

# Evaluation of Mediterranean Sea water and heat budgets simulated by an ensemble of high resolution regional climate models

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**Abstract** Air-sea heat and freshwater water fluxes in the Mediterranean Sea play a crucial role in dense water formation. Here, we compare estimates of Mediterranean Sea heat and water budgets from a range of observational datasets and discuss the main differences between them. Taking into account the closure hypothesis at the Gibraltar Strait, we have built several observational estimates of water and heat budgets by combination of their different observational components. We provide then three estimates for water budget and one for heat budget that satisfy the closure hypothesis. We then use these observational estimates to assess the ability of an ensemble of ERA40-driven high resolution (25 km) Regional Climate Models (RCMs) from the FP6-EU ENSEMBLES database, to simulate the various components, and net values, of the water and heat budgets. Most of the RCM Mediterranean basin means are within the range spanned by the observational estimates of the different budget components, though in some cases the RCMs have a tendency to overestimate the latent heat flux (or evaporation) with respect to observations. The RCMs do not show significant improvements of the total water budget estimates comparing to ERA40. Moreover, given the large spread found in observational estimates of

precipitation over the sea, it is difficult to draw conclusions on the performance of RCM for the freshwater budget and this underlines the need for better precipitation observations. The original ERA40 value for the basin mean net heat flux is  $-15 \text{ W/m}^2$  which is  $10 \text{ W/m}^2$  less than the value of  $-5 \text{ W/m}^2$  inferred from the transport measurements at Gibraltar Strait. The ensemble of heat budget values estimated from the models show that most of RCMs do not achieve heat budget closure. However, the ensemble mean value for the net heat flux is  $-7 \pm 21 \text{ W/m}^2$ , which is close to the Gibraltar value, although the spread between the RCMs is large. Since the RCMs are forced by the same boundary conditions (ERA40 and sea surface temperatures) and have the same horizontal resolution and spatial domain, the reason for the large spread must reside in the physical parameterizations. To conclude, improvements are urgently required to physical parameterizations in state-of-the-art regional climate models, to reduce the large spread found in our analysis and to obtain better water and heat budget estimates over the Mediterranean Sea.

## 1 Introduction

The Mediterranean Sea can be considered to be a thermodynamic machine that exchanges water and heat with the Atlantic Ocean through the Strait of Gibraltar and with the atmosphere through its surface. On average, the Mediterranean basin shows an excess of evaporation over freshwater inputs and a heat loss through air-sea interaction. It has an overall freshwater deficit, as the loss to the atmosphere by evaporation is larger than the gains by precipitation and runoff from the main rivers and input from the Black Sea. The total heat budget is negative, that is, the Mediterranean Sea loses more energy than it gains.

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These losses of freshwater and heat are compensated by the two-layer exchange at the Strait of Gibraltar comprising a relatively warm and fresh (15.4°C, 36.2 psu) upper water inflow and a relatively cooler and saltier (13°C, 38.4 psu) outflow to the Atlantic (Bryden et al. 1994; Tsimplis and Bryden 2000). On long timescales, the losses of freshwater and heat from the surface are compensated and the net salt flux is close to zero. Note that this closure hypothesis does not apply for short periods of time, as at monthly or yearly timescales (Castellari et al. 1998; Brankart and Pinardi 2000; Pettenuzzo et al. 2010). One main concern is to what extent the closure hypothesis is true under a changing climate. Some preliminary studies show a large drying of the Mediterranean area, leading to an increase of the freshwater loss at the end of the twenty first century (Somot et al. 2006; Mariotti et al. 2008; Sanchez-Gomez et al. 2009). The implications of these changes in the water cycle for the properties of the Mediterranean water masses and on the exchange at Gibraltar Strait need to be elucidated.

The circulation in the Mediterranean Sea is determined to a large extent by the air-sea exchanges of heat and freshwater, which depend on the meteorological conditions and ocean characteristics (Timplis et al. 2006). The water and heat fluxes play a crucial role in dense water formation, and hence in the Mediterranean Thermohaline Circulation (MTHC) (Béthoux et al. 1999). Consequently they affect the Mediterranean water mass characteristics (temperature, salinity, density) and then can potentially influence the Atlantic Ocean circulation by changing the properties of the Mediterranean Outflow water (MOW) (Béthoux et al. 1999; Potter and Lozier 2004; Artale et al. 2005; Millot et al. 2006). The Mediterranean water and heat budgets can also influence the atmospheric water content, the properties of the low level atmosphere and the occurrence of coastal intense precipitation events (Li 2006; Lebeaupin et al. 2006; Gimeno et al. 2010).

Improving our knowledge of the water and heat budgets and their variability is a challenging goal for the observational and modelling community of the Mediterranean region. Obtaining accurate estimates of every term in the water and heat budgets is crucial for understanding the Mediterranean ocean circulation and climate, and their evolution under climate change. Accurate modelling the Mediterranean air-sea fluxes will also provide the long-term atmospheric forcing for regional ocean models (Madec et al. 1991; Castellari et al. 2000; Somot et al. 2006; Beuquier et al. 2010) and will help to improve the design of fully-coupled Atmosphere–Ocean Regional Climate Models (Somot et al. 2008).

The Mediterranean basin mean water and heat flux estimates available in the literature over the last 30 years, vary depending on the processing techniques and datasets used. They can be estimated either from the atmospheric

branch of the water cycle or from the oceanic branch, that is to say the Gibraltar net transport. Estimates obtained using these two independent methods are not fully consistent especially for the heat budget, and lead to a wide range of uncertainty. For the water budget, the atmospheric branch estimates range from a basin average of 520 to 950 mm/year (Castellari et al. 1998; Gilman and Garret 1994; Béthoux et al. 1999; Mariotti et al. 2002). This large uncertainty range shows the need to improve the dataset quality, since over the Mediterranean Sea, evaporation and precipitation observations are very sparse. Concerning the net water transport at the Strait of Gibraltar, large discrepancies also exist. Direct measurements of the inflow rate are extremely difficult to perform and currently there are very few. In the last 20 years, the estimations of the oceanic branch range from 0.04 to 0.09 Sv ( $1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$ ) that is to say equivalent to a basin average surface flux of between 515 and 1,150 mm/year (Bryden and Kinder 1991; Bryden et al. 1994; Tsimplis and Bryden 2000; Candela 2001; Baschek et al. 2001; Garcia de La Fuente et al. 2007). More recently estimates from the available reanalyses (NCEP/NCAR, Kalnay et al. 1996 or ERA40, Uppala et al. 2004) have also been proposed. They vary between 391 to 524 mm/year (Bouktir and Barnier 2000; Mariotti et al. 2002), showing an underestimation of the water loss by the Mediterranean sea surface. This underestimation may be due to the use of coarse spatial resolution models that are unable to resolve the complexity of the Mediterranean basin (orography, coast-line, islands). Thus, the use of higher resolution atmosphere models may allow resolving this problem (see Elguindi et al. 2009 for an impact of the resolution on the Mediterranean Sea water budget). The question of the potential added-value of high-resolution regional climate models (RCM) with respect to the ERA40 reanalysis is one of the scientific issues addressed in the current study. However dynamical downscaling techniques using RCMs is only one way of attempting to improve the low-resolution reanalysis. Another technique recently applied by Pettenuzzo et al. (2010) is to fit adjustment factors to the reanalysis variables in order to re-compute the various terms of the water (or heat) budget. The adjustment factors are applied to the wind, the downward radiation flux, the temperature or the humidity and are fitted with respect to observed estimates. Using this adjustment method, Pettenuzzo et al. (2010) provide an estimate of E–P freshwater loss of 640 mm/year over the 1958–2001 period with 1180 mm/year for the evaporation and 530 mm/year for the precipitation but do not provide estimate for the river and Black Sea freshwater inputs.

The net heat transport through the Strait of Gibraltar has been estimated by using mooring-based measurements. Results vary between 3 and  $10 \text{ W/m}^2$  (Béthoux 1979; Bunker et al. 1982; McDonald et al. 1994) with the most

recent of these values being about  $5 \text{ W/m}^2$ . The positive sign indicates a heat gain of the Mediterranean Sea. This gain should be compensated by an equivalent heat loss through the Mediterranean Sea surface, i.e. a basin mean net surface heat flux of around  $-5 \text{ W/m}^2$ , as the climate change signal remains weak up to now and so closure is expected to hold. However, earlier studies have shown that climatological estimates of the mean heat budget, determined from the surface heat fluxes, show discrepancies compared with the Strait of Gibraltar estimates of up to  $20\text{--}30 \text{ W/m}^2$  (Garrett et al. 1993; Gilman and Garret 1994; Artale et al. 2005; Tsimplis and Bryden 2000). These authors suggested that the bias is caused by a combination of overestimated shortwave gain and water vapour and underestimated longwave loss, latent and sensible heat fluxes. Subsequently a heat budget estimate over the Mediterranean Sea of  $+6 \text{ W/m}^2$  has been obtained from a modified version of the ship-based NOC flux dataset (Josey et al. 1999), using radiative flux formulae appropriate for this basin as discussed later, which reduces the discrepancy to about  $10 \text{ W/m}^2$ . In their analysis, Pettenuzzo et al. (2010) attempted to close the heat budget by making various plausible adjustments to the ERA40 meteorological fields (which have an imbalance of  $-15 \text{ W/m}^2$ ). Using these adjustments with the transfer coefficient scheme of Kondo (1975) they are able to achieve closure with a mean net heat flux of  $-5 \text{ W/m}^2$ . However, this scheme is not supported by high quality direct measurements of the heat flux made in recent years by Fairall et al. (2003). Using the more up to date scheme of Kara et al. (2005) based on these measurements they instead obtain a value of  $4 \text{ W/m}^2$  which does not close the heat budget.

Mediterranean water and heat budgets have also been investigated recently using numerical simulations (Sotillo et al. 2005; Ruiz et al. 2008; Elguindi et al. 2009; Beuquier et al. 2010). The spatial resolution of typical general circulation models (GCMs) is unlikely to represent well the local thermal and dynamical processes occurring in the Mediterranean Sea. Such processes are very important in the Mediterranean area, since the air-sea exchanges (particularly the latent heat flux) strongly depend on a correct resolution for the temperature, humidity and wind effects. In a study using the ARPEGE atmosphere model, it has been shown (Elguindi et al. 2009) that increasing model resolution yields a more intense evaporation and hence water budget estimates that are closer to observed values. The surface heat fluxes have been analyzed (Ruiz et al. 2008) from a high resolution dataset issued from a dynamical downscaling performed with the regional climate model REMO, forced at its boundaries by the NCEP/NCAR reanalysis (HIPOCAS dataset, Sotillo et al. 2005). These authors show that the RCM experiment significantly improves the heat budget estimation when compared with

the NCEP/NCAR reanalysis. This is a very promising result from the regional climate modeling community, and suggests that RCMs driven by reanalyses can constitute useful tools to study the air-sea fluxes over the Mediterranean region; the work reported here further develops this idea. We have used an ensemble of limited-area models to evaluate their performance in simulating the water and heat budgets in the Mediterranean Sea. Due to their reduced spatial domain, limited-area models provide an attractive approach allowing high spatial resolution climate simulations at an affordable computational cost. The database comes from the EU-FP6 ENSEMBLES project (Hewitt and Griggs 2004; Sanchez-Gomez et al. 2008) and consists of an ensemble of experiments performed by different RCMs with a spatial resolution of  $25 \text{ km}$  over the European-Mediterranean domain. This ensemble includes 12 RCMs driven by the ERA40 reanalysis for the period 1961–2000 at their lateral boundaries. A second ensemble is also available in the FP6 ENSEMBLES data base. This one includes the same RCMs but driven by different GCMs.

