VERTICAL LAND MOTION AND LOW-FREQUENCY SEA LEVEL VARIABILITY ALONG THE SOUTH-EUROPEAN COASTS

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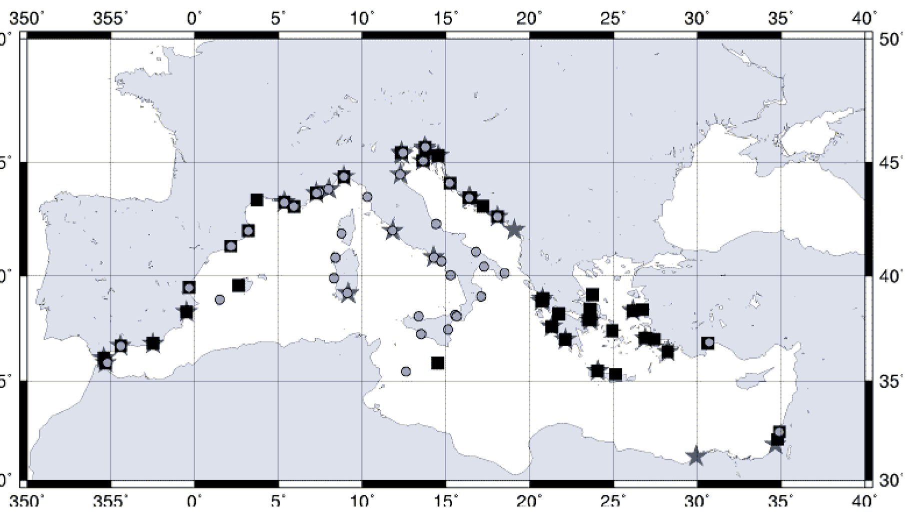
1. ABSTRACT

We have computed estimates of the rate of vertical land motion in the Mediterranean Sea and along the spanish coasts of the Atlantic Ocean from differences of sea level heights measured by the Topex/Poseidon radar altimeter and by a set of tide gauge stations.

2. Local data versus PSMSL data



At 16 tide gauge stations in the Mediterranean Sea monthly data computed from hourly local datasets and monthly data from the PSMSL dataset are compared. Significant differences are found at only one location.

Figure 1: Tide gauge stations in Mediterranean Sea with monthly averages available in the PSMSL dataset before 1993 (stars) and after 1993 (squares) and with hourly data available from local organisations after 1993

3. Linear trend of the ALT - TG differences

Linear-term of sea level computed from monthly altimetric grids (0. 5 x 0.5 degrees) and from monthly averages of tide gauge records in the interval 1993-2001 show similar patterns of long-term variability (Figure 2). Differences of nea-simultaneous, monthly and de-seasoned monthly sea level height time-series are considered in order to reduce the error in the estimated linear-term.

