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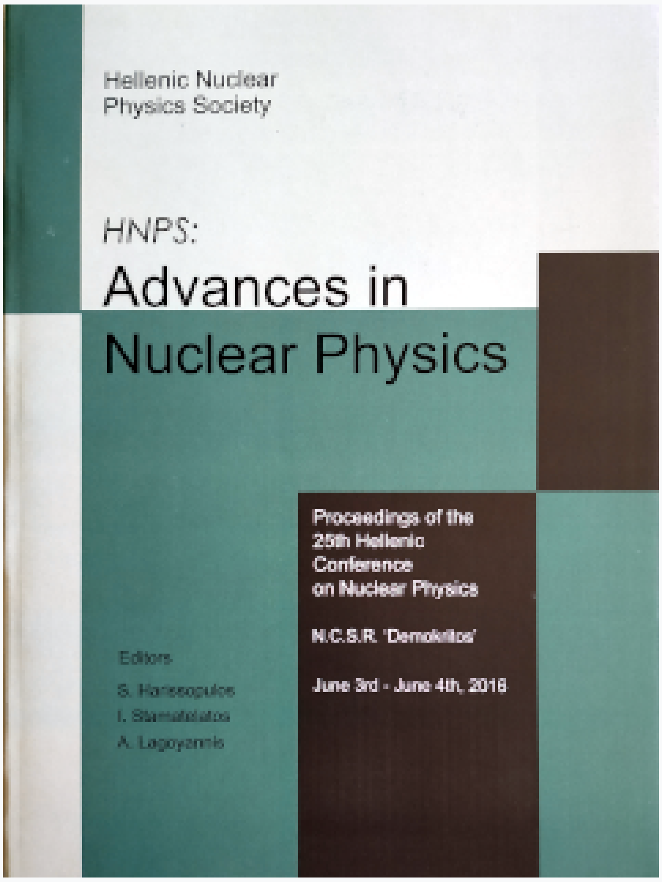

Remote radiological assessment in the marine environment: A pilot study based on Cs-137 measurements and satellite observations in the Aegean Sea

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Remote radiological assessment in the marine environment: A pilot study based on Cs-137 measurements and satellite observations in the Aegean Sea

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Abstract A program concept has been developed to utilize sea parameters like sea surface temperature (SST), ocean colour (OC) and sea surface salinity (SSS), in order to explore their potential relations with ^{137}Cs activity concentrations in sea water. These relations are expected to lead to the creation of an innovative tool based on remote sensing data and in real time ^{137}Cs measurements, for the remote radioactivity detection of the Greek marine ecosystem both for routine control and emergency recordings.

The presented results are a preliminary effort of the tool's development. Remote sensing data have been acquired from MIRAS and MODIS instruments on-board ESA-SMOS and NASA-TERRA/AQUA satellites respectively. Satellite data comprise of SST and OC measurements. The ERL's data of ^{137}Cs activity concentrations (204 measurements) in seawater have been used for the period March 2012 to February 2015. Therefore, a) map analyses in a GIS including interpolation and integration of 83 real time measurements corrected with the effective half live of 7.2 y according to the monthly data of satelites and spatial linear regression have been implemented for the Aegean Sea, b) additional temporal analyses using linear and polynomial regression have been performed for the area of Souda-Crete, for which the most frequent measurements of ^{137}Cs activity concentration in sea water have been measured in ERL.

In this study, the first derived results on the correlation between SST measurements with ^{137}Cs activity concentrations are presented, whereas the respective correlation with OC is being under invstigation. Further investigations include multivariate polynomial analyses into the Geographic Information System (GIS) platform with more extensive sampling and satellite data from new systems, whereas comparative correlations of ^{137}Cs with seawater parameters derived by conventional means will be performed.

Keywords Remote Sensing, Geographic Information Systems, Environmental Radioactivity, Sea Surface Temperature, Ocean Color

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INTRODUCTION

The capability of remote sensing satellites to monitor changes of ecological parameters in the environment is well documented. Nevertheless, radionuclide dispersion cannot be

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directly detected by the satellites. However, the levels of radionuclides in the marine environment, are associated with physical, chemical and biological parameters of the natural environment such as sea surface temperature (SST), sea surface salinity (SSS), chlorophyll-A (Chlor_a), weathering processes and pollutant charge [1,2]. For this reason NASA-TERRA/AQUA - MODIS and ESA - SMOS - MIRAS data have been acquired, processed and correlated with real time measurements of ^{137}Cs activity concentrations from the Aegean Sea in general and in particular for the area of Souda. The investigation of the potential relations,would be essential for the remote radioactivity monitoring and forecasting both for routine and emergency control.

