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Recent advances in selected areas
of ocean sciences
in the regions of the Caribbean,
Indian Ocean and the Western Pacific

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Preface

Presented during the nineteenth session of the Executive Council of the Intergovernmental Oceanographic Commission, this series of lectures is dedicated to the memory of the noted Danish oceanographer and first chairman of the Commission, Dr. Anton Frederick Bruun. The "Bruun Memorial Lectures" were established in accordance with IOC resolution VI-19 in which the Commission proposed that important intersessional developments be summarized by speakers in the fields of solid earth studies; Physical and chemical oceanography and meteorology; and marine biology. The Commission further requested Unesco to arrange for publication of the lectures and it was subsequently decided to include them in the "IOC Technical Series".

Anton Bruun was born on 14 december 1901, the first son of a farmer; however, a severe attack of polio in his childhood led him to follow an academic, rather than an agrarian, career.

In 1926 Bruun received a Ph.D in zoology, having several years earlier already started working for the Danish Fishery Research Institute. This association took him on cruises in the North Atlantic where he learned from such distinguished scientists as Johannes Schmidt, C.G. Johannes Petersen and Th. Mortensen.

Of even more importance to his later activities was his participation in the Dana Expedition's circumnavigation of the world in 1928-1930, during which time he acquired further knowledge of animal life of the sea, general oceanography and techniques in oceanic research.

In the following years Bruun devoted most of his time to studies of animals from the rich Dana collections and to the publication of his treatise on the flying fishes in the Atlantic. In 1938 he was named curator at the Zoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945 to 1946 he was the leader of the Atlantide Expedition to the shelf areas of West Africa. This was followed by his eminent leadership of the Galathea Expedition in 1850-1952, which concentrated on the benthic fauna below 3,000 m. and undertook the first exploration of the deep-sea trenches, revealing a special fauna to which he gave the name "hadal".

The last decade of Bruun's life was devoted to international oceanography. He was actively involved in the establishment of bodies such as the Scientific Committee on Oceanic Research (SCOR), the International Advisory Committee on Marine Sciences (IACOMS), the International Association for Biological Oceanography (IABO) and the Intergovernmental Oceanographic Commission (IOC); he was elected first Chairman of the Commission in 1961.

His untimely death a few months later, on 13 december 1961, put an end to many hopes and aspirations, but Anton Bruun will be remembered for his inspiring influence on fellow oceanographers and his scientific contribution to the knowledge of the sea which he loved so much.

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Opening statement

Ms. Marie-Annic Martin-Sané, First Vice-Chairman

Ladies and Gentlemen,

It is both a privilege and a honour for me to welcome you to the Bruun Memorial Lectures on the occasion of the Fourteenth Session of the Assembly of the Intergovernmental Oceanographic Commission. Dr. Anton Bruun, as many of us know was not only known for his outstanding contribution in the field of Marine biology, but also for the role he played as the First Vice-Chairman of this Commission. While holding this office, Dr. Bruun dedicated himself to consolidated, in many ways, the work of the Commission and planned for its future development. With his untimely death in 1961, the International Oceanographic Commission suffered a great loss. The Commission in recognition of Dr. Anton Bruun's contribution decided in 1961 to dedicate in each of its Assemblies a scientific Session in his honour.

The IOC Executive Council at its Nineteenth Session, held in Paris, 6-12 March 1986, endorsed that the 1987 Bruun Memorial Lectures should revolve around regional themes dealing with the scientific basis for the prevention of marine pollution in the IOCARIBE region, and monsoon and currents in the Indian ocean region.

Ladies and Gentlemen, it is with great pleasure that I should now like to introduce to you our first speaker today, Dr. Jorge E. Corredor. Dr. Corredor is an Associate Professor at the Department of Marine Sciences of the University of Puerto Rico. He obtained his Ph.D in Biological Oceanography in 1978 from the Rosenthal School of Marine and Atmospheric Sciences, Miami, Florida (U.S.A). His major contributions are in the field of marine pollution in the Caribbean region. As Chairman of CARIPOL Petroleum Pollution Monitoring Programme's Steering Committee of IOCARIBE, Dr. Corredor provided a great impetus to the development of this important programme in the region.

May I present Dr. Jorge Corredor.

1. The scientific basis for the assessment of marine pollution Caribbean sea and adjacent regions: the CARIPOL experience

Dr. Jorge E. Corredor

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Universidad de Puerto Rico
Mayaguez, Puerto Rico

Summary

Co-ordinated regional efforts in marine pollution monitoring in the Caribbean and adjacent areas were concentrated, initially, in the monitoring of petroleum pollution, using rapid and easy-to-use methods that are easily available to the greatest possible number of participants. The application of this criteria has allowed a large database to be assembled on the presence of tarballs on beaches (7 005 data), on floating tarballs (681 data) and on dissolved/dispersed hydrocarbons (1 461 data) in fourteen countries of the region.

The data indicated large quantities of tarballs in the Caribbean, in particular on the Leeward beaches of the Antilles Island Arc, the Dutch Antilles and of the Cayman Islands where the amount exceeds 1 kilogramme per meter of beachfront. The least affected zone so far seems to be the extreme south-western part of the Caribbean from Campeche Sound and from the east coast of Florida range between 10 grammes to 100 grammes. The data on floating tarballs shows an average of 1.84 mg/m^2. In the Puerto Rico area and the strait of Florida 50 % of the floating tarballs can be attributed to local tanker traffic while the remaining 50 % to sources outside the region. The analysis of dissolved/dispersed hydrocarbons shows an average of 1.26 ug/l in the eastern Caribbean rising to an average of 12.58 in the north-western Caribbean.

However, as part of the second phase of the CARIPOL programme, is the preliminary results obtained on contaminated sediments samples in Puerto Rico indicated rapid degradation of the homologous aliphatic hydrocarbon fractions while complexed mixtures of isomeric alkanes and aromatic hydrocarbons remained more persistent.. There is little information on the effect of petroleum on marine organisms in the region.

Other major pollution problems caused by pesticides and heavy metals, eutrophication and the run-off of terrestrial sediments, in particular the latter two are receiving regional importance and will be the subject of detailed study in the future.

Dado el exito del Programa Piloto de Vigilancia de Contaminaciòn Marina (Petròleo) (MAPMOPP por sus siglas en inglès) y la expresion regional en el Caribe y àreas adyacentes de grave preocupaciòn por la magnitud del problema de contaminaciòn por petròleo, el programa regional de vigilancia de contaminaciòn marina, bajo las siglas CARIPOL, comenzò con la implementaciòn de ràpidas y sencillas metodologìas similares a aquellas desarrolladas para el programa piloto. Este criterio ha permitido el acopio de una gran base de datos referente a la presencia de agregados de alquitràn en playas (7005 datos), de agregados de alquitràn flotantes (681 datos) y de hidrocarburos disueltos y dispersos (1461 datos) de un total de 14 paises del area.

La incidencia de agregados de alquitràn en las playas conlleva un marcado impacto econòmico dada la importancia del aprovechamiento turìstico de playas y àreas costeras en la regiòn. Aunque los datos reflejan un promedio de 84 gramos por metro de frente de playa, la distribuciòn de este contaminante no es homogènea y se presentan focos de altìsimas concentraciones llegàndose a reportar playas con cargas de hasta 1 kg por metro de frente de playa. La distribuciòn de agregados de alquitràn en las playas obedece claramente a los patrones de viento y corrientes predominantemente orientados del este. Por este motivo las mayores arribazones se documentan en las playas de barlovento. Asì, en las islas del arco de las Antillas y los archipièlagos de las Antillas Holandesas e Islas Cayman, es comùn encontrar cargas de entre 10 y 100 g por metro de frente de playa. Por otro lado, la incidencia de agregados de alquitràn en las playas es tambièn funciòn de la actividad econòmica relacionada al petròleo, especialmente en lo que se refiere a explotaciòn y transporte. Las playas de la Sonda de Campeche, àrea de intensa explotaciòn marina en el Golfo de Mèxico, demuestran cargas elevadas de estos materiales. Los estrechos son especialmente vulnerables ya que no solo sirven de embudo para las grandes masas de agua de las cuencas mayores con sus correspondientes cargas de alquitranes flotantes, sino que son tambièn sujetos de intenso tràfico marìtimo. Estas circunstancias causan significativas acumulaciones en las playas de la Penìnsula de Yucatàn sobre el Caribe mexicano y en las playas orientales de la Penìnsula de la Florida adyacentes al estrecho del mismo nombre. La acumulaciòn de agregados de alquitràn en las playas de barlovento de islas del arco de las Antillas tales como Barbados y Granada demuestran que buena parta de los alquitranes de petròleo que penetran en el Caribe son acarreados desde el Atlàntico abierto por la corriente de las Antillas.

Los datos sobre agregados de alquitràn flotante (Figura 1) demuestran diferencias subregionales mucho menores que aquellos de agregados en playas indicando que la distribuciòn regional es relativamente homogènea. Esta homogeneidad debe atribuirse, al menos en parte, a la menor intensidad de muestreo para esta variable. No obstante, la presencia de agregados de alquitràn flotantes varìa notoriamente con el tiempo y presenta, al menos en el Estrecho de La Florida y al sur de Puerto Rico para donde existen series de tiempo considerables, correlaciòn significativa con la intensidad de tràfico de buques tanqueros (Van Vleet y Pauly, 1985; Morell y Corredor, 1985). En el Golfo de Mexico, la distribuciòn de agregados de alquitràn flotantes se correlaciona estrechamente con la posiciòn de la corriente de meandro (loop current) que transporta la gran masa de aguas provenientes del Mar Caribe a traves del Golfo hasta llegar al Estrecho de La Florida. Esta observaciòn indica que gran parte de estos contaminantes tienen un origen externo al Golfo, presumiblemente en el Caribe o aun el Atlantico norte (Atwood et el., 1985; Van Vleet y Pauly, 1985).

Los resultados de anàlisis de hidrocarburos disueltos y dispersos reflejan un promedio regional de 5.78 ug/1 y un màximo promedio subregional de 12.58 ug/1 en el Caribe noroccidental. El màximo de 12.58 sinembargo, se debe en gran parte al intenso muestreo llevado a cabo en la Bahìa de Kingston, àrea altamente contaminada (Wade et al., 1985). Los altos resultados promedio para la Sonda de Campeche reflejan las actividades petroleras del àrea al igual que los resultados para el sistema de lagunas costeras de las costas maxicanas del Golfo (Celis et al., 1985). En general, los màs altos valores para concentraciòn de hidrocarburos se encuentran en las bahìas y estuarios de mayor actividad econòmica. Los resultados hasta ahora obtenidos reflejan seria contaminaciòn en las bahìas de La Habana, Cartagena, Veracruz y Kingston (Figura 2).

Los promedios de valores para las tres variables documentadas durante el estudio aparecen en la Tabla 1. Dadas las diferencias en muestreos, es difìcil comparar los datos recopilados durante el presente estudio sobre la incidencia de contaminantes de petròleo y aquellos obtenidos durante el estudio MAPMOPP (Levy et al., 1981). Los niveles de agregados de alquitràn flotantes en el Golfo de Mèxico reflejados en este estudio parecen ser los mayores, indicando un aumento de incidencia de estos contaminantes durante los ultimo años. Los resultados obtenidos para la regiòn del Caribe en cuanto a la presencia de agregados de alquitràn en playas concuerdan bien con aquellos obtenidos en el archipièlago japonès durante el estudio MAPMOPP en el sentido de que las acumulaciones son mayores en playas de barlovento. Aunque las concentraciones promedio para la regiòn del Caribe (84.92 g/m de frente de playa) estàn muy por debajo de las reportadas para el àrea màs contaminada del archipièlago japonès, la isla de Okinawa con 630 g/m, algunas àreas dentro de la regiòn superan este promedio. Tal es el caso de la Sonda de Campeche donde las concentraciones promedio exceden los 1.6 kg/m.

El promedio aritmètico para distribuciòn de hidrocarburos disueltos y dispersos obtenido durante el estudio CARIPOL excede a todos los promedios regionales reportados por Levy y colaboradores durante el estudio MAPMOPP salvo los del ocèano Indico. Al subdividir los datos en forma de promedios subregionales (Tabla 1), encontramos que los altos valores se centran principalmente en el Golfo de Mèxico y Estrecho de La Florida mientras que los valores para el Mar Caribe propiamente no solamente son menores que los del ocèano Indico, sino que se encuentran por debajo de aquellos encontrados para el Mar Mediterràneo. Debe anotarse sinembargo que las desviaciones en la normalidad de la distribuciòn de los datos tanto del estudio CARIPOL como del programa MAPMOPP invalida las pruebas estadìsticas paramètricas. En efecto, las modas de distribuciòn de datos tanto para alquitràn flotante como para hidrocarburos disueltos son en general menores que las medias y las desviaciones estandar son extremadamente altas indicando que la ocurrencia de valores altos esporàdicos es responsable de los altos valores de las medias computadas (Corredor, Morell y Mendez, 1983).

En la Fase II del programa CARIPOL, se viene implementando el estudio de la acumulación de hidrocarburos de petróleo en sedimentos y organismos marinos. Aunque el programa está solamente en su comienzo, algunos datos iniciales obtenidos en la zona costera de Puerto Rico indican una insospechada persistencia de hidrocarburos del petróleo en sedimentos marions tropicales: El derrame de aproximadamente 5000 toneladas de petróleo crudo por parte del buque Zoe Colocotronis en 1973, causó serio impacto sobre las comunidades de mangle de la zona suroccidental de la isla (Tosteson, 1977). Muestreos recientes de sedimentos en la zona intermareal demuestran la presencia de una capa subsuperficial de alquitrán a una profundidad de aproximadamente 30 cm. Análisis cromatográficos de estos materiales indican la pérdida de los hidrocarburos alifáticos livianos pero la preservación de una compleja mezcla de hidrocarburos sustituídos, aromáticos polinucleares y alquenos (Figura 4). Igualmente sucede con los hidrocarburos recuperados en sedimentos de la Bahía de Guayanilla al sur de Puerto Rico donde hasta recientemente operaba un complejo petroquímico y puerto de buques tanqueros. Los cromatogramas de la porción alifática de estos sedimentos presentan una distribuciòn bimodal tìpica de residuos de centinas de tanqueros (Figura 3).

Aunque el petròleo crudo vertido en aguas marinas tropicales sufre ràpida degradaciòn por evaporaciòn y oxidaciòn tanto fotoquìmica como microbial (Botello y Macko, 1982) los resultados aquì presentados indican que las tasas de degradaciòn disminuyen notoriamente una vez los hidrocarburos llegan al sedimento. En general, el patròn de persistencia en sedimentos es sorprendentemente similar a aquel observado en latitudes altas tal como el derrame en Buzzard's Bay, Estados Unidos (Blumer y Sass, 1972; Teal et al., 1978).

Van Vleet y Pauly (1985) han documentado la ingestiòn de agregados de alquitràn flotante por parte de tortugas marinas varadas en las costas de La Florida. Los anàlisis cromatogràficos de residuos de alquitràn recuperados de estos organismos reflejan una distribuciòn bimodal de la fracciòn alifàtica. Esta observaciòn demuestra un impacto deletèreo directo sobre el ecosistema marino atribuible a la pràctica de lavado de centinas en la regiòn.

Aunque los esfuerzos regionales coordinados se han concentrado hasta el presente sobre el problema de los derivados del petròleo, existen otros problemas de contaminaciòn de gran magnitud en la regiòn. Estos incluyen la contaminaciòn por pesticidas y metales pesados, la eutroficaciòn y el deslave de sedimentos terrìgenos. De èstos, los dos ùltimos parecen haber adquirido dimensiones regionales y deberàn ser objeto de detallado estudio dado su severo impacto deletèreo sobre comunidades marinas costeras.

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TABLA 1

Concentraciones promedio (+/- desviaciones estandar) de agregados de alquitràn en playas (AAP: g/m de frente de playa), agregados de alquitràn flotante (AAF: mg/m^2) e hidrocarburos disueltos y dispersos (HDD: ug/l) por sub-regiones. (n = nùmero de observaciones).

Sub-Regiòn	AAP		AAF		HDD	
	media	D.E.	media	D.E.	media	D.E.
	(n)		(n)		(n)	
Golfo de Mèxico Occidental	-	-	1.32	5.77	4.77	5.1
	(0)		(36)		(52)	
Golfo de Mèxico Oriental	31.1	48.3	1.58	6.06	5.10	8.8
	(69)		(328)		(283)	
Sonda de Campeche	1616.3	3070	1.31	7.76	8.83	10.5
	(230)		(39)		(281)	
Estrecho de La Florida	61.3	71	1.90	4.74	3.10	4.30
	(157)		(42)		(119)	
Caribe Noroccidental	248.7	855	1.34	6.61	12.58	23.3
	(339)		(95)		(239)	
Caribe Suroccidental	21.2	75	0.73	0.63	1.39	3.49
	(321)		(3)		(273)	
Caribe Oriental	20.5	18	3.09	29.2	1.26	0.99
	(5885)		(138)		(181)	
Promedios Regionales	84.9	693	1.84	14.2	5.78	12.2
	(7005)		(681)		(1461)	

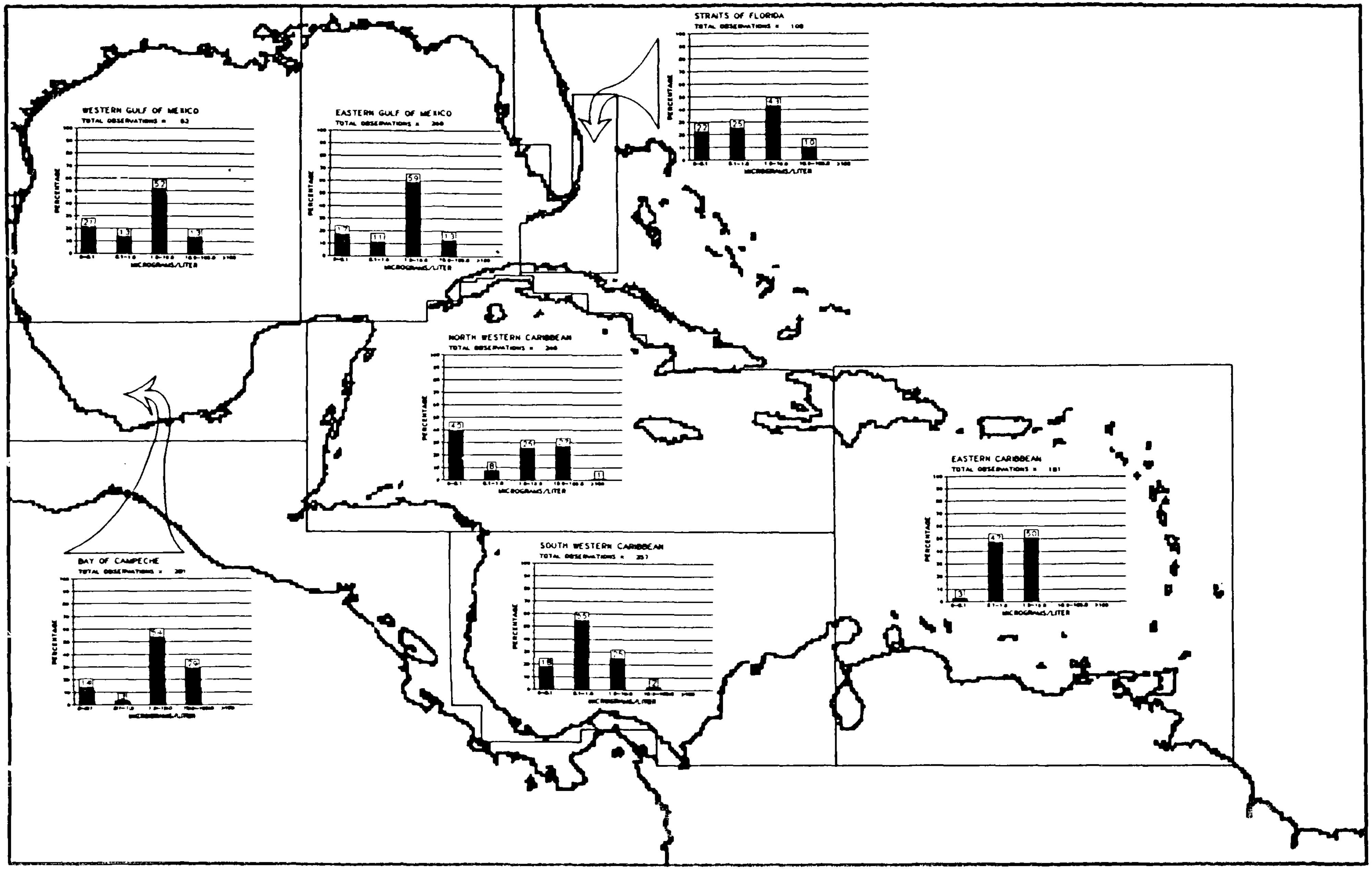

FIGURA 1
Histogramas de distribuciòn subregional de contaminaciòn por agregados de alquitràn flotantes. Fuente: Base de datos CARIPOL (NOAA/AOML, Miami, Fl).

