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Surface Heat and Water Fluxes in the Adriatic Sea: Seasonal and Interannual Variability

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Abstract. Adriatic Sea surface heat and water fluxes for the period 1991–1994 have been computed from the ECMWF (European Center for Medium Range Weather Forecast) operational analyses data. The obtained surface heat flux climatology is in good agreement with previous estimates, while the surface water flux climatology reveals an higher fresh water loss with respect to the known values. Our results reveal important interannual variations in the magnitude and the sign of the heat budget. In particular, the heat budget for the year 1994 is positive, in contrast with the long term mean negative heat flux estimates. Implications connected with the Adriatic Sea thermohaline circulation are discussed.

1 Introduction

This study estimates the surface heat and water fluxes budgets of the Adriatic Sea, computed using atmospheric data from weather forecast operational analyses. The final goal of this work is to obtain surface fluxes to be used as boundary conditions for general circulation numerical models of the Adriatic Sea, in order to simulate its climatological structures and its interannual variability. Despite the possible systematic errors, operational analyses, and the successive surface fluxes computations, are very suitable for the definition of model atmospheric forcing, given the often inadequate spatial and temporal coverage of data arising from direct observations. The validity of using this kind of information to model the general circulation of the Mediterranean Sea has been demonstrated by previous modelling efforts at climatological (Roussenov et al., 1995) as well as interannual time scales (Pinardi et al., 1997).
Here we show the basin averages of the surface heat and water fluxes relative to the period 1991–1994, computed from the European Center for Medium Range Weather Forecast (ECMWF) atmospheric data and compare the derived climatologies with the known climatological estimates. Furthermore, we discuss the interannual variability features and their possible implications for the thermohaline circulation of the Adriatic Sea.
An attempt to compare and validate these fluxes with ECMWF Reanalysis and COADS data is also made. In this paper, the heat and water budgets are defined in such a way that positive values indicate heat gain and fresh water loss respectively.

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2 Background information

The Adriatic Sea is a Mediterranean Sea sub-basin located between the Italian peninsula and the Balkans. Its northern end is very shallow and gently sloping (average depth: 35 m). The middle Adriatic is 140 m deep on the average, with two depressions, the so-called Pomo depressions, or Jabuka Pits, both reaching 260 m depth. The southern end is characterized by a strong topographic gradient leading to a wide depression deeper than 1200 m. Water exchange with the Mediterranean Sea (Ionian Sea) takes place through the Otranto channel, being about 800 m deep at its sill.
The Adriatic basin is subject to strong forcing functions that produce a clear seasonal variability in the general circulation (Artegiani et al., 1997b). The current knowledge about the climatological characteristics of the Adriatic Sea heat and water budgets has been reviewed by Raicich (1996) and Artegiani et al. (1997a). It has been found that the surface mean heat budget corresponds to a heat loss of 19–22 W m^{-2}, which, at the climatological time scale, should be compensated by heat advection through the Otranto channel.
The balance between evaporation and precipitation (surface water flux) is estimated to range between 0.06 and 0.52 m/yr. Evaporation determines a water loss comprised between 1.08 and 1.34 m/yr, while precipitation

determines a water gain ranging between 0.82 and 1.02 m/yr. To obtain the net freshwater budget of the Adriatic Sea, we need to add the river runoff contribution (1.17 m/yr), which then leads to a water gain of 0.65–1.10 m/yr and makes the Adriatic Sea a dilution basin. The basin is a well known site of dense water formation (Artegiani et al., 1989; Pollak, 1951) related to the winter surface heat losses. In the northern basin this process involves the convection and sinking of relatively cool waters. In the period March-April, this dense water flows along the western coast, following isobaths at a depth of 50-150 m and mixing with intermediate water of Levantine origin. Part of this water enters the Pomo depressions and the Southern Adriatic. The dense water formation process is suspected to be extremely sensitive to interannual variations in the atmospheric forcing, as it might not occur every year, or the amount of dense water formed can considerably vary from year to year. It should be noted that a dilution basin with deep water formation is rather uncommon. The contrasting effects of dilution and cooling on density are probably responsible for the high sensitivity of the deep water formation to changes in boundary conditions.