The first findings on the spatial correlations of ^{137}Cs measurements with MODIS L3 SST in the Aegean Sea are presented in this study, whereas temporal correlations of ^{137}Cs measurements with MODIS L2 SST and MIRAS SST in Souda Bay area are also studied. Acquisitions and correlations span the period between March 2012 and February 2015.

MATERIALS AND METHODS

Study Area

This study focuses in the broader area of the Aegean Sea and the area of Souda Bay (Crete island). a) The Aegean Sea is an elongated embayment located at the north-eastern part of the Mediterranean. It is characterized by a typical Mediterranean-type of climate, which has two distinctive periods a cool and rainy one and a hot and dry one [3]. SST values vary from a minimum of 15^{o}C in February to a maximum of 26^{o}C in August [4]. Cs-137 activity concentrations in the Aegean are characterized by high values in the North Aegean and especially near the Dardanelles, where the mean concentration in 2014 is reported about 10 Bq/m^3 (Fig. 1), presenting a decrease in the Southern Aegean with a mean value of about 1 Bq/m^3 (Fig. 1) [5], b) Souda Bay, in the north-western part of the island of Crete (Southern Aegean Sea), for which the most frequent measurements of ^{137}Cs activity concentration in sea water are provided by the Environmental Radioactivity Laboratory (ERL) database.

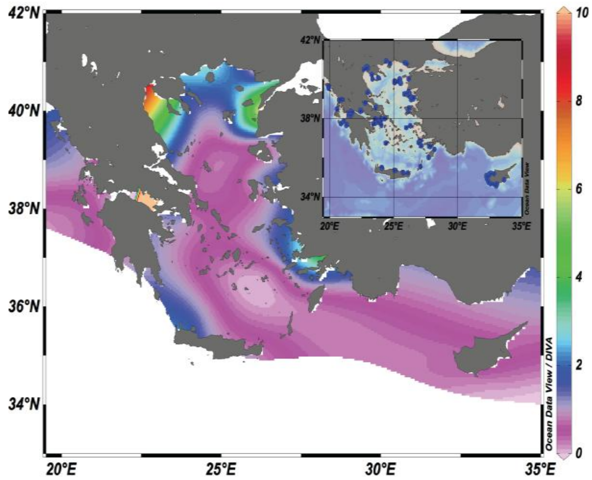

Fig. 1. ^{137}Cs activity concentrations (Bq m^{-3}) in the Aegean and Ionian Seas for 2014 corrected using the effective half-life [5].

^{137}Cs activity concentrations

Caesium is an alkali metal with only one stable isotope ^{133}Cs. Cs-137 is a long lived radionuclide with a half-life of 30.2 years and is an atomic fission product of both uranium (U-) and plutonium (Pu-) reactors. It has been released to the environment as a result of the global fallout from the nuclear weapons testing and nuclear accidents, while marine nuclear propulsion is a potential source of impact [6]. It the most important indicator of radioactive pollution in aquatic environments [7].

The activity concentrations of ^{137}Cs from the ERL's data base updated to 2015 are used in this study . In the Aegean Sea, a total of 85 sampling stations are considered. In terms of the main methodology used for the analyses: the sea water samples analyzed for ^{137}Cs using an ammonium molybdophosphate (AMP) radioanalytical preconcentration method [8]. This method is based on the ion-exchange of dissolved ^{137}Cs with microcrystalline ammonium molybdophosphate $[(NH_4)_3P(Mo_3O_{10})_4]$ which is an insoluble yellow reagent. To obtain a statistically significant result, the necessary volume of pre-concentration of seawater is 60-100 L. Subsequently, the treated samples are measured using gamma spectrometry on a Canberra system comprising of a High Purity Germanium (HPGe) Detector for 70,000 s. The 83 real time measurements used for the Aegean Sea of ^{137}Cs are corrected using the effective half-life of 7.2 years [5] to the time of the respective satellite acquisitions. Cs-137 activity concentration measurments span the period of March 2012 to February 2015. In the Souda Bay area, 121 real time measurements of ^{137}Cs activity concentrations are used for the same daily passes of the satellites for this period.