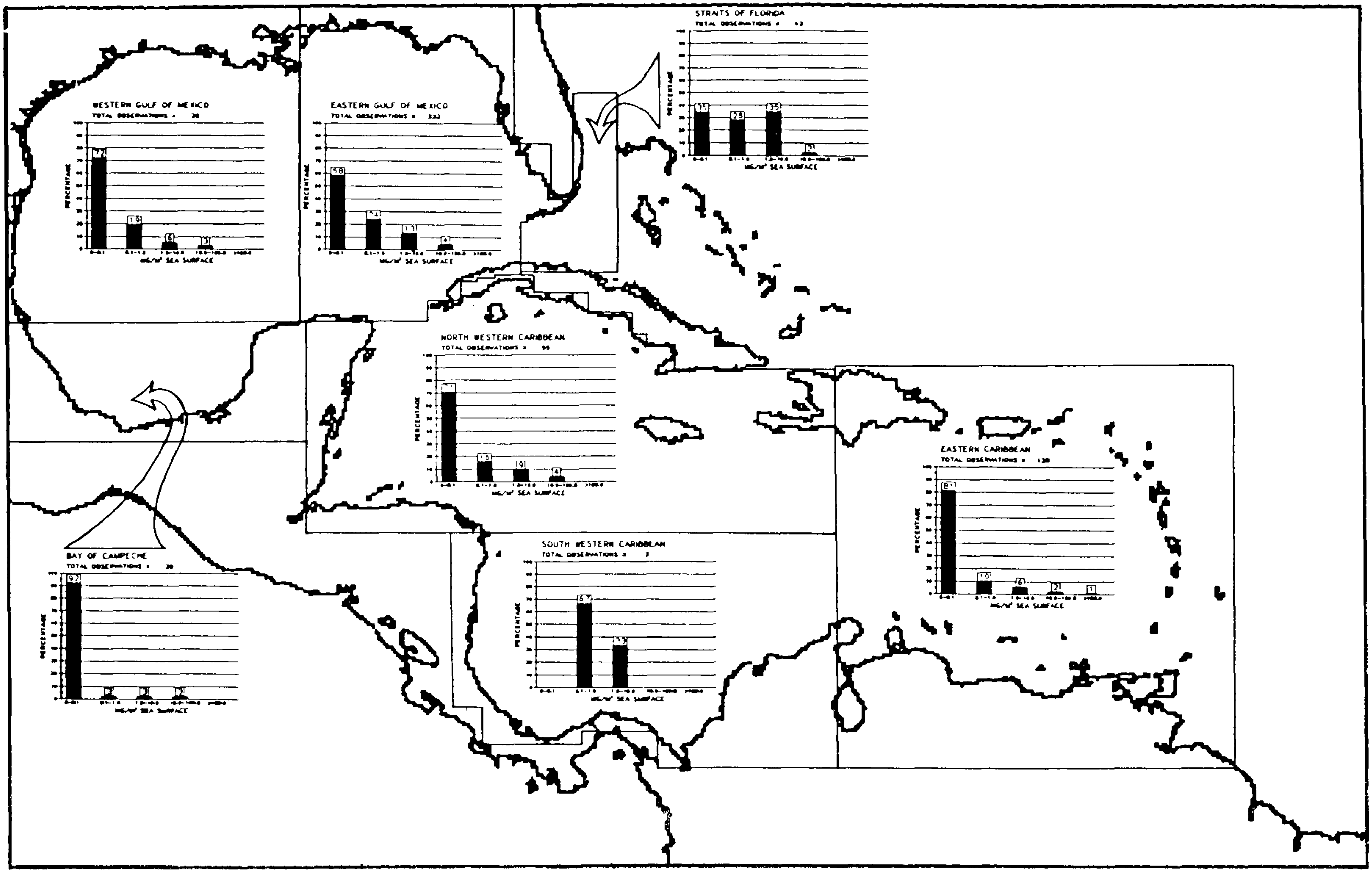

FIGURA 2
Histogramas de distribuciòn subregional de contaminaciòn por hidrocarburos disueltos y dispersos. Fuente: Base de datos (CARIPOL (NOAA/AOML, Miami, Fl).

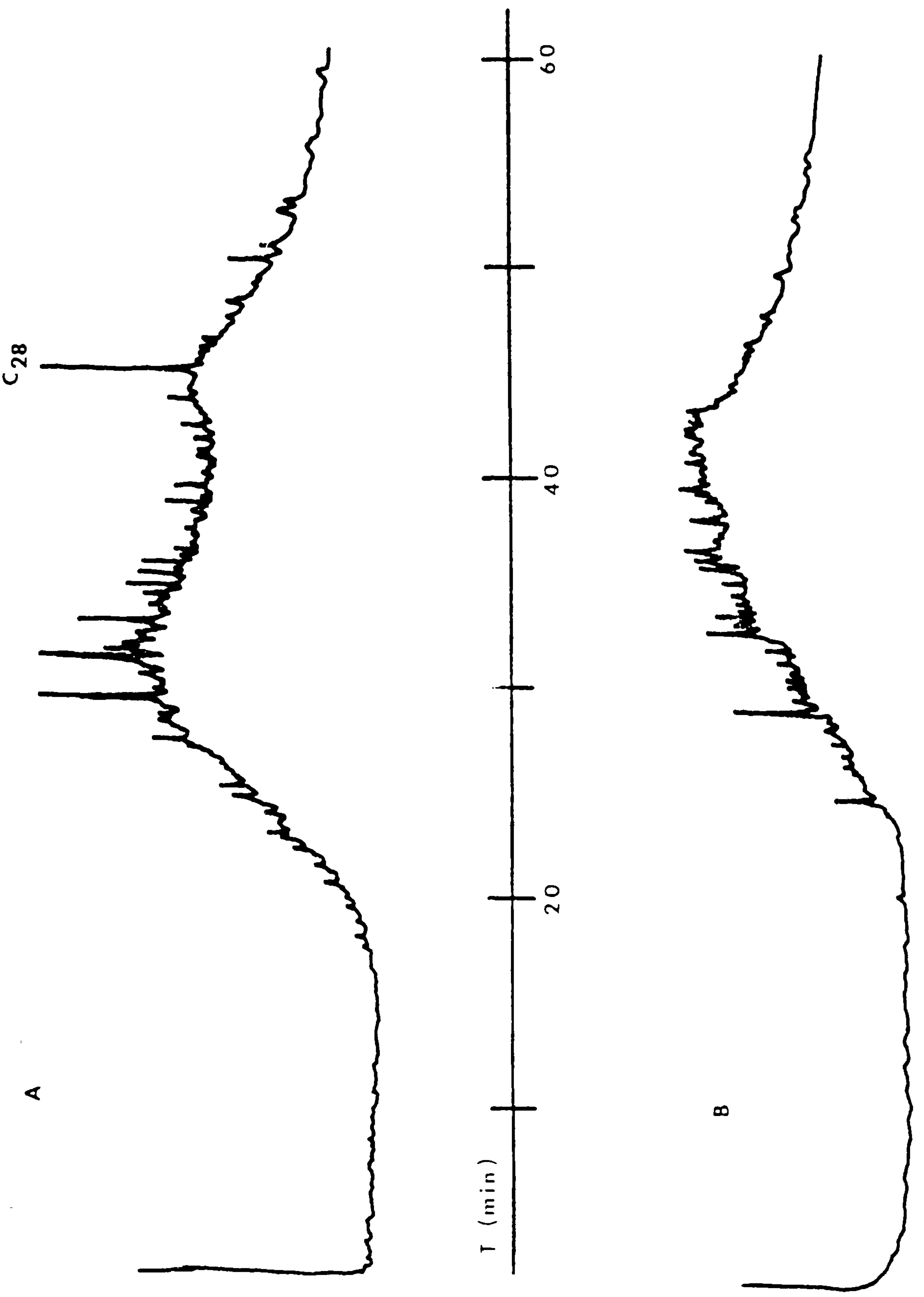

FIGURA 3

Cromatogramas de la fracciòn de alcanos de sedimentos contaminados por hidrocarburos de petròleo al sur de Puerto Rico. (A) Bahìa de Guayanilla. Muestra tomada a 3 m de profundidad. C-28: Patròn interno de n-octacosano. Cromatograma por J. Morell. (B) Bahìa Sucia. Sedimentos intermareales de la regiòn afectada por el derrame del M/V ZOE COLOCOTRONIS. Cromatograma por J. Acuña, G. Gold y J. Morell. Notar distribuciòn bimodal de la mezcla compleja no resuelta (UCM) en (A).

Discussion[1]

B. Battaglia

The methods described by Professor Corredor in his interesting lecture appear very effective in cases of large scale contaminations such as those observed in the Caribbean. However, when pollution events are sporadic, and the amount of pollutants not so great, an effective technique to detect them consists in the so called "mussel" or "barnacle watch". Bivalves such as Mylitches or **Crossostrea**, filter enormous quantities of water and they are powerful bio-accumulators. Gas-chromatography applied to extracts of soft tissues from these organisms, permit, for instance, to carry on reliable qualitative and quantitative analysis of hydrocarbons and other contaminants. We have applied techniques of this kind extensively in the upper Adriatic and in the Lagoon of Venice with satisfactory results. Not only were we able to record even episodical pollution events, but we could also evaluate the persistence of their toxicals in the animals, and the time and environmental factors required for their complete elimination. Have you considered the opportunity of utilizing such methods ?

J.E. Corredor

We have no appropriate mussel species in the Caribbean and consequently we have chosen the mangrove oyster as the principal sentenal organisms.

G. Kullenberg

You have mentioned about higher concentration of floating tarballs and dissolved/dispersed hydrocarbons in certain parts of the Caribbean, principally associated with the local tanker traffics. I wonder if you have data to show the possible influence of other factors such as local circulation on their distribution on the one hand, and the correlation between the floating tarballs and the dissolved/dispersed hydrocarbons on the other.

J.E. Corredor

The data subset, especially from Puerto Rico, was analyzed statistically and we found no significant correlation between the presence of floating tar and the presence and concentration of dissolved and dispersed hydrocarbons.

N. Andersen

Eutrophication affects the coastal area. The phenomenon also exists in the open ocean, but we virtually do not know about it. It seems, however, to have an impact on the living resources and we need to know more about it.

J.E. Corredor

I agree that this problem is reaching regional approach and hence concerted action by co-operating states is essential, especially due to its deleterious effects on the near shore benthic community.

A.R. Bayoumi

You have referred to the oil tankers as the only source of tar ball. Is it the only source ? Could there be other sources such as refineries and activities such as exploration and exploitation?

J.E. Corredor

In answer to your question, I did not want to give the impression that tankers alone are responsible for petroleum pollution. There are certainly other sources or activities of which the principal source could be exploitation of sea bottom hydrocarbons. A clear example of this is the IX TOC-I accident in Campeche Sound off the Gulf of Mexico.

1 Names and titles of speakers are given at the end of the publication.

Marie-Annic Martin-Sané

Our next speaker is Dr. Michele Fieux.

Dr. Fieux obtained her doctorate in the field of Physical oceanography from France, in 1972. She served as Professor at the Ecole Nationale Superieure des Techniques Avancees in France, and is presently serving as Professor at the Laboratoire d'Oceanographie Dynamique et de Climatologie in Paris. Dr. Fieux carried out extensive studies in the field of ocean dynamics of the Mediterranean, the Atlantic, and, more recently of the tropical Indian ocean, and in this context, had the opportunity of working with several eminent oceanographers, such as Professor Lacombe, Henry Stommel and John Swallow. As a member of SCOR Working Group 47 on Oceanographic Programmes During FGGE, Dr. Fieux has been actively involved in the world Experiment as part of GARP. She will deliver her talk on recent developments in our knowledge of the monsoon and currents in the Indian ocean.

Ladies and Gentlemen, please welcome Dr. Michele Fieux.

2. Monsoon and currents in the Indian ocean

Michèle Fieux

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Summary

The Indian Ocean has the particularity of being closed to the north as against the Atlantic and the Pacific Ocean. The presence of the continent thus generates one complete seasonal reversal of the atmospheric circulation to the north of about 10 latitude south; this is the regime of monsoons. The atmospheric circulation so specific of the Indian Ocean has also generated a specific oceanic response which makes the Indian Ocean a privilege area of ocean atmosphere interaction studies. This is true, in particular of the western Indian Ocean which receives the strongest seasonal oceanic variabilities as compared with other regions of the globe.

Unfortunately, this ocean has somewhat tended to be neglected in its plan of observation. The first large scale programme of international exploration of this ocean was the international Indian Ocean Expedition, 1960-1965, initiated by SCOR and later co-ordinated by the IOC. Then, it was only in 1979 that a new international programme known as the First Global GARP Experiment (FGGE) brought together again many nations to undertake a common oceanographic programme initiated by a SCOR Working Group. Having described the general characteristics of the Indian Ocean in relation with its seasonal atmospheric cycle, a review will be made of the main results now obtained from these two large-scale international programmes concerning the upper circulation of this ocean. This will be followed by a description of recent studies since FGGE and others envisaged in the context of the large-scale international programmes coordinated by CCO and IOC, namely TOGA (Tropical Ocean and Global Atmosphere) and WOCE (World Ocean Circulation Experiment). The importance of the participation of surrounding countries in these programmes have been stressed.

INTRODUCTION

L'océan Indien, éloigné des grands centres océanographiques, a été très longtemps délaissé. C'est l'un des océans les moins bien connus.

Les périodes d'études intensives furent tout d'abord l'Expédition Internationale de l'Océan Indien (EIOI) qui s'est déroulée de 1960 à 1965 sous l'égide du SCOR et qui a donné lieu, entre autres, à l'atlas océanographique réalisé sous la direction du Professeur Klaus WYRTKI. C'est le Docteur John SWALLOW, un des grands spécialistes de cet océan, qui, en 1971, vous a présenté ici même une analyse des travaux d'océanographie physique effectués lors de cette expédition. Puis ce n'est qu'en 1979 qu'un nouveau programme international, la Première Expérience Mondiale du GARP (Programme de Recherche Atmosphérique Globale), a provoqué le rassemblement de plusieurs nations pour mettre en oeuvre un programme océanographique associé au programme atmosphérique. Dans l'océan Indien, le programme atmosphérique était représenté par le programme MONEX (MONsoon EXperiment) dont nous ne parlerons pas en détail ici . Le programme océanographique associé, INDEX (INDian ocean EXperiment), était coordonné par le groupe de travail du SCOR n°47. Ce programme, dont la planification a commencé en 1973, était principalement orienté vers la zone équatoriale et la frontière ouest.

Mais avant d'analyser les résultats de ces différentes études sur le plan océanographique, nous allons décrire la circulation atmosphérique de surface, tout à fait particulière, qui régne sur la région et qui représente la fcrce externe dominante dans la genèse du système dynamique observé dans l'océan.

CIRCULATION ATMOSPHERIQUE SUR L'OCEAN INDIEN

S'il est largement ouvert au sud vers l'Antarctique, l'Océan Indien, contrairement à l'océan Atlantique et à l'océan Pacifique, est complètement fermé au nord, vers le tropique du Cancer, par la masse continentale asiatique. En raison du mouvement saisonnier relatif du soleil et du fait que la terre se réchauffe et se refroidit plus vite que l'océan, la répartition des pressions atmosphériques va subir de fortes variations au point d' engendrer un renversement saisonnier complet de la circulation atmosphérique: c'est le **régime des moussons** (figure 1).

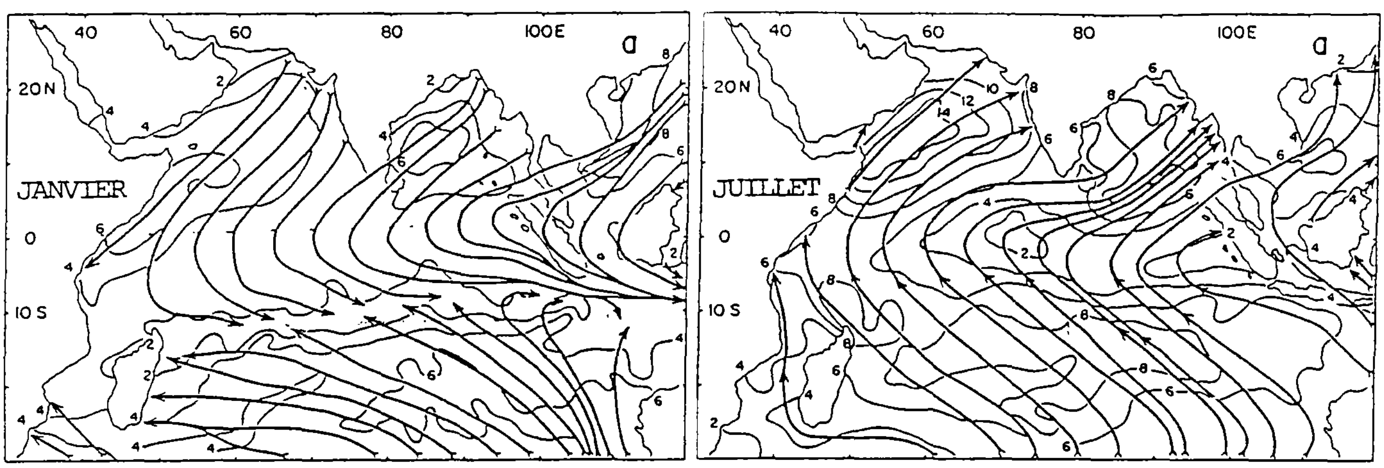


FIGURE 1 - Circulation atmosphérique moyenne à la surface de l'océan, en janvier et juillet, d'après HASTENRATH and LAMB, 1980 (isolignes en m/s).

Ce renversement des vents intéresse toute la région située au nord d'environ 10°S, atteignant même 20°S le long de la côte d'Afrique orientale et débordant largement sur le Pacifique occidental.

On peut définir **quatre saisons** distinctes :

a) En hiver de l'hémisphère nord (décembre à février), le continent asiatique très froid est le siège de la plus importante zone de hautes pressions du globe. Tandis que, sur l'océan, régne une zone de basses pressions vers 10°S, correspondant à la zone chaude de convergence intertropicale. Plus au sud, vers 30°S, au-delà de l'influence du système des moussons, régnent les hautes pressions subtropicales , dont on rencontre l'équivalent dans les autres océans à ces mêmes latitudes et qui engendrent, en particulier, les alizés de sud-est, vents permanents plus ou moins forts selon la saison. Entre la zone de hautes pressions asiatiques et la zone de basses pressions intertropicales s'établit la mousson de nord-est qui souffle de décembre à mars modérément. C'est pendant cette saison que la situation atmosphérique est la plus semblable à celle rencontrée sur les autres océans , avec toutefois un décalage vers le sud de la zone de convergence intertropicale.

b) Au contraire, en été de l'hémisphère nord (mai à septembre), le continent se réchauffe plus vite que l'océan et il apparait, centrée sur le Pakistan et le nord-ouest de l'Inde, une importante zone de basses pressions. Les basses pressions intertropicales ont disparu et la circulation atmosphérique, à cette saison, est continue entre les alizés de sud-est et le flux de mousson de sud-ouest dans l'hémisphère nord qui, se chargeant d'humidité en passant sur l'océan, va apporter les pluies sur Inde. C'est pendant cette saison que les vents sont les plus forts, avec une intensification dans l'ouest, le long de la côte de Somalie, où les vents atteignent 25 à 30 noeuds en moyenne sur plus de 3 mois. C'est la région tropicale où les vents sont les plus forts du globe pendant aussi longtemps. La circulation atmosphérique est intensifiée le long des plateaux éthiopiens et débouche sur l'océan dans la région du cap Guardafui. On peut l'assimiler à un courant atmosphérique de frontière ouest , souvent nommé le "jet" de FINDLATER; ce dernier a montré la progression de ce "jet" vers le nord de mai à juillet, saison de son plein développement.

c) Entre ces deux saisons bien distinctes, il existe deux périodes de transition, en mars-avril et octobre-novembre, pendant lesquelles les vents sont très faibles et désorganisés dans toute la partie nord sauf à l'équateur où apparaissent, entre les deux moussons, des vents d'Ouest, à l'Est d'environ 55°E. Ces vents ne sont pas très forts, mais suffisants pour engendrer un courant zonal équatorial vers l'est pendant ces deux périodes de transition.

Le champ de vent n'est uniforme ni dans l'espace ni dans le temps, et la circulation océanique va être extrêmement sensible au renversement complet du champ de vent dans toute la partie nord de l'océan Indien.

CIRCULATION OCEANIQUE DE SURFACE

Nous nous intéresserons ici particulièrement à la circulation des couches océaniques subissant l'influence de la circulation atmosphérique, c'est à dire des couches superficielles.

A - A GRANDE ECHELLE

Par l'intermédiaire de la tension du vent de surface, la circulation atmosphérique, spécifique de l'océan Indien, engendre une réponse océanique elle aussi spécifique. C'est un des exemples les plus typiques d'une action directe de l'atmosphère sur l'océan à l'échelle de temps de l'ordre de la saison. L'apparition saisonnière du sous-courant équatorial (en fin de mousson de nord-est), du "Jet" équatorial de surface ou Jet de Wyrtki (en période d'intermoussons) , la renverse du Courant de Somalie et la formation du Tourbillon de Somalie (en début de mousson de sud-ouest) sont des éléments marquants de la forte réponse saisonnière de l'océan (figure 2). La nature de cette réponse est un problème complexe d'interactions océan-atmosphère qui fait de l'Océan Indien un **champ d'étude de ces interactions tout à fait privilégié**. C'est dans l'océan Indien occidental que l'on rencontre **la plus forte variabilité océanique saisonnière** du globe.

Au sud, où les variations des vents n'intéressent que leur vitesse et non leur direction, la circulation ne présente que des variations d'intensité. En revanche, dans la région soumise au régime des moussons, l'océan réagit au renversement des vents par un renversement complet de la circulation de surface. Le schéma présenté ici (figure 2) représente un aspect général de cette circulation de surface, réalisé à partir de l'atlas des dérives de surface de A.N. CUTLER et J.C. SWALLOW.

