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SEA SURFACE TEMPERATURE
OF THE COASTAL ZONES OF FRANCE

HEAT CAPACITY MAPPING MISSION - HCM M
INVESTIGATION N° 15
FINAL REPORT

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JUIN 1982
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SUMMARY

1 - INTRODUCTION
2 - TECHNIQUES
   2-1 - Technical organization of the investigation
      2-1-1 - Documents
      2-1-2 - Photographic products
      2-1-3 - Digital products
   2-2 - Photographic product techniques
   2-3 - Digital product techniques
      2-3-1 - Digital product facilities
         2-3-1-1 - Digital product facility at LOA
         2-3-1-2 - Digital product facility at CTAMN
         2-3-1-3 - Digital product facility at ENS
      2-3-2 - Digital product interpretation
         2-3-2-1 - Digital product interpretation at LOA
         2-3-2-2 - Digital product interpretation at CTAMN
         2-3-2-3 - Digital product interpretation at ENS
   2-4 - Ground truth techniques
      2-4-1 - Routine observations
      2-4-2 - Oceanographic cruises
3 - ACCOMPLISHMENTS
   3-1 - HCMR calibration
   3-2 - Comparison of HCMR vs VHRR and AVHRR data
   3-3 - HCMR products
4 - SIGNIFICANT RESULTS
   4-1 - Mesoscale variability of the SST field
   4-2 - Diurnal heating
   4-3 - Residual flow through the Dover Strait
   4-4 - Tiwé fronts in the western approaches of the British Channel
   4-5 - Upwelling at the continental shelf break in the Bay of Biscay
   4-6 - Coastal studies in the Bay of Biscay
   4-7 - Western Mediterranean Sea test site
      4-7-1 - Results obtained with VHRR/NOAA-5
      4-7-2 - Results obtained with HCMM
5 - PUBLICATIONS
   5-1 - Reviews
   5-2 - Proceedings and Conferences
   5-3 - Thesis
6 - PROBLEMS
   6-1 - HCMM data geometry
   6-2 - Periodic noise
   6-3 Contrast of thermal imagery
7 - IMAGE QUALITY AND DELIVERY
   7-1 - Image quality
   7-2 - Test sites coverage
   7-3 - Delivery
8 - RECOMMENDATIONS
9 - CONCLUSIONS

Appendix A - Permanent addresses of the investigators
Appendix B - Ground truth data and HCMM measurements
Appendix C - Sea surface temperatures of the coastal zones of France observed by the HCMM satellite
Appendix D - Satellite determination of the mesoscale variability of the Sea surface temperature
Appendix E - Large diurnal heating of the sea surface observed by the HCMM experiment
Appendix F - Satellite evidence of cold water areas near islands along the south Brittany shore
Appendix G - Mesoscale eddies detected in the Ligurian Sea by satellite infrared radiometers - a statistics through the year
Appendix H - List of the received HCMM data
LIST OF ABBREVIATIONS

AVHRR - Advanced Very High Resolution Radiometer on TIROS-N, NOAA-6 & 7 satellites

CCT - Computer Compatible Tape

CMS - Centre de Météorologie Spatiale

CTAMN - Centre de Télédetection et d'Analyse des Milieux Naturels

ENS - Ecole Normale Supérieure

HCMM - Heat Capacity Mapping Mission

HCMR - Heat Capacity Mapping Radiometer

LOA - Laboratoire d'Optique Atmosphérique

SST - Sea Surface Temperature

VHRR - Very High Resolution Radiometer on NOAA-1 to 5 satellites
1 - INTRODUCTION

The main objective of this investigation was to map the thermal gradients in French coastal zones for the period of one year in order to enable a coherent study of certain oceanic features detectable by the variations in the sea surface temperature field and their evolution in time. The phenomena examined were meso-scale thermal features in the English Channel, the Bay of Biscay, and the northwestern Mediterranean; thermal gradients generated by French estuary systems; and diurnal heating in the sea surface layer.

The investigation was conducted by the following researchers: Dr. P.Y. DESCHAMPS (Principal Investigator); and Dr. M. CREPON, Mr. J.M. MONGET, and Professor F. VERGER (Co-Investigators).

Appendix A gives related organizations and addresses.

2 - TECHNIQUES

2.1 - TECHNICAL ORGANIZATION OF THE INVESTIGATION

2.1.1. Documents

Every document received by the Principal Investigator from NASA and concerned with the HCMM investigation was duplicated in order to provide the Co-Investigators with individual copies. When necessary, feedback was requested from the Co-Investigators.
2.1.2. Photographic products

Two negative transparencies were on standing order by the Principal Investigator. As they were received, one transparency was archived at L.O.A (Laboratoire d'Optique Atmosphérique, Université de LILLE) and the other at ENS (Ecole Nationale Supérieure) from which additional positive prints were made for each of the Co-Investigators.

2.1.3. Digital products

Request orders for CCTs were collected from the Co-Investigators and submitted by the Principal Investigator. When received, he both catalogued the CCTs and forwarded copies to the appropriate individuals.

2.2 - PHOTOGRAPHIC PRODUCT TECHNIQUES

The photographic products used within the investigation did not require any special developing techniques.

2.3 - DIGITAL PRODUCT TECHNIQUES

2.3.1. Digital product facilities

Most of the facilities used in the investigation are located at C.T.A.M.N. (Centre de Télédétection et d'Analyse des Milieux Naturels). Ecole des Mines, where the processing of remotely sensed data has been extensively developed for a variety of applications. The other investigators had the choice of using this main facility or their own smaller, in-house facilities.

2.3.1.1. Digital product facility at L-OA (Laboratoire d'Optique Atmosphérique, Université de LILLE)

This facility is divided into the CII model IRIS 80 computer of the University with specific terminals located at LOA, and a communication link between the two locations. Main processing is done on the IRIS 80 computer.
Digital data may then be transferred and stored on floppy disks at LOA, each containing 6 small scenes of 256x256 pixels. A small scene may be displayed on a PERICOLOR-system color graphic device (256x256 pixels). An HP 9825 A calculator permits minor processing of the stored data. Additional outputs of the processed data may be obtained on a graphic plotter and/or in the form of printer listings.

2.3.1.2. Digital products facilities at CTAMN (Centre de Télé-détection et d'Analyse des Milieux Naturels)

The CTAMN was equipped with a self contained computer system for image processing based on two HP 21 MX minicomputers. An improved computing facility, consisting of an array processor FPS (Floating Point System) has been implemented at CTAMN during the investigation.

This system is linked to specific output devices such as:

- a VERSATEC printer/plotter with special gray scale display software developed by CTAMN which allows cartography of satellite data using any given scale and cartographic projection,
- a BENSON ink-plotter with adequate software for mapping with various symbols and colors, as well as cartographic projection,
- a TEKTRONIX digitizer with associated graphics display for landmark acquisition and input capability for rectification or registration.

The main body of the CTAMN system is an interactive image processing system TRIM-CIT ALCATEL. This versatile equipment allows display and manipulation of images in a man-interactive loop. Image memory is 512 x 512 x 8 bits with an overlay graphical memory of 512 x 512 bits. A realtime processor allows color selection, pixel selection with cursor tracking, zooming, and lateral displacement of the image.
2.3.1.3. Digital product facility at ENS (Ecole Nationale Supérieure)

This facility is divided into:

- an IBM 370 main computer at CIRCE, the computer centre of CNRS (Centre National de la Recherche Scientifique), with special output devices:
  - a VERSATEC printer plotter and a BENSON color printer plotter,
  - a MOD'COMP CLASSIC minicomputer located at ENS which is linked to CIRCE, in association with a TEKTRONIC 4013 graphic display.

2.3.2. Digital product interpretation

The three laboratories working on the present investigation had already developed appropriate interpretation techniques for the NOAA and LANDSAT satellites. As they are used for collaborative programs, there are many common points between the techniques they have implemented on each of their own digital systems.

2.3.2.1. Digital product interpretation at LOA

Digital data may be processed more or less routinely with the following options:

- radiometric calibration if necessary,
- resampling for uniform scaling if necessary,
- smoothing,
- stripes filtering.

Localization and display of a typical scene (containing 1024 x 1024 pixels) is usually done in the following procedure:

- Display is attained by reducing the whole scene to 256 x 256 pixels after sampling every n pixels and every n lines, or after averaging over an n x n pixel square,
- selection of a small scene (256 x 256 pixels) and visualization at full ground resolution,
- localization with reference to map locations and addition of coordinates on the color graphic display,
- mapping of surface isotherms or isocontours on the printer plotter after the necessary filtering.

Computation and display of a selected scene is possible using the following methods:
- histograms,
- spatial spectrum of temperature variance density,
- structure functions of temperature variations,
- spatial cross-correlation function between two different acquisition of the same area.

2.3.2.2. Digital product interpretation at CTA^NN

Upon receiving the HCMM data on magnetic tapes, the processing was organized as follows:
- "Quick look" of available data, at a scale of 1 : 2 000 000, using a black and white printer plotter:
- transformation of data into surface temperature by using the calibration curve,
- destriping of imagery
- isotropic filtering, to reduce the noise level, This algorithm was constrained to local variance in order to leave untouched the strong gradients along the coastlines,
- geometric corrections in order to rectify the imagery at a specified projection (ex.: LAMBERT),
- display of sea-surface temperature as colored maps.

2.3.2.3. Digital product interpretation at ENS

The following programs were used to produce a convenient automatic cartography.

The FRALISET program performs a fast and low cost print-out visualization of a part of a given scene. The HCMR digital counts were converted to alphanumeric characters.
After selection by the operator, each printed character was associated to one or several pixels. The 1/500 000 scale appeared to be suitable for the HCMM applications in the Bay of Biscay. Isotropic filtering of the data could be applied once or several times. The additional legend was selected by the operators. Output was done on the BENSON plotter both in black and white and white 6 color prints.

2.4. GROUND TRUTH TECHNIQUES

Ground truth techniques were not assigned to this specific investigation. The necessary oceanographic and meteorological data was obtained either from routine observations or from dedicated oceanographic cruises conducted by the following organizations.

2.4.1. Routine observations

Periodical sea surface temperature measurements are performed by the "Reseau National d'Observation de la Qualite du Milieu Marin", in the French coastal and estuarine zones. As an example, six stations are sampled every week in the Loire estuary. Some of these measurements were simultaneous with the HCMM data (09/15/78 ; 05/28/79 ; 06/18/79).

The "Etablissement d'Etudes et de Recherches Meteorologiques" in the "Centre Oceanologique de Bretagne", Brest, performs a statistical treatment of the sea surface temperature field from the routine observations of the merchant ships in the Bay of Biscay, the Celtic Sea and the Western English Channel. As a result of this analysis, a thermal map (SST-GASC) is produced three times a month with a temperature accuracy of about 0.5°C.

Lighthouseboats also routinely measure sea surface temperature at several locations in the eastern British Channel and the southern North Sea. They report these measurements through the meteorological network.

2.4.2. Oceanographic cruises

In addition to these routine procedures, this investigation had access to data from several oceanographic experiments.
conducted by various French organizations and complementary to the objectives of the HCMM experiment:

- **LION 78** (June to September 1978), a summer experiment in the Gulf of Lions, Mediterranean Sea for the coastal upwellings.

- **PHYGAS 78** (8 November 1978 to 2 December 1978) in the Bay of Biscay.

- A drifting buoy experiment in the Bay of Biscay, starting February 1979, for the study of ocean dynamics.

- **PROLIFIC** (5 to 24 March 1979), an experiment in the Ligurian Sea, to support remotely sensed data of sea surface temperature and ocean color.

- Several cruises in the British Channel to support remotely sensed data of sea surface temperature and ocean color:
  - 19 to 29 June 1979, in the "Golfe de Saint Malo"
  - 20 to 28 July 1979, in the "Golfe de Saint Malo"
  - 4 to 14 September 1979, in the "Golfe de Saint Malo"
  - **SATIR 1**, 17 to 27 July 1979, in the Celtic Sea
  - **SATIR 2**, 3 to 22 September 1979, in the Celtic Sea.

No airborne temperature measurements were performed for the HCMM experiment since specific request for this type of data appeared within the investigation.

The major omission in the ground truth data collection was due to the unavailability of **BOHRA II**, a French buoy previously anchored at a fixed station in the Mediterranean Sea, about 100 km south of Marseille. **BOHRA II** was removed prior to the AEM-A spacecraft launch for technical reasons. **BOHRA II** was intended to support the investigation by continuously recording the vertical thermal structure of the upper water layers. The absence of this instrument seriously restricted the scope of the studies relating to diurnal heating of the surface layer.
3.1. - HCMR CALIBRATION - SEE APPENDIX B

Several comparisons were made between HCMR digital data and in situ measurements obtained in the Bay of Biscay - see Appendix B. HCMR radiometric temperatures were found to be 7°C less than in-situ measurements of the sea surface temperature. This difference is rather large and cannot be accounted for solely by the atmospheric correction of water vapor absorption for which the mean computed value was only a few °C (2 to 3°C). A HCMR calibration bias of several °C should probably have been added to the data in order to derive more accurate absolute temperatures. Still this calibration bias was not a severe problem for the objectives of the investigation, because it appeared rather constant, and because HCMR data were only used as relative temperatures.

3.2. - COMPARAISON OF HCMR TO VHRR AND AVHRR DATA - SEE APPENDIX C

Comparisons were made of radiometric data obtained over the same marine area at the same time by both HCMR and VHRR/NOAA-5, or by HCMR and AVHRR/TIROS-N. They demonstrate a definite improvement in the radiometric quality of the HCMR data over that of the VHRR, primarily in the area of radiometric resolution. The comparison between HCMR and AVHRR shows that these two instruments have similar improved radiometric performances. The higher repetitiveness of data acquisition and the possibility of a multi-channel (3.7 and 11 µm) atmospheric correction are in favour of the AVHRR experiment, while the HCMR experiment offered the unique advantage of delivering geometrically corrected photographic and digital products. The ground resolution of the HCMR instrument (≈ 500 m) was better than the AVHRR experiment (≈ 1 km) but the value of this feature is limited to the studies of areas having a large surface temperature variability at small scales, typically the coastal marine areas and the sharp thermal fronts. While over some very homogeneous oceanic areas, the spatial variability of the SST field at scales below 5 km is too low to be detected by the two instruments.
Data from AVHRR onboard TIROS-N and NOAA-6 can now be directly transmitted to CMS, LANNION, FRANCE and it was this facility that did the processing for the HCMM experiment. An atmospheric algorithm has been implemented at CTAMN, which uses the equivalent radiometric temperatures $T_3$ and $T_4$ in AVHRR channels 3 and 4 (3.7 and 11 µm), to determine the actual sea surface temperature, $T_0$:

$$T_0 = 1.054 \left( 1.42 T_3 - 0.42 T_4 \right) + 1.13$$

($T_0$, $T_3$ and $T_4$ in °C).

This relation has been obtained by Mc CLAIN(1) from a comparison between AVHRR data and actual surface measurements over the Gulf Stream and is very close to the one predicted by DESCHAMPS and PHULPIN(2) from theoretical simulation:

$$T_0 = 1.48 T_3 - 0.48 T_4 + 2.02.$$

3.3. - HCMM PRODUCTS

HCMM photographic products with a suitable enhancement of the grey scale in the range of sea surface temperatures and a geometric correction were highly applicable to the objectives of the investigation because they enabled direct utilization of the data. In contrast, VHRR and AVHRR photographic products from meteorological satellites received at CMS, LANNION, FRANCE, have a standard enhancement for the meteorological needs in a large temperature range, which only permits the selection of cloudfree areas: consequently, the main body of the work is held up until after a heavy procedure of digital data processing has been completed.

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In addition to providing a more extensive and accurate overview of the thermal features in the French coastal zones, facilitating initial detection and mapping of thermal eddies and fronts, etc., the expediency provided by the HCMM photographic products allowed the investigators to conduct a preliminary assessment of the data in order to select the digital sets to receive processing and to recommend guidelines for further elaboration and analysis. This consequently allowed a more productive and efficient evaluation of the data by the oceanographic community prior to any computerized processing.

A more detailed description of the results achieved by the experiment is given in section 4 and corresponds to the following outline.

1. During the period of investigation, May 1978, May 1979, HCMM photographic products used to make a qualitative analysis of certain persistent thermal features:
   - thermal fronts in the western British Channel, and north of Balearic Islands, western Mediterranean Sea;
   - large eddies north of the Algerian and African coast;
   - upwellings northwest of Portugal in the Gulf of Lions and in the western Mediterranean Sea.

2. HCMM photographic products were used to obtain an assessment of the frequency of occurrence of diurnal heating of the sea surface in the Mediterranean Sea. Prior to the HCMM experiment, the importance of frequent and extensive diurnal heating of the sea surface was unexpected, but its subsequent establishment leads to the conclusion that for oceanographic purposes, daytime satellite imagery should be used cautiously because the SST field may be interpreted erroneously.

3. HCMM digital products were used to perform a statistical spectral analysis of the mesoscale variability of the SST field in the range of scales 3-30 km, thanks to the low noise level of the HCMR.
4.1. - **MESOSCALE VARIABILITY OF THE SST FIELD - SEE APPENDIX D**

Using VHRR and HCMR infrared digital data, a statistical analysis of the mesoscale variability of the SST field was performed in order to characterize the random properties of this field. The power law exponent, \( n \), of the spatial spectrum of variance density, \( E(k) \propto k^{-n} \) (\( k \) is wavenumber), was deduced from the computation of the structure function of the SST. When the study was first started on VHRR/NOAA-5, the range of scales was on the order of 40-100 km but HCMR data allowed an extension of the study down to a scale of 3 km. From an examination of 11 VHRR and 9 HCMR scenes, in the range of 3-100 km, \( n \) was found to vary from 1.5 to 2.3, with a mean value of 1.8. These values of \( n \) are on the order of those predicted by turbulence theories.

