# IMPROVED MONITORING OF OCEANOGRAPHIC FEATURES IN THE GULF OF OMAN THROUGH COMBINED USE OF SATELLITE THERMAL INFRA-RED, OCEAN COLOUR & RADAR ALTIMETER OBSERVATIONS

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**Abstract**

Traditionally, satellite thermal infrared sensors have provided the oceanographer with a unique source of synoptic information. ATSR data have been used to detect and monitor ocean features including fronts and eddies. Due to the sensitivity of the ATSR instrument fine-scale structure in ocean surface flow are often evident in image data. This study has compared ATSR-2 thermal infra-red (IR) measurements in the Gulf of Oman (GOO) with near-coincident ocean colour observations from OrbView-2 SeaWiFS, and TOPEX/Poseidon and ERS radar altimeter data. Observations from these complementary instruments can be combined to provide a more robust means of detecting and tracking oceanic and coastal features. The study has important implications for the subsequent synergistic use of AATSR and MERIS sensors on board the future ENVISAT platform

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## 1. Introduction

Effective Naval operations require knowledge of the spatial and temporal variability of the oceanic environment. In pursuit of this objective, satellite-borne remote sensing has provided a unique source of information allowing synoptic assessment of large expanses of the ocean, which is impractical to achieve by other means. The ability to routinely detect and track oceanographic features, which cause a change in Sea-Surface Temperature (SST), has been established using satellite-borne thermal IR imagery (mainly through use of NOAA AVHRR data). However, IR data are limited due to the presence of cloud.

Recently, the Remote Sensing section at Defence Evaluation and Research Agency (DERA), Winfrith have had access to ATSR-2 Sea-Surface Temperature (SST) imagery of the GOO region covering the period 1997 to 1999. The data have mainly been obtained via the 3rd ERS Announcement of Opportunity. The image data reveal the complex nature of circulation patterns in the region and indicates the presence of several semi-permanent features of interest. It is noted that greater sensitivity and resolution of ATSR instrument compared with the AVHRR sensor has allowed improved detection of these ocean features.

Recently there has been a growing realisation that ocean monitoring can potentially be greatly improved by combining information from complementary satellite-borne instruments, including ocean colour sensors and radar altimeters, synthetic-aperture radar and thermal IR radiometers. By combining data from these sensors it should be possible to improve coverage (both spatial & temporal), and to improve detection and tracking of features, compared with that available from any single sensor (traditionally IR – for ocean monitoring). This is possible since different instruments are sensitive to different properties of the sea-surface / near sea-surface and because radar and radar-altimeter observations are not limited by cloud, as is the case with IR and visible instruments. The purpose of this paper is to highlight the potential for an improved monitoring capability using a multi-sensor approach.

### 1.1 Study Data

ATSR-2 SST data covering the GOO were supplied in SADIST-2 Gridded Sea Surface Temperature (GSST) format (Bailey, 1995). The GSST image product contains 512 × 512 pixels sampled at 1 km intervals in both axes. Raw data were processed into image form, cloud-masked, land-masked, and geo-located using TeraScan software.

Satellite ocean colour sensors detect radiation reflected from the Earth's surface at visible wavelengths and provide information on the colour of water masses. The colour of the ocean is dependent on the concentrations of phytoplankton, suspended sediment and dissolved organic matter (yellow substance) present in the water. Light penetrating the water surface is scattered within the upper layers of the water column and passes up through the surface again, giving rise to the actual colour of the water. The substances in the ocean can all act as passive tracers and can be used to identify areas of mixing or entrainment, and provide information on the location of ocean features such as fronts and eddies. Ocean colour imagery can be used to detect ocean features which do not have a strong thermal feature such as salinity dominated fronts.

SeaWiFS ocean colour data for the GOO region have been obtained via NASA Goddard Space Flight Center (GSFC), under the Authorised SeaWiFS Science Data User scheme. Several ocean colour scenes at 1 km resolution were selected, to be as temporally coincident as possible with the ATSR-2 data collected for the latter part of 1998 and early 1999. The imagery was processed from raw data to chlorophyll concentration maps using the NASA GSFC SeaDAS application and the standard NASA chlorophyll algorithm.

