A STUDY OF UPWELLINGS USING GIS

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ABSTRACT

A GIS development for the study of coastal and open-sea upwellings is presented in this paper. Remotely sensed sea surface temperature (SST), wind data (WD, remotely-sensed and measured), and bathymetric contours are used to identify upwellings, measure mean SST inside and outside the upwelling patches, calculate upwelling area, duration, gravity center, and track gravity center movement of subsequent events. This GIS development is called Upwelling Identification and Measurement System (UPWELL) and features a complete user-interface. UPWELL is applied in two different upwelling sea areas of Greece, one with coastal upwellings (North Aegean Sea) and another with open-sea upwellings (West Cretan Sea). Upwelling indices for these areas are presented from 1993-95 (North Aegean Sea) and 1993-97 (West Cretan Sea) in a weekly resolution. The GIS-based UPWELL system works in three stages: The upwelling patches are identified from an SST image, they are verified by wind data according to upwelling theory, and finally, they are measured and tracked into upwelling index reports. The use of GIS in this study proved ideal because GIS integrated multi-year SST and WD data in a set of interfaced routines.

Keywords

Upwelling, GIS Database, Remote Sensing, Grid Analysis, Wind Data, Sea Surface Temperature

1 INTRODUCTION

Upwelling areas are important because they supply 50% of the available seafood. The reason is that sub-surface nutrient reach water is added to the surface waters and stimulates development of phytoplankton blooms which in turn provide the food supply for the zooplanktonic, nektonic and benthic components of the ecosystem.

Upwelling is caused by a divergence of the surface flow field that can be initiated by the interaction of the flow with the wind, bottom topography or internal waves. When wind blows over water, the surface water does not move directly in front of the wind but about 90° towards the right of the wind's direction (North Hemisphere) in a process called Ekman transport as a result of the Coriolis effect. Where winds cause the surface water to move towards a coastline, the surface water will try to move downward to create a downwelling current. Where winds cause the surface water to move away from a coastline, deeper water will move up to the sea surface, creating an upwelling current (e.g. Tomczak and Godfrey, 1994). In the open ocean, due to the absence of the shoreline, more complicated wind patterns are needed to produce upwelling. Typically, cyclonic wind stress along with suitable bottom topography can cause divergence of the surface water and uplift of the thermocline (Ekman pumping).

In this paper, two upwelling areas in the Greek Seas are studied (Fig. 1). The first area is a coastal upwelling area in the North Aegean Sea and the second area is the open-sea cyclonic upwelling region of West Cretan Sea Cyclone (e.g. Poulos et al, 1997).

