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'Prestige' oil spill and Navidad flow

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The spread of the oil spill from the tanker 'Prestige' was analysed in relation to the occurrence of the exceptional 2002/2003 *Navidad* using airborne and AVHRR satellite measurements. Altimeter-derived geostrophic velocity and Envisat ASAR observations were also used to investigate the structure of this Cantabrian extension of the poleward current around Iberia.

INTRODUCTION

The oil spill off the Galician coast (north-west Spain) that followed the wreckage (13 November 2002) and sinking (19 November 2002) of the tanker 'Prestige' has been a matter of great concern for environmental scientists and ecologists. One year later, the figures and consequences of this maritime accident are still overwhelming: more than 60,000 tn of fuel shed to the sea according to independent reports (CEDRE; http://www.le-cedre.fr/fr/prestige/index.htm), and approximately 20,000 birds found dead or polluted by July/September 2003 along north-west and northern Spain (SEO/BirdLife, 2003; http://www.seo.org/2002/prestige/noticias.asp?id=207). This short paper analyses how the oil slicks were driven eastwards along northern Spain by using combined airborne observations and thermal infra-red, altimeter and Envisat ASAR satellite measurements.

MATERIALS AND METHODS

The spread of the 'Prestige' oil slicks is shown on top of AVHRR (Advanced Very High Resolution Radiometer) images as colour spots (Figure 1). The occurrence of the 2002/2003 *Navidad* is further analysed (Figure 2) using the North Atlantic Oscillation index (November–December NAO) and Sea Surface Temperature (SST) values along northen Spain (4° and 8°W). Some complementary altimeter (geostrophic velocity) and Envisat ASAR (oil slicks) observations are presented in Figure 3. The AVHRR images (channel 4 thermal infra-red) have been processed following Holligan et al. (1989) and using Dundee University (NOAA-17) and own (NOAA-15) data. The altimetric maps of geostrophic velocity (Sea Level Anomaly derived velocity; $cm\,s^{-1}$) have been constructed using merged altimetric data (ERS-2, GFO and JASON satellites) from the AVISO datasets (CLS, France). Envisat ASAR wide swath data have been provided by the Earth Watching Programme of the ESA (European Space Agency). The positions of the oil slicks or spots have been obtained from aeroplane surveys and are used with permission of CEDRE (Centre de documentation de recherche et d'experimentations sur les pollutions accidentelles des eaux). The NAO–SST relationships (1979–2004) extends to the winters of 2000/2001 and 2002/2003 ('Prestige' accident) the relationships described in Garcia-Soto et al. (2002). The 2001 and 2003 SST values have been obtained from AVHRR data of the SATMOS public archive (http://www.satmos. meteo.fr/; Meteo-France; 1–10 January 2001 and 11–20 January 2003). The NAO index values have been extracted from the Climate Prediction Centre (NOAA-CPC; ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/tele_index.nh). The diagnostic procedure at CPC is the Rotated Principal Component Analysis (RPCA; Barston & Livezey, 1987), that isolates the primary teleconnection patterns for all months and allows for time series of the amplitudes of the patterns to be constructed.

RESULTS AND DISCUSSION

The AVHRR image on 26 November 2002 (Figure 1A) was acquired only seven days after the ship sank. This and the image on 13 January 2003 represent the first clear thermal observations for the follow up study after the 'Prestige' accident. The warm water of the Poleward Current (Deschamps et al., 1984; Pingree & Le Cann, 1989, 1990) is seen to have entered the Bay of Biscay around Galicia and extended eastwards along the Cantabrian shelf and slopes. During winter (Figure 1B), when the inflow of warm water tends to be a maximum (December–January; Pingree & Le Cann, 1992), the outer temperatures become more sharply defined and the warm *Navidad* water exhibits the characteristic decreasing thickness from west to east thought to result (Pingree & Le Cann, 1989) from a flow that decays spatially alongslope (eastward). The interannual variability of this warm winter structure and its relation to the NAO has been recently described (Garcia-Soto et al., 2002) and the present 2002/2003 observations (November–December NAO Index: −1.8; Figure 2) correspond to its fourth strongest development over the last 25 years (1995/1996, 1997/1998, 1989/1990 and 2002/2003, ranked by order of intensity).