Radar altimeter data have been used successfully to provide all-weather information about dynamic topography and mesoscale features in numerous locations globally. More locally, Manghnani et al., 1998 have used ERS Altimeter data to assist in the study of upwelling processes off the East coast of Oman. The radar altimeter essentially measures variations in sea surface height

(SSH) along the satellite ground track (nadir). Deviations from the mean SSH, or anomalies (SSHA), can be estimated by removing the mean SSH, which is estimated using long time-series of SSH measurements. Quasi-synoptic maps of SSHA can be derived by interpolating between adjacent and intersecting altimeter ground-tracks. In this study we have used a SSHA map product produced by the University of Colorado, Colorado Centre for Atmospheric Research (CCAR), that uses both ERS-2 and TOPEX/Poseidon altimeter data (Lillibridge et al., 1997). It is known that measurements made by altimeters can be difficult to use proximal to the coast due to atmospheric effects and tracking of returns across the land/sea boundary. Additionally, in shallow, tidal areas accurate tidal corrections are needed to render the data useful. Despite these problems, Larnicol et al., 1995, have successfully monitored gyres in the Alboran Sea, a region not dissimilar to the GOO. To mitigate errors in coastal areas the CCAR SSHA maps in this study are limited to areas deeper than 200 m. The maps are sampled at 1/4º spacing in latitude and longitude.

### 1.2 Study Region

The GOO is essentially relatively deep in comparison with the Arabian Gulf, reaching depths of over 2500 m. At its north-western extreme, approaching the Straits of Hormuz, depths shallow to less than 100 m (see Figure 1).

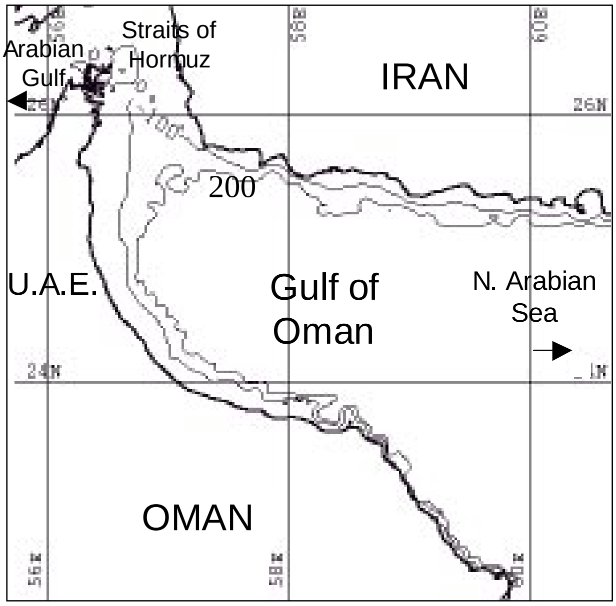


**Figure 1 - The study region.**

The alternating sequence of monsoons that prevail in the GOO area result in complex ocean flow patterns. During the North-East (NE) monsoon, which occurs in winter and generally lasts from November to February, the Arabian Gulf cools considerably in relation to the GOO and N. Arabian sea. The cooling leads to a net flow of warm, less dense, water through the Straits of Hormuz into the Arabian Gulf from the GOO. During the south-west monsoon season (May to September) the flow through the Straits is reversed and warm water entering the GOO from the Straits flows south-west and is mainly confined in a jet that stays close to the Omani coast. Large-scale circulatory gyres can be set up within the GOO and have been previously observed by several authors including Reynolds, 1993 and Sultan & Ahmad, 1993.

## 2. Image Interpretation

The following discussion briefly summarises the interpretation of the multi-sensor image data (SST, SSHA and Colour) acquired for the GOO region during two winter (NE Monsoon) seasons.