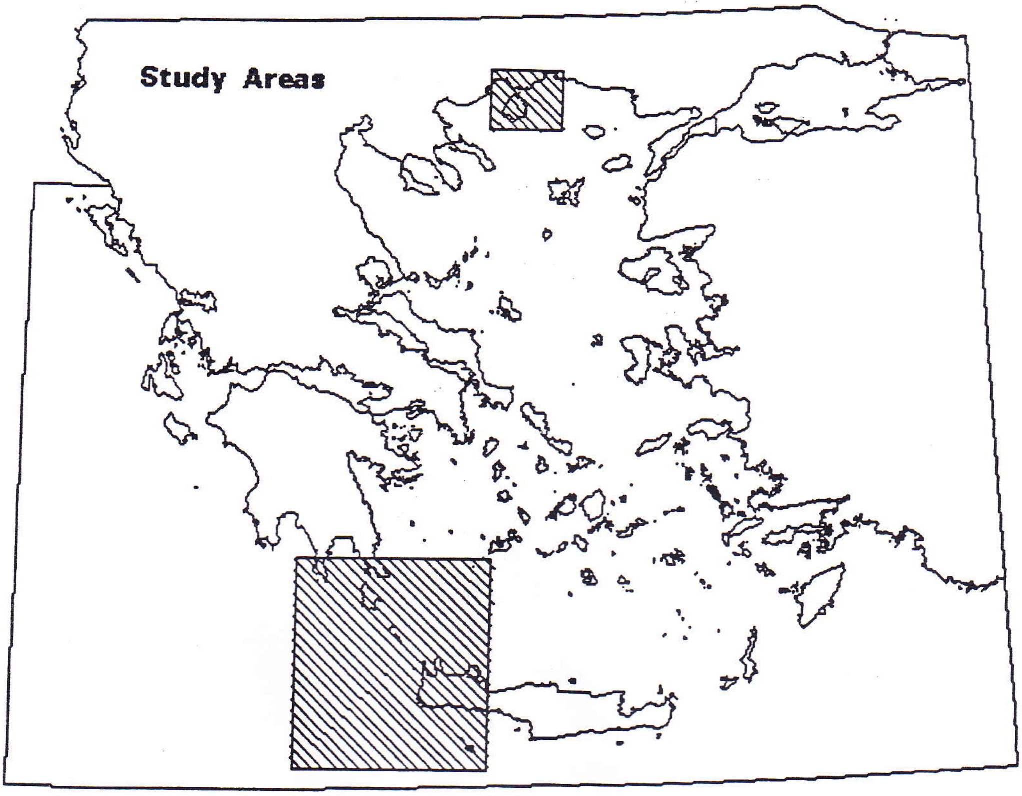

Fig. 1. The two Greek sea-areas that are under study for upwelling events. The smaller area (top – North Aegean Sea) is characterised by coastal upwellings while the larger area (bottom – West Cretan Sea) is characterised by dynamic uplifts of cold bottom water.

2 DATA AND METHODOLOGY

Measured wind data (MWD) for the North Aegean Sea was acquired from the Greek National Meteorological Service while remotely-sensed wind data (RSWD) was acquired by TOPEX-Poseidon (T-P) satellite. MWD are on-coast station measurements of wind direction (degrees from North, N=0) and force (knots) and are inserted to a workstation ARC/INFO GIS (A/I) as point information using AML (Arc Macro Language). The A/I wind point coverage is overlaid to the sea surface temperature (SST) data. RSWD are T-P wind stress images from NASA Jet Propulsion Laboratory, USA (JPL) and are inserted to A/I as grids (JPL, 1999). SST were acquired by the Deutsches Zentrum fur Luft_ und Raumfahrt, Germany (DLR) and are inserted to A/I as grids (DLR, 1999). All data cover the Greek Seas, the 1993-97 period, and they are in weekly resolution (Valavanis et al., 1998).

The SST and WD GIS database, a developed user-interface, and the routines for data integration consist the Upwelling Identification and Measurement System (UPWELL). UPWELL works in three stages :

a) SST grids with cold patches of surface water are visually identified

b) WD for these grids are integrated with cold patches of SST and selected cold SST patches are characterised as upwellings according to the upwelling theory.

c) Integration measurements and gravity center tracking are calculated.

Specifically, the selected SST grids that contain cold patches of water are treated in the following way: Each grid is automatically classified by vector polygons based on a 2°C classification table. The user selects the polygons that describe the cold patches of water and the surrounding area and saves the selected grid values in a new grid. Then, the mean SST and the cold patch gravity center (lowest cell value) are calculated. The patch area is calculated from the vector polygons. Then, a validation by WD is performed. WD are overlaid on the selected set of SST grids and the gravity center location is compared to wind direction. From this comparison, a sub-set of cold SST patches are characterised as upwellings because their location in relation to the coastline and wind direction meets the upwelling theory.

The above procedures are performed by a user via UPWELL's user-interface. The interface is based on ARC, GRID, and TABLES A/I modules and consists of a main menu that calls a hierarchy of additional menus and AMLs. The user saves all upwelling measurements in TABLES-INFO files as upwelling index reports.

3 Results and Discussion

UPWELL user-interface is presented in Figure 2. The interface features several analytical tools: Users specify a year to study, they run a weekly SST animation for that year, and they select the grids of interest. Then, further analysis is performed with measuring the upwelling area and location. Mean temperatures inside and outside the upwelling spot are calculated. Wind data integration is performed by overlaying wind measurements on each upwelling location, thus, checking for compatibility between location and wind direction (based on upwelling theory).

