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A whirling ecosystem in the equatorial Atlantic

Christophe E. Menkes
IRD, LODYC/UPMC, Paris, France

Sean C. Kennan
Nova University Ocean Ctr., FL, USA

Pierre Flament
DRO/OS, IFREMER, Plouzané, France
University of Hawaii, Honolulu, HI, USA

Yves Dandonneau, Sébastien Masson, Benjamin Biessy, Emile Marchal,
Gérard Eldin, Jacques Grelet, Yves Montel, Alain Morlière, and Anne Lebourges-Dhaussy
IRD, LODYC/UPMC, Paris, France

Cyril Moulin
LSCE, CE Saclay, Gif sur Yvette, France

Gisèle Champalbert
LOB, Campus de Luminy, Marseille, France

Alain Herbland
CREMA L'houmeau, Nieul sur mer, France

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[1] The equatorial Pacific and Atlantic oceans exhibit remarkable meridional undulations in temperature and chlorophyll fronts visible from space over thousands of kilometers and often referred to as tropical instability waves. Here, we present new observations of an ecosystem ranging through three trophic levels: phytoplankton, zooplankton and small pelagic fish whirling within a tropical vortex of the Atlantic ocean and associated with such undulations. Cold, nutrient and biologically rich equatorial waters are advected northward and downward to form sharp fronts visible in all tracers and trophic levels. The equatorward recirculation experiences upwelling at depth, with the pycnocline and ecosystem progressively moving toward the surface to reconnect with the equatorial water mass. The observations thus indicate that it is a fully three-dimensional circulation that dominates the distribution of physical and biological tracers in the presence of tropical instabilities and maintains the cusp-like shapes of temperature and chlorophyll observed from space. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4279 Oceanography: General: Upwelling and convergences; 4231 Oceanography: General: Equatorial oceanography; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4817 Oceanography: Biological and Chemical: Food chains

1. Introduction

[2] In the eastern equatorial Atlantic and Pacific Oceans, upwelling is strong and primary productivity is high within a few degrees of the equator, where wind-driven surface currents diverge [*Chavez and Barber*, 1987; *Voituriez and Herbland*, 1981]. When the zonal equatorial currents become unstable, meridional oscillations of temperature and currents, along with regions of intensified vertical motions, appear north of the equator [*Legeckis*, 1977; *Weisberg and Weingardner*, 1988]. These oscillations form remarkable cusp-like shapes visible from space in sea surface temperature or surface chlorophyll over thousand of kilometres [*Legeckis*, 1977; *Chavez et al.*, 1999]. In the equatorial Pacific Ocean, such sea surface temperature patterns are now known to result from the passage of tropical instability vortices [*Kennan and Flament*, 2000; *Flament et al.*, 1996]. They may thus similarly affect the distributions of nutrients, CO_2, primary productivity, phytoplankton, and zooplankton [*Murray et al.*, 1994; *Roman et al.*, 1995; *Foley et al.*, 1997; *Chavez et al.*, 1999] and, more generally, the equatorial ecosystem just as eddy-induced processes have been invoked to enhance production in other regions [e.g. *Falkowski et al.*, 1991]. Indeed, in the equatorial Atlantic Ocean, the coincidence of high eddy kinetic energy from instabilities [*Richardson and McKee*, 1984] with a major fishing zone for skipjack tuna [*Ménard et al.*, 2000] have suggested a causal relationship between the dynamics of unstable currents and variations of the ecosystem to the highest trophic levels [*Morlière et al.*, 1994]. Yet synoptic biological and physical measurements of these processes in the equatorial oceans have been so far lacking. This is the aim of this paper to fill this gap, to set a framework to understand how equatorial vortices affect the equatorial marine ecosystem to the highest trophic levels and connect to the striking cusp-like shapes observed from space. To that end, the observational program PICOLO was conducted, in June 1997, in the eastern tropical Atlantic aboard the research vessel Antea, to observe the distribution of nutrients, plankton and nekton in the presence of a tropical instability vortex.

2. Data and Gridding Strategy

[3] Ocean currents were measured using a shipboard Acoustic Doppler Current Profiler (ADCP) [*Wilson and Leetmaa*, 1988] and an array of 10 surface drifting buoys [*Niiler et al.*, 1987].