3 The data-sets

The ECMWF (1994) operational analyses used, are covering the period January 1 1991 to December 31 1994. The data utilized for the fluxes computations were: air temperature, relative humidity, wind speed (all of them calculated at 1000 hPa), total cloud cover and precipitation. Air temperature, relative humidity and wind velocity have a temporal resolution of 6 hours (0.00, 6.00, 12.00, 18.00 UTC), while precipitation is calculated as part of the daily forecast relative to 12.00 UTC. The spatial resolution of the ECMWF operational analyses (for the period of time considered) is the T213 reduced Gaussian Grid, which corresponds to 0.5625°×0.5625° of a rectangular grid.
The sea surface temperature (SST) information, required for the computation of the air-sea heat fluxes, were obtained from the Reynolds (1988) SST data set, which has a temporal resolution of one week and a spatial resolution of 1°×1°.
We calculated also the heat and water fluxes using the 10 m wind velocity and the 2 m air temperature of the ECMWF Reanalysis data (Gibson et al., 1997). The use of surface atmospheric data eliminates the bias introduced by the 1000 hPa in the estimation of the latent heat flux, mainly due to the stronger 1000 hPa winds with respect to 10 m. The relative humidity has been calculated, using the same formulation of the ECMWF model, from the mean sea level pressure and 2 m absolute and dew point air temperature. The spatial resolution of the Reanalysis data is the T106 Gaussian Grid, with a longitude resolution of 1.250° and a latitude resolution of 1.1213°. The temporal resolution is the same of the Analyses. The cloud cover and precipitation data used in the calculation based on the Reanalysis comes from the COADS (Comprehensive Ocean Atmosphere Data Set, see da Silva et al., 1995) monthly mean data. They have a spatial resolution of 1°×1°.
Both the atmospheric and the SST data were interpolated (using a cubic splines interpolation scheme, with the exception of cloud and precipitation data, which required a bilinear interpolation) onto a rectangular grid with a horizontal resolution of 0.25°×0.25°. The computation of the fluxes were carried out from each individual set of interpolated atmospheric parameters (that is every 6 hours) and subsequently the monthly averages were calculated.

Table 1. The parameterisations of the heat flux components.

Component	Parameterisation
solar radiation flux (Q_s)	Reed (1975)
longwave radiation flux (Q_b)	May (1986)
sensible heat flux (Q_h)	Kondo (1975)
latent heat flux (Q_e)	Kondo (1975)

4 Surface fluxes computation

Surface heat fluxes were computed using the bulk formulae parameterization (listed in Table 1) proposed by Castellari et al. (1997) in a study of the Mediterranean Sea heat budget based on the NCEP (National Center for Environmental Predictions) operational analyses. More detailed information on the computation can be found in the appendix.
Total heat flux (Q_t) was computed according to:

$$Q_t = Q_s \pm Q_b \pm Q_h \pm Q_e \quad (1)$$

where Q_s is the short wave radiation flux, Q_b is the net longwave radiation flux, Q_h is the sensible heat flux and Q_e is the latent heat flux.
Surface water flux has been computed as the balance between Evaporation and precipitation (E–P). Evaporation was computed according to:

$$E = Q_e/L_e \quad (2)$$

where L_e is the latent heat of vaporization, linearly depending on the sea surface temperature (Gill, 1982).

