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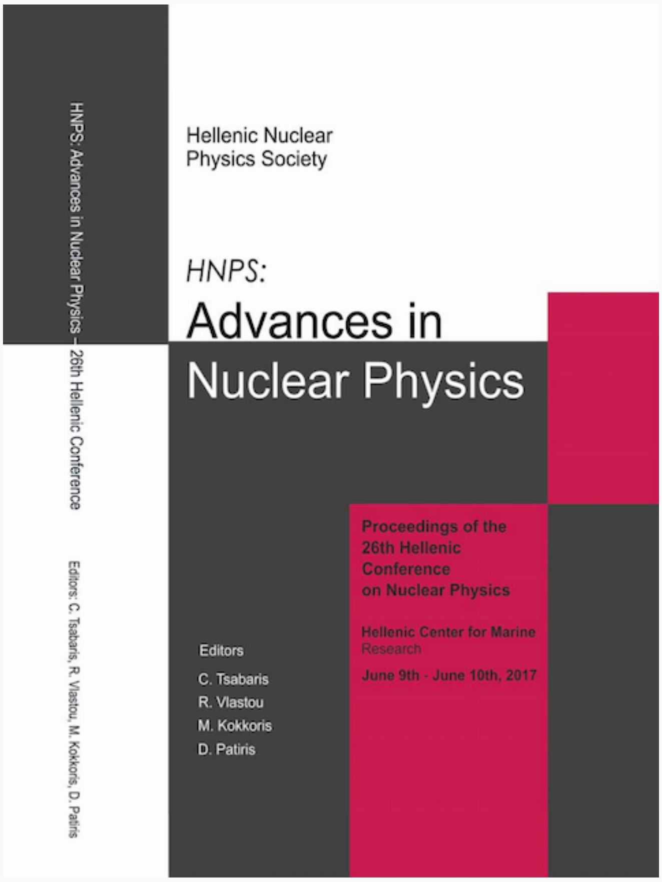

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Correlation of ^{137}Cs activity concentrations with MODIS Ocean Colour Data in the Aegean Sea

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Abstract A program has been developed to explore the relations of ^{137}Cs activity concentrations with Ocean Colour (OC) parameters in the marine environment, as a first step for the development of an innovative tool for the remote radioactivity detection of the marine ecosystem. The presented results show the relations between the ^{137}Cs activity concentrations and OC parameters from MODIS satellite data. OC measurements have been retrieved from NASA's MODIS Ocean products from both AQUA and TERRA satellites and include Chlorophyll-A concentration (Chlor_A), Particulate Inorganic Carbon concentration (PIC), Particulate Organic Carbon concentration (POC), Instantaneous and Daily Photosynthetically Available Radiation (iPAR and PAR). The ^{137}Cs measurements have been derived from the database of Environmental Radioactivity Laboratory, whereas updated measurements have been carried out by analyzing seawater samples from South Aegean Sea (Souda bay), using a radioanalytical pre-concentration method (AMP method and ^{134}Cs additive as carrier and yield tracer) and gamma spectrometry. In the Aegean Sea, eighty five ^{137}Cs sampling stations have been considered for the time period spanning March 2012 to February 2015. Simultaneous satellite OC measurements have been acquired for the same time span. The linear geographically weighted regression (GWR) analysis results show a good correlation of Chlor_A with ^{137}Cs, with the highest observed r^2 of 0.59. Correlations with PIC and POC are very good, with the highest observed r^2 of 0.88 and 0.67 respectively. Moreover, correlations with iPAR and PAR seem to be good, with the highest observed r^2 of 0.40 and 0.77 respectively. Additionally, forty five ^{137}Cs activity concentration measurements and satellite OC measurements from Souda Bay (Crete) in the South Aegean have been used spanning March 2011 to February 2015. The second degree polynomial regression analysis results show an evident correlation between PIC and PAR with ^{137}Cs activity concentrations, with the observed r^2 of 0.56 and 0.38 respectively; when stricter measures were applied (uncertainties inserted) the r^2 values were significantly lower. More accurate measurements of ^{137}Cs (real time) and satellite observations (simultaneous to field sampling) are expected to document better the derived relations.