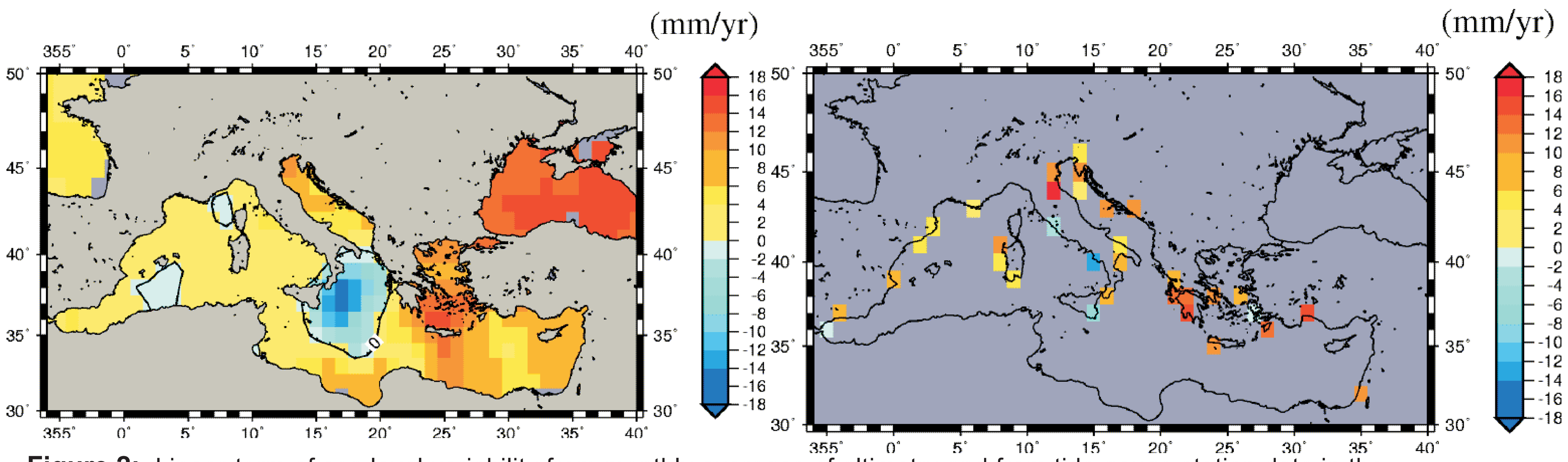


Figure 2: Linear-term of sea level variability from monthly averages of altimetry and from tide gauge station data in the Mediterranean Sea

Table 1 : Lag-1 autocorrelation, Effective degree of freedom, inflation factor, formal error and accuracy in Ceuta

Time-series	r^1	EDOF	F_l	(mm/yr)	1 (mm/yr)
Monthly ALT	0.50	34	1.74	2.7	4.8
Monthly TG	0.51	34	1.75	2.1	3.7
Monthly ALT-TG	0.20	70	1.23	1.5	1.9
De-seasoned monthly ALT	0.31	55	1.38	2.1	2.8
De-Seasoned monthly TG	0.33	53	1.42	1.6	2.3
De-Seasoned monthly ALT-TG	0.06	94	1.06	1.3	1.4

The accuracy is evaluated accounting for the effective degree of freedom computed from the lag-1 autocorrelation (Maul and Martin, 1993). Table 1 gives formal error and accuracy of the linear-trends of monthly and monthly-de-seasoned data in Ceuta. Monthly de-seasoned data are used in Table 2.

By differencing records from altimetry and tide gauge data most of the coherent sea level variability is removed, the residual time series reflects the Vertical Land Motion (VLM) at the tide gauge site and any instrumental errors (datum shifts and data spikes, bias and drift in the altimeter). Differential sea level variability due to currents and tides remains. By differencing records from adjacent stations the differential VLM of the stations and the differential sea level variability is left.

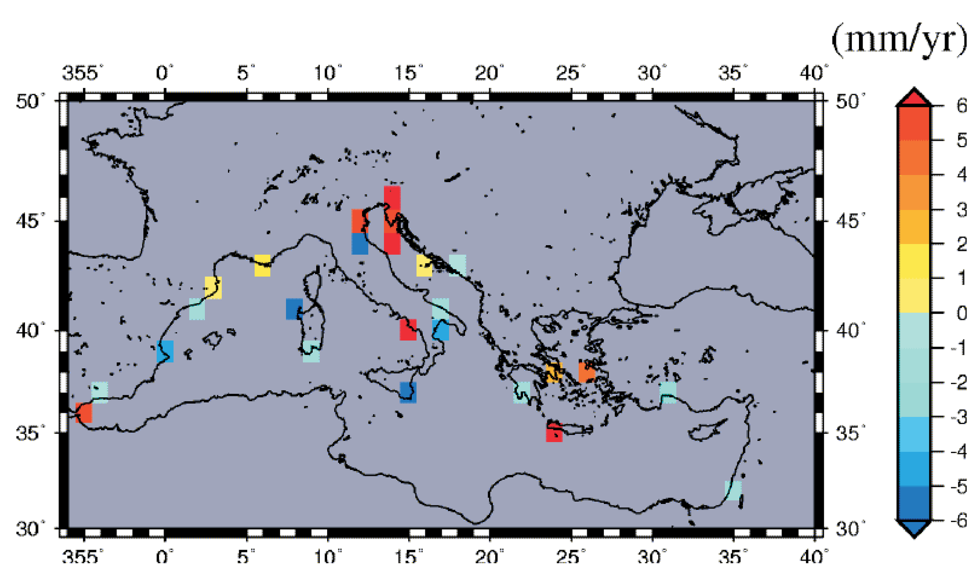


Figure 3: Vertical Land Motion estimated from de-seasoned monthly differences of sea level heights from altimetry and tide gauge data

Table 2 : Comparison of de-seasoned monthly T/P altimetry and tide gauge data sea level heights at 24 tide gauge stations in the

