Extreme cross-shelf transport induced by eddy interactions southwest of Iberia in winter 2001

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[1] Unusually high for winter time satellite-derived chlorophyll-a concentrations southwest of Iberia were detected in February 2001. Analysis of satellite data (SeaWiFS, AVHRR, sea level anomaly from TOPEX/POSEIDON and ERS) revealed that the phytoplankton-rich waters were associated with an extremely long filament (up to 400 km) induced by eddy-eddy interactions occurring in the vicinity of the continental margin. The eddy interaction occurred simultaneously with an accumulation of coastal fresh water over the shelf. The event promoted an export of biogenic material offshore along with an estimated shelf flushing in a 5 to 6 day period that resulted in a dramatic offshore growth of phytoplankton. A description of the event is given and preliminary estimates of the cross-shelf transport are presented and discussed. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4219 Oceanography: General: Continental shelf processes; 4855 Oceanography: Biological and Chemical: Plankton. **Citation:** Peliz, Á., A. M. P. Santos, P. B. Oliveira, and J. Dubert (2004), Extreme cross-shelf transport induced by eddy interactions southwest of Iberia in winter 2001, *Geophys. Res. Lett.*, *31*, L08301, doi:10.1029/2004GL019618.

1. Introduction

[2] Phytoplankton biomass in the surface layers southwest of the Iberian Peninsula is low in wintertime. Chlorophyll-a concentrations (*Chl-a*) are typically below 0.3 mg m^{-3} in this area [e.g., *Peliz and Fiúza*, 1999]. The poor phytoplankton biomass concentrations are associated with relatively deep surface mixed layers (about 100 m to 150 m in wintertime) and with the northward advection of southern oligotrophic water originating in the recirculation of the Azores Current Eastern Branch. Phytoplankton biomass enrichment in the offshore zones is usually observed during summer after persistent upwelling (filaments, separated coastal jets, etc.). *Santos et al.* [2004] report a winter situation off the northwestern coast of Iberia where relatively high *Chl-a* offshore concentrations were induced by the joint effect of wind-driven dynamics and buoyant plumes. However, off the southwestern coast the influence of buoyant plumes is usually much less. In this paper, we analyse an extreme event of high offshore concentrations of *Chl-a* detected in satellite imagery. We show that the high concentrations are associated with an extreme offshore transport promoted by eddy interactions.

2. Data

[3] Surface *Chl-a* concentrations are derived from SeaWiFS L1A-LAC scenes obtained from NASA's GSFC, USA. Sea surface brightness temperature (calibrated channel 4-SST) images were processed from NOAA-14; AVHRR-HRPT level 1b data from Dundee RSF (UK). Sea surface level anomalies (SLA) result from a combination of TOPEX/POSEIDON and ERS data produced by the CLS Space Oceanography division. Winds from re-analyses by the National Center for Environment Prediction (NCEP-USA), were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, USA.

3. The *Chl-a* Filament

[4] Figure 1 shows a *Chl-a* image from 11 February 2001. A southwestward oriented pigment-rich filament protruding into the offshore oligotrophic waters is clearly visible. The difference in concentrations is on average one order of magnitude (around 0.1–0.2 mg m^{-3} for the background and 1.0–1.5 mg m^{-3} inside the filament). The filament appears to be rooted in the coastal zone between Cape Sines and Cape S. Vicente (S and SV in Figure 1). The pigment structure is about 400 km long reaching as far as 13°W and 35°N, and shows clear signs of turbulent interactions along its path. Unfortunately, visible and infrared imagery from the preceding days is strongly contaminated by clouds and it is not possible to follow the development of the filament. The clearest image of the zone corresponds to 16 January and no evident signs of the filament were observed on that date. The filament is still visible on 18 February and appears to be decaying by 28 February. This indicates that the structure took less than a month to develop and remained active for a period of two to three weeks.