Keywords Cs-137 activity concentrations, Satellite observations, Ocean Color

INTRODUCTION

It is commonly known that satellite systems have a wide range of applications with the

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most important one being environmental monitoring in terms of pollution. New advanced remote sensing technologies have been developed for the detection of marine pollution like oil spills. However, the dispersion of radionuclides cannot be directly detected and monitored by the satellite systems. Nevertheless, the levels of radionuclides in the marine environment, especially of the soluble ones like ^{137}Cs, are associated with various physical, chemical and biological parameters like sea surface temperature (SST), salinity, chlorophyll-A, weathering processes and pollutant charge[1,2]. For this reason a program has been developed to explore the relations of ^{137}Cs activity concentration measurements with NASA's MODIS (MODerate resolution Imaging Spectroradiometer) instrument (on board TERRA and AQUA satellites) Ocean Color (OC) parameters. The OC parameters are Chlorophyll-A (Chlor_a) concentration, Particulate Inorganic Carbon (PIC) concentration, Particulate Organic Carbon (POC) concentration and Instantaneous and daily Photosynthetically Available Radiation (iPAR, PAR).

In this study the first findings on the spatiotemporal correlations of ^{137}Cs activity concentration measurements with MODIS L3 OC data (Chlor_a, PIC, POC, iPAR, PAR) for the area of Aegean Sea and the temporal correlations of ^{137}Cs activity concentration measurements with MODIS L2 OC data (Chlor_a, PIC, POC, iPAR, PAR) for the area of Souda Bay (Crete) are presented for the time period between March 2012 and February 2015.

MATERIALS AND METHODS

Study Area

The present study focuses in the area of Aegean Sea and the area of Souda Bay (Crete Island, Southern Aegean). The Aegean Sea is an elongated embayment located at the north-eastern part of the Mediterranean. Chlorophyll-A concentration values vary from 0.03 mg/m3 to 0.70 mg/m3 with the higher values present in North Aegean due to incoming water from Black Sea [3]. 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, presenting a decrease in the Southern Aegean with a mean value of about 1 Bq/m^3 [4].

Souda Bay is located in the north-western part of the island of Crete. It is chosen due to the most frequent ^{137}Cs activity concentration measurements provided by the Environmental Radioactivity Laboratory (ERL, NCSR"Demokritos") database.

^{137}Cs activity concentrations

Cs-137 is a long lived radionuclide with a half-life of 30.2 years and it 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 [5]. It is considered the most important indicator of radioactive pollution in aquatic environments [6].

The ^{137}Cs activity concentrations have been mostly acquired from the ERL's database and updated to the time period from March 2011 to February 2015 for the present study. In the Aegean Sea area, a total of eighty five sampling stations are considered. The obtained sea water samples are analyzed for ^{137}Cs using an ammonium molybdophosphate (AMP) radioanalytical pre-concentration method [7]. This method is based on the ion-exchange of the dissolved ^{137}Cs with the microcrystalline ammonium molybdophosphate $[(NH_4)_3P(Mo_3O_{10})_4]$ which is an insoluble yellow reagent. In addition to the AMP compound 0.5 Bq of ^{134}Cs per litre of sample is addes as a carrier and yield tracer. To obtain a statistically significant result, the necessary volume of pre-concentration of seawater is needed to be 60-100 L. Afterwards, the AMP 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 [4] to the time of the respective satellite acquisitions. Cs-137 activity concentration measurments span the period of March 2012 to February 2015. For the Souda Bay area, 121 real time measurements of ^{137}Cs activity concentrations are used during the daily passes of the satellites for this period.