However, a discrepancy exists and further advanced theories are needed to explain this experimental determination of the mesoscale SST variability.

The feasibility of the spectral analysis in the range of scales 3-30 km was only made possible by the low noise level of the HCMR data.

4.2. - **DIURNAL HEATING - SEE APPENDIX E**

Daytime HCMR data occasionally exhibited warmer sea surface areas which extended over 10 to 100 km. The warming was of several °C and easily detected on photographic products because these warmer areas usually have graded margins that cannot be confused with the sharper boundaries of other oceanic thermal phenomena.

These warmer areas were interpreted as a large diurnal heating of the upper surface layer under low wind speed conditions. Evidence of this is supported by several arguments.
(1) Meteorological observations and analysis show that warmer areas are associated with low wind speed conditions - i.e. anticyclonic conditions or coastal breeze effects.

(2) Glitter - i.e. the portion of solar radiation reflected by the uneven sea surface directly toward the satellite sensor - has been used to derive an equivalent wind speed from the HCMR visible channel (feasible when observation is close to the specular reflection of a flat sea). Warmer areas are always associated with changes in the glitter patterns and decreasing wind speeds.

(3) Warmer areas disappear on consecutive nighttime HCMR data.

Under low wind speed conditions, turbulence induced in the sea surface by the wind stress is strongly reduced, and most of the solar radiation absorbed is stored in the surface layer without downward propagation. Theoretical simulations using a radiative and heat transfer model have been performed. They predict large heating rates in the upper meters and a maximum heating of several °C in the upper layer, and have been confirmed by in-situ measurements. Significant heating only occurs in the upper few centimeters of the surface and is very rapidly destroyed by the nighttime cooling.

HCMR data allowed us to discover that diurnal heating of more than 1°C was affecting large areas. The frequency of occurrence was relatively high in the western Mediterranean Sea where more than 10% of marine surface was affected one day or another, while large diurnal heating was very rarely observed in the North Sea (only one scene). In strongly affected areas, daytime satellite data could consequently yield misleading SST fields, leading to the conclusion that a less deceptive picture of the SST field is more likely to be obtained from observations restricted to nighttime or early morning when the surface layer is more homogeneous.
4.3. - RESIDUAL FLOW THROUGH THE DOVER STRAIT - SEE APPENDIX C

The time sequence of HCMM scenes allowed us to outline the influence of meteorological conditions on the residual current which flows to the N.E., from the British Channel through the Dover Strait, and into the North Sea. Southwestern winds enhance this residual flow, and, as a result, the thermal effluent of the Rhine River is forced northward along the Dutch coast in a very narrow coastal band. Northeast winds oppose the residual flow, reduce its speed and deflected it toward the English coast allowing the Rhine thermal effluent to expand seaward at a distance of up to 25 nautical miles. A close correlation exists between wind speed direction and the offshore spread of the effluent.

4.4. - TIDAL FRONTS IN THE WESTERN APPROACHES OF THE BRITISH CHANNEL - SEE APPENDIX C

Tidal fronts occur in shelf areas where the tidal currents are large enough to destroy the seasonal thermocline. In shallow depths, the tidal currents induce turbulence that mixes the water column. The warmer stratified and colder homogeneous waters are separated by a tidal front that appears as a surface thermal front on satellite imagery.

Tidal fronts in the western approaches of the British Channel were first detected with the VHRR. HCMM photographic products have since been used to further analyse the time and space variability of these thermal fronts during summer 78.

4.5. - UPWELLING AT THE CONTINENTAL SHELF BREAK IN THE BAY OF BISCAY - SEE APPENDIX C

HCMM data confirm the existence of a permanent upwelling phenomenon at the continental shelf break in the Bay of Biscay. The upwelling is outlined by the appearance of cold water in summertime. This has already been observed in previous VHRR data. From HCMM scenes, a more complete description and interpretation of the upwelling has been obtained.
(1) The upwelling is probably permanent, but is enhanced by colder upwelled water in summertime when a seasonal thermocline is formed. On one occasion, January 17, 1979, warmer water appeared in wintertime at the shelf break (HCMM scene A-A 0265 - 01090); this is probably an intermediate warmer water, possibly of Mediterranean, flowing out through the Gibraltar Strait, into the Atlantic, at a depth of several hundred meters.

(2) The upwelling is more pronounced after spring tides, which suggests that the basic mechanism for the upwelling is a tidal one. On two occasions after spring tides, August 25 and September 21, 1978, HCMM scenes (A-A 0121-13260 and A-A 0148-13320) show very similar patterns of cold water at the shelf break, with a maximum intensity between 48N-8E and 46.30N-5E where the tidal currents are at a maximum.

4.6. COASTAL STUDIES IN THE BAY OF BISCAY - SEE APPENDIX F

The action of tidal currents in shallow regions produces a turbulence that mixes the water column and destroys the seasonal thermocline. The resulting colder, homogeneous shelf water is separated from the warmer stratified offshore water by a zone where the thermal gradient is high. This phenomenon, unexpected prior to HCMM observations, is similar to the tidal fronts in the western approaches of the British Channel (section 4-4).

4.7. WESTERN MEDITERRANEAN SEA TEST SITE

Results reported here are based on VHRR/NOAA-5 and HCMM data.

4.7.1. Results obtained with VHRR/NOAA-5

The region of Ligurian Sea between Corsica and the southern coast of France was studied in 100 VHRR/NOAA-5 images taken from the period 1975-79. The study revealed a cyclonic surface circulation quasi-permanent and emphasized by its thermal pattern.
Annual variations of the horizontal thermal gradient structure have been described and agree very well with previous in-situ measurements. Low frequency waves in the Ligurian Sea have been observed on time-series of VHRR/NOAA-5 in December 1977, with associated wavelength and phase velocity of 40 km and 0.18 m.s\(^{-1}\). These waves are analysed in terms of large amplitude baroclinic waves as those discussed in the theory of baroclinic instability.

A similar study using VHRR/NOAA-5 was done for the Gulf of Lions, an area where coastal upwelling is common in summertime. The data shows strong evidence for a relation between the location of the upwelling and the contour of the adjacent coastline. The phenomenon is much more intense along straight coastal segments of 10 to 20 km in length than in the vicinity of capes and small bays. The whole imagery suggests that the associated circulation in the surface layer is strongly variable in space and time a fact verified by in-situ measurements and consistent with the very real presence of wind induced eddies in the surface layer.

The effect of the Mistral wind on the Ligurian current has been studied by using a time sequence of VHRR/NOAA-5 data. The Ligurian current flows along the French coast from the Ligurian Sea into the Gulf of Lions where a frontal zone separates the Ligurian current and colder water upwelled in the Gulf of Lions. It has been found that the surface flow associated with the current is stemmed by strong westerly winds and when the wind drops, the frontal zone moves westward at speeds up to 0.3 m.s\(^{-1}\).

4.7.2. Results obtained with HCMM – see Appendix C and G

HCMM photographic products allowed us to capture several features of the large scale surface circulation in the northern part of the western Mediterranean Sea (see Appendix C):

- to study the seasonal variation of the mean location of the front formed north of Balearic Islands, at the juncture between the Atlantic current flowing from the Gibraltar Strait to the north-east and the Ligurian current flowing to the south-west along the southern coast of FRANCE.
to confirm previous observations of cyclonic circulation in the Ligurian sea and upwellings in the Gulf of Lions,

to detect for the first time large anticyclonic eddies (≥ 100 km diameter) in the southern part of the Mediterranean Sea.

HCMM digital products were also used to make a statistical analysis of small cyclonic and anticyclonic eddies in the Ligurian sea (see Appendix G).

5 - PUBLICATIONS

Included in this section are all the materials published by the investigators on infrared remote sensing of the sea surface temperature. Publications which pertain more specifically to the HCMM experiment are marked with an asterisk.

5.1. - REVIEWS


- C.MILLOT (1979) - Wind induced upwellings in the Gulf of Lions - Oceanologica Acta, 2, 261-274.


P.Y. DESCHAMPS, R. FROUIN, M. CREPON - Sea surface temperature of the coastal zones of FRANCE observed by the HCMM satellite - (submitted to) Oceanologica Acta.

P.Y. DESCHAMPS, R. FROUIN - Large diurnal heating of the sea surface observed by the HCMM experiment - (submitted to) Journal of Physical Oceanography.

5.2. PROCEEDINGS OF CONFERENCES


5.3. - THESIS


6 - PROBLEMS

6.1 - HCMM DATA GEOMETRY

The geometric correction performed on HCMM data was partly disappointing. The accuracy with which it was performed on the day or night products was generally of several pixels. Occasionally, the vertical scale was different from the horizontal scale: when transferred onto map locations, there was a discrepancy between lines distances (500 m) and pixel distances (450 m), lacking correspondence to the nominal value (470-480 m).

Additional geometric correction of digital data for registering one HCMM scene to another, was sometimes necessary in order to arrive at a better accuracy. In some cases, it would have been simpler to start from non geometrically corrected data.

Photographic were products without problems in geometry and were used to detect and map with sufficient accuracy most of the oceanic features.

6.2 - PERIODIC NOISE

A periodic signal of variable amplitude was present in the data when analysed by FOURIER transform or structure function, particularly along a line; with a tropical period of 6 pixels. This was only a problem for the statistical analysis of the sea surface temperature at the smallest scales (less than 5 km).

6.3 - CONTRAST OF THERMAL IMAGERY

Some of the standard photographic products were not enough enhanced in the infrared channel, making it impossible to derive from these images any formation over the oceanic areas where temperature variations were small.
This mainly occurred on the day-infrared photographic products when the grey scale was then extended over a large temperature range to adjust for the warm temperature of land surfaces. Specific enhancement for the purposes of oceanographic research would be very useful and is proposed as a recommendation (section 8).

7 - IMAGE QUALITY AND DELIVERY

7.1 - IMAGE QUALITY

Image quality was generally good except for those periods corresponding to high noise levels in the thermal channel. Another problem was the geometry of the images (see section 6-1). Defects occasionally occurred: stripes, or anomalous lines, grids of periodic black or bright pixels, but did not seriously affect the objectives of the investigation.

7.2 - TEST SITES COVERAGE

A list of the received data, photographic and digital products, is given in Appendix H.

Coverage was generally good over all the test sites, and excellent in the Mediterranean Sea, as excepted from the cloud cover analysis.

The major lack of cloudfree data was for studies of estuarine thermal gradients during winter.

7.3 - DELIVERY

Photographic products started to arrive one year after launch on a erratic schedule. It would have been preferable to receive them in chronological order, e.g. as complete monthly data sets. This would have enabled a more efficient and definite selection of the request orders within a given period.
Some of the digital data on requested were received twice, some completely omitted. Most of the tapes received contained only one or two scenes, against a potential of 5 scenes at the very minimum. The amount of tapes was increased consequently: 200 tapes that were finally received were eventually copied onto only 35 tapes.

8 - RECOMMENDATIONS

The following recommendation is specific to oceanographic investigation of the SST field. It is our opinion that it would be better to study photographic products (infrared imageries) having a constant contrast temperature, i.e. a grey scale expanded over a constant range of temperature (≈10°C) around the mean climatological value of the SST.

9 - CONCLUSIONS

1° - HCMM and AVHRR data were comparable quality for oceanographic studies of SST. Both instruments show a large improvement over the VHRR, primarily due to a reduction in noise level. Repetitiveness and multichannel atmospheric correction favour the AVHRR, while geometric correction performed on suitably enhanced HCMM photographic products is a great help to detection mapping oceanic features.

2° - Day and night infrared HCMM data were used in a number of studies of oceanic and coastal phenomena:
- the interaction of the residual flow through the Dover Strait with the Rhine River effluent,
- the tidal fronts in the western approaches of the British Channel,
- the upwellings at the shelf break in the Bay of Biscay,
the formation of coastal cold water regions in the Bay of Biscay,
- the surface circulation and eddies in the Ligurian sea,
- the coastal upwellings in the Gulf of Lions,
- the thermal front north of the Balearic islands,
- large eddies associated with the Atlantic current north of Algeria,
- statistical analysis of the mesoscale variability of the SST.

3° - Day - night differences were used only for a study of diurnal heating of the surface layer of the sea during periods of low wind speed.

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Appendix B

GROUND TRUTH DATA and HCMR MEASUREMENTS

1) Periodical sea surface temperature measurements are performed by the "Réseau National de la Qualité du Milieu Marin" along the Atlantic shore. For example, in the Loire estuary, measurements are performed by the "Institut Scientifique et Technique des Pêches Maritimes", Nantes, every week, at 6 stations. On 09/15/78, SST measurements were made simultaneously by the HCMM satellite and the I.S.T.P.M.

Results: for 2 stations A and B, sea surface temperatures measured I.S.T.P.M. were 290°C. Calculated temperatures from calibrated count of HCMR were 283°C. Thus, in this particular case, the temperatures observed by the satellite were cooler than the ground truth by 2°C.

2) The "Etablissement d'Etudes et de Recherches Météorologiques" situated at the "Centre Océanologique de Bretagne", in Brest, performs a statistic treatment of sea surface temperature measurements in the Bay of Biscay, the west of Channel, and the southern region of the Irish sea (SST-GASC is the name of the processing). (Visualization of the results) are printed twice a day and a thermography in this area is produced three times a month...The range of precision of these measurements (obtained from merchant-ships) is about ±0.5°C.

From three HCMM scenes of good quality, comparisons were made between Satellite and SST-GASC measurements.

The following table presents results of this analysis. For each station are given: temperature in °C from SST-GASC measurements, temperature in °C calculated from calibrated count of the HCMR, and difference between ground truth data and satellite measurement.

In each case, the satellite observed temperatures were cooler than the ground truth (about 7°C). These results are similar to R.N.O. observations.
| stations in gulf of bissay | SST-GASC | HCM | \( \Delta T \) | SST-GASC | HCM | \( \Delta T \) | SST-GASC | HCM | \( \Delta T \) | SST-GASC | HCM | \( \Delta T \) |
|---------------------------|---------|-----|------------|---------|-----|------------|---------|-----|------------|---------|-----|------------|---------|-----|------------|
| 06/10/78                  | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      |
| 09/15/78                  | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      |
| 10/28/78                  | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      |
| 11/20/78                  | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      | 17.9C   | 11  | -6.2C      |
SEA SURFACE TEMPERATURES OF THE COASTAL ZONES OF FRANCE OBSERVED BY THE H.C.M.M. SATELLITE

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ABSTRACT

The HCMM (Heat Capacity Mapping Mission) experimental satellite was launched in April 1978 and provided data until 1980. Although the basic objective of the experiment was the measurement of diurnal temperature variations of the earth's surface for applications to geology and hydrology, the good performance of the HCMR (Heat Capacity Mapping Radiometer) on board the satellite recommended it for use in oceanographic studies. The data were acquired in the form of photographic products and magnetic tapes, and systematically utilized for evaluation of surface temperature in French oceanic regions according to an investigation accepted by NASA (National Aeronautics and Space Administration).

A comparison of the radiometric performances of the HCMR to those of the VHRR (Very High Resolution Radiometer) and AVHRR (Advanced Very High Resolution Radiometer) on board meteorological satellites is presented, demonstrating the decisive gain in quality of the HCMR over the VHRR for the observation of mesoscale structures in the ocean. The similarities between the radiometric properties of the HCMR and AVHRR are also discussed.

The utilization of photographic products proved very suitable since they had already been geometrically corrected and enhanced in the temperature range of the sea surface, consequently avoiding many of those cases requiring involved computer treatment. Examples of results obtained by photo interpretation of marine structures observed in the regions relevant to the investigation (North Sea, British Channel, Celtic Sea,
Bay of Biscay and western Mediterranean) are presented in this study. From these, conclusions have been drawn regarding several oceanic phenomena.

- The thermal effluent of the Rhine is affected by the tidal residual current of the North Sea. The extent of the offshore diffusion of the estuary system is influenced by winds from the NE and W which respectively retard or accelerate the residual current.

- Images showing cold water along the edge of the continental shelf strongly support the hypothesis of a mixing process due to internal waves generated by the action of tidal currents at the edge of the shelf.

- Large scale eddy structures detected during the summer in the western Mediterranean region around 6°E and 38°N may be linked to a phenomenon of barotropic - baroclinic instability.

- The presence of significant diurnal heating of the surface layer (several °C) is related to weak winds in the Mediterranean, leading to interpret with caution daytime SST (Sea Surface Temperature) satellite observations made during the summer period.
RESUME

L'expérience satellitaire H.C.M.M. a été lancée en avril 1978 avec
pour objectif de mesurer les variations diurnes de la température de surface
de la Terre, en vue d'applications en Géologie et en Hydrologie. Les bonnes
performances du radiomètre H.C.M.R. à bord du satellite (NEDT de 0,3 °C,
résolution au sol de 500 m) l'ont aussi désignée pour des études en Océanog-
raphie. Les données fournies par le satellite ont couvert la période allant
de avril 1978 à juillet 1980. Ces données, sous forme de produits photogra-
phiques et de bandes magnétiques, ont été systématiquement utilisées pour
l'observation de la température de surface des régions océaniques fran-
çaises, dans le cadre d'une investigation acceptée par la NASA.