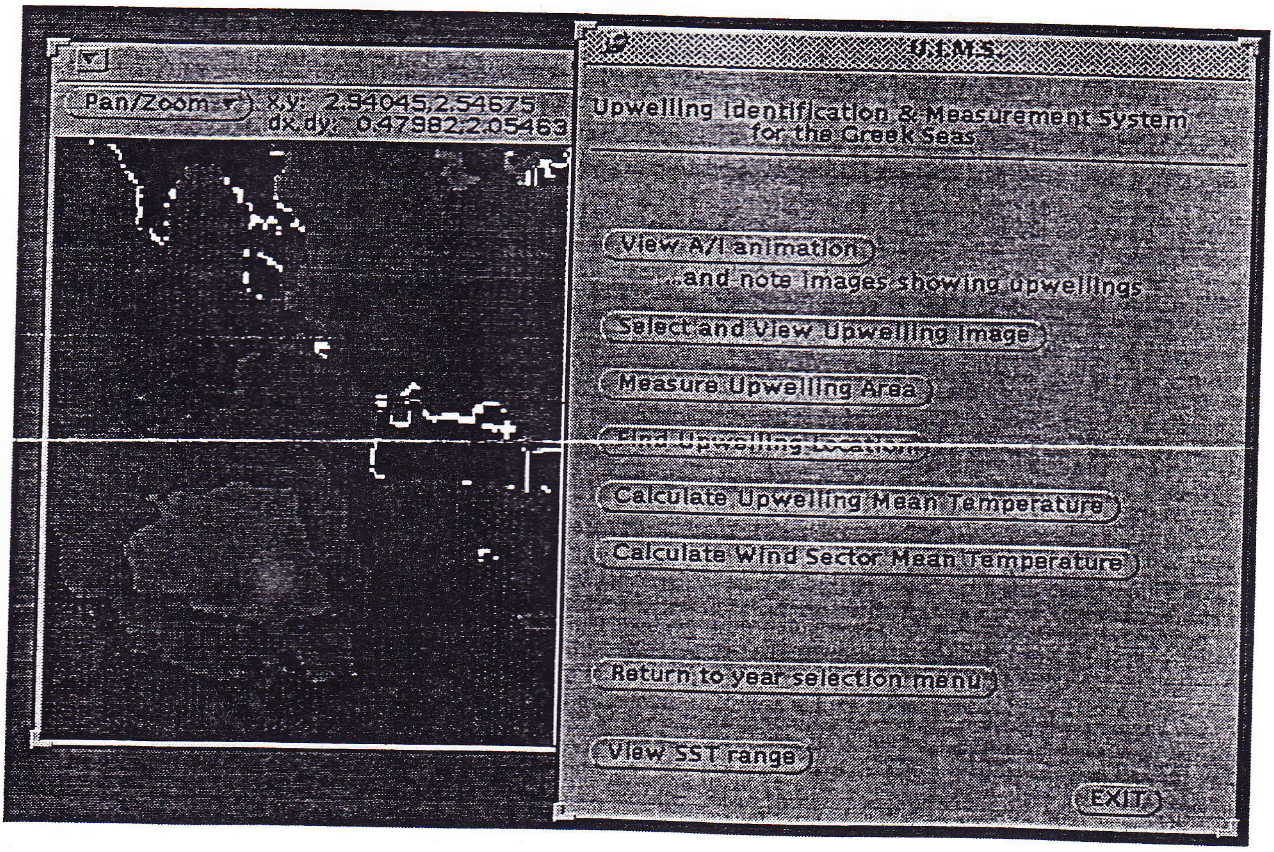

Fig. 2. The analysis menu of UPWELL. An upwelling event in West Cretan Sea is shown (image colors show various SST with 2°C difference).

Upwelling gravity centers are presented in Figures 3 and 4. In the case of North Aegean Sea (coastal upwelling) the majority of winds are of NW and NE direction with forces from 5-20 knots. The bathymetry of the area facilitates the vertical mixing of water masses because it creates a plateau going smoothly from 0-50m depth. In the case of West Cretan Sea (open sea upwellings) the general pattern is a vertical and upward movement of cold bottom water to the surface, which then drifts following the prevailing cyclonic surface currents. The bathymetry of the area is compatible with presence of cyclonic gyres and facilitates the upward movement of water masses because it is funnel-shaped ranging in depth from approximately 3000m to surface.