Entre 20°S et 10°-8°S, le Courant Equatorial sud (CES), entrainé par les alizés de sud-est, se divise en deux branches en arrivant sur la côte orientale de Madagascar, où l'on remarque aussi une divergence des vents de surface. La branche dirigée vers le sud, ou courant côtier est Malgache, semble subir une rétroflexion vers l'est, au sud de Madagascar, comme le courant

CS = COURANT DE SOMALIE

BSCS = BRANCHE SUD DU COURANT DE SOMALIE

TS = TOURBILLON DE SOMALIE

CMNE = COURANT DE DERIVE DE MOUSSON DE NORD-EST

CMSO = COURANT DE DERIVE DE MOUSSON DE SUD-OUEST

CCES = CONTRE-COURANT EQUATORIAL SUD

CCEA = COURANT COTIER EST AFRICAIN

CES = COURANT EQUATORIAL SUD

JW = JET EQUATORIAL DE WYRTKI

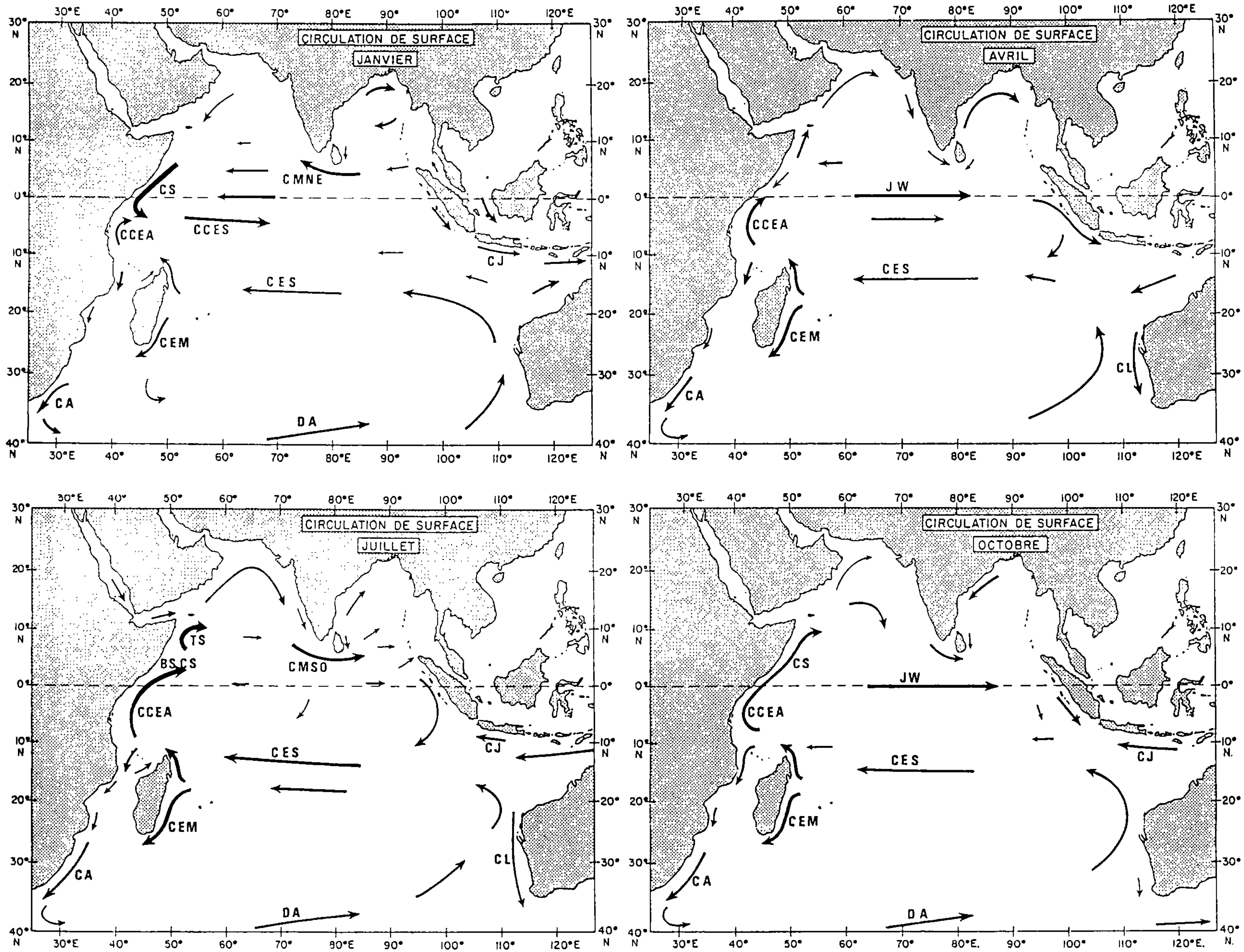
CJ = COURANT DE JAVA

CEM = COURANT EST MALGACHE

CA = COURANT DES AIGUILLES

CL = COURANT DE LEEUWIN

DA = DERIVE ANTARCTIQUE



M. FIEUX (d'après A.N. CUTLER et J.C. SWALLOW)

FIGURE 2 - Schéma de la circulation océanique de surface dans l'Océan Indien pendant les quatre saisons.

des Aiguilles au sud de l'Afrique. La branche passant au nord de Madagascar va se diviser de nouveau en deux près du cap Delgado sur la côte orientale africaine.

La branche sud (ou courant de Mozambique) rejoint le canal de Mozambique, la branche nord (Courant Côtier est Africain, CCEA, ou courant de Zanzibar) alimente, selon la saison, ou le contre-courant équatorial sud (CCES), qui existe seulement en été de l'hémisphère sud, lorsque la mousson de nord-est souffle sur le nord du bassin, ou le courant de Somalie, pendant la mousson de sud-ouest. Il traverse alors l'équateur en un puissant courant de frontière ouest, c'est la branche sud du courant de Somalie qui se détache de la côte en début de mousson vers 4°N. Au nord, entre 5°N et 10°N, quand la mousson de sud-ouest est bien établie, apparaît le grand tourbillon anticyclonique de Somalie. En mousson de nord-est, le courant le long de la côte de Somalie se renverse et entre en convergence avec le CCEA, au sud de l'équateur, au niveau du CCES qui n'existe que pendant cette saison.

En mer d'Arabie et dans le golfe du Bengale, la circulation suit aussi le renversement des moussons, avec un flux vers l'est en mousson de sud-ouest et un flux vers l'ouest en mousson de nord-est, intensifiés au sud de l'Inde et de Sri Lanka. Dans le golfe du Bengale, en mousson de nord-est, la circulation est anticyclonique.

A l'est du bassin, en raison du renversement saisonnier des vents autour de l'Australie et sur l'Indonésie le flux provenant du Pacifique est plus ou moins important. En juin-septembre, la circulation atmosphérique autour de l'Australie est anticyclonique et les vents, de sud-est sur l'Indonésie, ont donc tendance à entrainer les courants de surface vers l'ouest. En décembre-février, les vents se sont renversés et le courant le long des côtes de Sumatra et de Java se dirige alors vers le sud-est.

B - LE LONG DE LA COTE DE SOMALIE

Ce n'est qu'au cours du programme INDEX-PEMG que l'évolution détaillée du système du courant de Somalie en mousson de sud-ouest a pu être observée. C'est une zone privilégiée où l'on peut étudier l'influence sur les courants du déclenchement brutal de la mousson de sud-ouest, dans une zone de frontière ouest, où donc les courants sont intensifiés.

Les travaux de STOMMEL, SWALLOW, WARREN, WOOSTER, BRUCE, LEETMAA, DÜING, FIEUX, MOLINARI, BROWN, EVANS, SCHOTT, QUADFASEL, JOHNSON ... ont montré que le système du courant de Somalie était beaucoup plus complexe qu'il n'était apparu au premier abord. Contrairement à l'image que l'on avait d'un fort courant continu le long de la côte jusqu'à 9°N, qui n'existe en réalité qu'en fin de mousson de sud-ouest, il comprend de nombreux tourbillons. La figure 3 présente un résumé des différentes phases observées au cours du déclenchement de la mousson de sud-ouest de 1979.

- En fin de mousson de nord-est, la convergence entre le CCEA et le courant de Somalie commence à remonter vers l'équateur en raison de l'affaiblissement des vents de nord-est.

- En avril, période d'inter-mousson (pas de vent au nord de l'équateur), le courant le long de la côte de Somalie, aux salinités élevées et dont la vitesse est de l'ordre de 1 à 2 noeuds, porte vers le sud-ouest au sud de 4°N et converge, vers l'équateur, avec le CCEA, aux salinités basses, dont la vitesse est de l'ordre de 4 noeuds. Le courant de dérive de mousson de nord-est est particulièrement marqué vers 4°-5°N au large de la côte de Somalie . Par contre, la circulation tout à fait côtière au nord de 5°N porte déjà au nord-est depuis le mois de mars. A l'équateur, le "Jet" équatorial porte à l'est sous l'effet des vents d'ouest équatoriaux .

- Début mai, c'est le renversement des vents vers le nord-est le long de la côte de Somalie. La réponse de l'océan est très rapide (quelques jours): le CCEA, intensifié par le renforcement des alizés de sud-est, traverse l'équateur jusqu'à 2°30N, pour former la branche sud du courant de Somalie dont la vitesse atteint 4 noeuds. Les masses d'eaux transportées ont les caractéristiques du courant équatorial sud dont les salinités sont basses par rapport à celles de la mer d'Arabie, car il se trouve dans une zone de fortes précipitations (zone de convergence intertropicale en été austral). Le front de salinité a donc migré vers le nord-est. Au nord de 5°N il n'y a pas de grand changement. A l'équateur, le 'jet' de surface, portant à l'est, est toujours fort avec des vitesses de l'ordre de 1.5 à 2 noeuds.

- Fin mai, la branche sud du courant de Somalie, en quittant la côte vers 3°N, provoque une zone de remontée d'eau sous-jacente froide et riche en matières nutritives, centrée vers 4°N. Une recirculation vers le CCEA a été observée plusieurs fois à l'aide de bouées dérivantes.

- Début juin, c'est le véritable déclenchement de la mousson de sud-ouest sur toute la mer d'Arabie, avec des vents beaucoup plus forts, en particulier au nord de 5°N. A cette évolution des vents, l'océan répond par la formation du grand tourbillon de Somalie ("the great whirl" déjà décrit par FINDLAY en 1866), entre 5°N et 10°N environ, qui engendre une deuxième zone d'upwelling vers 10°N. Au sud de ce tourbillon, la branche sud s'intensifie , atteint 4°N et présente des vitesses atteignant 7 noeuds

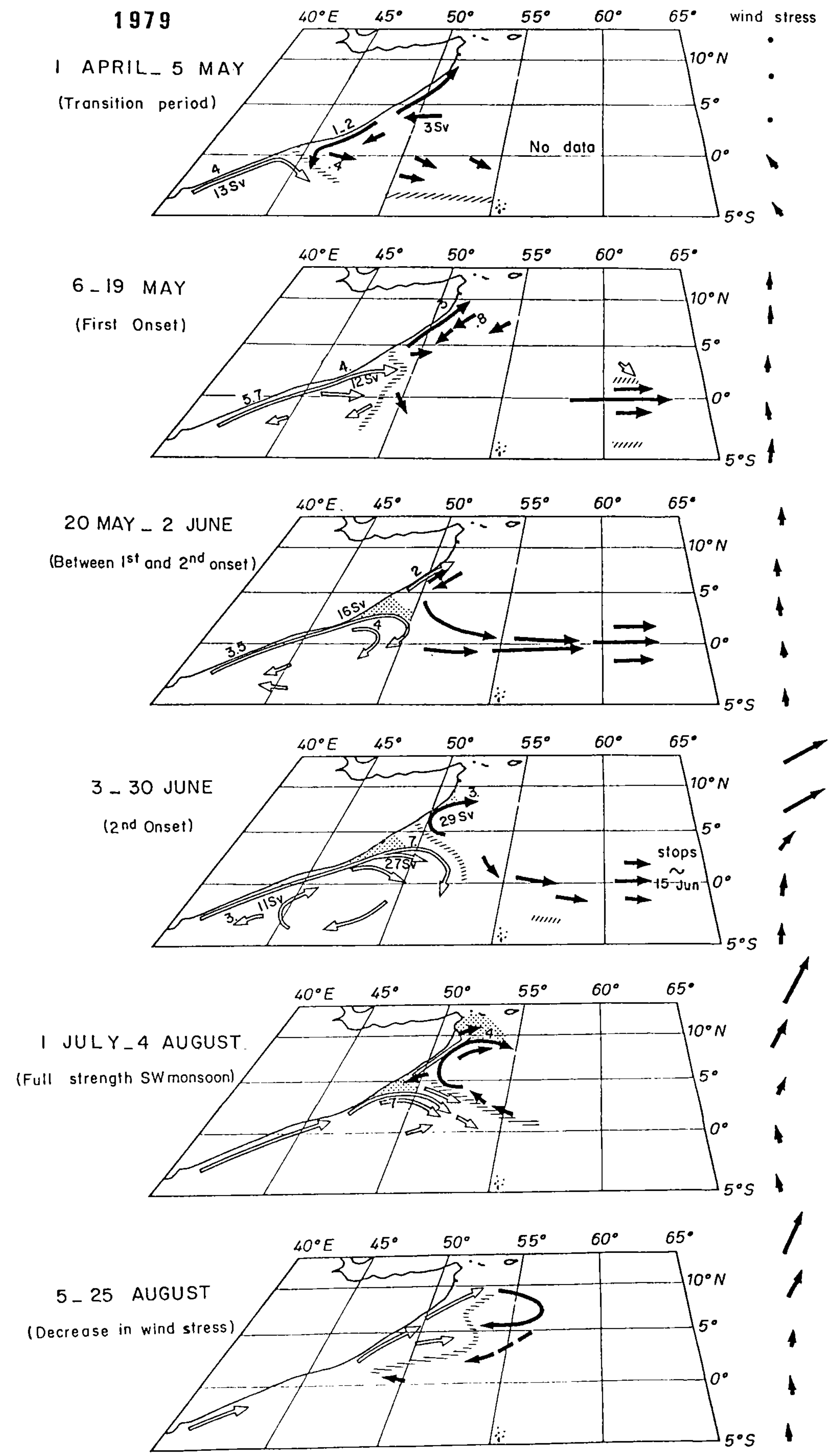


FIGURE 3 - Evolution de la circulation de surface d'après les observations de 1979 (vitesse en noeuds , flux en $Sv=10^6 m^3 s^{-1}$, ⟹ = salinités basses, ➞ = salinités élevées, ⫽ = fronts, ▒ = upwellings).

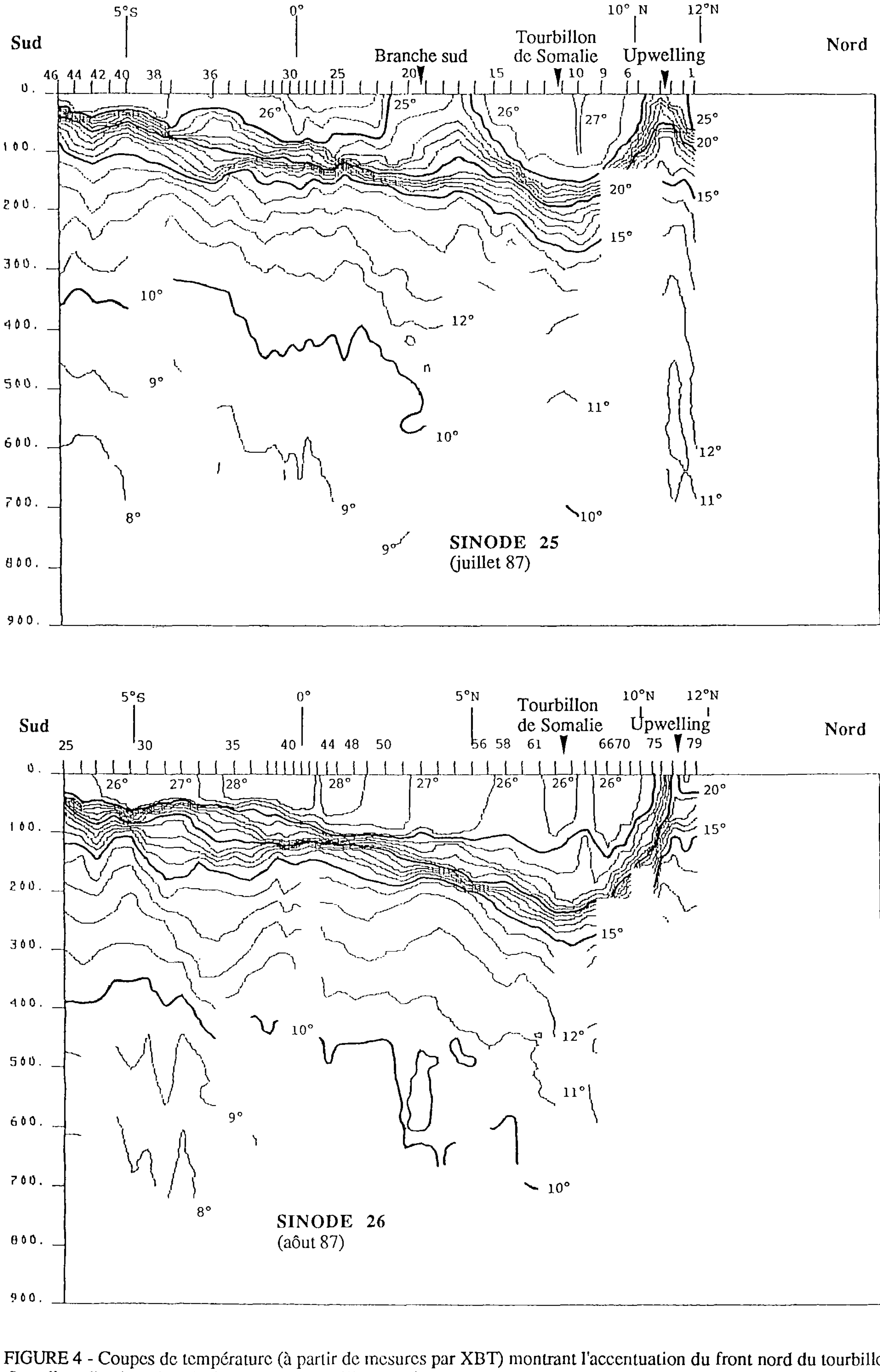


FIGURE 4 - Coupes de température (à partir de mesures par XBT) montrant l'accentuation du front nord du tourbillon de Somalie et l'atténuation du front sud entre juillet et août .

(vitesse océanique maximale en dehors des courants de marée). A l'équateur, le 'jet' équatorial cesse vers le 15 juin, dès que la mousson de sud-ouest est pleinement établie en 1979.

- En juillet, la mousson est à son maximum, le tourbillon de Somalie se renforce, avec des vitesses de l'ordre de 4 à 5 noeuds dans la branche nord, et toujours des vitesses de l'ordre de 7 noeuds dans la branche sud du courant de Somalie. Le tourbillon de Somalie, aux salinités élevées, est formé d'eaux originaires du nord de l'océan Indien, tandis que la branche sud, aux salinités plus basses, trouve son origine dans les eaux moins salées de l'hémisphère sud (CES et CCEA).

- En août, la mousson de sud-ouest commence à decroître. On voit alors appaître une migration de la zone d'upwelling sud vers le nord qui atteint 10°N vers fin août. La branche sud en migrant vers le nord entraine des eaux moins salées et plus oxygénées qui atteignent alors 10°N. Le front de salinité est donc rejeté vers l'Est. Ce n'est qu'en fin de mousson de sud-ouest que le courant de Somalie, qui porte au nord-est à cette saison, est continu le long de la côte jusqu'à 10°N.

Les valorisations de transit de pétroliers le long de la côte ou du Marion Dufresne entre le cap Guardafui et La Réunion ont permis de suivre, à l'aide de sondes thermiques perdables XBT, l'évolution du tourbillon de Somalie. Le front nord du tourbillon présente une accentuation de la pente des isothermes, tandis que le front sud présente une diminution de cette pente au cours de son évolution dans le temps à partir du début de la mousson de sud-ouest (figure 4); ce tourbillon semble persister en profondeur jusqu'en mousson de nord-est. Un tourbillon plus petit a été observé au nord-est de celui-ci, c'est le tourbillon de Socotra.

Les différentes campagnes au large de la Somalie, réalisées pendant les années 80, ont montré que la branche sud réapparaissait en fin de mousson de sud-ouest, avec une séparation de la côte vers 2°N . Le long de la côte de Somalie, des mesures directes de courant ont montré que la renverse des courants cross-équatoriaux commence en surface pour atteindre plusieurs centaines de mètres , très rapidement en mousson de sud-ouest, mais beaucoup plus lentement en mousson de nord-est, saison pendant laquelle existent de nombreuses renverses en profondeur .

En 1972-1973, LEETMAA observa qu'au sud de l'équateur, le long de la côte du Kenya, le courant se renverse vers le nord bien avant le renversement du vent sur la mer d'Arabie, et que cette renverse était associée au vent local. Par contre, plus tard l'intensification du courant pourrait être due au forçage lointain. De même, entre 5°N et 10°N, le courant côtier coule déjà vers le nord-est en mars, bien que les vents soient encore de sens contraire sur le bassin.

En réalité l'évolution du courant de Somalie est liée à la complexité du champ de vent qui est loin d'être régulier, que ce soit dans le temps ou dans l'espace.

C - A L'EQUATEUR

Les observations de TAFT, KNAUSS, WYRTKI, SWALLOW, STOMMEL, LEETMAA, KNOX, LUYTEN, ROEMMICH, ERIKSEN, REVERDIN, GONELLA, CRESSWELL , FIEUX,... entre autres, ont permis d'obtenir quelques traits caractéristiques de la circulation équatoriale de l'océan Indien . Pendant les deux périodes de transition (avril-mai et octobre-novembre) , sous l'effet de vents d'Ouest, il apparaît un "jet" équatorial de surface orienté vers l'Est, contrairement à ce que l'on rencontre dans le Pacifique ou l'Atlantique. Des mesures réalisées , pendant deux ans, à partir de l'île de Gan, mettent bien en évidence sa naissance deux fois par an en corrélation avec l'apparition des vents d'Ouest. Il est plus intense dans la partie centrale du bassin et pendant la période d'octobre-novembre. Ce courant équatorial, portant à l'Est, induit une convergence en surface, il n'y a donc pas d'upwelling équatorial comme dans les autres océans et les bouées dérivantes suivies par satellite y restent piégées (figure 5). Ces bouées ont permis d'observer la phase de cessation et de renverse de ce courant sous l'effet d'ondes se propageant à partir de la frontière orientale. Certaines ont vécu plus de 2 ans (figure 6) en restant piégées dans le système des courants équatoriaux.