The oil slicks (colour spots on the AVHRR images) during late November enter the north Spanish region and extend eastwards along the shelf-break and slopes (200–2000 m depth) near the outer edge of the warm water (see Figure 1A). The leading edge of the oil spots on 30 November (44.15°N 5.56°W) and 5 December

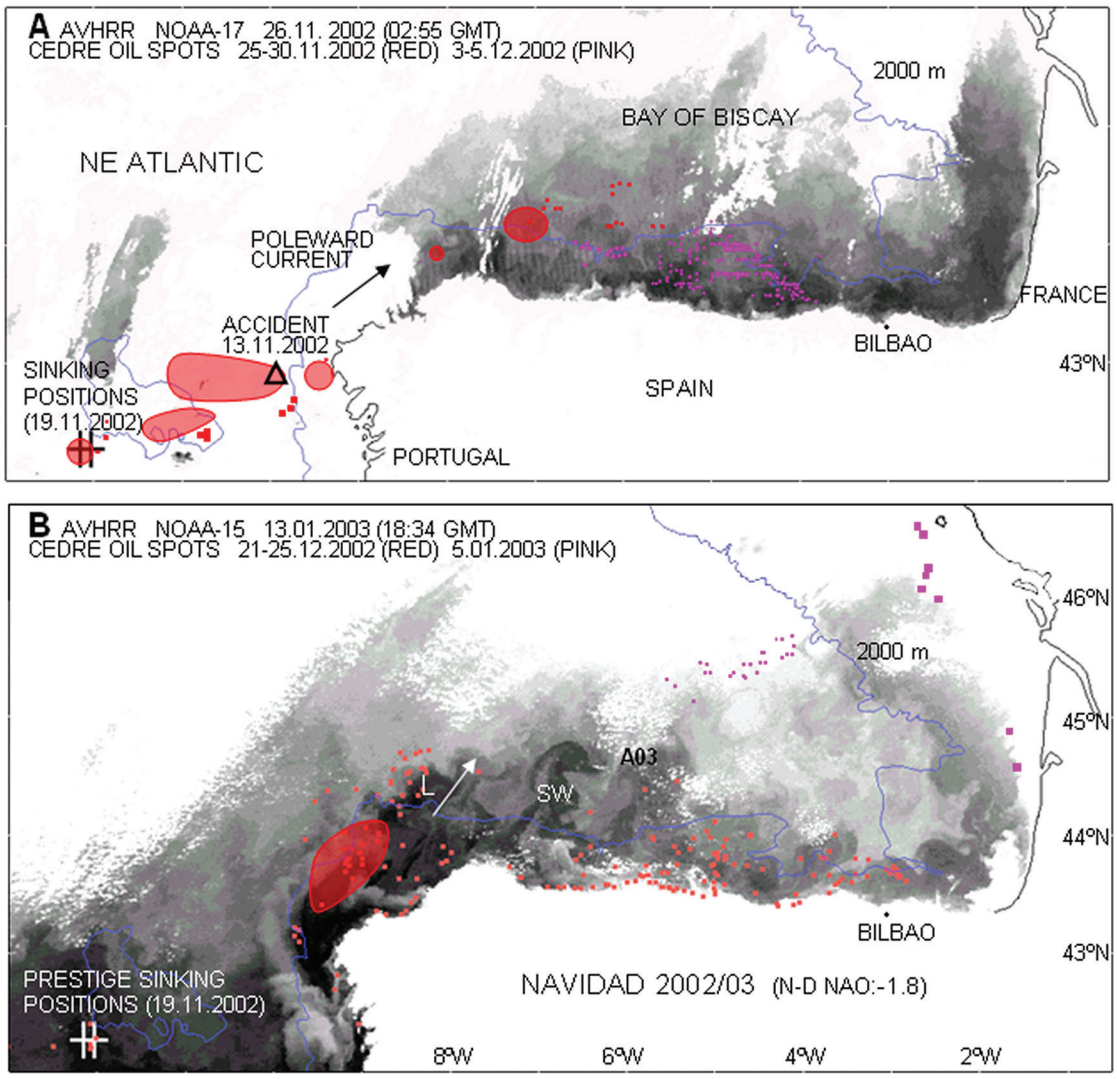

Figure 1. Thermal infra-red images (AVHRR) showing the warm water (dark shades) of the Poleward Current extending along the Cantabrian shelf and slopes after the sinking of the tanker 'Prestige'. (A) 26 November 2002 and (B) 13 January 2003 (2002/2003 *Navidad*). Poleward pulses of warm water extending from 36°N (Portugal) to north-west Spain can be observed in the satellite archive from as early as 7 November (6 days before the initial 'Prestige' accident). Strong south-west winds were also recorded along the Galician coast at the time of the accident (up to 21 m s^{-1} at Corón (7 m altitude) on 13 November 2002; MeteoGalicia, http://www.siam-cma.org/meteoroloxia/busca.asp). Colour spots show positions of oil slicks from aerial surveys (e.g. http://www.le-cedre.fr//fr/prestige/carto.htm); data provided by CEDRE (Dr Franck Laruelle). Some oil spots can still be seen in the sinking region itself in late December, and can correspond to 'Prestige' oil that has surfaced from the sea bottom (~3800 m depth). SW and A03 (A from Aviles Canyon region) represent possible formation of slope water oceanic eddies or swoddies (Pingree & Le Cann, 1992). L indicates leakage of warm slope water to the oceanic Bay of Biscay from north-west Spain. A large concentration of oil spots was driven to the ocean from this region on 24 December, and by 5 January (see pink dots) was centred near 45.50°N 4.75°W.