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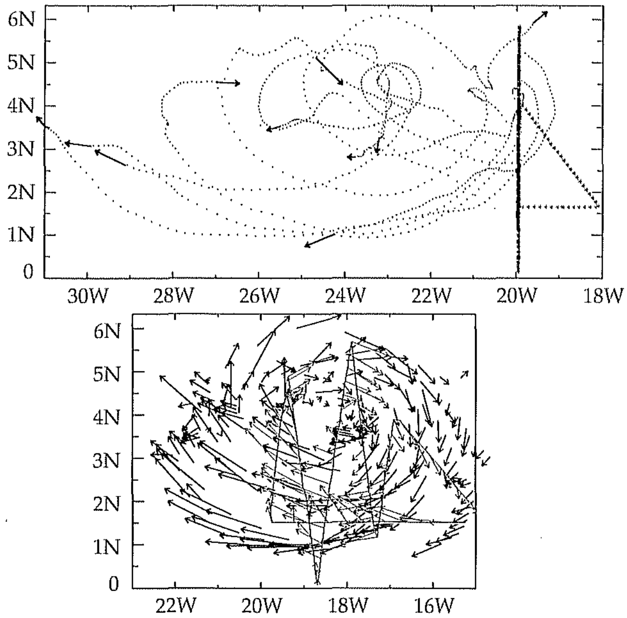

Figure 1. top panel: buoy trajectories in the fixed frame for the first 25 days after launch at 20°W, dotted every 6 hour. The arrows represent their final velocity. The ship track is also shown by stars. Bottom panel: Buoy trajectories and speed in the reference frame moving at -35 cm s^{-1} (black) and surface currents from ADCP along the ship tracks (red). The longitude scale corresponds to the position of the vortex on June 20th, 1997.

Seventy-five hydrographic stations were conducted to 250 meter depth with a 20 nautical mile spacing, yielding profiles of temperature, salinity, nutrients, excited and natural fluorescence [*Chamberlin et al.*, 1990], pigments and the phytoplankton species distribution. Prokaryotes dominated phytoplankton as indicated by an abundance of divinyl chlorophylls and zeaxanthine. Zooplankton biomass vertically integrated to 150 meters was sampled by net tows at each station [*Lebourges-Dhaussy et al.*, 2000]. An equivalent of zooplankton concentration was also inferred from 150 kHz ADCP backscatter [*Flagg and Smith*, 1989] and micronekton biomass from 38 kHz echosounder. Micronekton consisted mostly of small pelagic fishes: *Vinciguerria nimbaria* [*Lebourges-Dhaussy et al.*, 2000]. Surface chlorophyll concentrations were obtained from the POLDER sensor onboard the ADEOS-1 satellite [*Deschamps et al.*, 1994], and weekly sea surface temperatures (SST) were obtained from pathfinder AVHRR data.

[4] Daily SST images from the METEOSAT satellite guided the ship to a vortex at 20°W. Five repeated sections were conducted between the equator and 6°N while deploying drifting buoys. The buoys followed cycloidal trajectories, indicating that they moved within a vortex translating westward at 35 cm s^{-1} (Figure 1, top panel). In a frame of reference moving with the vortex, the buoy trajectories become mostly closed loops and the ADCP currents from the ship track closely follow those of the drifters north of 1.5°N (Figure 1, bottom panel). Thus, north of 1.5°N, the vortex can be assumed to be steady at first order and synoptic maps of the properties of the vortex can be constructed from observations separated in time and space [*Kennan and Flament*, 2000] by transforming all time-dependent information into spatial information.

3. Results

[5] The anticyclonic (clockwise) vortex was centered at 3.5°N, 18.5°W on July 20th, in the shear of the North Equatorial Counter Current and westward South Equatorial Current, with a diameter of 500 km and velocities reaching 1.3 m s^{-1} at its border (Figure 2a). The equatorial chlorophyll maximum exhibited a meridional undulation, with maximum at 20°W, and minimum at 15°W, mirroring the classic wave, or cusp-like pattern also seen in SST (Figure 2b). Cold, chlorophyll-rich, equatorial waters were transported poleward by the instability vortex (Figure 2).

[6] Surface divergence was estimated from the gridded surface velocities (Figure 2b) and plotted only when exceeding its standard error, obtained through stochastic simulations [*Kennan and Flament*, 2000]. Convergence between the cold, chlorophyll-rich, equatorial waters and the warmer, chlorophyll-poor, waters in the northward flow, and divergence (upwelling) near the vortex center, agree with previous observations from the Pacific [*Kennan and Flament*, 2000; *Flament et al.*, 1996]. This upwelling does not have any apparent effect on SST or surface chlorophyll.

