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To cite this version:

J. Haapkylä, F. Ramade, B. Salvat. Oil pollution on coral reefs: A review of the state of knowledge and management needs. Vie et Milieu / Life & Environment, 2007, pp.91-107. hal-03234945

HAL Id: hal-03234945
https://hal.sorbonne-universite.fr/hal-03234945

Submitted on 25 May 2021

VIE ET MILIEU - LIFE AND ENVIRONMENT, 2007, 57 (1/2) : 91-107

OIL POLLUTION ON CORAL REEFS: A REVIEW OF THE STATE OF KNOWLEDGE AND MANAGEMENT NEEDS

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OIL
CORAL REEFS
POLLUTION
HYDROCARBONS
DISPERSANTS
CLEAN-UP METHODS FOR OIL

ABSTRACT. – This paper reviews the current state of knowledge of the effects that oil pollution has on scleractinian corals. A review of results obtained in laboratory as well as in field conditions are given and suitable management tools are discussed. Studies made in the 1970s and 1980s presented conflicting results regarding the impacts of oil on coral physiology, but later results confirmed the detrimental effect of oil on corals. The world's coral reefs are severely threatened by an array of factors, one of which is oil pollution. More laboratory and field work with current oils and dispersants is urgently needed in order to update our knowledge in this field and reduce impacts in case of a major oil spill on coral reefs.

Introduction

Coral reefs are the most diverse and complex communities in the marine environment. Hermatypic corals play a key role in forming the structure of coral reefs and providing substrate and shelter for a wide variety of organisms. Acute damage to corals may result in a collapse of this complex community.

Coral reefs are seriously threatened by human activities in most parts of the world. Globally, 20% of the world's coral reefs have been effectively destroyed and show no immediate prospects of recovery, approximately 40% of the 16% that were seriously damaged in the 1998 bleaching event are either recovering well or have recovered. It is predicted that 24% of the world's reefs are under imminent risk of collapse through human pressures and a further 26% are under a long-term threat of collapse (Wilkinson 2004). This decline is due to increasing human pressures; poor land management releasing more sediment, nutrients and other pollutants that stress the reefs; over-fishing with destructive fishing methods; coral diseases and coral predators such as the crown-of-thorns starfish and the predicted increases in ocean temperatures as a result of global climate change. Reef health varies between oceans and is the most critical in South-East Asia (Salvat 2005).

Sources of oil pollution in the oceans

The principal causes of oil pollution in the oceans are a) extraction of oil, b) transportation with ballast water release and tanker accidents and c) war-related incidents (Ramade 2000). At a global scale, it has been estimated that an important fraction of the 6 millions of tonnes of oil per year spilled into the world's oceans (Capone & Bauer 1992) is released into reef ecosystems (Ramade & Roche 2006). The distribution of oil pollution in the world's oceans is shown in Fig. 1. The polycyclic aromatic hydrocarbons, which are permanent components of crude oil and are also generated in incomplete combustions, rank among the most dangerous contaminants due to their acute and long-term toxicity (Ramade & Roche 2006).

Oil extraction has caused incidences of severe pollution. In 1966, 40 000 t of oil leaked out of a broken pipeline off California. The worst pipeline accident happened in 1979 at the Ixtoc I pipeline offshore the Mexican coast and over 500 000 t of oil was spilled (Ramade 2000). Five out of six of the world's worst pipeline disasters have occurred in the Caribbean region (OSIR 1999).

Transportation with ballast water release and tanker accidents are the second category of oil pollution. Over one billion tonnes of oil is transported annually in the world's oceans. It is estimated that 0.1-0.3% (about 1-3 million t) of this oil is released into the oceans in ballast water (Ramade 2000).

The majority of big spills (> 700 tonnes) between 1974-2005 were caused by tanker groundings (34.4%) and collisions (28.3%) (ITOPF 2006). The average quantity of oil spilled into the oceans during the 1990s was less than a third (1 140 000 t) of that witnessed during the 1970s (3 142 000 t) (ITOPF 2006). Between 1999 and 2004 there has been less than 50 000 t of oil spilt per year. It is notable, however, that a few very large spills are responsible for a high percentage of the oil spilt (ITOPF 2006).

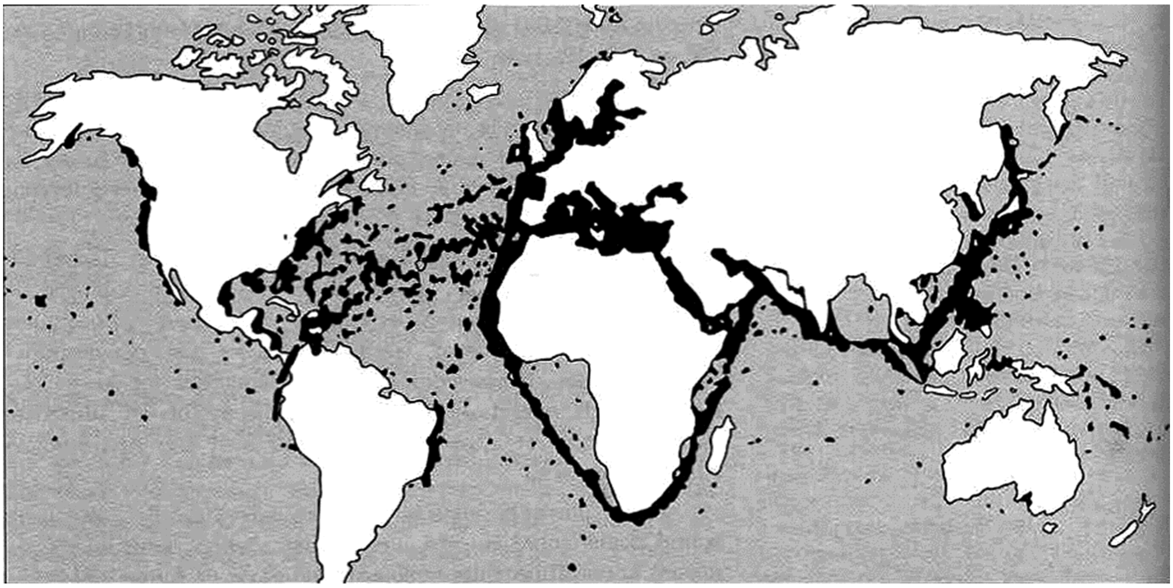

Fig. 1. – Distribution of oil pollution in the oceans (Ramade 1995, p. 286 after BP, op. cit.).

Fig. 2. – Major routes of oil transportation (Ramade 1995, p. 246 in OCDE, op. cit. p. 84).

No major oil pollution accidents on coral reefs have taken place recently, but the location of coral reefs in near-shore waters means that there is a potential danger to corals from tanker accidents, refinery operations, oil exploration and production (IPIECA 1992). The biggest accidental spills in tropical seas (offshore) occurred in 1972 in the Gulf of Oman (115 000 t), in 1979 off Tobago (287 000 t), and in 1992 off Mozambique (72 000 t). Smaller incidents have been recorded in 1968 from Panama (2 856 t of Marine Diesel and Bunker-C), in 1970 from the Seychelles (20 000 t of fuel), in 1970 from Saudi Arabia (14 280 t of Arabian Light Crude Oil) (Loya & Rinkevich 1980) and about 7 784 t of medium-weight crude oil (70% Venezuelan crude and 30% Mexican Isthmus crude) off Panama in 1986 (Jackson *et al.* 1989). This was the largest recorded spill into a sheltered coastal habitat in the tropical Americas.