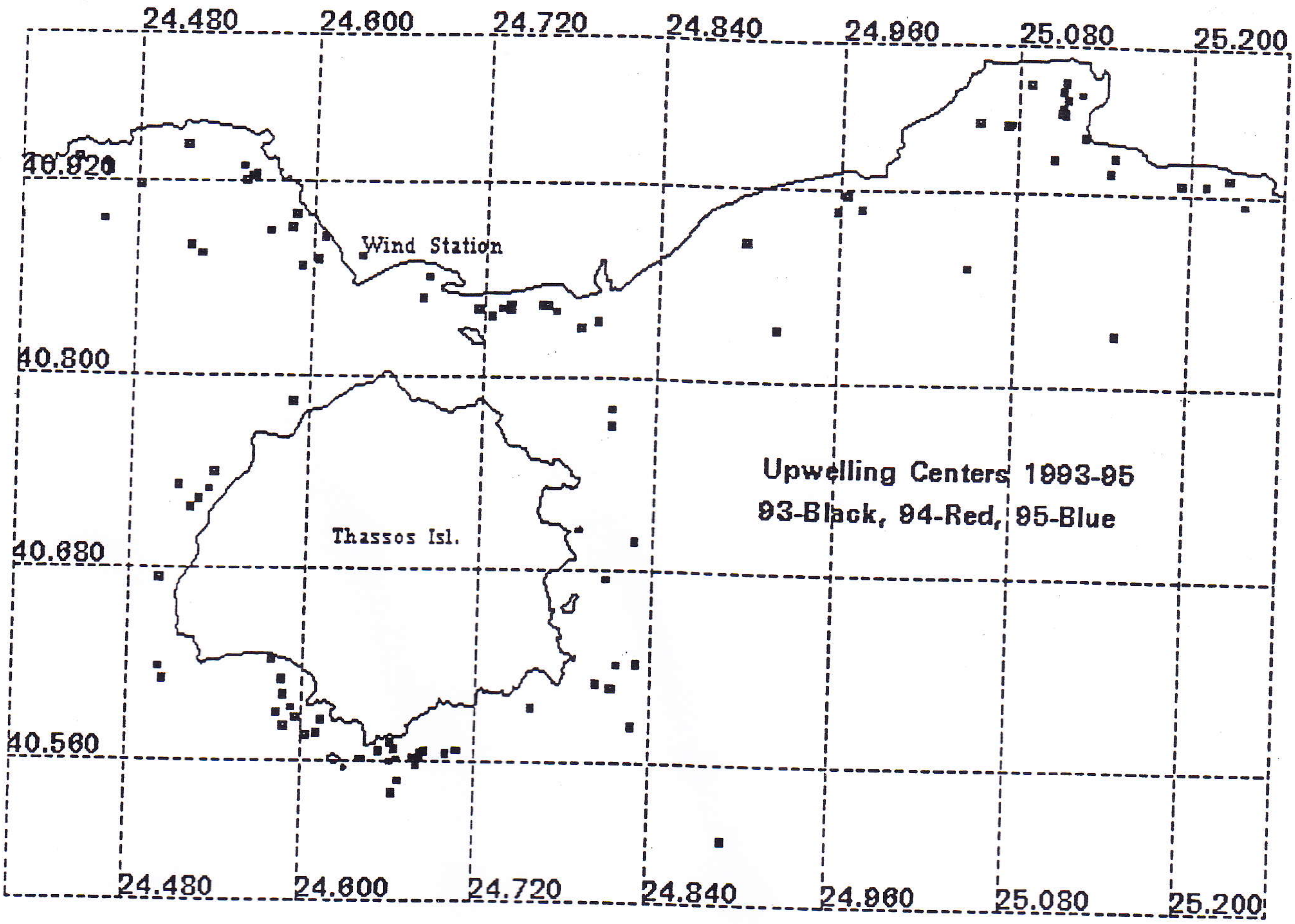

Fig. 3. Coastal upwelling gravity centers for North Aegean Sea for the period 1993-95. The wind station is also shown.