Une comparaison des performances radiométriques du H.C.M.R. à
celles du V.H.R.R. et du A.V.H.R.R. des satellites météorologiques de la
NOAA est d'abord effectuée, mettant en évidence le gain de qualité décisif
du H.C.M.R. sur le V.H.R.R. pour l'observation des structures à moyennes
échelles en zone océanique, ainsi que la qualité radiométrique similaire

L'utilisation du produit photographique, particulièrement bien
adapté puisque corrigé géométriquement et augmenté en contraste dans la
gamme des températures de surface de la mer, s'est avérée fructueuse, évi-
tant dans la plupart des cas de procéder à un traitement informatique sou-
vent lourd. Des exemples de résultats obtenus par photo-interprétation pour
l'observation des structures marines dans les régions concernées par l'in-
vestigation (Mer du Nord, Manche, Mer Celtique, Golfe de Gascogne, Méditer-
ranée occidentale) sont présentés. En particulier, des conclusions ont été
obtenues sur plusieurs aspects océanographiques :

- influence du courant résiduel à travers le Détroit du Pas de Calais sur l'effluent thermique du Rhin ; la plus ou moins grande diffusion de cet effluent à partir de la côte est associée à des vents de secteurs Nord-Est et Ouest qui respectivement freinent ou accélèrent le courant résiduel ;

- les images obtenues sur l'apparition d'eaux froides en été à la limite du plateau continental au large de la Bretagne soutiennent fermement l'hypothèse d'un mécanisme déclenché par les ondes internes générées par les courants de marée à la rupture de la pente ;

- la détection de structures tourbillonnaires de grande amplitude (100 km) en Méditerranée Occidentale dans la zone voisine de 60E et 380N en période estivale ;

- l'apparition d'échauffements superficiels diurnes importants (plusieurs °C) liés à des vents très faibles, en Méditerranée : cela doit conduire à utiliser avec suspicion les observations satellitaires de jour en période estivale.
INTRODUCTION

Examination of the earth's surface temperature field is now becoming a common practice. The first space experiments in this area were launched in the 60's, but it wasn't until the early 70's that the VHRR experiment on meteorological NOAA (National Oceanographic and Atmospheric Administration) satellites permitted a systematic and fairly precise observation of the temperature field of the earth's surface. Although a large number of ocean phenomena have been studied in this manner from space (see among other reviews, those by LEGECKIS, 1978, and Mc CLAIN, 1980), examination of even pronounced ocean structures has still been somewhat limited by the instrumental performances of the VHRR (Noise Equivalent Differential Temperature, NEDT of 0.5 to 1°C).

During 1978, radiometers of a new generation were installed on different satellites: the HCMR on HCMM; the AVHRR on TIROS-N; and secondarily, the CZCS (Coastal Zone Color Scanner) on NIMBUS-7. All included channels in the infrared, and permitted a hope of improved performance for observing the sea surface temperature field primarily by a notable reduction in instrumental noise.

The present study essentially concerns the HCMR experiment launched in April 1978, for which an investigation had been accepted by NASA. The materials provided by NASA consisted of both photographic products and magnetic tapes. The utilization of photographic products was particularly well adapted to the purposes of this oceanographic study since they were already geometrically corrected and enhanced in the sea surface temperature range. A description of the satellite experiment is first presented, then a comparison of the radiometric performances of the HCMR to the VHRR and AVHRR, followed by the results obtained through
photo interpretation of the marine features observed in the regions relevant to the investigation.

II - THE HCMM SATELLITE EXPERIMENT

The fundamental objective of the HCMM space experiment was the measurement of the diurnal temperature variation on the surface of the earth (solar heating during the day, radiative cooling at night) for applications to earth resources (geology, hydrology, etc...) For this, the HCMM satellite was placed at an altitude of 620 km in a sun-synchronous orbit, circular, quasi-polar, characterized by an inclination of 97.79° and a period of 97.2 minutes. The passage over the equator took place at approximately 02 and 14 hours local time in order that data could be obtained near the minimum and the maximum of diurnal temperature variation. The radiometer onboard the satellite was a scanning radiometer that acquired data in 2 channels: the visible and near infrared (0.5 - 1.1 μm), and the thermal infrared (10.5 - 12.5 μm). Similar channels had already been used on previous meteorological satellites, but the purpose of the modified instrumentation of the HCMM experiment was:

(i) to significantly improve measurement in the thermal infrared by an NEDT of 0.3°C and a ground resolution of 0.5 km (as opposed to an NEDT between 0.5 and 1°C and a ground resolution of 1 km for the VHRR radiometer of NOAA satellites), and

(ii) to increase the possibility of obtaining maps of the day/night surface temperature differences at 12 and 36 hour intervals. The main objective of the HCMM experiment was to determine the thermal inertia of the earth's surface with the intentions of: measuring variations of
ground humidity and evapotranspiration of the vegetation; discriminating different rock types and locating mineral beds; and measuring the extent of snow covered areas for the purpose of forecasting runoff due to the melting of ice. Moreover, the good performance of the HCMR recommended it for studies in oceanography.

The data were available in the form of photographic products and digitalized magnetic tapes. Each scene covered an area 700 x 700 km² and contained the following information:

(i) diffuse albedo (or reflectance) from the channel in the visible;
(ii) surface temperature from the channel in the infrared; eventually
(iii) day/night temperature difference, and
(iv) thermal inertia.

III - COMPARISON BETWEEN DIFFERENT RADIOMETERS (HCMR, VHRR and AVHRR)

Radiometers of the same type as the HCMR have been operational for the past few years for measurement, on an observational basis, of the earth's surface temperature: the VHRR on NOAA satellites (NOAA 3 to 5) from 1972 to 1978; the AVHRR on TIROS-N and NOAA 6 in 1978 and 1979, and recently (April 1981) on NOAA 7 which replaced TIROS-N. The performances of these radiometers are compared to those of the HCMR and summarized in Table 1. Note that the HCMR and AVHRR exhibit respectively a gain in radiometric quality (product of NEDT by the ground resolution) by a factor of 3 and 5 times over the VHRR.

In order to demonstrate the gain in radiometric performances of the HCMR over the VHRR and to evaluate its impact on the measured tempe-
The HCMR data acquired 10 May 1978 at 2 h TU on the Bay of Biscay have been compared to those of the VHRR acquired 11 May 1978 at 8 h TU on approximately the same area centered at 45°30' N - 4°30' W. An eddy ∼ 50 km wide is clearly visible in the HCMR data (Fig. 1-a) while it appears only weakly in the VHRR data (too noisy) (Fig. 1-b). The refined quality of the HCMR data has allowed the detection and study of even those structures having weak amplitudes (less than 1°C).

Fig. 2 gives the spatial spectrum of variance density of the sea surface temperature E(k) (where k is the wavenumber) for the same region (64 x 64 km²) corresponding to the preceding eddy, drawn from the data of the VHRR and HCMR and calculated in the direction of the satellite track. The E(k) spectra, which characterize the surface temperature variability in the study region, tend to a limit at high wavenumbers, equal to the variance of the noise divided by τ (when τ is the sampling rate of the data : 1 km in the case of the VHRR ; 0.5 km in the case of the HCMR). Consequently the observed noise level is 0.03 (°C)² in the case of the HCMR and 0.6 (°C)² in the case of the VHRR - i.e. 20 times more elevated for the VHRR. Note also in Fig. 2 that the physical information begins to be significant at wavenumbers greater than 1/40 (km⁻¹) in the case of the VHRR, and 1/5 (km⁻¹) in the case of the HCMR. This indicates that in such an area of weak variance, the analysis of the surface temperature field is limited, due to noise, to a scale greater than 40 km in the case of the VHRR and to 5 km in the case of the HCMR.

A similar comparison was made on data acquired almost simultaneously by the HCMR and the AVHRR, 17 July 1979 in the Bay of Biscay (12 h 45 TU for HCMR, 15 h 15 TU for the AVHRR). The AVHRR data were acquired by the receiving station LANNION, France, and were not geometrically correc-
ted. The figures 3-a and 3-b present an enhanced visualization of an eddy structure of amplitude greater than 100 km in the south eastern region of the Bay of Biscay. The comparison of Fig. 3-a and 3-b shows a similar quality in the restituted temperature field by the HCMR and AVHRR that is confirmed by spectral analysis (Fig. 4). The spatial spectrum of temperature variance density, $E(k)$, corresponding to the western portion of the eddy structure, was calculated in the direction of the satellite track.

In this oceanic zone, it seems that the surface temperature field could be characterized by $E(k) \propto k^{-2}$. The determination is limited at high wavenumbers by the noise level of the radiometers: 0.02 $(°C)^2$ for the HCMR, and 0.01 $(°C)^2$ for the AVHRR. This dependence of the spectrum on wavenumber has not been explained by any turbulence theory (DESCHAMPS et al., 1981). Note also in Fig. 4 that for the two experiments, the physical information begins to be significant at a scale greater than 5 km. This indicates that the relation between noise level and ground resolution by the radiometers is not optimal for study of surface temperature in those oceanic zones where variance is weak, particularly in the HCMR case. A better compromise would be to have a variance of noise less than 0.01 $(°C)^2$ and a ground resolution on the order of 2 km.

This comparative study emphasizes the following conclusions.

(1) The quality of the radiometric performances of the HCMR (ground resolution and NEDT) as compared to those of the VHRR, shows a net improvement in the observation of sea surface temperature field and its application to oceanography.
2) The analysis of the spatial spectrum of temperature variance density shows that the interpretation of the data is generally limited by radiometric performances (noise level) at scales below 5 km in oceanic regions. One can also conclude from this analysis that a NET less than 0.1°C and a ground resolution of 2 km give more optimal radiometric performances for the study of surface temperature in oceanic regions.

3) The HCMR data has the potential of being very useful for the detailed analysis of the sea surface temperature field, particularly in coastal regions, due to a ground resolution of 500 m.

4) The HCMR/HCMM and AVHRR/TIROS-N, NOAA 6 have comparable radiometric performances. The repetitivity and the existence of a channel at 3.7 μm for atmospheric correction (DESCHAMPS and PHULPIN, 1980) are in favor of the AVHRR; however, the HCMR has the unique advantage of delivering the photographic products and digital data radiometrically and geometrically corrected, which enables direct utilization.

IV - OCEANOGRAPHIC PHENOMENA OBSERVED OFF THE FRENCH COAST

Due to the operational features of the VHRR experiment on board the NOAA satellites, it has been possible since the 70's to systematically observe from space the surface temperature of french oceanic regions. Direct reception of the data at CMS (Centre de Météorologie Spatiale) in LANNION, France, has been routinely employed, being limited only by the radiometric performances of the VHRR and by the presence of clouds in the instrument field of view. In regions of the British Channel and North Sea, submitted to a continual regime of atmospheric perturbances, the cloud cover has the effect of considerably reducing the quality of observation from space, however, the meteorological situation in the Mediterranean is much more favorable.
The utilization of channels in the visible for discriminating regions of clouds and the time scales of atmospheric perturbations (generally much shorter than comparable oceanic perturbances) has permitted effective observation even though the presence of clouds has often rendered difficult those dynamic studies requiring continual survey of the phenomena of interest.

An HCMR with improved radiometric performance was launched in April 1978 with the hope of providing more detailed observation of fine structure phenomena. The photographic products provided by NASA were particularly appropriate since prior geometric correction and enhancement in the temperature range of the sea enabled direct interpretation of the data.

From May 1978 to May 1979, the HCMR provided approximately 1000 such images of French oceanic regions that have since been examined and analysed.

That which follows is a presentation of the work accomplished on 3 regions of study (figure 5): the southern portion of the North Sea (zone 1); the western British Channel, the Celtic Sea, and the Bay of Biscay (zone 2); and the northwestern Mediterranean (zone 3). On the photo images, the darkest shades correspond to either the lowest temperature (thermal infrared channel) or to the lowest reflectance (visible channel).

ZONE 1

The Thermal effluent of the Rhine

Systematic observations of the effluent from the Rhine-Meuse-Escaut system have been obtained by the HCMR experimental satellite and
are presented in figures 6 and 7.

On entering the sea, the effluent is entrained by the circulation characteristic of the southern portion of the North Sea. The mean residual circulation (NIHOUL and RONDAY, 1975) is directed from the south west to the north east (fig. 8) and the current tends to flow in a straight line from the Dover Strait following the isobaths deeper than 30 m which are located at the center of the southern Bight. It moves off the dutch coastline at the level of the Rhine-Meuse-Escaut estuary system permitting the effluent to diffuse offshore—i.e. westward. At the Frisonnis archipelago the current more or less follows again the dutch coast.

The interaction of the effluent (warmer in summer, colder in winter) with the residual circulation is complex, but an examination of the photos shows that it can be separated into 2 parts:

- The southern portion of the effluent (Escaut and Meuse) has a tendency to flow towards the southwest before being entrained by the residual current, forming a diffuse wedge-shaped plume along the belgian coast. This is particularly visible during the winter period shown in figure 7. A LANDSAT image (figure 9) reveals that sediments are transported southward in a similar manner. The southern region receives fresh water of lower density ejected by estuary system but the energetic action of tidal currents rapidly destroys and prevents stratification in the marine environment.

- The northern position of the effluent (Rhine principally) is generally entrained directly toward the northeast and forced along the dutch coast by the residual current (figure 6 during the summer). The effluent forms a pronounced offshore boundary separating the non-stratified atlantic water in the center from the coastally stratified water. In northern section, stratification is made possible by the combined actions of transport of less dense fresh water and the higher values of the SIMPSON-HUNTER
parameter (NIHOUL, 1980) which governs the stability of stratification. Unlike NIHOUL's model, the one's developed by PINGREE (1978) does not indicate this tendency toward increased stratification along the dutch coast from the city of the Haye to Texel Island (Fig. 10).

An examination of the meteorological situation (mean wind speed direction and speed) for the period May-June 1978, reveals the interaction between the residual current and the thermal effluent. In the situation of winds dominating from the west (4-10 June), the northern portion of the plume is observed to extend along the dutch coast in the direction of the Frisonnis Islands (see the observations of 4 and 9 June). On the other hand, when winds were from the northeast (16-19 and 25-31 May, 14-20 June) a broad seaward dispersion of the plume (typically 40 km) is noted (observations of 18, 30 May; 19-20 June). During 19-20 June, following relatively strong winds from the northeast, cold unstratified water, encountered offshore the Frisonnis Islands, penetrated southward along the dutch coast. The offshore transport of freshwater rapidly diffused and was then insufficient to maintain stratification near the coast, which is in agreement with the diminution of the SIMPSON-HUNTER parameter.

The diffusion system of the northern portion of the thermal effluent is interpreted as being connected to changes in the residual current that arise as a consequence of wind action. Western winds tend to create a wind driven current which contributes to intensify the residual current, particularly along the dutch coast (PINGREE and GRIFFITHS, 1980), where it forces the effluent shoreward while entraining it farther to the north. When the winds are from the northeast they counteract the flow of the residual current, reducing its speed and deflecting it toward the english coast, thus permitting a broad seaward diffusion of the thermal effluent and only
limited northward entrainment.

Observation of the thermal effluent of the Rhine-Meuse-Escaut system by photographic products of the HCMM enables the following conclusions to be drawn, which are also supported by results based on numerical simulation (NIHOUL and RONDAY, 1975) of the circulation in the southern Bight of the North Sea:

- The average circulation is directed from the southwest to the northeast away from the Dover Strait (NIHOUL and RONDAY, 1975).

- The western winds reinforces the residual current toward the dutch coast, whereas winds from the northeast oppose this current and deflect it toward the english coast (PINGREE and GRIFFITHS, 1980).

- Stratification is absent to the south of the Rhine-Meuse-Escaut estuary system, but present to the north along the dutch coast (NIHOUL, 1980) where it is maintained by the transport of freshwater from river outflow.

ZONE 2

A - TIDAL FRONTS WEST OF BRITTANY AND IN THE WESTERN BRITISH CHANNEL

Figures 12-a and 12-c show HCMR observations of tidal fronts in the western approaches of the British Channel, west of Brittany (Ushant front), near the cape of Cornwalls (front of Scilly Islands), and between Ireland and England (front of the Irish Sea). These fronts have been known for a long time (already observed by DIETRICH, 1950) and the mechanisms forming them have been studied by various authors (SIMPSON and HUNTER, 1974; FEARNHEAD, 1975, PINGREE and GRIFFITHS, 1978; GARZOLI, 1979).
These fronts are produced by the action of tidal currents which mix the water column in the shelf region when the depth is shallow and the tidal current speed, $U$, is high, and eventually destroy the summer stratification. As a result, surface water is colder and a well-marked surface thermal front separates the regions of stratified and homogenous waters.

The stratification is governed either by the SIMPSON-HUNTER parameter, $S = \log_{10}(H/C_D U^3)$ (SIMPSON and HUNTER, 1974) or by the parameter $S' = H/U^2$ (GARZOLI, 1979) where $C_D$ is the drag coefficient ($C_D \approx 0.0025$). According to PINGREE and GRIFFITHS, when $S < 1$ ($H/U^3$ is expressed in cm$^{-2}$ s$^3$) the medium is stable and stratified, and when $S > 2$ mixing occurs and the fluid becomes homogeneous. In the model of GARZOLI, $H/U^2 = 1$ cm$^{-1}$ s$^2$ is the critical value beyond which stratification no longer takes place. The thermal front appears at the boundary between the stratified and homogeneous waters.

Fig. 13 shows locations of the fronts predicted by FEARNHEAD (1975), and PINGREE and GRIFFITHS (1978). These positions, already captured by NOAA satellites (SIMPSON et al., 1978; PINGREE and GRIFFITHS, 1978), are confirmed by HCMM observations. Note also in fig. 12-a and 12-c that the Ushant front, though pronounced at the level of Ushant Island ($\approx 3^\circ$C), progressively disappears farther north. This is explained by the fact that the gradient of $S$ or $S'$ is weaker in the northern portion than around Ushant Island (weaker tidal currents and the slope less steep) rendering the separation between the stratified and homogeneous regions less distinct.