### 2.1. Winter Monsoon 1997

A sequence of 4 ATSR-2 SST images covering the GOO is shown in Figure 2. The images span the late half of the NE monsoon period through to the subsequent transition period, between monsoons. The presence of a cyclonic cold-core gyre feature (centred at 57.5°E and denoted "C") is evident in the images in the west of the GOO. (A smaller cold-core eddy to the east, "C1", is evident in January, which later moves out of the imaged area). During January, the gyre is typically composed of a warm filament, evident as a warm jet that leaves the Omani coast at around 58.5 °E extending firstly north into the GOO, then west, and finally back towards the south. SST observations reveal that the core SST, in January, is about 22 °C and surrounded by warmer water around 23-24 °C. From January to the end of March, the gyre can be seen to migrate east in the GOO, with its core moving about 50 km during this time. During this period, the wind was predominantly from the north-west, and strong, as revealed by ADEOS satellite scatterometer data. In April, the gyre appears to move less markedly, which coincides with a period of variable winds. As overall SST increases from late March onwards, the gyre surface signature appears to weaken and the centre-to-periphery temperature difference reduces to about 0.5°C.

The gyre is also evident in the series of SSHA maps shown in Figure 3. The sequence spans the same three-month period as the SST images as shown in Figure 2. The cyclonic nature of the gyre, evident in SST imagery, is confirmed by the derived geostrophic currents superimposed on the SSHA maps. The negative values for SSHA (around -10 cm) indicate the lowering of dynamic height over this feature, as expected for a cold-