The Straits of Malacca and the South China Sea are nowadays considered as the area with the highest risk of tanker accidents (ITOPF 2006 pers comm). There is also a high risk for oil spillage in the Arabian Gulf which constitutes the busiest oil transport route in the world, through which more than half of the world's oil passes (Fucik *et al.* 1981)(Fig. 2). South and Central America and the Caribbean stand as the second largest potential producers of oil in the world after Saudi Arabia (OSIR 1999). In the Red Sea, poor environmental standards in the Egyptian oil fields of the Gulf of Suez, and deballast-

Table I. – Concentration of some PAH in the sediments from the Australian Great Barrier Reef (in $mg.kg^{-1}$ d.w.) (after Haynes & Johnson 2000).

Locality	fluorene	pyrene	benzo(a) anthracene	chrysene	benzo(e) pyrene	benzo(k) fluoranthene	benzo(a) pyrene	benzo(ghi) perylene
Green island	<0.1-7.2	<0.1-15	<0.01-6	0.04-0.08	<0.1-6	<0.001-2.5	<0.004-4.3	<0.001-2.5
Port of Townsville	6.5 - 14000	10-4500	4.4-1700	7.5-1500		1-200	10-2600	3-1500
Heron island		<0.6-1.3	<0.1-8	<0.3-2		<0.001-0.5	<0.1-2.6	<0.3-6.7
National Park of D'Inchinbrook Island	7.3-15	7-15	<0.4-2.2	<2.2	0.3- 0.7		2.9-4.4	0.5-2.6
Port of Gladstone	<0.05	<0.1	<0.04	<0.2		16	820	200
John Brewer reef	<0.05	<0.1	<0.04	<0.2		<0.01	<0.01	<0.02

ing by ships in the southern Red Sea and Gulf of Aden (Gupta & Kureishy 1981) are major factors contributing to oil pollution.

Acts of war are responsible for the worst oil spills in the world. In 1983, Iraqian airforces destroyed the Nowruz oil well platforms in the war between Iran and Iraq, and a total of 1 million t of hydrocarbons were released into the ocean (Ramade 2000). During the Gulf War (1991) the largest oil spill ever recorded (about 856 800-1 142 400 t) was released into the marine environment of the northern Gulf (e.g. Price 1998). The total leakage of oil into the marine environment was estimated to be about 159 936 000 t (Sadiq & McCain 1993), which was 42 times as extensive as the Exxon Valdez spill in Alaska in 1989 (Saenger 1994).

Ways of oil contamination in coral reef habitats

After an oil spill, oil components dispersed in the water column can contaminate a reef in three different ways. Firstly, the surface oil at the air-water interface floats over the reefs and subsequently contaminates the intertidal scleractinian corals as they become exposed to air at low tide. Secondly, wave action can disperse oil as droplets within the water column. These droplets will sooner or later come into contact with corals. In some cases, these droplets can sink into deeper waters as they become combined with particles. Weathered oil can also sink in this way and come into contact with corals at greater depths (NOAA 2003). When dispersants are used, they may have a detrimental effect on corals as they strongly increase the incorporation of oil into the water column and subsequently the potential of contact with corals. Thirdly, and far worse, is the long-term contamination due to oil incorporated into bottom sediments. This has a heavy impact on benthic biota with the cyclic release of toxic components of the oil from the sediment, and later through sedimentation of the un-degraded components from this oil that has been incorporated into faeces and dead organisms (Farrington 1989).

Impacts of oil pollution on corals

The impact of oil on coral ecosystems depends on many varying physical, chemical and biological factors that influence spilled oil and tend to make each incident a unique ecological problem.

Oil is a complex mixture of several thousand different molecular compounds, some of them can cause acute and/or long-term toxicity. A number of toxic molecules occur in the volatile fraction of oil, hence ecological damage can be lower when a spill takes place far off-shore, since the oil has time to loose a significant part of its toxic components before it reaches coastal waters. However, the most hazardous oil components are included in the heavy fractions, namely the Polycyclic Aromatic Hydrocarbons (PAH) as well as various sulphur and nitrogen organic derivatives of high molecular weight.

PAHs can occur chronically in coral reef systems (Haynes & Johnson 2000), due to tanker wreckage, deballasting, and the deposition of atmospheric pollutants in rainwater. Investigations have shown evidence of significant PAH contamination in the sediments of the Australian Great Barrier Reef (Table I).

Interacting factors which determine the nature and extent of the biological consequences of each spillage include: the type of oil, dosage, physical environmental factors, prevailing weather conditions, nature of the biota, seasonal factors, prior exposure of the area to oil, presence of other pollutants and type of remedial action (Straughan 1972). The recognition of a large range of stress responses shown by corals is complicated by the wide range of oils, oil fractions, and bioassay methodologies used in laboratory studies to date. Consequently,

Table II. – Range of property values for the lightest fraction of oils, light crude oils, medium oils with high and low pour points, and heavy oils. Examples for each group are given in parenthesis (Cormack 1999, reproduced by ITOPF and ETC Spills Technology Databases).

Type of oil	Specific gravity	Pour point	Viscosity cSt @ 15°C	% Boiling below 200°C	% Boiling above 370°C
Lightest oils (e.g. gasoline, naphtha, kerosene)	<0.8 (°API>45)	too low to need quoting	0.5-2.0	50-100	0
Light Crude Oils (e.g. diesel, No. 2 fuel oil, Argyll, Beatrice, Nigerian Light)	0.8-0.85 (°API35-45)	>5 or <5 (are treated like heavy oils)	4-solid; average 8	10-48; average 35	0-40; average30
Medium oils with high pour point (e.g.: Suez Mix, Trinidad, Zaire, Mexican Isthmus) Medium oils with low pour point (e.g.: Arabian Light, Santa Maria, Forcados)	0.85-0.95 (°API 17.5-35)	>5 or <5 (are treated like heavy oils)	8-solid; average 275	14-34; average 25	28-60; average 45
Heavy oils (e.g. Bahia, Tia Juana Pesado, Wafra Eocene, Prudhoe Bay, Iranian crude, Venezuelan, Bunker-C)	0.95 (°API <17.5)	variable	1500-Solid	3-24; average 10	33-92; average 65

identification of trends or patterns of acute and sublethal responses of corals exposed to oil is difficult (Fucik *et al.* 1981). A summary of different types of oils is given in Table II.

Although oil pollution in the marine environment has been regarded as a major environmental hazard for several decades, little is known about the mechanisms in which crude oil affects natural marine populations and communities (Kushmaro *et al.* 1997). Most of the published scientific papers date from the 1970s and 1980s. A review article on the effects of oil pollution on corals was made in 1984 by Loya & Rinkevich.

These earlier papers have presented contradictory results. Johannes *et al.* (1972) concluded that some reef building corals may be seriously damaged if coated with oil when exposed to air at low tide, whereas Shinn (1972), stated that 'it would seem safe to conclude that crude oil spills do not pose a significant threat to Atlantic reef corals'. However, Shinn's (1972) conclusions were based on a qualitative study, without really measuring the rate of re-colonization and without having any data on the coral community structure prior to the study. Spooner (1970) reported no damaging effects to corals in a site chronically polluted by oil. It seems, however, that short-term, incidental or scattered observations may result in misleading conclusions and Stirling (1977) argued that ecological phenomena, such as those caused by oil spills in tropical seas, can be interpreted only when the physiological ecology and population dynamics of the fauna in relation to stability, recruitment and mortality are adequately understood.