The main goals of this study are the following:

- To compare state-of-the-art observational datasets in terms of the heat and water budgets for the Mediterranean Sea;
- to evaluate the ability of an ensemble of ERA40-driven RCMs in simulating the components and net budgets of the heat and freshwater fluxes over the Mediterranean Sea. The RCM estimates will be compared to observed estimates available in the literature and those obtained in step (a). We will also determine whether the estimates of both heat and water budgets in the Mediterranean Sea provided by the RCMs are in accordance with the closure hypothesis at the Gibraltar Strait. The multi-model approach will allow us to assess the uncertainties associated with the water and heat budget estimates and
- to analyze for the several variables of water and heat budgets whether there is an added value of RCMs against the driving reanalysis (in our case ERA40).

While significant interannual variations have been observed in the water and heat budgets in the Mediterranean basin (Bouktir and Barnier 2000; Mariotti et al. 2002; Josey 2003; Struglia et al. 2004; Josey et al. 2011), and also long-term as a response to global warming (Mariotti et al. 2008; Sanchez-Gomez et al. 2009), in this work we focus only on the long-term annual estimates and on the seasonal cycle for the current climate.

The structure of the paper is as follows: In Sect. 2 we present the numerical RCM simulations and observational datasets, and a brief description of the methodology to compute the heat and water budgets. In Sect. 3 we present the water and heat budget estimates from different

observational datasets and ERA40 and then the validation of RCMs according to these estimates. Finally, in Sect. 4 we summarize and draw our main conclusions.

## 2 Datasets and methodology

### 2.1 Regional climate models experiments

A summary of the main characteristics of the RCMs used in this work is presented in Table 1. More details about each individual model can be found in the ENSEMBLES project website: <http://ensemblesr3.dmi.dk>. To produce this multi-model ensemble all RCM experiments have been performed for the time period 1961–2000 using six hourly lateral boundary conditions provided by the ERA40 reanalysis at 1.125° horizontal resolution. The sea surface temperature (SST) and sea-ice concentration are also from ERA40 dataset. All models are required to cover the entire Mediterranean Sea, though only a few cover the entire Black Sea basin. The RCMs used their own model setup as well as grid specifications like rotation and number of vertical levels, but a similar horizontal resolution of 25 km. The ENSEMBLES project has produced a second set of dynamical downscaling experiments (not used in this work) with the same horizontal resolution over the same geographical area, but in this case the RCMs are driven by diverse GCMs for the period 1950–2000.

### 2.2 Water Budget in the Mediterranean Sea

Following Mariotti et al. (2002), the long term mean of the Mediterranean water deficit is approximately equal to the

net water flux at the Strait of Gibraltar over a long period of time:

$$E - P - R - B \approx GW \quad (1)$$

where E is the evaporation, P the precipitation, R is the river discharge into the Mediterranean Sea, B the fresh-water input from the Black Sea (B is actually equal to the E–P–R budget of the Black Sea over its own catchment area), and GW the Gibraltar Strait net water transport. In the following, all freshwater flux values are given in mm/year considering a Mediterranean Sea surface equal to  $2.5 \times 10^{12} \text{ m}^2$ . A summary of the observational datasets used to compute the estimates for the different water budget terms is presented in Table 2.

For the evaporation (E) we use estimates of the turbulent latent heat flux from three different products a.) the Objectively Analyzed air-sea Fluxes (OAFlux) (Yu and Weller 2007; b) the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data set (HOAPS) (Andersson et al. 2007), and c.) a modified Mediterranean Sea version (referred to as NOC hereafter) of the National Oceanography Centre 1.1 (NOC1.1 - referred to as NOC hereafter) dataset (Josey et al. 1999). The OAFlux is a 50 year global dataset on a  $1^\circ \times 1^\circ$  grid for the period 1958–2008. This product is a result of merging satellite observations with surface moorings, ship reports, and atmospheric model reanalysed surface meteorology. The HOAPS data is derived from satellite measurements over the ice free global ocean and covers the period 1988–2005 with a resolution of  $0.5^\circ \times 0.5^\circ$ . The NOC dataset is based on Voluntary Observing Ships observations from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, Woodruff et al. 1998), and is presented on a  $1^\circ$  spatial grid for the period 1980–2004. The Mediterranean NOC dataset used in the current study has been developed by modifying the formulae employed to estimate the radiative flux components. In particular, the longwave flux is estimated using the formula of Bignami et al. (1995), which was developed using high quality radiometer measurements made in the Mediterranean Sea during several research ship cruises. The net longwave ocean heat loss obtained with the Bignami formula is typically stronger than that obtained with various other formulae developed over the North Atlantic (Josey et al. 1997, 2003). In addition, the shortwave flux has been corrected for aerosol loading following the method of Gilman and Garret (1994). The NOC dataset is only based on in situ data without satellite or model inputs, contrary to OAFlux or HOAPS. Note also that the higher resolution dataset HOAPS is also the shortest in time (19 years).

The observational datasets for precipitation (P) are the Global Precipitation Climatology Project (GPCP), the CMAP (CPC Merged Analysis of Precipitation) and the

**Table 1** Summary of the main features of the Regional Climate Models participating in the EU-FP6 ENSEMBLES project

Institution	RCM	Vertical levels	Reference
CNRM	ALADIN	31	Radu et al. (2008)
C4I	RCA	31	Kjellström et al. (2005)
DMI	HIRHAM	31	Christensen et al. (1996)
ETHZ	CLM	32	Bhöm et al. (2006)
ICTP	RegCM	34	Giorgi and Mearns (1999)
KNMI	RACMO	40	Lenderink et al. (2003)
METNO	HIRHAM	31	Haugen and Haakensatd (2006)
METOHC	HadRM	19	Collins et al. (2006)
MPI	REMO	27	Jacob (2001)
SMHI	RCA	24	Kjellström et al. (2005)
UCLM	PROMES	28	Sanchez et al. (2004)
OURANOS	CRCM	28	Plummer et al. (2006)

**Table 2** Summary of the observational datasets used to evaluate the heat and water budgets simulated by the RCMs

Variable	Dataset	Period
Evaporation	OAFflux, HOAPS, NOC	1958–2008, 1988–2005, 1980–2004
Precipitation	GPCP, HOAPS, CMAP	1979–2008, 1988–2005, 1979–2008
River discharge	Ludwig et al. (2009)	1960–2000
Black sea discharge	Stanev et al. (2000)	1923–1997
Short wave	ISCCP2, NOC	1984–2008, 1980–2004
Long wave	ISCCP2, NOC	1984–2008, 1980–2004
Latent heat	OAFflux, HOAPS, NOC	1958–2008, 1988–2005, 1980–2004
Sensible heat	OAFflux, HOAPS, NOC	1958–2008, 1988–2005, 1980–2004

HOAPS datasets; each of which has its limitations. The GPCP (Adler et al. 2003) has been built by merging satellite and rain gauge data for the period 1979–2008. The horizontal resolution is  $2.5^\circ \times 2.5^\circ$  which is unlikely to be adequate for studying the Mediterranean Sea, especially because it merges land and sea points leading to a likely overestimation of the precipitation estimate. The CMAP precipitation consists of monthly values from January 1979 to July 2008. The spatial coverage is global with a  $2.5^\circ \times 2.5^\circ$  horizontal resolution. This dataset are obtained from gauge measurements, satellite data and reanalyses data (Xie and Arkin 1997 and [http://daac.gsfc.nasa.gov/CAMPAIGN\\_DOCS/hydrology/hd\\_main.shtml](http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/hydrology/hd_main.shtml)). The HOAPS dataset has a higher spatial resolution and provides data only over the sea areas. However, it does not provide data over the Adriatic and Aegean seas because of issues with the land-sea mask in these regions. The HOAPS dataset is also known to underestimate the precipitation as it does not measure precipitation amounts less than 0.1 mm/h.

The river discharge  $R$  in the Mediterranean Sea has been provided by the dataset described in Ludwig et al. (2009). It consists of reconstructions of 40-year time series (1960–2000) of river discharges observed for the main rivers or reconstructed by using time series of temperature and precipitation. In our case we have computed the runoff for each of the 11 sub-regional catchments considered in Ludwig et al. (2009). The total runoff in the Mediterranean Sea results from the addition of the values from the 11 catchments. To evaluate the Black Sea discharge in the Mediterranean Sea simulated by the RCMs we have used hydrological data from Stanev et al. (2000). These data provide time series of precipitation, evaporation and runoff for the Black Sea basin over the 1923–1997 period. We recall that to obtain the term  $B$  in eq. (1) we compute the  $P + R - E$  budget of the Black Sea from Stanev et al. (2000) estimates. Table 2 summarizes all the datasets used for the water budget terms.

For the model runoff computations we have considered only the 7 RCMs containing the runoff field as an output (see Table 3). Most of models are non conservative, that is,

the difference  $E - P$  over the river catchments is not equilibrated to the river discharge. In this case, it is preferable to use the runoff computed by the internal adjustments and hypotheses of the models. This is the case also for ERA40, whose runoff is not conservative and results in negative precipitation minus evaporation values over several catchments (Hagemann et al. 2005). This is a well known behaviour in the reanalysis data, in which the soil moisture is corrected to decrease the bias of the 2 m temperature. ERA40 runoff presents also other deficiencies as an unrealistic separation of total runoff into surface runoff and drainage and the absence of river routing that gives rise to instantaneous runoff (Betts et al. 2003; Hagemann et al. 2005). Hence in order to avoid misleading interpretations, we have omitted the comparison between the ERA40 and RCMs runoff estimates from our analysis and we only consider the comparisons for the precipitation and evaporation variables.