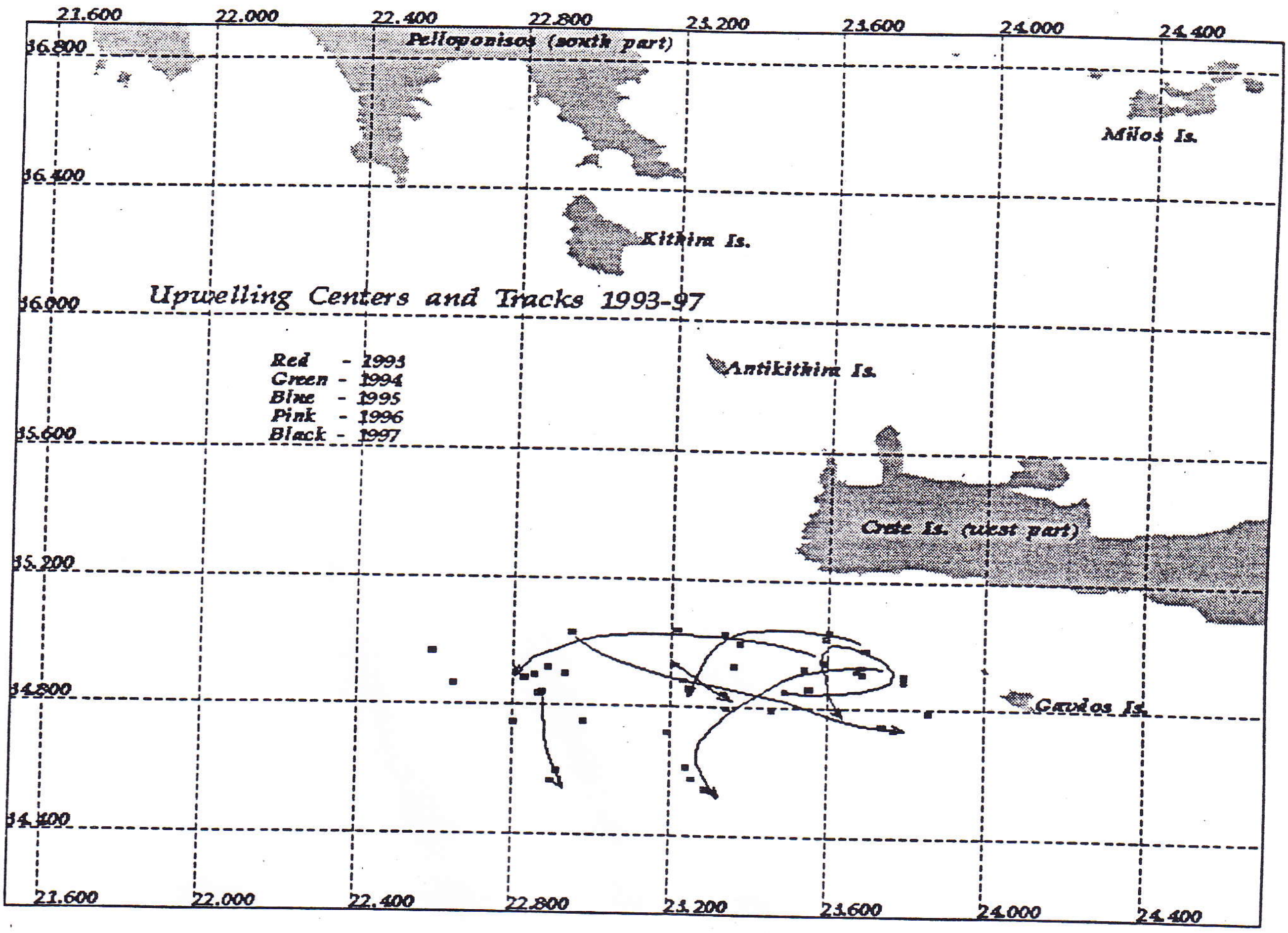

Fig. 4. Open-sea upwelling gravity centers for West Cretan Sea for the period 1993-97. Center tracking is also shown.

Coastal upwelling measurements are presented in Table 1. For most cases that involve wind forces greater than 10 knots, upwelling location and wind direction are compatible with theory. The remaining cases are included in the results and are characterised by a possibility of aliasing due to cold freshwater outflow in the area and the presence of the colder Black Sea waters. The duration of these events are of short-term (average 1 week) and are not characterised by a well-defined seasonality.

TABLE 1. Upwelling index for the North Aegean Sea for the period 1993-95. The date, location (decimal degrees), weekly average of wind force (Knots) for all four-wind directions, upwelling area (square kilometers), and the temperature difference inside from outside the upwelling patch (°C) are noted.