Papers describing chronic pollution in the field (e.g. Rinkevich & Loya 1977), as well as short-term laboratory-based investigations (e.g. Harrison *et al.* 1990, Mercurio *et al.* 2004, Negri & Heyward 2000) have established that oil pollution may cause significant damage to reef corals.

The aim of this review article is to summarize scientific findings of the impacts of oil on corals both in the field and in the laboratory, and to suggest suitable management tools for oil spills on coral reefs.

1. Field observations of oil impacts

Field observations offer the best opportunity to understand the effects of oil spills, but they have been uncommon in coral reef habitats. Here we give an overview of the most important field studies. Table III summarizes these studies.

***In situ* experiment at Enewetak Atoll, Marshall Islands**

Johannes *et al.* (1972) used Santa Maria crude oil in an *in situ* experiment at Enewetak Atoll, Marshall Islands. Twenty-two species of corals were transplanted and placed on two floating frames where a proportion of the corals was exposed to air. Oil was poured into the water around but not over the corals on one frame, producing an oil layer averaging 0.6 mm thickness. Oil adhered with greatest affinity to branching corals of the genera

Table III. – Summary of principal studies made on the effects of oil on corals in a natural environment.

Place and year	Type of oil	Effect on corals	Reference
Enewetak Atoll, Marshall Islands, 1971	Santa Maria crude oil. Oil was poured on corals exposed to air to form a 0.6 mm thick layer	Oil adhered with greatest affinity to branching *Acropora* and *Pocillopora* and some was still visible after 4 weeks. Corals showing no affinity for oil included *Fungia* and *Symphyllia*, both with large polyps and abundant mucus.	Johannes *et al.* 1972
Arabian Gulf field experiment, 1989	Arabian light crude oil for 24-120 hrs	No visible effects on corals.	LeGore *et al.* 1989
Panama, 1986	Medium-weight crude oil (70% Venezuelan, 30% Mexican Isthmus)	Total coral cover, species diversity and growth decreased, only *Zoanthus* sp. Has returned to normal after 18 months. *Acropora palmate* and *Siderastrea siderea* decreased the most. No recruitment of most formerly dominant species. Gonad size larger at un-oiled reefs.	Jackson *et al.* 1989 Guzmán *et al.* 1991 Guzmán *et al.* 1993 Guzmán and Holst 1993
The Gulf War, Arabian Gulf, 1991	Different types of oils	War-related events had only minor influence on changes observed on coral reefs.	Downing and Roberts 1993 Vogt 1995 Price 1998
Oil refinery in Aruba, chronic effects (1923-1985)	Heavy crude oil (Lake Maracaibo, Venezuela), refinery waste water, discharge clean-up with the dispersant Corexit since 1975	Spatial structure of the reef deteriorated, living coral cover low, less juveniles present. *Acropora palmata* most affected. *D. strigosa* quite tolerant to oil pollution.	Bak 1987 Eakin *et al.* 1993
Eilat, Red Sea, chronic oil pollution	Different types of oils	In the polluted area, only 44.6% of colonies contained gonads compared to 75.5% in the clean area.	Rinkevich and Loya 1977
Vessel grounding at Rose Atoll, American Samoa, 1993	Diesel fuel and lubricating oil	A massive die-off of coralline algae and invertebrates, blue-green algal blooms and a shift in algal communities.	Maragos 1994 Green *et al.* 1997
TROPICS Experiment, Panama (1984-1994)	Prudhoe Bay crude oil	A decrease in coral cover was observed after 20 months. After 10 years, neither coral cover or coral growth showed impacts of oil. Effects more serious to mangroves.	Ballou *et al.* 1987 Guzmán *et al.* 1991 Dodge *et al.* 1995 NOAA 2001 Ward *et al.* 2003

Acropora and *Pocillopora* and was visible on the corals after four weeks of observation. However, most of the oil disappeared within 1 day after colony submersion in clean water in corals with large and fleshy polyps and abundant mucus, such as *Fungia* and *Symphyllia*. A complete breakdown of soft tissue was seen on areas where oil adhered to the coral. It was concluded that floating oil may kill coral tissue if it adheres to corals when they are exposed to air.

Field experiment in the Arabian Gulf

LeGore *et al.* (1989) tested responses of corals to dispersed oil under realistic spill conditions on Jurayd Island, off the coast of Saudi Arabia. The design included exposure to Arabian Light crude oil with and without dispersants over periods of 24 h and 120 h. Study plots were established over existing coral reefs that were comprised mostly of *Acropora* spp. (more than 95%), with scattered colonies of *Platygyra* spp., *Goniopora* spp., and *Porites* spp. The plots measured 2 m by 2 m, located over approximately 1-m depth at low tide, and anchored in place.

The intention of this treatment was to simulate conditions of a typical Arabian Gulf oil spill and not to overwhelm the corals with “extraordinary and catastrophic stresses.” As such, oil was added to test plots to produce a slick of 0.25 mm in thickness, in the 24-h oil-only treatment, and 0.10 mm thick in the 120 h-experiment. Water concentrations of hydrocarbons were measured by infrared methods, and no water column elevations were detected in the oil-only plots. The oil-only plots were visually inspected at the end of the 24-h and 120-h exposures, and they appeared normal. These areas were monitored for one year, and no extraordinary changes occurred relative to the un-oiled plots (seasonal changes in degree of bleaching, however, were noted across all monitored plots). While dispersed oil appeared to delay the recovery from seasonal bleaching, this was not observed in the oil-only plots. Growth rates, expressed as skeletal extension along branch axes, showed no correlation to treatment in the 24-h exposure. There was some indication that growth rates were depressed with 120-h exposure, but LeGore *et al.* (1989) cautioned that these were not definitive. In summary, after one year of monitoring, the corals showed no visible effects after exposure to surface oil for 24 hours and for 120 hours. The authors concluded that healthy reef corals can tolerate brief (1 to 5-day) exposures to floating oil with no observable effect. They did note the potential for seasonal susceptibility to exposure in this region in the wintertime when low water temperatures stress corals.

Oil spill in Panama

Jackson *et al.* (1989) observed extensive mortality of subtidal reef corals and infauna of seagrass beds after an oil spill off the Panamanian coast in 1986. This spill consisted of about 7 784 t of medium-weight crude oil (70% Venezuelan, 30% Mexican Isthmus crude oil). Damage caused by the accident was most extensive at the seaward border of the reef, where the oil accumulated at low tide. Most of the scleractinian corals still alive in depths less than 3 m showed signs of recent stress. These signs included bleaching or swelling of tissues, conspicuous production of mucus, recently dead areas devoid of coral tissue, and globules of oil. The most common sessile animals before the spill were zoanthids (*Zoanthus sociatus* and *Palythoa* spp.), hydrocorals (*Millepora* spp.), and scleractinian corals (*Porites* spp.). At the seaward border of the reef flat, populations of all these animals were severely reduced, and only *Zoanthus sociatus* had returned to typical abundance after 18 months. Total coral cover decreased by 76% at depths between 0.5-3 m and by 56% between depths of 3-6 m on the heavily oiled reef 3 months after the accident. Average size of coral colonies (all species) and species diversity also decreased significantly in relation to oiling (Guzmán *et al.* 1991). Cover of the large branching coral *Acropora palmata* decreased the most after the accident. This result lends further support to the claim that branching corals are most sensitive to human disturbance (Brown & Howard,1985). Frequency and size of recent injuries on massive corals increased with level of oiling, particularly for *Siderastrea siderea* (Guzmán *et al.* 1991).