We have taken into account the missing drainage area in the models' spatial domain for two of the river catchments: the Nile and the Black Sea. For the former we have replaced the runoff from the model by the observed Nile discharge ( $\approx 8$  mm/year) in all the models, since the missing drainage area is too large to make a good estimate. In addition since the Aswan dam building at the beginning of the 60 s and the intensive use of irrigation in Egypt, the Nile river can be considered as mainly anthropogenically-driven (see Skliris and Lascaratos 2004; Ludwig et al. 2009, for a discussion of the problem). For the Black Sea we have estimated the missing contribution from the fraction of missing area as in Struglia et al. (2004). To compute the river discharge over each of the Mediterranean catchments we have interpolated the drainage area mask (available at a resolution of  $0.5^\circ \times 0.5^\circ$ ) to the RCM native grids.

### 2.3 Heat budget in the Mediterranean Sea

The total heat budget is determined by the radiative and turbulent heat flux components. The radiative terms are the net solar (shortwave) flux at the surface ( $Q_{sw}$ ) and the net infrared radiation (longwave,  $Q_{LW}$ ). The turbulent

**Table 3** Long term annual mean estimates for the different terms of the Mediterranean Sea water budget for the RCMs, for the observations considered in this study and for the ERA40 reanalysis

DATA	E	P	E–P	R	B	WB
C4I	1,227 ± 50	372 ± 54	854 ± 72			
CNRM	1,132 ± 50	377 ± 50	950 ± 72	80 ± 35	40 ± 32	635 ± 90
DMI	1,377 ± 55	425 ± 57	952 ± 80	116 ± 30	116 ± 53	720 ± 100
ETHZ	1,370 ± 40	483 ± 73	887 ± 84	210 ± 58	187 ± 60	490 ± 120
ICTP	1,618 ± 68	530 ± 70	1,087 ± 98			
KNMI	1,104 ± 90	404 ± 67	694 ± 110	146 ± 60	80 ± 45	470 ± 140
METNO	1,424 ± 52	568 ± 60	856 ± 80	140 ± 50	–	
METOHC	1,265 ± 20	377 ± 73	888 ± 75			
MPI	1,066 ± 60	416 ± 53	650 ± 74	110 ± 42	72 ± 43	468 ± 120
OURANOS	1,208 ± 72	606 ± 80	602 ± 107	73 ± 40	110 ± 50	420 ± 130
SMHI	1,126 ± 44	347 ± 54	778 ± 70			
UCLM	1,130 ± 52	400 ± 52	730 ± 74	120 ± 46	104 ± 60	506 ± 110
MEAN	1,254 ± 164	442 ± 84	812 ± 180	124 ± 46	87 ± 60	540 ± 150
ERA40	1,167 ± 50	386 ± 80	781 ± 90			
WB1	1,095 ± 80	594 ± 56	501 ± 98	142 ± 22	80 ± 44	280 ± 110
WB2	1,095 ± 80	256 ± 44	840 ± 90	142 ± 22	80 ± 44	617 ± 104
WB3	1,137 ± 90	256 ± 44	881 ± 98	142 ± 22	80 ± 44	660 ± 110
WB4	1,115 ± 60	256 ± 44	834 ± 70	142 ± 22	80 ± 44	612 ± 90
WB5	1,115 ± 60	467 ± 44	648 ± 70	142 ± 22	80 ± 44	426 ± 90

In the table E is the evaporation, P the precipitation, R the total river discharge in the Mediterranean Sea, B the Black Sea input and WB the net water balance (E–P–R–B). WB1 refers to the various terms estimated from a combination of OAFflux and GPCP data; WB2 results of combining E from OAFflux and P from HOAPS; WB3 from the HOAPS dataset, WB4 from the NOC evaporation and HOAPS precipitation and WB5 from NOC evaporation and CMAP precipitation. The water budget estimates have been calculated according to eq. (1). Values have all been converted to mm/year assuming an area for the Mediterranean Sea of  $2.5 \times 10^{12} \text{ m}^2$

components are the latent ( $Q_{LH}$ ) and the sensible ( $Q_{SH}$ ) heat fluxes. For long time scales (several decades), we assume that the net heat transport through the Strait of Gibraltar (GH) is balanced by the Mediterranean Sea surface heat fluxes (Matsoukas et al. 2005; Ruiz et al. 2008). This hypothesis implies that the water masses do not show a significant warming. Rixen et al. (2005) found a warming equal to  $[1.3\text{--}1.5] \times 10^{21} \text{ J}$  for the 1950–2000 period (that is to say a trend of  $[0.0018\text{--}0.0020] \text{ }^\circ\text{C/year}$ ) that corresponds to an imbalance less than  $0.4 \text{ W/m}^2$ , so our hypothesis is reasonable. The total heat budget is given by the expression:

$$Q_{SW} + Q_{LW} + Q_{LH} + Q_{SH} \approx GH \quad (2)$$

positive sign denotes a heat gain by the sea and negative sign indicates a heat loss from the sea. We estimate the different terms in eq. (2) from the RCMs and ERA40 data. The Black Sea heat budget is not considered in our computations since its contribution can be neglected (Garrett et al. 1993). In the first stage of our analysis, the simulated Mediterranean heat budget is evaluated for the ERA40 driven RCM runs and compared with the observational datasets described in the next paragraph and summarized in Table 2.

We consider various combinations of the flux components from different datasets. The turbulent terms are taken from the OAFflux, HOAPS and NOC datasets. The observations for the radiative fluxes come from the NOC data and also from the International Satellite Cloud Climatology project (ISCCP 2) dataset (Zhang et al. 2004). The ISCCP data are based on satellite data measurements and gridded with horizontal resolution of  $2.5^\circ \times 2.5^\circ$ . It starts at 1984 and currently it is planned to continue through 2010.

### 3 Results

In this study an evaluation of different water and heat budget components obtained from the observational datasets described above has been carried out. By combining different datasets and taking into account the Gibraltar constraint, we provide three observational estimates for water budget and only one for heat budget. We also analyze the E and P estimates of eq. (1) and all the terms in eq. (2) from the ERA40 data. For model data an assessment of whether the RCMs are in closer agreement with the observations than the low resolution reanalysis (i.e.

whether the RCMs have ‘added value’) is performed for multi-annual means and seasonal cycle.

Note that the time periods covered by the various observational datasets and RCM experiments are different. To evaluate the uncertainties associated with the interannual variability in the budget estimates, we provide an error bar estimated as  $\text{std} \times t_{\alpha(n-1)}/\sqrt{(n)}$ , where  $\text{std}$  is the standard deviation of the interannual time series, and  $n$  is the number of years. Here we consider the value of the  $t$ -student test  $t_{\alpha(n-1)}$  for an error corresponding to 5%. For RCMs the multi-annual ensemble mean is also computed and the spread among the model obtained as  $\text{std} \times t_{\alpha(n-1)}/\sqrt{(n)}$ , where  $\text{std}$  is the inter-model standard deviation and  $n$  the number of models.

### 3.1 The Mediterranean Sea water budget

#### 3.1.1 Multi-annual averages

First, we study the spatial structure of the two main water budget components simulated by the RCMs. Figure 1 presents the multi-annual average of E–P for the RCM ensemble mean (Fig. 1a) and the inter-model spread (Fig. 1b) calculated as the standard deviation of the climatological annual means computed for each individual model. In Fig. 1c the multi-annual mean of E–P for ERA40 is also represented. The multi-model mean (Fig. 1a) shows the well known west-east gradient of freshwater deficit in the Mediterranean Sea (Bouktir and Barnier 2000). The largest freshwater losses occur in the north coast of Libya, the Levantine basin and in the Aegean Sea. In the Levantine basin intense evaporation is produced by high sea surface temperatures. In the Aegean Sea, evaporation is mainly driven by the local wind system (Etesian winds). There is a secondary maximum located in the Gulf of Lyon, a deep convection zone in the Mediterranean Sea, also as a result of local wind forcing (Mistral winds). Precipitation larger than evaporation (negative values) only occurs over the coastal regions, where inflowing maritime air interacts with orography to yield strong precipitation. The west-east gradient is also observed in ERA40 (Fig. 1c), whereas the finer spatial structures described above are not always present because of the coarser horizontal resolution and of the land-sea mask. It can be observed that areas of strong E–P values are missing in ERA40 (Gulf of Lyon, Aegean Sea) as well as a major part of the coastal effects. Note that for ERA40 the Adriatic and Aegean basins are not fully included in the computations of water and heat budgets.

The inter-model spread (Fig. 1b) shows a maximum over the coast, where the orography influence is strongest, and in the Aegean Sea, a land-enclosed basin where it is more difficult to accurately represent processes related to

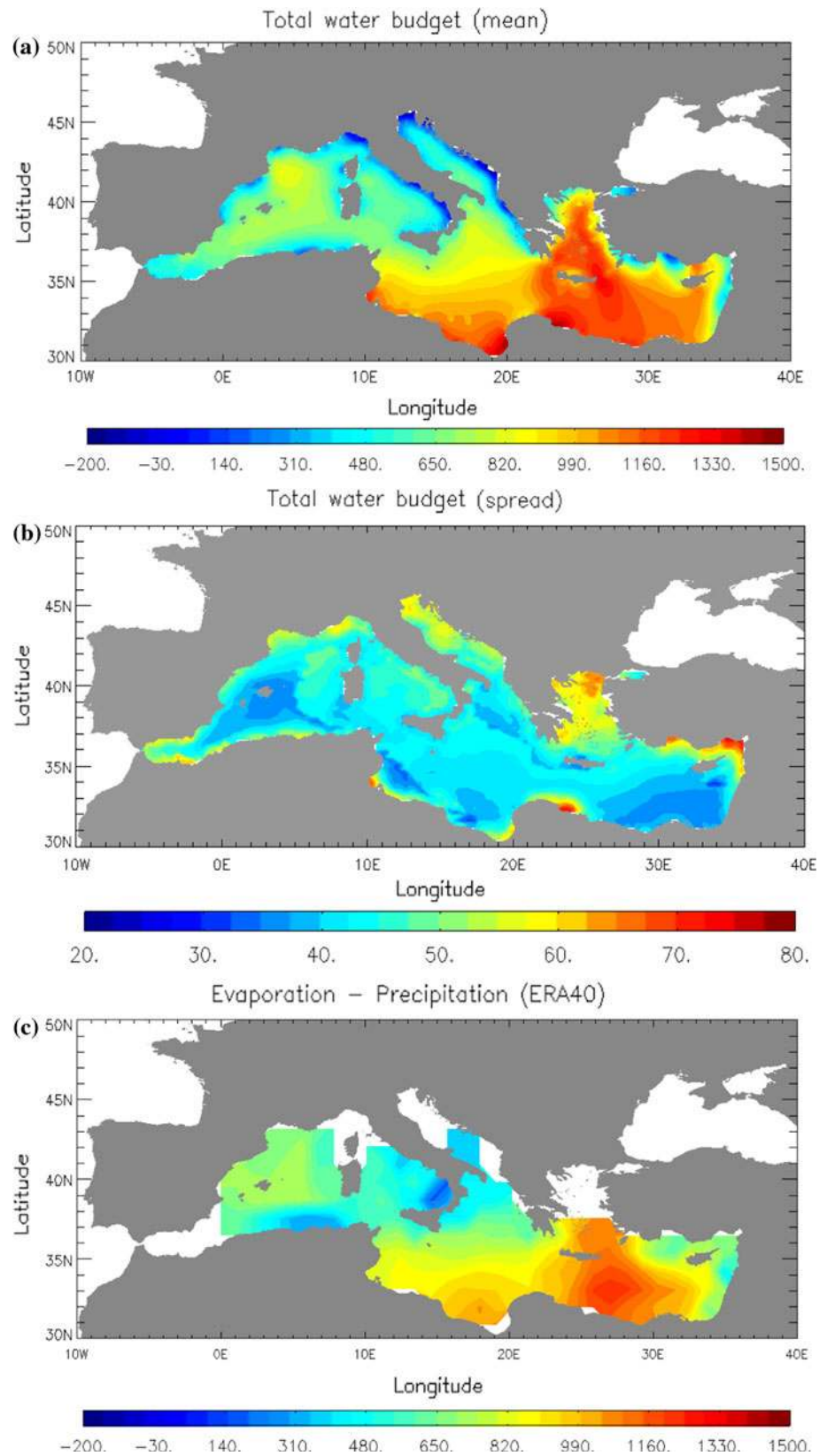
the local wind fields and orography. This suggests that future improvements could be achieved by increasing the model resolution in the Aegean basin. A further cause of the larger spread in the Aegean basin may be internal variability of the RCMs, a process recently studied by Lucas-Picher et al. (2008). The internal variability is the inter-member spread of an ensemble generated using an RCM with the same lateral boundary forcing but different initial conditions. In a recent paper, Sanchez-Gomez et al. (2008), show that the internal variability and the inter-model spread are related. They found that the inter-model spread and also internal variability are larger in the eastern part of the ENSEMBLES domain, with a maximum located over the Balkan Peninsula, since the control exerted by the lateral boundary forcing (westerly flow) decreases with distance moved eastwards. The large spread observed over the Aegean Sea in Fig. 1b may also reflect the signature of internal variability.