Satellite Measurements

MODIS (MODerate resolution Imaging Spectroradiometer) instrument is onboard NASA's TERRA and AQUA satellites (part of NASA's Earth Science program). MODIS has 36 spectral bands spanning 0.4 μm to 14.4 mm and its spatial resolution varies as 250 m, 500 m and 1000 m, depending on the spectral band [9]. It has a worldwide coverage every 1-2 days. In this study, L2 (daily measurements, for Souda Bay, 1km spatial resolution) and L3 (monthly measurements, for Aegean Sea, 4km spatial resolution) MODIS ocean products were used to extract information on SST and ocean colour parameters. In particular, each SST product comprises short-wave and long-wave SST measurements, where the long-wave SST algorithm produces SSTmorning and SSTnight (Fig.2). The short-wave SST at μm (SST4night) (Fig.2) retrieval is complementary to the 11μm measurement SSTnight. The MODIS ocean colour products comprise of derived chlorophyll-A (Chlor_a), particulate inorganic carbon (PIC), particulate organic carbon (POC) concentrations and instantaneous and daily photosynthetically available radiation (iPAR, PAR). MODIS images are retrieved for the same time period, both for Aegean Sea and Souda Bay, spanning March 2012 to February 2015.

SMOS (Soil Moisture and Ocean Salinity) satellite, part of ESA's Earth Explorer missions, was launched on 02/11/2009. The MIRAS (Microwave Imaging Radiometer using

Aperture Synthesis) instrument on board SMOS records the microwave emissions from the Earth's surface in the L band (frequency 1.4 GHz, wavelength 21 cm), with a spatial resolution of 50 km [10]. Due to Radio Frequency Interferences (RFI) only 39 points are resolved within the Aegean Sea. In this study, MIRAS L2 SST images (Fig.2) of both ascending and descending passes, are considered only for Souda Bay Area and retrieved for the time period of March 2012 to February 2015.

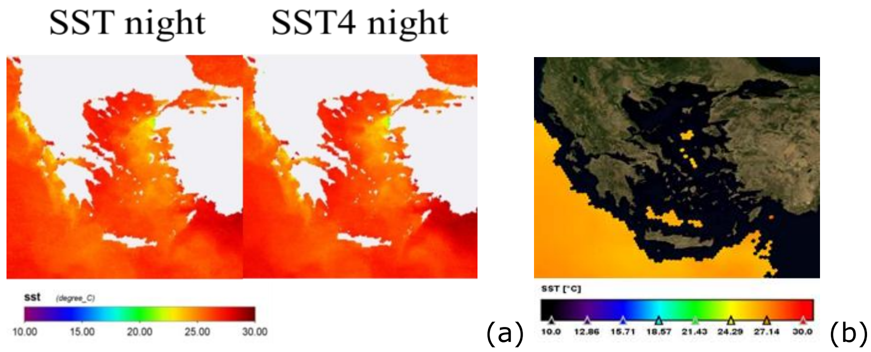

Fig. 2. Example of the retrieved MODIS product maps: MODIS AQUA L3 SSTnight, SST4night of August 2014 (a) and example of the retrieved MIRAS L2 SSTAscending image for 01/08/2014 (b)

Analyses

Spatiotemporal analyses for the Aegean Sea, into the GIS (Geographic Information System) consists of creating a spatial database, interpolation and integration of ^{137}Cs activity concentration data using the Inverse Distance Weighted (IDW) function and performing geographically weighted regression (GWR) in order to observe the relations between ^{137}Cs and satellite retrieved parameters. IDW uses a method of interpolation that estimates cell values by averaging the values of sample data points in the neighborhood of each cell [11]. GWR is a local form of linear regression that constructs a separate equation for every feature in the dataset [12]. However, when using the GWR method, the shape and the extent of the bandwidth are dependent on the user input and in particular the spatial distribution of data. The results of this process correspond to local r^2 maps depicting the relations between satellite and ^{137}Cs activity measurements.

Statistical temporal analyses for Souda bay, are performed using MODIS, MIRAS and ^{137}Cs activity data. The analyses consisted of the application of linear and second degree polynomial regressions. The results of this process correspond to calculated r^2 values for each correlation.