En subsurface, un sous-courant équatorial, orienté vers l'Est comme dans les autres océans équatoriaux, n'apparaît qu'en fin de mousson de nord-est, de mars à juin environ, et semble plus fort dans la partie occidentale du bassin. Ce sous-courant transporte des eaux de salinité relativement élevée.

En profondeur, de nombreuses renverses ont été observées, en particulier vers 700 m de fortes variations semi-annuelles du courant zonal ont été mises en évidence dans la partie occidentale du bassin, à l'aide d'un réseau de mouillages équatoriaux.

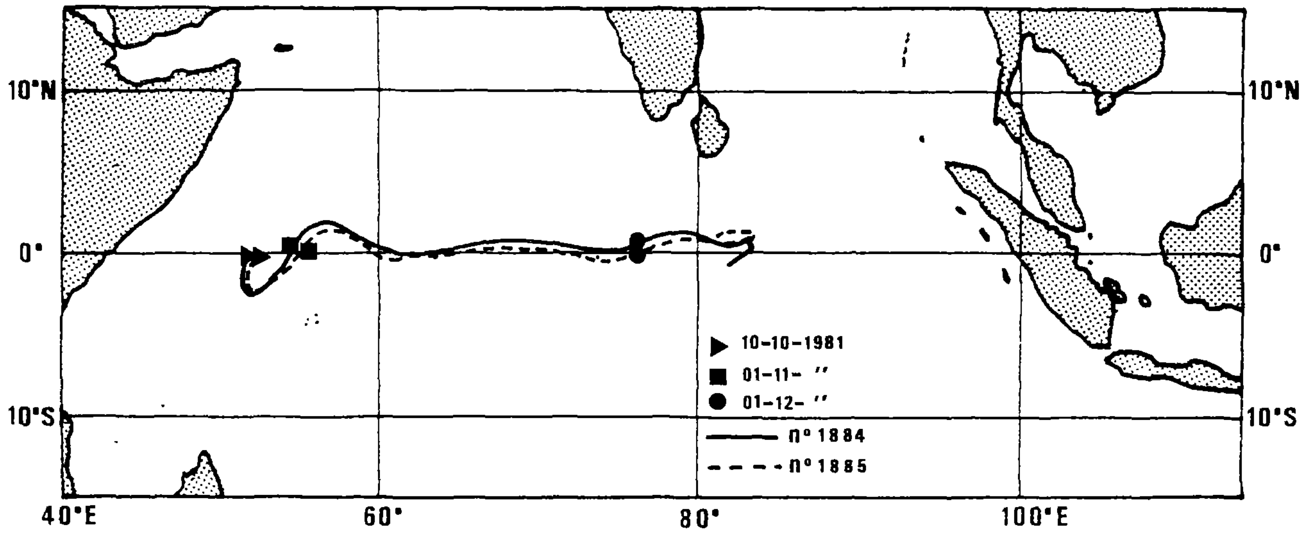


FIGURE 5 - Trajectoires de deux bouées dérivantes entrainées dans le "jet" équatorial de WYRTKI portant à l'Est, en octobre-novembre 1981.

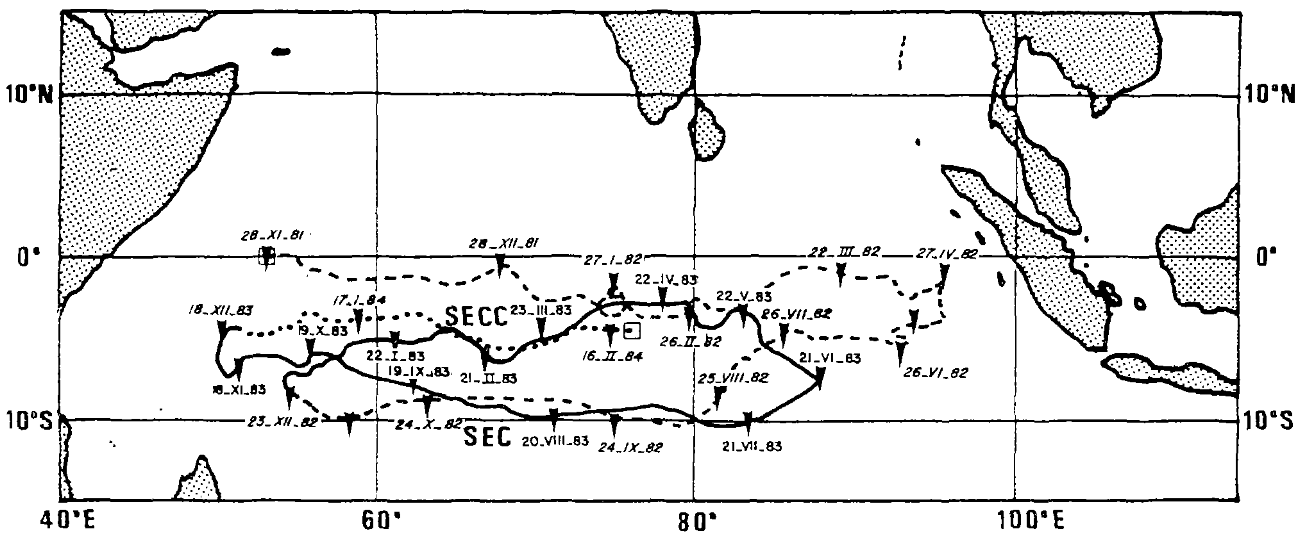


FIGURE 6 - Trajectoire de la bouée n°1886, entrainée dans le contre-courant équatorial sud puis dans le courant équatorial sud, pendant deux années successives. La bouée a fonctionné du 28 novembre 81 au 16 février 84.

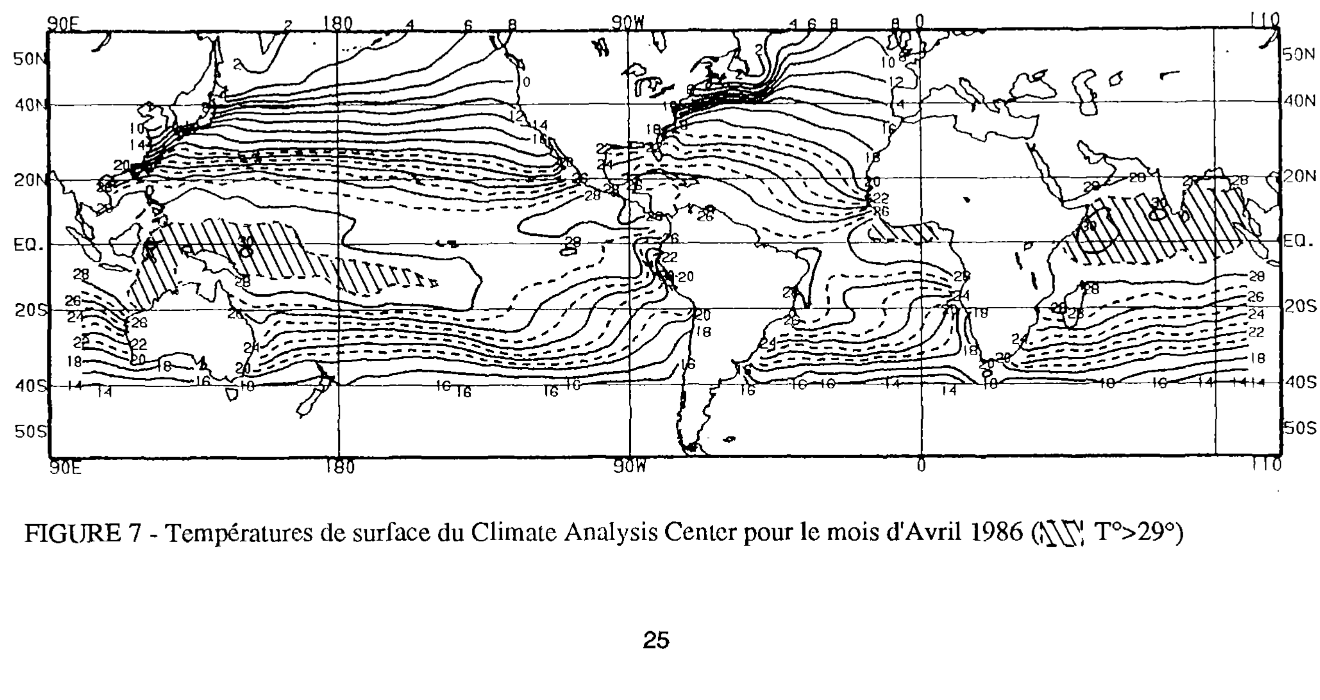


FIGURE 7 - Températures de surface du Climate Analysis Center pour le mois d'Avril 1986 (hachures, T°>29°)

QUELQUES RESULTATS DE MODELES

Des modèles ont été mis en oeuvre pour comprendre l'évolution de cette circulation.

A - FRONTIERE OUEST

En 1969, LIGHTHILL proposa que le courant de Somalie soit un prototype de courant de frontière ouest entrainé par le rotationnel de la tension du vent sur l'océan Indien. Le courant est engendré par des ondes de Rossby qui se propagent vers l'Ouest de la région où le rotationnel est imposé. Parce que ces ondes voyagent beaucoup plus rapidement aux basses latitudes, le courant de Somalie peut s'établir en quelques semaines après le déclenchement des vents, tandis qu'aux moyennes latitudes (comme dans le cas du Gulf Sream) cela prendrait plusieurs années. Il s'est donc intéressé aux effets du forçage par le vent lointain, dans un modèle linéaire à réponse barocline équatoriale rapide. Il fait souffler un vent d'Ouest en partant de zéro, dans une bande située entre 500 et 1800 kms de la côte (nord-sud) et au nord de 2°N. Ce modèle lui a permis de mettre en évidence la possibilité d'une réponse barocline se propageant rapidement aux basses latitudes (environ 1 mois) par des ondes piégées à l'équateur. Il obtint un courant de frontière analogue au courant de Somalie dont la vitesse méridienne s'annulait vers 6°N. Mais les observations météorologiques ont révélé que le déclenchement de la mousson de sud-ouest commençait près de la frontière ouest et non au centre du bassin.

En même temps, dans un modèle numérique de tout l'océan Indien avec vent mensuel moyen, COX, en 1970, montrait aussi un développement rapide du courant de Somalie.

Les observations de LEETMAA posèrent le problème de l'importance relative entre l'influence du vent lointain et celle du vent local dans le forçage du courant de frontière ouest.

ANDERSON et ROWLANDS, en 1976, dans un modèle analytique à mode vertical, montrèrent que le courant de frontière présentait une croissance séculaire (en t) pour le forçage par le vent local, et en t^2 pour le forçage par le vent lointain. C'est-à-dire que si le vent souffle sur l'ensemble du bassin en même temps, c'est d'abord l'influence du vent local qui domine dans l'apparition du courant, puis ensuite celle du vent lointain. Mais séparer l'influence du vent lointain de celle du vent local n'est pas simple . La latitude de séparation de la côte du courant de frontière apparaît dans leur modèle comme un équilibre très délicat entre la tendance de leur forçage lointain à entrainer un courant vers le sud à une certaine latitude et la tendance de leur forçage local à entrainer un courant vers le nord.

ANDERSON et MOORE, en 1979, ont montré que le CCEA, sous le seul effet des vents de l'hémisphère sud, pourrait traverser l'équateur jusqu'à 6°N-8°N par inertie. En réalité, en mousson de nord-est, le courant de Somalie l'empêche de remonter vers l'équateur. C'est seulement quand la mousson de nord-est cesse que le CCEA peut commencer à migrer vers le nord. Leur étude a suggéré l'existence de deux branches distinctes dans le courant de Somalie, engendrées par des processus physiques différents, et a montré l'importance des vents de l'hémisphère sud dans la naissance du courant de Somalie.

COX, en 1979, dans un modèle à 3 dimensions, stratifié et non linéaire, spécifiait seulement le forçage par le vent local sous la forme d'une bande de vent parallèle à la côte , s'étendant sur 1000 kms et mettant 6 jours à s'établir. Il obtenait un système de 2 tourbillons , en 60 jours, se déplaçant vers le nord lorsque la côte était nord-sud. Avec une côte inclinée, la migration des tourbillons cessait. Il obtenait deux latitudes distinctes de séparation à peu près en accord avec les observations. Les latitudes des points de séparation se situaient d'autant plus près de l'équateur que la non linéarité était forte.

PHILANDER et DELECLUSE, en 1983, utilisent un modèle numérique dans lequel les vents n'ont pas de rotationnel mais sont uniformément du sud. Dans un système linéaire, cela conduit à un flux vers l'Est au nord de l'équateur et vers l'ouest au sud. Avec les effets non-linéaires, l'équateur n'est plus une ligne de symétrie et le flux vers l'est est intensifié. Le courant côtier rejoint le flux vers l'est, à travers quelques méandres. Un upwelling intense souligne le bord nord de la région de séparation du courant. Pour obtenir une localisation de la zone de séparation similaire aux observations, il faut également tenir compte de l'inclinaison du vent et de la ligne de côte. Le modèle reproduit bien la branche sud du courant de Somalie mais ne peut rendre compte du tourbillon nord pour lequel le rotationnel du vent joue un rôle.

ANDERSON, dans un modèle numérique à plusieurs couches, a essayé de combiner les différents points indiqués plus haut. La côte est nord-sud, et le forçage est une combinaison de:

(1)- vents d'est uniformes sur l'hémisphère sud,

(2)- vents modérés du nord sur une bande de 10° parallèle à la côte,

(3)- vents de sud, sur une bande de 40° parallèle à la côte, avec un maximum de vitesse vers 10°N.

Avec les vents (1) seuls, le modèle donne un courant inertiel traversant l'équateur jusqu'à 4°N.

Avec les vents (1) et (2) le modèle donne les conditions d'hiver. Avec les vents (1) et (3) le système avec deux tourbillons apparaît avec les séparations aux bonnes latitudes. Les non-linéarités apparaissent importantes dans toute la région du courant de frontière Ouest : en effet les courants calculés par la géostrophie plus la dérive d'Ekman sont trop faibles de 30%. Le modèle ne simule pas le stade final avec la migration vers le Nord de la branche Sud car les champs de vents ne correspondent pas à la situation en fin de mousson de Sud-Ouest.

La réponse de la circulation océanique aux variations saisonnières du champ de vent en mer d'Arabie est étudiée dans le modèle numérique de LUTHER et O'BRIEN. C'est un modèle non-linéaire avec une géométrie très proche de la réalité, comprise entre 40°E - 70°E et 10°S - 25°N. Les vents sont des moyennes climatiques mensuelles sur 60 ans et sur 1° x1°. Leur modèle produit des tourbillons successifs, le long de la côte, migrant vers le Nord-Est.. La branche Sud près de l'équateur se forme sous l'influence des vents locaux. Afin d'étudier les variations interannuelles, ils doivent faire tourner leur modèle avec les vents moyens mensuels observés entre 1954 et 1976. Pour obtenir ces résultats ils sont obligés d'augmenter les valeurs de vents observés.

Dans l'océan Indien la réponse du courant de frontière Ouest est si forte que, pour obtenir une simulation réaliste du système, un modèle non-linéaire est nécessaire; il faut aussi une géométrie réaliste et une bonne représentation du champ de vent à grande échelle, comprenant l'hémisphère Sud , aussi bien local que lointain, ainsi que son évolution .

Mais nous manquons d'observations sur le cycle saisonnier complet de la circulation, en particulier pendant la mousson de Nord-Est et sur ses variations interannuelles pour pouvoir comparer les résultats des modèles avec la réalité.

B - EQUATEUR

CANE a étudié l'évolution du courant de surface et du sous-courant équatorial dans un modèle numérique non-linéaire à faible résolution verticale, permettant cependant de simuler l'évolution de la thermocline et d'estimer le cisaillement vertical de courant entre la surface et la thermocline. Ce modèle donne des réponses au vent d'Est et au vent d'Ouest asymétriques. Les vents d'Ouest transmettent une quantité de mouvement vers l'Est qui peut pénétrer en profondeur par l'effet de convergence d'Ekman et par frottement entre les deux couches. Par vent d'Est , l'effet d'Ekman est divergent, et la pénétration en profondeur de la quantité de mouvement vers l'Ouest est donc entravée.

Au démarrage des vents d'Ouest à l'équateur, des ondes de Kelvin sont engendrées sur la frontière occidentale, se propagent le long de l'équateur, puis sont réfléchies en ondes de Rossby sur la frontière orientale. Un gradient de pression s'établit alors, illustré par la pente de la thermocline. Par vents d'Est, la force de gradient de pression est la plus importante dans la couche de subsurface, et il apparaît un sous-courant équatorial vers l'Est au niveau de la thermocline. Par vents d'Ouest, le courant vers l'Est est seulement diminué au niveau de la thermocline par l'effet de ce gradient de pression zonal. Mais dès que les vents d'Ouest cessent à l'équateur, les courants vers l'Est qui se trouvent contre le gradient de pression, cessent ; ce qui explique la décélération rapide du jet dès que la mousson se déclenche. De plus, la composante Sud, à l'équateur, des vents de mousson, engendre des flux vers l'Ouest à l'équateur, ce qui explique la renverse vers l'Ouest.

Les observations directes de courant ont montré que l'énergie se propageait vers le bas. McCREARY a montré que les côtes jouaient un rôle important dans la réflexion de l'énergie vers la profondeur.

GENT, O'NEILL et CANE ont utilisé un modèle linéaire dans un bassin fermé, avec frottement et forçage semi-annuel par un vent zonal pour expliquer la phase du signal semi-annuel observé par LUYTEN et ROEMMICH. L'accord avec les observations est meilleur sur la phase que sur l'amplitude.

IMPORTANCE DE L'OCEAN INDIEN DANS LE SYSTEME CLIMATIQUE GLOBAL

L'établissement de la mousson de Sud-Ouest provoque sur l'océan le plus chaud du globe (avec le Pacifique Ouest) un très fort refroidissement de la couche de surface sur toute la mer d'Arabie, accentué dans les zones de remontées d'eaux froides le long de la côte de Somalie. L'importance des différents processus, évaporation, mélange par le vent de la couche de surface, advection d'eau froide, n'est pas encore bien quantifiée. Les flux de surface dans cette région présentent des variations spectaculaires au cours du développement de la mousson. Mais on n'a pas encore déterminé en détail, les impacts de ces variations sur le flux de mousson et sur les pluies en Inde. Un bilan détaillé des flux à l'interface reliés à la circulation océanique et atmosphérique dans cette région, apparaît nécessaire pour mieux en comprendre les interactions à moyenne et grande échelle.

D'après les résultats de certains modèles climatiques , il semble que des anomalies de température de surface aient des effets d'autant plus importants sur la circulation atmosphérique que la température des eaux de surface est élevée. Or l'océan Indien, pendant les périodes de transition, est au moins aussi chaud (> 29°C) que le Pacifique occidental (figure 7), mais il existe beaucoup moins de séries d'observations de température à long terme dans l'océan Indien.

Dans la région équatoriale , avec l'apparition du jet vers l'Est pendant les périodes de transitions, la circulation est opposée à celle du Pacifique équatorial, il y a donc accumulation d'eau chaude près de l'Indonésie (figure 8). Malgré le peu d'observations, en groupant toutes les observations équatoriales de température correspondantes aux années El Nino, il apparaît des anomalies sur la profondeur de la thermocline corrélées à celles que l'on rencontre dans le Pacifique : il y a une diminution de la pente zonale de la thermocline à l'équateur dans l'océan Indien pendant les années El Nino (figure 9). Mais on ne peut étudier les variations d'une année à l'autre en raison du manque de données. Il apparaît donc nécessaire d'augmenter le nombre d'observations systématiques dans toute la zone de l'océan Indien tropical afin de pouvoir quantifier ses variations et déterminer son influence climatique.

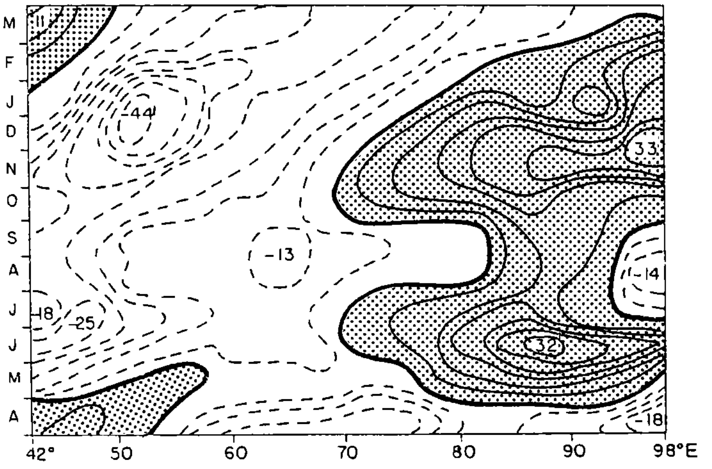


FIGURE 8 - Cycle saisonnier de la profondeur de l'isotherme 25°C à l'équateur dans l'océan Indien, en mètres (+65m). (G.REVERDIN)

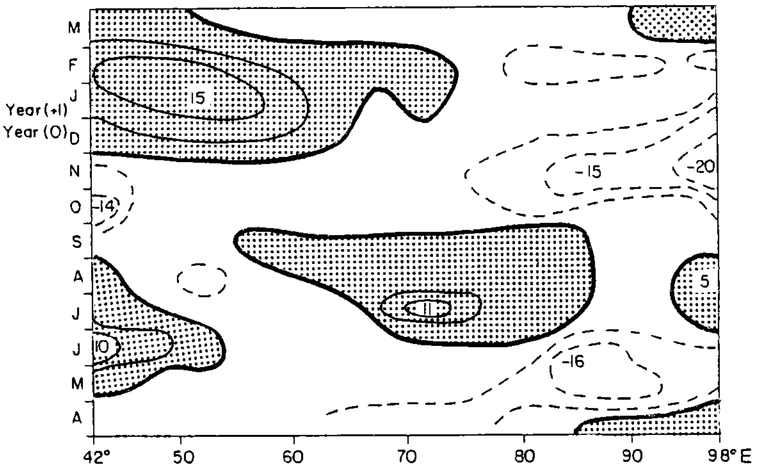


FIGURE 9 - Anomalies de l'isotherme 25°C, en mètres, à l'équateur pour une année El Nino composite (1957,1965,1969,1972 et 1976). (G.REVERDIN)

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Discussion[1]

S.M. Haq

I should like to congratulate you on the excellent presentation of this paper. As a biological oceanographer who had worked in the past in the region, I found some interesting new developments in our knowledge of the area. You referred to the movement of isothermal layer (20^0C or 25^0C) under the impact of wind stress on the sea surface. This can establish a very important relationship between the wind stress, which depends on the intensity of the monsoon, and the consequence rise and fall of the isotherm. I wonder, in your view, if such a relation between the above-mentioned parameters could allow us to predict of, say for instance, the intensity of upwelling based on information of prevailing climatic conditions.

