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Combining airborne thermal infrared images and radium isotopes to study submarine groundwater discharge along the French Mediterranean coastline

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A B S T R A C T

Study region: The French Mediterranean coastline, which includes karstic springs discharging into coastal seas and coastal lagoons.
Study focus: We investigated submarine groundwater discharge (SGD), an important vector for many chemical elements that may impact the quality of the coastal environment. First, we acquired airborne thermal infrared (TIR) images to detect terrestrial groundwater inputs. Then we report *in situ* data (salinity; temperature; radium isotopes). We use these data i) to confirm the presence of groundwater discharge and to characterize the different systems, and ii) to quantify SGD fluxes and estimate the residence time of the water bodies.
New hydrological insights for the region: Few studies have been conducted on SGD along the French Mediterranean coastline. The terrestrial groundwater spring inputs in La Palme and Salses-Leucate coastal lagoons are in the range (0.04–0.11) $m^3 s^{-1}$, ≤ 2% of the local river inputs. In comparison, total SGD estimates to La Palme lagoon (0.56–1.7 $m^3 s^{-1}$) suggest that the re-circulation of lagoon water through the sediment is two orders of magnitude greater than the terrestrial groundwater inputs. At the Calanque of Port-Miou, the terrestrial groundwater flux to the coastal seas was between 0.6 and 1.2 $m^3 s^{-1}$ in July 2009. This study demonstrates the application of airborne TIR remote sensing for detecting surficial groundwater springs, and the inability of the method to detect deeper, submerged springs.

1. Introduction

Submarine groundwater discharge (SGD) is recognized as an important pathway at the continent-ocean interface for the transfer of chemical elements and species into coastal waters. Global estimates of terrestrial SGD vary between 0.2–10% of the global river flow (COSOD II, 1987; Taniguchi et al., 2002), therefore, SGD can be both volumetrically and chemically important to coastal waters (Slomp and Van Cappellen, 2004). This input term may have a significant impact on the quality of the coastal waters and ecosystems,

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as well as on geochemical cycles. In its commonly used definition, SGD includes both i) the discharge of terrestrial (i.e. fresh) groundwater driven by a positive hydraulic gradient between the coastal aquifer and the sea and ii) seawater recirculation through permeable sediments driven by physical processes, such as waves and tides (Burnett et al., 2006). The mixing zone between groundwater and seawater within the coastal aquifer is defined as the subterranean estuary, where many chemical reactions take place, thus releasing or removing chemical species into coastal waters (Moore, 1999). Several studies have concluded that SGD has a significant impact on oceanic biogeochemical cycles, such as radium (Kwon et al., 2014; Moore, 2008; Rodellas et al., 2015), rare earth elements (Johannesson and Burdige, 2007), nutrients (Beusen et al., 2013; Slomp and Van Cappellen, 2004) and mercury (Bone et al., 2007).

Among the methods employed to study SGD, airborne thermal infrared (TIR) remote sensing can be used to detect cold or warm groundwater inputs into coastal seas because of the thermal contrast between groundwater and the surrounding coastal waters. This technique has been used in various places of the world, and is effective because of its combined use with *in-situ* measurements, including salinity and geochemical tracers such as radon and radium (Kelly et al., 2013; Lee et al., 2009; Mejías et al., 2012; Mulligan and Charette, 2009; Tamborski et al., 2015; Wilson and Rocha, 2012). Radon and radium isotopes are powerful tools to quantify SGD fluxes as they are enriched in groundwater relative to coastal waters. Ra is produced in the aquifer by the decay of Th on or near the sediment grain surface. Ra is particle-reactive and is adsorbed onto the surfaces of sediments at low ionic strengths (i.e. freshwater), but is released into solution upon contact with higher ionic strength (i.e. saline) waters, making Ra isotopes useful tracers of SGD (Swarzenski, 2007; Charette et al., 2008). The radium quartet's wide-range of half-lives (^{224}Ra, 3.66 d; ^{223}Ra, 11.4 d; ^{228}Ra, 5.75 y; ^{226}Ra, 1600 y) can be used to quantify SGD fluxes on different time-scales (Moore, 1996; Charette et al., 2001).