Station	Starting year	d_{at} (km)	Δ_{at} (mm)	Δ_a / Δ_t (mm)	Nm	r_{at}	$b_a \pm \sigma_a$ (mm/yr)	$b_t \pm \sigma_t$ (mm/yr)	$b_{at} \pm \sigma_{at}$ (mm/yr)	σ^1_{at} (mm/yr)
Ceuta	1993	21	37	55 / 43	107	0.74	3.6 +/- 2.0	-1.3 +/- 1.7	5.0 +/- 1.3	1.4
Malaga	1993	87	50	64 / 52	108	0.64	4.1 +/- 2.4	5.0 +/- 1.9	-0.9 +/- 1.9	2.1
Valencia	1993	58	48	55 / 56	107	0.62	0.8 +/- 2.1	5.4 +/- 2.1	-4.6 +/- 1.8	3.6
Barcelona	1993	41	36	56 / 57	106	0.80	1.9 +/- 2.1	3.5 +/- 2.1	-1.5 +/- 1.3	2.1
Estartit	1993	66	23	56 /58	108	0.92	3.0 +/- 2.1	2.4 +/- 2.2	0.5 +/- 0.9	1.0
Toulon	1993	15	29	50 / 54	106	0.85	1.9 +/- 1.9	0.1 +/- 2.1	1.8 +/- 1.1	1.5
Venezia	1993	65	50	85 / 64	96	0.75	14.1 +/- 3.0	8.5 +/- 2.7	5.6 +/- 2.1	2.5
Trieste	1993	93	53	85 / 70	108	0.78	15.0 +/- 2.8	8.5 +/- 2.5	6.5 +/- 1.9	1.9
Rovinj	1993	50	50	85 / 67	108	0.81	15.0 +/- 2.8	9.2 +/- 2.4	5.7 +/- 1.8	1.9
Split	1993	63	40	67 / 64	108	0.81	9.2 +/- 2.4	8.8 +/- 2.3	0.3 +/- 1.5	1.7
Dubrovnik	1993	73	30	58 / 59	108	0.87	7.7 +/- 2.0	8.6 +/- 2.1	-0.9 +/- 1.1	1.5
Antalya	1993	101	42	50 / 56	95	0.69	9.4 +/- 1.7	12.4 +/- 1.7	-3.0 +/- 1.6	2.1
Kalamai	1993	12	44	56 / 58	100	0.71	12.4 +/- 2.0	14.0 +/- 2.0	-1.6 +/- 1.8	3.0
Pyraeus	1993	109	60	64 / 71	67	0.63	13.6 +/- 2.1	15.2 +/- 2.2	-1.6 +/- 2.4	4.6
Khalkis North	1993	69	50	60 / 51	107	0.64	12.5 +/- 2.0	6.8 +/- 1.8	5.7 +/- 1.7	3.6
Khios	1993	45	51	62 / 63	99	0.67	12.0 +/- 2.2	7.6 +/- 2.4	4.4 +/- 1.2	2.4
Soudhas	1993	56	44	64 / 52	103	0.72	15.1 +/- 1.8	6.8 +/- 1.8	6.3 +/- 1.5	2.2
Hadera	1994	60	42	50 / 49	88	0.65	15.1 +/- 1.7	12.4 +/- 1.7	-3.0 +/- 1.6	4.5
Catania	1995	95	37	71 / 59	96	0.87	-16. +/- 2.3	-8.3 +/- 2.1	-7.9 +/- 1.2	2.0
Taranto	1995	53	40	55 / 57	94	0.76	-0.4 +/- 2.3	4.3 +/- 2.2	-4.7 +/- 1.5	2.2
Bari	1995	101	29	55 / 51	84	0.85	1.6 +/- 2.6	2.9 +/- 2.4	-1.2 +/- 1.4	2.1
Cagliari	1995	79	34	49 / 55	77	0.79	1.2 +/- 2.0	3.2 +/- 2.2	-2.0 +/- 1.4	1.6
Porto Torres	1995	38	32	49 / 54	52	0.80	-0.5 +/- 3.6	4.6 +/- 3.1	-5.1 +/- 2.0	2.7
Ravenna	1996	80	114	85 / 100	63	0.56	10.6 +/- 6.3	18.7 +/- 6.0	-8.1 +/- 6.0	13.0

Table 3: Vertical motion at five tide gauge station from GPS (left) and from altimetry and tide gauge (right)