I should also appreciate your clarifying the following points. Along the Somalia coast the upwelling is caused by the prevailing wind and by the deflection of the current on the right to the coast line. What about the situation along the coast of India and Pakistan where apparently the wind stress is less intensive, but the phenomena is fairly wide spread.

M. Fieux

Yes, indeed, it seems that the 25^0C isotherm (which is related to the depth of the thermocline) at the Equator is linked to the strength of the eastward wind at the Equator during the period of transition between the two monsoons. However, the direct relationship between the wind stress and the depth of the isotherm is not established with certainty, due to scanty observations which do not allow to establish correlation between these parameters.

About the upwelling along the coast of Somalia and further north along the coast of Arabia, Pakistan and India, they are slightly different. In the north along the coast of Arabia, Pakistan and India, they are principally due to the action of the wind which moves the host surface water towards offshore. On the other hand, along the coast of Somalia, the triangular zone of strong upwelling between 5^0N and 10^0N corresponds to the points of separation of the coastal current which also depend on the wind-field but not as directly in the north.

D. Krause

It is obvious that the surface circulation of the Arabian Sea is very complex. Is the circulation in the deeper waters also very complex ?

M. Fieux

Yes, the circulation in the deepest layers is also very complex. From long-term current measurement in the Equatorial zone one could see many reverses vertically with seasonal variability at the same level. Similarly, along the Somalia coast variation in the deep layers seems to occur.

S. N. Dwivedi

What is your view about the effect of circulation on the coastal regimes.

M. Fieux

I am sorry to say that we do not have enough data to answer.

G. S. Quraishee

A large convective zone centred around Indonesia splits into two halves: one half moves to the east and creates El Nino, the other half moves to the west which appears to effect the S.W. monsoon circulation. As you mentioned about the intricate relationships between the oceanic and atmospheric circulation in connection with the S.W. monsoon, early changes in atmospheric jets, Somali current, thermal field, etc., it appears that changes in S.W. monsoon occurs earlier than El Nino, as such changes in S.W. monsoon precedes El Nino. Therefore, we may say whenever monsoon fails, El Nino occurs. Instead, weak monsoon corresponds with El Nino. Will you please throw light on these aspects.

M. Fieux

You are right in most of the cases when the monsoon is weak there is an El Nino in the Pacific, but we do not have enough observations in the Indian Ocean to be able to correlate year to year anomalies. However, from recent studies in the atmosphere, it seems that anomalies which start around Himalaya heights can be followed through the Indonesian convection zone and the Pacific.

Marie-Annic Martin-Sané

Our next speaker is Dr. Peter Cook.

Dr. Cook received his doctorate in Geology from the University of Colorado, USA, in 1968.

1 Names and titles of speakers are given at the end of the publication.

He was later awarded a D.Sc. by the Dudhan University, in 1986. A sedimentologist by training, Dr. Cook worked extensively in both modern and ancient sediments, particularly in the Australian region and made very valuable contributions in the field of geology which are reflected in his numerous publications on the subject. In addition to his official assignment as the Chief of the Division of Continental Geology, Bureau of Mineral Resources in Australia, Dr. Cook is also the Vice-Chairman of the IOC Guiding Group of Experts for OSNLR. He is eminently well qualified to address on the subject of "Eustatic Sea-level Changes, Environments, Tectonics and Resources".

Ladies and Gentlemen, please welcome Dr. Cook.

3. Eustatic sea-level changes, environments, tectonics and resources

Dr. Peter J. Cook

Chief Research Scientist
Bureau of Mineral Resources
Canberra, Australia

Summary

The formation and preservation of non-living resources such as building material (sand, gravel, calcium carbonate), placer deposits and phosphorites, depend on a complex interplay of sea-level fluctuations, environmental change and tectonic processes. These occur on a variety of time scales. Sea-level rises and falls range in magnitude from diurnal tidal changes to very major fluctuations of sea-level associated with the development of ice caps or the formation of mid-ocean ridges. Some of these changes may be sporadic and irregular, others may be regular manifestations of Milankovitch cycles. Environmental changes may be closely linked with climatic variations (and hence to sea-level change) and can be associated with tectonism producing uplift or depression of the sea floor or changes to patterns of sedimentation or the type of sediment being deposited. In addition we have evidence to suggest major changes of ocean chemistry during earth history which can profoundly affect the deposition of authigenic minerals on the sea floor. Not only can tectonic processes result in a relative rise or fall of sea-level, they can also have a major effect on ocean circulation through the development of sea-ways, or the movement of continental fragments, and their attendant shelves, into new latitudes where new sedimentary assemblages will result.

This paper describes the processes involved in the formation of phosphorites including oceanic upwelling and high organic productivity, post-depositional processes within the sediment column, reworking of the phosphate grains, and a large number of other factors operating over a range of scales which together are responsible for whether or not a phosphate deposit is formed at a particular place and time.

Within the western Pacific (WESTPAC) region, offshore phosphorites occur on submarine ridges and plateaux such as the Chatham Rise off New Zealand, on seamounts, for example, in the vicinity of Fiji, and on continental margins, notably the east Australian margin. Some guyot and lagoonal deposits of the Southwest Pacific may represent subsided (or inundated) guano deposits. The IOC has recognized this and in co-operation with various bodies, notably CCOP and CCOP-SOPAC has established resource-related research programmes, such as SEATAR (South East Asian Tectonics and Resources) and STAR (South Pacific Tectonics and Resources). As OSNLR develops further impetus in the future there will be a need to develop more of these regional co-operative programmes that will focus on eustatic sea-level environmental and tectonic changes as a basis for future marine non-living resource exploration by the countries of the WESTPAC region and elsewhere.

Introduction

In the coming decades we will look increasingly to the oceans for many of our non-renewable resources (McKelvey & Chase, 1966; McKelvey & Wang, 1968). No doubt the pace of this move will on occasions falter as commodity prices fall or as new onshore resources are discovered, but already oil and gas worth several billion dollars per annum is extracted from the offshore zone. Also, commercial extraction of several mineral commodities with a total value of around $500 million per annum from the territorial waters of at least 27 countries. However, it is now recognized that the sea floor is not a host for vast cornucopia of riches waiting to be readily exploited. The sea floor does not give up its resources easily, and the successful exploitation of offshore deposits commonly requires a blend of good science, high technology, adequate capital, a deal of courage and an element of luck.

In this paper I shall briefly consider recent initiatives taken by IOC in the area of marine non-living resources, review some of these resources, and examine processes leading to their formation. One of these resources, phosphate, will be examined in some detail in order to provide an example of the way that basic marine geoscience, ranging in spatial scale from local to global and in temporal scale from a few years to millions of years, can provide us with a better understanding of how mineral deposits form on the ocean floor. Finally, the WESTPAC region of IOC will be briefly considered, as an example of a part of the sea floor where marine phosphate deposits formed and how as-yet-undiscovered deposits might be located in the future.

The Role of IOC

For many smaller countries, particularly the WESTPAC island countries of the SW Pacific with vast Exclusive Economic Zones (Fig. 1), the resources of the sea, and the sea bed, may offer the only prospect for developing a viable and self-sustaining economic future. There are numerous national and international marine geoscience programmes, but despite this, many non-living resources are not adequately addressed. Also it is desirable to put questions of an economic significance into a strong scientific framework and where appropriate, to take a global view. Whilst the WESTPAC region for example might be reasonably well served by marine geoscience organizations this is not typical for the world as a whole and several of the IOC regions lack any significant marine non-living resources programmes at the present time. With its established regional framework, IOC is in a position to catalyze scientific activity in these areas. There is also a need to establish a body with a communicative role and IOC, with its 117 Member States (and a function "To define those problems, the solution of which requires international co-operation in the field of oceanic research; and to develop, recommend and co-ordinate international oceanic programmes") is an ideal body for meeting the communicative needs of many countries.

It was with this point in mind that the Intergovernmental Oceanographic Commission (IOC), in association with the United Nations Ocean Economics and Technology Branch (UNOETB) decided to establish a programme of Ocean Science in Relation to Non-Living Resources (OSNLR) (Fig. 2) to parallel its Ocean Science in relation to Living Resources Programme (OSLR). The OSNLR Programme was initiated in 1985 by the holding of the first meeting of the Guiding Group of Experts for OSNLR. This Group produced a list of priorities for OSNLR based on:
-Scientific interest
-Economic significance
-The needs of developing countries
-The potential impact that OSNLR might make.

and are able to recognize changes with a periodicity ranging from 10^7 years (first order curves) to 104 years (fourth order curves) (Fig. 6). A finer resolution, to 103-102 years (essentially the Holocene sea-level record) has been developed using evidence from ancient shoreline features such as coral reefs (Fig. 5) and beach ridges (Fig. 7), and dating techniques ranging from the historical (human) record to radiometric, paleontological and palaeomagnetic methods.

In the case of deep sea research OSNLR will probably need to be rather selective in the types of activities it will support. For example, the provision of training opportunities in deep ocean geoscience to scientists from developing countries is seen as a high priority, while research related to manganese nodules may be a lower priority.

Having examined IOC's role in non-living resources, let us now consider the nature of those resources.

Marine Non-Living Resources

It is convenient to classify offshore resources into three types:

Offshore bedrock deposits are essentially seaward equivalents of the more familiar onshore de-

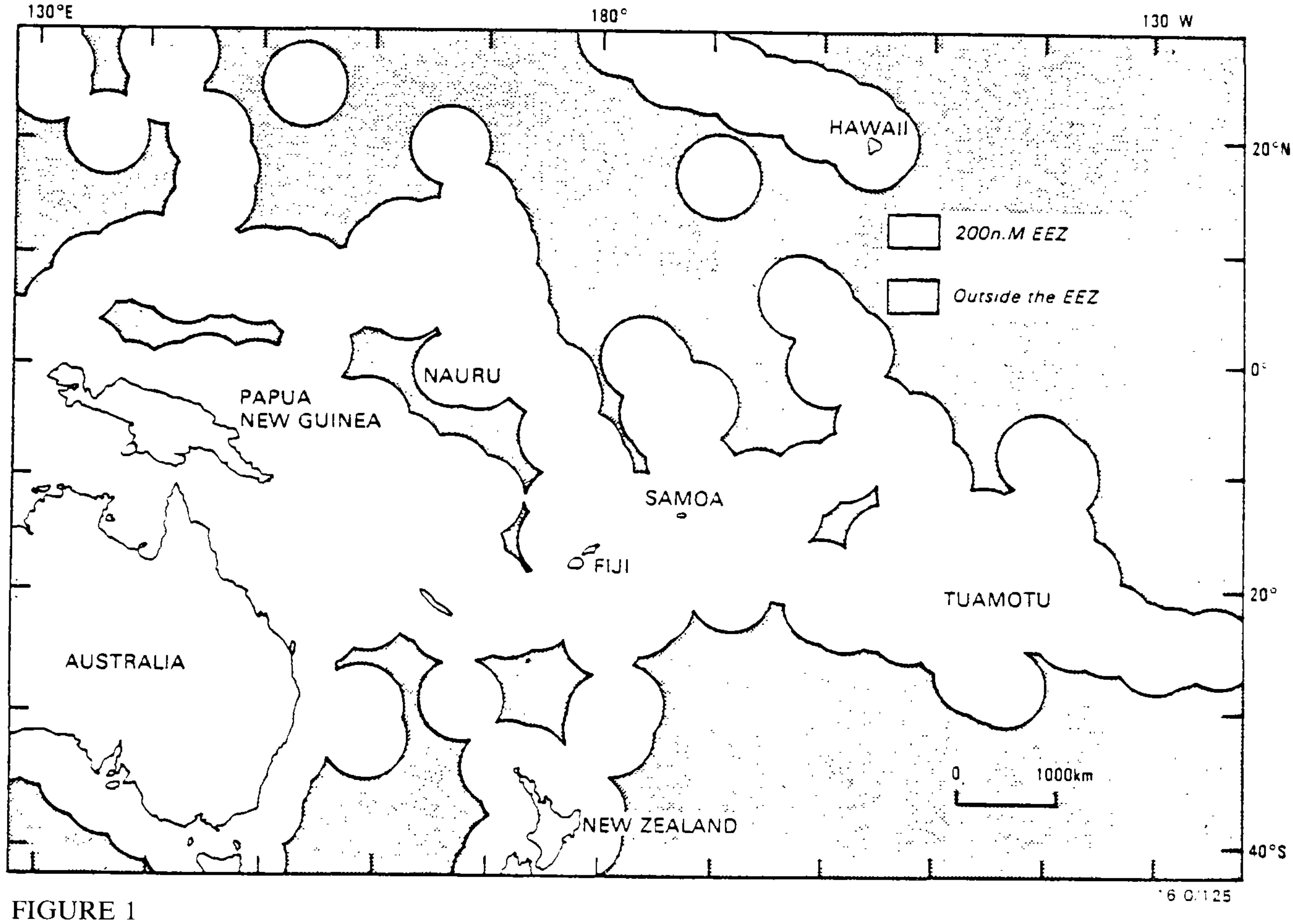

FIGURE 1
Exclusive economic zones in the southwest Pacific portion of the WESTPAC region (after Dupont, 1977).

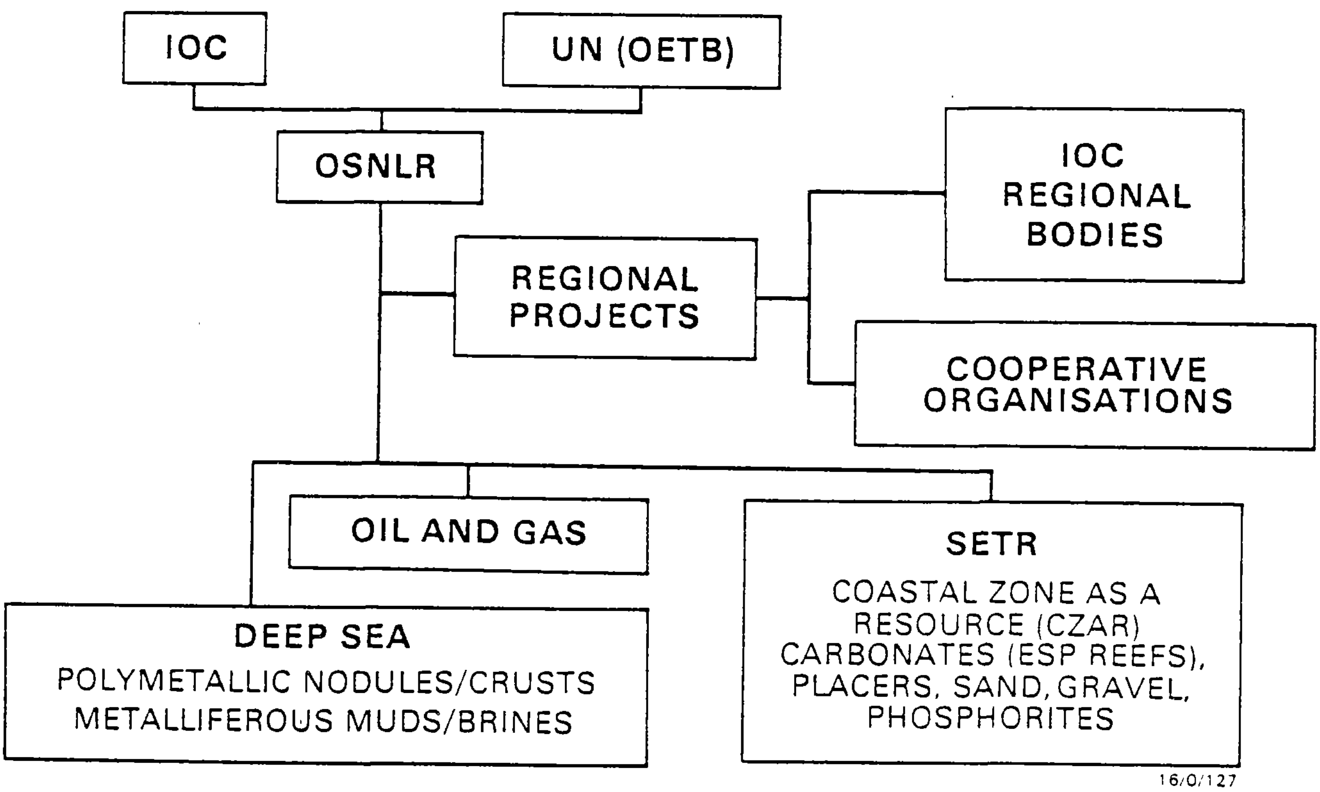

FIGURE 2
Organisation arrangements for the IOC program of Ocean Science in relation to Non-Living Resources (OSNLR).

posits and include oil and gas, coal, metalliferous deposits, sulfur and evaporites. They can extend offshore for hundreds of kilometres and down to depths of thousands of metres below the sediment-water interface. For the most part deposits of this type are exploited by modified onshore-type operations such as the use of various types of drilling platforms in the case of hydrocarbons. Drilling and solution mining (the Frasch process) are used for sulfur in areas such as the Gulf of Mexico, and could conceivably be used for offshore extraction of evaporites, particularly potash. Sub-sea mining of coal from shore-developed operations has been underway for many years off Japan, the United Kingdom and Canada. Similarly, metalliferous deposits have been followed (and mined) offshore in various parts of the world. Also much of the world's present oil and gas production (and a majority of the world's undiscovered oil and gas) is located offshore. These bedrock resources are obviously important to identify, particularly as most of them occur in the EEZ[1] and constitute significant national resources.

Deepsea mineral deposits are found in the open ocean down to abyssal depths, usually far from land, where chemical and biochemical sediments are not diluted by input of terrigenous material (Cronan, 1980). No deepsea deposits have been commercially exploited to date. There have been various attempts to commercially evaluate them and it is evident from these, that development and mining costs will be enormous. Up to now, the main interest has focussed on manganese (polymetallic) nodules, which are found in many parts of the deep ocean at abyssal depths (Cronan, 1980). The commercial interest in these nodules is not in their manganese but rather in their nickel, copper and cobalt contents (Hubred, 1975). In areas of the northeast Pacific, the Cu + Ni + Co content of the nodules is around 3% and Mn around 25%. It is in the Pacific area that much of the commercial interest has been focussed. Manganiferous (and Fe-Mn) crusts rich in cobalt, are found in the open ocean, mainly on upper slopes, marginal plateaux and seamounts at depths of 1-2000m rather than at the depths of 4-6000m that manganese nodules characteristically occur. This shallower depth may make them commercially more attractive but the crusts are likely to be irregular in their occurrence and therefore somewhat difficult to extract.

Recently, the occurrence of sulfide-bearing metalliferous sediments in association with so-called "black smokers" has been the subject of a great deal of scientific attention. These deposits were first discovered on the East Pacific Rise where hydrothermal vents form a series of "chimneys" along parts of the spreading ridges. Subsequently they have been found in the vicinity of other spreading centres. The metalliferous sediments contain high concentrations of copper, zinc, lead, silver, and iron sulfides in places. Some of this is precipitated near the vents but the hot dense brines expelled from the vents can form metalliferous mud, that are many kilometres from the actual vents.

The metalliferous mud and brines of the Red Sea are also a type of sulfide-rich resource but with a somewhat different origin in that the hot metal-rich brines are derived from the circulation of hot groundwaters through evaporites of the Red Sea graben, resulting in sediments and brines rich in metals such as copper, zinc and silver (Degens & Ross, 1969; Whitmarsh et al, 1974; Manheim, 1974).

In conclusion, there is no doubt that metalliferous nodules, sediments and brines of the deep sea constitute an important potential resource for the future but there is little or no prospect of them being developed in the near future due to a combination of low metal prices, recent successes in onshore metal exploration, and widespread substitution of many metals by cheaper materials. Indeed it may be that some of the deep sea oozes such as siliceous oozes, may ultimately have more commercial relevance because of their physical properties, than the more "glamorous" metalliferous sediments of the deep sea.

Shallow Marine Mineral Deposits

It is towards the nearshore zone that the greatest OSNLR effort will probably be directed, through a project with the acronym SETR (eustatic sea-level changes environments tectonics and resource). In addition to oil and gas this project (Fig. 2) is directly relevant to a number of important marine commodities notably the coastal zone as a resource in its own right, placers (mineral sands, tin, gold, etc.), construction materials (gravel, sand, carbonates) and phosphorites (se-

1 Exclusive Economic Zone

dimentary phosphate deposits) many of which are being extracted from the sea floor at the present day (Fig. 3). These resources will be considered in a little more detail below.

