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Short Communication

Three ocean state indices implemented in the Mercator-Ocean operational suite

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We present three indices for the state of the ocean, all computed using the Mercator-Ocean analyses and ocean forecast system: an upwelling index based on sea surface temperature (SST), the tropical cyclone heat potential, showing the thermal energy available in the ocean to enhance or decrease the power of cyclones, and the Indian Ocean dipole mode index based on SST. Such indices are updated on a weekly or monthly basis.

Keywords: environmental indicators, ocean, operational forecast system.

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Introduction

Ocean environmental indices provide information that leads to a better understanding of the oceans and their ecosystems, as well as providing a simple representation of ocean-climate variability. In the best-case scenario, they also allow users to anticipate the effects of environmental hazards and pollution crises. Mercator-Ocean is a public institute based in Toulouse, France, whose goal is to deliver comprehensive, worldwide information on the oceans' physical state from surface to bottom, using ocean modelling and data assimilation. To this end, Mercator-Ocean operates a large range of operational systems [ocean forecast system (OFS)] that can analyse and forecast the three-dimensional ocean state, including temperature, salinity, and currents at various resolutions. We briefly present the OFS, then describe three currently available ocean environmental indices.

The OFS

The first component of the OFS is the ocean model. The primitive-equation general-circulation model, in the global and regional case, is based on the Nucleus for European Modelling of the Ocean (NEMO) code (Madec *et al.*, 1998). Daily surface atmospheric conditions are given by the analyses and forecasts of the European Centre for Medium Range Weather Forecast (ECMWF). The second component is the assimilation system. It was developed to assimilate satellite sea-level anomaly (SLA) data coming from the SSALTO/DUACS data centre gathering all available missions (JASON, ENVISAT, and GFO), as well as sea surface temperature (SST) and vertical profiles of *in situ* temperature and salinity measurements from the CORIOLIS centre (ARGO profiling floats, XBT, CTD, TAO/PIRATA/TRITON moorings). The weekly analyses/forecast run for day D begin with two successive 1-week analyses, starting at day D − 14. Then, from day D, the system performs 2 weeks of forecasts, driven at the surface by the ECMWF atmospheric forecast. Weekly runs provide daily mean analysis and forecast fields of temperature, salinity, and currents among other fields.

Currently, three different global systems are running weekly, together with one regional system covering the North Atlantic and Mediterranean basins:

(i) 1/15° grid on the horizontal (5–7 km)/43 vertical levels North Atlantic and Mediterranean Sea OFS, with assimilation of SLA, SST, and *in situ* temperature and salinity profiles.

(ii) 2° (1/2° in tropical regions) grid on the horizontal/31 vertical levels Global OFS, with assimilation of SLA only. This low-resolution system spans the global ocean and has provided initial oceanic conditions for the Météo-France seasonal forecasting ocean–atmosphere coupled model since 2003.

(iii) 1/4° grid on the horizontal/46 vertical levels Global OFS, with assimilation of altimetry alone. This system allows evaluation of mesoscale circulation features in the ocean and has produced weekly analyses and forecasts since October 2005.

(iv) 1/4° grid on the horizontal/50 vertical levels Global OFS, with assimilation of SLA, SST, and *in situ* temperature and salinity profiles. The sea-ice life cycle is realistically represented with the implementation of the LIM2 model with sea-ice concentration, sea-ice/snow thickness, sea-ice drift, and sea-ice thermal content.

Other systems, such as a global 1/12° grid, a European coast 1/36° grid, and a coupled ocean-physics and ecosystem global 1° model, are being developed and will be operational within the next few years.

Daily quality control and assessment are performed on each system. The OFSs have been proven to give good descriptions of the state of the ocean (temperature, salinity, and currents) from surface to bottom (Drévillon *et al.*, 2008). They serve various applications, from ocean and climate-research projects to environmental monitoring. They also provide useful products for the fishing industry, coastal management (such as oil-spill monitoring/prediction using surface currents), real-time support for scientists during oceanographic cruises and yacht racers, as well as the initial conditions for seasonal prediction and ocean reanalysis.

Three environmental indices under development

Upwelling index

Upwelling indices based on SST information (Demarcq and Faure, 2000; Atillah *et al.*, 2005; Benazzouz *et al.*, 2006; Marullo *et al.*, 2006) have been proven efficient in an operational context (Demarcq and Faure, 2000; Benazzouz *et al.*, 2006). These indicators represent proxies for the actual process leading to the lift of deep water onto the shelf, i.e. the upwelling process itself.