Now we compare estimates of the water budget and its components obtained from the observational datasets, from the RCM ensemble and from ERA40. The basin averaged annual means of evaporation, precipitation, rivers and Black Sea discharges are shown in Table 3.

The observational datasets give a consistent picture of the Mediterranean basin evaporation term with a range going from  $1,095 \pm 80$  (OAFflux) to  $1,137 \pm 90$  mm/year (HOAPS), the highest spatial resolution dataset giving the highest water loss by evaporation. The ERA40 mean E value is  $1,167 \pm 50$  mm/year which is within the error of the others estimates. Note that the ERA40 correction made by Pettenuzzo et al. (2010) leads to a consistent value (1,180 mm/year for the period 1958–2001) which however strongly depends on the bulk formula used to re-compute the evaporation terms from the atmosphere and ocean variables.

The RCM simulated annual mean estimates for the evaporation range between 1,066 mm/year (MPI model) and 1,618 mm/year (ICTP model). The interannual variability for the RCMs is typically 50–60 mm/year which is close to ERA40 but smaller than the observations which have values of about 80 mm/year. The ensemble mean value is 1,254 mm/year which is 7% higher than ERA40 and stands above all the observational estimates of evaporation. 7 out of the 12 RCMs present evaporation values higher than the largest observational estimates (HOAPS). The high evaporation values found for several RCMs can be explained by stronger local winds channelled by a better representation of the Mediterranean surrounding orography. This explanation is sustained by recent studies focusing on the Mediterranean winds and air-sea fluxes (Sotillo et al. 2005; Ruti et al. 2007; Herrmann and Somot 2008; Schroeder et al. 2010). Note that the inter-model spread of 164 mm/year constitutes 13% of the ensemble

**Fig. 1** **a** RCM ensemble mean of the climatological annual E–P budget, **b** Inter-model spread, calculated as the standard deviation of the individual model climatological annual mean E–P fields, **c** Climatological annual E–P field for ERA40. Units are in mm/year





mean, indicating large differences among the regional models, forced by the same lateral and surface boundary conditions. Note also that in the ERA40 driven run all the RCMs used the same SST dataset.

The annual mean precipitation amount over the Mediterranean Sea is not coherent when comparing the GPCP ( $594 \pm 56$  mm/year), CMAP ( $467 \pm 44$  mm/year) and HOAPS ( $256 \pm 44$  mm/year) datasets, the difference exceeding 100% of the lower value. GPCP is known to overestimate the precipitation over the sea as it mixes land and sea points. Moreover its low resolution is not appropriated to the Mediterranean precipitation study. CMAP lies between GPCP and HOAPS values. On the contrary HOAPS is known to underestimate the precipitation as explained in the previous section. The “true” value is perhaps around 400 mm/year which is in the range 331–447 mm/year given by Mariotti et al. (2002). ERA40 gives a value of  $386 \pm 80$  mm/year in agreement with the observation range, and the RCM ensemble mean a value of 442 mm/year which indicates stronger precipitation on average. We can thus characterise the difference of the 25-km dynamical downscaling mean with respect to the driver as an increase in precipitation by 15%. Contrary to evaporation, the interannual variability of precipitation is generally higher in ERA40, than the RCMs and most of the RCMs provide values that are similar to observations. None of the models has a value as low as HOAPS, and only one model (OURANOS) has a value even higher than GPCP. Note that the ERA40 correction applied by Pette-nuzzo et al. (2010) with respect to the CMAP dataset gives a value of 530 mm/year; lying in the observation range.

The observed annual mean runoff is  $142 \pm 22$  mm/year (Ludwig et al. 2009), which is larger than previous river discharge estimates given by Struglia et al. (2004) and Mariotti et al. (2002) who obtained a value of 102 mm/year from other observational datasets. Very recently a new estimate (116 - 135 mm/year) has been provided by Bouraoui et al. (2010) for the 1980–2000 period using a reconstruction method. The KNMI and METNO models have similar values of 146 and 140 mm/year respectively and the ensemble mean is 124 mm/year with a spread of 46 mm/year. The interannual variability of R is greater than the observed range for most of the RCMs with the closest being CNRM.

For the Black Sea discharge, the RCM ensemble mean is 87 mm/year showing a good agreement with the observational value of 80 mm/year by Stanev et al. (2000). In this computation, we have omitted the METNO model because its value (negative) is not realistic. However this variable presents the largest discrepancies among the RCMs, with an inter-model spread of 60 mm/year. Indeed the Black Sea input is mainly estimated from the river runoff term ( $P + R - E$ ) of the Black Sea catchment, which is very

large and covers a relatively flat area. As mentioned in a previous paragraph, the inter-model spread and also internal variability of RCMs are larger in the eastern part of the domain, since the control exerted by ERA40 decreases with distance as we moved eastwards. This can contribute to the large inter-model spread observed for the B term.

The use of different observation sources for evaporation and precipitation leads to five different estimates for the Mediterranean Sea water budget determined from eq. (1): WB1 (OAFflux for E, GPCP for P), WB2 (OAFflux for E and HOAPS for P), WB3 (HOAPS for both E and P), WB4 (NOC for E, HOAPS for P) and WP5 (NOC for E and CMAP for P). In all cases R is given by Ludwig et al. (2009) and B by Stanev et al. (2000). The choice for P drives the difference obtained between WB1 (280 mm/year) and the four other estimates (617, 660, 612 and 426 mm/year). We decided to discard the very low WB1 because it largely underestimates the lowest observation estimate of the Gibraltar Strait net transport (GW, which is between 515 and 1,150 mm/year as discussed earlier). WB2, WB3 and WB4 are considered to be more realistic on this basis as they lie within the GW range. WP5 is not coherent with Gibraltar Strait measurements. Note that the most recently cited value in the literature is 0.05 Sv for the Gibraltar Strait net transport (Baschek et al. 2001; Garcia de la Fuente et al. 2007 for example), that corresponds to about 630 mm/year (with a Mediterranean Sea surface equal to  $2.5 \times 10^{12}$  m<sup>2</sup>).

Because of the physics consistency in a climate model, it is interesting to look at the E–P budget too. Indeed a model having a high evaporation over the sea also tends to have a high precipitation. Despite this effect, the ERA40 E–P mean of 781 mm/year, lies slightly below the RCM ensemble mean of 812 mm/year. The E–P values from the models are closer to those provided by the observational WB2–WB3–WB4, estimates than ERA40 (Table 3). The WB1 and WP5 estimates of E–P seems to be unrealistic mainly due to the high GPCP and CMAP precipitation values.

The ERA40 water budget estimate has not been analyzed in this paper, since ERA40 based runoff values are not realistic (Hagemann et al. 2005). For the RCMs, the annual averages of the total Mediterranean water budget can be computed for only 7 models (CNRM, DMI, ETHZ, KNMI, MPI, OURANOS, UCLM, excluding METNO due to its unphysical Black Sea value). The ensemble mean is equal to 540 mm/year, which is below the observational estimates by approximately 100 mm/year. The RCMs range from a freshwater deficit of 420 mm/year for OURANOS to 720 mm/year for DMI. These are also the models with the highest and lowest E–P balance respectively. DMI has the highest E term and OURANOS the highest P term of the remaining 7 models. The CNRM