Shallow Marine Non-Living Resources

The coastal zone, as a resource (CZAR) in its own right, is one of our precious commodities, much of the world's population lives (and grows its food) within the coastal zone. It is a fragile zone which may respond adversely to change. These changes may be induced by man, for example, the development of a harbour or the dredging of a channel in one area may induce erosion in another area. Building a dam can affect the input of sediment, or nutrients, leading to drastic changes of both living and non-living resources of the nearshore zone. Natural phenomena, for example, earthquakes or floods, can result in major changes to the shoreline. Some of the changes can be global in extent; for example, a eustatic rise of sea-level as a result of global warming will have a major effect on the coastal zone including marine inundation, salination, and the destruction of coastal aquifer systems.

Construction materials, particularly sand and gravel, are extracted from many offshore areas, particularly adjacent to the highly populated areas of western Europe, the eastern United States and Asia. Sand and gravel were, for the most part, deposited during a previous low sea-level stand, then subsequently inundated by the post-glacial rise in sea-level. Calcium carbonate, the second most important offshore mineral resource, in terms of total extracted value, is mined from many coastal areas where there are accumulations of shells, calcareous sands or old "coral" reefs.

Marine Placers form in response to present day conditions or are residual deposits left from a previous energy regime (Emery, 1968). For example, mineral sands, containing economically significant minerals such as rutile, ilmenite and zircon occur in present-day beaches in various parts of the world including Australia (Emery and Noakes, 1968), the southeastern United States (Bates, 1963) and West Africa (United Nations, 1985). However, mineral sands also occur in older beach systems, generally landward, but occasionally seaward of the present day shoreline. Therefore obviously a knowledge of relative sea-level changes should assist exploration for mineral sands. Many placer deposits, for example, the offshore tin deposits of southeast Asia, are found in old river channels that have been inundated by the post glacial rise of sea-level. Diamonds have been mined from the beaches and immediately offshore of Nimibia with varying degrees of success. Similarly gold has been mined through offshore dredging operations in Canada, Alaska and the Philippines (McKelvey and Wang, 1969; Nelson and Hopkins, 1972; Moore, 1979; Moore and Welkie, 1972).

Phosphorites (sedimentary phosphate deposits) are an example of shallow marine mineral deposits that form in part in response to physical, chemical and biochemical changes within the water column and at the sediment-water interface (Cook, 1976). However they are not solely shallow marine; they have been known since the Challanger Expedition (Murray & Renard, 1891) to extend to occur as crusts and nodules on plateaux, seamounts and the upper slope. Phosphorites will be discussed in some detail later in this paper.

Therefore non-living resources form in response to a wide range of physical, chemical and biological conditions in a variety of shallow marine environments. There are nevertheless common threads, and it is these which provide the scientific framework and enable us to, both, develop a better understanding of the interplay of the processes responsible for producing offshore non-living resources, and develop predictive models for exploration in the case of minerals, and management, in the case of the coastal zone. There are three basic processes or driving mechanisms responsible for the formation of shallow marine resources; the eustatic rise and fall of sea-level, changes in the environment and tectonic processes. Of course these three "processes" are themselves inter-related (Fig. 4). The WESTPAC programme group first proposed a regional project entitled SET (Sea-level changes, Environment and Tectonics). This was adopted as a global project by the Guiding Group of Experts of OSNLR in 1985 but focussing in particular on the last million years of earth history. It was given the acronym SETMY (Sea-level changes, Environments and Tectonics in the pas Million Years). This period of one million years encompasses the time necessary to form and accumulate most of the significant non-living resources of the nearshore zone (though not of course oil and natural gas). More recently (1987), this has been modified to SETR (eustatic sea-level change, environments tectonics and resources) as it became evident that it was necessary to step outside the stricture of one million years in order to better understand offshore non-living resources.

Eustatic Sea-Level Changes, Environments and Tectonics

Let us briefly examine each of these three factors that influence deposition of mineral resources in the nearshore zone and continental shelf. However, it must be recognized that these are not totally independent factors. There are feedback mechanisms (Fig. 4) that result in the development of various inter-relationships and in some cases the formation of non-living resources (Table 1).

Tectonics is described in the AGI Dictionary as "Study of the broader structural features of the earth and their causes". Processes such as volcanic activity, earthquakes, faulting, folding, uplift and downwarping all fall within the perview of tectonics. All of these processes could be regarded as manifestations of plate tectonics and the attendant mechanisms of plate separation, collision and subduction. Tectonic processes are of fundamental importance to the formation of oil and gas fields and mineral deposits both onshore and offshore (Mitchell & Garson, 1981). Mineralization, is commonly associated with so-called "black smokers" that occur on mid-ocean ridges where new ocean floor is being generated. Deformation of the continental margin can produce trap structures for oil or gas. An increase in the geothermal gradient under the continental margin can result in the sediments entering the "oil window" and generating hydrocarbons. Onshore, the formation of a mountain range can result in the exposure and erosion of rocks containing gold, ilmenite or diamonds which are then transported down the rivers into the coastal zone to form marine placer deposits.

Not only does tectonics play a direct role in the formation of marine non-living resources but it can also indirectly play a role through its influence on sea-level changes, marine environments and on climate, as shown schematically in Fig. 4. An example of this influence on the local scale is tectonic uplift of a coastal area producing a relative fall of sea-level and a climatic change in the hinterland. On the global scale, the drift of a continental plate to a high latitude location can result in the development of a large continental ice-cap, a sea-level fall and global cooling. Tectonicsm can occur on a range of scales. In tectonically active areas such as Papua-New Guinea, uplift can be of the order of millimetres to centimetres a year (Chappell, 1974a,b). This high rate of uplift is in part responsible for the superb preservation of the raised reefs of the Huon Peninsular (Fig. 5). It can also produce measurable rates of coastal progradation, so that even in a lifetime the effect of tectonic processes on marine non-living resources can be quite profound. Seafloor spreading occurs at a rate of a few millimetres a year, consequently the drift of a continental fragment to a high latitude and the onset of glaciation may take many millions of years. Conversely, very rapid global cooling may result from increased rate of input of volcanic ash into the atmosphere.

Therefore tectonic processes can be very important to the formation of marine non-living resources. They can take place on scales of a few years to many millions of years and can affect a relatively small part of the earth's crust, in the case of localized uplift for example, or vast parts of the globe, in the case of plate movement.

Eustatic sea-level change

Changes of sea-level occur on a variety of scales ranging from diurnal tidal changes to very major changes of sea-level, associated with the development of ice caps, and uplift and sinking of major parts of the earth's crust. The major changes of sea-level that are global in extent are referred to as eustatic. In recent years we have greatly improved on documentation of the earth's eustatic sea-level history largely through the efforts of the petroleum industry, particularly through interpretation of seismic profiles. Using this method, Vail et al (1977), Haq et al (1987), and various other workers have developed a global sea-level curve, and are able to recognize changes with a periodicity ranging from 10^7 years (first order curves) to 104 years (fourth order curves) (Fig. 6). A finer resolution, to 103-102 years (essentially the Holocene sea-level record) has been developed using evidence from ancient shoreline features such as coral reefs (Fig. 5) and beach ridges (Fig. 7), and dating techniques ranging from the historical (human) record to radiometric, paleontological and palaeomagnetic methods.

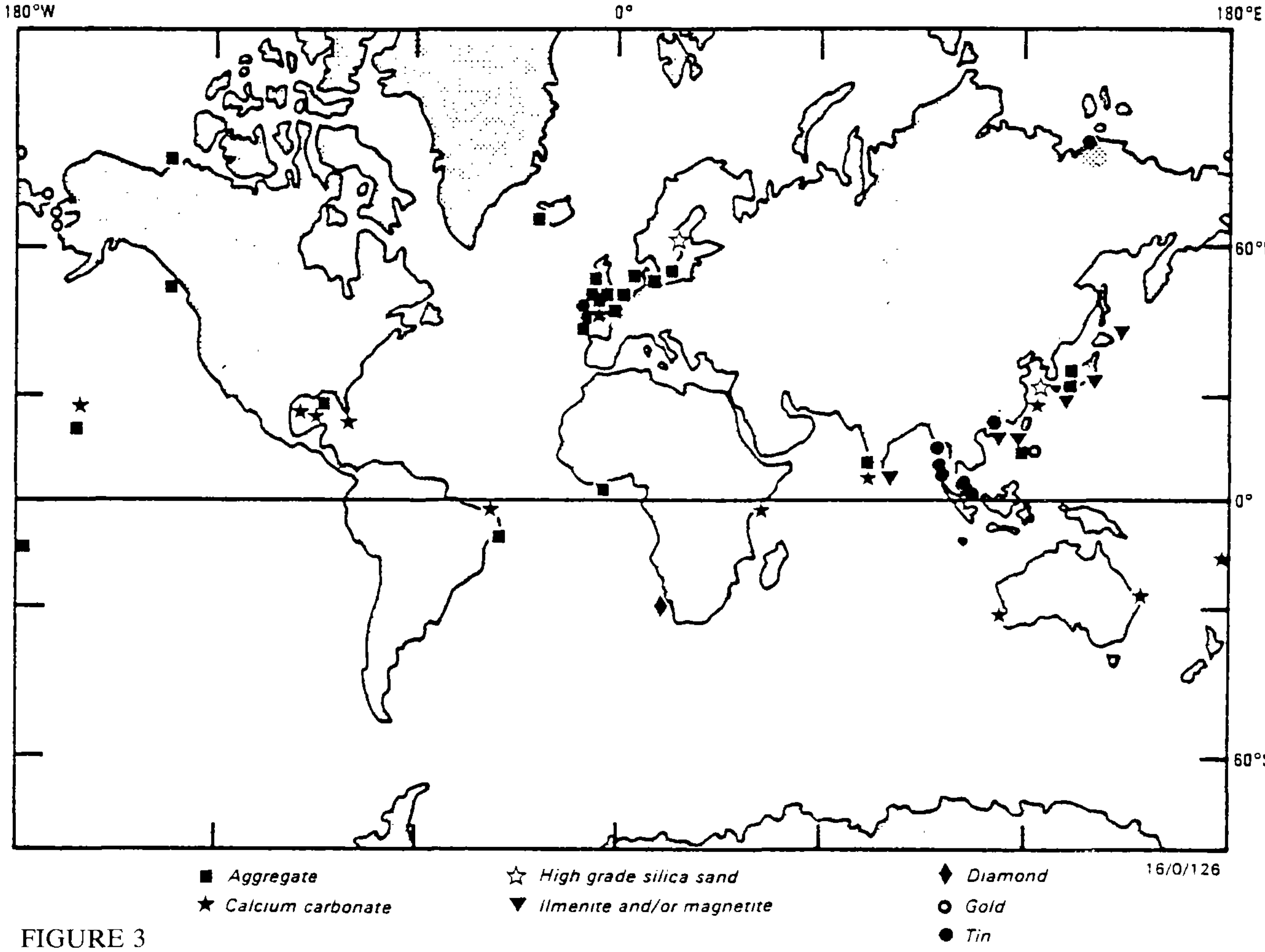

FIGURE 3
Current or recent offshore mining activities (International Centre for Ocean Development).

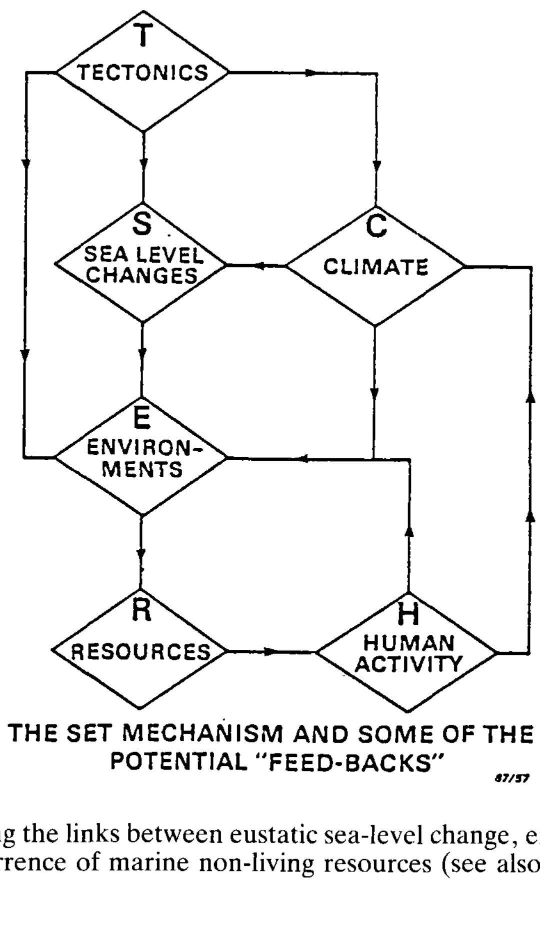

FIGURE 4
The SETR "mechanism" showing the links between eustatic sea-level change, environmental change and tectonism and their influence on the occurrence of marine non-living resources (see also Table 1).

TABLE 1

EXAMPLES OF THE SETR MECHANISM ILLUSTRATED IN FIGURE 4

Inter-relationships	Example
T→S	Development of a mid-ocean ridge producing major rise of sea-level over 10^6-10^7 years.
T→E	Uplift of source area producing major changes in depositional area such as destruction of reefs by influx of terrigenous sediments over 10^2-10^6 years.
T→C	Drifting of plate into a high latitude location producing a major change in the regional and global climate over 10^6-10^7 years.
C→S	Development of a new polar ice cap produces an eustatic fall in sea-level over 10^4 to 10^6 years.
S→E	A relative rise of sea-level resulting in the migration of paralic conditions across the continental shelf over a period of 10^3-10^5 years.
T→S→E→R	The interaction of sea-level changes, environments and tectonics produce non-living resources such as oil and gas (10^5-10^7 years), phosphate deposits (10^4-10^7 years) and mineral sands (10^3-10^6 years).
R→H→E	The use of non-living resources whether by extraction (in the case of the mineral sands) or modification (in the case of the coastal zone) can affect the nearshore marine environments over a period of 10^1-10^3 years).
H→C→S	The burning of fossil fuels and the resultant "greenhouse effect" is likely to lead to significant changes of sea-level over 10^1-10^2 years.

Whilst all non-living shallow marine resources are influenced to varying degrees by eustatic sea-level change, they react at different temporal scales. For the coastal zone as a resource (CZAR) it is necessary to understand record of sea-level change over 10^0 to 10^4 years; for marine placers we need to be concerned mainly with sea-level change over 10^3 to 10^6 years; for phosphorites it is necessary to understand the sea-level record for 10^6 to 10^8 years.

The mechanisms responsible for eustatic sea-level change are varied and the subject of considerable controversy (Pittman, 1978). Eustatic rises or falls of sea-level can occur through changes in the geometry of the lithosphere. For example, eustatic rise may occur as a consequence of the development of a new mid-ocean ridge; a fall can take place when a previously isolated depression becomes linked to the world oceans and flooded as a consequence, for example the Messinian Mediterranean (Hodell et al, 1986). Perhaps the best known eustatic changes occur as a result of climatic change and particularly the growth or diminution of the polar ice caps (Broecker & Van Donk, 1970). Such changes are a direct consequence of climatic cooling or warming. Climatic variation has in turn been linked to a range of potential driving mechanisms such as cooling due to the drift of large continental fragments to high latitudes or a major volcanic episode (Frakes, 1979). A range of poorly understood extra-terrestrial mechanisms have been invoked on the basis of their apparent influence on climatic cycles. The best documented of these cycles are the so-called Milankovitch cycles which have periodicities of 20,000, 40,000 and 100,000 years. These result from variations in the earth's orbital elements such as the eccentricity of the orbit, the tilt of the axis of rotation and "wobble" of the axis. This can combine to reduce the level of solar radiation, leading to development of high latitude ice sheets and the onset of global cooling and a eustatic sea-level fall (Milankovitch, 1938). The Milankovitch cycles have been documented from various parts of the world including the WESTPAC region. The raised coral terraces of Papua-New Guinea (Chappell, 1974a,b, 1983; Aharon, 1983; Aharon & Chappell, 1986); Chappell & Polack, 1976; Bloom et al, 1974) have provided a well defined climatic record that can be used not only to determine a sea-level curve (Fig. 5) but can also be used to test the Milankovitch theory. Similarly the beach ridges of southeast South Australia (Fig. 7) provide strong evidence in favour of the Milankovitch theory (Sprigg, 1952; Cook et al, 1977; Idnurm and Cook, 1980).

Therefore, truly eustatic sea-level changes of global extent that are approximately (though not necessarily precisely) synchronous do exist. However the difficulty in many areas is to separate out genuine eustatic sea-level change from relative sea-level change due to uplift or subsidence of the land. As is evident from Figures 5 and 7, it is in fact necessary to have uplift in order to preserve the sea-level record. In some cases the actual rate of uplift can be measured, but frequently it is necessary to assume a uniform rate of uplift. Perhaps the best climatic (and hence eustatic sea-level) record is obtained from the $0^16/018$ isotopic record of marine sediments, which provides an indication of the palaeotemperature of the water column (Broecker et al, 1968; Broecker & Van Donk, 1970).

For many marine non-living resources such as placers, the effect of a relative rise of sea-level and a eustatic rise of sea-level are essentially the same in terms of their influence on the distribution of resources. However in some cases, notably phosphorites, there appear to be wide scale, perhaps even global episodes in phosphogenesis that in some cases can be related to eustatic sea-level rises (Arthur & Jenkyns, 1981; Riggs et al, 1985). Therefore in such cases, in order to use sea-level change predictively for locating deposits it is necessary to separate out relative and eustatic sea-level changes.

A different type of prediction is needed to evaluate the effect of the so-called greenhouse effect on non-living resources particularly CZAR. The increased use of fossil fuels, the associated rise in the CO_2 content of the atmosphere and the net global warming has produced a measurable rise of sea-level. Therefore here we see a significant feedback mechanism (Fig. 4) from the extraction and use of non-living resources (in this case fossil fuels) in turn affecting the climate and bringing about eustatic sea-level change. If current trends continue this will produce a global rise of sea-level of several metres. This will have a catastrophic effect on the coastal zone with the seas invading coastal areas that are presently under cultivation, and many of the world's major cities. It is therefore essential that we accurately predict the consequences of the greenhouse effect on the coastal zone.

Environmental change in the nearshore zone can occur most dramatically as a result of eustatic sea-level change so that what was previously a

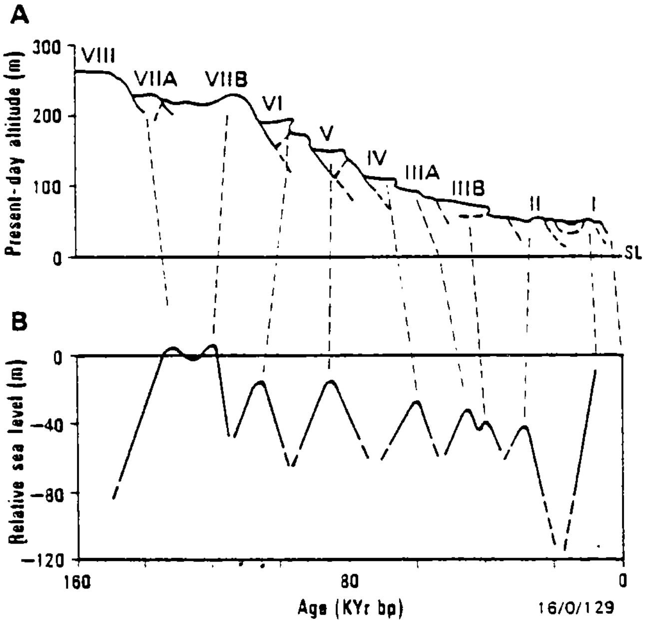

FIGURE 5
The coral reef terraces of the Huon Peninsular, Papua New Guinea and the Pleistocene sea-level curve developed from these terraces and the associated oxygen isotope record (after Aharon, 1983; Aharon & Chappell, 1986; Chappell, 1974a).

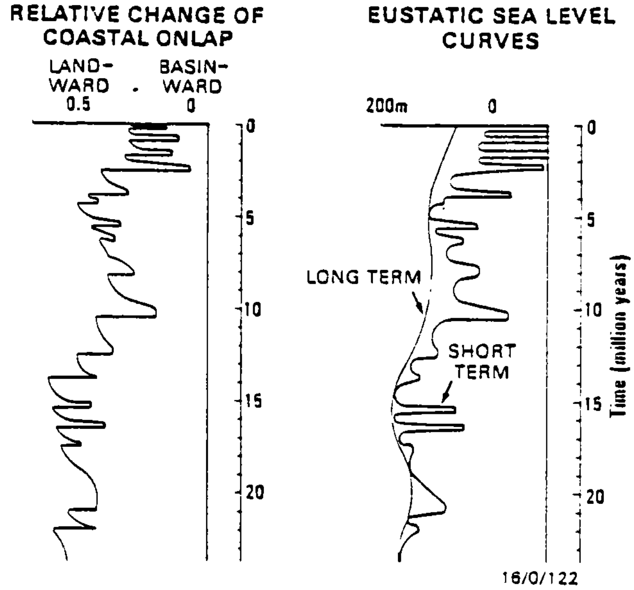

FIGURE 6
The coastal onlap and eustatic sea-level curves developed by Haq, Hardenbol and Vail (1986).