Although SGD has been investigated in many places of the world (Charette et al., 2001; Burnett et al., 2007; Moore, 2006; Stieglitz, 2005), including the Mediterranean Sea (Garcia-Solsona et al., 2010; Rodellas et al., 2015; Trezzi et al., 2016), very few studies have been conducted along the French Mediterranean coastline, despite the presence of several well-known karstic springs. The magnitude of SGD and its relative importance in chemical budgets of the Mediterranean Sea, and specifically the French Mediterranean, are unknown. Several karstic springs are indeed known to discharge into coastal seas or into coastal lagoons along the French Mediterranean coastline, including the submarine springs of Port-Miou and Cassis located in Calanques of Marseille-Cassis (Arfib and Charlier, 2016), Vise spring in Thau Lagoon (Condomines et al., 2012; Elbaz-Poulichet et al., 2002), Font Estramar and Font Dame springs that are connected to Salses-Leucate Lagoon (Fleury et al., 2007) and springs in La Palme lagoon (Wilke and Boutiere, 2000; Fleury et al., 2007; Stieglitz et al., 2013).

To our knowledge, Lévêque et al. (1972) conducted the first TIR survey along the French coastline, along the south-western Atlantic coast. Stieglitz et al. (2013) published a TIR image acquired in La Palme lagoon; this image comes from the same airborne survey used in this study. Schubert et al. (2014) used Landsat images of sea surface temperature anomalies from the bay of Roquebrune (southern France) to investigate a submarine spring (Cabbé). Few studies have been conducted on SGD along the French Mediterranean coastline using Ra and Rn as geochemical tracers: Ollivier et al. (2008) measured radium isotopes in the Gulf of Lions to estimate a SGD flux that was 1.6–29% of the regional river flow, Condomines et al. (2012) studied the thermal waters of Balaruc-les-Bains on the Mediterranean coast and Stieglitz et al. (2013) studied SGD in several coastal lagoons using radon as a tracer. Stieglitz et al. (2013) thus quantified groundwater discharge and seawater recirculation in La Palme lagoon, where the discharge of low-salinity karstic groundwater was found to maintain a brackish ecosystem functioning throughout the dry summer months, while wind-driven seawater circulation contributed up to 50% of the total radon fluxes to the lagoon.

Airborne thermal infrared images as well as radium isotopes have been widely used to detect and/or quantify SGD all over the world. Despite the presence of many well-known springs along the French Mediterranean coastline, these methods have hardly ever been used in this region. The aim of the present study is thus to apply thermal imagery and radium to provide information on SGD fluxes along the French Mediterranean coastline. Here, we report airborne TIR images that were acquired along the French Mediterranean coastline. To complement the TIR images, we collected *in situ* data (salinity, temperature, radium isotopes) to characterize the different sites and to provide quantitative information (SGD fluxes, residence times of surface waters) regarding the different systems.

2. Material and methods

2.1. Study sites

In this study, we report data obtained throughout four different regions along the French Mediterranean coastline where groundwater discharge is known to take place (Fleury et al., 2007). The four investigated areas include coastal seas and coastal lagoons (Fig. 1). For many of these locations, there are known groundwater-fed karstic springs that connect to the adjacent water body *via* a small stream. We follow Stieglitz et al. (2013) in defining these systems as groundwater discharge. In this manuscript, we categorize SGD into two categories: terrestrial groundwater and marine groundwater. Terrestrial groundwater includes all flow derived from meteoric water (precipitation) coming from springs driven by a positive terrestrial hydraulic gradient. We keep the terminology "terrestrial groundwater" despite the salinity (2–10) of the discharging water at the spring outlets because these waters have a terrestrial origin. On the other hand, marine groundwater includes seawater (and lagoon water) recirculation through permeable coastal sediments, which subsequently flows back to the sea (and lagoon) with a different chemical composition. Marine SGD is driven by various physical forcing mechanisms, and is distinct from water fluxes driven by pore water exchange and bioturbation (Santos et al., 2012). The four investigated areas are described below (Fig. 1):