On the image of 25 August, and less clearly on that of 21 September, one can observe a phenomenon mentioned by PINGREE (1979) - colder and more homogenous water east of the front of Brittany diffusing westward in fingers perpendicular to the margin of the front. According to PINGREE, these intrusions
of cold water play an important role in the mechanism of expanding thermocline
erosion which occurred during this period (the end of the summer). As surface
heat was reduced, the front progressed westward.

The positions of these fronts are subjected to changes due to a variety
of factors.

- Variations of the tidal coefficient can double the amplitude of the tidal
current.

- The evolution of energy and heat exchanges at the surface throughout the
season can create conditions of different stratification.

- The wind can be a dominant factor in regions of weak tidal current (SIMPSON
et al., 1978).

- The phenomenon of advection may play a role, advancing the front margin
(GARZOLI, 1979).

HCMR observations show the evolution in the position of the Ushant front
during May-September 1978 (Fig. 14). The position is very fluctuating. Note
an eastward displacement, due to increased stability of the stratified water,
is absent during May-September in contradiction to studies by PINGREE (1975)
and GARZOLI (1979).

Moreover, in Fig. 14, the situation of May 21 is different from that of
26 May in that the front is displaced more than 100 km westward at 49°30' N.
These observations occurred before and after a period of strong tidal coef-
cients, the meteorological situation being the same during 15-26 May with rela-
tively weak winds in the northern sector. These observations suggest the follo-
wing hypothesis: the currents became more important between 21 and 26 May,
and as $S$ and $S'$ parameters diminished, the stratification was progressively
destroyed in the region where the front was localized on 21 May. In response
to the diminution in the $S$ and $S'$ parameters, the thrust of the front advanced
to greater depths (westward) until $H$ was large enough to render ineffective
the tidal currents on the destruction of the stratification.

**B - OBSERVATIONS ON THE EDGE OF THE CONTINENTAL SHELF**

Summer satellite observations (PINGREE, 1979, DICKSON et al., 1980) show a band of cold water situated at the edge of the continental shelf, where the ocean bottom drops from 200 m to several 1000 m. This band of cold water (reported by PINGREE from VHRR data in 1976-1978) persisted from July to September between 5° and 10°W. DICKSON et al. Presented observations in May and June 1979 obtained from AVHRR data, in which the band of cold water followed the edge of the continental shelf from the south of Ireland (11°W) to the south of Brittany (4°W). The explanation for this phenomenon that appears as an upwelling remains uncertain. Based on the works of KILLWORTH (1978), DICKSON advances the hypothesis of an interaction between Kelvin waves and the shelf break, an interaction which is intensified by the presence of canyons. The theory proposed by KILLWORTH supposes winds dominate from the northwest, blowing parallel to the slope. HEAPS (1980) suggests an upwelling generated at the shelf break when winds dominate from the southwest. Note, however, that satellite observations generally correspond to a cloud-free situation associated with an anticyclone high over the Bay of Biscay and the British Isles, and that the resulting winds were frequently from the east. This is contrary to the preceding theory unless one admits to a shift of a few days between meteorological forcing and the response of the sea.

During the period May 1978-1979, 10 HCMR images focused on the edge of the continental shelf. These permitted a pinpointing of phenomena and enabled the following observations to be made.

1) The well established band of cold water corresponds to the local destruction of the thermocline under the action of a mixing process linked to the presence of the shelf limit. This band appears in May-June at the onset of
summer when the thermocline is formed, and disappears in the autumn (october) when the stratification is destroyed.

2) The phenomenon is more intense after spring tides, (Fig. 12-a from 25 August 1978, and Fig. 12-c from 21 September 1978), whereas during the period of neap tides, the band of cold water appears as a more diffuse feature (Fig. 12-b from 15 September 1978). The physical process provoking this upwelling of cold water has a possible a relation to the interaction of tidal waves with the edge of the shelf.

3) One can follow an evolution of phenomena during the course of the summer. Early in the season (a period of weak stratification) a narrow band of cold water (several 10ths of km) was observed on the edge of the armorican and celtic shelves from south of Ireland to 46°N - 4°W in the Bay of Biscay. At the end of the summer (a period of strong stratification), the band of water had expanded and was particularly intense between 5 and 9°W though not discernable on the segment oriented NW-SW at the edge of the shelf from 49°N - 11°W to 46°N - 4°W. The observations of 25 August and 21 September 1978 are typical of this. Both were obtained near the close of the spring tide period. The zones of more intense phenomena which correspond to the colder water are located in precisely the same regions for both documents. It is worth emphasizing that the part of the shelf edge between 5 and 9°W coincides with the segment where the slope of the shelf break is larger (it varies between 0.05 and 0.1, whereas in the region farther north, the slope is less than 0.03) and where the tidal currents are stronger (1.5 knot during spring tide). This group of observations indicates a direct correlation between the presence of cold water along the edge of the continental shelf and the amplitude of the tidal current. MAZE (1980) has shown that the passage of a barotropic tide over the slope can generate an internal baroclinic wave (elevation of the thermocline) of an amplitude of the same order as the depth of the thermocline, thereby suggesting an explanation for the appearance of cold water.
at the surface. The amplitude of the internal wave is increased by the speed of the current and the inclination of the shelf break. The appearance of cold water is restricted to the summer, i.e. when the thermocline is pronounced, and to areas where the strongest currents and steepest slopes are encountered, as in the situation along the coast of Brittany. The observation of 25 August 1978 shows clearly a complex system of internal waves of wavelengths approximating 50 km which correspond to those of internal waves \((c_i = 1 \text{ m s}^{-1})\) having a tidal period. The stationary regime of the internal waves is occasionally visible between the south of Brittany and the shelf break where it seems to be in resonance within the limited conditions constituted by the shape of the basin.

On one occasion observed in the winter (Fig. 12-e from 16 January 1979) a band of warm water along the slope was shown extending very shoreward into the Bay of Biscay. In the location of the cold upwelling usually present off northwest coast of the iberian peninsula, warm water is also observed, having the appearance of a warm upwelling. It is difficult to attribute the phenomenon to the resurfacing of Mediterranean water because its depth is on the order of 1000 m. The hypothesis of a mechanism of advection linked to wind induced circulation in the Bay of Biscay can be equally advanced. This would imply current values (on the order of 1 m. s\(^{-1}\)) established over an extended time (on the order of a week).

C - COOLING ON THE CONTINENTAL SHELF DURING THE AUTUMN PERIOD

Starting in September, the surface layer begins to cool and become homogeneous to progressively greater depths. The mechanism is more rapid and abrupt in shallow areas, such as coastal zones \((\eta < 20 \text{ m})\). At the end of September,
cold water that began to appear at several localized points along the southern coast of Brittany to Gironde (Fig. 12-c), had, by the end of October, formed a continuous coastal band extending to the 50 m isobath (Fig. 12-d). Note that when the thermocline is in complete erosion, cold water spans the entire shelf and extends seaward as successive intrusions with the characteristic scale of 20-50 km. Observations in the winter period of 16 January and 27 February 1979 (Fig. 12-e and 12-f) show a persistent band of cold homogeneous coastal water that extended to the 100 m isobath forming a distinct front of several °C, south of Brittany.

ZONE 3

A - NORTH BALEARIC FRONT

Figs 15-a, 15-b and 15-c provide observations of the north balearic front on 11, 16 July and 12 August 1978. This front results from circulating waters in the western Mediterranean which are characterized by a substantial surface current (LACOMBE and TCHERNIA, 1972) (extending to a depth of approximately 150 m) of Atlantic water and which flows eastward along the Algerian coast in leaving the Alboran Sea (Fig. 16). West of Algeria, the current stems and divides into 2 branches:

- One continues in the eastward direction along the African coast to the Strait of Sicily where it penetrates into the eastern Mediterranean.

- The other curves northeast, merges with the Ligurian current, and follows along the southern coast of France and Spain. This circulation forms two cyclonic rings, one in the Ligurian Sea and another trapped around Balearic Islands which generates the north balearic front.
In Fig. 15-a, 15-b and 15-c, one can detect two major oscillations in the front; the first along the coast of Spain around 4°30' E and the second around 8°E and 42°N. The average position of the front during the summer of 1978 can be seen in Fig. 17. Note the southward displacement at 7°E, from May to August which can be related to wind action dominating from the NW that produces upwellings along the coast of Gulf of Lions and entrains the circulation to the south (MILLOT and WALD, 1981).

Aside from this general form, the north balearic front induces small scale meanders (typically 10-20 km) in response to baroclinic instability in the frontal zone (radius of deformations; several km). Equally notable is an anticyclonic ring near the coast of the french-spanish border, which corresponds to the deviation of the Ligurian current by the Cape of Creux.

**B - LARGE SCALE EDDIES OFFSHORE THE ALGERIAN COAST**

On the observations of 11, 16 and 21 July (Fig. 15-a, 15-b and 15-c), two large anticyclonic eddies, having dimensions approximating 100 km, are clearly visible. They are practically stationary and centered at 38°N - 7°E. A weak propagation E - NE is noted. These eddies are revealed by the entrainment of colder water derived either from upwelling on the Algerian coast (cape Bougaroun) or by cold water flowing along the Sardinian coast. Although they have been systematically observed by satellite photos during the summer period, their origin still remains unclear. They could be linked to experiments made in a rotating tank (GRIFFITHS and LINDEN, 1981) in which similar undulations were attributed to a combination of barotropic and baroclinic instabilities. The horizontal scale $L_E$ (100 km), of the ocean eddy is in partial agreement with the theory of baroclinic instability:
\[ L_E = \pi R_H \]

with \( R_H \), the radius of deformation:

\[ R_H = \frac{1}{f} \left( gh \frac{\Delta \rho}{\rho} \right)^{1/2} = 20 \text{ km} \]

where \( H = 150 \text{ m} \) is the depth of the surface layer of the Atlantic water; \( \frac{\Delta \rho}{\rho} \approx 3 \times 10^{-3} \) is the relative difference in density between the surface water and deep water; \( f \approx 0.9 \times 10^{-4} \text{ s}^{-1} \) is the Coriolis parameter at the latitude in consideration; and \( g \) is acceleration due to gravity. Fig. 15-c of 21 July seems to support the following. From eddies forming along the Algerian coast at 3°E, there seems to be an amplification developing into rings from 5°E. Elsewhere, between 5°E and 90°E, anticyclonic eddies seem to induce smaller cyclonic rings along the Algerian coast.

The observation of 16 July reveals a remarkable phenomenon between the Balearic and Sardinia islands around 40°N. The surface temperature field is very inhomogeneous. Structures more or less organized in bands 5 to 10 km wide give the surface temperature field a filamentous appearance for which the following explanation is proposed. From 5-8 July, a violent wind from the northwest, the Mistral, blew on the Gulf of Lions, entraining the thrust of the north Balearic front toward the south (particularly pronounced on the image of 11 July). Then just prior to 16 July, the winds were extremely weak resulting in minimum surface agitation and the cold water entrained southward to 40°N mixed with Atlantic surface water in a series of warm and cold pockets, elongating in the direction of the current. During such a period, the direction of warm and cold fingers of water can be considered as an indication of the direction of the surface currents; this being equally evident in the region of the large scale eddies on 16 July (38°N).
C - THE LIGURIAN CURRENT AND UPWELLINGS IN THE GULF OF LIONS

The situation in the liguro-provencal basin is well illustrated in Fig. 15-e, 12 August 1978. A cold water mass is located in the center of the basin bounding by a contrastingly warm water circulation that follows along the coast of Corsica, Italy and France (WALD and NIHOUS, 1980). The interface between the central water and the coastal current exhibits a series of deformations having an anticyclonic tendency and wavelengths of ~ 50 km, particularly in the northern portion. This process has been outlined by CREPON et al. (1980), and is analogous to deformations in the polar front of the atmosphere and due to a phenomenon of baroclinic instability.

After flowing along the french coast, the Ligurian current penetrates into the Gulf of Lions, where it encounters coastal summer upwellings produced by strong gusts of winds from north (Mistral) and west (Tramontane) (Fig. 15-d, of 22 July and 15-e, of 12 August 1978). The image of July 22 gives a clear view of the extent of these upwellings created by the strong winds of the preceding days (17-21 July). Colder water appeared on the coast in diverse locations (MILLOT, 1979): cape of Adge, mouth of the Rhone, cape Sicié and, in spreading seaward, was deflected to the right of the wind as a consequence of Coriolis acceleration.

The southward expansion of the cold upwelling extends to 100 km south of Marseille and is an important feature. The LANDSAT image of September 1976 (Fig. 18) confirms the mechanism that at the time of the upwelling, coastal sediments were entrained offshore at the cape of Adge and tended to describe an anticyclonic circuit. Only the western border of the upwelling generated at the mouth of the Rhone, is visible, but significant entrainment of suspended material farther south is apparent.

These phenomena have been numerically modelled by HUA and THOMASSET (1982), and good agreement has been obtained between the satellite observations and the results of the model.
Following release from the upwelling, the Ligurian current flows along the slope of the continental shelf of the Gulf of Lions and entrains towards the southwest those masses of cold water upwelled east of Marseilles (Fig. 19, for 12 August 1978).

5 - IMPORTANT DIURNAL HEATING DETECTED BY THE HCMR IN CONDITIONS OF WEAK WINDS

During the period extending from May 1978 to August 1978, a large amount of data acquired daily on the Mediterranean by the HCMR revealed marine zones of similar spatial structures in both visible and thermal infrared channels. Fig. 20 shows an example of these features; one located in the area between Corsica and the southern coast of France, and the other in the area near the eastern coasts of Corsica and Sardinia. One observes higher temperatures in the infrared channel (Fig. 20-b) and at the same time, important changes in the reflectance in the visible channel (Fig. 20-a). These structures have been identified as significant heating of several degrees, of the first few centimeters of the surface layer during periods of weak wind (DESCAMPS and FROUIN, 1982).

The changes in reflectance observed in the visible channel are interpreted as variations in "glitter", i.e. in the specular reflection of direct solar radiation of the agitated sea surface. During the period around the summer solstice, the geometric conditions of observation were favorable for the detection of glitter phenomenon in the western portion of the scenes. Glitter is usually pronounced when the sea is relatively calm, and a maximum in reflectance occurs when the direction of satellite observation is near that of the specular reflection of the sunlight. One such patch of uniform brightness is noticeable in southwestern portion of Fig. 20-a. In the case of a very calm sea, the reflection of the surface becomes almost specular and a reduction of reflectance can usually be noted, because it is very improbable that the angle of the satellite observation would be aligned exactly in the direction of the specular reflection.

Fig. 20-a illustrates this reduction in reflection: two phenomena are presented with the more or less brilliant areas corresponding respectively to weak and zero winds. The fact that the change in sea surface agitation can produce an increase or reduction of the observed reflectance has already been mentioned by MC CLAIN and STRONG (1969), and LA VIOLETTE et al. (1980).
When the surface agitation due to wind stress decreases, the heating of the surface layer increases (HASSE, 1971). In the absence of wind, the gain in temperature is almost entirely determined by the local absorption of solar radiation. The effect is that the diffusivity in the upper layer tends towards the limit value given by the thermal molecular diffusivity which, on a scale of several hours, is insufficient for distributing the heat to deeper layers. Thus one can observe substantial diurnal heating of several degrees in the surface layer.

The meteorological observations (Fig. 20-d) are in good agreement with the fact that the zones of weak winds correspond to zones of weak reflectance and strong diurnal heating.

Radiative cooling during the night rapidly destroys most of the diurnal heating at least in the upper surface layer. The evidence of diurnal heating can then be established by making a comparative analysis of successive day/night observations Fig. 20-c gives the difference between day and night temperatures at 12-hour interval, corresponding to the day time image shown in Fig. 20-b and furnished by NASA: the warm anomalies are always present yet very well correlated to variations in reflectance in the visible channel.

From May 1978 to August 1978, approximately 60 images were obtained on the western Mediterranean, among 34 of which it has been possible to identify several marine regions showing significant diurnal heating of more than 1°C and involving surface areas of dimensions ranging from 10 to 100 km. The frequency of these events is therefore of consequence in the Mediterranean. Diurnal heating seems much weaker in the near Atlantic and the North Sea where the authors have been able to observe only one scene possessing this phenomenon. Because regions such as the Mediterranean can be strongly affected by diurnal heating, the measurement of the sea surface temperature field obtained by daytime satellite observation may be without any oceanographic significance and should be restricted to night or early morning when the surface layer is more homogeneous.

6 - CONCLUSIONS

In this study, photographic products and numerical data provided by the HCMM experiment have been systematically utilized. Two types of conclusions
can be drawn from this. The first bears on the adequacy of the experiment itself and the pictorial documents provided for the aim of the research: observation of the sea surface temperature field. The other conclusions put in evidence some results of oceanographic interest.

The comparison of the radiometric performances (product of ground resolution by resolution in temperature, NEAT) between the HCMR and the VHRR indicates a gain by a factor of 7 in favor of the HCMR, a gain similar to that of the AVHRR which makes them comparable for selected operations. This gain is decisive and essential for observation of mesoscale structures (10-100 km) in the ocean. Evidence has been provided as much by the study of the spatial spectrum of temperature variance density as by certain original observations which can be found in section 4 (large scale eddies in the western Mediterranean).

The photographic products provided by NASA, already geometrically corrected and enhanced in the sea surface temperature range, greatly facilitated the interpretation of the data obtained. It avoided heavy computer treatment that is necessary with certain meteorological satellites (data of the VHRR and AVHRR). It also greatly improved the amount and quality of possible interpretations through an economy of means and by facilitating a more rapid and wider dissemination to the community of involved and interested oceanographers. A similar treatment of AVHRR data, furnishing operational items of similar photographic products corresponding to the needs of oceanographers, would certainly enable the use of satellite data complementary to in-situ measurements, to progress more rapidly.