[5] Filaments off western Iberia usually develop after long and persistent upwelling driven by northerly winds. Alternatively, this filament could have developed as a consequence of the separation of a northward coastal flow driven by long and intense east-southeasterly winds on the southern coast. This situation is, however, unlikely and NCEP data for the period from the beginning of January to mid-February indicate that neither of these scenarios occurred. The winds were predominantly from the southwest. Therefore, the hypothesis that the filament relates to wind-driven dynamics alone should be eliminated.

4. The Eddy-Eddy Interaction Event

[6] Analysis of SST imagery (Figure 2) reveals that significant mesoscale activity was taking place southwest

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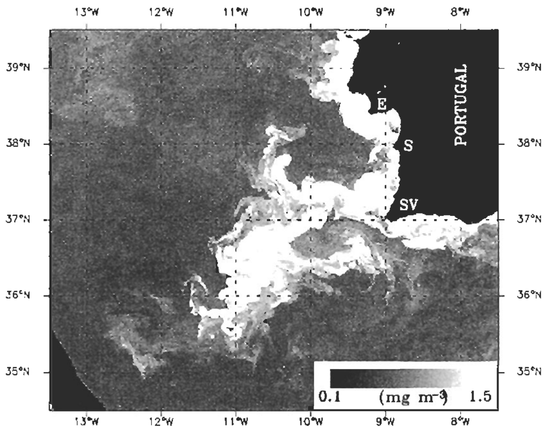

Figure 1. SeaWiFS-derived surface *Chl-a* concentrations (mg m^{-3}) southwest of the Iberian Peninsula on 12 February 2001 (E, Cape Espichel; S, Cape Sines; and SV, Cape St. Vincente).

of Iberia during January and February 2001. In the infrared images, two counter-rotating eddies (A1 and C1) are observed to interact in the slope zone between Cape S. Vicente and Cape Espichel. An anticyclone to the north (eddy A1, about 80 km wide) was already evident in the SST image of 11 February over the slope off Cape Sines. Later, a cyclone is generated (C1) as a result of a developing northward intrusion from the Gulf of Cadiz contouring the southwestern tip of Iberia. This current intensifies and rotates cyclonically between 16 and 25 February (Figures 2b and 2c). This northwestward flow interacts with the anticyclonic eddy (A1) and both contribute to the further development of the offshore jet (marked with a black arrow). Afterwards the dipolar interaction slowly migrates northward, pushing the cross-shelf jet in the same direction several tens of kilometers from Cape S. Vicente to the zone off Cape Sines.

[7] During the two week period (covered by the available IR data), while the squirt is advected northward, it acts to drain mass from the shelf into the deep ocean. On the ocean side, two larger eddies (A2 and A3) further induce the evolution of the filament. The large anticyclone (A2) in the southwest pushes the filament to the south while A3 together with C1 promote an eastward branching (Figure 1). Finally, it should be noted that the source waters for the filament are colder (~14.5°C) than the offshore waters (~16.5°C) (absolute SST not shown). Taking a climatological value of salinity (~36.35) the filament waters must be less than 35.7 to ensure static stability. This is a clear indication of their runoff origin (most likely from the southern coasts given the prevailing wind direction). The winter of 2001 was also characterized by a high precipitation rate (the second highest weekly values after 1990 from NCEP data).

5. The Origin of the Filament

[8] Although it is relatively easy to track the peak of development and decay of the filament, the lack of data for the development period as noted above precludes a clear description of the origin of the eddies and of the generation of the filament. However, the SLA maps (Figure 3) show that by 17 January a large anticyclonic feature was already present off southwest Iberia. It appears to be composed of two anticyclones (A1 and A2) which lie on the edge of a clearly defined cyclonic zone to the south. The large gradient in SLA is coincident with the axis of the filament in Figure 1. By 31 January (Figure 3b) the cyclonic zone extends offshore and to the north and (C1) starts developing. The sequence of weekly SLA maps show that at the end of January, A1 and A2 separate, and by 14 February (Figure 3c) the SLA maps match the situation described in the SST images. In this context, the preconditions for the generation of the filament had started by 17 January, and were promoted by the interaction of the two large anticyclones with the cyclonic flow south of Iberia. After 31 January the positive anomalies (anticyclones) apparently lose intensity and the SLA gradient becomes zonally oriented in the vicinity of the coast. Also the two anticyclones are then separated, giving rise to a north-

