Water Mass Cycle in the Mediterranean and Black Seas

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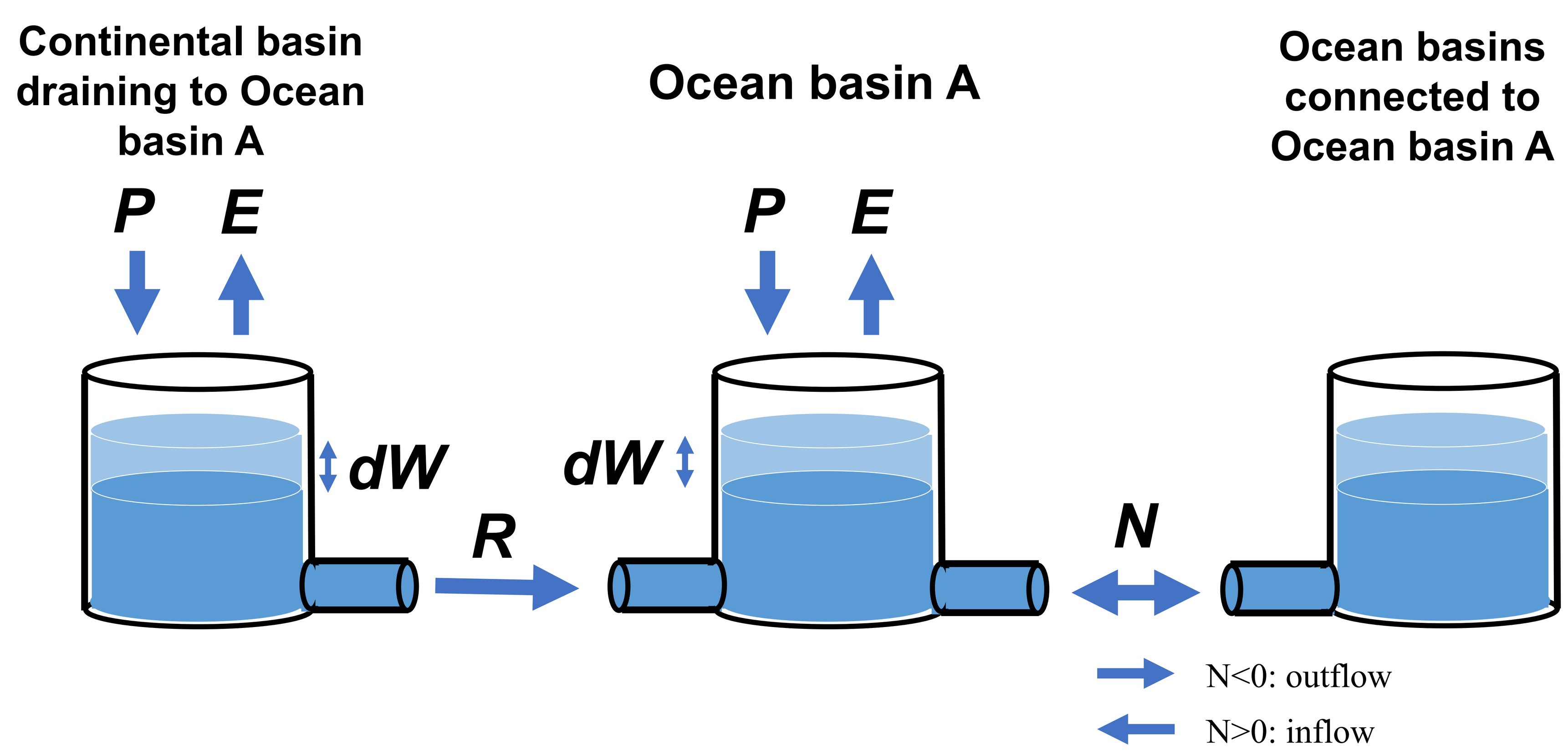
Abstract. The Black Sea is a semi-enclosed sea only connected to the Mediterranean Sea through the Turkish Straits. In turn, the Mediterranean is also a semi-enclosed sea connected to the open ocean through the Gibraltar Strait. Then, the water mass budget of these seas is driven by freshwater exchanges via precipitation, evaporation, and runoff, and by salty freshwater exchanges through the mentioned straits. Quantification of such fluxes, especially its time evolution, is essential to understand the water cycle in the region. In this study, we have estimated them from the time-variable gravity observations from the Gravity Recovery and Climate Experiment (GRACE) and GRACE follow-on satellites, and from ERA5 reanalysis, which assimilates observational data into general-circulation modelling provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). In the Black Sea, rivers introduce 396 ± 24 km³/year, from which one third escapes through the atmosphere and two thirds go to the Mediterranean Sea. In the latter, 1776 ± 24 km³/year are lost via net evaporation. The water budget is restored with 504 ± 36 km³/year from runoff, and 1058 ± 62 km³/year (0.032 ± 0.002 Sv) from Atlantic ocean. The balance is not reached instantaneously, which introduces seasonal variability in all the fluxes.