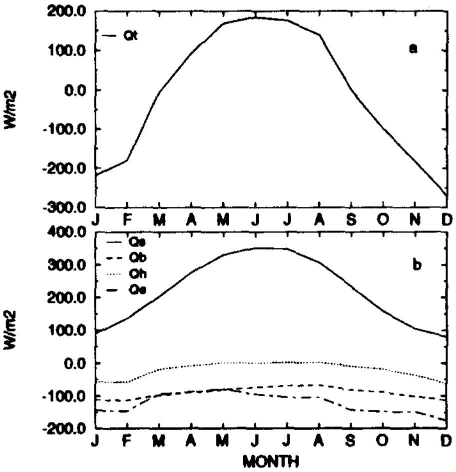

Fig. 1. Monthly total heat flux at the sea surface computed from the 1991–1994 ECMWF data. a: Annual cycle of the total heat flux. b: Annual cycle of its components.

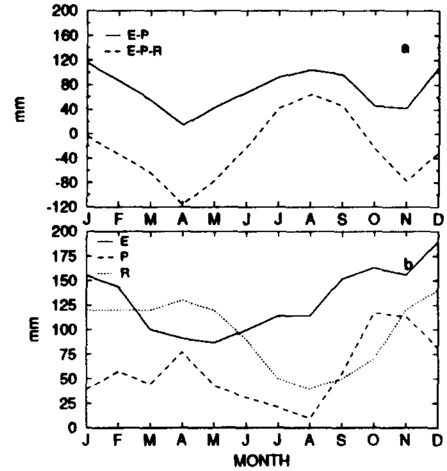

Fig. 2. Monthly surface and total water flux from the 1991–1994 ECMWF and Raicich (1996) data. a: Annual cycle of the surface and total water flux. b: Annual cycle of evaporation, precipitation and river runoff

5 Results

5.1 Climatology 1991–1994

5.1.1 Surface heat flux

The monthly 1991–1994 climatological cycle of the total heat flux and of its components, calculated from the ECMWF analysis data, is shown in Fig. 1a and b respectively. The total heat flux annual mean value (−17 W m^{-2}), is in agreement with the results of Artegiani et al. (1997a). The annual cycle is also in agreement with such computations, as the monthly value is ranging between a minimum of −272 W m^{-2} (December) and a maximum of 184 W m^{-2} (June), and the basin has a negative heat budget from October to March and positive during the rest of the year. However, we note that, with respect to the climatological values of Artegiani et al. (1997a), the Q_s monthly averages are shifted toward higher values, probably determined by the ECMWF cloud cover data, which appear considerably lower than the correspondent COADS data relative to the Mediterranean region (Angelucci et al., 1997). In Sec. 6 we will briefly illustrate the results obtained using COADS cloud data.
The total surface heat flux depends strongly on the longwave and latent heat fluxes. The Q_b cycle shows the lowest amplitude and ranges between −111 W m^{-2} (January) and −74 W m^{-2} (August). The Q_e flux, on the contrary, shows a large amplitude, as the monthly values are ranging between −80 W m^{-2} (May) and −175 W m^{-2} (December). Also the loss terms values are, in general, larger than the climatological values reported in Artegiani et al. (1997a). This is particularly evident for the latent heat flux during the summer period. Possible explanations for these departures from the known climatologies are offered in Sec. 6, but it has to be stressed that differences arising from the comparison might depend from the different data used (according to Raicich, 1996, summer sea surface temperature is a particularly critical factor), to a different averaging methodology and covered time periods. Consequences of these higher Q_e values on the computation of evaporation are described in Sec. 5.1.2. The only component showing a reversal of the sign from negative to positive, is the sensible heat flux. From May to August, the basin is, in fact, characterized by a weak sensible heat gain, reaching its maximum in August (2 W m^{-2}). The strongest sensible heat loss is −63 W m^{-2} (December).