Station	Time interval GPS	$b \pm\sigma$ (mm/yr)	Time interval TG	$b \pm\sigma$ (mm/yr)
Ceuta	2000.6 - 2002.9	-6.3 +/- 4.6	1993 - 2001	5.0 +/- 1.3
Dubrovnik	2000.7 - 2002.9	-0.7 +/- 0.8	1993 - 2001	-0.9 +/- 1.1
Valencia	2001.0 - 2002.9	-2.4 +/- 0.9	1993 – 2001	-4.6 +/- 1.8
Ravenna	1996.5 - 2000	-10.3 +/- 0.1	1996 - 2001	-8.1 +/- 0.6
Antalya	1992 - 2002	-2.4 +/- 0.9	1993 - 2001	-3.0 +/- 1.6

In a subset of 23 tide gauge stations the mean accuracy of the estimated vertical rates is 2.3 +/- 0.8 mm/yr. A comparison with vertical motion estimated by GPS at 4 locations shows a mean difference of -0.04 +/- 1.8 mm/yr. Rate differences greater than 10 mm/yr have been excluded from the comparison. The first three in Table 3 (Ceuta, Dubrovnik and Valencia) are the rates of CGPS stations given by Sonel, the forth is a CGPS stations (Zerbini, 2002), the value at Antalya correspond to GPS campains over the last decade (Yildiz et al., 2003). The lenght of the GPS time-series and the number of locations are too small to draw general conclusions.

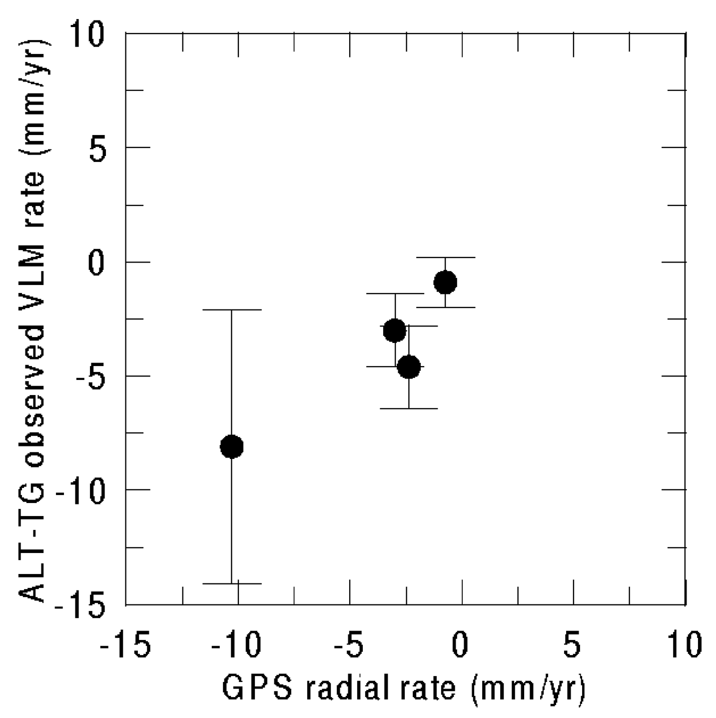


Figure 4: Comparison at four locations of the Vertical Land Motion derived from the combination of altimetry and tide gauge data with GPS rates. Rate differences greater than 10 mm/yr have been excluded from this comparison (Table 2)

4. Comparison in the iberian peninsula

For a further comparison of altimetry and tide gauge stations during 1993-2001 we have selected the iberian peninsula, as hourly data from a set of stations are here available from local organisations (IEO, REDMAR).