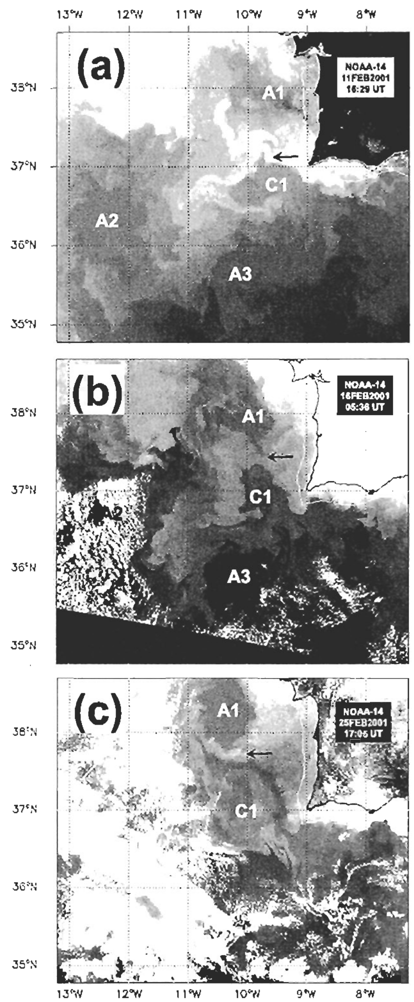

Figure 2. Sequence of NOAA-14 AVHRR SST (channel 4 brightness temperatures) images of the SW Iberian Peninsula: (a) 11, (b) 16 and (c) 25 February 2001. SST values increase from light (colder waters) to dark grey (warmer waters).

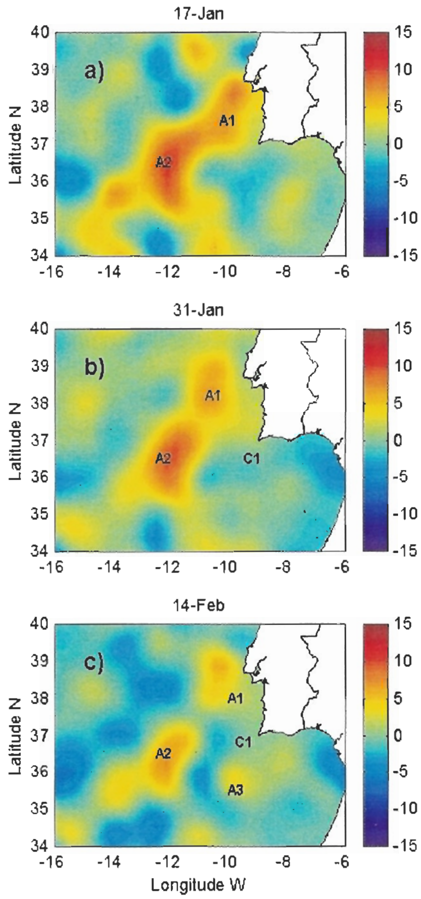

Figure 3. Maps of Sea Surface Level Anomalies (cm) for southwestern Iberia on 17 and 31 January and 14 February. Labels indicate eddy structures discussed in the text.

ward branching of the advective path (see A1 in Figures 1 and 2a).