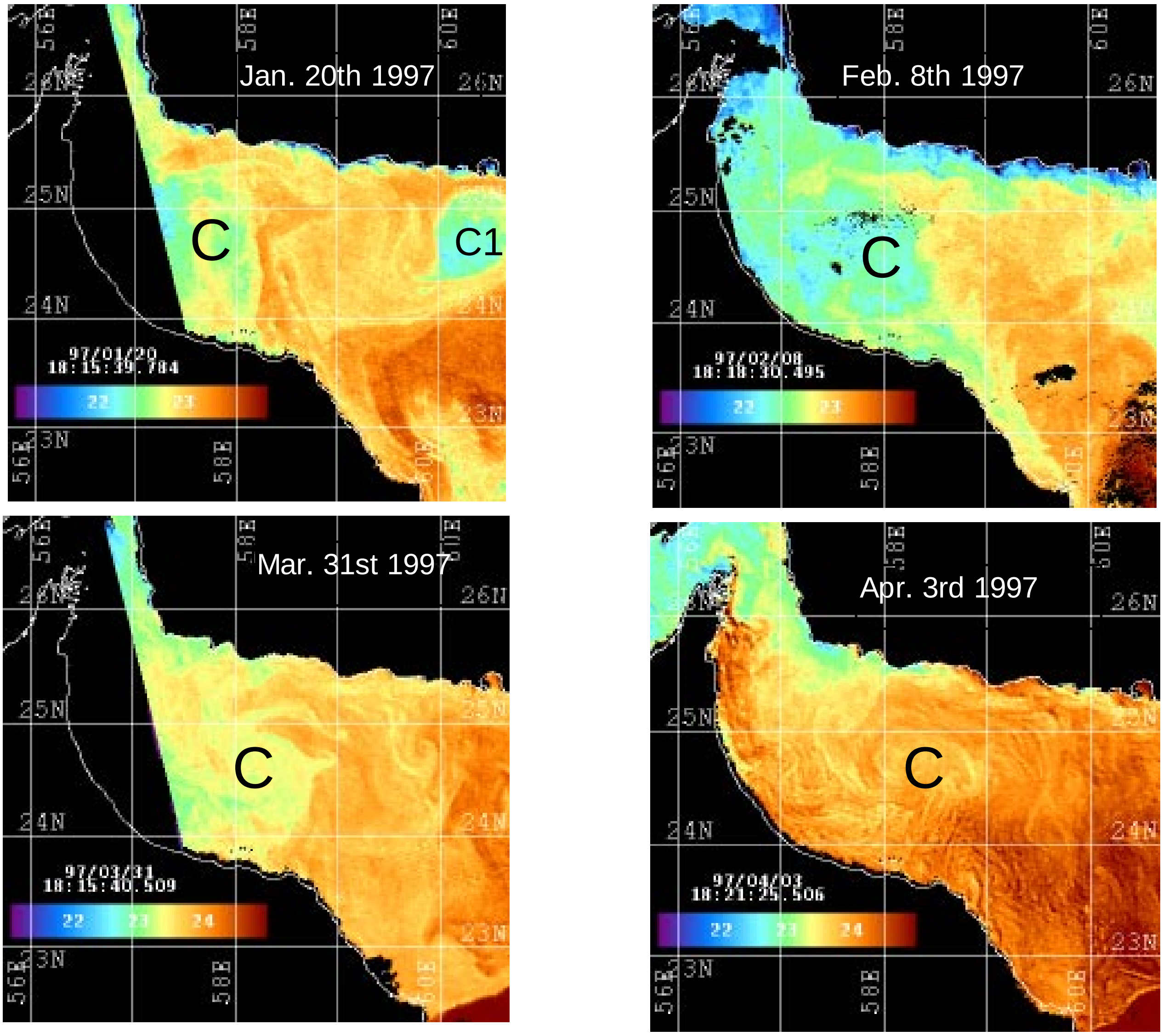


**Figure 2 - Sequence of ATSR-2 SST images from Gulf of Oman, January - April 1997. The cyclonic gyre feature is denoted by "C". © ESA, 1997**

core cyclonic gyre. The gyre is apparent as a stable negative anomaly during January and February, after which the gyre can be seen to move east and the SSHA anomaly can be seen to reduce, this corresponds with weakening of the gyre signature in the SST imagery (Figure 2). Finally, the SSHA reduces to around -7 cm in April, which together with the weak signature in the April SST image suggest the gyre is decaying. In general it should be noted that there is good correspondence between the features evident in the SST images (Figure 2) and the SSHA maps (Figure 3).

Similar features have been observed previously in this region (Reynolds, 1993). Reynolds found evidence for two counter-rotating gyres using AVHRR and drifter data collected during February and March 1992. However, the position of the cyclonic gyre as established from Figures 2 and 3, here, corresponds roughly with the position of an anticyclonic gyre as reported by Reynolds. The cyclonic gyre observed by Reynolds was around 200 km to the east of the cyclonic gyre in Figures 2 and 3. These different findings give an indication of the oceanic variability that may exist in the GOO region.

### 2.2 Winter Monsoon 1998/99

The series of ATSR-2 SST images shown in Figure 4 cover the 1998/99 NE winter monsoon period, which begins around November and ends around February. The image sequence indicates the development of an anticyclonic gyre feature "A" in the western GOO, together with a faint cyclonic circulatory feature "C" further east. The western anticyclonic feature is situated