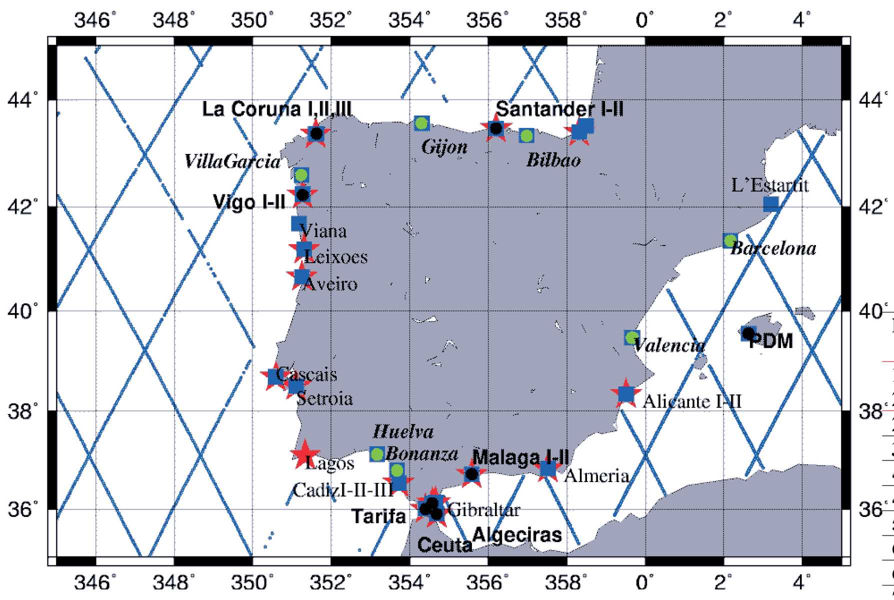


Figure 5: Tide gauge stations in the iberian peninula with monthly PSMSL records before 1993 (red stars), in interval 1993-2001 (blue squares) and from local organisation REDMAR (green dots) and IEO (black dots)

Hourly data are available at 13 different locations in 1993-2001. At 4 of those locations measurements from two tide gauge stations are available.

Table 3: Set of tide gauge stations in the iberian peninsula

Number	PSMSL Code	Location	Source	Sea	Data Interval	Data frequency
1	200006	Bilbao	PDE	Atl	1993-2001	H
2	200011	Santander I	IEO	Atl	1993-2001	H
2	200013	Santander II	PDE	Atl	1993-2001	H
3	200022	GijonII	PDE	Atl	1996-2001	H
4	200030	La Coruna I	IEO	Atl	1993-2001	H
4	200031	La Coruna II	PDE	Atl	1993-2001	H
5	200036	Villagarcia	PDE	Atl	1997-2001	H
6	200041	Vigo I	IEO	Atl	1993-2001	H
6	200042	Vigo II	PDE	Atl	1993-2001	H
7	220005	Huelva	PDE	Atl	1996-2001	H
8	220008	Bonanza	PDE	Atl	1993-2001	H
9	220003	Cadiz III	IEO	Atl	1993-2001	H
10	340008	Ceuta	IEO	Med	1993-2001	H
11	220011	Algeciras	IEO	Med	1993-2001	H
12	220021	Tarifa	IEO	Atl	1993-2001	H
13	220031	Malaga I	IEO	Med	1993-2001	H
13	220032	Malaga II	PDE	Med	1993-2001	H
14	220056	Valencia	PDE	Med	1993-2001	H
15	225011	Palma de Maillorca	IEO	Med	1997-2001	H
16	220061	Barcelona	PDE	Med	1993-2001	H
17	220081	L'Estartit	UPC	Med	1993-2001	H

The linear-term of the differences ALT - TG is generally small. At a few locations the trend of the difference is too high to be realistic (as in Cadiz) or is in disagreement with a station at the same location (for example the two stations at each of the Santander and Malaga locations). The same behaviour is found in the PSMSL dataset.

Table 4: Linear-term of monthly averages of sea level heights and of their differences