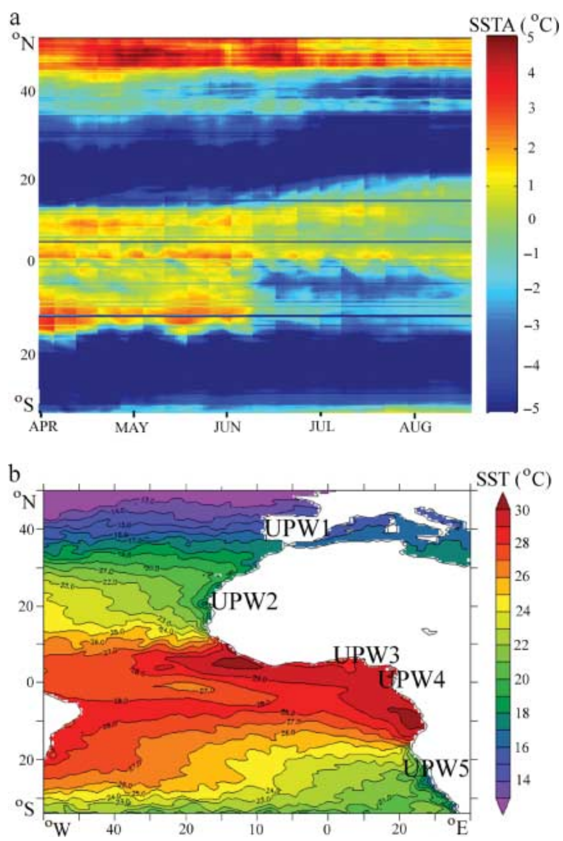

Figure 1. Upwelling index in the Atlantic Ocean: (a) SST anomalies (°C) as a function of time (end of March until August, 2007) and latitude (34°S – 50°N) in the Mercator-Ocean Global 1/4° OFS assimilating SLA, SST, and *in situ* profiles; and (b) geographic location of upwelling areas 1 – 5 in relation to the continental land mass.

Marullo *et al.* (2006) have defined an upwelling index that is a simplified version of the Demarcq and Faure (2000) index. It is therefore easier to implement and has been chosen for a test implementation in the OFS. However, the normalized upwelling index defined by Demarcq and Faure (2000) is independent of various local characteristics and will be implemented soon because it appears more robust and independent of latitude. Another upwelling index using the three-dimensional velocity field (Blanke *et al.*, 2005) will also be implemented because it makes better use of the three-dimensional information provided by the OFS.

Quantities required for the Marullo *et al.* (2006) upwelling index have been computed in the Atlantic Ocean (Figure 1a) from 50°N down to 34°S, from the end of March 2007 until August 2007, in the Global 1/4° OFS, assimilating SLA, SST, and *in situ* temperature and salinity profiles. Upwelling events are characterized by a negative temperature anomaly event and can be clearly identified. Five upwelling events have been identified in the Atlantic basin along the European–African coast (Figure 1b). The results are still considered preliminary because the index is using only SST information. However, it does provide an upwelling-index prediction 2 weeks in advance.

Tropical cyclone heat potential

The thermal energy available in the ocean partly controls whether the power of cyclones is enhanced or decreased. The thermal energy of warm water that partly powers a cyclone is known as tropical cyclone heat potential (TCHP; Goni and Trinanes, 2003) or ocean heat content (Shay *et al.*, 2000). TCHP is defined as a measure of the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm (Leipper and Volgenau, 1972).

Several hurricanes have intensified when their tracks passed over eddies or other warm-water masses with high TCHP values (Shay *et al.*, 2000; Goni and Trinanes, 2003; Scharroo *et al.*, 2005). For example, in late August 2005, when Hurricane Katrina passed over the Loop Current and a large warm-core ocean ring in the Gulf of Mexico, it evolved quickly from a Category 3 to a Category 5 event in a matter of 9 h. Therefore, the monitoring of the upper-ocean thermal structure has become a key element in the study of cyclone–ocean interaction with respect to the prediction of sudden cyclone intensification.

TCHP is usually computed from the altimeter-derived vertical temperature-profile estimates in the upper ocean (http://www.aoml.noaa.gov/phod/cyclone/data/intro.html or http://iwave.rsmas.miami.edu/ñick/heat). The OFS derives the TCHP directly from the prognostic variables of the ocean numerical models that are run in real time and that are constrained by the altimeter data (SLA). Thus, the OFS provides more precise information about the upper-ocean thermal structure, complementing that derived from the surface altimeter. The great advantage is the ability to provide TCHP predictions 2 weeks in advance. An example (Figure 2) shows the TCHP forecast from the Global 1/4º OFS assimilating SLA, SST, and *in situ* temperature and salinity profiles, along Cyclone Krosa's track in the Northwest Pacific in October 2007.