Satellite Measurements

The satellite measurements used in this study have been retrieved by the MODIS (MODerate resolution Imaging Spectroradiometer) instrument which 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 [8]. It has a worldwide coverage every 1-2 days. For this study, L2 (daily measurements, for Souda Bay, 1km spatial resolution) and L3 (monthly measurements, for Aegean Sea, 4km spatial resolution) MODIS ocean products are used to extract information on Ocean Colour (OC) parameters. In particular, the MODIS OC parameters comprise of derived chlorophyll-A (Chlor_a) concentration, particulate inorganic carbon (PIC) and particulate organic carbon (POC) concentrations and instantaneous and daily photosynthetically available radiation (iPAR, PAR) (Fig.1). MODIS images are retrieved for the same time period, both for Aegean Sea and Souda Bay, spanning March 2012 to February 2015.

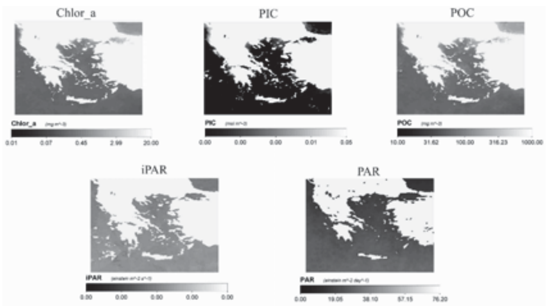

Fig. 1. Example of the retrieved MODIS AQUA L3 OC product images for the month of February 2013.Top, from left to right: Chlor_A, PIC, POC. Bottom, from left to right: iPAR, PAR

Analyses

In the Aegean Sea, the spatiotemporal analyses into the GIS (Geographic Information System) consist 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 derive the relations between ^{137}Cs and satellite retrieved parameters. IDW function uses a method of interpolation that estimates cell values by averaging the values of sample data points in the neighborhood of each cell [9]. The selected radius for IDW is 4km. GWR is a local form of linear regression that constructs a separate equation for every feature in the dataset [10]. The results of this process correspond to local r^2 maps depicting the relations between the OC satellite and ^{137}Cs activity measurements.

In Souda Bay, statistical analyses are performed using MODIS L2 OC measurements and ^{137}Cs activity concentration 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.

RESULTS AND DISCUSSION

The Aegean Sea results correspond to local r^2 value maps between ocean colour satellite data and ^{137}Cs measurements for a period spanning March 2012 to February 2015. Figure 2 shows the three examples of the produced r^2 maps for ^{137}Cs activity concentrations and MODIS Chlor_a for January 2013, MODIS PIC for March 2014 and MODIS POC for January 2013; In this figure it can be seen that the GWR method used for the spatiotemporal regression analysis, possibly affected the spatial distribution of the results (presenting better correlations near the coastlines) since it is designed mainly for terrestrial analyses.

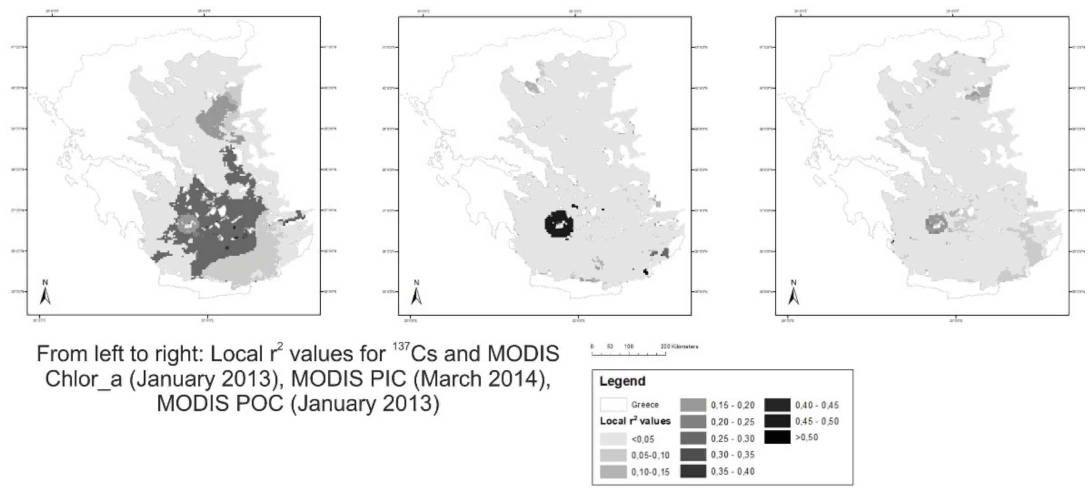

Fig. 2. From left to right: indicative local r^2 map for for ^{137}Cs activity concentrations and MODIS Chlor_a for January 2013, MODIS PIC for March 2014 and MODIS POC for January 2013 (Aegean Sea)

