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Reply to Santana *et al*. Twenty-five years of continuous temperature and salinity observations on the Uruguayan Atlantic coast

DANILO L. CALLIARI

Lab. de Oceanografía y Ecología Marina, Facultad de Ciencias, Universidad de la República, Montevideo, Uruguay.
Grupo Oceanografia Biológica y Ecofisiología del Plancton. Comisión Sectorial de Investigación Científica, Universidad de la República, Uruguay. E-mail dcalliar@fcien.edu.uy

Abstract: Variability in a salinity time series from La Paloma (Uruguay) presented by Santana et al. (2025) was attributed to the Rio de la Plata plume (RPP). While the influence of RPP is beyond reasonable doubts, submarine groundwater discharges (SGD) constitute a complementary, highly likely and relevant mechanism for modulating the salinity and biogeochemistry of Uruguayan marine coastal waters. SGD in Uruguay remains to be quantified and characterized. The relevance of those processes needs to be recognized in order to contribute to filling that significant gap in our knowledge regarding the functioning of marine coastal systems.

Key words: submarine groundwater discharges, salinity, Rio de la Plata, Uruguay.

Respuesta a Santana *et al*. Veinticinco años de observaciones continuas de temperatura y salinidad en la costa atlántica uruguaya. Resumen: La variabilidad de la salinidad en una serie temporal de La Paloma (Uruguay) presentada por Santana et al. (2025) es atribuida a la pluma del Rio de la Plata (PRP). La influencia de la PRP está más allá de toda duda razonable, pero las descargas submarinas difusas (DSD) representan un mecanismo complementario, altamente probable y relevante para la modulación de la salinidad y biogeoquímica de las aguas marinas costeras uruguayas. Las DSD aún deben ser cuantificadas y caracterizadas en el Uruguay. Es necesario reconocer la relevancia de estos procesos para contribuir a completar estos vacíos críticos en el conocimiento del funcionamiento de los sistemas marinos costeros.

Palabras clave: descargas submarinas difusas, salinidad, Rio de la Plata, Uruguay.

In a recent article Santana and collaborators presented a 25 years long series of nearshore temperature and salinity records from La Paloma, a locality on the eastern coast of Uruguay (Santana et al. 2025). Such effort is very welcomed as long-term environmental time series are critical for the identification of temporal trends and for the understanding of mechanisms operating on multi-annual time scales. In the referred article several patterns in those series were effectively explored and potential mechanisms discussed. Among them, the variability of salinity was shown to follow a seasonal pattern, to present an intriguing increasing trend for the period 1996-2021 (albeit non-statistically significant at $p \sim 0.05$), and a negative correlation with an estimate of the freshwater flux from the Rio de la Plata estuary.

The discussion of above results abounds on considerations regarding potential processes behind observed patterns, anchored on actual data (i.e., a qualitative inspection of weekly and monthly series of salinity at nearshore La Paloma and Río de la Plata outflow, and an estimated correlation between both series), as well as on well established knowledge of the wind-driven advection of the Rio de la Plata plume (RPP) over the continental shelf. All in all, Santana et al. build a convincing case regarding the influence of the brackish RPP in their study site. Here I argue that key points in that discussion may

be misleading, though. More specifically, the attribution of the observed variability in the salinity time-series from La Paloma solely to the effect of the RPP cannot be taken at face value.