Guzmán & Holst (1993) studied the effects of chronic oil-sediment pollution (type of oil not indicated, but expected to be the same as in the oil spill in 1986, i.e. 70% Venezuelan crude and 30% Mexican Isthmus crude) on the reproduction on *Siderastrea siderea* 5 years after the Panamanian oil spill in 1986. Coral fecundity (number of gonads/polyp and gonad size) was measured from ‘healthy-looking’ coral colonies, and coral colonies showing recent injuries or partial mortality (bleached areas), during the peak of reproductive activity at heavily oiled and un-oiled reefs over a period of 15 months. Gonad size (area) was larger at un-oiled reefs for most of the sampling period. According to Guzmán & Holst (1993), the size of gonads is a more sensitive measure of long-term (more than 3 yrs in this study) sub-lethal effects of oil on reproduction, than is the number of gonads or proportion of fertile colonies. Guzmán *et al.* (1993) found that there had been virtually no recruitment of most formerly dominant coral species, and that sub-lethal effects on vital processes (regeneration, growth, reproduction, and recruitment) are likely to persist for decades. This has been reported before from other areas by other authors (Loya & Rinkevich 1980, Bak 1987, Eakin *et al.* 1993). The causes of these effects are complex, but the 2 most important factors are re-oiling and sedimentation from adjacent mangroves. Estimated minimum times for recovery of the reef after the Panamanian oil spill in 1986 were 10-20 years on the assumption that no other events would further depress coral populations (Brown 1997).

The Gulf War, Arabian Gulf

The Gulf War in 1991 resulted in the largest oil spill ever recorded in history (about 856 800-1 142 400 t) (e.g. Price 1998). The type of oil spilled in the incident has not been indicated.

Given the quantity of spilled oil, the recorded impacts to the environment were surprisingly low. Downing and Roberts (1993) observed some coral mortalities of a few species (*Acropora* spp., *Porites* spp. and *Platygyra* spp.) in Kuwait affecting different reefs in different ways, but thought it was unlikely that oil released during the war was the only cause of the decline. On the basis of video recordings made along transects between 1992 and 1994, Vogt (1995) concluded that live coral cover had significantly increased and that corals offshore from Saudi Arabia had survived the largest spill on record “remarkably unscathed.” These findings were in accordance with other results (e.g. Price 1998). It must be notified that other environmental impacts from the war, such as reduced water temperature and lowered ambient light from oil fire smoke, may have obscured the actual effects of oil on coral (Vogt 1995).

Providing a single index as a “snapshot” of the health of an environmental system, which also captures the dynamics of the different ecosystems impacted, remains elusive, like in the Gulf War case. Additional difficulties include incomplete time-series, the possibility of misjudgments about species abundance and mortality from incomplete sampling, and the likelihood of synergism and antagonism between war-related effects, background impacts, and natural stresses (Price 1998).

The Gulf environment has many peculiarities which could have affected the fate of the oil. Being a semi-closed waterway linked to the Indian Ocean by the narrow Strait of Hormuz, the turnover time for waters of the Arabian Gulf has been estimated to 3.5 years. As a consequence of this slow turnover time and its dimensions, extremely adverse and long-lasting effects were expected from this spill, raising considerable international concern. Oil pollution self-purification processes are considerably enhanced in the Arabian Gulf compared elsewhere. The Gulf environment has been subjected to hydrocarbon pollution for thousands of years through natural oil seeps originating in the seabed. Therefore, there is an assemblage of micro-organisms, that are adapted and acclimatised to oil pollution. The exceptionally high ambient temperature (reaching up to 35˚C during summer) accelerates the evaporation of light toxic fractions and some intermediate products of biodegradation and photo-oxidation (light-induced breakdown). The rate of photo-oxidation in the Gulf is extremely high compared to data reported from other parts of the world (Saenger 1994).

Chronic oil pollution in Aruba, Caribbean Sea

Bak (1987) & Eakin *et al.* (1993) showed clear evidence of chronic oil pollution (between 1923 and 1985) near a refinery in Aruba. Most of the oil processed was heavy crude from Lake Maracaibo, Venezuela. However, the dispersant Corexit had been used in clean up activities since 1975 (Bak 1987). The spatial structure of the reef had deteriorated, living coral cover was low and there were less juveniles in front and up to at least 9 km downcurrent of the refinery (Bak 1987). According to Eakin *et al.* (1993), *Montastrea annularis* had slowed growth rates in areas most affected by the refinery. *Acropora palmata* was the most affected species (Bak 1987), *M. annularis* and *Agaricia agaricites* were absent directly downcurrent of the refinery. It appeared that the gap in the distribution of *A. agaricites* was more extensive than that of *M. annularis*. *Diploria strigosa* was exceedingly dominant in the gap created by the absence of *M. annularis* and *A. agaricites* (Bak 1987). It was also suggested by laboratory experiments (Dodge *et al.* 1985) that *Diploria* spp. is possibly a hardier species with respect to oil pollution. According to Eakin *et al.* (1993), coral recruitment at the highly impacted sites showed hope for recovery if these environments are protected from renewed perturbation.

Chronic oil pollution in Eilat, Red Sea

Rinkevich & Loya (1977) studied the reproduction of *Stylophora pistillata* in a chronically oil-polluted area and a pollution free area in the northern Gulf of Eilat. In the clean area, 75.5% of 98 colonies studied contained gonads in their polyps, while in the polluted area, only 44.6% of 103 colonies contained gonads.

Vessel grounding at Rose Atoll, American Samoa

In October 1993, a Taiwanese fishing vessel ran aground on the remote Rose Atoll in American Samoa. The grounding resulted in the spillage of 379 tonnes of diesel fuel, 1 895 litres of lubricating oil, and 1 125 kg of ammonia onto the reef. The vessel eventually broke up before a salvage operation could take place and in six weeks, all the content of the ship was released onto the surrounding coral reefs. Substantial injuries from the physical impact of the vessel and the contaminant releases were detected (Maragos 1994). The most widespread and severe injuries to the atoll were from the release of diesel fuel. A massive die-off of coralline algae and many reef-dwelling invertebrates was observed after the release, blue-green algae blooms were recorded where they are typically not found, and the structure of algal communities had shifted substantially. Green *et al.* (1997) stated that four years after the grounding, the affected areas remained visibly impacted – particularly with respect to cover of coralline algae. Natural re-colonization of the affected areas by native biota has been deemed by the preferred restoration alternative. It has been estimated that the impacted area of Rose Atoll reef will take several more years or perhaps decades to recover (Green *et al.* 1997).

TROPICS Experiment, Panama

The 1984-1994 Tropical Oil Pollution Investigation in Coastal Systems (TROPICS) effort, sponsored by the American Petroleum Institute, exposed a whole ecosystem (comprised of mangrove, seagrasses, and coral) to oil and chemically dispersed oil, in two separate boom-enclosed areas (NOAA 2001).