RESULTS AND DISCUSSION

The Aegean Sea results correspond to local r^2 value maps between satellite data and ^{137}Cs measurements for a period spanning March 2012 to February 2015. Fig. 3 shows the two examples of the produced r^2 maps for ^{137}Cs activity concentrations and MODIS SST4night for March 2014 and February 2015. Correlations show that the highest r^2 values

(>0.4) are observed mainly in the South Aegean and North Aegean whereas the Central Aegean shows the lowest ones; this phenomenon is observed probably due to the distribution of the sampling stations for ^{137}Cs (there are no stations in the central Aegean Sea), which affects the output of the GWR. Furthermore, ^{137}Cs measurements correlate best to MODIS SST4night (4 μm) and less to SSTnight (11 μm) and SSTmorning(11 μm) . Local r^2 values are variable in time, presenting seasonal patterns with higher r^2 values during winter and lower r^2 values during summer. It must be noted, that the spatial linear correlations with the OC (Ocean Colour parameters) seem to show no statistical significance at the moment, and are currently under investigation.

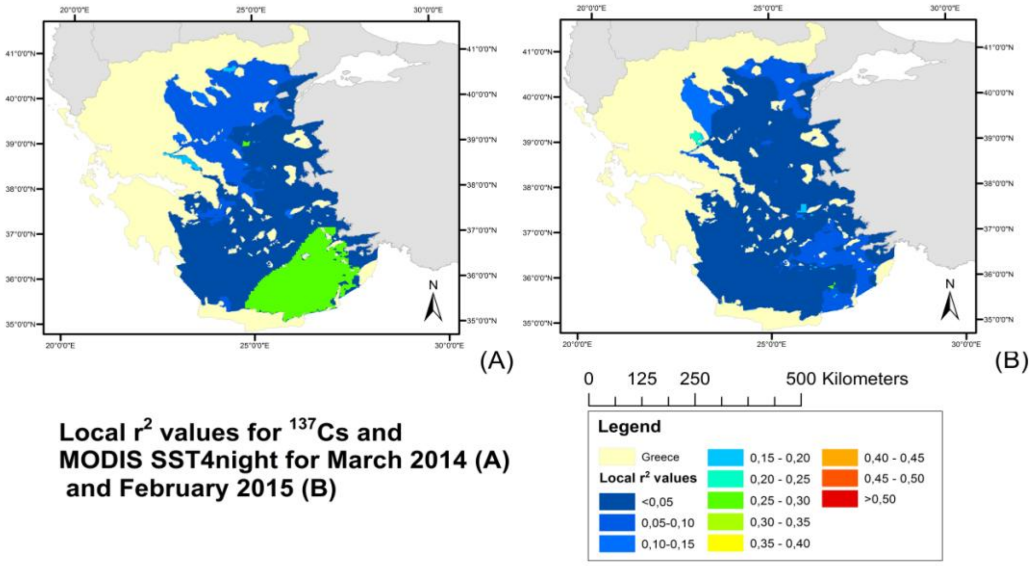

Fig. 3. Local r^2 map for ^{137}Cs measurements and MODIS SST (4μm) night pass measurements for March 2014 and February 2015.

The Souda Bay results correspond to the calculated r^2 for linear and second degree polynomial regressions between ^{137}Cs activity concentrations and satellite measurements. In Fig. 4, indicative scatterplots of the second degree polynomial results for MODIS SSTnight, SST4night and MIRAS SST Ascending are presented for the time period spanning March 2012 to February 2015. Statistical analysis reveals that there is a significant difference between the application of linear and polynomial regression. Linear regression results show similarities with the corresponding ones from the Aegean Sea map analysis; the relatively highest r^2 values are observed using MODIS SST4 night (r^2 = 0.34). On the other hand, the application of a second degree polynomial regression produces much better r^2 results; the highest r^2 (r^2 = 0.64) is observed when using the MODIS SST4 night parameter. MODIS SSTnight also displays a good correlation (r^2 = 0.47). MIRAS SST (both ascending and descending passes) presents r^2 values lower than 0.3; this is probably due to the fact that the MIRAS pixel centers are located about 50km far from the Souda Bay sampling station. The correlation with the ocean colour parameters is currently under investigation.