There is great interest in the hurricane-modellers' community for realistic TCHP products (Shay *et al.*, 2006), because coupling forecast models to ocean models allows them to take into account the influence of TCHP on hurricane behaviour. Hence, realistic ocean-model products are needed.

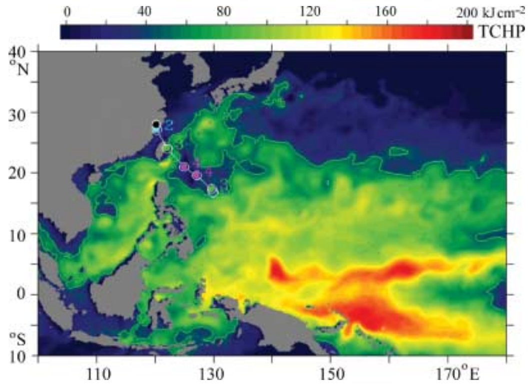

Figure 2. TCHP (kJ cm^{-2}) in the Mercator-Ocean Global 1/4° OFS in the Northwest Pacific Ocean, October 2007, with the track of Cyclone Krosa superimposed (numbers indicate category).

Indian Ocean dipole

Saji *et al.* (1999) have described a coupled ocean–atmosphere dipole mode for the Indian Ocean. Periods of a persistently high dipole mode index (DMI) could trigger extreme September–November rainfall in tropical East Africa (Black *et al.*, 2003). This mode is characterized by a negative (cold) SST anomaly (SSTA) in the southeastern tropical Indian Ocean (SETIO) and a positive (warm) SSTA in the western tropical Indian Ocean (WTIO; Saji *et al.*, 1999). It is also characterized by an intensified easterly wind anomaly over the central Indian Ocean, as well as a change in the position of the thermocline, which becomes shallower in the eastern and deeper in the western equatorial Indian Ocean. DMI is defined as the difference of SSTA between areas of WTIO (50–70°E, 10°S–10°N) and SETIO (90–110°E, 10°S–Equator; Figure 3a).

DMI, as estimated in the Global 1/4° OFS assimilating SLA, SST, and *in situ* temperature and salinity profiles (Figure 3b), is in agreement with analyses of weekly SST observations (Reynolds *et al.*, 2002). The Indian Ocean underwent a period from mid-June to mid-July 2007 with a negative DMI, before returning to a positive situation from mid-July to the present.

Concluding remarks

The three examples of ocean environmental indicators represent parts of larger work going on at Mercator-Ocean within the Global Monitoring for Environment and Security (GMES) framework. Currently, work is directed towards publishing several ocean indicators on the website and updating these on a weekly or monthly basis. The aim is to promote these new services to a wider audience and to provide a simple representation of ocean-climate variability. The development of environmental ocean indices is being tuned to the requirements of targeted users—including European agencies (e.g. European Environment Agency), intergovernmental bodies, and Member State agencies—to ensure the best match between the services and existing policies and regulations. Also, three-dimensional ocean fields are provided to downstream users to let them define other environmental indices.

The description of the ocean is continuously being improved by using more sophisticated data-assimilation techniques and a more realistic ocean model with improved parameterizations and higher spatial resolution (1/12°).

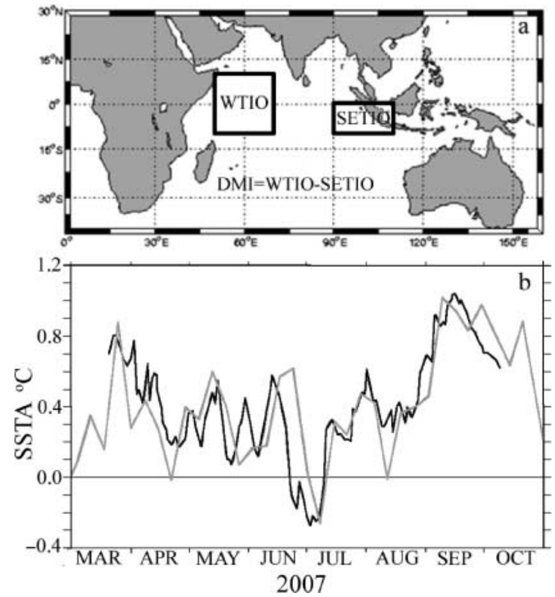

Figure 3. DMI: (a) location of WTIO and SETIO boxes in the Indian Ocean (after Saji *et al.*, 1999); and (b) difference of SSTA (relative to 1971–2000 climatological data from Reynolds *et al.*, 2002) in WTIO and SETIO boxes in the Mercator-Ocean global 1/4° OFS (black line) and in the weekly SST analysis (grey line; from Reynolds *et al.*, 2002).

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