The oiled site was treated with 953 litres of Prudhoe Bay crude oil released onto a boomed area of the water surface and allowed to remain for about two days. Tides and winds distributed the oil over the study area. After the exposure period free-floating oil was removed with sorbents. Chemical and biological monitoring continued for two years. Chemical monitoring, conducted hourly for the first 24 hours, confirmed that sediments and biota were exposed to rising and then rapidly declining dispersed and undispersed oil. For coral reefs, detailed transects were conducted to measure abundance of epibiota living on the reef surface. Four measurements were taken: total organisms, total animals, corals, and total plants. Growth rates of four coral species (*Porites porites, Agaricia tenuifolia, Montastrea annularis,* and *Acropora cervicornis*) were also measured. The only statistically significant effect documented over the first 20 months at the oiled site was a decrease in coral cover. No significant changes in growth rates of the four targeted corals were noted (Ballou *et al.* 1987). Ten years later, neither coral cover nor coral growth showed oil impacts (Dodge *et al.* 1995). The authors contrasted the finding of no impact from oiling alone to that described by Guzmán *et al.* (1991) at Bahía Las Minas, where significant effects of oil alone were found in several of the same species studied at TROPICS. Dodge *et al.* (1995) implied that these differences may have been due to the size of the spill at Bahía Las Minas and continued chronic exposure from oil trapped in the sediments.

Ward *et al.* (2003) returned to the site in 2001 and 2002 and found that there were still visible traces of the oil added in 1994 in the non-dispersed site sediments. The authors confirmed that the effects were more serious to the mangroves than to seagrass areas and corals: mangrove trees showed morphological prop-root deformations. The coral cover had increased from a pre-treatment value of 33.5% to 67.5% in 2001.

2. Laboratory studies on oil impacts

Many laboratory studies exist on the impacts of oil on corals. Extrapolating these results to real-life oil spill scenarios is complicated by the various exposures to different types of oil. Because only a fraction of the oil mixes directly into the water, actual toxicity levels can be assumed to be much lower than reported in many studies. During actual oil spills, oil is most concentrated at the very beginning of a spill and concentrations rapidly decline. When trying to estimate real-life exposures, it is important to carefully evaluate the methods used when extrapolating results from laboratory studies (NOAA 2001). Table IV summarizes the effects of oil on corals in laboratory studies and the associated references.

Growth

Several studies suggest that exposure to hydrocarbons affects coral growth especially by decreasing calcium deposition into the polyp's exoskeleton (Dodge *et al.* 1984). Guzmán *et al.* (1994) found an overall slow-down of coral growth after the Bahia Las Minas oil spill in Panama.

Histopathological effects

Peters *et al.* (1981) exposed the Caribbean coral *Manicina areolata* to No. 2 fuel oil (Chevron/Pascagoula, gravity, °API = 33-39) for three months (dosage 10 ml min^{-1}). The expected concentrations were 0.1 ppm and 0.5 ppm. Although corals remained alive, evidence of pathological responses were found which included impaired development of reproductive tissues, degeneration and loss of symbiotic zooxanthellae, and atrophy of mucous secretory cells and muscle bundles. Corals examined after two, four and six weeks after the start of the experiment showed an extensive increase in mucous secretory cell activity. This was indicated by a proliferation of mucous secretory cells as well as an increase in size of these cells in the epidermis and mesenteries. Many cells had increased to such an extent that their cell walls were broken and huge vacuoles were formed. Many mucous secretory cells were also noted in the tips of the mesenterial filaments, where they are not usually present. Zooxanthellae were not only lost from the gastrodermis, but also from the mesenteries.

Harrison *et al.* (1990) observed a dramatic decrease in zooxanthellae concentrations and a thinning of the tissue of *Acropora formosa* branches after 24 h of exposure to water accommodated fractions (WAF) of marine fuel oil. The response of the coral was similar in both 5 and 10 ppm treatments.

Reimer (1975) observed tissue rupture and flaking off of tissue especially at the edges of the *Pocillopora damicornis* colonies after 18, 55, 76 and 210 h exposure to Marine Diesel and Bunker-C oils. A massive extrusion of zooxanthellae was observed in *P. damicornis* when exposed to Marine Diesel. This led to bleaching, which occurred within 5-13 days of exposure to oil, and it affected mostly the lower side of the colonies. *Pocillopora damicornis* showed tissue death sooner than all other species investigated, it was affected more by longer expo-

Table IV. – Summary of the principal responses of corals to oil in laboratory.

Responses of corals to oil	Reference
Decreased growth rate	Dodge *et al.* 1984, Guzmán *et al.* 1994
Histopathological anomalies	Peters *et al.* 1981, Harrison *et al.* 1990, Reimer 1975, Mercurio *et al.* 2004
Changes in chemoreception, feeding response and behaviour	Blumer *et al.* 1971, Cohen *et al.* 1977, Reimer 1975, Loya and Rinkevich 1979
Oil-sediment rejection	Bak and Elgershuizen 1976
Mucus expulsion and changes in mucus bacteria	Johannes *et al.* 1972, Ducklow and Mitchell 1979, Loya and Rinkevich 1980, Palmork and Solbakken 1980, 1981, Knap *et al.* 1982, Harrison *et al.* 1990, Mitchell and Chet 1975, Garrett and Ducklow 1975, Ducklow 1977, Ducklow and Mitchell 1979, Antonius 1981
Decreased reproduction	Rinkevich and Loya 1979, Peters *et al.* 1980
Impaired larval metamorphosis and recruitment	Chia 1973, Rinkevich and Loya 1977, Cohen *et al.* 1977, Rinkevich and Loya 1979, Harrison *et al.* 1984, Kushmaro *et al.* 1997, Negri and Heyward 2000
Bioaccumulation	Burns and Knap 1989, Readman *et al.* 1996

sures than by shorter ones and is more susceptible to tissue damage and bleaching by Marine Diesel than by Bunker-C.

Zooxanthellae expulsion was also observed in colonies of *Acropora formosa* exposed to hydrocarbon components originated from lubricating oils. A decrease of the maximum quantic photosynthetic efficiency (F_v/F_m) occurred at concentrations ranging from 150 $\mu g.l^{-1}$ and over (Mercurio *et al.* 2004).

Chemoreception, feeding response and behaviour

Crude-oil products may interfere with chemically mediated behaviors by blocking the taste receptors of marine organisms or by mimicking natural stimuli and thus eliciting false responses (Blumer *et al.* 1971).

Cohen *et al.* (1977) exposed the soft coral *Heteroxenia fuscescens* to different concentrations of Iranian crude oil in static bioassays (1-30 ml^{-1}). The initial effect of crude oil (even in the lowest concentration) was a reduction in pulsation rate to less than 50% of the rate in untreated colonies. At concentrations of 10 ml^{-1} and greater, pulsation stopped almost completely within 72 h. After 17 days of recovery, the pulsation rate of treated colonies was 20-30% lower and less regular than in control colonies. In large tanks (1500 l, 1-2 m deep) with a continuous flow of seawater (oil concentration of 10 ml-1), a similar reduction in pulsation rate was recorded.