Even though the HCMR and AVHRR have potentially comparable radiometric performances, the AVHRR of TIROS-N and NOAA-6 has certain advantages: increased repetitivity that is essential for eliminating the effect of cloud coverage, correction of atmospheric emission by means of a channel centered at 3.7\mu m, and operational character of the experiment until the mid 80's.

The analysis of the HCMR photographic products has permitted conclusions to be drawn on several aspects of oceanography:

- the influence of the residual current, as it passes through the Dover Strait, on the thermal effluent of the Rhine, and the rather broad offshore diffusion of the effluent associated with winds from the northeast or west which respectively retard or accelerate the residual current,
- the analysis of images obtained revealing the presence of cold water in the summer along the edge of the continental shelf to the west of Britanny firmly supporting the hypothesis of an upwelling mechanism produced by the action of tidal currents over the slope of the shelf break,

- the detection of large scale eddy structures (100 km) in the western Mediterranean around 6 E - 39°N during the summer, probably due to a phenomenon of instability of the baroclinic - barotropic type,

- the frequent appearance of significant diurnal surface heating (several °C) linked to weak winds in the Mediterranean, that should lead one to use with caution the daytime observations of the summer season.

The results presented here reflect upon a fairly restricted period: May 1978 to May 1979. It is evident that in the coming years, the infrared images of the AVHRR satellite will continue to be of broad interest to the oceanographic community by offering systematic and repetitive observations and by, for example, filtering cloud cover for the study of temporal changes in ocean-atmosphere phenomena.
ACKNOWLEDGMENTS

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1. Satellite observations in the thermal infrared of the Bay of Biscay region around 45° N and 4°30' W (a) by the VHRR, 10 May 1978 at 8 h TU and (b) by the HCMR, 11 May 1978 at 2 h TU. Each grey shade corresponds to (a) 0.1°C and (b) 0.3°C. In the center of these images one notes the presence of an eddy approximating 50 km in diameter, basely visible on the VHRR image due to the instrumental noise but clearly distinguishable on the HCMR image.

2. Density spectrum of variance of the surface temperature field for the same region (64 x 64 km²) in the Bay of Biscay obtained from HCMR and VHRR data. The direction of analysis corresponds to that of the satellite track.

3. Satellite observations in the thermal infrared of the Bay of Biscay 17 July 1979 (a) by the HCMR at 12 h 45 TU and (b) by the AVHRR at 15 h 15 TU. Each grey shade corresponds to (a) 0.2°C and (b) 0.1°C. One notices the presence of a large eddy structure approximately 300 km wide.

4. Density spectrum of variance of the surface temperature field for the same region (64 x 64 km²) in the Bay of Biscay obtained respectively from HCMR and AVHRR data. The direction of analysis corresponds to that of the satellite track.

5. French oceanic regions: southern portion of the north sea (zone 1), the British Channel, the Celtic sea, and Bay of Biscay (zone 2), the north-western Mediterranean (zone 3).

6. HCMR observations of the thermal effluent of the Rhine-Meuse-Escaut system during the summer season. Significant offshore diffusion on images (a), (b), (e) and (f) (A-A 0022-12470, A-A 0034-13110, A-A 0054-12470 and A-A 0055-02030), effluent abutting the coast on images (c) and (d) (A-A 0039-13050 and A-A 0044-12570).

7. HCMR observation A-A 0263-01320 of thermal effluent of the Rhine-Meuse-Escaut system during the winter season (14 January 1979 at 2 h TU). The southern position of the effluent flows toward the southeast forming a diffuse, wedge-shaped plume along the Belgium coast.
8. - Residual circulation in the southern position of the north sea, according to NIHOUL and RONDAY (1975). Stream lines in $10^4 \text{ m}^3/\text{s}$

9. - Landsat image of 12 June 1975 showing the transport of sediment (clear shades) from the Meuse-Escaut system toward the southwest along the belgian coast.

10. - Value of the SIMPSON-HUNTER parameter, S, in the southern portion of the North Sea: (a) according to the model of PINGREE and GRIFFITHS (1978), and (b) according to the model of NIHOUL (1980). The S values greater than 2 correspond to a stratified medium; value less than 1, to a homogeneous medium; and values of 1.5 to a system in transition where thermal fronts can be encountered.

11. - Mean wind speed and direction on the surface in the southern position of the North Sea for the periods of (a) 8-31 May 1978, and (b) 1-20 June 1978.

12.a - HCMM observation A-A 0121-13260 in the thermal infrared channel for 25 August 1978 at 13h26 TU. Tidal fronts at the entrance of the Manche. Relatively cold water at the shelf break and offshore of Brittany.

12.b - HCMM observation A-A 0142-13190 in the thermal infrared channel for 15 September 1978 at 13h19 TU. Following a period of weak tidal coefficients, the band of cold water at shelf break and offshore Brittany is less distinct.

12.c - HCMM observation A-A 0148-13320 in the thermal infrared channel for 21 September 1978 at 13h31 TU. Tidal fronts at the entrance of the Manche, near Cape of Cornwall, and between Ireland and England. Relatively cold water at the shelf break offshore of Brittany. Upwelling along the coast of Spain.

12.d - HCMM observation A-A 0185-13180 in the thermal infrared channel for 28 October 1978 at 13h18 TU. Cooling on the continental shelf in the autumn season. Note the characteristic structure corresponding to turbulent offshore diffusion of cold coastal water.
12.e - HCMM observation A-A 0265-02090 in the thermal infrared channel for 14 January 1979 at 2h09 TU. Relatively warm water at the limit of the continental shelf southeast of Brittany, in the Bay of Biscay along the coast of Spain.

12.f - HCMM observation A-A 0307-01530 in the thermal infrared channel for 21 February 1979 at 1h53 TU. Note the band of cold water along the French coast.

13.- Tidal fronts in the summer season at the entrance of the Manche and in the Celtic Sea as predicted by the models of (a) FEARNHEAD (1975) and (b) PINGREE and GRIFFITHS (1978).

14.- Evolution of the tidal front position at the entrance of the British Channel during the period of May through September 1978, deduced by HCMR observations.

15.a - HCMM observation A-A 0076-01590 in the thermal infrared channel for 11 July 1978 at 1h59 TU. North Balearic front. Large scale eddies offshore of the African coast.

15.b - HCMM observation A-A 0081-01510 in the thermal infrared channel for 16 July 1978 at 1h51 TU. Apart from the large scale eddies offshore of the Algerian coast, note the irregularity of the surface temperature field between Baleares and Sardinia.

15.c - HCMM observation A-A 0086-01450 in the thermal infrared channel for 21 July 1978 at 1h45 TU. Eddies forming along the Algerian coast and expanding toward the coast.

15.d - HCMM observation A-A 0087-02020 in the thermal infrared channel for 22 July 1978 at 2h02 TU. Coastal upwelling in the Gulf of Lion.

15.e - HCMM observation A-A 0108-01510 in the thermal infrared channel for 12 August 1978 at 2h02 TU. Coastal upwelling in the Gulf of Lion. Liguro-Provençal Current.

16.- Summer surface circulation in the Mediterranean, according to LACOMBE and TCHERNIA (1972).
17. - Seasonal positions of the North Balearic front during the summer of 1978.

18. - LANDSAT image of September 1976. Upwellings in the Gulf of Lion. Coastal sediments entrained offshore and very much to the south in the case of the upwelling produced at the mouth of the Rhone.

19. - Diagram illustrating the situation on 12 August 1978 (Fig. 15. c). After driving various masses of cold upwelling ligurian water the progression of the current is interrupted by a later upwelling released near the Cape of Sicily.

20. - Diurnal heating in the western Mediterranean (a) HCMM observation A-A 0038-12440 in the visible channel on 3 June 1978 at 12h44 TU. Note bright patches (high reflectance) to the coast and west of Corsica and Sardinia. (b) idem (a), but in the thermal infrared channel. Note the warmer water to the east and west of Corsica and Sardinia. (c) Day/night temperature difference from HCMM observations obtained on 3 June 1978 at 1h50 TU (night) (A-A 0038-01500) and 12h44 TU (day). The darker shades correspond to cooler diurnal temperatures. (d) Meteorological situation on 3 June 1978 at 12h TU.

21. - Diurnal heating in the North Sea. (a) HCMM observation A-A 0034-13120 in the thermal infrared channel on 30 May 1978 at 13h10 TU. Note the warm patch east of Scotland in the center of the dark (cold) field. (b) HCMM observation A-A 0035-02280 in the thermal infrared channel on 31 May 1978 at 2h30 TU. The warm patch has disappeared during the night. (c) Meteorological situation on 30 May 1978 at 12h TU.
Table 1 - Performances of the different radiometers on board the satellites:

<table>
<thead>
<tr>
<th>Radiometer</th>
<th>NEDT (300 K)</th>
<th>Ground Resolution</th>
<th>Repetitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHRR/NOAA</td>
<td>0.5 to 1K</td>
<td>1 Km</td>
<td>2/day</td>
</tr>
<tr>
<td>AVHRR/TIROS-N</td>
<td>0.1</td>
<td>1</td>
<td>4/day</td>
</tr>
<tr>
<td>HCMR/HCMN</td>
<td>0.3</td>
<td>0.5</td>
<td>1/day</td>
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11. - Mean wind speed and direction on the surface in the southern position of the North Sea for the periods of (a) 8-31 May 1978, and (b) 1-20 June 1978.
12.a - HCMM observation A-A 0121-13260 in the thermal infrared channel for 25 August 1978 at 13h26 TU. Tidal fronts at the entrance of the Manche. Relatively cold water at the shelf break and offshore of Brittany.
12.b - HCMM observation A-A 0142-13190 in the thermal infrared channel for 15 September 1978 at 13h19 TU. Following a period of weak tidal coefficients, the band of cold water at shelf break and offshore Brittany is less distinct.
12.c - HCMM observation A-A 0148-13320 in the thermal infrared channel for 21 September 1978 at 13h31 TU. Tidal fronts at the entrance of the Manche, near Cape of Cornwalls, and between Ireland and England. Relatively cold water at the shelf break offshore of Brittany. Upwelling along the coast of Spain.
12.d - HCMM observation A-A 0185-13180 in the thermal infrared channel for 28 October 1978 at 13h18 TU. Cooling on the continental shelf in the autumn season. Note the characteristic structure corresponding to turbulent offshore diffusion of cold coastal water.
12.e - HCMM observation A-A 0265-02090 in the thermal infrared channel for 14 January 1979 at 2h09 TU. Relatively warm water at the limit of the continental shelf southeast of Brittany, in the Bay of Biscay along the coast of Spain.
12.f - HCMM observation A-A 0307-01530 in the thermal infrared channel for 21 February 1979 at 1h53 TU. Note the band of cold water along the French coast.
13.- Tidal fronts in the summer season at the entrance of the Manche and in the Celtic Sea as predicted by the models of (a) FEARNHEAD (1975) and (b) PINGREE and GRIFFITHS (1978).
14. - Evolution of the tidal front position at the entrance of the British Channel during the period of May through September 1978, deduced by HCMR observations.
15.a - HCMM observation A-A 0076-01590 in the thermal infrared channel for 11 July 1978 at 1h59 TU. North Balearic front. Large scale eddies offshore of the African coast.
15.b - HCMM observation A-A 0081-01510 in the thermal infrared channel for 16 July 1978 at 1h51 TU. Apart from the large scale eddies offshore of the Algerian coast, note the irregularity of the surface temperature field between Baleares and Sardinia.
15.c - HCMM observation A-A 0086-01450 in the thermal infrared channel for 21 July 1978 at 1 h 45 TU. Eddies forming along the Algerian coast and expanding toward the coast.
15.d - HCMM observation A-A 0087-02020 in the thermal infrared channel for 22 July 1978 at 2 h02 TU. Coastal upwelling in the Gulf of Lion.
15.e - HCMM observation A-A 0108-01510 in the thermal infrared channel for 12 August 1978 at 2h 02 TU. Coastal upwelling in the Gulf of Lion. Liguro-Provençal Current.
16. - Summer surface circulation in the Mediterranean, according to LACOMBE and TCHERNIA (1972).
17. - Seasonal positions of the North Balearic front during the summer of 1978.
18.- LANDSAT image of September 1976. Upwellings in the Gulf of Lion. Coastal sediments entrained offshore and very much to the south in the case of the upwelling produced at the mouth of the Rhone.
19.- Diagram illustrating the situation on 12 August 1978 (Fig. 15.c). After driving various masses of cold upwelling ligurian water the progression of the current is interrupted by a later upwelling released near the Cape of Sicily.
20. - (a) : HCMM observation A-A 0038-12440 in the visible channel on 3 June 1978 at 12 H.44 TU. Note bright patches (high reflectance) to the coast and west of Corsica and Sardinia.
20. - (b) : Idem (a), but in the thermal infrared channel. Note the warmer water to the east and west of Corsica and Sardinia.
20. - (c) : Day/Night temperature difference from HCMM observations obtained on 3 June 1978 at 1 H.50 TH (night) (A-A 0038-01500) and 12 H.44 TU (day). The darker shades correspond to cooler diurnal temperatures.
20. - (d) : Meteorological situation on 3 June 1978 at 12 H TU.
SATELLITE DETERMINATION OF THE MESOSCALE VARIABILITY OF THE SEA-SURFACE TEMPERATURE

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ABSTRACT

Satellite infrared data have been used to investigate the mesoscale variability of the SST (sea surface temperature) field. A statistical analysis of the SST field has been performed by means of the structure function. Results give the equivalent power-law exponent $n$ of the spatial variance density spectrum $E(k) = k^{-n}$. The exponent $n$ was found to vary from 1.5 to 2.3 with a mean value of 1.8 in the range of scales 3–100 km which is in agreement with previous one-dimensional analysis from shipborne and airborne measurements. These observed values of $n$ are discussed and compared with the values predicted by turbulence theories.

1. Introduction

Present-day satellite infrared radiometers permit the determination of the mesoscale SST (sea surface temperature) field on an operational basis thanks to their improved radiometric performances, which typically are of a few tenths of °C for a nadir resolution of 1 km². This gives a potential tool for a systematic investigation of mesoscale thermal features such as thermal fronts, eddies and plumes which have been already observed and studied by means of IR pictures or derived SST maps. In addition to these observable features, a part of the SST field must be considered as random and containing some other information which can only be retrieved by a statistical analysis—e.g., the spectral density of variance.

Attempts to compute the spatial spectrum of the SST have previously been made by McLeish (1970), Saunders (1972a) and Holladay and O’Brien (1975), from airborne infrared measurements along an aircraft track. Examples of mesoscale spectra have also been determined from shipborne measurements (Voorhis and Perkins, 1966; Fieux et al., 1978). Satellite observations give a unique opportunity to investigate the mesoscale variability of the SST field, down to scales of 1 km, at any given time, with a frequency which is limited only by the cloud cover. In the present study, we intend to demonstrate the feasibility of using satellite data to obtain statistical parameters of the mesoscale SST field.

2. Statistical analysis of the SST field

Studies of the variability of the temperature (or any scalar) field usually make extensive use of spectral methods, i.e., the computation of the density spectrum of the scalar variance by means of Fourier transformation or autocorrelation function, to obtain a typical power law which characterizes the variability of the temperature field and which can be related to turbulence theories. In the present study, the structure function has been employed in order to more accurately determine the power-law exponent in the presence of the large noise level found in satellite infrared data.

a. Structure function

If the SST field is considered as being an isotropic random process with homogeneous increments (at least locally), the structure function can be computed as

$$D_{TT}(h) = \frac{1}{2} \langle [T(x + h) - T(x)]^2 \rangle,$$

where $T(x)$ is the temperature at $x$, $h$ the spatial scale, and an overbar denotes an average operator. In the following, $k$ denotes the wavenumber of the form $k = h^{-1}$.

The main advantage of the structure function $D(h)$ when compared with the spectrum of the variance density $E(k)$ or with the autocorrelation function $B(h)$ is that its experimental determination is more accurate and much less affected by random variations because only increments are taken into account (Panchev, 1971). An example is given in Fig. 1 where both $E_{TT}(k)$ and $D_{TT}(h)$ have been computed and are shown for the same sample of the SST field, measured by the AVHRR (Advanced Very High-Resolution Radiometer) experiment on board the TIROS-N.
satellite. This example shows clearly that the structure function is more regular than the spectrum, allowing an easier determination of the characteristic parameters, e.g., the power-law exponent given by the slope when using logarithmic coordinates.

b. Interpretation of the structure function

The structure function \(D(h)\) represents the statistical influence of a point upon other points at distance \(h\). For a homogeneous and isotropic random process, \(D(h)\) and \(B(h)\) are linked by

\[
D(h) = |B(0) - B(h)|. \tag{2}
\]

As \(B(h)\) and \(E(k)\) are the Fourier transformations of each other, \(D(h)\) may thus be related to \(E(k)\) (Panchev, 1971):

\[
D(h) = \int_0^\infty (1 - \cos 2\pi kh)E(k)dk, \tag{3}
\]

for a one-dimensional analysis.

In the inertial range, the spectrum is usually characterized by

\[
E(k) \sim k^{-\alpha}, \tag{4}
\]

From (3), it can be shown that the structure function may then be written as

\[
D(h) \sim h^{-\eta}, \tag{5}
\]

where

\[
n = p + 1 \tag{6}
\]

when \(n > 1\) in order to respect the convergence of the integral (3) at small scales. The exponent \(n\) of the spectral density thus can be alternately determined from the structure function using (6), if the field under study is homogeneous.

Two kinds of error may affect the satellite-based determination of the SST field—instrumental data noise and atmospheric effects.

