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Upwelling velocity and ventilation in the Mauritanian upwelling system estimated by CFC-12 and SF_6 observations

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ABSTRACT

Transient tracer data (CFC-12 and SF_6) from three oceanographic field campaigns to the Mauritanian Upwelling area conducted during winter, spring and summer from 2005 to 2007 is presented. The transient tracers are used to constrain a possible solution to the transient time distribution (TTD) along 18°N and to quantify the mean ages in vertical sections perpendicular to the coast. We found that an Inverse Gaussian distribution where the ratio of the moments Δ and Γ equals 1.2 is a possible solution ($\Delta/\Gamma = 1.2$) of the TTD. The transient tracers further show considerable under-saturation in the mixed layer during the winter and spring cruises that can only be maintained by mixing or upwelling by tracer-poor water from below the mixed layer. We use dissipation data from microstructure measurements and the tracer depth distribution to quantify the flux of tracers to the mixed layer by vertical diffusivity and wind data from the ship to quantify the air–sea flux. We then use the magnitude of the under-saturation in the mixed layer to estimate the advective upwelling velocity which is the balance the first two processes, in a steady state assumption. We find that the upwelling velocities range from less than 1 to 5.6×10^{-5} m s^{-1} (<0.8–4.8 m d^{-1}), with generally higher values close to the coast, but with comparable upwelling velocities during spring and winter. During the summer cruise the transient tracers were close to equilibrium with the atmosphere, suggesting no upwelling. We have shown the use of CFC-12 and SF_6 transient tracer data for calculating upwelling velocity, and found an overall uncertainty of roughly ±50%.

1. Introduction

Coastal upwelling along the eastern boundaries of the world ocean is an important process that brings cold, low-oxygen and high-nutrient sub-surface seawater to the surface ocean, where it fuels some of the most productive areas in the world ocean. It is driven by alongshore winds causing an offshore Ekman transport within the surface layer of the ocean. The Mauritanian upwelling system is an Eastern Boundary Upwelling System (EBUS) that stretches from the Iberian Peninsula to about 10°N along the Northwest African coast. Due to changes in wind forcing associated with the migration of the Intertropical Convergence Zone, coastal upwelling off Mauritania exhibits a pronounced seasonal cycle. Winds favorable to upwelling prevail primarily from December to April (e.g. Barton et al., 1998; Pelegri et al., 2005; Schafstall, 2010; Schafstall et al., 2010). The Mauritanian upwelling system is the most productive branch of the Canary Current upwelling system (e.g. Cropper et al., 2014), and the extension cold surface waters can be observed by sea surface temperature observations from, for instance, satellite (e.g. Pelegri et al., 2005).

Upwelling also brings climate relevant trace gases, such as N_2O and CO_2, to the surface where they can outgas to the atmosphere. For instance, Rees et al. (2011) estimate an annual flux of N_2O to the atmosphere by following upwelling filaments with a deliberately released tracer (SF_6) and without separating supply to the mixed layer by vertical advection from vertical diapycnal flux of 1.3 to 2.1 Gg N per filament. Similarly, Kock et al. (2012) calculate the diapycnal flux of N_2O for the Mauritanian upwelling area to 0.019 (0.007 to 0.048) nmol m^{-2} s^{-1} and a corresponding average air–sea flux of the same magnitude (0.020 nmol m^{-2} s^{-1}), although they estimate the vertical advection to be an order of magnitude lower. This would correspond to an annual N_2O air–sea flux of ~90 Gt N over an area of 10^4 km^2, roughly corresponding to the Mauritanian upwelling area. Steinhoff (2010) report on high concentrations of CO_2 from the Mauritanian upwelling region during the upwelling season, and as a result high fluxes of CO_2 into the atmosphere. During the weak upwelling season (summer), the partial pressure of CO_2 is close equilibration with the atmosphere. This is a result of the combined effect of physical gas exchange of air–sea interface, biological activity and upwelling intensity. A study by Loucaides et al. (2012) from the same experiment as Rees et al. (2011) explores the effect of high CO_2 concentration waters on the calcium carbonate saturation state in the upwelling filaments.

Understanding of the intensity and duration of upwelling, as well as the circulation and ventilation of the area is thus of importance for

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regional climate, primary production, fisheries, and for the flux of trace gases to the atmosphere. This is often achieved with measurements of sea surface temperature as a proxy for upwelling (e.g. Benazzouz et al., 2014), or surface ocean measurements of, for instance, CO_2. Direct measurements of the upwelling velocity, however, are virtually impossible due to the low velocities; in the order of 10^{-5} m s^{-1}. Indirect methods of estimating upwelling velocities must be used. Upwelling velocities have been estimated from arrays of current moorings in the tropical Atlantic and Pacific Oceans with values in the range of 10^{-5} m s^{-1}, although with large uncertainty (e.g. Weingartner and Weisberg, 1991; Gouriou and Reverdin, 1992; Weisberg and Qiao, 2000). The Mauritanian upwelling system is carefully examined in a recent study by Cropper et al. (2014) using upwelling indices based on seas surface temperature of wind speed/direction characterizing the integrated effect of diapycnal mixing and advective upwelling. Schafstall (2010) calculated positive Ekman transports for the Mauritanian coast up to 10^{-5} m s^{-1} during the January to June period based on climatological winds.

In a different approach Klein and Rhein (2004) laid out the principles for using ^{3}He in the upper ocean for estimates of upwelling velocities, a concept that was later applied to a larger data-set of ^{3}He measurements in the equatorial Atlantic where an upwelling velocity in the order of 10^{-5} m s^{-1} could be quantified with an uncertainty of 42% (Rhein et al., 2010). Helium surface disequilibrium measurements have also been used for determining upwelling velocities off Mauritania and Peru (Steinfeldt et al., 2014). An alternative method using the short lived ^{7}Be isotope found comparable upwelling velocities (calculated as the combination of diapycnal flux and advective transport) in the tropical Atlantic and Pacific oceans (Kadko and Johns, 2011; Haskell Ii et al., 2015).