[7] The depth-averaged circulation of the vortex illustrates the overall effect of the vortex on the ecosystem as the motion was coherent down to the pycnocline. It transported cool, nutrient, chlorophyll and zooplankton-rich, equatorial water poleward, west of 18°W (Figure 3). Warmer, nitrate, chlorophyll, zooplankton-poor waters moved equatorward east of 18°W. A similar pattern could be observed in the pelagic fish (Figure 3f). Gross primary production was enhanced in the phytoplankton-rich region with peaks reaching 3 gC m^{-2} d^{-1} (Figure 3c). The corresponding net primary production was about 1.5 gC m^{-2} d^{-1} [*Bender et al.*, 1999], characteristic of productive areas observed in the Atlantic [*Morlière et al.*, 1994] and Pacific [*Murray et al.*, 1994; *Foley et al.*, 1997], probably under the influence of such vortices. The data indicate successively higher trophic levels extending increasingly further northward downstream away from the equator (Figures 3b, 3d, and 3e). This suggests that the ecosystem is streaming poleward under the influence of a passing instability vortex.

[8] As suggested by the pattern of surface convergence and divergence (Figure 2b), vertical motions within the vortex flow field also influence the tracer distributions. In particular, the intense convergence along the leading edge of the vortex leads to subduction, creating sharp gradients, or fronts, in all observed fields (Figure 3). Figure 4 shows a vertical section of all depth-dependent fields along one streamline selected to pass through the ship tracks

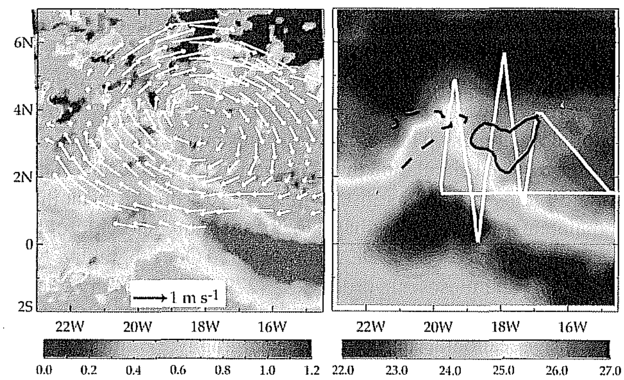

Figure 2. Left panel: shaded is POLDER-derived surface chlorophyll as seen from ADEOS-1 platform in mg m^{-3}. This image is a composite of daily images spanning June 18th to June 30th 1997. Each daily image is translated in the frame of reference centered on June 20th 1997, prior to compositing. Arrows represent the gridded surface velocities from drifters and ADCP. Right panel: 8-day averaged sea surface temperatures from AVHRR pathfinder centered on June 22nd, 1997. Surface divergence contoured every 2×10^{-6} s^{-1} is overlaid. Divergence (upwelling) is indicated by a solid black contour and convergence (downwelling) by a dashed black contour. The ship track in the translating reference frame is shown in white.