5.1.2 Surface and total water flux.

The annual climatological cycles of the surface and total water flux are shown in Fig. 2a. The separated components are shown in Fig. 2b. The river runoff contribution comes from long term estimates of Raicich (1996). Obviously these data are not consistent with the data used for the surface flux computations, but we just want to stress the fundamental importance of the river runoff in determining, on an annual basis, the dilution character of the Adriatic Sea and the related thermohaline circulation features.
The annual average surface water flux amounts to 0.87 m. It ranges between a minimum of 0.01 m (April), depending on both a decrease in evaporation and an increase in precipitation and a maximum of 0.11 m (Jan-

uary) determined mostly by a strong evaporation. Despite the discrepancy in the calculated annual average value the surface water flux annual cycle trend is roughly in agreement with the one obtained by Raicich (1996). The seasonal cycle is characterized by low values in Spring and Autumn and by higher ones during Winter and Summer. The average evaporation is 1.56 m and the average precipitation is 0.69 m. Such values are respectively higher and lower than those estimated by Raicich (1996) and reported in Sec. 2. The higher evaporation is clearly a consequence of the strong (with respect to other climatological computations) latent heat flux values. With respect to precipitation, it has to be noted that Raicich (1996) values are considered overestimated and that our result agrees with the one adopted by Zore-Armanda (1969b) (0.70 m/yr), obtained from open-sea observations.

Also evaporation and precipitation annual cycles appear to be consistent with Raicich's ones. In particular, precipitation cycle shows a well defined Autumnal maximum and Summer minimum.

While the surface water flux is positive all the year, the total budget is always negative (with its absolute minimum in April, −0.11 m), with the exceptions of July, August and September. In particular, in August it shows its maximum value (0.06 m), due to the absolute minimum of precipitation (0.01 m) and runoff contribution (0.04 m). On an annual basis, the river runoff (1.17 m) determines the inversion of the sign of the total water budget with respect to the surface water flux (−0.30 m against 0.87 m).

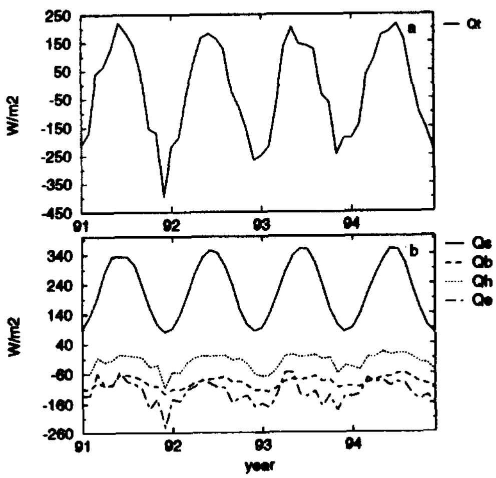

Fig. 3. Time series of surface monthly averaged heat fluxes for the period 1991–1994 from ECMWF data. **a:** Time series of Q_t. **b:** Time series of its components

Table 2. 1991–1994 interannual variations of the surface heat fluxes (W m^{-2}).

Year	1991	1992	1993	1994
Q_s	215	218	222	218
Q_b	-93	-93	-93	-85
Q_h	-28	-21	-24	-15
Q_e	-119	-125	-131	-114
Q_t	-25	-21	-26	4

5.2 1991–1994 interannual variability

5.2.1 Surface heat flux

In Sec. 5.1.1 we have shown that the 1991–1994 climatological Q_t annual value is in good agreement with previous estimates. In Table 2 we examine now the interannual variability. The important result is that during 1994 a significant change in the surface heat budget of the Adriatic basin occurred. From 1991 to 1993 the annual heat budget was negative, ranging between −21 and −26 W m^{-2}, while in 1994 it was positive, amounting to ±4 W m^{-2}.

Table 2 indicates also that this strong change is due to the loss terms (Q_b, Q_h, Q_e), rather than to the solar radiation flux, as in 1994 such components of the surface heat flux reach their lowest annual mean values, a consequence of the increase of the air temperature predicted by the ECMWF operational model (about 1°C increase in the 1994 annual average value with respect to the 1993 annual mean, Fig. 4a). Figures 3a and 3b show