Station	d_{at} (km)	at (mm)	a / t (mm)	r_{at} ia	b_a a (mm/yr)	b_t t (mm/yr)	b_{at} at (mm/yr)
Bilbao	73	46	68 / 80	0.82	5.9 +/- 2.5	6.5 +/- 2.9	-0.6 +/- 1.7
Santander I	62	57	64 / 88	0.76	5.6 +/- 2.5	11. +/- 3.2	-5.8 +/- 2.1
Santander II	62	46	64 / 82	0.73	5.6 +/- 2.4	5.4 +/- 3.0	0.2 +/- 1.7
La Coruna I	77	67	69 / 95	0.70	3.8 +/- 2.7	2.4 +/- 3.6	1.4 +/- 2.6
La Coruna II	77	61	81 / 87	0.73	3.0 +/- 2.9	1.2 +/- 3.4	1.8 +/- 2.4
Vigo I	35	63	66 / 95	0.75	3.9 +/- 2.5	0.3 +/- 3.6	3.6 +/- 2.4
Vigo II	35	51	66 / 90	0.83	3.6 +/- 2.5	2.0 +/- 3.4	1.6 +/- 1.9
Bonanza	40	58	60 / 77	0.66	3.6 +/- 2.2	11. +/- 2.7	-7.7 +/- 2.1
Cadiz III	64	72	64 / 83	0.55	4.4 +/- 2.5	-6.0 +/- 3.1	10.4 +/- 2.6
Ceuta	21	53	80 / 56	0.76	2.8 +/ 3.0	-0.1 +/- 2.1	2.9 +/- 2.0
Algeciras	41	60	80 / 61	0.67	3.0 +/- 3.0	5.8 +/- 2.2	-2.7 +/- 2.2
Tarifa	36	38	48 / 48	0.74	4.2 +/ 2.4	6.2 +/- 2.1	-2.0 +/- 1.7
Malaga I	87	56	77 / 72	0.73	4.3 +/- 2.9	13. +/- 2.3	-9.4 +/- 1.9
Malaga II	87	51	77 / 68	0.77	6.0 +/- 4.6	9.8 +/- 3.7	-3.0 +/- 3.0
Valencia	59	45	84 / 90	0.86	4.4 +/- 3.2	8.2 +/- 3.3	-3.8 +/- 1.7
Barcelona	41	41	86 / 83	0.88	4.8 +/- 3.2	5.6 +/- 3.0	-0.8 +/- 1.5
L'Estartit	66	28	77 / 78	0.94	4.8 +/- 2.8	4.4 +/- 2.9	0.4 +/- 1.0

Table 5: Correlation of altimetry and tide gauge data using monthly, monthly de-seasoned averages and inter-annual sea level heights

TG & TX	r_{at} monthly	r_{at} monthly de-seasoned	r_{at} inter-annual lp 1 yr
Bilbao	0.82	0.63	0.88
Santander II	0.73	0.74	0.87
La Coruna II	0.73	0.72	0.63
Vigo II	0.83	0.75	0.77
Bonanza	0.66	0.63	0.65
Cadiz	0.55	0.50	0.46
Ceuta	0.76	0.67	0.77
Algeciras	0.67	0.56	0.64
Tarifa	0.74	0.68	0.79
Malaga II	0.77	0.68	0.84
Valencia	0.86	0.67	0.60
Barcelona	0.88	0.80	0.56
L'Estartit	0.94	0.92	0.96

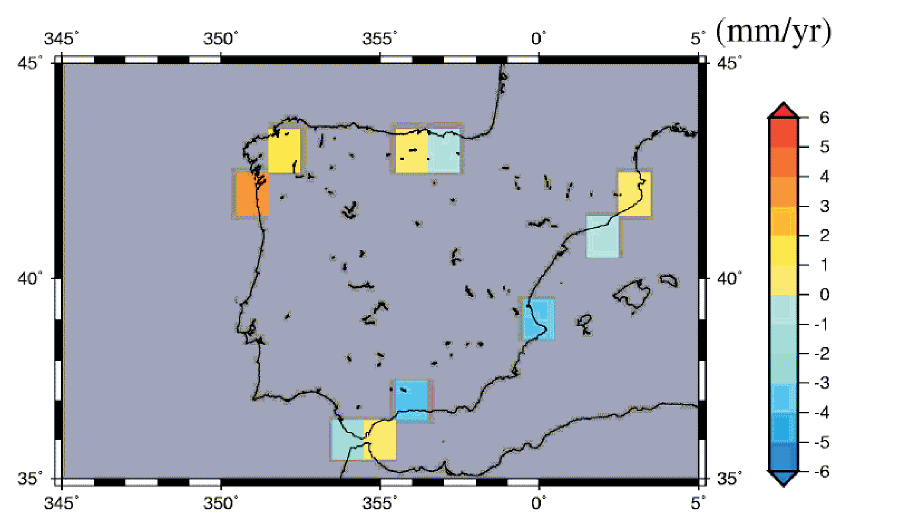


Figure 6: Linear-term of ALT - TG in 1993-2001

The de-seasoned monthly time-series are low-pass filtered to focus on inter-annual signals, that is on periods longer than one year. The filtering consists in averaging the series every half an year using one full year if data. The correlation between altimetry and tide gauges in 1993-2001 increases using inter-annual time-series (Table4). The NAO index has a significant negative correlation with sea level height change both along the Mediterranean and the Atlantic coasts, the correlation is higher at inter-annual time-scales. Coherent regional signals are identified and used to characterise regional inter-annual variability.

