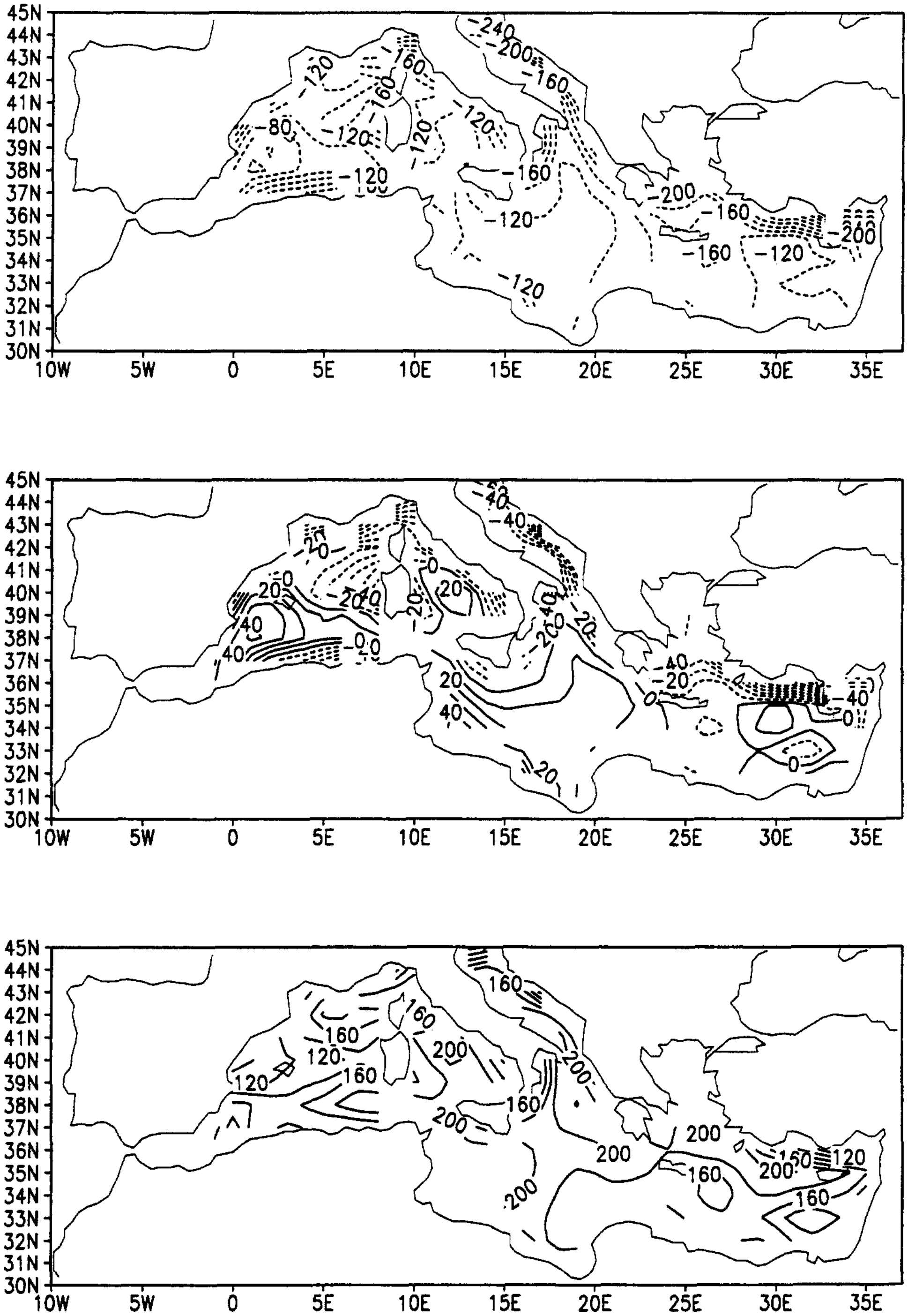

Fig. 1. Monthly 1987-93 climatological surface heat fluxes computed from experiment *RB6_K*: winter (top), spring (middle), summer (bottom). Units are $\frac{W}{m^2}$.

The LP area is characterized by the west-northerly Mistral wind, blowing mainly during wintertime over the Gulf of Lions, whereas over the LA region the northerly Etesian winds blow mainly during summertime. Nevertheless it should be noted that the Etesians, as represented in the *ECMWF* operational analysis data set, show high wind speed also in winter, leading to high evaporation rates all over the year. The spring map (Fig.1,b) exhibits more positive values with respect to the corresponding climatological field computed for the period 1980-88 by Castellari et al. (1997) with *N12_K* parameterizations. Also the summer plot (Fig.1,c) depicts more positive patterns in *RE6_K* than in the *N12_K* case. This is the manifestation of the large heat gain occurring in these years, also shown by the large positive heat budgets of Table 1.

Final remarks concern the evaporation budget, computed from the latent heat flux. We have estimated the evaporation field for the period 1987-1993 for experiment *RE6_K* and then the fresh water budget (mainly E -P) for the period 1991-93, using the *ECMWF* precipitation field for the period 1991-1994. The 7-year mean for E is $1.1\frac{m}{y}$, which is out of the range of values given by Castellari et al. (1997). The 4-year mean for precipitation is $0.45\frac{m}{y}$, which is smaller than the climatological values of $0.59\frac{m}{y}$ (Bethoux, 1979) and $0.7\frac{m}{y}$ (Legates and Willmott, 1990). These budgets lead to a long-term mean for E -P of $\sim 0.65\frac{m}{y}$, lower than the climatological value $0.95\frac{m}{y}$ for the Mediterranean Sea (Bethoux, 1979).

4 Conclusions

The present analysis provides estimates of heat fluxes with different atmospheric data sets and parameterizations. The most appropriate set of bulk formulae to estimate correct heat fluxes for the Mediterranean Sea depends on the atmospheric data set used. For instance, by using a self-consistent data set from *ECMWF* with the Smith scheme, we have found heat budgets comparable to those estimated with NCEP data, but a Q_S component too high with respect to past results (Gilman and Garrett, 1994; Castellari et al., 1997).

On the other hand, by using the *ECMWF* meteorological data together with COADS cloud cover and the Kondo and Smith schemes for the latent and sensible heat fluxes, we have found incompatible results. Finally by using the surface *ECMWF* Re-Analysis data together with COADS cloud cover and the Kondo scheme we have found heat budgets comparable to the ones estimated with the *NCEP* data and to independent results from COADS (da Silva et al., 1995), which were obtained only by observational data.

An important consideration is provided by the result that both 1987 and 1988 are years of heat accumulation in the basin. This feature by itself is very important for the water masses and circulation structures of the Mediterranean Sea. It is evident that, in all data sets used, this positive heat balance is connected to warm air mass anomalies over the basin, a phenomenon which should deserve more attention in the future. Future work involves also the recomputation of the long term mean heat budget by using the 15-year *ERA* data set and the test of a calibrated set of air-sea physics formulations to force ocean circulation models.

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