Although the structure function has the advantage of being much more regular than the spectrum, the study of the structure function and of its shape is generally limited by the noise level at the smallest scales. This effect is illustrated in Fig. 1b, where the observed slope giving the power law exponent of the structure function decreases from \(-1\) at large scales to zero at the smallest scales.

In the particular case of random fluctuations due to an instrumental white noise, both the spectral density and the structure function reduce to constants \(E_n\) and \(D_n\), with \(E_n = \sigma_n^2/k_p\) and \(D_n = \sigma_n^\eta\), where \(\sigma_n\) is the noise variance and \(k_p\) the upper wavenumber limit of the spectral analysis. This noise constant adds to the actual structure function of the SST, which restricts the exponent determination at the largest scales where the noise constant may be neglected \([D_n < D(h)]\). When necessary, a suitable spatial smoothing may reduce the noise, with a corresponding degradation of the ground resolution.

Smoothing also introduces a bias in the determination of the structure function. If \(D_r(h)\) is the structure function of the smoothed field, and \(Q\) is the convolution square of the smoothing function \(F\) it may be shown (Matheron, 1970), that

\[
D_r(h) = D \ast Q - A, \tag{7}
\]

where \(\ast\) is the convolution operator and \(A\) is a constant, i.e.,

\[
A = \int_{-\infty}^{\infty} D(u)Q(u)du. \tag{8}
\]
When $F$ is the spatial average in a square of side $a$, $A = D(a)/3$ for $p = 1$. As with the noise constant, the influence of the bias introduced by smoothing rapidly decreases when $h$ increases, and is less than $10\%$ at $h > 3a$. Above this scale, the influence of smoothing can then be neglected [$A < D(h)$].

The atmospheric transmittance $\tau$, in the 10.5–12.5 µm channel generally used on satellites, mainly depends on the atmospheric water vapor content and typically varies between 0.9 and 0.3 (Kneizys et al., 1980). The radiometric temperature $T_{b}$ measured from space must thus be expressed as

$$T_{b} = \tau T_{w} + (1 - \tau) T_{a},$$

(9)

where $T_{w}$ is the water temperature and $T_{a}$ an appropriate mean air temperature. From (9) it is obvious that the structure function computed from satellite data depends not only on the variations of $T_{w}$, but also of $T_{a}$ and $\tau$. Atmospheric variability generally is assumed to be at larger scales than oceanic variability, so that atmospheric fluctuations could be neglected at scales $< 100$ km. Nevertheless, the satellite determination of the structure function may on some occasions be partially contaminated by air temperature and water vapor variations, but it is very unlikely that this would occur over the open sea where it can be assumed that atmospheric parameters are stable within the scale range. A further study involving satellite and surface measurements along the same track would have been necessary in order to resolve this problem. Assuming a constant atmosphere,

$$T_{b}(x + h) - T_{b}(x) = \tau (T_{w}(x + h) - T_{w}(x))$$

(10)

where the influence of the atmosphere affects only the determination of the structure function amplitude, and not the determination of the power-law exponent $p$. Because the atmospheric transmittance cannot be accurately determined over the oceans, only one parameter of the structure function can be determined from a satellite: this is the power-law exponent $p$ obtained from the slope of the curve in a log-log plot.

The hypothesis of the homogeneity of the random field must be verified, otherwise erroneous determinations of the exponent could be obtained. For example, a frontal zone would have a spectrum $E_{p}(k) \sim k^{-2}$, but $D_{\tau}(h) \sim h^{2}$. Since these exponents are close to the physically expected values, it is necessary to carefully check the homogeneity of the SST field and to remove the existing trend if necessary. When the mean horizontal SST gradient $\partial T/\partial x$ is small, it is sufficient to take

$$\frac{(\partial T/\partial x) \Delta x^{3}}{4 D(h)} \ll 1$$

(12)

over the study range of scales; otherwise, the standard procedures must be applied to detrend the data.

### Table 1. Radiometer performances of the satellite experiments used in this study.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Ground resolution at nadir (km$^{2}$)</th>
<th>Noise equivalent temperature difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHRR/NOAA-5</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>HCMR/HCMM</td>
<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>AVHRR/TIROS-N</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### 3. Results

The results of two independent but complementary studies are hereby presented. The first study deals with data obtained from the VHRR (Very High-Resolution Radiometer) on board NOAA-5, and was limited to the range of scales 40–100 km because of the large level of instrumental noise. The improved radiometric performances of the HCMR (Heat Capacity Mapping Mission) data, —i.e., a nadir resolution of 0.5 km and NEDT = 0.3 K (see Table 1)—allowed us to extend the study down to scales of 3 km. The visible channel was used to select cloud-free study areas in the northeastern Atlantic Ocean and the Mediterranean Sea. Only areas in which no large-scale specific features were viewed on fully enhanced images were considered homogeneous and used in this study.

Locations are shown in Fig. 2 and dates are given in Table 2. At each location, the one-dimensional structure functions were computed in four directions, $\theta = 0$ (across the satellite track, i.e., approximately east to west), $\pi/4$, $\pi/2$ (along the satellite track) and $3\pi/4$. Examples of the computed structure functions are given in Fig. 3 for VHRR/NOAA-5 and in Fig. 4 for HCMR. The results generally show that the SST field is not exactly isotropic. Nevertheless, the structure functions, if not equal, are roughly parallel on a log-log plot, so that the anisotropy is confined in the amplitude $A(\theta)$, i.e.,

$$D_{\tau}(\theta, h) = A(\theta) h^{p}$$

(13)

but the slope $p$ remains very nearly isotropic. Values of $p$ from 0.5 to 1.3 have been observed in this study with an estimated accuracy of $-0.1$. Using VHRR/NOAA-5 data, 44 estimations of $p$ were made in the range of scales 40–100 km, and HCMR data were used to make 37 estimations in the range of scales 3–30 km. The corresponding histograms of the observed $p$ are given in Figs. 5a and 5b. The most frequent values are 0.9–1.0 and the mean values are 0.8 (3–30 km) and 0.9 (40–100 km) with a standard deviation of $0.2$. About 90% of the observed values are distributed between 0.5 and 1.1. The results correspond to a mean value of the power-law exponent of the spectrum $n$ of 1.8 in the wavenumber range 0.01–0.3 km$^{-1}$. 

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The amplitude of the structure functions varied from $10^{-2}$ to $10^{-1}$ ($^\circ{C}$)² at $h = 40$ km. Even after spatial smoothing, it was noted that the noise level tended to slightly reduce the estimated values of $\rho$ because the structure function of the noise is a constant ($\rho = 0$). This is particularly true when the noise level ($5 \times 10^{-3}$ ($^\circ{C}$)² for the HCMM data, $3 \times 10^{-2}$ ($^\circ{C}$)² for the VHRR/NOAA-5 after smoothings) is of the same order as the structure function (see Fig. 1). Whenever possible, the estimates of $\rho$ were corrected for this effect, but the effect could partly explain the lowest values of $\rho$.

On the other hand, a mean horizontal thermal gradient would give $D(h) \sim h^4$. The areas studied were carefully selected to avoid the existence of thermal gradients which would increase the estimate of $\rho$ toward larger values; nevertheless some influence on the data could remain. Both of these effects, noise level and horizontal thermal gradients, could partly but not totally explain the spread of the results around the mean value, between 0.5 and 1.3, which remains significant. There is no evidence of correlation between the estimates of $\rho$ and the corresponding geographical locations or seasons but, nevertheless, we would guess that it is probably necessary to involve physical processes in the explanation of the observed $\rho$ values.

4. Discussion

Using (6) and the results from this structure function analysis, we obtain a spectral density power exponent with a range of $1.5 < n < 2.3$. This agrees fairly well with the previous results reported by several authors either from shipborne measurements (Fieux et al., 1978), or from airborne measurements (Saunders, 1972a), for the one-dimensional temperature spectra (see Table 3). Holladay and O'Brien (1975) attempted to reconstruct the two-dimensional SST field from the tracks of the aircraft survey and found $n = 3$ for the isotropic part of the two-dimen-
physical processes are of importance in the area studied, the 3–100 km range is not an inertial one. In fact, we cannot specifically determine whether or not the 3–100 km range is an inertial one from our observations; by looking at Fig. 3 and 4, one can notice that the structure functions do not exhibit any peak characterizing a very energetic scale in the range we deal with, but this may only mean that the energy inputs are from outside the studied range.

In the range of scales 3–100 km, horizontal scales are larger than vertical ones, and the observed variability may be considered a quasi two-dimensional process. Therefore the observations can be related to the $n$ values predicted by the theories of two-dimensional turbulence (Kraichnan, 1971) and of geostrophic turbulence in the atmosphere (Charney, 1971). These theories take into account either the conservation of energy and of enstrophy (half of the mean square of the vorticity) in the case of Kraichnan's theory, or the conservation of energy and of the pseudo-potential enstrophy (Charney). Both of these theories agree when predicting the power law of the kinetic energy spectrum: $E_k(k) \sim k^{-5/3}$. But the relations between current and temperature are not obvious and the different mechanisms involved lead to drastically different theoretical power laws for the temperature variance spectrum. Kraichnan's theory, considering that temperature is a passive contaminant implies that $E_T(k)$ only depends on $k$ and on the dissipation rates of enstrophy and temperature variance. Then, from a dimensional analysis, $E_T(k)$ must follow a $k^{-1}$ power law. Charney made use of the perfect gas law and of the hydrostatic relation to compute a relation between the temperature and the streamfunction and he found the same law for $E_T(k)$ as for $E_k(k)$, i.e., $E_T(k) \sim E_k(k)$.

The interactions between internal waves and mesoscale eddies are uncertain. Müller (1974) predicts that internal waves gain energy from eddies, while the critical-layer absorption theory of Ruddick (1980) suggests the opposite. The typical scales of internal waves are to the lower limit of the studied range and interactions may occur.

Input of kinetic energy related to wind is found at scales of the same order as the wind waves (100 m), and the meteorological systems (1000 km or more). Energy inflow due to thermodynamic forcing is found at even larger scales. All of these scales are one or two orders of magnitude smaller or greater than those studied. At some locations, interior processes such as baroclinic instability may also play an important role in converting energy through nonlinear mechanisms. The scales of these phenomena are on the order of one to six times the internal radius of deformation, depending on the physics of the problem. This radius is of approximately 50 km in the open ocean and 7 km in the Mediterranean sea. If these...
\[ E_h(k) \sim k^{-2} \]

This means that the observed values of \( n \) are higher than those predicted by the theories. This discrepancy may be due to the fact that the conditions of the theories have not been fully met, namely that the study range is not an inertial one.

Three-dimensional theories of turbulence (Kolmogorov, 1941; Bolgiano, 1962) or space-time variability theories of internal waves (Garrett and Munk, 1972, 1975) report values of \( n \) close to those found in our study (1.7, 1.4 and 2, respectively), but the physical basis of their hypothesis can hardly be extended to the mesoscale range.

We may also notice that several experimental studies of air temperature variability mention values of \( n \) in agreement with our study at similar range of scales (100–1000 km). See reviews by Gage (1979) and Panchev (1971). Some of these results are obtained by using spectral analysis on time-series data and equivalent wavenumbers are computed by using Taylor’s relation. As the validity of this relation is dubious for such scales, these time-series results must be viewed skeptically. But as for the oceanographic observations, there is no atmospheric theory to explain the observed results.

In summary, the power law exponent \( n \) of the spectral temperature variance observed in the range of scales 3–100 km is nearly 2. This is very discordant with the values predicted by turbulence theories which are widely spread around this value. Results and conclusions from the present study are very similar to the experimental results published by Saunders (1972) nearly a decade ago but it is emphasized that further advanced theories are still needed in order to explain the experimental determination of the mesoscale SST variability.

### Table 3. Summary of observed mesoscale SST variability.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Range of scales (km)</th>
<th>Power-law exponent ( n )</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saunders (1972)</td>
<td>3–100</td>
<td>2.2 ± 0.1</td>
<td>one-dimensional, surface temperature, airborne infrared sensor</td>
</tr>
<tr>
<td>Holladay and O’Brien (1975)</td>
<td>3–20</td>
<td>3</td>
<td>two-dimensional, SST maps from aircraft surveys</td>
</tr>
<tr>
<td>Fieux et al. (1978)</td>
<td>1–64</td>
<td>2</td>
<td>one-dimensional, surface temperature, ship-towed sensors</td>
</tr>
<tr>
<td>This study</td>
<td>3–100</td>
<td>1.5 &lt; ( n ) &lt; 2.3; ( \tilde{n} = 1.8 )</td>
<td>two-dimensional, surface temperature, satellite data</td>
</tr>
</tbody>
</table>

![Fig. 5. Histograms of the observed values of the power-law exponent \( p \) of the structure function in the range of scales (a) 40–100 km and (b) 3–30 km.](image-url)
lite data allowed us to perform more systematic study, including the isotropy of the SST field. Using the structure function, the power-law exponent $n$ of the SST field variance density spectrum can be retrieved with good accuracy ($\pm 0.1$). A mean value of 1.8 and a standard deviation of 0.2 have been found in the range of scales 3–100 km, and extreme values of 1.5 and 2.3 have been observed.

The results give rise to several questions: 1) Is the range of scales 3–100 km an inertial one? 2) If yes, is there any turbulence theory which would explain the spectrum power law observed? 3) If not, at which scales are the inputs of energy and to which processes are they related? At the present time, further investigations, both theoretical and experimental, are needed to interpret the physical mechanisms and parameters involved in the mesoscale variability of the SST field.

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REFERENCES


Appendix E

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LARGE DIURNAL HEATING OF THE SEA SURFACE OBSERVED
BY THE HCMM EXPERIMENT'

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Day-night surface temperature differences measured in the infrared (10.5-12.5 μm channel) by the HCMM satellite experiment frequently show large diurnal heating (several °C) of the upper layer of the ocean during summer months in the Mediterranean Sea, when the wind speed is low. When observed in the 0.5-1.1 μm channel, glitter reflectance - i.e. direct solar radiation specularly reflected towards the sensor - correlates with diurnal heating. Glitter reflectance has been modeled to retrieve an equivalent wind speed, and observed diurnal heatings, ΔT, rapidly decrease from their maximum value of about 5 °C as the wind speed, U, increases. A mean diurnal heating of nearly 1 °C is calculated for the marine coastal areas of southern France in summer time. During this period, satellite observations should be restricted to night and early morning orbits, or to periods of high wind speed (U > 5 m.s⁻¹) at noon and during the afternoon.
A daily variation in the temperature of the surface layer of the oceans is known to be produced by diurnal heating due to absorbed solar radiation. The amplitude of the daily temperature variation is usually small because of turbulent mixing which usually prevails over the molecular thermal diffusivity. A solar irradiance of 1000 W.m\(^{-2}\), when absorbed in a mixed layer of 10 m, would give a heating rate of only 0.1 °C per hour, and a daily variation of less than 0.5 °C. If the turbulent mixing is reduced and the mixed layer is less than 1 m thick a heating rate of 1 °C per hour may be expected and daily variations of several °C should be observed. With the exception of very shallow waters, large diurnal surface temperature variations in open oceans correspond to low wind speeds because turbulence in the upper surface layer is mainly induced by the surface wind stress.

From a theoretical simulation of radiative and heat transfer in the upper ocean layer, HASSE (1971) predicted that the deviation of the sea surface temperature (SST) \(T_0\) from the bulk temperature \(T_{10}\) taken at 10 meter depth should vary as:

\[
T_0 - T_{10} = C_2 Q U^{-1}
\]

where \(Q\) is the solar irradiance, \(U\), the wind speed, and \(C_2 = 3.5 \times 10^{-3}\) when \(Q\) is expressed in W.m\(^{-2}\), \(U\) in m.s\(^{-1}\). According to HASSE, Eq. (1) is only valid for \(U > 2\) m.s\(^{-1}\), but the evidence that the SST diurnal variations increase when \(U\) decreases is supported by several observations: ROMER (1969), STOMMEL et al. (1970) occasionally found diurnal variations of more than 1 °C at very low wind speeds - i.e. for \(U < 2\) m.s\(^{-1}\). These observations were nevertheless restricted to a single location and were isolated events.
Satellite infrared radiometers offer the opportunity to more systematically investigate such large diurnal variations of the SST. The first satellite experiment to provide adequate capability for this purpose was the HCMR (Heat Capacity Mapping Radiometer) experiment launched in late April 1978 with an improved temperature resolution (0.3 °C) and a nearly noon overpass. Results from this experiment are hereby reported in order (i) to investigate large diurnal SST variations at low wind speeds (ii) to give an assessment of the relative frequency of such an event and its impact on the determination of the SST field in such areas as the Mediterranean Sea where diurnal heating is frequent.

II - OBSERVATIONS OF DIURNAL HEATING FROM HCMR SATELLITE DATA

II-1 - The HCMR experiment

The basic objective of the HCMR experiment is the measurement of variations of the earth surface temperature for applications to earth resources (geology, hydrology...). For this purpose, the satellite is sun-synchronous and crosses the equator at about 2 a.m and 2 p.m local time so that surface temperature data are obtained close to the minimum and the maximum of the diurnal variation. Satellite altitude is 620 km, and orbit inclination is 98.87°. The HCMR consists of a two-channel scanning/imaging radiometer, with a 0.5-1.1 μm spectral bandwidth in the visible and 10.5-12.5 μm in the thermal infrared. Similar channels have been used on previous meteorological satellites, but the interests of the HCMR experiment are (i) a large improvement of the radiometric performances in the thermal infrared channel for which the temperature resolution is 0.3 °C and the nadir ground resolution is 500 m as compared with 0.5 to 1 °C and 1 km for the previous VHRR/NOAA satellites, (ii) the new ease with which the user can obtain differential surface temperature maps between day and
night at 12 or 36 hour intervals. The HCMR experiment was originally designed to produce thermal inertia data for soil and geology applications but the very good performances of HCMR are also suitable for oceanographic studies. Data were received from NASA (National Administration for Space Research) through an investigation concerned with sea surface temperatures of the coastal zones of France.