(43.52°N 3.82°W) gives an estimated eastward speed of ~30 cm s^{-1} (26 km a day) for the central Cantabrian region. In a first approximation to the main contributing factors, this oil velocity results in a wind ratio of ~3% of westerly wind speed using the *in situ* wind data at 43.47°N 3.80°W (INM) and the mean altimeter derived current (~10 cm s^{-1}; eastwards) in the region (43.86°–44.34°N 3.67°–6.00°W). The value compares with the 3.4% wind factor determined in Smith (1968) in the 'Torrey Canyon' oil spill (with weak shelf currents) though some of the 'Prestige' oil spots would have been further assisted eastwards in the warm water flow. In the western region (6–7°W), values of eastward geostrophic velocity (altimeter derived) up to 35 cm s^{-1} on 27 November and 20 cm s^{-1} on 4 December are for example recorded. Overall the altimeter measurements reveal the horizontal structure of the current during late autumn and winter (see Figure 3A; 18 December 2003) that is seen to extend continuously from Galicia to the vicinity of Bilbao (43°15′N 2°56′W). The distribution of oil slicks in the Envisat ASAR image of 16 December (Figure 3B) also appears to trace the winter slope current or *Navidad* coming from the west, with a slick on the continental shelf/slope region where the currents are expected to reach maximum values.

Oil spills in the region of influence of large-scale currents, such as the Poleward Current or *Navidad*, can

