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GRADHIST — A method for detection and analysis of oceanic fronts from remote sensing data

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ABSTRACT

Oceanic shelf sea fronts have significant effects on local dynamics, ecology and climate. An assessment of the impact of climate change on frontal positions and frontal gradients requires reliable reference data and the possibility to monitor oceanic fronts. Therefore, the development of algorithms which automatically detect frontal positions from Earth Observation (EO) data is an important tool to analyse long EO time series, i.e. to process big data volumes. The development of GRADHIST was driven by the need to generate a climatology for North Sea fronts. GRADHIST is a new algorithm for the detection and mapping of oceanic fronts, which is based on a combination and refinement of the gradient algorithm of Canny (1986) and the histogram algorithm of Cayula and Cornillon (1992). GRADHIST preserves the main principles of both algorithms and can be applied to various ocean parameters as well as to different sensors with very little effort. GRADHIST was validated and tested using both synthetic and real data and applied to sea surface temperature and ocean colour parameters retrieved from satellite data; i.e. data from MODIS (Moderate Resolution Imaging Spectroradiometer), MERIS (MEdium Resolution Imaging Spectrometer), AVHRR (Advanced Very High Resolution Radiometer) and AATSR (Advanced Along-Track Scanning Radiometer). Selected results and statistical analysis of a new North Sea climatology for oceanic fronts are presented and discussed.

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1. Introduction

Oceanic fronts are highly energetic mesoscale features separating water bodies with different properties. Associated with down- and up-welling, they have a strong influence on the local dynamic, ecology and the dispersion and concentration of substances such as nutrients and contaminants. The North Sea, and in particular the German Bight, is dominated by two types of fronts: River Plume Fronts (RPF) between the freshwater run-off of the rivers and coastal North Sea water, and Tidal Mixing Fronts (TMF) between the seasonally stratified deeper North Sea water and the vertically mixed coastal waters. Other fronts separate North Sea water from the low-saline Baltic Outflow or North Sea water from Atlantic water at the open northern boundary of the North Sea.

Fronts are often associated with strong vertical and horizontal transports (e.g. frontal jets) and high biological activity. Adjacent stratified regions play a key role in marine ecosystems and their importance in the modulation of biological processes is widely recognised. They affect ecosystem components at all levels, directly, or through cascading across the food-web (ICES, 2006). Frontal upwelling can lift nutrients into the euphotic layer and enhance the productivity of the ocean (Ferrari, 2011). In the North Sea frontal downwelling whereas contributes to continental shelf sea pumping which transfers CO_2 taken up from the atmosphere to the open ocean (Thomas, Bozec, Elkalay, & de Baar, 2004).

These facts emphasise the impact of fronts on local dynamics, ecology and on climate related issues and the necessity for having an operational front monitoring programme as well as a statistical analysis of frontal positions and frontal gradients to be used as reference data to assess the effects of climate change on fronts. ICES (2006) stated that an understanding of fish response to climate change requires that mesoscale oceanic features are detected and tracked over long periods of time. This can only reasonably be achieved by the use of satellite Earth Observation (EO) data. Ferrari (2011) asked: “Given the importance of frontal physics and biogeochemistry, how are we going to make substantial progress in understanding and quantifying the effect of fronts on the global climate system?” Miller and Christodoulou (2013) used frequent front locations as a proxy for pelagic diversity in the designation of Marine Protected Areas. They analysed a decade of EO data and included sea surface temperature (SST) fronts within the North Sea at 1 km resolution. Belkin, Cornillon, and Sherman (2013) used remotely sensed thermal fronts to identify the large marine ecosystems on a global scale. They used a fairly coarse resolution of 9 km which is not sufficient for areas like the German Bight, but were able to identify the general location of the major North Sea frontal systems. In order to

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Table 1
Data sets used for the front's climatology.

Parameter	Sensor	Satellite	Time period	Units
Sea surface temperature	AATSR	ENVISAT	2002–2011	K
Sea surface temperature	MODIS	AQUA	2003–2011	K
Sea surface temperature	AVHRR	NOAA & METOP	1990–2011	K
Chlorophyll	MERIS	ENVISAT	2002–2010	mg/m³
Total suspended matter	MERIS	ENVISAT	2002–2010	g/m³
Yellow substance absorption	MERIS	ENVISAT	2002–2010	1/m
Turbidity	MERIS	ENVISAT	2002–2010	1/m

derive a reference data set of frontal positions and of frontal gradients for the North Sea a reprocessing of historic EO, data more precisely ocean colour (OC) and SST data, is needed to assess the changes already observed or projected by climate scenarios.