Available HCMR data are photographic or digital products covering a 700 x 700 km square scene. The following information is displayed:

1. Diffuse surface albedo or reflectance in the visible channel (day only),
2. Surface temperature from the infrared channel,
3. Surface temperature difference between day and night,
4. Thermal inertia, which was not used in the present study. About 1000 scenes covering the coastal zones of France were received during the May 1978 - May 1979 period. Examples of the photographic products are given for two areas in the Western Mediterranean Sea (Fig. 1) and in the North Sea (Fig. 2) where large diurnal variations of the SST were observed.

II-1 - Diurnal heating and glitter (sun glint) patterns

A large number of the data received for the Mediterranean Sea during May, June, and July of 1978 exhibited very interesting and concordant features in both the visible and the infrared channels, as shown in Fig. 1 between the Island of Corsica and the Southern coast of France, and also close to the east coasts of Corsica and Sardinia. Warmer areas in the thermal channel are associated with brightness changes in the visible.
The observed brightness changes in the visible are identified as glitter or sunglint patterns - i.e., specular reflection of direct solar radiation by the wavy sea surface. During the concerned time period around the summer solstice, the observation angle of the HCMR imagery was very close to the angle of the specular reflection of direct solar radiation in the western part of the scenes. This favors the observation of glitter patterns. Glitter generally increases when the wind decreases and the sea surface becomes calmer and more specular. The surface exhibits a maximum brightness when the observation angle is close to that of the specular reflection of solar radiation: a homogeneous bright area is thus noted in the south-west part of Fig. 1-a. For very calm seas, the surface reflection becomes nearly specular, and a brightness decrease may be observed, because it is very unlikely that the observation angle be strictly in line with the specular reflection. Both processes are present in the northwest part of Fig. 1-a, where bright and dark areas respectively correspond to weak and null wind speeds. The fact that smoothing of the surface could produce either an increase or a decrease of the glitter brightness was previously mentioned by LA VIOLETTE et al (1980). A physical and detailed description is given in the Appendix, to aid in a further quantitative analysis of the data. The dark patterns in a mean bright glitter can thus be clearly interpreted as null wind and calm sea areas, which obviously favor greater diurnal heating of the upper layer of the ocean because the heat transfer to deeper ocean layers is limited by reduced turbulent mixing and thermal diffusivity.

II-3 - Meteorological observations

Evidence of a large diurnal heating corresponding to low wind speed conditions is also given by correlative meteorological observations. Surface observations are presented in Fig. 1-b for the case of the Mediterranean Sea, and in Fig. 2-c for another case found in the North Sea where, due to higher latitudes, glitter is almost always unobservable. On Fig. 2-a a large warm
spot was detected by HCMR in the middle of the North Sea which was coincident with the center of an anticyclonic high where null wind speed was reported. Warmer areas observed in the Mediterranean Sea on Fig. 1-b are also coincident with low or null wind speeds, but the observed wind field is much more complicated because most of the reporting coastal weather stations are affected by some breeze effects which are superimposed upon an anticyclone high. Cloudfree satellite SST observations are frequently acquired during similar anticyclonic situations with moderate wind speeds. It must be outlined that satellite estimations of SST may thus be systematically affected by diurnal heating, and a tentative statement of this is discussed in section III-4.

II-4 - Day-Night observations

At least in the upper layers, heat loss during the night very rapidly destroys most of the diurnal heating, which was produced during day time. Evidence of a diurnal heating may thus be found from a comparative analysis of two successive day and night observations at 12 hour intervals. For the two cases given in Fig. 1-b and 2-a, the corresponding night observations (Figs. 1-c and 2-b) show a much more constant SST field and the warmer features noted during day time disappear.

Figure 1-d gives the result of the computed day-night temperature differences after the proper calibration algorithms have been applied by NASA. These differences present the advantage of being independent of the mean mesoscale SST field and allow enhancement of the diurnal heating, which again closely correlates with glint patterns in the visible channel. Day-night temperature differences are used in the following for a more quantitative analysis of diurnal heating.
III - DEPENDENCE OF DIURNAL HEATING ON SEA STATE AND WIND SPEED

The observed diurnal heating were further quantified by analysis to derive their relationship with the sea state and the wind speed. Day-night temperature differences were correlated to the reflectance of the 0.5-1.1 μm channel. This reflectance, mostly due to sun glitter, is related to the surface slope variance and to a mean wind speed using the statistical model of COX and MUNK (1954).

III-1 - Diurnal heating and glitter reflectance

Day-night temperature differences (Fig. 1-d) - i.e. SST diurnal variations - show patterns similar to the glitter patterns (Fig. 1-a), on June 3, 1978. Fig. 3 gives the result of the correlation obtained when the diurnal heating, ΔT, is plotted as a function of the glitter reflectance, ρg, in a small study area east of Sardinia. It is evident that a close correlation exists and ΔT rapidly decreases when ρg increases. To further interpret that fact, ρg has to be related to the wind speed, or more exactly to the statistics of surface slopes.

Using the statistical distribution of surface slopes from COX and MUNK (1955), a model was developed to relate the glitter reflectance to the wind speed. This model is detailed in the Appendix. Results indicate that ρg could either increase or decrease with wind speed: ρg presents a maximum value for a given wind speed value, both of which depend on solar and observation angles through θn (tg θn is the surface slope allowing specular reflection toward the sensor). Fig. 4 gives the relationship between ρg and the wind speed, U, for θn = 8°, 10°, and 12°, corresponding to the area previously studied for ΔT = f(ρg). In this case ρg increases rapidly at the lower wind speeds and then is rather constant for U > 3 m.s⁻¹ so that U can be estimated with a good accuracy from ρg, only when U < 3 m.s⁻¹. The study has thus to be limited to this
wind speed range. It should also be noted that $p_g$ is physically linked to the surface slope variance, and only statistically to the wind speed. Local anomalies may thus occur, in particular when the fetch of the wind over the sea is variable. Keeping precautions in mind these, we may now transform $\Delta T(p_g)$ into $\Delta T(U)$ which is given in Fig. 5.

III-2 - Diurnal heating and the wind speed

The first point to be noted on Fig. 5, which gives the diurnal heating as a function of the wind speed, is that $\Delta T$ rapidly decreases from several °C to 1 °C when $U$ increases up to 2 m.s$^{-1}$. The scatter of observations $\Delta T(U)$ on Fig. 5 is remarkably less than $\Delta T(p_g)$ on Fig. 3, because the variations of $p_g$ with changes of observation angles within the study area have been eliminated. A fit of $\Delta T(U)$ on Fig. 5 would give:

$$\Delta T = 0.4 \ U^{-1} + 0.5$$

(in °C for $U$ in m.s$^{-1}$)

Some uncertainties related to the model $p_g(U)$ have previously been outlined. Additional errors may be due to atmospheric effects on the measured radiances. An aerosol atmospheric reflectance of about 0.02 was estimated from the minimum reflectance within the scene ($p_g = 0$) and subtracted in the 0.5-1.1 µm channel. Day-night temperature differences have not been corrected for atmospheric emission in the infrared. This approximation would be valid only if the atmosphere were to remain the same between the two satellite overpasses, but a bias due to a change of atmospheric parameters - i.e. temperature and water vapor concentration - could have occurred which would possibly change the 0.5 °C constant found in (2). Lastly, the observed $\Delta T$ are certainly under-
estimated by a factor $\tau$, the atmospheric transmittance in the 10.5-12.5 $\mu$m band, for which $\tau$ typically equals 0.7 for a midlatitude summer atmosphere.

The results may be compared to the values predicted by HASSE (1971). Using a mean solar irradiance at sea level $Q = 900 \text{ W.m}^{-2}$ in (1), $\Delta T$ is found to vary as 1.5 $U^{-1}$ ($U$ in m.s$^{-1}$). This formula is shown in Fig. 5 and when compared to HCMM observations, gives a systematic overestimation of the diurnal heating for $U < 3 \text{ m.s}^{-1}$. Elsewhere, the HASSE formula does not respect a limit value of $\Delta T$ when $U = 0$. As pointed out by HASSE, the results of the model given in (1) can not be applied to the lower wind speed range because the model used by HASSE refers to a steady state assumption not respected by scales of a few hours.

III-3 - Limit value of the diurnal heating

Fig. 5 and other HCMM scenes with large diurnal heatings indicate that diurnal heatings do not exceed about 5 °C, and that a limit value should exist at low wind speed. This value may be obtained by solving the heat transfer equation:

$$\frac{d}{dz} \left( k(z) \frac{dT(z,t)}{dz} \right) + \frac{dF(z,t)}{dz} = \rho c \frac{dT(z,t)}{dt}$$

for $k(z) = k_m$, the thermal molecular conductivity of seawater - i.e. no turbulent diffusivity is assumed at $U = 0$. Eq. (3) was solved using the following conditions:

$$F(z,t) = F(0,t) g(z) - F_0$$
where $F(o,t)$ is the solar irradiance at sea level, $F_o$ the heat loss by the surface, and

$$g(z) = \sum \lambda \; a_i \; \exp(-k_i z)$$  \hspace{1cm} (5)

where $a_i$, $k_i$ are given in Table 1 and were obtained from a fit of $g(z)$ according to the work of PRUVOST (1975). $g(z)$ is considered independent of time in (4) which is a rather good approximation since the underwater penetration of the direct solar radiation is close to the nadir even at low solar elevation angles. A homogeneous layer was assumed to exist just below the surface. The depth $z_0$ of this layer is defined similarly to the model of KRAUS and TURNER (1967): the variation of potential energy produced by solar radiation and surface heat loss is equal to the work of the wind stress on the sea surface, i.e. null for this study case where we look for a limit value of $\Delta T$ at $U = 0$. Under these conditions, $\Delta T$ variance correlated well with the net heat budget of the surface:

$$\Delta T_{\text{max}} = C \int_{0}^{t} (F(o,t) - F_o) \; dt$$  \hspace{1cm} (6)

where $C = 0.85 \times 10^{-6} \; \text{K.J}^{-1} \; \text{m}^2$. For the HCMM observations on June 3, 1978, \(\frac{1}{t} \int_{0}^{t} (F(o,t) - F_o) \; dt\) was estimated to be a mean value of about 600 W.m\(^{-2}\), over a period of 4 hours (in fact a maximum value of 900 W.m\(^{-2}\) at noon at satellite overpass) and we found:

$$\Delta T_{\text{max}} = 5.6 \; ^\circ\text{C}$$  \hspace{1cm} (7)
This value is in agreement with the observations reported in Fig. 5. At the lower wind speed, the observed diurnal heating is widely scattered with in the range of $2 < \Delta T < 4 \, ^\circ C$, and thus below the estimated limit value. The large variations of the observed $\Delta T$ at $U = 0$ may be explained by the fact that Eq. 6 requires a null wind speed during the entire heating period preceding the observation, i.e. several hours, which is very unlikely. The scatter of the diurnal heating at $U = 0$ therefore is probably linked to the time variations of the local wind speed.

### III-4 - Frequency of diurnal heating

From May 13 to August 28, 1978, 30 HCMM scenes taken over the Western Mediterranean Sea were examined of which about 34 scenes exhibited large (typically more than $1 \, ^\circ C$) diurnal heating of particular areas of 10 to 100 km width. Relative frequency of the event is rather large, and is enhanced in some areas which are affected by a breeze effect and where the wind systematically becomes null at some distance from the coast. Table 2 gives relative frequencies of low wind speeds ($U < 3 \, m.s^{-1}$) at some stations along the Coast of France during the summer months (from Darchen (1974)). The frequency of null wind allowing a diurnal heating of more than $1 \, ^\circ C$ is between 10 and 30%. The frequency of low wind speed ($1 < U < 3 \, m.s^{-1}$) is from 20 to 50%, allowing a diurnal heating of about $1 \, ^\circ C$. From these frequencies, $N_1$ and $N_2$, a mean heating $\bar{\Delta T}$ was calculated as

$$\bar{\Delta T} = 2.5 N_1 + N_2 \quad (8)$$

and is also given in Table 2. The mean diurnal heating ranges from 0.5 to $1.5 \, ^\circ C$ along the south coast of France with a maximum on the French Riviera (Cap Ferrat).
The present investigation, using SST satellite observations from the HCMM experiment has shown a high frequency of large diurnal heatings (more than 1 °C) of the sea surface during summer months in such areas as the Mediterranean Sea where low wind speeds are very frequent. This shows that satellite observations made at noon and during the afternoon should be rejected, or at least checked to eliminate those corresponding to low wind speed \( (U < 3 \text{ m.s}^{-1}) \). If not, a systematic bias could be introduced in the SST analysis of some areas, particularly the marine coastal areas affected by a sea-land breeze effect.

Using simultaneous observations of the glitter reflectance, the diurnal heating was correlated to the wind speed. Diurnal heatings of about 0.8 °C were found for \( U = 2 \text{ m.s}^{-1} \), which is two time less than the formulation given by HASSE (1971). A maximum diurnal heating of 5 °C is found for null wind conditions, which is in agreement with the value calculated from the radiative and heat transfer equations assuming the thermal diffusivity is only molecular.
Glitter refers to direct solar radiation reflected by the sea surface. This reflection is specular for a planar surface. When there is wind, the surface is agitated and consists of elements which are statistically distributed around the horizontal plane. This produces a more or less bright spot of variable dimensions which is commonly called glitter.

The radiance $L_g$ reflected by the agitated sea surface can be expressed (Cox and Munk, 1956)

$$L_g = \frac{E_s \cdot R(\omega)}{4 \mu_v \mu_n} p$$

and the equivalent reflectance $\rho_g$ will be expressed as

$$\rho_g = \frac{\pi L_g}{\mu_s \mu_n} = \frac{\pi}{4} \frac{R(\omega)}{\mu_s \mu_v \mu_n} p$$

where $E_s$ is the direct solar radiation at sea level, $R(\omega)$ is the reflection coefficient of water at a given incidence $\omega$, $p$ is the probability of encountering a properly oriented surface element.

$\mu_v = \cos \theta_v$, $\mu_s = \cos \theta_s$, $\mu_n = \cos \theta_n$, respectively define the zenithal angles of the observation direction, the direction of incidence, $\mu$ is the probability of encountering a properly oriented surface element.

$\mu_v = \cos \theta_v$, $\mu_s = \cos \theta_s$, $\mu_n = \cos \theta_n$, respectively define the zenithal angles of the observation direction, the direction of incidence, and their bisector.

$\phi$ is the angle between the incidence and observation planes:

$$\phi = \frac{\mu_s + \mu_v}{2 \cos \omega}$$
\[ \cos2\omega = \mu_s^2 + (1 - \mu_s^2) \left( \frac{1}{2} \right) \frac{1}{(1 - \mu_v^2)^{1/2}} \cos \phi \]  
\hspace{1cm} (A-4)

From a study of aerial photographs of glitter patterns, COX and MUNK (1954) developed \( p \) in a Gram Charlier series which in a first approximation is reduced to a gaussian distribution, with revolution symmetry:

\[ p = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(\tan \theta_n)^2}{2\sigma^2} \right) \]  
\hspace{1cm} (A-5)

with \( \sigma^2 = 0.003 + 5.12 \times 10^{-3} U_{m.s} - 1 \pm 0.004 \)  
\hspace{1cm} (A-6)

for \( 1 < U < 14 \text{ m.s}^{-1} \).

Figure 6 gives an example of the glitter spot \( p_g \) thus computed as a function of solar zenithal angle for different values of \( \phi \), and for a nadir viewing (\( \theta_v = 0 \)). In accordance with the reciprocity principle, by permutation (\( \theta_s, \theta_v \)), Fig. 6 also gives \( p_g \) as a function of the observation angle, for a sun at the zenith (\( \theta_s = 0 \)). For a given angle \( \theta_s \) presents a maximum, \( p_{gm} \), at a certain value of \( \sigma_m \) which is related to wind speed. \( \sigma_m \) and \( p_{gm} \) are given by:

\[ \sigma_m^2 = \tan^2 \theta_n = \mu_n^{-2} - 1 \]  
\hspace{1cm} (A-7)

\[ p_{gm} = \frac{R(\omega)}{4 \mu_s \mu_v \mu_n^2 (1 - \mu_n^2)} \]  
\hspace{1cm} (A-8)

The dashed curve in Fig. 6 envelops the preceding curves and represents the maximum glitter \( p_{gm} \) as defined by (A-8).
HCMM data have been received from NASA as a support to HCMM Investigation No 15. Thanks to L.F. MARTIN for his aid in the translation. Support for this work has been provided by the following French agencies: C.N.R.S. (Centre National de la Recherche Scientifique) and C.N.E.S. (Centre National d'Etudes Spatiales).
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Figure 1 - Diurnal heating in the Western Mediterranean Sea:

(a) - Day HCMM scene A-A0038-12440 on June 3, 1978 at 12.44 TU. Image center is at 40.54°N, 011.04°E. Visible channel: darker tones are lower reflectances. Note the bright patterns East and West of Corsica and Sardinia.

(b) - Same as (a) but infrared channel: darker tones are colder surface temperatures. Note warmer waters East and West of Corsica and Sardinia.

(c) - Night HCMM scene A-A0038-01490 on June 3, 1978 at 1.49 TU. Infrared channel: darker tones are colder temperatures.

(d) - Day-night temperature differences between HCMM scenes obtained on June 3, 1978 at 1.49 TU (night) and 12.44 TU (day). Darker tones are smaller diurnal heatings.