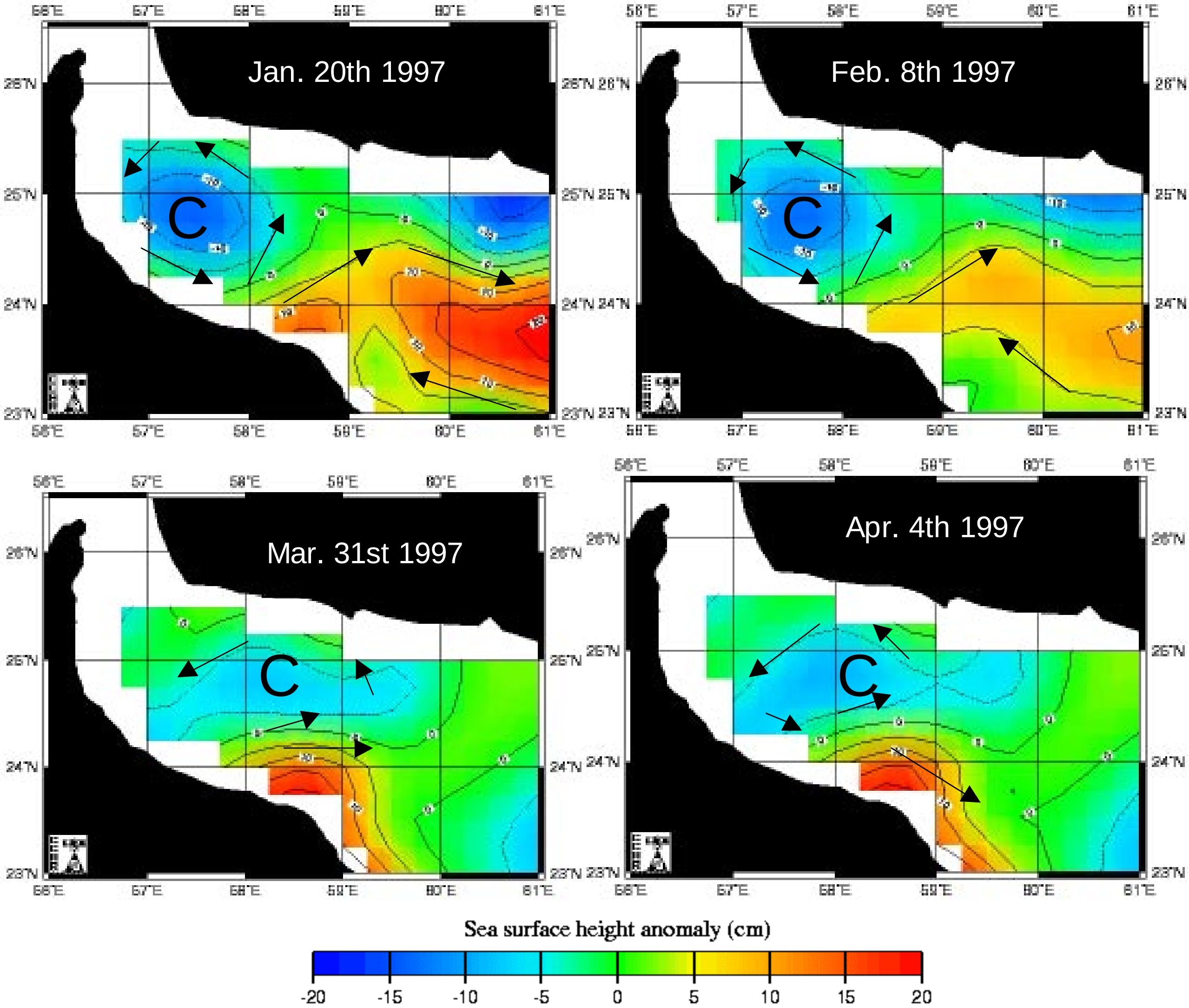


**Figure 3 - SSHA maps derived from blended TOPEX/Poseidon and ERS-2 Altimetry from Gulf of Oman, January - April 1997. Maps are annotated with circulation patterns. The cyclonic gyre feature is denoted by "C".**

roughly where the cyclonic feature was observed during the winter of 1997 (Figures 2 and 3), centred around 57.5 ºE, but also where Reynolds observed an anticyclonic feature in 1992. The anticyclonic feature appears to entrain a filament of water that extends east from the warm southerly flow emanating from the Straits of Hormuz (see image for 3rd November). The weak cyclonic gyre centred around 60.5 ºE, is clearly evident in the SSHA maps, Figure 5, as a strong negative anomaly (-15 cm) with associated geostrophic cyclonic circulation. There is evidence for the existence of a warm gyre in the SSHA maps shown for December and February, Figure 5, as indicated by the positive height anomaly located around 57 ºE. The presence of two gyres is confirmed in Figure 6, a SeaWiFS image of the GOO from 13th November 1998. The image, showing derived chlorophyll–*A* values, clearly indicates the location of the gyres marked "A" & "C" in Figures 4 and 5. Gyre feature "A" also appears to be entraining upwelled water from the north, not evident from the corresponding SST image. The position of the gyres in Figure 4 to 6 is similar to that found by Reynolds during the 1992 NE monsoon.

Several smaller eddies are also apparent in the SeaWiFS image, including one to the north of gyre "C". The use of satellite ocean colour data for detection of eddies is potentially more robust than detection using thermal IR data. The main reason for this is that ocean colour is determined by scattering and absorption that occurs in the top few metres to tens of metres of the water column, depending on water clarity (see section 1.1). Whereas, IR sensors measure the only the temperature of the surface skin (top few millimetres) which can be locally warmer than the underlying water, during sunny, low-wind speed conditions. Localised heating of the surface skin can effectively mask temperature changes that occur in the bulk of the ocean due to the presence of oceanographic features (fronts and eddies), which are of interest.