1. Methodology and datasets

- *W*: Water budget → **GRACE RL06 mascon**, Center of Space Research (CSR), University of Texas
- *dW*: Change of water budget → Discrete derivative as difference of consecutive months
- *P*: Precipitation → **ERA5 reanalysis**
- *E*: Evaporation → **ERA5 reanalysis**
- *R*: River runoff → Residual from Equation 1
- *N*: Net water exchange between neighbouring ocean regions through the ocean boundaries → Residual from Equation 2



Equation 1 (**for land**):

$$dW = P - E - R$$

Equation 2 (**for ocean**):

$$dW = P - E + R + N$$

2. Results

2.1 Water transport components

Equation 1 is applied to:

(1) the Mediterranean and Black Sea continental drainage basins to estimate R at each basin

Then, Equation 2 is applied to:

(2) the Black Sea to estimate *T* (net water transport through the Turkish Straits)

(3) the Mediterranean Sea to estimate *G* (net water transport through the Gibraltar Strait)

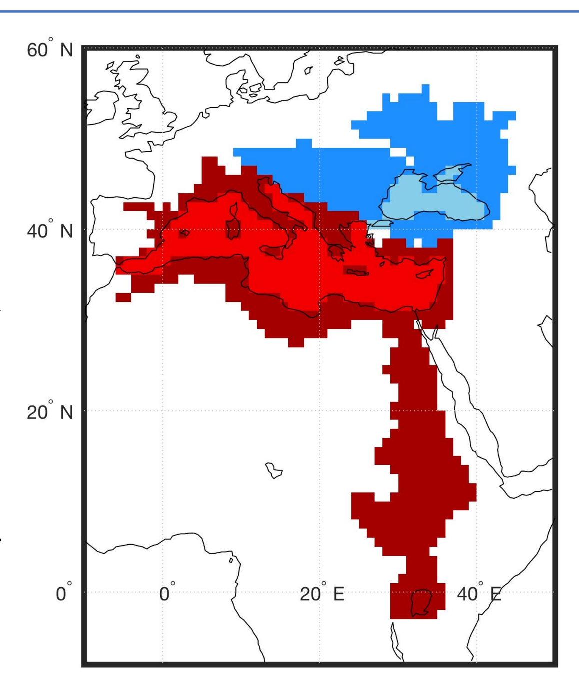


Figure 1. Mediterranean and Black Seas. Light red: Mediterranean Sea; dark red: continental basins draining to the Mediterranean Sea; Light blue: Black Sea; dark blue: continental basins draining to the Black Sea.

Associated drainage basins: Estimated from the global continental runoff pathways scheme of Oki and Sud (1998). There are no direct water exchanges in the form of R among land drainages (see Figure 1).