6. Simulations of the Filament With Lagrangian Trajectories

[9] Velocity fields were calculated for the period between 1 January and 15 February 2001. Space and time interpolation has been used to regrid the SLA to a 5 × 5 km grid for the domain shown in Figure 4. The geostrophic velocities derived from SLA were calculated according to

$$fv_{geo} = g\partial\eta/\partial x, \quad fu_{geo} = -g\partial\eta/\partial y, \qquad (1)$$

where η represents SLA. The Ekman velocities, $v_{ek} = \tau/(\rho d f)$, with d (Ekman layer depth) being 15 m, f the Coriolis parameter for the given latitude, and the surface stress $(\tau_x, \tau_y) = \rho_a Cd|w|(w_x, w_y)$, with $\rho_a = 1.22$ kg m^{-3} being an average air density, w wind velocities from NCEP reanalysis and $C_d = 0.0012$, a drag coefficient. Lagrangian trajectories were calculated with the estimated velocity fields using a 2nd order Runge-Kutta integration scheme. The paths were calculated for sets of particles released off southwestern coast of Iberia at the beginning of January. Different experiments with varying parameters were conducted. Figure 4 shows the results for three of these experiments. In the first (Figure 4a) it is assumed that the particles are advected within the Ekman layer and the geostrophic velocity is zero ($v = v_{ek}$). It was observed that all particles migrate uniformly in a southeasterly direction (coastward). For the second experiment (Figure 4b) the Ekman velocity was added to the velocities derived from the SLA values ($v = v_{ek} + v_{geo}$). In this case, a considerable number of particles drift offshore in the direction of the filament, but the generated filament is rather short. Finally, in the last experiment (Figure 4c), the SLA-derived velocities were multiplied by a factor of two and the influence of the wind was disregarded ($v = 2 * v_{geo}$). In this case it is observed that a number of patterns of the real filament could have been simulated (compare Figure 4c with Figure 1). Notably the southwestward extension of the filament is very similar to that which is observed in the satellite imagery. Also the particles describe paths

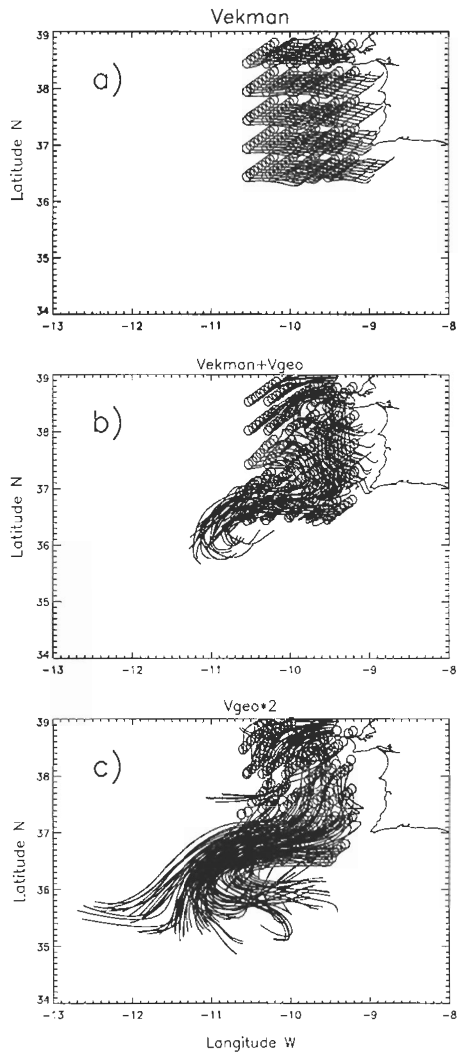

Figure 4. Estimated Lagrangian trajectories from 1 January to 15 February 2001. Open circles indicate the start of the trajectory. (a) Lagrangian trajectories estimated with Ekman velocity only. (b) Trajectories estimated with Ekman and geostrophic velocities (calculated from SLA) summed. (c) Trajectories estimated with geostrophic velocities (from SLA) multiplied by two.

recirculating eastward, resembling an eastward branching (contouring cyclone C1) of the filament (see Figure 2). We conclude that, off the coast, the wind has little influence on the generation of the advective path. Secondly, the geostrophic velocities derived from the SLA seem to be rather weak in relation to the ones that were necessary to generate the filament. This may be caused by the smoothing used to produce the SLA maps from the altimeter tracks. *Hernandez and Le Traon* [1995] also found a factor of 2 for the difference in the steepness of the altimeter dynamic height circulations maps in the Azores Region. Also, the advective path created between the eddies may in reality be rather narrow, and so the filament widens due to mixing and Ekman transport.