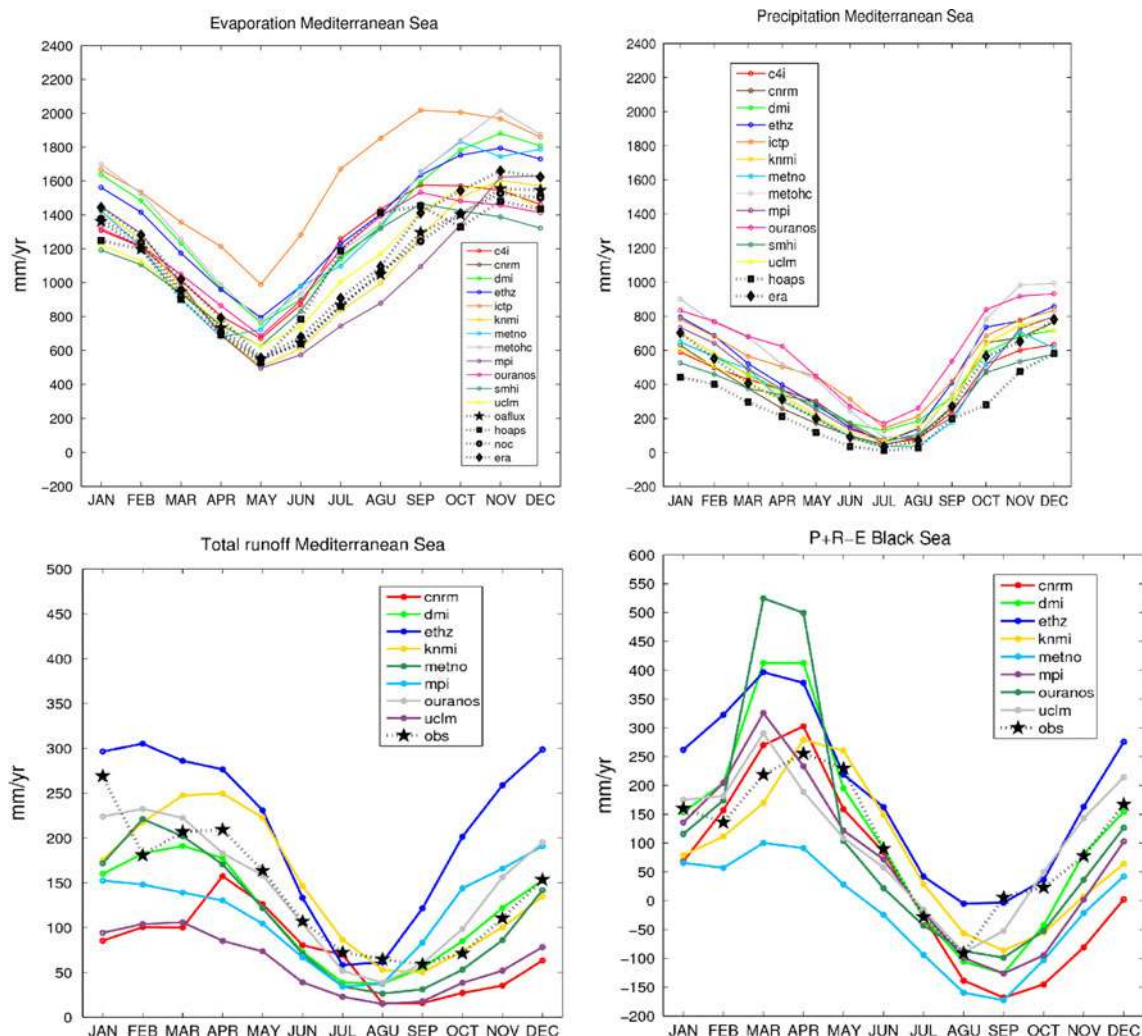
model gives the best representation of the water budget with 635 mm/year (close to the Gibraltar 0.05 Sv value and the WB2 estimate). The ETHZ, MPI, KNMI and UCLM models stand surprisingly very close to each other between 470 and 506 mm/year.

Overall, our results demonstrate that regional climate models show some deficiencies to provide realistic water budget estimates, consequently some improvements may be required for the dynamical downscaling estimates in order to decrease the large discrepancies observed between different RCMs. The Mediterranean water budget strongly depends on the choices of physics model parameterizations and this study suggests that more effort needs to be made in this regard. As regards the observational datasets, our results also reinforce the need for improving the quality of data over the sea, especially the spatial resolution. Increasing resolution is crucial to a better representation of

local phenomena that in the case of the Mediterranean Sea, play an important role in the water budget such as orography-driven local winds, orography-driven precipitation over land, land-sea contrast, wind-driven intense evaporation events and Mediterranean cyclones induced precipitation.

### 3.1.2 Seasonal cycle

We now consider the climatological annual cycles of evaporation, precipitation, river discharge and the Black Sea input, for both the RCMs and observations, which are shown in Fig. 2. In this figure only observations used in the net water budget estimates coherent with the Gibraltar Strait constraint (WB2–WB3–WB4, see Table 3) have been considered. These values have been averaged over the entire Mediterranean basin. We observe that in general,



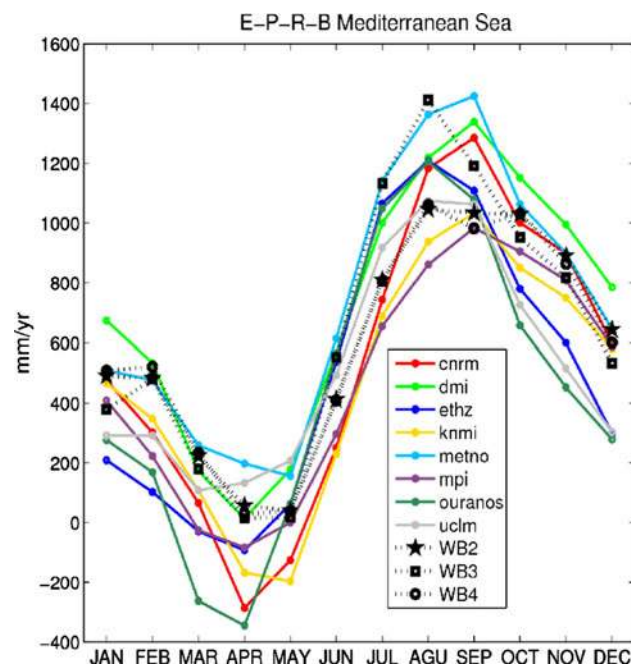
**Fig. 2** Climatological seasonal cycle for the components of the water budget averaged over the whole Mediterranean basin. **a** Evaporation from RCMs, OAFlux and HOAPS data. **b** Precipitation from RCMs,

GPCP and HOAPS data. **c** River discharge from RCMs and Ludwig et al. 2009. **d** Black Sea input from RCMs and Stanev et al. 2000

despite some spread among the models, the seasonal cycles for the various water budget terms are well represented by the RCMs.

The Mediterranean evaporation (Fig. 2a) presents a minimum in late spring (May) and is most intense in autumn (November). The amplitude of the seasonal cycle for evaporation is very large. Consequently evaporation is the leading term of the water budget seasonal cycle as will be seen in Fig. 3 (discussed below). The seasonal cycle amplitude for E (Fig. 2a) is 1,052 mm/year for OAFflux, 950 mm/year for HOAPS and 980 mm/year for NOC. These values are comparable to the ERA40 value (1,004 mm/year) and to the RCM ensemble mean (1,012 mm/year), showing a good agreement between all the data sources. The HOAPS data presents larger evaporation values during summer and autumn than OAFflux and NOC. The observed seasonal cycle is well represented by the RCMs although the ICTP model is a noticeable outlier with extremely strong evaporation.

The annual cycle of the area-averaged precipitation over the Mediterranean Sea (Fig. 2b) is also well simulated by the RCMs. ERA40 lies above the HOAPS observed precipitation with closer values from May to September. The RCMs mainly stay also above the observational dataset. The difference between the maximum and minimum value



**Fig. 3** Climatological seasonal cycle for the area-averaged Mediterranean freshwater deficit estimates for the period 1979–2000. The RCMs estimates are represented by lines in colors. The estimate WB1 has been obtained by combining the OAFflux with the GPCP datasets. The estimate WB2 has been obtained from HOAPS data, and the WB3 from NOC for E and HOAPS for P. R is given by Ludwig et al. (2009) and B by Stanev et al. (2000) for all estimates

for the precipitation is 570 mm/year for HOAPS, 716 mm/year for ERA40, and 664 mm/year for the RCMs ensemble mean. These estimates are in agreement with the values obtained by Mariotti et al. (2002). In this case, we observe fewer discrepancies among the estimates of the amplitude of the seasonal cycle than in the annual values.

For the observed river discharge term minimum values are reached in summer and maximum values in winter (Fig. 2c), following the precipitation seasonal cycle. A second maximum is reached in March–April during the snow-melting season. For the models, the river discharge term has been analyzed only for the 7 RCMs having the runoff as an output. The seasonal cycle for the basin-integrated Mediterranean river discharge is reasonably well simulated by all the models, as they capture the main timing characteristics of the observed seasonal cycle with the minimum in summer and the maximum in winter with the snow-melting peak. However, the minimum in February between the two peaks is rarely represented by the models. Note also that throughout the year the ETHZ model overestimates the observational value, yielding to a large annual mean (see Table 3).

Although the timing of the river discharge seasonal cycle extremes are in reasonable agreement across observations and models, we observe large discrepancies concerning its amplitude. We obtain for the observations an amplitude of 82 mm/year. The ensemble mean underestimates the amplitude with 50 mm/year. Our results here support the suggestion of Elguindi et al. (2009), that higher resolution than 50 km is needed to adequately simulate the river runoff for an area of complex orography such as the surrounding of the Mediterranean Sea. Up to now, only some preliminary tests have been performed with 10 km-resolution RCMs for ERA40 dynamical downscaling since longer experiments at such high resolution are still far to be implemented. This new configuration often covers sub-regions of Europe as in the European project CECILIA or in Déqué and Somot (2008a, b).

The Black Sea input to the Mediterranean Sea has been also calculated only for the 7 models having the runoff as a diagnostic variable. This term is computed as  $P + R - E$  for the Black Sea. Indeed this is equivalent to the freshwater amount that flows into the Mediterranean Sea through the Dardanelles Strait assuming that the Black Sea level is constant over a long period of time. Positive values indicate a freshwater gain for the Black Sea and therefore for the Mediterranean Sea, whereas negative values correspond to a freshwater deficit (excess of evaporation against precipitation and runoff). The annual cycle of the Black Sea input (Fig. 2d) reaches the maximum value in spring (March–April), when the river discharge over the Black Sea drainage area is most intense due to the snow-melt. For the Black Sea input in the Mediterranean Sea,

a lag is expected between the maximum in freshwater and the discharge in the Aegean Sea (Stanev et al. 2000). Indeed a hydraulic control is imposed by the Bosphorus Strait—Marmara Sea—Dardanelles Strait system, which leads to a maximum flow between the Black Sea and the Aegean Sea. During spring, a sea level increase is observed in the Black Sea due to a freshwater excess. Then the freshwater is transported through the Bosphorus Strait during late spring and summer, when the water balance is negative in the Black Sea. This delay is not taken into account here.

In April, the Black Sea input from the observations is 255 mm/year. The simulated values range between 91 mm/year for METNO model, which clearly underestimates the Black Sea water budget, and 500 mm/year for OURANOS. The freshwater deficit is largest in August, when the evaporation rates are most intense, with observed values of  $-91$  mm/year. The RCM estimates for this minimum value vary between  $-168$  mm/year (DMI model) and  $-20$  mm/year (ETHZ model). The amplitude of the annual cycle for the Black Sea input is 350 mm/year for observations. This amplitude is about 20% greater for the RCM ensemble mean, which has a value of 423 mm/year.