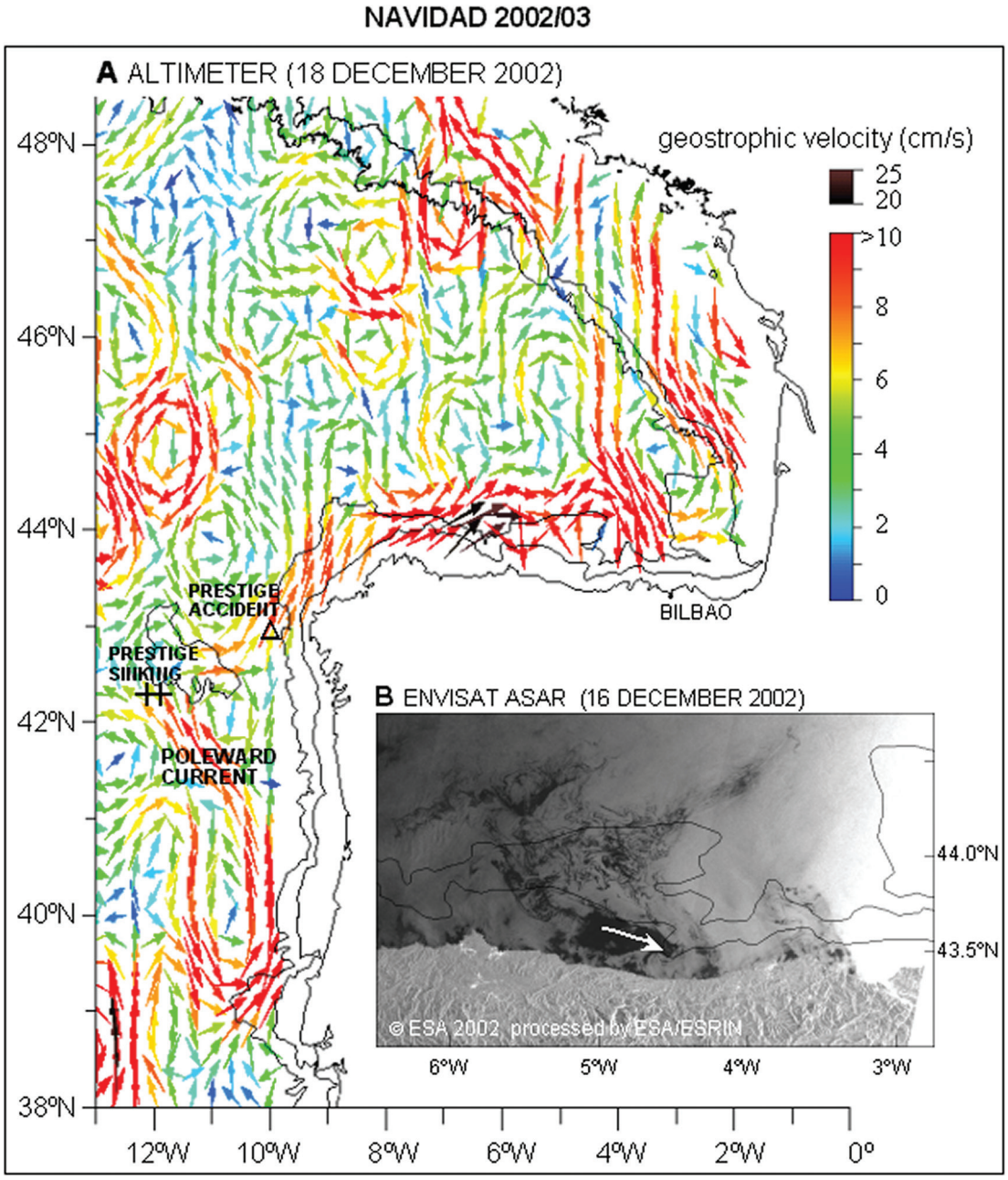

Figure 3. (A) Map of altimeter-derived geostrophic velocity (cm s^{-1}) showing the 2002/2003 Poleward Current extending from southern Portugal to the Celtic Sea on 18 December 2003. Near Bilbao the geostrophic currents appear to disrupt the slope flow continuity with cyclonic conditions around the cooler surface water in the south-east (see also Figure 1B). The maximum speed of the poleward flow (20–25 cm s^{-1}; see black arrows) is observed in the vicinity of Aviles Canyon (Cantabrian or *Navidad* region). The maximum values of eastward current (altimeter derived) at this region (6–7°W) are given here to the nearest 5 cm s^{-1} for dates 6 November 2002 (7 days before the 'Prestige' accident) to 15 January 2003: 10 cm s^{-1} (6 November), 15 cm s^{-1} (13 November), 20 cm s^{-1} (20 November), 35 cm s^{-1} (27 November), 20 cm s^{-1} (4 December), 10 cm s^{-1} (11 December), 25 cm s^{-1} (18 December), 20 cm s^{-1} (25 December), 25 cm s^{-1} (1 January), 30 cm s^{-1} (8 January) and 5 cm s^{-1} (15 January). (B) Envisat wide swath ASAR image showing possible oil slicks off northern Spain on 16 December 2003 (2002/2003 *Navidad*). Data provided by the Earth Watching Programme of the ESA (European Space Agency; http://earth.esa.int/ew/oil_slicks/galicia_sp_02/os_galicia_nov_02.html).