'MN/WK/YR'	LON (dd)	LAT (dd)	N (knots)	S (knots)	E (knots)	W (knots)	AREA (Km²)	DTEMP (°C)
'mar193'	24.919	40.832	7.59	1.10	2.46	9.57	53	1.38
'mar293'	24.516	40.880	9.57	0.00	1.27	5.46	204	1.13
'mar293'	25.047	40.873	9.57	0.00	1.27	5.46	693	1.00
'apr393'	24.607	40.887	9.02	1.31	6.38	2.24	58	0.50
'apr493'	24.662	40.540	4.74	2.01	4.40	3.82	15	1.00
'may493'	24.501	40.618	10.08	0.00	4.22	3.30	15	1.38
'jun193'	25.149	40.832	4.84	2.55	7.03	2.58	33	3.25
'jun293'	24.829	40.622	6.68	1.75	4.96	1.47	15	2.13
'jun393'	24.666	40.548	6.03	2.47	1.15	6.31	43	0.75
'jun493'	24.724	40.839	4.96	2.15	1.49	6.38	51	1.25
'jun493'	24.808	40.781	4.96	2.15	1.49	6.38	20	1.25
'jun593'	24.681	40.565	0.00	0.00	0.00	0.00	61	1.38
'jul193'	24.661	40.572	9.61	0.73	2.08	4.04	15	2.13
'jul293'	24.707	40.567	5.25	0.39	6.91	0.00	33	0.50
'jul393'	24.700	40.565	4.18	4.66	7.46	2.61	76	1.00
'sep293'	24.665	40.561	6.22	0.60	7.77	0.83	23	1.25
'oct193'	24.663	40.567	3.91	1.45	1.59	8.46	12	1.13
'oct193'	25.109	40.971	3.91	1.45	1.59	8.46	17	1.50
'oct293'	24.652	40.566	3.89	1.45	4.18	0.88	30	1.75
'oct293'	24.438	40.934	3.89	1.45	4.18	0.88	7	2.13
'oct293'	24.680	40.862	3.89	1.45	4.18	0.88	23	2.13
'oct393'	24.890	40.513	5.14	1.08	2.10	6.55	48	2.63
'nov193'	24.524	40.876	3.61	1.13	0.00	10.03	250	1.63
'nov293'	24.511	40.732	2.63	2.53	1.00	7.38	41	1.50
'nov393'	25.110	40.973	0.00	4.60	0.00	18.39	104	1.00
'dec193'	24.826	40.583	0.40	4.05	0.00	18.87	15	5.75
'dec293'	25.126	40.955	0.35	3.20	4.71	6.38	56	1.63
'dec393'	24.578	40.623	0.44	6.44	5.57	4.18	53	1.50
'dec493'	24.551	40.930	3.29	5.23	6.32	3.68	43	1.88
'dec493'	24.585	40.610	3.29	5.23	6.32	3.68	23	1.75
'dec493'	25.105	40.942	3.29	5.23	6.32	3.68	58	1.63
'dec393'	24.587	40.900	0.44	6.44	5.57	4.18	71	1.13
'dec293'	24.737	40.846	0.35	3.20	4.71	6.38	71	1.75
'oct293'	25.147	40.943	3.89	1.45	4.18	0.88	20	2.00
'dec393'	25.226	40.930	0.44	6.44	5.57	4.18	79	1.50
'dec293'	24.612	40.586	0.35	3.20	4.71	6.38	28	1.88
'jul493'	24.641	40.561	6.45	0.00	1.93	10.40	87	1.75
'jan294'	24.583	40.592	3.95	4.18	1.48	10.78	110	1.00
'jan294'	24.592	40.871	3.95	4.18	1.48	10.78	28	2.00
'jan594'	24.737	40.843	3.51	4.05	6.78	9.67	10	1.13