The seasonal cycle for the total water budget in the Mediterranean Sea is displayed in Fig. 3 for models and the three WB estimates that verify the closure hypothesis. Note that the time lag between the the Black Sea E–P–R budget and the Black Sea input to the Aegean Sea is neglected (see Stanev et al. 2000 for a discussion). As mentioned above, we have combined the OAFflux, the HOAPS precipitation and river discharge data to obtain WB2 estimate. WB3 has been built from HOAPS and river runoff datasets, and WB4 is based on NOC evaporation, HOAPS precipitation and the river runoff datasets. For all three observational based estimates, the freshwater loss presents a maximum in the late summer, between August and September. During these months, the evaporation rate over the basin largely exceeds the freshwater input from precipitation and river discharge. In August the freshwater deficit is approximately 1,040 for WB2, 1,400 mm/year for WB3 and 1,060 mm/year for WB4. The water balance reaches its minimum in spring, from April to May. For WB2, WB3 and WB4 the water budget is close to zero because of the minimum of evaporation and a maximum for the river and Black Sea inputs. For some models, the water budget becomes negative, indicating that the freshwater input from precipitation and especially from river discharge is more important than evaporation. During the spring season (April–May), freshwater excess in the Mediterranean Sea is on average approximately  $+30$  mm/year for WB2, WB3 and WB4.

## 3.2 The Mediterranean Sea heat budget

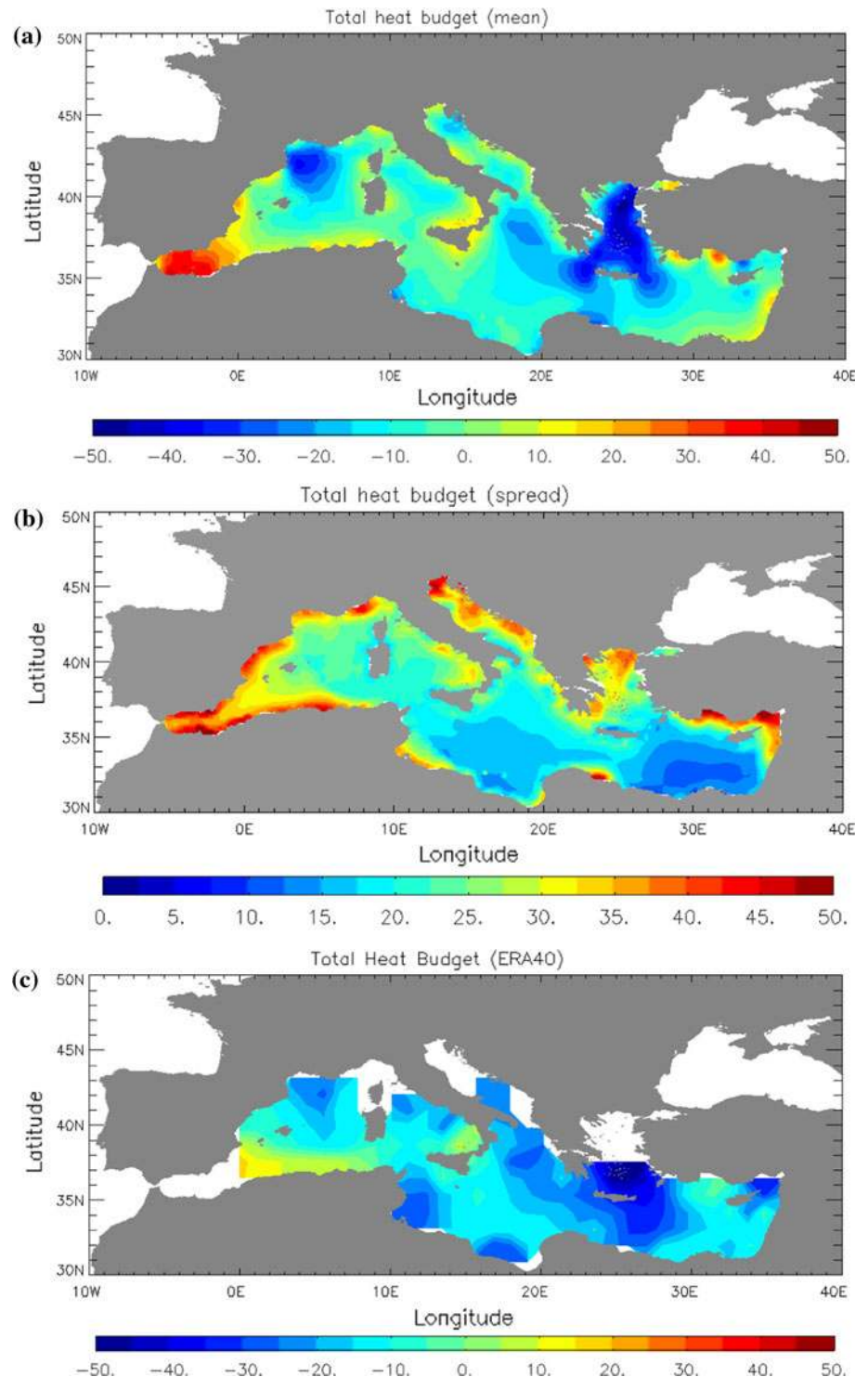
### 3.2.1 Multi-annual averages

As for the water budget, we first study the spatial structure of the total heat budget simulated by the RCMs. Figure 4a shows the multi-model annual mean over the whole period together with the spread among the models (Fig. 4b). In Fig. 4c the total heat budget for ERA40 is also represented. The spatial distribution of the multi-model total heat budget (Fig. 4a) is characterized by maxima of heat loss over the deep convection zones which are the Gulf of Lyon, and the Adriatic and Aegean Seas. Heat gain occurs over the Alboran Sea primarily as a result of reduced latent heat loss in this region (due to a smaller sea-air humidity difference and weaker winds). The spatial distribution of ERA40 total heat budget (Fig. 4c) differs from the RCM ensemble mean. Differences can be found in particular over the Gulf of Lyon, where the heat loss of the models is stronger than for ERA40. This is due to the higher resolution of the RCMs that results in stronger local winds and then enhanced evaporation over the region (Sotillo et al. 2005; Ruti et al. 2007; Herrmann and Somot 2008). Some differences are also observed in the Levantine basin, where the small scale coastal phenomena are not present in ERA40 and in the southern Lybian coast.

The inter-model spread (Fig. 4b) shows maxima over the coastal regions and also over the Alboran Sea, the Gulf of Lyon, Adriatic and Aegean Seas, where the influence of complex orography-related processes and local wind systems (e.g. Samuel et al. 1999) are dominant. Note that in the case of the total heat budget the signature of internal variability is not as evident as for the E–P budget. One reason for this is that the precipitation field may be more affected by internal variability than the radiative and turbulent fluxes.

The annual long term means for the heat budget terms from the different RCMs are displayed in Table 4. In the rows of Table 4 are indicated the estimates obtained with the RCMs for the ERA40 driven experiments and also the ensemble means values. The corresponding observational estimates and ERA40 are in Table 5. The net shortwave absorbed by the sea is  $187 \pm 3$  W/m<sup>2</sup> for ISCCP2 and  $185 \pm 2$  W/m<sup>2</sup> for NOC. The NOC estimate is close to the 183 W/m<sup>2</sup> value provided in Gilman and Garret (1994). ERA40 has a lower value of  $165 \pm 3$  W/m<sup>2</sup> which is likely due to an overestimation of the cloud cover. The RCMs shortwave estimates show a wide range from 154 W/m<sup>2</sup> for DMI to 214 W/m<sup>2</sup> for METOHC, with an RCM ensemble mean of  $181 \pm 18$  W/m<sup>2</sup> which is slightly lower than, but in reasonable agreement with, the ISCCP2 and NOC estimates.

**Fig. 4** **a** Multi-annual ensembles mean for the total heat budget. **b** Inter-model spread, calculated as the standard deviation of the individual model climatological annual means. Units are in  $\text{W/m}^2$



The annual mean estimate of the longwave radiative flux from ISCCP2 is  $76 \pm 4 \text{ W/m}^2$ , while the NOC longwave is considerably larger,  $84 \pm 1 \text{ W/m}^2$ . Contrary to the short-wave behaviour, the ERA40 longwave estimate of  $78 \pm 3 \text{ W/m}^2$  lies between the two observation based values. Except for MPI and METNO that have very low values, all the other RCMs give values close to or within

the range spanned by the ISCCP2 and NOC datasets. The RCM ensemble mean is  $75 \pm 6 \text{ W/m}^2$ , which is close to ERA40. However individually, RCMs provide values that are quite different from the driving field, showing that the downscaling has a major impact on the longwave flux.

The latent heat flux annual mean is given either by OAFflux (HB1), NOC (HB2) or HOAPS (HB3) with an

**Table 4** Long term annual mean estimates for the different terms of the Mediterranean Sea heat budget for the RCMs driven by ERA40

	C4I	CNRM	DMI	ETHZ	ICTP	KNMI	METNO	METOHC	MPI	SMHI	OURA	UCLM	MEAN
ERA40 forced runs													
Q <sub>SW</sub>	190 ± 2	190 ± 2	154 ± 2	157 ± 3	185 ± 4	165 ± 6	178 ± 3	214 ± 3	162 ± 2	190 ± 3	202 ± 3	180 ± 4	181 ± 18
Q <sub>LW</sub>	78 ± 2	80 ± 2	70 ± 2	72 ± 2	74 ± 2	77 ± 4	100 ± 2	85 ± 1	90 ± 1	78 ± 2	80 ± 2	74 ± 2	75 ± 6
Q <sub>LH</sub>	97 ± 4	90 ± 4	109 ± 4	108 ± 3	128 ± 5	88 ± 7	112 ± 4	100 ± 1	85 ± 5	90 ± 3	96 ± 6	91 ± 4	100 ± 13
Q <sub>SH</sub>	10 ± 1	8 ± 1	15 ± 1	13 ± 1	22 ± 2	10 ± 2	15 ± 1	8 ± 1	9 ± 1	9 ± 1	18 ± 2	20 ± 2	13 ± 5
HB	+5 ± 3	+12 ± 3	-40 ± 3	-36 ± 3	-39 ± 4	-10 ± 3	-14 ± 3	+21 ± 3	-22 ± 3	+13 ± 3	+8 ± 3	-5 ± 3	-9 ± 21

In the table Q<sub>SW</sub> is the shortwave flux, Q<sub>LW</sub> the longwave, Q<sub>LH</sub> and Q<sub>SH</sub> the latent and sensible heat fluxes respectively. The heat budget estimates have been calculated according to eq. (2). Values have all been converted to W/m<sup>2</sup>.