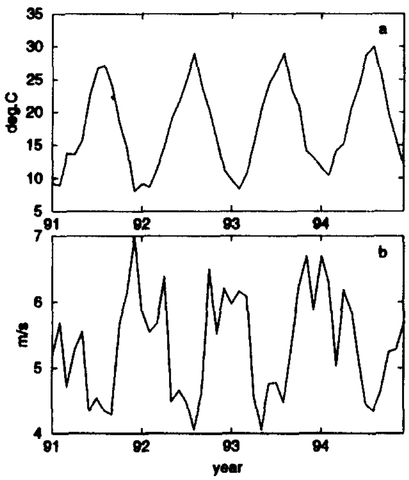

Fig. 4. Time series of 1000 hPa monthly averaged air temperature (a) and wind speed absolute value (b) for the period 1991–1994 from ECMWF analyses data.

weaker (but still noticeable) changes from year to year. The most noteworthy is the highest (395 W m^{-2}) heat

Table 3. Annual basin averages of the surface water flux (m).

Year	1991	1992	1993	1994
E	1.50	1.60	1.70	1.50
P	0.80	0.70	0.71	0.57
E-P	0.70	0.90	0.99	0.93

loss, occurring in December 1991. It should be noted that it is determined by a decrease in the net longwave, sensible and latent heat fluxes (maximum of their absolute values), determined by the absolute maximum of wind speed (Fig. 4b) and minimum of air temperature in the ECMWF analyses data. Solar radiation flux is characterized by a weak interannual signal, since cloudiness is the only parameter, in its parameterization formula, varying interannualy. On the contrary, it shows a strong and regular seasonal signal, characterized by a minimum in December for all the years, and a maximum in June, with the exception of the 1991 (maximum, the lowest of the time series, in May, 334 Wm^{-2}). This strong seasonality is connected to the variability of the orbital parameters (solar noon altitude and sun declination), more than to cloudiness, which, in the examined period, does not show a regular seasonal signal. The other heat flux components show stronger variations from year to year, in particular the sensible and latent heat flux. The lowest latent heat loss occurs in June 1991 (-55 W m^{-2}). The sensible heat flux time series is well correlated with the latent heat one, but with smaller values (in absolute value). The highest gain occurs in May 1994 (12 W m^{-2}). The longwave heat flux lowest value occurs in July 1994 (-60 W m^{-2}). The absolute minimum in the net longwave, sensible and latent heat flux time series occurs in December 1991.

5.2.2 Surface water flux

We were not allowed to study the total water budget because of the lack of river runoff information relative to the examined period. The annual averages for the surface water flux, for the evaporation and precipitation (Table 3) show a different interannual variability than that found in the surface heat flux values. The annually averaged surface water flux ranges from 0.70 to 0.99 m. The lowest value occurred in 1991 and corresponds to the higher precipitation and lower evaporation averages. Evaporation increased from 1991 to 1993, while in 1994 it decreased to the 1991 value following the cycle of the latent heat flux described in sec 5.2.1. This does not result in a significant decrease of the surface water flux value as also precipitation exhibits during 1994 its lowest annual mean value. The monthly surface water flux is always positive (Fig. 5a) with the only exceptions of November 1991 and October 1992, when precipitation slightly overwhelmed evaporation. In general, low surface water flux values correspond to high peaks in the

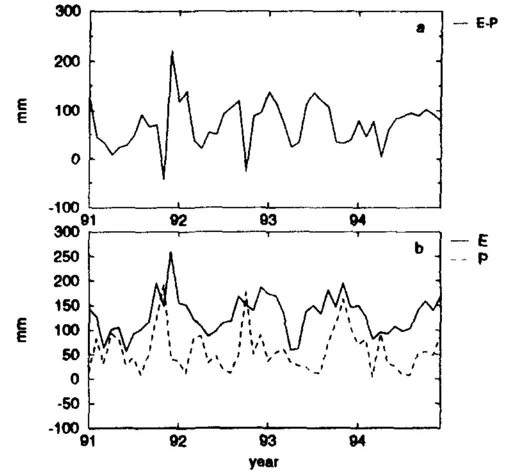

Fig. 5. Time series of surface monthly averaged water flux for the period 1991–1994 from ECMWF data. a: Time series of E-P. b: Time series of its components.

precipitation rather than to a decrease in evaporation. The high latent heat loss of December 1991 is mirrored in the high evaporation value (0.26 m).