TABLE 1. (continued)								
'MN/WK/YR'	LON (dd)	LAT (dd)	N (knots)	S (knots)	E (knots)	W (knots)	AREA (Km²)	DTEMP (°C)
'jan594'	25.123	40.984	3.51	4.05	6.78	9.67	7	2.00
'mar394'	24.559	40.926	7.38	2.14	6.37	3.40	71	0.88
'apr294'	24.661	40.562	5.62	2.90	0.32	12.97	86	1.13
'apr294'	24.459	40.928	5.62	2.90	0.32	12.97	48	0.88
'may394'	24.533	40.732	4.44	1.71	8.11	0.00	12	1.25
'may494'	24.458	40.933	9.07	0.44	4.00	5.37	40	1.25
'may494'	24.759	40.846	9.07	0.44	4.00	5.37	51	1.50
'may494'	24.816	40.623	9.07	0.44	4.00	5.37	61	1.63
'jun194'	24.801	40.611	5.30	1.01	8.09	4.63	48	1.38
'jun194'	24.513	40.945	5.30	1.01	8.09	4.63	7	2.50
'jun394'	24.603	40.874	6.64	2.20	4.44	6.11	33	1.13
'jun394'	24.595	40.589	6.64	2.20	4.44	6.11	33	1.13
'jun494'	24.758	40.596	4.43	5.07	5.78	3.91	23	1.63
'jul194'	24.676	40.565	5.01	6.24	4.98	3.80	92	2.50
'jul194'	24.768	40.843	5.01	6.24	4.98	3.80	79	1.25
'jul194'	25.210	40.929	5.01	6.24	4.98	3.80	46	1.75
'jul294'	24.559	40.926	3.25	4.86	2.68	10.79	28	2.25
'jul294'	24.592	40.595	3.25	4.86	2.68	10.79	74	0.50
'jul294'	25.112	40.992	3.25	4.86	2.68	10.79	53	2.25
'jul394'	24.399	40.900	2.43	7.27	4.21	13.93	58	1.50
'jul394'	24.812	40.608	2.43	7.27	4.21	13.93	194	0.50
'jul394'	25.053	40.966	2.43	7.27	4.21	13.93	66	2.38
'aug194'	24.536	40.742	4.62	4.37	3.26	4.07	25	1.75
'sep194'	24.500	40.676	8.81	0.50	3.80	5.84	5	1.63
'sep494'	24.974	40.910	5.84	2.14	3.32	1.73	25	1.00
'sep494'	24.807	40.676	5.84	2.14	3.32	1.73	7	1.13
'sep494'	24.366	40.892	5.84	2.14	3.32	1.73	5	1.38
'oct194'	25.113	40.980	4.40	3.40	2.64	8.80	43	3.25
'oct194'	24.964	40.918	4.40	3.40	2.64	8.80	7	4.00
'oct294'	24.504	40.613	5.68	0.00	0.00	15.77	38	0.75
'nov394'	25.237	40.917	0.55	2.94	0.00	16.35	15	1.50
'dec194'	24.786	40.833	1.38	5.50	2.00	16.15	30	2.25
'dec294'	25.111	40.971	1.82	0.88	2.53	9.51	74	1.25
'dec394'	24.958	40.909	1.72	3.85	0.00	9.55	63	1.13
'dec494'	25.088	40.990	0.42	2.34	0.00	13.75	7	3.25
'jan495'	24.584	40.892	0.00	10.13	19.18	2.68	161	2.75
'jan495'	24.798	40.836	0.00	10.13	19.18	2.68	89	2.63
'jan495'	25.074	40.963	0.00	10.13	19.18	2.68	117	2.13
'jan495'	25.306	40.928	0.00	10.13	19.18	2.68	86	2.00
'jan595'	24.457	40.897	3.34	1.57	2.41	12.32	309	1.50

TABLE 1. (continued)								
'MN/WK/YR'	LON (dd)	LAT (dd)	N (knots)	S (knots)	E (knots)	W (knots)	AREA (Km²)	DTEMP (°C)
'jan595'	25.073	40.962	3.34	1.57	2.41	12.32	173	2.13
'jan595'	24.679	40.558	3.34	1.57	2.41	12.32	71	2.13
'feb195'	24.762	40.845	0.83	2.89	3.61	6.70	43	3.13
'feb395'	24.676	40.849	4.34	2.59	2.95	5.92	28	0.88
'mar295'	24.556	40.924	3.15	1.54	3.75	13.49	25	1.50
'apr495'	24.731	40.843	5.55	4.63	2.49	14.95	15	1.25
'may395'	24.525	40.723	7.09	1.17	7.43	3.50	74	1.88
'may495'	25.111	40.971	6.45	0.00	9.54	2.15	23	2.25
'may495'	24.588	40.784	6.45	0.00	9.54	2.15	23	2.50
'may595'	24.587	40.601	6.61	0.37	9.03	3.40	15	1.50
'may595'	24.897	40.886	6.61	0.37	9.03	3.40	15	1.75
'jun195'	24.602	40.576	5.42	0.00	8.53	0.39	56	0.88
'jun395'	24.520	40.718	6.35	3.97	11.29	0.00	17	5.00
'jun495'	24.684	40.566	2.75	3.95	2.57	10.70	63	1.13
'jul295'	25.111	40.984	2.47	0.88	5.07	8.16	7	4.50
'aug495'	24.682	40.564	8.26	0.00	7.67	5.05	43	1.25
'sep195'	24.715	40.842	1.55	2.15	9.59	1.97	89	1.00
'sep395'	24.481	40.918	4.67	1.14	5.48	3.93	217	1.63
'sep395'	24.826	40.699	4.67	1.14	5.48	3.93	33	1.88
'sep495'	24.808	40.771	6.56	5.53	4.42	0.92	12	0.25
'oct295'	24.587	40.582	2.52	0.84	1.46	11.35	23	0.50
'nov195'	25.193	40.926	4.44	2.42	3.06	2.98	145	1.38
'nov295'	24.610	40.577	0.49	7.62	9.10	1.48	43	0.63
'nov295'	24.569	40.890	0.49	7.62	9.10	1.48	97	0.75
'nov295'	25.144	40.933	0.49	7.62	9.10	1.48	186	0.63
'dec195'	24.552	40.921	0.42	3.23	1.71	5.51	38	1.00
'dec195'	24.331	40.813	0.42	3.23	1.71	5.51	38	0.63