**Table 5** Long term annual mean estimates for the different terms of the Mediterranean Sea heat budget for the observations considered in this study and for the ERA40 reanalysis

	HB1	HB2	HB3	ERA40
Q <sub>SW</sub>	187 ± 3	185 ± 2	185 ± 3	165 ± 3
Q <sub>LW</sub>	76 ± 4	84 ± 1	84 ± 1	78 ± 3
Q <sub>LH</sub>	88 ± 6	89 ± 5	90 ± 7	93 ± 4
Q <sub>SH</sub>	14 ± 2	7 ± 1	14 ± 2	9 ± 1
HB	+9 ± 8	+5 ± 5	-3 ± 8	-15 ± 6

In the table Q<sub>SW</sub> is the shortwave flux (positive values), Q<sub>LW</sub>, the longwave, Q<sub>LH</sub> and Q<sub>SH</sub> the latent and sensible heat fluxes respectively. HB1 is the heat balance estimated from the combination of ISCCP2 (Q<sub>SW</sub>, Q<sub>LW</sub>) and OAFflux (Q<sub>LH</sub>, Q<sub>SH</sub>) data. HB2 is the estimate obtained entirely from the NOC dataset. HB3 is the heat budget estimates from HOAPS (Q<sub>LH</sub>, Q<sub>SH</sub>), and NOC (Q<sub>SW</sub>, Q<sub>LW</sub>) datasets. The heat budget estimates have been calculated according to eq. (2). Values have all been converted to W/m<sup>2</sup>.

observation range from 88 to 90 W/m<sup>2</sup> (Table 5). The ERA40 value of 93 ± 4 W/m<sup>2</sup> is just above the upper limit of this range, while the RCMs tend to lie well above the observation range (as noted in the previous section with the evaporation term of the water budget). The RCM ensemble mean estimate for the latent heat flux is 100 ± 13 W/m<sup>2</sup> with values going from 85 to 128 W/m<sup>2</sup>. The RCMs at the lower end of this range (CNRM, KNMI, MPI, SMHI, UCLM) are clearly in better agreement with the observations than those at the upper values, although recall that closure of the water budget implies the latent heat flux may be higher than the observation range noted here.

For the sensible heat fluxes, the OAFflux and HOAPS datasets provides an estimate of 14 ± 2 W/m<sup>2</sup> for the averaged basin and NOC a smaller estimate of 7 ± 1 W/m<sup>2</sup>. ERA40 (9 ± 1 W/m<sup>2</sup>) lies within the observed range as the model ensemble mean (13 ± 5 W/m<sup>2</sup>). However 5 models over 12 lie out of the observed range.

Overall, if we summarize the behaviour of the models compared to observations for the four different components of the heat budget, ERA40 performs well for Q<sub>LW</sub>, Q<sub>LH</sub> and Q<sub>SH</sub> but strongly underestimates Q<sub>SW</sub>. The RCM ensemble mean generally performs well but with a potential

overestimation of Q<sub>LH</sub> and a significant model spread. Very few models perform well for all the components and this underlies the need for model physics improvements as regards the air-sea exchange. To conclude, the dynamical downscaling of ERA40 seems to have a major impact on all the components of the Mediterranean heat budget, since the RCMs provide values quite different from the driving reanalysis. In view of the large inter-model spread observed, the reasons of these discrepancies are not likely related with the increase of horizontal resolution. Since the boundary conditions are identical for all models, the differences are probably related to the choice physical parameterisations used for each model.

Concerning the total heat balance, we have combined the different available datasets to obtain three values (see Table 5): HB1 uses ISCCP for Q<sub>SW</sub> and Q<sub>LW</sub> and OAFflux for Q<sub>LH</sub> and Q<sub>SH</sub>; HB2 uses NOC estimates for all the fluxes and HB3 uses NOC for Q<sub>SW</sub> and Q<sub>LW</sub>, HOAPS for Q<sub>LH</sub> and Q<sub>SH</sub>. The HB1 and HB2 estimates are positive (+9, +5 W/m<sup>2</sup>), indicating a non realistic heating of the Mediterranean Sea. Recall that the Gibraltar Strait net heat transport ranges from +3 to +10 W/m<sup>2</sup> (see the Introduction) indicating an equivalent cooling of the Mediterranean Sea through its surface. We have also combined in HB3 the lowest estimate of Q<sub>SW</sub> (NOC, 185 W/m<sup>2</sup>) and the highest for Q<sub>LW</sub> (NOC, 84 W/m<sup>2</sup>), with the high HOAPS estimates for the turbulent fluxes (90 and 14 W/m<sup>2</sup>). This leads to a more realistic negative heat budget equal to -3 ± 8 W/m<sup>2</sup>, for which the closure hypothesis is satisfied within the stated error bounds, although the mean value of -3 W/m<sup>2</sup> is greater than the -5 W/m<sup>2</sup> found by McDonald et al. (1994) on the basis of Gibraltar Strait heat transport measurements.

As a result of its low Q<sub>SW</sub> value, the ERA40 net heat flux estimate of -15 W/m<sup>2</sup> is outside the range implied by the net heat transport at the Gibraltar Strait. Regarding the RCMs, we find a large uncertainty around the heat budget estimates. The values vary between -40 W/m<sup>2</sup> for DMI and +21 W/m<sup>2</sup> for METOHC, with 5 models simulating a heat gain by the Mediterranean Sea and 7 a heat loss. This result shows that individual RCMs have difficulties in

simulating the net Mediterranean Sea heat budget. Moreover, the RCM ensemble mean of  $-9 \text{ W/m}^2$  underestimated by  $4 \text{ W/m}^2$  the McDonald et al. (1994) value. In comparison, Pettenuzzo et al. (2010) obtain basin mean values between  $-5$  and  $4 \text{ W/m}^2$  from their adjusted ERA40 fields depending on the choice of transfer coefficient scheme employed (see Sect. 1).

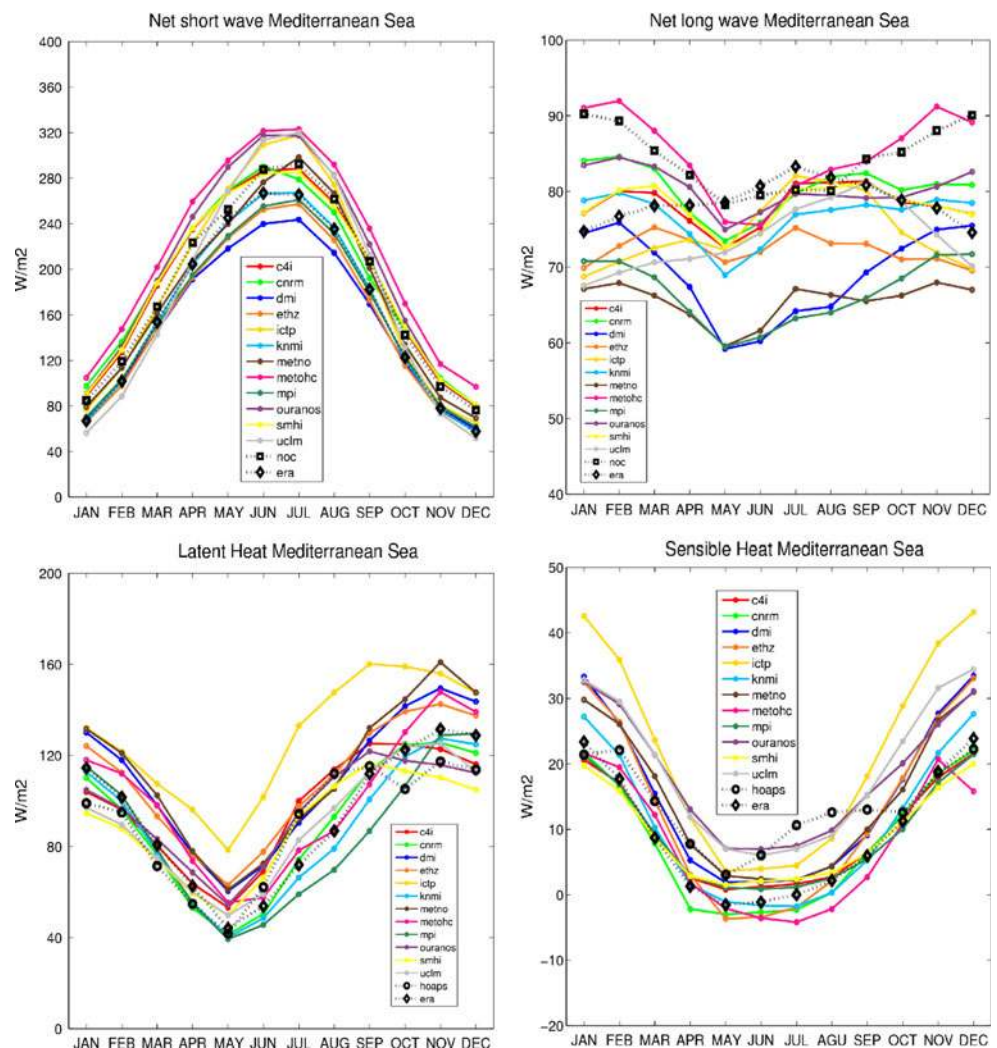
The model results show that, although closure is obtained with the ensemble mean, the individual RCMs are often not balanced in terms of the surface heat fluxes over the Mediterranean Sea. This is an important issue for the regional modelling community and suggests that more efforts are needed to improve the heat budget estimates. This is also an important message for the regional ocean modelling community, which is starting to evaluate the skill of dynamical downscaling of reanalysis over the Mediterranean Sea (Sotillo et al. 2005; Ruti et al. 2007), and to use them to force Mediterranean regional ocean models for climate-scale simulations (Herrmann and Somot 2008; Somot and Colin 2008; Sevault et al. 2009;

Tsimplis et al. 2008; Beuvier et al. 2010; Herrmann et al. 2010). Long-term well balanced water and heat budgets are required skills of atmosphere forcing.

### 3.2.2 Seasonal cycle

Figure 5 shows the climatological annual cycle for the radiative fluxes (short and longwave) and for the turbulent fluxes (latent and sensible) averaged over the whole Mediterranean basin. For these figures only observations used in HB3 are considered (see Table 5). The factor with the largest contribution to the heat budget is the net  $Q_{\text{SW}}$  radiation (Fig. 5.a), which has a pronounced seasonal cycle. The net shortwave flux is in general well simulated by the models, though a larger inter-model spread is observed during the summer months, when the short wave absorbed by the sea is maximum, with values ranging from  $240$  to  $320 \text{ W/m}^2$  for July–August. The ERA40 estimates lie below the NOC observational dataset during the whole year, with a maximum underestimation during the summer months.