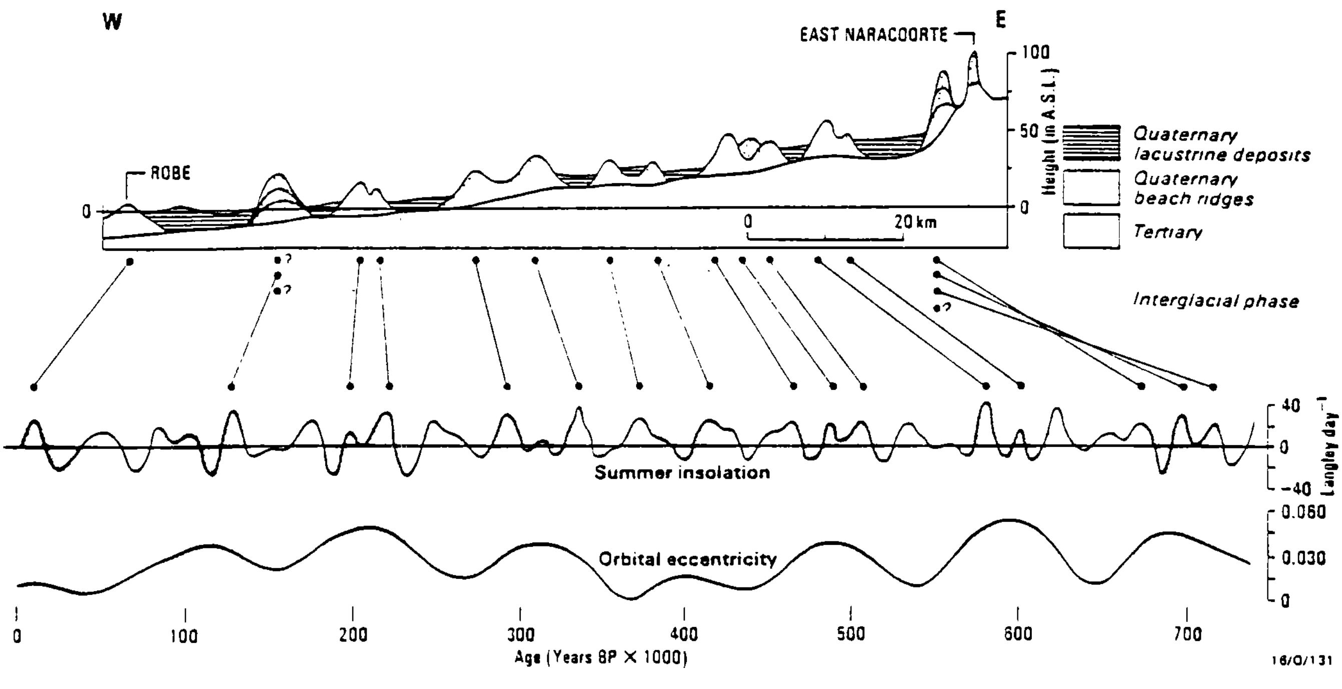

FIGURE 7
Beach ridges in southeast South Australia and the Pleistocene interglacial phases (after Cook et al, 1977; Idnurm & Cook, 1980).

shallow marine environment becomes dry land or vice-versa. This is shown by the link between "S" and "E" in Figure 4. It can similarly be linked to tectonism through relative sea-level change. Tectonism can also affect the depositional environment in other ways. Uplift in the coastal hinterland can result in a marked increase of sedimentation producing seaward progradation of the coastal zone, siltation of coastal lagoons or transformation of a shelf from carbonate-dominated to clastic-dominated. This type of relationship is indicated in Figure 4 by the link between "T" and "E". Environmental changes can also be linked to climatic change (which as pointed out earlier may in turn be linked to tectonics and eustatic sea-level change). Climatic change can affect rainfall which may affect freshwater input into the coastal zone, in the form of surface water and groundwater. Man can simulate this to some extent by damming rivers; the net effect of this on the coastal zone can be very considerable. This is an example of the H to E links shown in Figure 4. A local or regional fall in water temperature can bring about a decrease of coral growth. An increase in the storminess or the energy regime can have a very marked effect on the distribution and concentration of nearshore and continental shelf sands and on the formation or destruction of beach ridges.

We know that there have been times in earth history when fundamental changes in ocean chemistry have occurred. In some cases they have affected only relatively small bodies of water. The Messinian salinity crisis in the Miocene is an example of this (Hsu et al, 1973). Sometimes there have been much more widespread events such as the so-called oceanic anoxic events (Fischer and Arthur, 1977) which certainly affected large portions of the Atlantic Ocean and may even have been global in extent. Some of the so-called boundary events, when there were major faunal crises may have been in part associated with major changes in ocean chemistry (Cook & Shergold, 1984; Cook & Cook, 1985). There also seem to have been periods in earth history where iron-rich sediments or phosphorus-rich sediments were deposited on many of the world's continental shelves. This too is probably a consequence of changing environmental (i.e., chemical and biochemical) conditions in the world ocean.

In conclusion then, in some cases the processes of eustacy, tectonics and environmental change occur separately but commonly they are inter-related through a range of "feed back" mechanisms that together profoundly affect the distribution of marine non-living resources. Let us examine the effect of these mechanisms on the spatial and temporal distribution of one marine non-living resource - phosphorites.

Marine Phosphate Deposits

is are discussed in some detail by Cook (1984). Tectonism influences phosphogenesis over a range of scales (Sheldon, 1964). Broadscale tectonic processes commonly set the scene for global phosphogenesis, for example, through the development of a narrow east-west seaway in a near-equatorial location resulting in an increased rate of oceanic overturn and possibly an increase in the photic zone biomass (Cook & McElhinny, 1979; Sheldon, 1980a,b). Alternatively, a north-south seaway may be formed by plate tectonics, so that oceanic circulation develops and upwelling occurs on the east side of the ocean in response to the equatorially directed portion of the current and the coriolis force (Fig. 11). Phosphorites are frequently found in areas of oceanic upwelling (e.g., off Chile-Peru and off Namibia) (Baturin, 1971, 1978; Baturin & Bezrukov, 1979; Veeh et al, 1973; Burnett, 1977; Kolodny, 1969, 1981). On a smaller scale local tectonics can be very important. For instance a broadscale downwarp can produce an epicontinental seas -a preferred location for some types of phosphate deposits. Alternatively, faulting or folding can produce a sea bottom topography (such as bathymetric high) that will induce dynamic upwelling and produce local high productivity systems. Alternatively it can produce bays and estuaries in which phosphate grains, formed in high productivity areas, can be trapped to form significant deposits. Such traps are an important feature of many deposits (Slansky, 1980). Therefore we see that phosphogenesis can be influenced through tectonics as diverse in scale as the formation of a major new seaway, as a consequence of large scale plate tectonics, to the formation of an estuary by small scale faulting.

There are various types of phosphorites but by far the most important type is composed of well-rounded sand-size pellets (grainstone phosphorite - Cook & Shergold, 1986). In summary, whilst there is by no means universal agreement on how phosphorites form, the weight of evidence suggests that they form overwhelmingly under relatively shallow marine (shelf) conditions in areas of high organic productivity (Kazakov, 1938). As the organic remains accumulate they produce an organic-rich sediment but not necess-

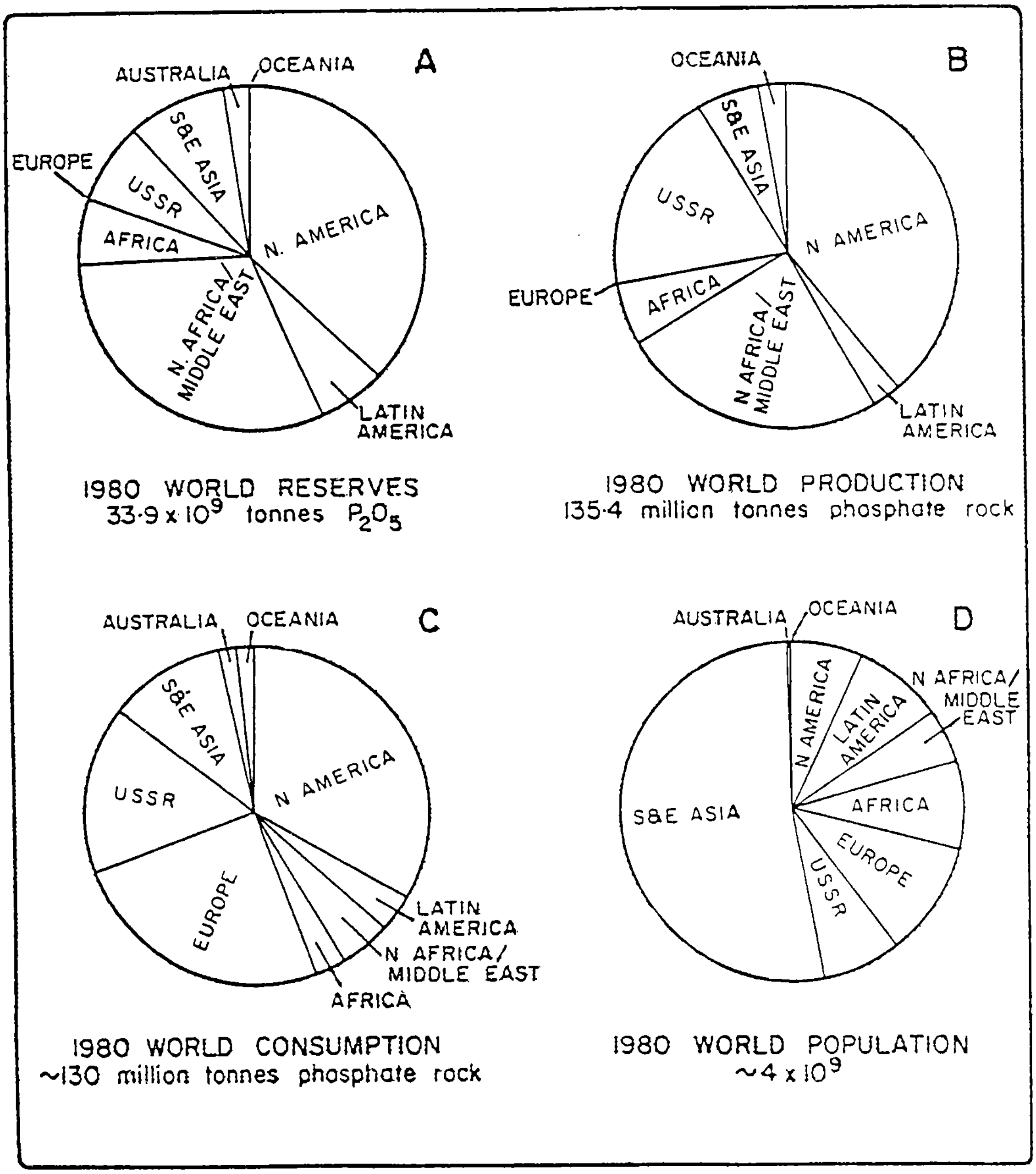

FIGURE 8
The world distribution of phosphate reserves, phosphate production, phosphate consumption and population (after Cook, 1983). In these compilations "North America" includes only Canada and the USA: "Latin America" includes the Caribbean and American countries from Mexico South; "North Africa–Middle East" includes all of Africa north of the Tropic of Cancer and the Asian countries as far east as Iran; "Africa" here excludes those countries north of the Tropic of Cancer; "Europe" here excludes the European portion of the USSR; "South and East Asia" includes all countries east of Iran but excludes the Asiatic portions of the USSR; "Oceania" is here taken to include Christmas Island (Indian Ocean). The WESTPAC program area of IOC is represented approximately by the "pie-slices" marked S&E Asia, Australia and Oceania.

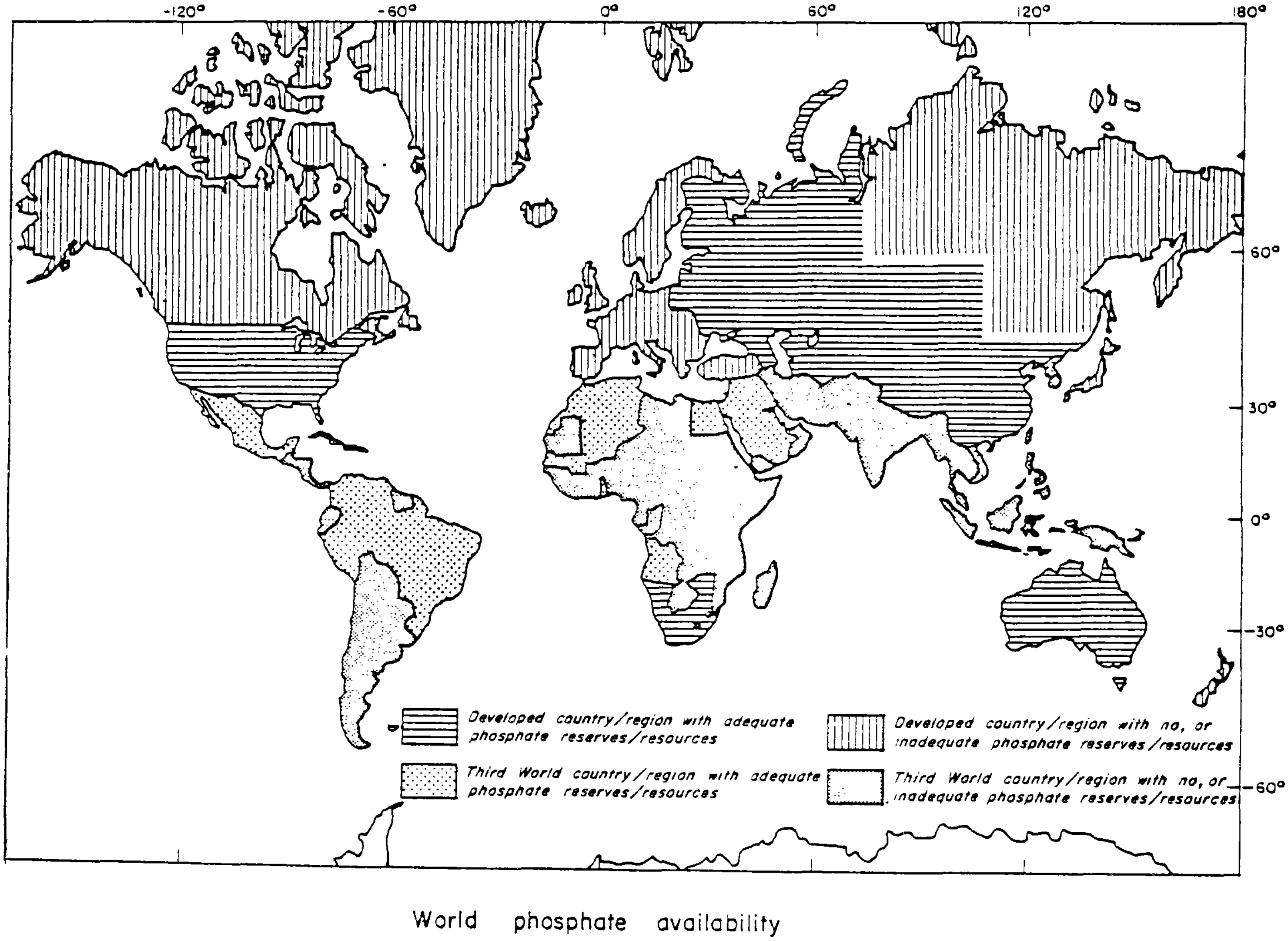

FIGURE 9
World phosphate availability and need amongst the developed and developing countries (after Cook, 1983).

arily on phosphorites. To form a phosphorite requires processes such as removal of the organic matter, diagenetic phosphatisation and, in the case of grainstone phosphorites, mechanical reworking (Cook, 1976). Inevitably, the actual processes involved are far more complex than this. Here I will concentrate on the "SETR mechanism" of eustatic sea-level change, environmental change and tectonism (Fig. 4). The way in which this works to produce a phosphorite is summarized in Figure 10. The formation of a major phosphate deposit is extremely complex and therefore Figure 10 is little more than an approximation. However this "flow chart" does show that there is a series of "steps"; the more these steps "coincide" the greater the prospect for forming a major deposit. In a brief overview paper such as this it is not possible to consider all of these steps in detail but let us briefly consider some of them.

The steps shown in Figure 10 range in scale from local e.g., mechanism in lower left-hand corner of the diagram) to global (e.g., mechanisms in the upper right-hand corner of the diagram). Let us examine briefly how tectonism, eustatic sea-level change and environmental change each exert influence on the formation of phosphorites but recognizing that rather than being discrete processes these are inter-related as shown schematically in Figures 4 and 10.

The range of spatial and temporal controls on phosphogenesis are discussed in some detail by Cook (1984). Tectonism influences phosphogenesis over a range of scales (Sheldon, 1964). Broadscale tectonic processes commonly set the scene for global phosphogenesis, for example, through the development of a narrow east-west seaway in a near-equatorial location resulting in an increased rate of oceanic overturn and possibly an increase in the photic zone biomass (Cook & McElhinny, 1979; Sheldon, 1980a,b). Alternatively, a north-south seaway may be formed by plate tectonics, so that oceanic circulation develops and upwelling occurs on the east side of the ocean in response to the equatorially directed portion of the current and the coriolis force (Fig. 11). Phosphorites are frequently found in areas of oceanic upwelling (e.g., off Chile-Peru and off Namibia) (Baturin, 1971, 1978; Baturin & Bezrukov, 1979; Veeh et al, 1973; Burnett, 1977; Kolodny, 1969, 1981). On a smaller scale local tectonics can be very important. For instance a broadscale downwarp can produce an epicontinental seas -a preferred location for some types of phosphate deposits. Alternatively, faulting or folding can produce a sea bottom topography (such as bathymetric high) that will induce dynamic upwelling and produce local high productivity systems. Alternatively it can produce bays and estuaries in which phosphate grains, formed in high productivity areas, can be trapped to form significant deposits. Such traps are an important feature of many deposits (Slansky, 1980). Therefore we see that phosphogenesis can be influenced through tectonics as diverse in scale as the formation of a major new seaway, as a consequence of large scale plate tectonics, to the formation of an estuary by small scale faulting.

Similarly, changes of environment can influence whether or not phosphorites form. Global (environmental) changes in ocean chemistry related to tectonics and the formation of new seaways or global climatic change, may also be important. We find that phosphogenesis is not spread randomly throughout earth history; there were quite specific times when large-scale phosphogenesis took place in many parts of the world for instance in the early Cambrian, the late Cretaceous-early Tertiary and the mid Miocene (Cook & McElhinny, 1979). As an aside, not only are these periods important to phosphogenesis but also they appear in some cases to be linked to major evolutionary events such as the evolutionary burst at the base of the Cambrian (Cook & Shergold, 1986) or the faunal and floral crises around the Cretaceous-Tertiary boundary (Cook & Cook, 1985). These major periods of phosphogenesis may also be related to (?preceded by) oceanic anoxic events (Fischer & Arthur, 1877; Arthur & Jenkyns, 1981).

More locally, environmental change such as the development of a relatively small scale high productivity system appears to be an important prerequisite for many, perhaps most deposits. Examples of how such systems can form in response to tectonics have already been discussed, but they can also occur in response to sea-level change (see later), or through a change in climate producing colder more phosphate-rich waters. Alternatively, the leaching of a phosphatic hinterland could conceivably produce phosphate-rich waters in a lagoon or an estuary. Frequently, the question of whether or not a high grade phosphorite forms, is dependent on whether or not other components, such as calcium carbonate or siliciclastics, are being added to the system. These can easily "swamp" out what might otherwise be a phosphorite-producing environment, so that the result is little more than a slightly phosphatic limestone or sandstone. Therefore an environmental change that results in a modification of

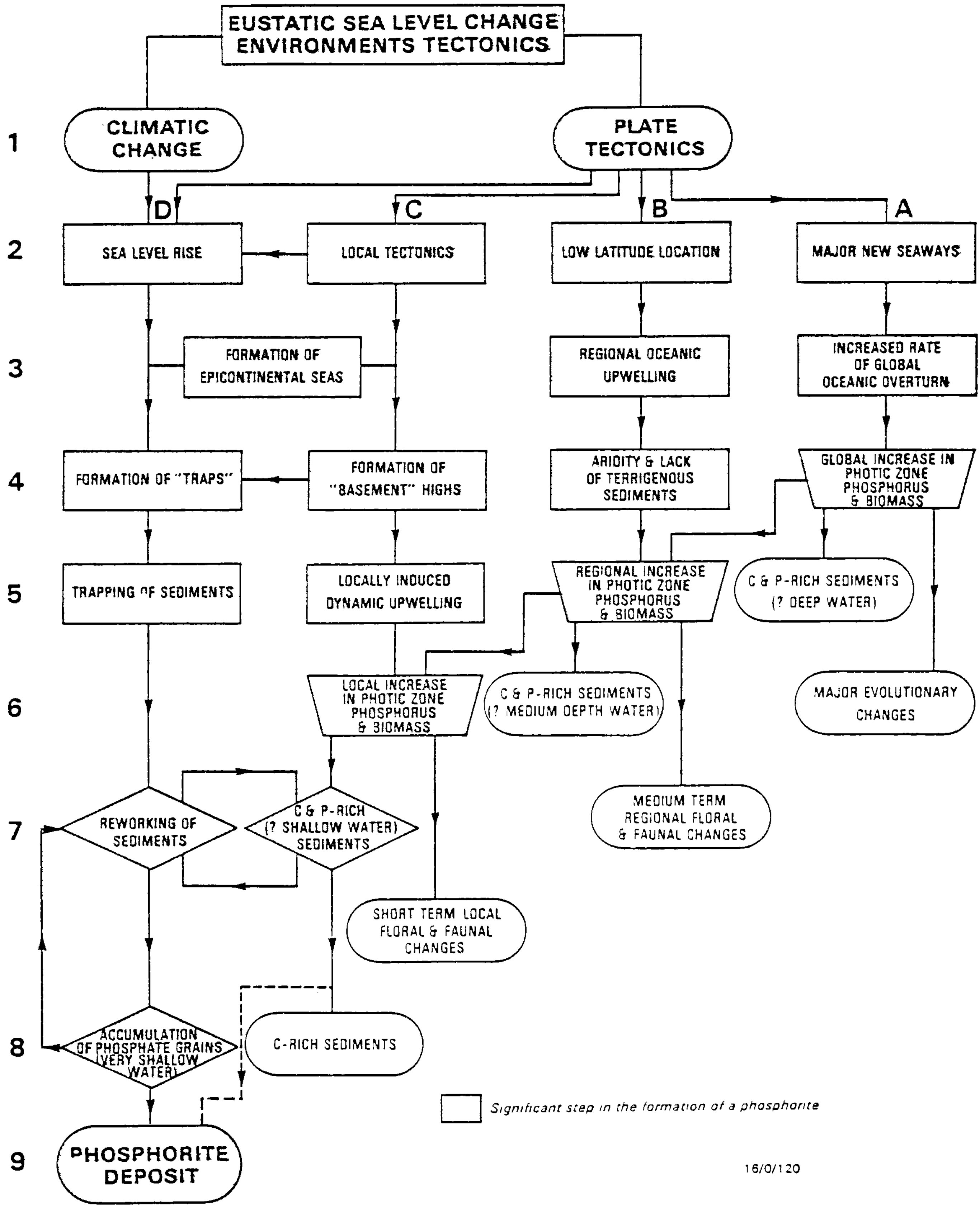

FIGURE 10
A model for phosphogenesis is showing the "SETR mechanism" at work (after Cook & Shergold, 1986).

the rate of input of non-phosphatic components can be fundamental to whether or not a phosphorite forms. Such changes can be physically, chemically or biochemically-induced. Alternatively a change in the physical environment, for instance, increasing storminess, can result in an increased level of reworking of the sediments and hence the potential upgrading of a phosphatic sediment to a high grade phosphorite. Therefore we see in the case of environmental change, as in tectonism, the scale of change can vary from global to local.