7. Estimates of Offshore Transport

[10] Assuming an average cross-shelf flow of about 0.15 m/s (estimates from SLA values), 30 km wide and 150 m deep (shelfbreak depth), the estimated offshore transport is 0.675 10^6 m^3/s (~58 km^3/day). The shelf zone where the core of the squirt was located (between Capes Espichel and S. Vicente) is about 20 km wide and 140 km long. Taking a mean depth of 80 m (half shelf depth) the total volume of this zone is approximately 280 km^3. The estimated period for shelf flushing is about 5 to 6 days. Assuming that the filament was active for about two weeks it is expected that shelf waters would have been completely renewed at least once. By means of image classification it was possible to estimate the area of the filament; 89260 km^2 and its average *Chl-a* concentration, 0.7 mg/m^3 (from which we subtract the background concentration 0.2 mg/m^3). Given a depth of 20 m for the vertical extension of the plume [e.g., *Santos et al.*, 2004], a total of 893 t of *Chl-a* were contributed by the filament to the offshore surface waters. The net *Chl-a* transport crossing the slope may be estimated using $C_{tot} = (C_{shelf} - C_{ocean})\ V_p$ where C_{shelf} and C_{ocean} are respectively reference values for *Chl-a* concentrations over the shelf and offshore (1.2 and 0.2 mg/m^3) and V_p is the cross-slope transport calculated as above but now for a depth compatible with the *Chl-a* plume (20 m). With these values the obtained cross slope *Chl-a* transport is only 8 t/day. Taking 20 days for the development of the filament (assuming a constant transport) the expected biomass within the filament due to cross-shore transport would be ~160 t. Though the values used are arguable, the difference suggests that a dramatic growth of *Chl-a* was registered inside the filament along with its development into deep ocean side.

8. Discussion and Conclusions

[11] Coastal summer filaments are known to be the most effective mechanisms of cross-shelf exchange in the Iberian region with lengths of up to 200–250 km from the coast [e.g., *Haynes et al.*, 1993; *Peliz et al.*, 2002]. These filaments relate to strong coastal fronts and jets that are generated in persistent summer upwelling conditions. The upwelled water is denser than offshore surface water and the filaments tend to subduct and dissipate as they cross the slope (no significant phytoplankton production is observed at large distances from the coast). In the present case, a set of eddies southwest of Iberia created an advective path that provided a conduit to transport coastal waters as far as 400 km from the origin. Buoyancy input from coastal river plumes (particularly intense in that winter) provided stratification and nutrients for an extensive phytoplankton development. In summary, the export mechanism from shelf to deep ocean described here is intrinsically different from that reported in literature for the western Iberia. Firstly, the process driving the cross-shelf transport is not related to wind but to extra-coastal mesoscale dynamics that generated an advective path between the offshore eddies, much longer than the ones observed in summer filaments. Secondly, coastal fresh water provided buoyancy along the length of the filaments, enabling phytoplankton production to occur very far from the coast.

[12] In this region, several sources of mesoscale eddy activity exist (Meddies [e.g., *Serra et al.*, 2002], the Iberian Poleward Current [e.g., *Peliz et al.*, 2003], and the Azores Current Eastern Branch [e.g., *Pingree et al.*, 1999]) rendering this narrow shelf zone particularly exposed to eddy-eddy interactions. It is possible that similar events occur frequently with large impacts on the local ecosystems.

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