Oceanic frontal zones, or briefly fronts, are regions where certain properties of sea water such as SST, total suspended matter (TSM) or chlorophyll concentration change significantly over a relatively short horizontal distance of some tens of meters to a few kilometres. As in the atmosphere this discontinuity is not generally a discrete line in the ocean but can span several kilometres, i.e. over several pixels in a typical medium resolution EO image. These property changes are the key feature used by the algorithms for the detection of fronts and their spatial structures described in the next sections. The development of the North Sea climatology for oceanic fronts was divided into four phases. The first phase consisted of the product definition which included a literature review, an inventory of the sensors and data available and the development of a validation method. During the second phase the new GRADHIST method was developed which optimally fulfils the requirement to detect fronts automatically and according to user requirements. For the North Sea climatology it was also important to detect weak fronts neglected by the gradient algorithm of Canny (1986). A feasibility study was performed to test the algorithm for processing of very large data volumes. The processing of the EO data archive was done in phase 3 (see Table 1). The last phase included the statistical analysis of the results. The oceanographic interpretation of these results are discussed in detail in Kirches, Paperin, Klein, Brockmann, and Stelzer (2013a, 2013b, 2013c), however, we demonstrate with selected results the advantages of the new algorithm in the last section of this paper.

The algorithms of Cayula and Cornillon (1992) and the front detection algorithm of Canny (1986) form the algorithmic baseline of the approach presented here. These methods are well known and have been used successfully for several applications (Castelao, Mavor, Barth, & Breaker, 2006; Hickox, Belkin, Cornillon, & Shan, 2000; Miller, 2009). By making slight adjustments to the combined algorithm with respect to thresholds and scaling, it can be applied to different sensors such as MERIS and MODIS for OC and AATSR, AVHRR and MODIS for SST. In the first step the new algorithm was validated using synthetic data, which allows for a control of the results by comparing the detected fronts and gradients against the synthetic data set (Kirches, Paperin, Brockmann, Klein, & Stelzer, 2013) and in the second step against real EO data.

2. Algorithm description

Miller (2009) and others (Belkin & O'Reilly, 2009; Shimada, Sakaida, Kawamura, & Okumura, 2005; Vazquez, Atae-Allah, & Luque-Escamilla, 1999) have demonstrated the general possibility of detecting SST and OC fronts in satellite data. In their works, as well as in other studies, the automatic detection of fronts in large data volumes is done either by a gradient algorithm, which exploits spatial gradients within a satellite image, or a histogram algorithm, which works on the frequency distribution of the values within image subsets. The strength of the gradient algorithms is that they enable the detection of any front regardless of its strength, as shown by Castelao et al. (2006), or by Belkin and O'Reilly (2009); however, gradient algorithms are unable to recognise and discard false fronts caused by noise. On the other hand, histogram algorithms are able to detect weak fronts in the

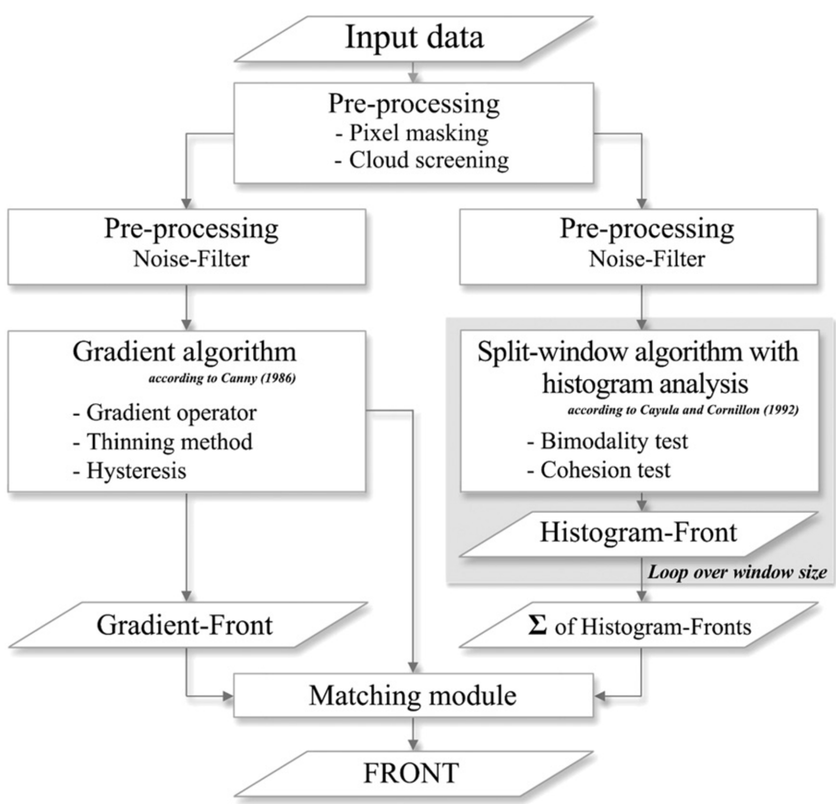

Fig. 1. Flowchart of the GRADHIST processing chain for front detection

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