The correlations with Chlor_a show that the best correlations are present during the winter and early spring months with r^2 values between 0.35 and 0.59. Moreover, correlations with PIC show that the best correlations are present during the winter and spring months with

r^2 values between 0.47 and 0.88. Likewise, correlations with POC show that the best correlations are present during the winter months with r^2 values between 0.36 and 0.67. Furthermore, the correlations with iPAR show that the best correlations are present during the winter and early spring months with r^2 values between 0.25 and 0.40. The correlations with PAR show that the best correlations are also present during the winter and early spring months with r^2 values between 0.23 and 0.77. The OC parameters seasonal maximum values are present during the winter, so far the better correlations could be attributed to the higher values that show lower errors.

The Souda Bay results correspond to the calculated r^2 for linear and second degree polynomial regressions between ^{137}Cs activity concentrations and OC satellite measurements. In Figure 3, indicative scatterplots of the second degree polynomial results for MODIS PIC, iPAR and PAR are presented for the time period spanning March 2012 to February 2015. The errors depicted in the graphs are the ^{137}Cs activity errors calculated from the regression, which in certain cases can render the results unstable. Statistical analysis reveals that there is a significant difference between the application of linear and polynomial regression. The statistical linear regression analyses seem to be less efficient to describe the potential association with ^{137}Cs activity concentrations. Whereas, the statistical polynomial regressions such as the second degree polynomial seem to describe better the relations between satellite derived OC parameters and ^{137}Cs activity concentrations. Linear regression results show that the highest r^2 values are observed using MODIS PIC (r^2 = 0.6). The second degree polynomial regression results show that the highest r^2 ($r^2 = 0.6$) is observed when using the MODIS PIC parameter. Futhrermore, MODIS iPAR and PAR parameters also display a good correlation (r^2=0.4, $r^2 = 0.5$).

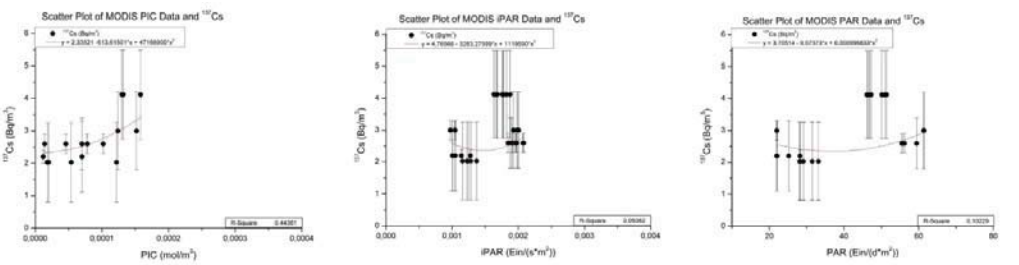

Fig. 3.From left to right: indicative scatterplots of the second degree polynomial results for MODIS PIC, iPAR and PAR are presented for the time period spanning March 2012 to February 2015 (Souda Bay).

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). A significant correlation between the ^{137}Cs activity concentrations and the OC parameters has been found, both spatially and temporally. These correlations can lead to an algorithm for the successful remote monitoring of ^{137}Cs activity concentration and dispersion in the Aegean Sea encapsulated in a GIS platform.

Future work will include a more systematic sea water sampling from the Aegean Sea according to the satellite passes, advanced laboratory radiochemistry, optimization of the calculation tools, optimization of the gamma spectrometry and the tools for spatial analysis, advanced statistical tools, point to point regression analysis and retrievals of ocean parameters from other satellite systems.

Acknowledgements

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http://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=am, http://oceancolor.gsfc.nasa.gov/cgi/l3

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