The time series of all the water components are shown in Figure 2

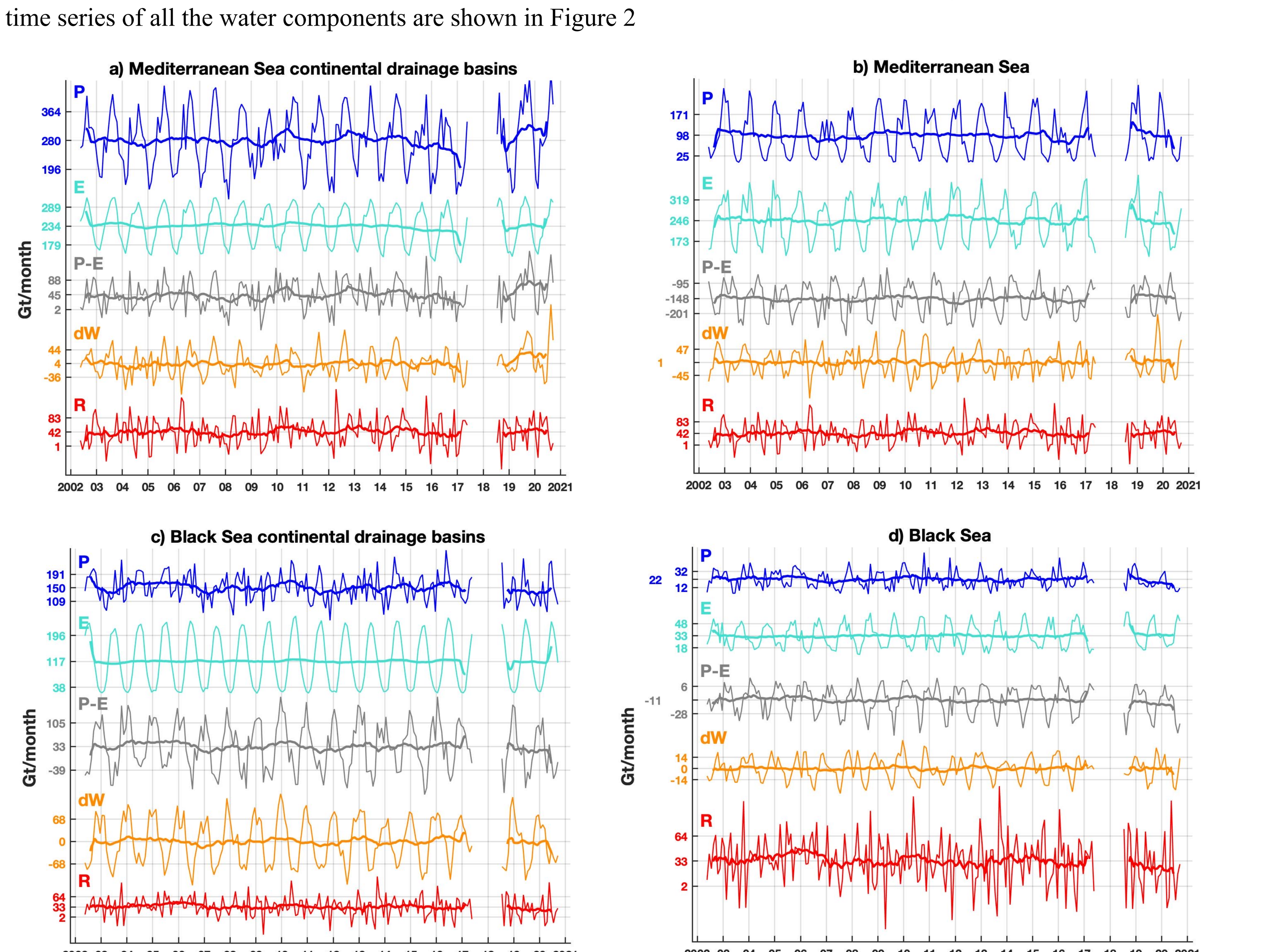


Figure 2. Water transports of Eqs. 1 and 2 in the Mediterranean (first row) and Black Seas (second row) and their drainage basins. First column: drainage basins; second column: ocean basins. The reported error corresponds to the standard deviation of the mean estimated from the stationary bootstrap (see Methods). Thick lines are 12-month running means. 1 Gt = 1012 kg for the weight of 1 km³ of freshwater. One nominal month is 30 days. Positive *G* and negative *T* correspond to Mediterranean Sea inflow.

2.2 Mean water transport

The Black Sea drainage basins receive 396 ± 24 km³/year of net precipitation that produces an identical amount of *R*. In the Black Sea, a third of the water supplied by *R* goes to the atmosphere via net evaporation, and the rest, 258 ± 25 km³/year, goes to the Mediterranean Sea through Turkish Straits (Table 1, Figure 3).