The reach of the RPP into the inner continental shelf of Uruguay nearly 100 km beyond the estuarine mouth is an expected outcome based on prior knowledge. However, the identification by Santana et al. of the mechanisms shaping La Paloma salinity time series overlooked other plausible and potentially significant processes, namely diffuse freshwater inputs along the coastline in the form of submarine groundwater discharges (SGD). SGD occur when aquifers connect with the sea through permeable sediments and the hydraulic head is above sea level (Paiva & Niencheski 2018). Under such conditions underground continental water is pushed to the sea and diffuses towards the open water column through marine bottom sediments, typically in the nearshore littoral zone and the inner shelf. The very low statistical explanatory power of the reported correlation between salinity measured in nearshore La Paloma and the Río de la Plata outflow (< 10%) strongly suggests the action of other relevant processes - besides the RPP - to account for the variability in the original salinity signal. To the author's knowledge there are currently no quantitative estimates of SGD fluxes for the sector of the coastline under scrutiny, but figures for nearby regions suggest those may be highly significant indeed. For example, for the Patos Lagoon Barrier system in southern Brazil SGD fluxes have been estimated to be in the order of $8.7x10^7$ m^3 d^{-1} (Niencheski et al. 2007), which represents a substantial fraction of the surface flow entering the coastal sea from the Patos Lagoon estuary. The strip of land along the Atlantic coast of Uruguay is characterized by abundant fresh and brackish water bodies, i.e., at least seven major coastal lagoon-barrier systems and extensive wetlands separated from the sea by a more or less narrow fringe of porous Quaternary deposits (Sprechmann 1978, Gonzalez-Carreira et al. 2025., among other), suggesting that it is reasonable to expect substantial SGD fluxes to the sea also along that region, including La Paloma. Still, the magnitude of such underground diffuse fluxes remains to be quantified, as well as their significance to regulate the salinity of coastal waters.

The significance of the identification and proper disentangling of processes involved in salinity regulation in the coastal zone extends far beyond a mere intellectual exercise. The character of the freshwater source, whether local or distant, will affect the delay and timing of the dilution effect on marine coastal waters in different ways, as well as the relationship between salinity and precipitation (for the present discussion it is important to bear in mind that the surface extension of the basin of the Rio de la Plata is in excess of 2 million km^2). And the identity of the freshwater source may also have profound qualitative ecosystem-level consequences besides the dilution of marine waters. On the one hand, the advection of an estuarine plume implies the transport of brackish biological plankton species which otherwise may not be found in coastal marine waters. That effect is of course absent in the case of SGD. On the other hand, surface fresh (or brackish) waters entering the sea as part of an estuarine plume vs SGD typically have contrasting chemical signatures. Nearshore aquifers and porous sediments can be thought of as underground estuaries (Moore 1999, Charrette and Sholkovitz 2006) where fresh and marine water mix; the resulting estuarine front moves in response to forcing by changes in the hydraulic head and the sea level, and the interaction of underground waters with the stationary phase (rocks, sediments) further modifies the chemistry of the water in the aquifer through leaching and the action of geochemical filters (roughly analogous but not quite equivalent to those in "surface estuaries"). Thus SGD waters impact the composition of chemical species in the coastal sea (Moore 2006), differently from surface point sources. For instance, SGD can be strongly enriched in macronutrients, micronutrients and other trace elements compared to estuarine and seawater end-members (Niencheski et al. 2014), notably supplying Co, Mn and Fe, as well as dissolved inorganic nitrogen. In southern Brazil SGD contributes up to 55% of the total nitrogen flux to the continental shelf (Niencheski et al. 2007), and the overall impact of SGD on seawater chemistry has been shown to effectively impact biological productivity elsewhere (Basterretxea et al. 2010). On the Uruguayan shelf, the RPP is enriched in specific macronutrients like dissolved inorganic phosphorous and silica, but typically contains very low levels of dissolved inorganic nitrogen (Calliari et al. 2018), the typically limiting nutrient in that marine shelf (Calliari et al. 2009, 2025). That opens the scope for highly relevant biological and biogeochemical impacts of SGD in Uruguayan shelf waters as well. As stated, for the Uruguayan coastline information on SGD flows (and their chemistry, and their impact on marine ecosystems) is currently lacking but strongly needed for a better understanding of physical, biogeochemical and ecological processes there. Recog-

nition of their existence and potential relevance is a necessary first step towards the generation of such knowledge.

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