dynamical processes responsible for the formation of an OMZ, though excluding the formation of OMZs in the Indian Ocean, where probably the most intense denitrification and nitrogen loss occur, and such as we will see here, do not include OMZs at a high subtropical latitude. It was shown from an analysis of the ESP OMZ off Chile (Paulmier et al., 2006) that the existence of three different layers has to be taken into account to evaluate the entire OMZ structure: the oxycline (upper $O_2$ gradient, ~5 times more intense than in the oxygenated ocean); the core ($O_2 < 20$ μM); the lower $O_2$ gradient. Indeed, the oxycline is considered as the OMZ engine, where the most intense remineralization occurs, leading to the OMZ's intensification, and where a specific denitrification and nitrification coupling (e.g., Brandes et al., 2007) could also occur with $O_2 > 20$ μM. OMZ core, specific to anaerobic processes as canonical (classical anaerobic) denitrification, and the lower $O_2$ gradient, where nitrification is a main process, could play an important role in the nitrogen cycling in the OMZ (e.g., Anderson et al., 1982). Thus, to consider the specific biogeochemical processes, it is necessary to include these three layers and the large range of $O_2$ concentrations, and not only the extremely low $O_2$ observed in the OMZ core. Finally, having in mind to answer the question of how denitrification criteria are or are not adapted to the evaluation of the extent of an OMZ, it is necessary to determine simultaneously the structure and extent of OMZ and the denitrification zones.

Hence, from the same $O_2$ criterion and comparison with the criteria for denitrification, the main and most intense OMZs in the open ocean are identified and characterized quantitatively (horizontally and vertically). The permanence and potential seasonality of the OMZs will be analyzed. However, OMZs formed over the continental shelf (such as the Benguela OMZ) and in semi-enclosed seas (such as the Black Sea) or over deep trenches (e.g. Gulf of Cariaco, Venezuela) reaching the level of anoxia will not be addressed in this study.

## 2. Methodology

To characterize and determine the surface and volume of an OMZ, the CRIO criterion on $O_2$, adapted to take into account the entire vertical thickness of an OMZ, and compared with the denitrification criteria, was applied to the WOA2005 (World Ocean Atlas, 2005) data.

### 2.1. CRIO (CRIterion on $O_2$) criterion for OMZ estimation

The CRIO OMZ criterion is based on a characteristic $O_2$ profile defined for the Chilean OMZ from ~200 data collected at 18 stations during four cruises (2000–2002; between 20°S and 30°S), with high vertical resolution (5–10 m) sampling and an achieved accuracy of 0.5–1.0 μM (Paulmier et al., 2006). CRIO has been defined to take into account the OMZ core, but also the upper and lower $O_2$ gradients, corresponding to the boundary layers between the core and the surrounding well oxygenated ocean, at the top and at the bottom of the OMZ, and contributing to the N perturbation (e.g., Anderson et al., 1982). These three OMZ layers, covering an $O_2$ continuum from aerobic to anaerobic conditions, exhibit anomalies that differentiate them from the surrounding more oxygenated seawater.