have international implications as the flow spreads the oil across EEZ waters of adjacent countries. By 25 December (Christmas or Navidad day), the oil has extended 780 km from the sinking region. The AVHRR satellite images in January (see Figure 1B) shows the warm *Navidad* water extending northwards a further ~400 km along the Armorican continental slope to 47°N, west of Brittany (France). This is expected for a strong *Navidad* year and oil spots along the Armorican region are first observed extending from ~44.5°N to ~46.5°N on 5 January (see also Figure 1B). It is the tragic concurrence of the man made factors and these strong environmental conditions

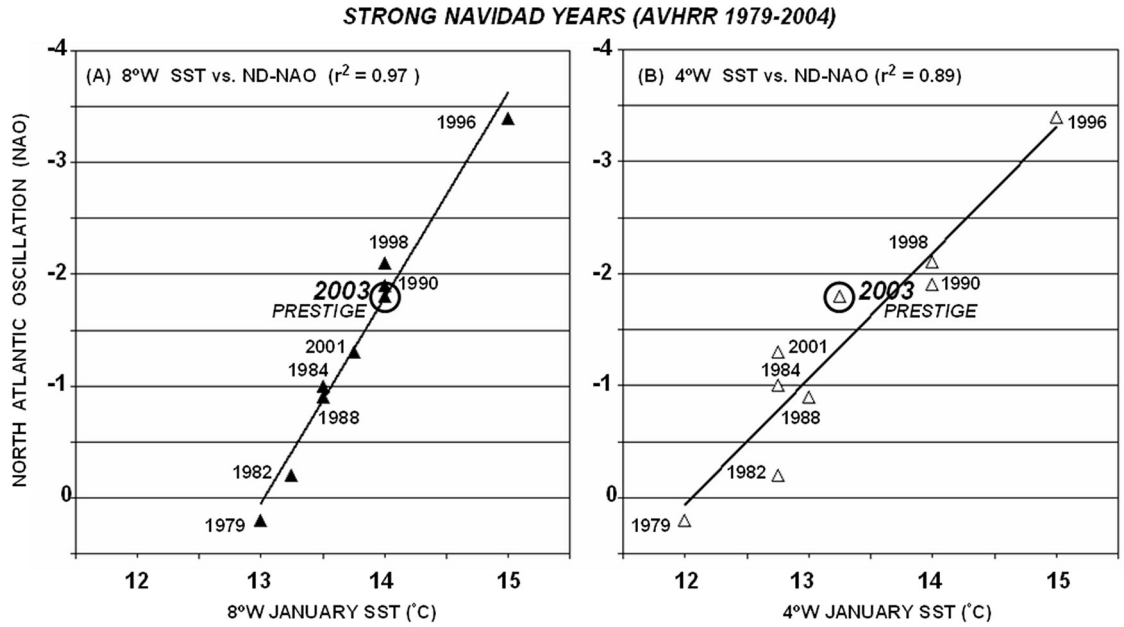

Figure 2. Relationships between North Atlantic Oscillation (NAO) index (November + December values) and Sea Surface Temperature (SST) off northern Spain (°C; January values to the nearest 0.25°C) at (A) 8°W and (B) 4°W during years of strong *Navidad*. Though the number of observations is low (N=9) the distributions are tight and significant (r^2=0.97 at 8°W and r^2=0.89 at 4°W). The figure extends to the winters of 2000/2001 and 2002/2003 ('Prestige' accident) the ND NAO–SST relationships described in Garcia-Soto et al. (2002). The SST data for the period 1979–1993 (CMS/CMM) were first published in Pingree (1994). During the last 25 years (1979–2004) the available AVHRR images have shown the *Navidad* warm water extending clearly from Galicia to France during nine winters: 1978/1979, 1981/1982, 1983/1984, 1987/1988, 1989/1990, 1995/1996, 1997/1998, 2000/2001 and 2002/2003. Among these nine events of strong *Navidad*, the winter of the 'Prestige' accident (2002/2003; highlighted in the Figure) shows the fourth most marked values of SST and ND NAO index (−1.8). NAO represents the first mode (32% of variance; Cayan, 1992) of low frequency variability over the North Atlantic and its regional extension and amplitude is most pronounced during the winter (December–February; Barston & Livezey, 1987), when the *Navidad* takes place.

that has made the 'Prestige' oil spill one of the most extensive oil spills in history.

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