Here we report on transient tracer (SF_6 and CFC-12) and oxygen data from the Mauritanian upwelling area collected during three field campaigns from 2005 to 2007. The data are used for characterization of the ventilation of the area and for inferring upwelling velocities. An introduction to the general oceanography of the area and specifics about these field campaigns can be found in Schafstall (2010) and Schafstall et al. (2010).

2. Data and methods

The data presented here were collected during three cruises conducted between 2005 and 2007 on the German research vessels Poseidon and Meteor, see Table 1 for details, and Fig. 1 for a graphic representation of the station network. These cruises were part of the field program for the German BMBF-funded project SOPRAN (Surface Ocean Processes in the Anthropocene) and the German DFG-funded project MUMP (Mauritanian upwelling and mixing process study). The cruises were carried out during different times of the year, and thus, potentially survey the area during variable strength of upwelling. We use stations sampled for transient tracers on short zonal sections along 18°N or 17°30′N. For more details on the cruises, please see references in Table 1.

Seabird CTD systems were used to measure the conductivity, temperature and pressure. The concentration of oxygen was measured by the Winkler titration during the cruises, for more details see the cruise reports (Table 1). The continuous under-way measurement of salinity and temperature (SST and SSS) were recorded by ship-based thermosalinographs (TSG).

2.1. Transient tracers

During the cruises samples for the determination of SF_6 and CFC-12 were taken for later analysis in the lab in Kiel. All transient tracer samples were taken in 300 ml glass ampoules that were flame sealed under a flow of tracer free nitrogen gas in a process similar to that described by Vollmer and Weiss (2002). The ampoules were stored for several years in the lab prior to analysis that were performed mainly during 2011. The integrity of the samples is conserved since the tracers are stable in seawater, and a correctly performed flame-seal is gas tight so that no exchange with the ambient atmosphere can take place. Incorrectly flame sealed ampoules can mostly be identified by abnormally high tracer concentrations, particularly for SF_6—the least soluble of the two tracers. CFC-12 and SF_6 have been shown to be stable in seawater, also at low oxygen concentrations, so we do not expect any degradation of these tracers in the ampoules during storage (e.g. Lee et al., 1999; Holtermann et al., 2012). Other potentially useful halogenated transient tracers that could have been used here include CFC-11, CFC-113 and CCl_4. These were not measured for mainly two reasons: 1) CFC-11 data provide only limited additional information to that of CFC-12 when it comes to mean ages (similar input function), although the higher solubility of CFC-11 compared to that of CFC-12 could potentially have provided additional information, and 2) CFC-113 and CCl_4 are known to be unstable in low oxygen environments (e.g. Tanhua et al., 1996; Tanhua and Olsson, 2005) and in warm sea-water (e.g. Huhn et al., 2001; Roether et al., 2001), introducing additional uncertainties in the calculations.

The procedure to measure the samples in the lab is based on purge-and-trap followed by chromatographic separation and detection on an electron capture detector (ECD), with the process similar to the one described by Vollmer and Weiss (2002). The ampoules were placed in an ampoule cracking device—the cracker—that allows for quantitative measurements of all the tracer in the ampoules including the headspace (Vollmer and Weiss, 2002). This is necessary since most of the tracer will be in the headspace of the ampoule due to the low solubility of the tracer. The purge efficiency is thus mostly an effect of how efficiently the headspace and cracker volumes are flushed with the purge gas. Each sample was purged at least twice for 10 min each with N_2-gas at ~80 ml min^{-1}; with this method the purge efficiency was close to 100%. A detailed description of the analytical methods and techniques used for the calibration is described in Schneider (2011), no correction for sampling blanks was made.

The samples from the 2005 cruise were measured on a capillary gas-chromatographic system with a dual-trap injection procedure. In this system the tracers are trapped at −100 °C on a 1 m, 1/16″ stainless steel trap filled with Haysep D. This back-flushed during desorption onto a precolumn (50 cm Porasil C and 50 cm molecular sieve 5A in a 1/8″ steel tubing at 35 °C) and to the second trap, which was a 1 m 1/32″ stainless steel tubing where 5 cm is filled with Carboxen 1000 kept at −70 °C. This trap is desorbed onto the main column (75 m DB 624 followed by 30 m RT-molecular sieve 5A). This system proved to be sensitive and somewhat fragile, so the samples from the 2006 and 2007 cruises were measured on a packed column gas-chromatographic system with a single trap (70 cm Haysep D in 1/16″ SS tubing kept at -70 °C). After desorption at 130 °C the sample was separated on a 30 cm 1/8″ Porasil C column and the SF_6 and CFC-12 fraction was passed on to the main column (180 cm Carbograph and 20 cm Molecular Sieve 5A tail-end). A thorough description of the analytical

Table 1
Chief scientists, cruise report reference and data repository for the three oceanographic cruises to the Mauritanian Upwelling region considered in this study.

Cruise	Chief scientist	Time	Cruise reports	Data repository
Poseidon 320	H. Bange	March 21 – April 7, 2005	(Bange, 2008)	http://doi.pangaea.de/10.1594/PANGAEA.817256
Meteor 68/3	A. Körtzinger	July 12 – August 6, 2006	(Körtzinger, 2009)	http://cdiac.ornl.gov/ftp/oceans/CLIVAR/Met_68_3.data/
Poseidon 347	M. Dengler	January 18 – February 5, 2007	(Dengler et al., 2008)	http://doi.pangaea.de/10.1594/PANGAEA.833885