Some scleractinian and zoantharian corals have been reported to respond to crude-oil pollution by mouth opening (Reimer 1975, Loya & Rinkevich 1979). Reimer (1975) described abnormal feeding reactions in four scleractinian corals (*Pocillopora damicornis, Pavona gigantea, Psammocora stellata* and *Porites furcata*) elicited by Marine Diesel and Bunker-C oils floating over the surface water covering the corals. *P. damicornis* was treated with 1 ml of Marine Diesel in a 250-ml finger bowl and was shown to exhibit exaggerated mouth opening which lasted up to 17 days. Control colonies kept their mouths closed throughout 20 d of observation. Mouth opening responses in *Pavona gigantea, Psammocora stellata* and *Porites* sp. were sustained for much longer periods than normal after exposure to Marine Diesel.

Oil-sediment rejection patterns in corals

The sediment rejection behaviour pattern of corals displays maximum and minimum rates dependent on the size and density of the oil-sediment particles. Viscosity of the oil determines the size of the oil-sediment particles (Bak & Elgershuizen 1976).

Different rejection patterns of sand-oil combinations by various coral species were tested by Bak & Elgershuizen (1976). The oil used in the experiment was a combination of Nigerian, Forcados and Tia Juana Pesado crude oils (see Table I for details), as well as Forcados long residue and Lagomar short residue. Small drops of these oils were introduced in the grastrovascular cavity of the corals. The viscosity of these oils increased in this sequence at the temperature of the experiments (26° to 28°C) (Bak & Elgershuizen 1976). No evidence of adsorption of oil to living coral tissue was found: if drops were introduced into the gastrovascular cavity they were invariably extruded through the stomodaeum. When oil drops arrived on the peristome they were removed by ciliary currents and by tentacular and polypal movements (Bak & Elgershuizen 1976).

The reaction of corals to sediment is intimately linked to the specific morphology of the coral colonies affected. Long, meandroid valleys are more advantageous than short, reticulate valleys. Calical morphology also affects the mobility of polyps. *Agaricia agaricites* is an example of a species depending on strong ciliary currents for sediment rejection. *Acropora palmata* and *Porites asteroides* are, without help of wave action or currents, unable to remove particles of any size (Bak & Elgershuizen 1976).

Mucus expulsion and coral reef food-web

Mucus secretion by reef corals as a protective mechanism in response to external perturbations is well known. Johannes *et al.* (1972) found that corals with large and fleshy polyps with abundant mucus cleaned themselves in 1 day after colony submersion in clean water. Harrison *et al.* (1990) observed massive amounts of mucus discharging from branches of *Acropora formosa* when exposed to 5 and 10 ppm of marine fuel oil.

Under normal conditions, mucus loss may be a major pathway of energy loss. Thus, 40% of the primary production of a species of *Acropora* is rapidly lost as mucus (Loya & Rinkevich 1980). In stressed corals this loss might constitute an enormous energy drain, which could lead to a deterioration in general coral health.

Knap *et al.* (1982) measured the uptake and the depuration of (9-14C) phenanthrene (Solbakken *et al.* 1979) in individual colonies of the brain coral *Diploria strigosa*. After 10 days, a 4000 times higher concentration of phenanthrene was found in the tissue than in the mucus. It was concluded that the uptake of (9-14C) phenanthrene by *D. strigosa* is similar to that of other invertebrates (Palmork & Solbakken 1980, 1981). The very low concentration of radioactivity in the mucus after 10 days may be due to a very high turnover rate of mucus by the coral or may be due to the chemical nature of the mucus (Ducklow & Mitchell 1979), and its inability to sorp petroleum hydrocarbons to any great extent. Knap *et al.* (1982) stated that the slow depuration rates exhibited by *Diploria strigosa* indicate that these organisms may prove to be useful bio-indicators of marine pollution incidents in coral reef areas.

Particulate mucus has been shown to be consumed by a large variety of coral-reef organisms (Johannes 1967, Knudsen 1967, Benson & Muscatine 1974, Richman *et al.* 1975, Lewis 1978). Although there is no conclusive evidence of possible transfer of oil derivatives through the reef food chain, which originates from coral mucus, this remains one possible route, as demonstrated in other organisms, such as clams (Stainken 1975). Another way is through direct feeding on coral tissue, which might contain accumulated hydrocarbons.

Effects of bacteria

The relationship between mucus production and bacterial growth was studied on colonies of *Platygyra* spp., which was exposed to crude oil (oil type not specified) (Mitchell & Chet 1975). It was concluded that crude oil alone fails to kill coral at concentrations of 100 ppm but the role of the bacteria which developed under such stress conditions was demonstrated. Three groups of microorganisms were suggested to be responsible for the observed coral death: predatory bacteria, *Desulfovibrio* and *Beggiatoa*.

A significant increase in mucus-bacteria populations and a significantly higher diversity of bacterial types in clean coral-mucus than in oil-exposed mucus were indicated by Ducklow (1977) and Ducklow & Mitchell (1979).

After the oil spill in Panama in 1986, bleached areas on corals were surrounded by a black halo characteristic of bacterial infection (Antonius 1981). Garrett & Ducklow (1975) suggested that naturally occurring diseases in corals, e.g. the black band disease (BBD), may result from stress conditions such as oil pollution. Recent evidence of the human impact on the occurrence of BBD has been suggested by Littler & Littler (1996) and Friaz-Lopez *et al.* (2002).

Reproduction

Rinkevich & Loya (1979) investigated the sub-lethal, detrimental effects of Iranian crude oil on *Stylophora pistillata* in a long-term laboratory experiment. The experiment consisted of four 1500-l capacity tanks with continuous flow of sea water; every week 2 of these tanks were polluted by Iranian crude oil (3ml^{-1} sea water) for 24 h. Large and mature colonies of *S. pistillata* were cut into halves, at the beginning of the reproductive period; one half was placed in a polluted tank, the other in a clean tank. After 2 months, a significant decrease in the number of female gonads per polyp was recorded in 75% of the polluted halves. This experiment showed that chronic oil pollution damages the reproductive system of scleractinian corals, a fact that had already been shown in the field by the same authors (Rinkevich & Loya 1977).

Harrison (1994) observed total sterilization of gametes of *Acropora tenuis* occurring at a concentration of 0.002 mgL^{-1} of heavy fuel oil.

Mercurio *et al.* (2004) stated that 150 mgL^{-1} of lubricating oil generated a 64% decrease in the fecundity of gametes of *Acropora microphtalma* in comparison to the control.

Larval metamorphosis and recruitment

Field documentation (Loya 1976) combined with laboratory experiments (Rinkevich & Loya 1979) recorded that chronic oil pollution inhibits successful settlement of coral planulae.

According to Rinkevich & Loya (1979), the shedding of larvae in *S. pistillata* is immediate in the presence of low concentrations of the water soluble fraction of Iranian crude oil, during day or night. Most larvae are prematurely released (planulae without complete mesenteries or with 2-4 pairs of complete mesenteries). The chances of survival of such planulae are very low, due to the high predation pressure existing in the reef from a wide variety of organisms. Chia (1973) demonstrated that species specificity, in terms of survival of the larvae in oil-polluted water, may be related to size; larger larvae are expected to survive longer because they are more robust. Larval extrusion due to sublethal concentrations of crude oil (10 ml l^{-1}) was also reported in the soft coral *Heteroxenia fuscescens* after 72 h of exposure (Cohen *et al.* 1977). Since planulae extrusion occurs during an oil spill, chances of survival and successful larval settlement are very low. Gametes of most spawning species tend to rise to the surface just after spawning (Harrison *et al.* 1984) where they are more likely to encounter oil, and their larvae spend one to several weeks in the plankton before attaining competence to settle (Fadlallah 1983, Jackson 1986). Brooding species release planulae throughout the year (Guzmán 1991). Serious impacts on coral recruitment would therefore follow in the case of a simultaneous spill and coral spawning.