**Fig. 5** Climatological seasonal cycle for the components of the heat budget averaged over the whole Mediterranean basin. **a** Shortwave from the RCMs, ISCCP and NOC data. **b** Longwave from the RCMs, ISCCP and NOC data. **c** Latent heat flux from the RCMs, OAFlux, HOAPS and NOC data. **d** Sensible heat flux from the RCMs, OAFLUX, HOAPS and NOC data



The net longwave radiation (Fig. 5b) emitted by the sea has a seasonality much less pronounced than  $Q_{SW}$  (note the major difference in scales between Figs. 5a and 5b). These values indicate a heat loss from the sea to the atmosphere. According to this, the heat loss for NOC is especially large in autumn, winter and spring. There is a minimum of  $Q_{LW}$  during late spring (May). Most of the RCMs also show this minimum in May, though the inter-model spread is large for  $Q_{LW}$ . In May,  $Q_{LW}$  is  $78 \text{ W/m}^2$  for NOC. ERA40 is very close to NOC with  $79 \text{ W/m}^2$  and the RCM estimates vary between  $60 \text{ W/m}^2$  and  $76 \text{ W/m}^2$ .  $Q_{LW}$  is maximum in summer, when cloud cover is at a minimum. For August the value is  $80 \text{ W/m}^2$  for NOC. ERA40 with  $82 \text{ W/m}^2$  is slightly higher than NOC and the RCM values range from  $64$  to  $83 \text{ W/m}^2$ . In general, differences between the observational dataset and models for the longwave are less important than those for shortwave given the smaller magnitude of the longwave flux. Note the discrepancy between the NOC and ERA40 seasonal cycles, ERA40 showing a very flat seasonal cycle.

The annual cycle of latent heat flux will be only briefly discussed in this section, since its behaviour is the same as for evaporation in Sect. 3.1.  $Q_{LH}$  always shows a heat loss from the sea by evaporation in Fig. 5c. The annual cycle has a minimum in May and reaches a maximum in late autumn. In November during the maximum we obtain estimates  $117 \text{ W/m}^2$  for HOAPS and  $131 \text{ W/m}^2$  for ERA40. A range of  $110$ – $160 \text{ W/m}^2$  is observed for the models at this time. In late spring,  $Q_{LH}$  drops to approximately  $40 \text{ W/m}^2$  for HOAPS and ERA40 and  $55$ – $77 \text{ W/m}^2$  for the RCMs. The RCMs have a tendency to overestimate the latent heat flux compared to observations in all seasons. Note also that a subset of the models reproduces the high June–September anomaly values obtained from HOAPS. However OAFUX and NOCS do not show this June–September anomaly values (not shown).

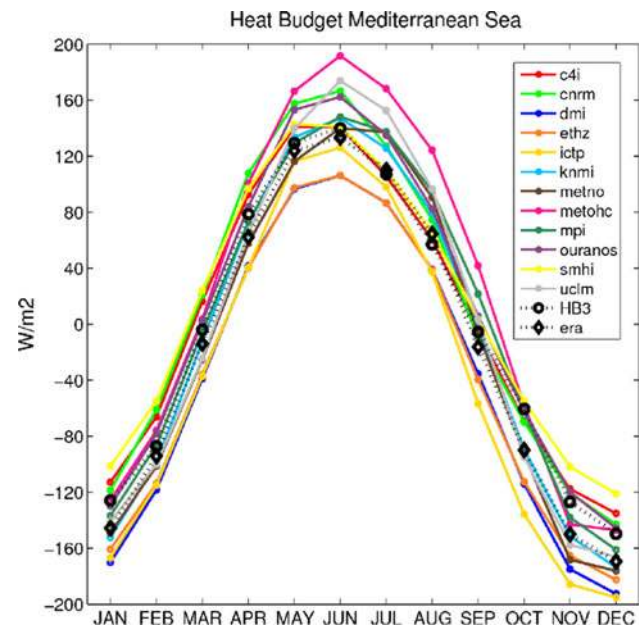
The sensible heat flux has the smallest contribution to the heat budget (again note the major difference in scales between Figs. 5c and 5d). Nevertheless it shows a pronounced seasonal cycle with a minimum in late spring and summer and a maximum from January to December (Fig. 5d). The values of  $Q_{SH}$  are in general an ocean heat loss, however during the minimum, the values of  $Q_{SH}$  for some models indicate a heat gain for the ocean, which is colder than the atmosphere. Again HOAPS shows an anomaly of the seasonal cycle for the June–September period compared to the other observational datasets (not shown). ERA40 lies below the observed estimate and the annual variations in  $Q_{SH}$  are reasonably well captured by the RCMs with ICTP an obvious outlier. None of the models shows the HOAPS anomaly. The amplitude of the seasonal cycle is on average  $26 \text{ W/m}^2$  for the RCM

ensemble mean, compared with approximately  $18 \text{ W/m}^2$  for HOAPS and  $25 \text{ W/m}^2$  for ERA40.

The total heat budget seasonal cycle, as computed following eq. (2) is represented in Fig. 6. The annual mean values for HB3 have been discussed in the previous section; we recall here that only HB3 has a Mediterranean Sea yearly-mean negative heat loss, and hence is more consistent with the Gibraltar net transport. Considering the seasonal cycle, the heat loss from the Mediterranean Sea is maximum in winter; with values of  $120 \text{ W/m}^2$  for HB3. This is a result of weak shortwave and strong turbulent fluxes due to intense wind events and the cold and dry atmosphere. This loss is compensated by a heat gain of  $120 \text{ W/m}^2$  during summer, with a peak reached in June for both observations and models. In general, the models reproduce the seasonal cycle seen in the observations reasonably well with no major anomalies.

#### 4 Summary and discussion

This main goal of this work has been to assess the performance of an ensemble of regional models in terms of heat and water budgets in the Mediterranean Sea. The RCMs have been driven by the ERA40 reanalysis for the 1960–2000 period and with a spatial resolution of  $25 \text{ km}$ . These high resolution model datasets have been compared



**Fig. 6** Climatological seasonal cycle for the area-averaged Mediterranean heat budget for the period 1983–2000. The estimate HB1 has been obtained by combining the OAFux for  $Q_{LH}$  and  $Q_{SH}$  with the ISCCP for  $Q_{SW}$  and  $Q_{LW}$ . The estimate HB2 has been obtained entirely from NOC data. And HB3 is obtained by merging HOAPS for  $Q_{LH}$  and  $Q_{SH}$ , and NOC for  $Q_{SW}$  and  $Q_{LW}$ .



to different lower resolution observational datasets and also to the ERA40 reanalysis. We have used a range of recent observational datasets over the Mediterranean Sea to evaluate the RCMs. The focus has been on the area-averaged climatological seasonal cycle and the long-term annual mean. The main conclusions can be summarized as follows:

There are still large uncertainties concerning the observations of the various terms of the heat and water budget of the Mediterranean Sea. Improvements of the observational estimates over the sea, especially for the latent heat flux, precipitation and radiative fluxes, are required to provide tighter constraints on the models. Precipitation is the most problematic term because of the large difference between the GPCP, CMAP and HOAPS datasets.

Difficulties in obtaining agreement between the estimates of the water and heat budgets and transport based values obtained from the Gibraltar Strait suggest that the latent heat flux may have been underestimated in all of the observational datasets. For example, the use of the HOAPS low estimate of the precipitation over sea is required to obtain a realistic total freshwater loss (WB2, WB3, WB4). For the heat budget, a combination of NOC for shortwave and longwave and HOAPS for sensible heat and latent heat (HB3) is required to obtain a net heat loss of  $-3 \text{ W/m}^2$  which is close to the value of  $-5 \text{ W/m}^2$  implied by measurements of the Gibraltar heat transport. Other combinations of the data sources give unrealistically positive values for the net heat flux. The estimates obtained in the current study are: 1,095–1,115 mm/year for E, 256 mm/year for P, 142 mm/year for R, 80 mm/year for B, 612–660 mm/year for the E–P–R–B total water budget and 185  $\text{W/m}^2$  for SW,  $-84 \text{ W/m}^2$  for LW, 88–90  $\text{W/m}^2$  for LH, 14  $\text{W/m}^2$  for SH and  $-3 \text{ W/m}^2$  for the total heat budget.

The ERA40 reanalysis latent heat flux or evaporation is slightly higher than the observational values and the net short wave radiation is significantly lower than the observations.

The ERA40-driven RCM ensemble is typically in good agreement with the observations of the shortwave, longwave, sensible heat, evaporation-precipitation, river runoff and Black Sea inputs. However, the RCMs overestimate the latent heat flux (or evaporation) and precipitation with respect to the observations (although as noted above the observation based latent heat flux may be an underestimate). For the water budget, good river runoff and Black Sea discharge estimates are obtained with the ensemble of RCMs. This change is likely to reflect the high spatial resolution which enables a more realistic representation of the complex orography (Elguindi et al. 2009). The long-term seasonal cycle of the water budget components (evaporation, precipitation and river discharge) is well simulated by the RCMs.

For the heat budget terms, and in view of our results, giving an overall conclusion about the added value of the dynamical downscaling is difficult. We note that the RCM ensemble mean value of  $-9 \text{ W/m}^2$  for the net heat flux is closer to the basin-wide average of  $-5 \text{ W/m}^2$  expected from the Gibraltar transport measurements than the original ERA40 value of  $-15 \text{ W/m}^2$ . Though the ensemble mean estimate is correct, the ensemble spread is large ( $+21 \text{ W/m}^2$ ), indicating the discrepancies of the state-of-the-art RCMs. We also note that previous studies have shown that dynamical downscaling has an added value with respect the coarse horizontal scale driving field in local and extreme phenomena (winds, air-sea exchanges) as shown in Sotillo et al. (2005), Ruti et al. (2007) and Herrmann and Somot (2008), but this is not the case for this work

There is a tendency for a large spread between RCMs in the terms of both the water and heat budgets. For example, the mean spread among the models is 164 mm/year for evaporation. The simulated precipitation also has a large inter-model spread of approximately 84 mm/year. Note that this spread is even stronger in the observational precipitation datasets between GPCP and HOAPS which demonstrates the difficulty in using them to constrain the freshwater budget. The inter-model spread is also large for the river discharge and the Black Sea input. As mentioned above, the uncertainties associated with the heat budget estimates for individual RCMs remain large with basin mean values from  $-40 \text{ W/m}^2$  to  $+21 \text{ W/m}^2$ . The extreme high and low values are likely due to the use of inappropriate physical parameterization of turbulent and radiative heat fluxes in some cases in the individual RCMs, or perhaps to the use of non coupled models.

To conclude, our results show that only a few of the RCMs considered provide balanced heat and water budgets when compared with observations, and also not significant improvements have been obtained with respect to the original ERA40 forcing. Previous studies have shown that the dynamical downscaling in the Mediterranean region improve the representation of air-sea exchanges (Sotillo et al. 2005; Ruti et al. 2007; Ruiz et al. 2008; Herrmann and Somot 2008) in several zones (Gulf of Lyon, Adriatic Sea). However we show here that for a basin wide average, the dynamical downscaling does not always yield to significant improvements of the water and heat budget estimates respect to ERA40.

From the information provided in this paper, it is possible to select an RCM that is suitable on budget grounds for use as a high resolution atmospheric forcing for an ocean model of the Mediterranean Sea. High resolution for the atmospheric forcing is vital to correctly represent the deep water formation and the Mediterranean thermohaline

circulation and our new results indicate that more progress can be made in this area in the near future.

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