The mean Mediterranean Sea water budget does not change with time, *dW* = 12 ± 25 km³/year, but it loses 1776 ± 24 km³/year through net evaporation. Therefore, the total inflows in the Mediterranean Sea must match such loss. Continental runoff contributes around a fourth (504 ± 36 km³/year) of that budget, while water transported from the Black Sea accounts for 258 ± 25 km³/year, half of the riverine contribution. The remaining 1058 ± 62 km³/year (0.032 ± 0.002 Sv) is water coming from the Atlantic Ocean through the Gibraltar Strait. Note that mean *G* is four times mean *T*. A schematic representation of the mean water cycle in the Mediterranean and Black Sea can be seen in Figure 3.

Table 1. Mean, annual and semiannual signal of WT components of Eqs. 1 and 2 in the Mediterranean and Black Seas, and their drainage basins. Units are Gt/month for mean and amplitudes, and degrees for phases. Error estimates are standard deviations. Region areas are estimated from our grid resolution (see Figure 1). Negative *T* means a flux from the Black Sea to the Mediterranean Sea. Water density is fixed to 1000 kg/m³ for freshwater and 1025 kg/m³ for sea water.

		Mean		Annual amplitude (km³/year)	Annual phase (º)	Semiannual amplitude (km³/year)	Semiannual phase (º)	Annual peak
		km³/year	Sv					
Mediterranean Sea drainage basins (5.34 · 10⁶ km²)	*P*	3360 ± 36	0.108±0.001	1185 ± 102	218 ± 5	293 ± 102	4 ± 20	9 Aug
	E	2808 ± 12	0.090±0.000	901 ± 29	213 ± 2	136 ± 29	10 ± 12	4 Aug
	P–E	540 ± 36	0.017±0.001	298 ± 90	233 ± 17	159 ± 90	180 ± 32	24 Aug
	dW	48±24	0.002±0.001	386 ± 71	232 ± 11	178 ± 71	76 ± 23	24 Aug
	R	504±36	0.016±0.001	88 ± 89	50 ± 58	264 ± 89	41 ± 19	20 Feb
Mediterranean Sea (2.43 · 10⁶ km²)	*P*	1176±24	0.038±0.001	1099 ± 77	356 ± 4	143 ± 77	103 ± 31	27 Dec
	E	2952±24	0.095±0.001	1121 ± 69	319 ± 4	188 ± 69	55 ± 21	20 Nov
	P–E	-1776±24	-0.057±0.001	696 ± 66	69 ± 5	303 ± 66	76 ± 12	11 Mar
	dW	12±25	0.000±0.001	520 ± 79	285 ± 9	240 ± 79	16 ± 19	16 Oct
	G+T	1316±62	0.040±0.002	1253 ± 161	262 ± 7	417 ± 161	83 ± 22	23 Sep
Black Sea drainage basins (2.42 · 10⁶ km²)	*P*	1800±36	0.058±0.001	259 ± 86	167 ± 19	190 ± 86	136 ± 26	19 Jun
	E	1404±12	0.045±0.000	1318 ± 19	177 ± 1	165 ± 19	158 ± 7	29 Jun
	P–E	396±24	0.013±0.001	1064 ± 83	360 ± 4	73 ± 83	76 ± 65	31 Dec
	dW	0±24	0.000±0.001	1053 ± 66	358 ± 4	69 ± 66	64 ± 54	29 Dec
	R	396±24	0.013±0.001	38 ± 72	73 ± 108	15 ± 72	145 ± 275	15 Mar
Black Sea (0.45 · 10⁶ km²)	*P*	264±12	0.008±0.000	108 ± 19	345 ± 10	2 ± 19	62 ± 459	16 Dec
	E	396±0	0.013±0.000	217 ± 13	255 ± 4	69 ± 13	82 ± 11	15 Sep
	P–E	-132±12	-0.004±0.000	242 ± 20	48 ± 5	71 ± 20	81 ± 16	18 Feb
	dW	0±12	0.000±0.000	182 ± 18	348 ± 6	95 ± 18	30 ± 11	19 Dec
	T	-258±25	-0.008±0.001	262 ± 83	270 ± 18	91 ± 83	158 ± 52	1 Oct
Gibraltar flux	*G*	1058±62	0.032±0.002	1513 ± 182	263 ± 7	449 ± 181	94 ± 23	24 Sep