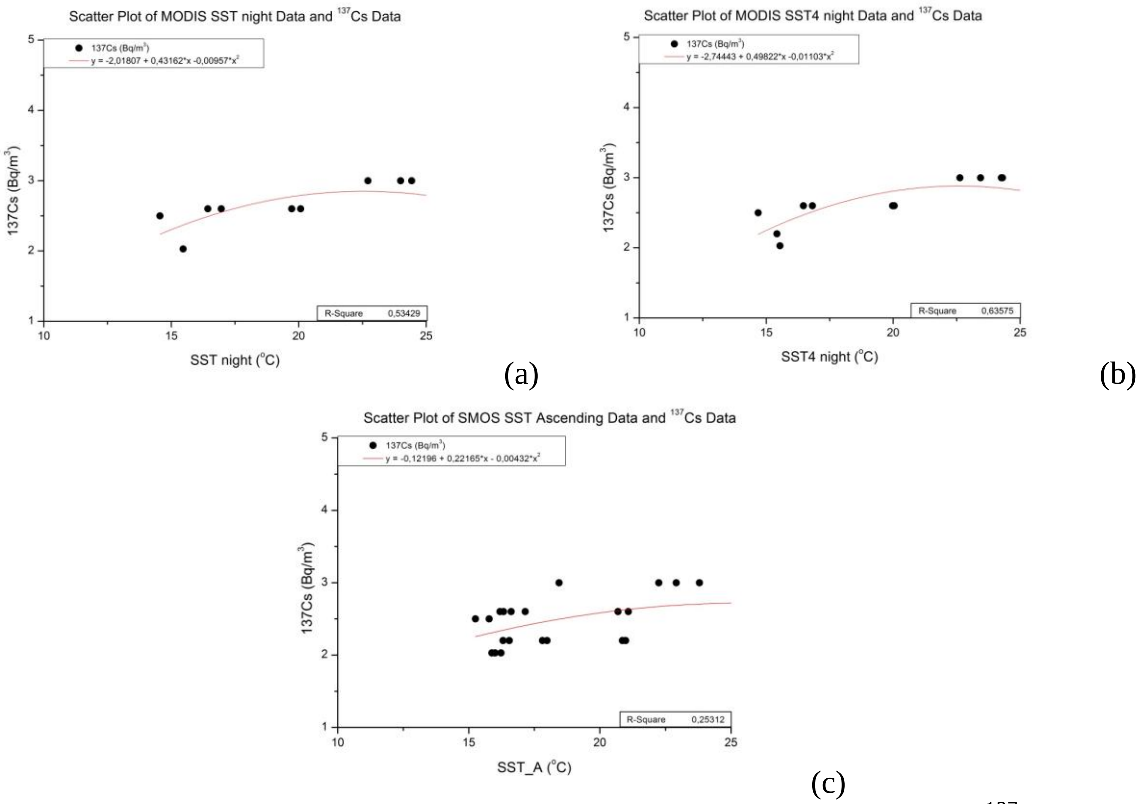

Fig. 4. Graphs showing the second degree polynomial relation between ^{137}Cs concentrations and SST measurements: MODIS SSTnight pass (a), SST4night (b), SMOS SST Ascending (c).

CONCLUSIONS

Spatiotemporal analyses in a GIS for the Aegean Sea and statistical temporal analyses for Souda Bay have been implemented for a 3 year period (2012-2015). The linear regression analyses for both map and statistical analysis seems to be less efficient to describe the potential association with ^{137}Cs activity concentrations. On the other hand, polynomial regressions such as the second degree polynomial seem to describe better the relations between satellite derived sea parameters and ^{137}Cs activity concentrations. For this purpose, more statistical and other non-linear (i.e. higher degree polynomial, logarithmic, exponential etc) regression analysis investigations will be conducted.

This is an ongoing study and future work will include a more systematic and conjoined with simultaneous satellite passes, sea water sampling from the Aegean Sea. Furthemore, laboratory analyses and retrievals of ocean parameters from other satellite systems, for the creation of an integrated GIS system is expected to illustrate a reliable remote radiological image.

Ackowledgements

MODIS data were retrieved from NASA Goddard Space Flight Center, Ocean Biology Distributed Active Archive Center that provided level 2 and level 3 Ocean Data products http://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=am , http://oceancolor.gsfc.nasa.gov/cgi/l3

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