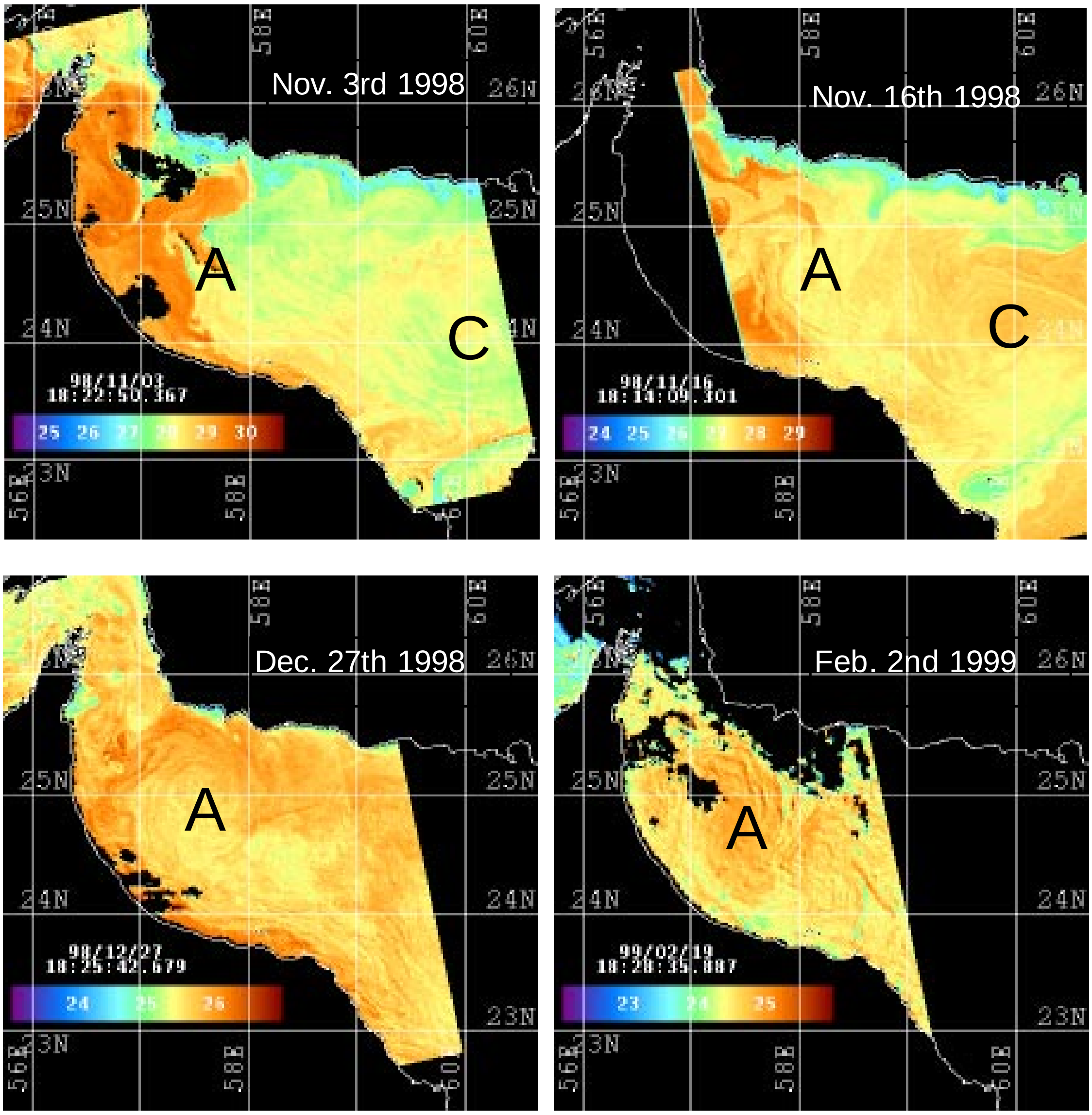


**Figure 4 - Sequence of ATSR-2 SST images from Gulf of Oman, November 98 - February 99. Anticyclonic and cyclonic gyre features are denoted by "A" and "C". © ESA, 1997**

### 3. Summary

Combined use of remotely sensed SST, colour and SSHA data has improved the monitoring of gyres within the GOO region during two winter monsoons, covering the periods, early 1997 and late 1998/early1999. The synergy that exists between these complementary sensors is exploited to provide better coverage (spatial and temporal) and improved detection and interpretation of relevant features, over reliance on SST alone.