Turning now to the third component of the "SETR mechanism" - eustatic sea-level change: it is by no means certain how sea-level change influences phosphogenesis but there is strong empirical evidence that it does (Arthur & Jenkyns, 1981). The evidence from the Miocene is particularly compelling with a clear temporal relationship between the mid-Miocene sea-level (Vail et al, 1977) and phosphogenesis on the continental shelf of the southeastern United States (Riggs et al, 1985). The same relationship is evident as far back as the Cambrian (Cook, 1984).

Possible genetic associations between sea-level change and phosphogenesis include, for example, the so-called broom effect - sea-level rise drives sediments landward across the shelf, and also sorts grains on the basis of their specific gravity (Frakes & Bolton, 1984). Therefore phosphate grains, which have a relatively high specific gravity can accumulate as a lag deposit. Alternatively (or perhaps additionally) the flooding of large areas of continent to produce broad shallow epicontinental seas, may have a profound effect on ocean chemistry (Arthur & Jenkyns, 1981), in turn leading to phosphogenesis. A change in sea-level can also result in new interactions between water masses and sea floor topography, and the consequent development of dynamic upwelling. This has been well documented off the east coast of the United States. In some cases the phosphogenesis - sea-level change linkage may be secondary. For example, a eustatic change in sea-level is commonly a reflection of global cooling or warming; this cooling or warming can itself lead to a change in organic productivity, or storminess, or in the pattern or magnitude of ocean currents, and hence influence the extent to which phosphogenesis occurs at a given time or place.

Change of sea-level may exert a rather different influence in the case of insular (guano) phosphate deposits (Tracey, 1979; Warin, 1968; White & Warin, 1964). One obvious effect is that previously-subaerial deposits can be submerged by a rise of sea-level. However a change of sea-level can have a more subtle influence. At times of low sea-level there are likely to be more islands; therefore assuming a constant regional biomass, and a constant bird population, there will be more deposits formed because there are more islands but they will be lower grade (non-commercial) guano deposits. At times of higher sea-level there will be fewer islands and therefore fewer but higher grade (?commercial) guano deposits.

Within the WESTPAC region (Fig.12), and elsewhere, phosphorites in the present-day ocean fall into two fairly well defined categories - continental margin phosphorites and open ocean phosphorites (Fig. 13). For the most part, the open ocean phosphorites are associated with seamounts - such as the well defined line of phosphate-encrusted seamounts tending northwest towards Japan, across the North Atlantic (Fig. 13). There is a clear association between such features and tectonic processes - in this case the migration of the Pacific plate over a hot spot. The resulting topographic high generates dynamic upwelling, particularly when the seamount "migrates" across the path of a strong current system. In the South Pacific (Fig. 14) the occurrence of phosphorites and insular guano deposits in near-equatorial locations (Cook, 1974; Cullen & Burnett, 1986) is almost certainly related to the strong equatorial current system, the associated dynamic upwelling, and the resultant development of high organic productivity systems. There is an additional association with the areas where the temperature differential between deep and shallow water is most marked and the upwelling most intense.

The continental margin phosporites of the South Pacific region are more problematical. They occur in areas such as the Chatham Rise to the east of New Zealand and off eastern Australia (von der Borch, 1970) (Fig. 14). These occurrences can be related to topography and hence in all probability, to tectonic features. They similarly appear to fall into the temporal pattern found in many parts of the world, in that for the most part, they are residual deposits of Miocene age, and therefore are probably related to eustatic sea-level change and possibly also environmental change during the mid-Miocene. However O'Brien & Veeh (1980) have documented the occurrence of modern phosphorites off eastern Australia. These eastern Australian occurrences do not fall into the "classical" picture of phosphogenesis associated with areas of major oceanic upwelling and indeed O'Brien & Veeh (1980) and O'Brien et al (1981) have suggested that there is little or no association

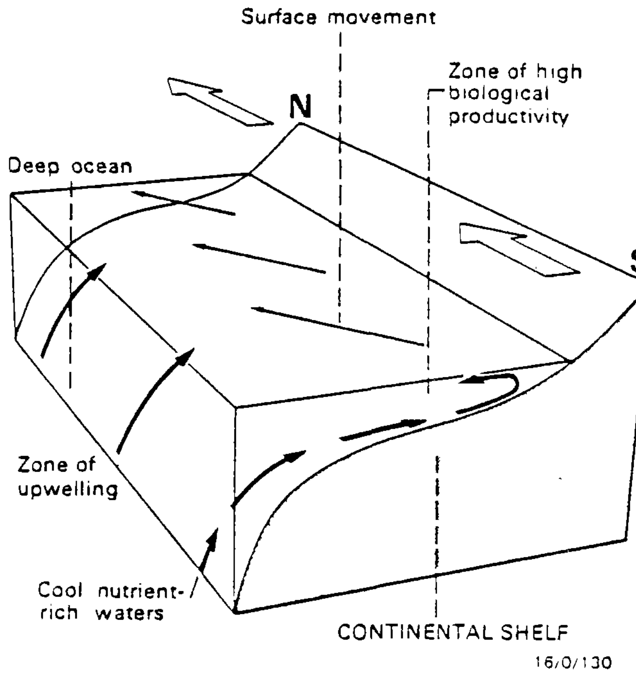

FIGURE 11
Oceanic upwelling on the east side of an ocean, south of the equator.

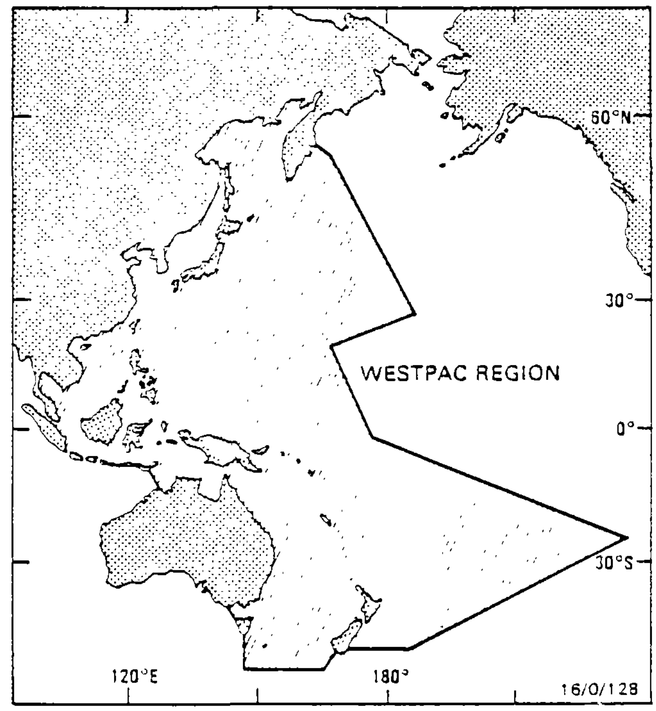

FIGURE 12
The WESTPAC program area of IOC.

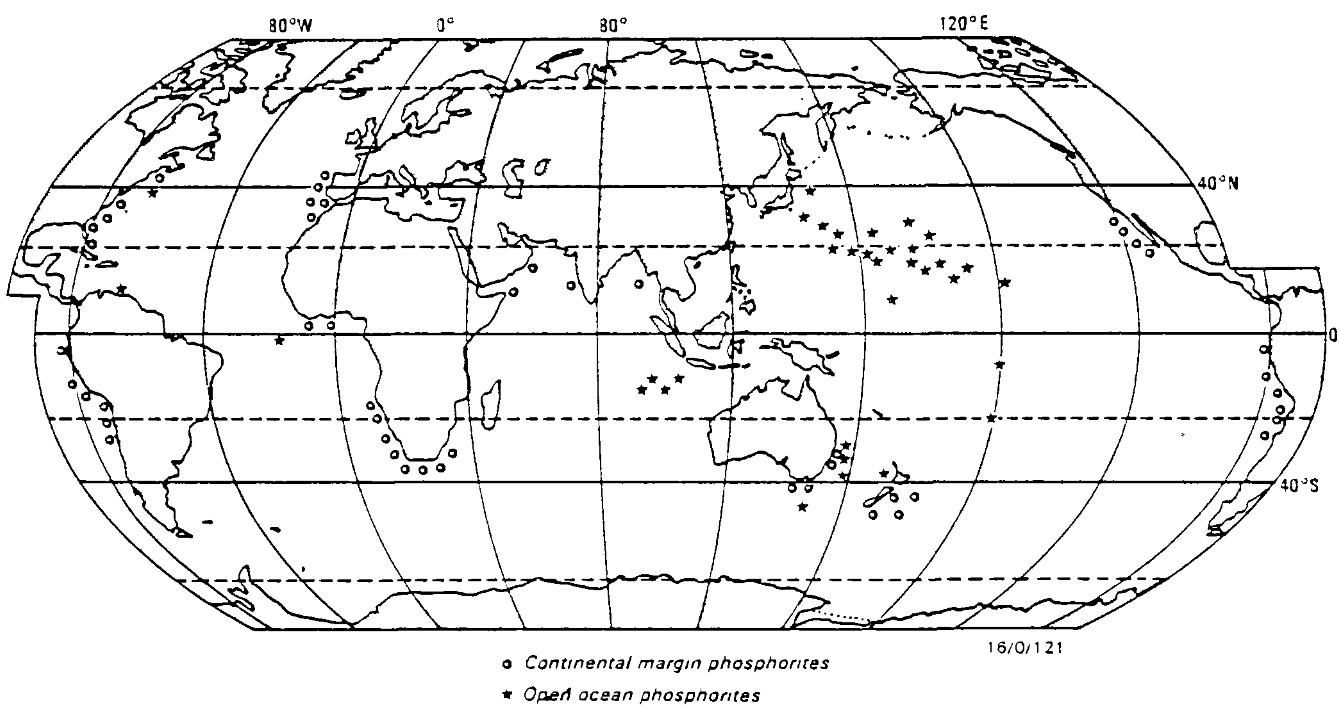

FIGURE 13
Distribution of offshore phosphorites (after Cullen & Burnett, 1986).

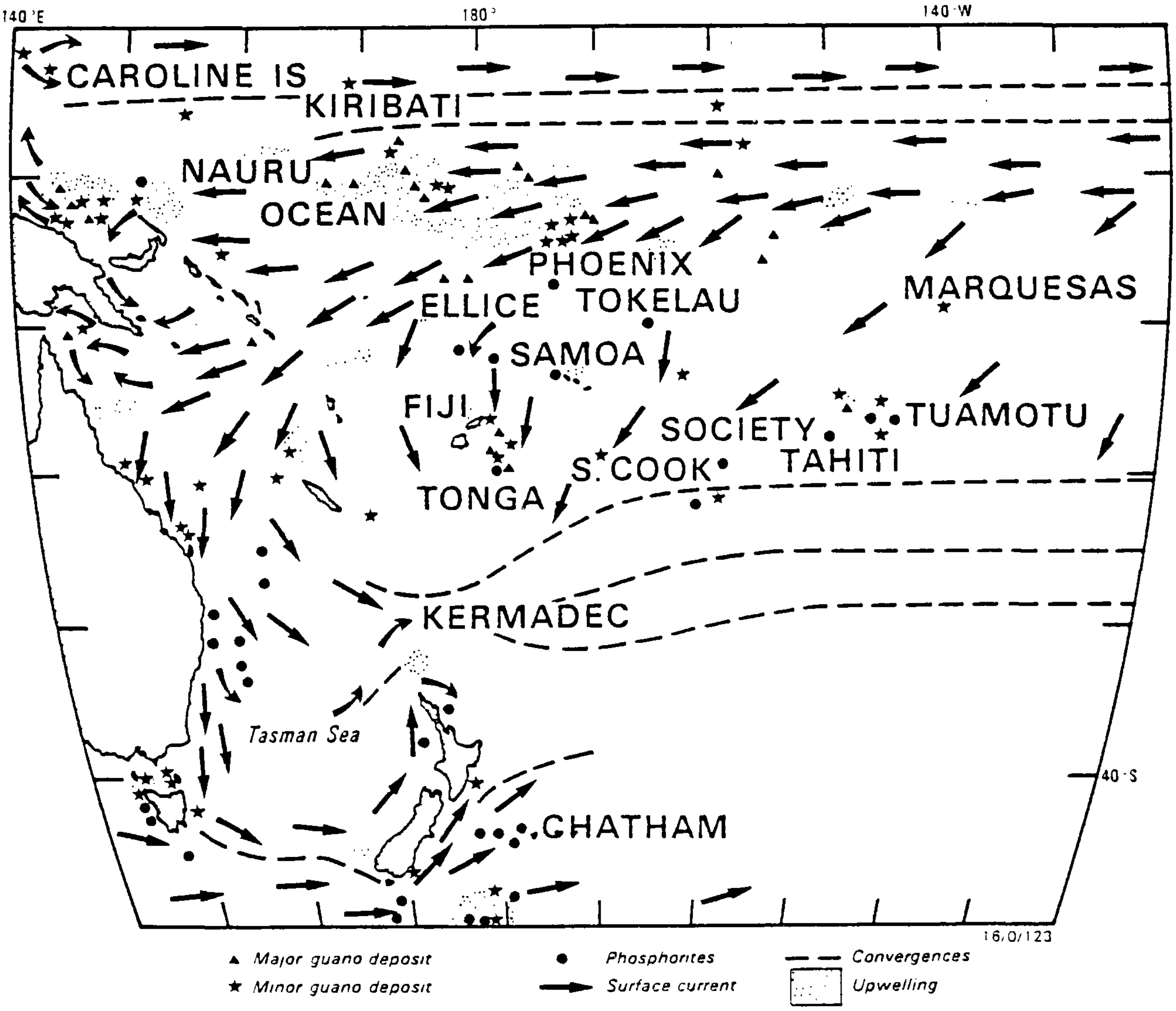

FIGURE 14
Location of offshore phosphorites and insular (guano) phosphate deposits in the South Pacific area (after Cook, 1975; Hutchinson, 1950; Sheldon & Burnett, 1980).

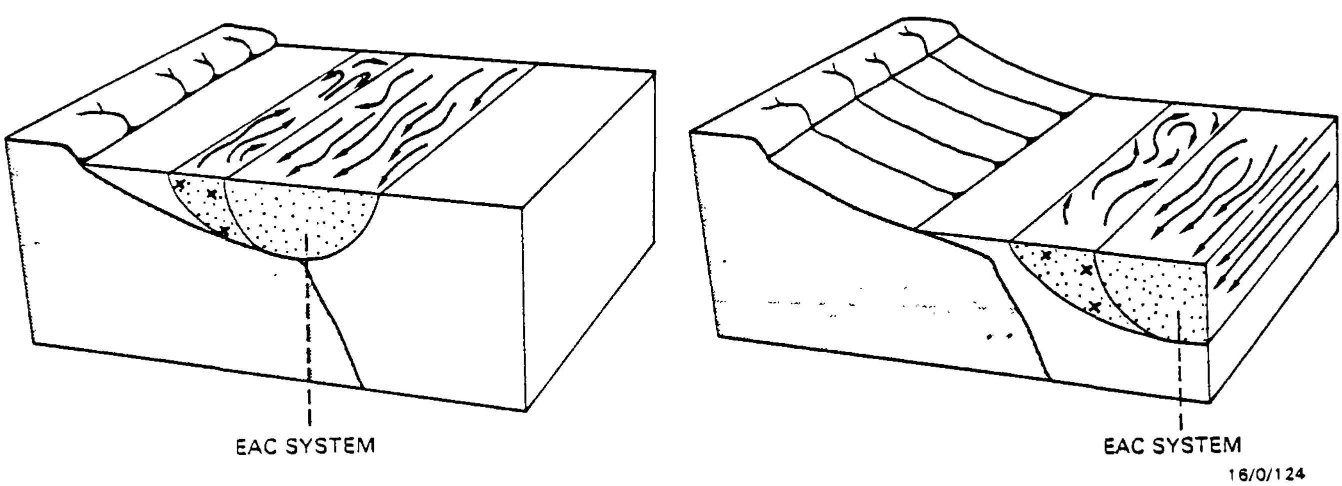

FIGURE 15
Influence of sea-level change on the southward-flowing East Australian Current (EAC) system. Upper diagram; high sea-level stand—maximum interaction with shelf. Lower diagram; low sea-level stand—minimum interaction with shelf. Both diagrams are viewed from the south looking north.

between these phosphorites and upwelling (or high organic productivity). However, the area is one where upwelling does indeed occur whether from oceanic gyrals related to the East Australia Current, or as a consequence of easterly-directed winds and the related coastal entrainment. There are similarities between the eastern Australian occurrences and those off the eastern United States (Riggs, 1984). Using the Riggs model, the Australian occurrences may also be related to the interaction between a major ocean current system and the continental shelf (Fig. 15). As sea-level changes, so the degree of interaction between the shelf and the current varies. It is suggested (Fig. 15) that this interaction is least at times of low sea-level. At times of intermediate to high sea-level, there was maximum interaction of the shelf and the ocean current and hence maximum upwelling and greatest organic productivity. However, our knowledge of the phosphorites of the WESTPAC area including the East Australian phosphorites is still far from complete and there is a need for much more information particularly on their stratigraphic setting, and the extent to which they persist below the sea floor.

Conclusions

1. Marine non-living resources are of great importance at the present time and this importance will increase in the years ahead.

2. For this reason, the exploration industry, national governments and international bodies such as IOC must give increasing consideration to these resources.

3. There is little immediate prospect of deep ocean non-living resources being economically exploited and for the foreseeable future attention will continue to be focussed on the coastal to upper slope zone and on some of the marginal plateaux.

4. Oil and gas will of course continue to dominate the offshore exploration scene. However, surficial resources and in particular the coastal zone, as a resource in its own right, will become an increasingly important resource. Other surficial resources such as (in decreasing order of importance) construction materials (sand, gravel, lime), placers, phosphorites and metalliferous crusts will also command greater attention in the future.

5. These non-living resources form in response to a number of physical, chemical and biochemical processes acting over a range of spatial and temporal scales. The delineation and understanding of these various processes is important if we are to attempt to determine patters of genesis and occurrence for marine non-living resources.

6. The geological processes of eustatic sea-level change, environmental change and tectonism are seen as the three primary "driving mechanisms" in the formation of marine non-living resources. These processes (referred to as the "SETR mechanism") whether acting separately or together, exert a profound influence on when and where these resources are formed.

7. Using as an example marine phosphate deposits - phosphorites - there is seen to be a complex interaction of the three major processes in the "SETR mechanism". This interaction is essential if major phosphorite deposits are to be formed. The scale at which these processes operate ranges temporally from a few thousand years to tens of millions of years and spatially from perhaps hundreds of square kilometres to global. Therefore it is necessary to use a wide range of skills and various lines of evidence to fully understand the genesis of phosphorites, and by implication all other marine non-living resources.

8. Good science, pursued on a range of scales, from the local to the global is an essential ingredient for any broad scale exploration of marine non-living resources and the way in which the resources formed. It is also essential if we are to fully understand the physical environment, in which much of the world's population lives - the coastal zone.

Acknowledgement

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Discussion[1]

A. R. Bayoumi

Should we use economic considerations when planning a programme of ocean science in relation to non-living resources?

P. J. Cook

That is not an easy question to answer. A limited number of programmes aimed at assessing marine non-living resources have been undertaken. For example, considerable effort has been expended in assessing the offshore phosphate resources of the southeastern United States. The United Nations has recently undertaken an assessment exercise on the nearshore non-living resources of part of West Africa. One of the major difficulties with giving too much prominence to economic considerations when planning research programmes is that the commodity market is highly volatile, and prices of minerals can change drastically during the life of a resource-related programme. The important thing is to establish the extent of the resource in the first place and to understand how the resource was formed.

But having pointed out the dangers of basing ocean science solely on economic considerations, OSNLR must obviously take it into consideration in establishing priorities and it is for this reason that shallow marine and coastal studies are being stressed, in contrast to say studies of manganese nodules, which are generally considered to be unlikely to be exploited commercially this century.

K. Vagn Hansen

Speaking as a biologist I was intrigued by your diagram on the effects of sea-level change on guano deposits. But doesn't this assume a constant bird population and constant productivity in the sea?

P. J. Cook

You are quite right to question the basic assumption of this model, however, I was taking, of necessity, a simplistic view. What I am saying is that if the biomass is constant, then times of high stands of sea-level (when there are smaller and fewer islands, due to marine inundation), will be periods when fewer, but larger insular avian guano deposits will be formed. If this is correct, then it obviously has implications to exploration programmes for insular phosphate deposits. Of course, if the productivity and the biomass changes through time then the model for the formation of such deposits becomes much more complex.

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