Negri & Heyward (2000) reported the effects of the water accommodated fraction (WAF) of crude oil, (specific gravity of 0.93 (19.4 API), kinematic viscosity of 128 cSt at 23°C, pour point -39°C and flash point 87.0°C) and production formation water (PFW) on fertilization and larval metamorphosis of *Acropora millepora*. At 20% v/v, PFW fertilization was inhibited by 25%. This concentration was equivalent to 0.0721 mg l^{-1} of total hydrocarbons (THC). In contrast, larval metamorphosis was more sensitive to this effluent, with 98% metamorphosis inhibited at the same concentration. Crude oil WAF did not inhibit fertilization of gametes until dispersant was introduced. Crude oil inhibited metamorphosis at 0.0824 mg l^{-1} THC.

Kushmaro *et al.* (1997) used TPA (12-tetra-decanoyl-phorbol-13-acetate) to induce metamorphosis of planulae of the soft coral *Heteroxenia fuscescens*. In the absence of crude oil (obtained from Haifa refineries, Israel, density: 0.8497 g/ml), TPA induced metamorphosis in 97% of these planulae. Only 50% of the planulae grown in experimental vessels with crude oil at a concentration of 0.1 ppm covering the bottom and walls of the vessels underwent metamorphosis when triggered by TPA. Of those planulae exposed to 100 ppm of the pollutant only 3% metamorphosed after being induced by TPA. In addition, after metamorphosis there was an increase in the number of deformed primary polyps compared to the control. The deformed polyps were elongated and had short non pinnate tentacles. Planulae also settled less frequently on the oil-covered surfaces. Thus, on the reef, even in the presence of low concentrations of crude oil, a decrease in both viability and successful settlement of coral planulae might occur following an oil spill.

Bioaccumulation

According to Ramade & Roche (2006), the high lipid content of coral polyps increases their ability to retain hydrocarbons (and more broadly any lipophilic pollutants). Researchers have found that petroleum hydrocarbons are deposited into the calcareous exoskeleton of corals, which introduces the possibility of using coral skeletons as historical records of hydrocarbon contamination in an area. Field studies in Bahía Las Minas indicated that corals took up hydrocarbons from the water column, as opposed to sediments (Burns & Knap 1989). Readman *et al.* (1996) analysed sections of the massive coral *Porites lutea* from the Gulf coast of Kuwait and Saudi Arabia and found clear evidence of the Gulf War oil spill recorded in the skeletons of these corals.

3. Oil spill management techniques on coral reefs

Unless otherwise stated, the following chapter is based on the information found in the “Field guide for oil spill response in tropical waters” published by the International Maritime Organisation (IMO) (1997) and the “Oil spills in coral reefs: Planning and Response Considerations” published by National Oceanographic and Atmospheric Administration (NOAA) (2001).

Generalities

The goal of spill response in coral areas is the same as in any other habitat – to minimize damage caused by accidents and any associated spillage. Choosing response methods carefully, with an understanding of the sensitivities of the reef environment, will minimize any additional impacts incurred from the cleanup. Variables such as type and amount of oil spilled, geology of the shoreline, rate of water flow, weather, and availability of equipment for salvage will determine which options can be considered during a response. Problems that have to be solved are the possible remoteness of the site, lack of adequate equipment, the difficulty of navigation in shallow waters, and storage and disposal of collected oil.

Possible clean-up methods for coral reefs

Booms and skimmers

The first stage of an effective response is to deploy a boom to limit further spreading and concentrate the oil for recovery (ITOPF 2006). Booms and skimmers can be used in relatively calm waters near reefs or in lagoons, but certain types of booms need to be limited to deeper waters (greater than 3 m) to avoid direct physical impacts to the corals.

Sorbents and vacuum pumping

Sorbents and vacuum pumping are techniques which could be used in lagoons. Vacuum pumping may be used to remove thicker oil layers and oil pockets, but care should be taken to avoid breaking coral heads.

Low-pressure flushing

This technique is an effective way of aiding natural removal, but care must be taken when treating reefs.

Natural cleansing

This is the best method in many cases if there is high wave action on fringing reefs.

Agents and nutrients

Several methods currently in the developmental stage appear to be potentially suitable for use in coral areas and other marine environments likely to be sensitive to oil. Among these are agents that have been developed that, when added to oil, gel in a semisolid form that can then be recovered. Research is also being carried out to use nutrients (e.g. nitrogen and phosphorous) in accelerating the bacterial biodegradation of oil. According to ITOPF (2006), the use of nutrients has not so far been demonstrated to be beneficial for large-scale restoration projects. Bioremediation products should be applied with care and the methods used must be specifically tailored to the environment and pollutant at each contaminated site because they might encourage the growth of alien species (ITOPF 2006).

Bacterial biodegradation

Oil degrading microbes are widely distributed throughout the world’s coastal areas and are more abundant in coastlines adjacent to chronically polluted waters such as those receiving industrial discharges and untreated sewage. Some commercially available products do combine oil-degrading microbes collected from assorted areas of the world with nutrient supplements. Their application at a spill site can result in the introduction of alien species resulting in concerns about their potential impact. However, in most cases it is likely that introduced species will not compete effectively with those species naturally occurring. Although bioremediation may improve the rate of degradation of floating slicks the process is still too slow to prevent the vast majority of the oil reaching the shoreline. One problem is that some of the more complex components of the oil may remain partially or totally undegraded (NOAA 2001).

In situ *burning*

To date, there have been no intentional large-scale *in situ* burns in coral reef habitats, neither has there been any studies of this technique in coral regions. Results from the Newfoundland Offshore Burn Experiment (NOBE) indicate that crude oil burn residue has a low inherent toxicity to test organisms, and incurred no additional toxicity over unburned oil (Blenkinsopp *et al.* 1997). Extrapolation of these results to tropical areas and coral reefs should be done cautiously, however. The physical impacts of contact (such as fouling or smothering) may be a concern, since the burn residue may sink. There would be no harm to corals caused by the temperature rise because it only takes place in the first few centimeters of water.

Dispersants

The use of dispersants should be restricted to deep water, away from the shore and away from environmentally fragile habitats. The use of dispersants should not be undertaken if the risk caused to the environment by dispersed oil is higher than the risk caused by the oil itself. The decision about using a dispersant has to be made quickly so that the oil does not have the time to reach the shore (Merlin 2005).

The use of dispersants is not recommended on coral reefs because they are likely to increase hydrocarbon concentration in the water column thereby increasing the exposure of corals to oil and because of their deleterious environmental impacts discussed in the following chapter.

4. Effects of dispersants

Most of the research on the effects of dispersants on corals has been done in the laboratory. All these results conclude that chemical dispersants are toxic to corals. Table V summarizes these findings.