In order to realise the full potential of satellites for ocean monitoring it is essential that all relevant sensors are blended together. This requires a multi-platform/multi-sensor approach to extend coverage and to improve feature detection, interpretation and tracking. Satellites due to be launched in the near future (such as Envisat) will provide an opportunity to assess the potential of such an approach.

The combined image data from two winter monsoon seasons suggests that conditions in the GOO exhibit considerable inter-annual variability and in general, conditions cannot be simply related to seasonal weather patterns. Imagery of the GOO from the winter monsoon season of early 1997 indicates the presence of a single cold-core cyclonic gyre in the western GOO region, centred around 58 °E. By contrast, remotely-sensed satellite data covering the winter monsoon season 1998-99, suggest the presence of two gyres; an anticyclonic warm cored gyre in the western GOO and a cyclonic cold cored gyre in the eastern GOO centred around 60 °E.

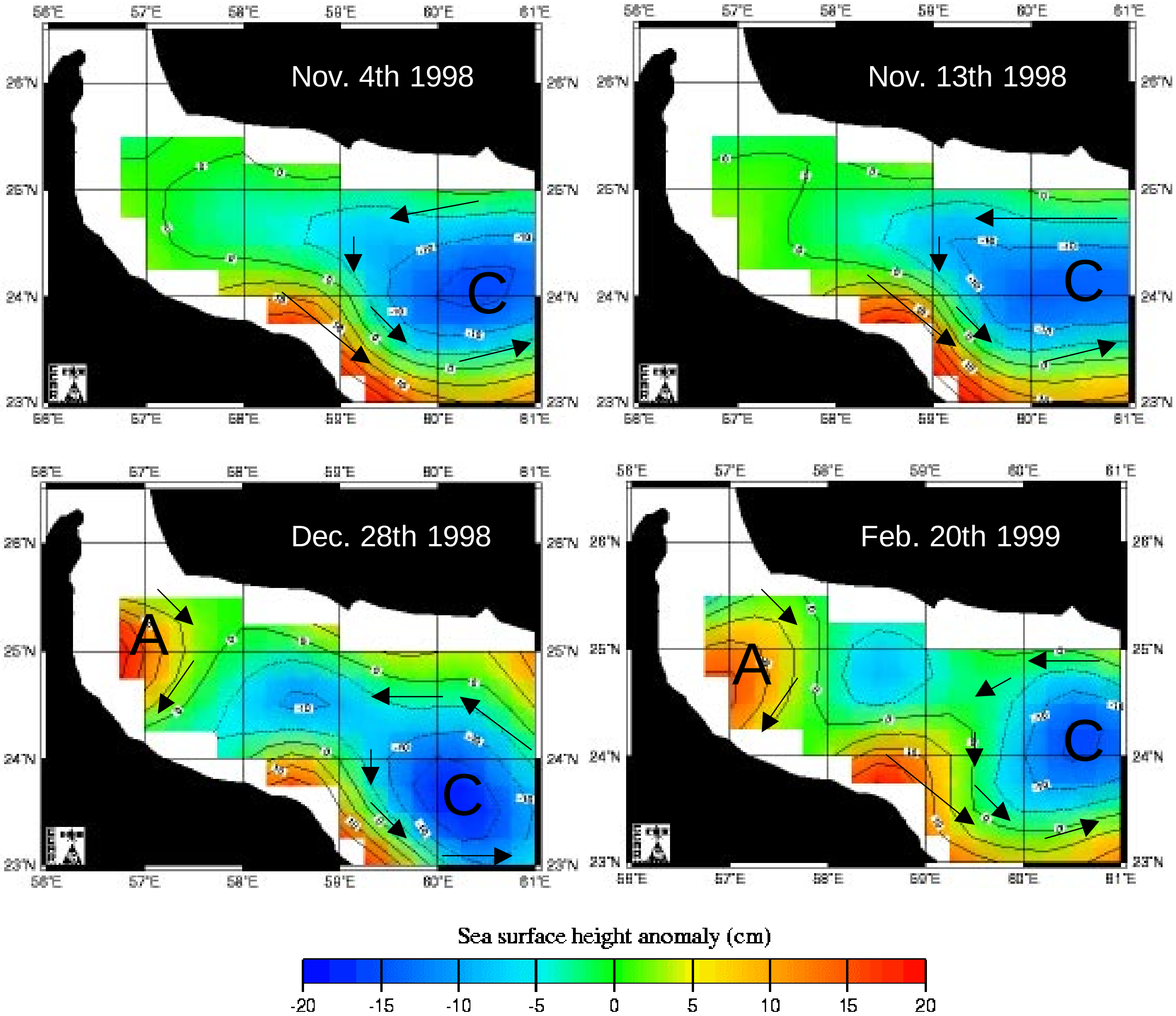