Open sea upwelling measurements are presented in Table 2. It appears that there is a seasonality in upwellings starting from late May and ending early November with peaks during early summer and mid-autumn. However, there is a possibility of masked phenomena during winter when surface waters are cold. These events are characterised as long-term events and their duration averages from 2-4 weeks (case of autumn 1995: 7 weeks).

TABLE 2. Upwelling index for the West Cretan Sea for the period 1993-97. The date, location (decimal degrees), area (square kilometers) and mean temperature difference inside from outside the upwelling patch (°C) are noted.

'MN/WK/YR'	LON (dd)	LAT (dd)	AREA (Km²)	DTEMP (°C)
'may493'	23.686	34.934	3935	1.50
'jun193'	23.794	34.907	507	2.50
'jun393'	23.675	34.919	381	3.88
'jun493'	23.541	34.927	1688	2.75
'jul193'	23.345	34.799	462	4.37
'jul293'	23.244	34.616	3454	3.25
'jul393'	23.256	34.579	1374	3.75
'aug193'	23.293	34.547	2448	4.38
'may594'	23.494	34.854	2627	2.25
'jun194'	23.796	34.890	94	2.25
'jun294'	23.595	35.021	266	1.75
'jun394'	23.626	34.799	8280	2.25
'aug594'	23.214	34.933	1760	3.50
'sep194'	23.333	34.847	3137	3.13
'may595'	23.196	34.723	8733	0.88
'jun395'	23.602	35.042	2909	2.50
'jun495'	23.696	34.987	2668	2.62
'jul195'	23.687	34.913	3477	1.75
'jul395'	23.339	35.031	1069	2.63
'jul495'	23.250	34.859	2430	4.75
'oct195'	22.872	34.844	2428	3.50
'oct295'	22.866	34.839	3469	4.25
'oct395'	22.854	34.897	5808	3.75
'oct495'	22.800	34.750	6401	2.25
'oct595'	22.979	34.753	4442	2.00
'nov195'	22.898	34.569	4447	2.13
'nov295'	22.912	34.601	1591	1.50
'jun196'	22.947	35.033	3298	1.25
'jun296'	23.232	34.886	2013	2.63
'jun396'	23.460	34.797	162	3.25
'jul196'	23.856	34.793	3766	2.50
'jul296'	23.740	34.749	8651	1.37
'jul496'	23.361	34.931	4633	1.37
'jul497'	23.592	34.947	542	0.88
'aug197'	23.551	34.864	913	1.12
'aug297'	23.376	35.004	4088	0.63
'aug397'	23.217	35.044	8593	0.12
'sep297'	22.931	34.901	2308	2.50
'sep397'	22.887	34.923	3641	1.00
'sep497'	22.593	34.970	1855	2.75
'sep597'	22.649	34.869	3021	2.25
'oct197'	22.829	34.887	5969	0.12

4 CONCLUSION

A GIS-based system (UPWELL) for the study of upwellings was presented. The associated data were remotely-sensed sea surface temperature and wind data. Two upwelling zones in the Greek Seas were studied for the period of 1993-97. UPWELL may integrate additional data, for example, fisheries production for the study of upwelling events on sea-food production or chlorophyll-a data (from CZCS or SeaWiFS imagery) for the study of primary production. In addition, wind fields from the ERS-2 and ADEOS/NSAT scatterometers can be integrated for the study of the open ocean dynamic uplift regions. A future advancement of the UPWELL-method will be the automatic classification of water masses quality using expert systems.

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