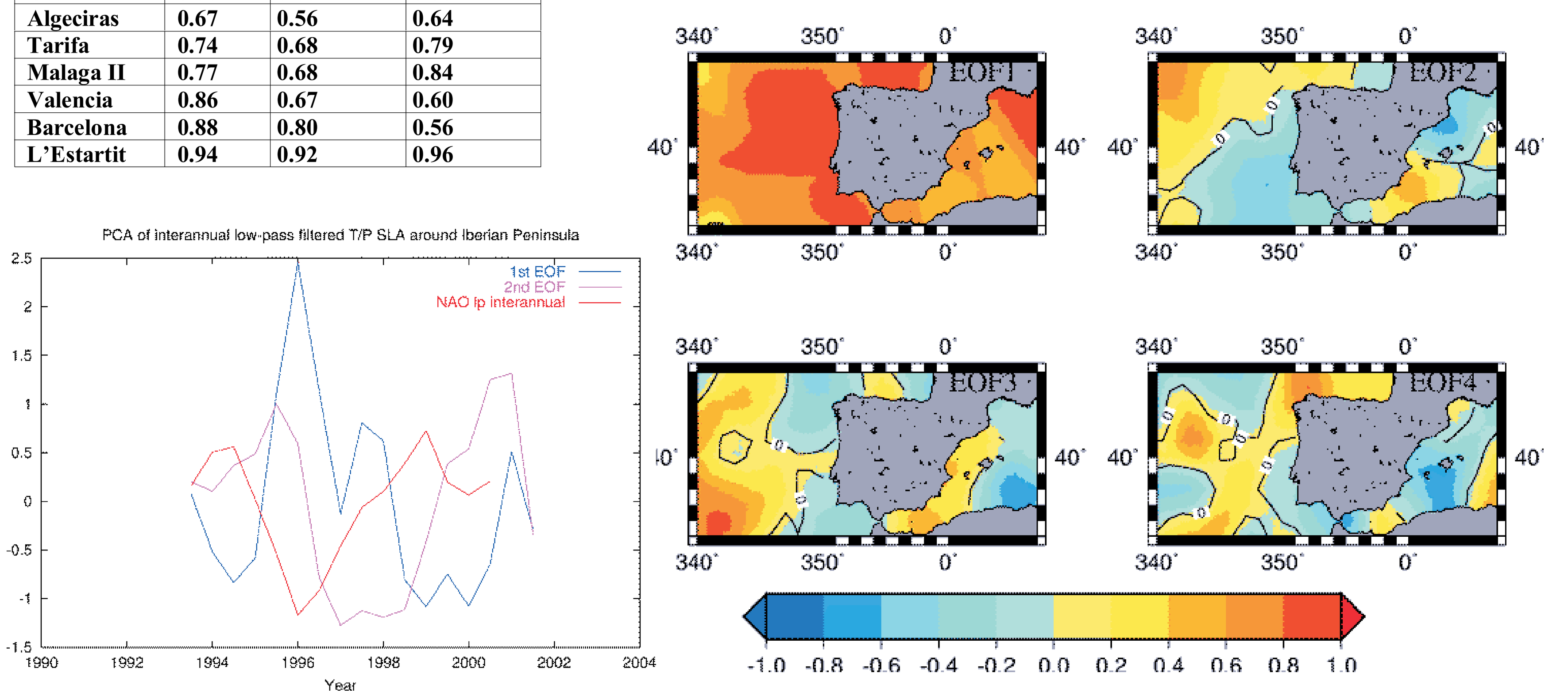


Figure 7: Correlation of altimetry and tide gauge station using monthly (left), monthly de-seasoned (centre) and inter-annual data (right)

5. CONCLUSIONS

Assuming that there is no drift in the altimeter masurements, the linear-term of the sea level height differences between altimetric and tide gauge measurements gives an estimation of the vertical land motion at the tide gauge location.

Quality-checked tide gauge data are necessary, hourly tide gauge data are preferable. For an external comparison the monitoring by GPS and Continuous GPS (CGPS) at the tide gauge station is required over a long time interval.

We have obtained an higher agreement between altimetry and tide gauge using the local data than using the PSMSL data, therefore care in the station selection and regular updates of the PSMSL dataset are needed.

The investigation will continue to estimate the Sea Surface Topography and low-frequency variability at

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