**Figure 5 - Sea surface height anomaly maps derived from TOPEX/Poseidon and ERS-2 Altimetry from Gulf of Oman, November 98 - February 99. Maps are annotated with geostrophic circulation patterns. Anticyclonic and cyclonic gyre features are denoted by "A" and "C".**

### 4. Future Work

Further multi-sensor satellite image data need to be investigated to establish both inter-annual and inter-seasonal variability of the GOO region. Meteorological data (in-situ and satellite) also need to be examined to assess the variability of the winds that force the oceanic processes in this region. It would also be useful to compare results with numerical ocean model data for this region, to compare modelled and observed variability, and to assess the influence that the Indian ocean may have on this region

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NASA GSFC for making SeaWiFS ocean colour data available under the Authorised SeaWiFS Science Data User scheme.

Colorado Centre for Astrodynamics Research, University of Colorado, for permission to reproduce the SSHA maps in this study.

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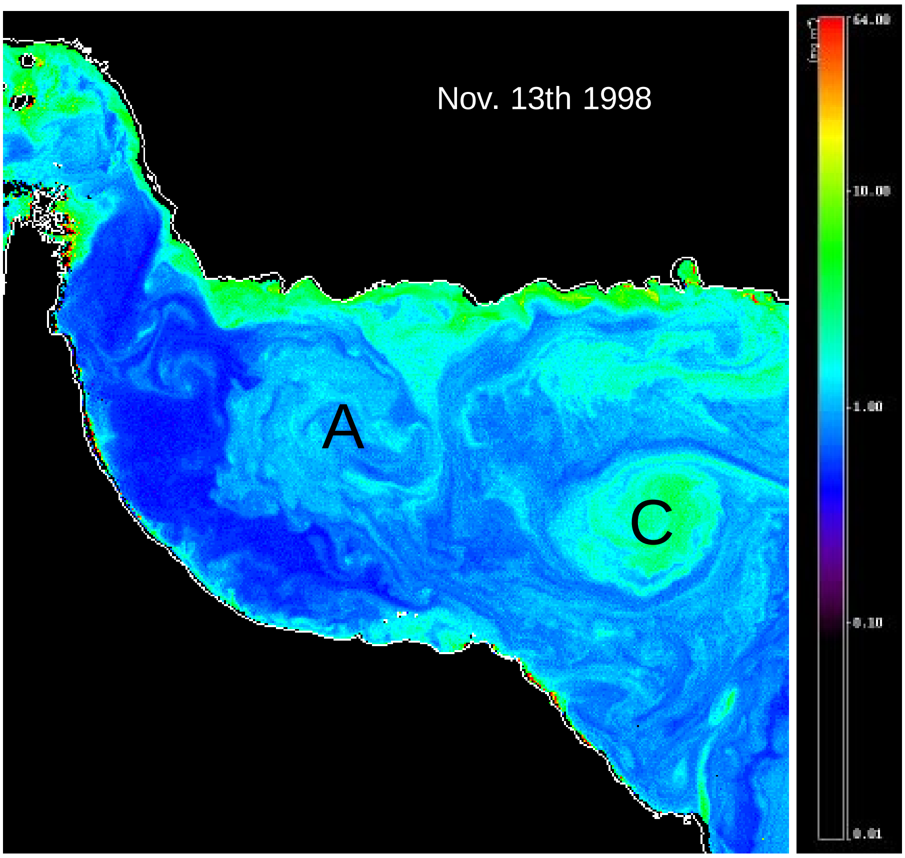


**Figure 6 - SeaWiFS Chlorophyll-A image of Gulf of Oman, November 13th 1998 indicating the presence of the two gyres labelled "A" & "C"**

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