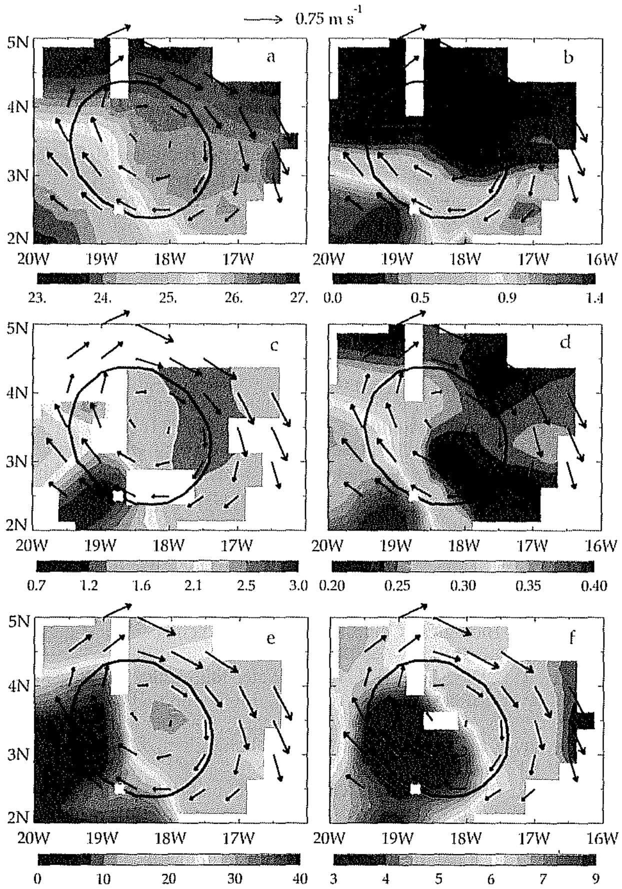

Figure 3. (a) temperature and velocities averaged down to the pycnocline depth. A non-divergent streamline is represented in black, the white star indicating the starting point of the vertical section presented in Figure 4; (b) nitrate, averaged down to the pycnocline depth, in μmol kg^{-1}; (c) gross primary production integrated down to the 0.1% light level, in gC m^{-2} d^{-1}; (d) in situ chlorophyll averaged down to the pycnocline depth, in mg m^{-3}; (e) zooplankton biomass averaged over 150 m, in dry weight m^{-3}; (f) micronekton biomass averaged over 500 m.

which cuts through the convergence/divergence dipole. Vertical velocities reaching ±10 m day^{-1}—typical of equatorial upwelling [*Weingartner and Weisberg*, 1991]—were estimated by integrating the horizontal divergence downward to the pycnocline.

[9] The section begins near 2.5°N/18.75°W, in the cold, saline, nutrient and biologically rich equatorial waters. These waters were upwelled and moved to the northwest away from the equator (Figure 3). As the water flowed poleward it encountered intense downwelling, and subducted north of 3°N (Figure 4a). The tracer distributions were consistent with this subduction: isotherms, the halocline, the nitracline, chlorophyll maximum, and zooplankton maximum all moved downward along the vortex streamline from the convergence zone downstream (Figures 4b–4f). In the equatorial Pacific during similar conditions, phytoplankton consisted mostly of *Rhizosolenia sp.*, which can adjust their buoyancy to remain at the surface, rather than subduct. The result was high surface concentrations of phytoplankton visible as a line from space [*Yoder et al.*, 1994]. Here, such a phenomenon can not occur as prokaryotes are unable to adapt their buoyancy. The downwelling explains the transition between the biologically-rich, cool waters and the biologically-poor, warm surface waters (Figures 2a and 2b).

[10] Downwelling moved nutrients down to a level of reduced light so that subsequent phytoplankton growth occurred only just above the nitracline, maintained at depth. Such a subsurface maximum is characteristic of oligotrophic waters (Figure 4e). In response to the fluid motion and food availability, zooplankton also concentrated at depth (Figure 4f). The equatorward return flow experienced upwelling at depth near 4°N/17.5°W, with the isotherms, halocline, and nitracline all progressively moving toward the surface until finally merging at the surface with the equatorial water mass (Figures 4a–4d).

4. Conclusion

[11] Thus, the cusp-like undulations of the surface fronts in temperature, chlorophyll and other variables can be primarily understood from advection processes induced by the fully three-dimensional flow field of the vortex: biologically-rich/cool/salty equatorial waters were subducted after being entrained by the vortex poleward flow, creating sharp surface fronts in all tracer fields. These biologically-rich waters favoured small pelagic fish concentration. The waters continued their circuit at depth where the ecosystem concentrated. Then they rejoined the surface after flowing equatorward, and upward.

[12] The observations are not sufficient to precisely estimate the dynamical and biological tracer budgets and determine how much