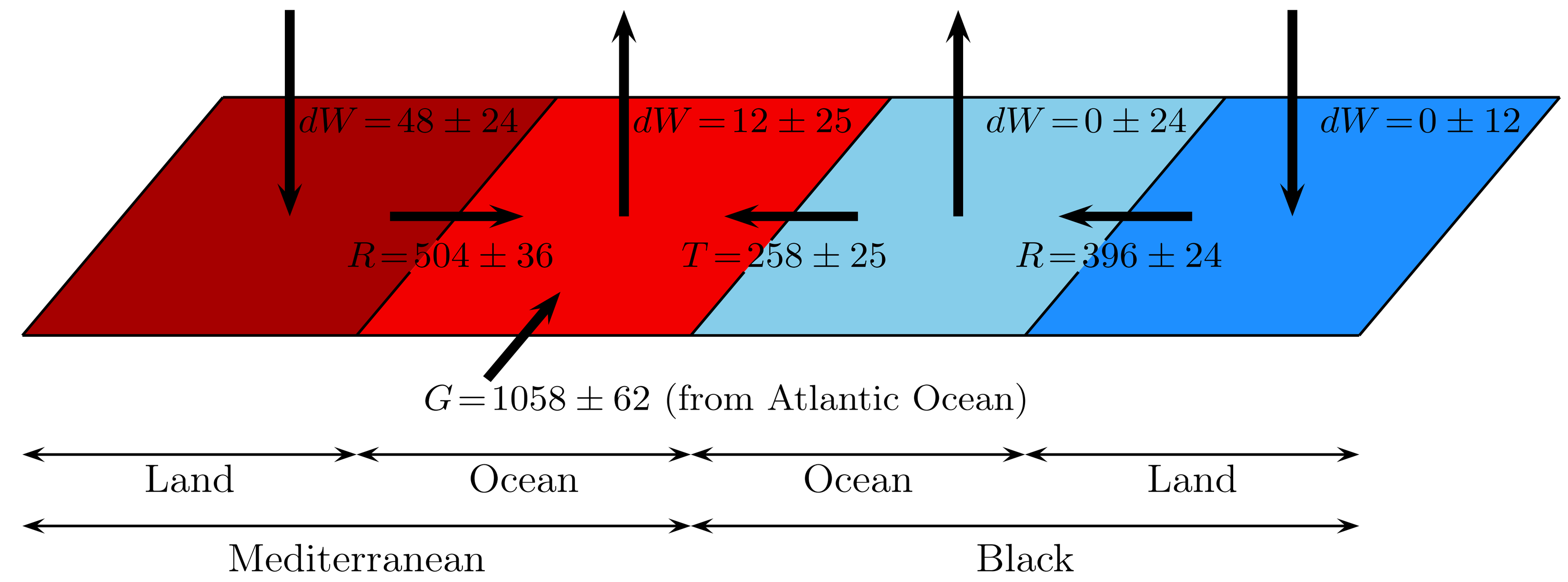


Figure 3. Schematic representation of the mean water cycle in the Mediterranean and Black Sea shown in Table 1. Units are km³/year.

2.3 Annual and semiannual components

The annual and semiannual signal are estimated applying a least-squares fitting of the time series to

$p0 + p1 \cdot t + Aa \cos(\omega_a \cdot t - \phi_a) + Asa \cos(\omega_{sa} \cdot t - \phi_{sa})$,

where t represents time, (ω, A, ϕ) = (frequency, amplitude, phase) and the suffix 'a' and 'sa' denotes annual and semiannual terms, respectively. Table 1 shows the annual amplitude and phases of all the components. From the differences in the phases can be inferred that the water transport balance among the components is not instantaneously reached.

3. Discussion

In this work we present an application of the new methodology presented by García-García et al. (2020) to estimate lateral water transport components in oceanic regions. In this case, as the Mediterranean and the Black Sea are semi-enclosed basins, such lateral water transport corresponds to the water transport through the Gibraltar and Turkish Straits. We have estimated all the water transport components, which gives a general picture of the hydrological cycle in the Mediterranean and Black Seas. The behaviour of the two seas is quite different. On the one hand, the Mediterranean Sea shows a deficit of freshwater inputs, which must be balanced by a net inflow of salty water from the Atlantic Ocean. On the other hand, the Black Sea has an excess of freshwater input that results in a net water transport from the Black Sea to the Mediterranean Sea.

Acknowledgements and References

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