Since, from our biogeochemical point of view, OMZs should necessarily allow denitrification, an OMZ core (called CORE) has been defined by $O_2 < 20$ μM. Indeed, $O_2 < 20$ μM corresponds to the maximum $O_2$ concentration for which water-column denitrification was observed in situ (Smethie, 1987). The $O_2 < 20$ μM concentration also corresponds to a usual suboxic condition used to separate the aerobic ($O_2$-respiration) from the denitrifying ($NO_3^-$-respiration) activity (e.g., Oguz et al., 2000). In addition, this threshold of 20 μM could be used with sufficient confidence, based on the $O_2$ detection limit and the uncertainties (~20 μM) of the main $O_2$ databases available. Using $O_2$ <20 μM, the CRIO criterion excludes the OMZs (or low $O_2$ zones called, LOZ) in the open tropical Atlantic Ocean ($O_2 > 40$, and 20 μM in the Canary and Benguela Current systems, respectively; Karstensen et al., 2008), in which no denitrification has yet been reported, except on the continental margin (e.g., in the Benguela Current system). The present study therefore focuses on the most intense OMZs of the open ocean, reaching the weakest concentrations (down to $O_2$ <1 μM) in the eastern Pacific Ocean and the northern Indian Ocean. In addition to the CORE, the upper OMZ boundary layer border, called the oxycline (OXY), which plays a role as an OMZ biogeochemical engine (Paulmier et al., 2006), is defined by gradients higher than 0.9 μM/m, as for the OMZ off Chile. The lower OMZ boundary layer, called the lower $O_2$ gradient (LOG), is delimited by the depth at which the $O_2$ gradient becomes less than 0.1 μM/m, corresponding to the strongest $O_2$ gradient for the "classical $O_2$ minimum".

### 2.2. Denitrification criteria for NMZ ("nitrate deficit" maximum zone)

Previous indirect quantifications of the vertical and horizontal extents of an OMZ used a criterion based on the denitrification activity, which focuses mainly on the calculation of different indices (e.g., Hattori, 1983): the $NO_3^-$ deficit (NDEF > 10 μM) and/or the $NO_2^-$ secondary subsurface peak (>5 μM).

Denitrification was evaluated quantitatively with NDEF approach and compared qualitatively with the subsurface $NO_2^-$ peak, which also indicates the presence of denitrification ($NO_3^-$-reduction into $NO_2^-$; Codispoti and Christensen, 1985). The 'NDEF > 10 μM' criterion corresponding to the historical definition ($NDEF = 15PO_4^{3-} - NO_3^-$; Broecker and Peng, 1982) and previously used at the global scale (Kamykowski and Zentara, 1990) will be here determined. $N^*$ (Gruber and Sarmiento, 1997) was not chosen, because the threshold corresponding to significant denitrification has not yet been well defined, absolute $N^*$ values being arbitrary (Gruber, 2004), although the same conclusions as with NDEF can be obtained with $N^* < -9$ μM. Thus here, from the computation of NDEF, and by analogy with the OMZ, an NMZ (NDEF maximum zone) has been defined corresponding to NDEF > 10 μM. In the figures, $NO_2^-$ secondary subsurface peaks have been delimited arbitrarily by an isoline corresponding to about half of the $NO_2^-$ maximum ($NO_{2max}^-$) to be coherent with the $NO_{2max}^-$ intensity of each area. This $NO_2^-$ criterion is in agreement with the conditions used previously for the eastern Pacific Ocean and the northern Indian Ocean (e.g., Codispoti et al., 2001).

### 2.3. WOA2005 database used for OMZ and NMZ estimations

CRIO and denitrification criteria were applied using WOA2005 (World Ocean Atlas 2005) data obtained between 1893 and 2004; this is the most recent and updated global $O_2$ and nutrient database. From WOA2005 data, including WOCE (World Ocean Circulation Experiment) data and respecting WOCE quality standards, a yearly climatology (Boyer et al., 2006) for $O_2$, $NO_3^-$ and $PO_4^{2-}$ global distributions was obtained and mainly used here.

$O_2$ climatology has been developed based on data from 632,888 profiles of bottle samples mainly taken in the last 30 years (>80% of the data; Boyer et al., 2006). The distribution of these $O_2$ profiles is, a priori, correctly covering all the already identified hypoxic areas (ENP, ESP, AS, BB; Kamykowski and Zentara, 1990). $O_2$ accuracy and reproducibility are <10 μM and 2–10 μM, respectively.

$NO_3^-$ and $PO_4^{2-}$ WOA2005 climatology's have been used to evaluate NDEF and is based on the same order of profile numbers and during the same periods as for $O_2$, though 2.7 (233,125) and 1.6 (400,399) times less abundant, respectively. Accuracy and