6 Discussion and conclusions

The calculation of the surface heat and water fluxes from weather forecast operational analyses poses, obviously, the problem of their validation. Here we compared the four years climatology (1991–1994) obtained from the ECMWF atmospheric data with the known climatological estimates of the Adriatic Sea surface heat and water fluxes, taking into account the limitations to such comparisons posed by the use of different data, methodologies and time periods (this could be a crucial point, if we consider the strong system variability). The estimates relative to the surface heat flux give values in reasonable agreement with the long term climatologies, but two main issues arise: a) the high solar radiation fluxes, requiring a more detailed check of the cloud coverage data; b) the high latent heat fluxes, requiring the use of 10 m winds and a check of its parameterization. As a preliminary inquiry into these issues we recomputed the surface heat fluxes for the period 1991–1993 utilizing the ECMWF Reanalyses and the COADS clouds data (1994 ECMWF Reanalyses and COADS data are not yet available). The obtained results are listed in Table 4. The strongest difference between Analysis and Reanalysis total heat flux annual averages is the 1991 value (-25 W m^{-2} against -15 W m^{-2}), mainly as a consequence of the much lower Reanalyses latent heat loss (-119 W m^{-2} against -82 W m^{-2}). Further inves-

Table 4. 1991–1993 interannual variations of the surface heat fluxes (W m^{-2}) calculated from ECMWF Reanalyses and COADS data.

Year	1991	1992	1993
Q_s	187	176	183
Q_b	-91	-86	-92
Q_h	-29	-25	-30
Q_e	-82	-84	-91
Q_t	-15	-19	-30

tigation has to be done about this point since it could have some relation with the change in the ECMWF model in September 1991. Apart from this discrepancy and in spite of the coarse spatial resolution of Reanalyses and COADS data, the 1992–1993 values appear similar, within known error bounds for heat flux estimates (5–10 W m^{-2}). The 3-years average of the total heat flux is -20 W m^{-2}, which is in agreement with the value from the Analyses data (-24 W m^{-2}). This gross accordance is the result of the balance between the two largest terms, showing, in the two analyzed cases, the largest discrepancies: solar radiation and latent heat flux. As a direct consequence of the higher COADS clouds cover, the Reanalyses solar radiation flux is sensibly lower than the Analyses. On the other hand, probably as a consequence of the weaker 10 m winds with respect to 1000 hPa, the Reanalyses latent heat flux values are lower than the Analyses.

As regard as the surface water flux, the ECMWF analyses values appear higher than the previous estimates (Raicich, 1996, Artegiani et al., 1997a). Based on a four years climatology, it is difficult to verify whether this discrepancy is due to a systematic error in the data or due to specific characteristics of the years considered. A more comprehensive answer can be achieved only from an extension of the time series considered. Here we have recomputed the surface water flux by means of ECMWF Reanalyses evaporation and COADS precipitations data (Table 5). We found that lower (with respect to Analyses) evaporation values (1991–1993 average of 1.09 m/yr) coincide with extremely low COADS precipitation data (1991–1993 average of 0.42 m/yr, even lower than ECMWF Analyses). Thus, the resulting surface water flux (1991–1993 average of 0.67 m/yr) is still higher than Raicich's estimates, although lower than ECMWF Analyses. Nevertheless, it is important to note the agreement between the evaporation values (ranging between 1.04 and 1.17 m/yr) and the Raicich's ones. Both the Analyses and Reanalyses surface water fluxes are consistent, on an annual basis and with regard to the sign, with a right total water budget (net water gain of 0.30 m/yr for the Analyses, 0.50 m/yr for the Reanalyses and 0.65–1.10 m/yr in Raicich's estimates), if we consider the river runoff contribution. Thus, our analysis confirms the crucial role of the river runoff contribution in estabilishing the water budget of the basin. The computed ECMWF Analyses fluxes have a correct seasonal variability and have highlited possible important interannual variations. In particular, the positive value of the total surface heat flux found in 1994 could affect the dense water formation processes, which have been found to be strongly reduced in that year (Artegiani, personal communication). Numerical experiments with a general circulation model of the Adriatic Sea forced with the surface heat and water fluxes discussed in this paper will provide more informations about the role of the forcing functions in determining the interannual variability of the general circulation and its water mass characteristics.