(e) - Meteorological situation on June 3, 1978 at 12.00 TU.

Figure 2 - Diurnal heating in the North Sea:

(a) - Day HCMM scene A-A0034-13120 on May 30, 1978 at 13.12 TU. Image center is at 54.27°N, 00.04°E. Infrared channel: darker tones are colder waters. Note the warm (bright) spot between Scotland and the top right of the image where a thermal front is shown close to Norway.

(b) - Night HCMM scene A-A0035-02280 on May 31, 1978 at 2.28 TU. Image center is at 56.13°N, 03.00°E. Infrared channel: darker tones are colder waters. The warm spot disappeared during the night.

(c) - Meteorological situation on May 30, 1978 at 12.00 TU.
Figure 3 - Day-night temperature difference vs glitter reflectance on June 3, 1978, for a study area East of Sardina.

Figure 4 - Retrieved wind speed vs glitter reflectance for the study area.

Figure 5 - Day-night temperature difference vs retrieved wind speed for the study area. The solid-dashed line shows the diurnal heating obtained from HASSE (1971), which is valid only at $U < 2 \text{ m.s}^{-1}$.

Figure 6 - Glitter reflectance vs zenithal viewing angle, for a sun at zenith, and several wind speeds from 0 to 15 m.s$^{-1}$. Maximum glitter reflectance is given by a dashed line.
Table 1 - Coefficients $a_i$, $k_i$ in (5) for water penetration by solar irradiance.

<table>
<thead>
<tr>
<th>$i$</th>
<th>$a_i$</th>
<th>$k_i$ (m$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.041</td>
<td>3365.9</td>
</tr>
<tr>
<td>2</td>
<td>0.139</td>
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</tr>
<tr>
<td>3</td>
<td>0.211</td>
<td>13.05</td>
</tr>
<tr>
<td>4</td>
<td>0.24</td>
<td>1.22</td>
</tr>
<tr>
<td>5</td>
<td>0.37</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Table 2 - Relative frequencies of low wind speeds:

\[ N_1 : \text{nul}; N_2 : \text{Beaufort forces 1 and 2 (}1 < U < 3 \text{ m.s}^{-1})\text{,}
\]
during June, July and August in the French Mediterranean coastal area, (DARCHEN, 1974). An estimate of the mean diurnal heating \( \Delta T \) is given in column (3).

<table>
<thead>
<tr>
<th>Station</th>
<th>( N_1 )</th>
<th>( N_2 )</th>
<th>( \Delta T ) °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap Bear</td>
<td>16.0</td>
<td>26.9</td>
<td>0.67</td>
</tr>
<tr>
<td>Sète</td>
<td>9.5</td>
<td>42.3</td>
<td>0.66</td>
</tr>
<tr>
<td>Panègues</td>
<td>21.3</td>
<td>26.8</td>
<td>0.80</td>
</tr>
<tr>
<td>Cap Camarat</td>
<td>10.8</td>
<td>46.6</td>
<td>0.74</td>
</tr>
<tr>
<td>Cap Ferrat</td>
<td>35.1</td>
<td>50.4</td>
<td>1.38</td>
</tr>
<tr>
<td>Cap Corse</td>
<td>18.4</td>
<td>35.5</td>
<td>0.82</td>
</tr>
<tr>
<td>Pertusato</td>
<td>6.4</td>
<td>21.0</td>
<td>0.37</td>
</tr>
<tr>
<td>42° N-62°</td>
<td>7.6</td>
<td>/</td>
<td></td>
</tr>
</tbody>
</table>

ORIGINAL PAGE IS OF POOR QUALITY.
Figure 1 - (a) - Day HCMM scene A-A0038-12440 on June 3, 1978 at 12.44 TU.

Image center is at 40.54°N, 011.04°E. Visible channel:
darker tones are lower reflectances. Note the bright pat-
terns East and West of Corsica and Sardinia.
Figure 1 - (b) - Same as (a) but infrared channel: darker tones are colder surface temperatures. Note warmer waters East and West of Corsica and Sardinia.
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Darker tones are colder temperatures.
Figure 1 - (d) - Day-night temperature differences between HCMM scenes obtained on June 3, 1978 at 1.49 TU (night) and 12.44 TU (day). Darker tones are smaller diurnal heatings.
Figure 1 - (e) - Meteorological situation on June 3, 1978 at 12.00 TU.
Figure 2 - (a) - U.S. HCMM scene A-A0034-13120 on May 30, 1978 at 13.12 TU.

Image center is at 54.27°N, 00.01°E. Infrared channel:
darker tones are colder waters. Note the warm (bright)
sporadic spot between Scotland and the top right of the image where
a thermal front is shown close to Norway.
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Figure 6 - Glitter reflectance vs zenithal viewing angle, for a sun at zenith, and several wind speeds from 0 to 15 m.s⁻¹. Maximum glitter reflectance is given by a dashed line.
Appendix F

SATELLITE EVIDENCE OF COLD WATER AREAS NEAR ISLANDS ALONG THE SOUTH BRITTANY SHORE

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ABSTRACT

From HCMM digital products processed at ENS, five scenes of high quality were selected for study because of their clear resolution of cold water areas around islands and shoals along the south Brittany shore. Tidal currents that induce turbulence in shallow depths and destroy the seasonal thermocline are responsible for the well-mixed cold coastal water that is separated from the warmer stratified offshore water by a transitional zone of high thermal gradient. Satellite measurements are compatible with ground truth data analysis.
I INTRODUCTION

Infrared satellite imagery (spectral band 10.5 μm - 12.5 μm) has been used to provide sea surface thermographies. For example, the HCMM and NOAA 5 imagery enabled the detection of the Ushant front which subsequently became the basis of various studies because of its importance in the distribution of phytoplankton.

The spatial and thermal resolution of the HCMM thermographies is more refined than that of the NOAA 5 thus providing better images of the frontal regions in the shallow shelf water along the coast of Brittany.

The thermal structure of these shallow coastal waters is not yet well-known. Cold water areas and high thermal gradients near reefs, shoals and Islands in the shelf region of the Bay of Biscay appeared several times in HCMM data. These areas are typified by their shapes and dimensions.

In this paper, they are described in relation to hydrological and meteorological conditions, and possible interpretations according with other observations are suggested.

II DATA ANALYSIS

Several HCMM photographic products (from May 1978 to November 1978) were studied because of their clear presentation of the existence and development of thermal boundaries and cold water areas. Due to the broad range in the dimensions of such phenomena (50 to 1000 square kilometers), digital products processing was applied.

Five scenes, to the area between Belle Ile, Yeu Island, and the Loire estuary, were selected for an in-depth study:

- 06/10/78 : A-A0045-13160-2 : Day IR
- 08/19/78 : A-A0115-02180-3 : Night IR
- 08/31/78 : A-A0127-13380-2 : Day IR
- 09/15/78 : A-A0142-13190-2 : Day IR
- 10/28/78 : A-A0185-13180-2 : Day IR
Geometric correction, resampling for uniform scaling (1/500 000), and smoothing were applied to them before automatic sea surface temperature cartography. Results are given for three scenes in figures 1, 2, and 3.

III HYDROLOGICAL AND METEOROLOGICAL CONDITIONS

HCMM scenes were registered from June to October 1978. During this period, the flow of the Loire river was not very strong. It fell from 800 m$^3$/s (06/10/1978) to 250 m$^3$/s during summer and autumn months. This last value is very weak considering that in the winter, the flow of the Loire can exceed 5000 m$^3$/s. Thus in all five cases, the influence of the river flow was trivial in comparison to the tidal stream, and could be neglected.

In the Bay of Biscay shelf region, the presence of bottom stress modifies direction and velocity of tidal currents. Thus the role of bathymetry in the dynamics of coastal currents is very important. For example, velocities near the shore are: 3 to 4 knots in the south of the "Presqu'île de Quiberon", in the "Passage de la Teignouse"; 2 to 3 knots in the west of Noirmoutier Island; and 1 or 2 knots between Yeu Island and Noirmoutier Island. Spring to neap ratios vary from 1.6 to 2. The contribution by offshore tidal currents has not yet been established (about 0.5 to 1 knot between Belle Île Island and Yeu Island) but should not be neglected.

In these five cases, meteorological conditions were very similar: Anticyclonic weather, high pressure, low pressure gradients, weak winds, low night-temperature, high day-temperature.

IV COLD WATER AREAS; DESCRIPTION

On the five different scenes, two typical cold water areas can be seen:

- An important circular area east and north of Belle Île Island in the "Passage de la Teignouse", and around Houat and Hoedic islands.
- The important area in the shape of an "S", between Yeu Island and Noirmoutier Island.

These two areas are surrounded by warm waters. We emphasize the similarity between the contouring of the cold water areas and the -20 m isobath (see fig. 7).
IV.1: 06/10/78 and 09/15/78

Thermal gradients near islands are important: $2\,^\circ C/5\, km$. It is worth noting that the shapes of the cold water areas are very similar. However, the typical "S" which was very near Noirmoutier island on 09/15/78, one hour before high water (spring tide) is further off shore on 06/10/78, one hour after low water (neap tide). This corresponds to the dynamics of tidal currents which flow into the bay of Bourgneuf, north of the Noirmoutier island.

IV.2: 08/19/78

The cold water area of Belle Ile island and the cold water area of Noirmoutier Island nearly join above shoals in front of the "Presqu'ile de Guérande". At the hour of the passage of the satellite pass occurred during the high water of a spring tide (tidal coef: 1.06)

Fig. 2: HCMM automatic cartography: sea surface temperature (08/19/78)
Fig. 3: Automatic cartography (09/15/78)
Sea surface temperature

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In both figures 4 and 5, the satellite pass occurred approximately one hour prior to high water, but a difference appears in the tides:

- 08/31/78: neap tides (coef. : 0.68)
- 09/15/78: spring tides (coef. : 0.94)

Figures 4 and 5 show that cold water are particularly wide-spread- ing near islands during spring tides.
Thermal structures are less visible and their contouring is less distinct due to the overriding presence of shallow coastal cold water during this season. However, a thermal front is visible, paralleling the shore. This appears more clearly on HCMM pictures of Nov. 78 and Jan. 79.

Fig. 6: HCMM scene (10/28/78); sea surface temperature

V INTERPRETATION

Each studied scene shows that the contouring of cold water areas corresponds fairly well to the isobaths. These areas are situated in zones where tidal streams are important. The water depth and the current velocity have a fundamental part in spreading the cold water area.

Several authors have already emphasized the importance of tidal currents in the formation of thermal fronts separating two water masses with different temperatures, especially near shoals and islands (FEARNHEAD, 1974).
V.1 Formation of thermal fronts:

During spring and summer, in regions of sufficient depth and weak currents a seasonal thermocline is established offshore, separating warm sea surface waters and cold bottom waters. In shallow waters more inshore, tidal currents create a turbulence which mixes the water column and presents the formation and development of the thermocline. It is for this reason that the sea surface temperature is colder in these shelf regions than it would be if thermocline existed.

The presence of this thermal front around British Isles, between stratified water and well mixed water has been studied by PINGREE and GRIFFITHS (1978). These authors have proposed a numerical model to determinate the position of the thermal fronts by the equation:

\[ S = \log \left( \frac{h}{C_d u^3} \right) \]

where:
- \( h \) is the water depth
- \( C_d \) is the bottom drag coefficient
- \( u \) is the current velocity

They have predicted the position of the front in zones where \( 1 < S < 2 \) and have proposed following classification:

- \( S > 2 \) : stratified water
- \( S = 1.5 \) : transitional water
- \( S < 1 \) : well mixed water.

The importance of the term \( h/u^3 \) in the localisation of fronts on the continental shelf has been shown by SIMPSON, ALLEN and MORRIS (1978).

RAILLARD (1976) described the formation of Ushant front and GARZOLI proposed for this front, a critical value of the Richardson number for determining the boundary between stratified water and well mixed water. She has proposed:

- \( h/u^2 < 1 \) in well mixed water
- \( h/u^2 > 1 \) in stratified water

V.2 Results:

We applied these numerical models to our study region, from Belle Ile island to Yeu island. Figure 7 shows stations where the water depth and currents were calculated. For each station, \( h, u, h/u^2 \) and \( S \) were calculated.
According to these numerical models, water should be stratified in stations A and S (h/u² > 1 ; S > 2).

Water should be well mixed in stations F, G, H, J, R, M, P, Q, where h/u² and S are less than 1.

h/u² and S reach critical values in stations E, L, N, R, in function of hydrological situations.

The boundaries between stratified and well mixed waters are shown in fig. 8. The h/u² = 1 limit presents the same shape as the - 20 m isobath. This result is in accordance with HCMM scenes.

Effects of diurnal heating are clearly visible on HCMM scenes, especially in the bay of Bourgneuf where water depth is less than 10 or 15 m.

Ground truth data and satellite measurements

Data collected from sea cruises (fig. 9) provide a picture of the vertical thermal structure near Yeu island. For example, during summers 1964 and 1965, the thermocline in B is situated between 18 and 30 m. This depth of thermocline seems to correspond with depth of transitional zone between stratified water and well mixed water.
Fig. 8: Thermal front near islands (average position)

A, B, C : N.N.D.O. data : coastal stations (1964, 1965)

Fig. 9: Vertical thermal structures in A, B, C (1964, 1965)
This study suggests that three factors are important in the location of thermal fronts:
- depth of the water column,
- strength of the tidal currents,
- distance from the thermocline to the sea floor.

We proposed in Fig. 10 a schematic interpretation for cold water area observed near Yeu island (09/15/78), according to previous results and observations.

CONCLUSION

In this investigation, sea surface temperature measurements from HCMR data were used for the examination local and coastal thermal structures which had not been observed before from other satellites. Cold water areas near shoals and islands were revealed. In these regions, tidal currents in shallow water create a turbulence which destroys the thermocline so that the sea surface of the well-mixed water is clearly visible by its cooler temperature, and is separated from stratified water by a transitional zone where the thermal gradients are two degrees higher. Numerical models proposed in the study of thermal fronts near Brittany and British Isles can be applied to this specific case with a fairly good fit.
REFERENCES:


Appendix G

Mesoscale eddies detected in the Ligurian Sea by satellite infrared radiometers

- A statistics through the year

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Introduction

Recent AVHRR and HCMR infrared images of the Ligurian Sea have revealed, thanks to the improved radiometric performances of these instruments, a much more complex surface temperature field than one could infer from previous VHRR observations. The images exhibit mesoscale eddies and tongues of colder or warmer waters, which give a characteristic inhomogeneous aspect to the surface temperature field. This spatial variability captured on satellite imagery has already been reported by DAHME et al (1971) and STOCCHINO and TESTONI (1977) from in situ experiments.

NELEPO et al. (1978) argued that the temperature field in the homogeneous layer is, to a large extent, subordinated to the pattern of the eddy field of the mesoscale perturbations. Thus, the investigation and modelling of the processes generating the horizontal singularities in the homogeneous layer are an important and inseparable stage of the research into mesoscale variability of the ocean that has developed with the employment of remote sensing techniques.

With this in mind, and also with the intention to better assess the mooring positions during the DYOME in situ experiment (the DYOME experiment is a part of the GARP Med-Alpex program), the C.T.A.M.N. entered upon a statistical study of mesoscales eddies detected in the Ligurian sea.

Inventory of mesoscale eddies detected in the Ligurian Sea

AVHRR scenes were used, along with a few HCMR ones. All data were geometri-
cally corrected in order to obtain the same projection for the different images. No filtering or smoothing was applied to the data. By displaying the data on the interactive processing system TRIM of the C.T.A.M.N., the central axis and diameter of the eddies were determined, and stored with additional information concerning date and rotational direction (cyclonic, anticyclonic) of the eddies.

Out of seventy-five cloud-free images examined over the course of a year, thirty-nine exhibited mesoscale eddies (52%) and the total number of eddies detected was eighty-nine (table 1). Note, that the frequency of anticyclonic eddies is three times more numerous than cyclonic ones. However except for May, June and July, the monthly samples did not contain enough observations to be representative of the situation. The diameter of the eddies ranged between 20 and 50 km with a mean value of 30 km, and was independent of the rotational direction. In figure 1, the central axes of the eddies are plotted. One can notice that most of the eddies are located south of the midline of the Ligurian Sea oriented NE-SW.

Discussion

In the Ligurian Basin (figure 2), the general circulation is cyclonic in the surface and intermediate waters. However currents from the east and west of Corsica merge north of Cape Corse creating instabilities in the mean flow. Eddies are generated to either side, with the predominant number being produced N.E. of a line joining Nice and Calvi. This result is close to SALUSTI's conclusions (1979) which were based on the work of McCREARY and WHITE (1979). It is likely that the presence of a sand bank in the trajectory of the mean flow contributes to the distribution and complexity of the eddy pattern. Unlike the Gulf Stream meanders which tend to produce
anticyclonic eddies north of the current and cyclonic ones south of the current, the mechanism generating eddies in the Ligurian basin appears more anomalous. To achieve a more complete understanding of the phenomenon, wind effect, residence time, and displacement speed of the eddies must be examined.
REFERENCES


SALUSTI E., 1979 - Private communication.

Table 1 - Summary of mesoscale eddies detected through the year in the Ligurian Sea.

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Fig. 1.a - Location of mesoscale cyclonic eddies
Fig. 1.b - Location of mesoscale anticyclonic eddies
Fig. 2 – The mean oceanic circulation in the North Western part of the Mediterranean Sea (after WALD et NIHOUS, 1980).
The following listing give the date, identification and location of center of image of HCMM scenes received from NASA by the Principal Investigator. The last column "ETAT" give the status of the corresponding digital data:

- R : received
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