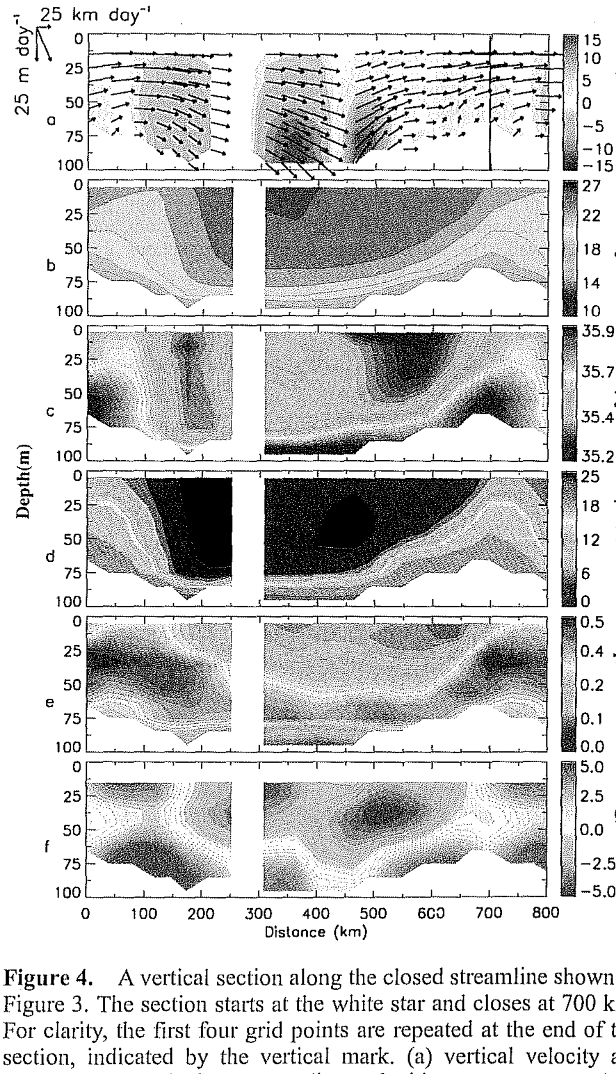

Figure 4. A vertical section along the closed streamline shown in Figure 3. The section starts at the white star and closes at 700 km. For clarity, the first four grid points are repeated at the end of the section, indicated by the vertical mark. (a) vertical velocity are colour-coded and along-streamline velocities are represented as arrows; (b) temperature; (c) salinity; (d) nitrate; (e) in situ chlorophyll; (f) acoustic backscatter anomalies, a proxy for zooplankton concentration. Day/night anomalies are defined as day/night deviations from the separately averaged day/night profiles.

of the flow recirculates versus how much is replenished with fresh equatorial water. The upwelling at depth, within the vortex acts primarily to connect the recirculating flow of the vortex, and may not imply cross isopycnal fluxes which would supply new nutrients in the system. However, it is plausible that a fresh supply of nutrients is the poleward surface flow from the equatorial upwelling.

[13] Finally, we examined SST from AVHRR and chlorophyll from SeaWifs satellite data for 1998–2000, finding 3–4 such meridional undulations each boreal summer in the equatorial Atlantic (2°N–6°N, 25°W–10°W). These instability-induced variations are clearly the dominant pattern of SST and chlorophyll variations on monthly time scales during the upwelling season. As we have seen that one such instability controlled the off equatorial distributions of tracers and organisms via a fully three-dimensional circulation, it is probable that recurrent generation of such vortices during the instability season dominates tracer and ecosystem variability on 500-km and monthly time scales. Just as instabilities contribute to the tropical ocean heat budget [*Flament et al.*, 1996; *Kennan and Flament*, 2000; *Baturin and Niiler*, 1997], they are likely to influence the seasonal biological budgets [*Kennan*, 1997]. This may be especially so in the equatorial Pacific Ocean, where equatorial upwelling acts on larger spatial and temporal scales, and tropical instabilities occur in greater numbers. Future observations should quantify these effects.

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C. Menkes, Y. Dandonneau, B. Biessy, S. Masson, J. Grelet, Y. Montel, A. Morlière, E. Marchal, G. Eldin, and A. Lebourges-Dhaussy, IRD, LODYC/UPMC, Case 100, 4 place Jussieu, 75252 Paris, France. (menkes@lodyc.jussieu.fr)

S. C. Kennan, Nova University Ocean Ctr., 8000 N. Ocean Dr. Dania Beach, FL 33004, USA. (skennan@nova.edu)

P. Flament, Department of Oceanography, University of Hawaii, 1000 Pope Rd., Honolulu, HI 96822, USA. (pflament@soest.hawaii.edu)

C. Moulin, LSCE, CE Saclay, bat. 709,91191 Gif sur Yvette, France. (moulin@lsce.saclay.cea.fr)

G. Champalbert, LOB, Campus de Luminy, 13000 Marseille, France. (champalbert@com.univ-mrs.fr)

A. Herbland, CREMA L'houmeau, Case 5, 17137 Nieul sur mer, France. (Alain.Herbland@ifremer.fr)