Table 5. Annual basin averages of the surface water flux (m) from ECMWF Reanalyses evaporation and COADS precipitation.

Year	1991	1992	1993
E	1.04	1.07	1.17
P	0.49	0.39	0.38
E-P	0.55	0.68	0.79

Appendix Heat fluxes computations

The heat fluxes computations have been performed by the bulk formulas (in SI units) summarized here. Further details could be found in Castellari et al. (1997). The solar radiation Q_s has been calculated according to Reed (1975):

$$Q_s = Q_{TOT}(1 - 0.62C \pm 0.019\beta)(1 - \alpha) \quad \text{(A1)}$$

where α is the sea surface albedo, C is the fractional cloud cover, β is the noon sun altitude, Q_{TOT} is the clear sky radiation. The last term is expressed as the sum of the direct and downward scattered radiation:

$$\begin{aligned} Q_{TOT} &= Q_{DIR} \pm Q_{DIFF} \\ Q_{DIR} &= Q_0 \tau^{\sec\theta} \\ Q_{DIFF} &= \frac{[(1 - A_a)Q_0 - Q_{DIR}]}{2} \end{aligned}$$

where Q_0 is the solar radiation at the top of the atmosphere, τ is the transmission coefficient for the atmosphere, A_a (=0.09) the absorption coefficient for the water vapor and the ozone and θ the zenith angle. Q_0 has been calculated according to:

$$Q_0 = \frac{S_0}{r^2}\cos\theta$$

where S_0 is the solar constant (1350 W m^{-2}) and r is the radius vector of the Earth, taken equal to 1. The relation A1 is used if $C \geq 0.3$, otherwise $Q_s = Q_{TOT}$ (Reed, 1977).

The net longwave radiation has been calculated using the May (1986) formula:

$$\begin{aligned} Q_b = -\ & [\sigma T_A^4(0.4 - 0.05\sqrt{e_A}) \pm 4\sigma T_A^3(T_S - T_A)] \\ & \cdot(1 - 0.75C^{3.4}) \quad \text{(A2)} \end{aligned}$$

where T_A is the air temperature, T_S is the sea surface temperature, σ is the Stefan-Boltzman constant, $e_A = 0.01 U e_{sat}(T_A)$ is the atmospheric vapor pressure, expressed as a function of the saturation vapor pressure e_{sat}, computed from Lowe (1977), and the relative humidity U (%).

The sensible and latent heat fluxes have been parametrized according to the classical formulae:

$$Q_h = - \rho_A C_p C_H \mid \vec{V} \mid (T_S - T_A) \quad \text{(A3)}$$

$$Q_e = - L_E \rho_A C_E \mid \vec{V} \mid [(e_{sat}(T_S) - U e_{sat}(T_A)] \cdot \frac{0.622}{p_A} \quad \text{(A4)}$$

where $\rho_A = \rho_A(p_A, T_A, U)$ is the moist air density, p_A is the surface air pressure, fixed at 1013 hPa, C_p is the specific heat capacity at constant pressure, C_H and C_E are the turbolent exchange coefficients, computed according to Kondo (1975), L_E is the latent heat of vaporization and $\mid \vec{V} \mid$ is the wind speed modulus. The number 0.622 is the ratio between the gas constants for dry air and water vapour. With these formulations the fluxes are positive if the ocean gains heat.

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