In Panama in 1986, the dispersant Corexit 9527 was both observed and reported to have been applied mostly offshore, and always > 2-3 km away from the heavily oiled reef (Guzmán *et al.* 1991). Refinery officials reported spraying from aircraft of over 21 000 litres of the dispersant (Guzmán *et al.* 1991). It was used too late and at concentrations too low relative to the volume of spilled oil to be effective (Cormack 1983), and may have mixed directly into the water column soon after spraying, or accumulated on top of the floating oil. Corexit has also been described as toxic to reef corals by other authors (Ballou *et al.* 1989, Thorhaug *et al.* 1989), or not toxic at concentrations up to 50 ppm (Knap *et al.* 1985). Ballou *et al.* (1989) stated that dispersants (Corexit) had less effects on mangroves than on corals.

Lewis (1971) reported detrimental effects to the feeding response and tactile stimuli of four Caribbean corals, due to Corexit. Of the four species tested (*Porites porites, Madracis asperula, Favia fragum* and *Agaricia agaricites*), *M. asperula* exhibited the greatest ill effects. Feeding activity decreased markedly upon additions of 100 ppm of Corexit, and at 500 ppm all but 5% of the colonies appeared moribund when compared to controls. All species were more affected by the dispersant than by the crude oil (General Crude Oil Co. of Barbados). This was also concluded in the case of the soft coral *Heteroxenia fuscescens* (Eisler 1975). Cook & Knap (1985) observed a photosynthesis reduction of 85 % in *Diploria strigosa* after an eight-hour exposure to a mixture of Arabian crude oil (19 ppm) and of the oil dispersant Corexit 1289 (1 ppm).

Negri & Heyward (2000) exposed corals to the dispersant Corexit 9527 and found that it inhibited fertilization as well as larval metamorphosis of *Acropora millepora*. But it was more toxic when combined with the crude oil. Dispersed oil was slightly more toxic to fertilization than dispersant alone, suggesting toxicity to that event may be additive. The minimum concentration of dispersed oil which inhibited fertilization was 0.0325 mg l^{-1} THC. Although crude oil and dispersant inhibited larval metamorphosis individually, this toxicity was magnified when larvae were exposed to combinations of both. Crude oil inhibited metamorphosis at 0.0325 mg l^{-1} THC when dispersed in 10% v/v (dispersant/oil).

Effects of the dispersant Shell LTX on the Caribbean coral *Madracis mirabilis* were studied (Elgershuizen & De Kruijf 1976). The Shell dispersant LTX, applied on the surface of the coral exposed to air was not toxic by itself, but mixed with seawater the toxicity increased 3-6-fold compared to the dispersant itself. The dispersant was added in a ratio of 1:10 (dispersant : oil). The increase in toxicity is probably caused by the increase in number of oil droplets and therefore, an increase in contact area between water, oil and dispersant. Elgershuizen & De Kruijf (1976) concluded that in the case of a major oil spill, reefs are more endangered by clean-up with chemical detergents than by the oil itself and the use of mechanical removal of the oil is preferred.

Harrison *et al.* (1990) observed a delayed stress response among branches of *Acropora formosa* exposed to dispersant BP A-B. Tissues began to lose zooxanthellae during the experiment and continued to deteriorate over subsequent weeks resulting in death of some branches after 1-2 months. The authors recommend not to use this dispersant in the vicinity of coral reefs until its toxicity is more thoroughly investigated.

Harrison (1994) reported inhibition of fertilization of the coral *Acropora tenuis* by fuel oil and the dispersant Ardrox 6120, noting that the dispersant was more toxic towards fertilisation than the water accommodated fraction of fuel oil.

TableV. – Summary of effects of dispersants on corals

Dispersant	Dose	Species	Effects	Reference
Corexit	100-500 ppm	*Porites porites, Madracis asperula, Favia fragum* and *Agaricia agaricites*	Ill effects on feeding response and tactile stimuli.	Lewis 1971
Corexit 9527	< 21 000 litres applied mostly offshore after the oil spill in Panama	Coral reef and mangrove ecosystem in Bahia Las Minas, Panama	Toxic effects on corals, less on mangroves.	Guzmán *et al.* 1991 Ballou *et al.* 1989 Thorhaug *et al.* 1989 Ward *et al.* 2003
	0.0325 mg l^{-1} THC	*Acropora millepora*	Inhibited fertilization and larval metamorphosis.	Negri and Heyward 2000
Corexit 1289	Mixture with Arabian crude oil (19 ppm) and Corexit 1289 (1 ppm)	*Diploria strigosa*	Reduction of photosynthesis by 85%.	Cook and Knap 1985
Shell LTX	1:10 (disp:oil)	*Madracis mirabilis*	Mixed with seawater the toxicity of the dispersant increases 3-6-fold.	Elgershuizen and Kruijf 1976
BP A-B	2-4 ppm	*Acropora formosa*	A delayed stress response (1-2 months) resulting in coral death.	Harrison *et al.* 1990
Ardrox 6120	Not known.	*Acropora tenuis*	Inhibition of fertilization.	Harrison 1994
Third generation dispersants (Inipol IP-90, Petrotech PTI-25, Bioreico R-93, Biosolve and Emulgal C-100)	0.1%, 1%, 10% and 100%	*Stylophora pistillata* and *Heteroxenia fuscescens*	Larval morphology deformations, loss of normal swimming behaviour and rapid tissue degeneration. Toxicity from the least toxic compound: Petrotech<Biosolve<Emulgal <Bioreico=Inipol	Epstein *et al.* 2000

Epstein *et al.* (2000) carried out a laboratory study on the survival of the planulae of *Stylophora pistillata* and *Heteroxenia fuscescens* from the Gulf of Eilat, Red Sea. Five third-generation oil dispersants, said to be environmentally friendly (Inipol IP-90, Petrotech PTI-25, Bioreico R-93, Biosolve and Emulgal C-100) were tested. Concentrations ranging from 0.5 to 500 ppm of dispersant compounds were mixed in 1/10 ratio with an Egyptian crude oil. A strong decrease of survival and settlement rate of planulae was observed for dispersant exposure ranging from 50 ppm and over, while metamorphosis rate was affected (60% to 84% fewer than control depending on the considered compound) at concentration as low as 0.5 ppm. Dispersants and water accommodation fractions (WAF) treatments caused larval morphology deformations, loss of normal swimming behaviour and rapid tissue degeneration. The dispersant Petrotech PTI-25 was shown to be the least toxic of the products, but Epstein *et al.* (2000) do not support the application of dispersants in the vicinity of coral reefs.

Ward *et al.* (2003) concluded that the TROPICS long-term study clearly showed the trade-off between using dispersants and not using them: efficient dispersant use saves the mangroves, but is harmful in shallow water where dispersants are in contact with the corals. The results in this study point out the trade-offs in habitat survival that different management decisions could make to inter-tidal and sub-tidal habitats (IPIECA 1992).

CONCLUSIONS

It has been stated that coral reefs are currently the most threatened ecosystem of the planet (Wilkinson 2004, Ramade 2005, Salvat 2005). Widespread occurrences of total coral colony mortality, partial mortality, population decline, and apparent decreases in coral recruitment have been reported on many reefs (Pandolfi *et al.* 2003). Since corals are among the most important organisms in tropical reef communities, both by providing habitat for other organisms and by entering in the overall metabolism of the reef community, any change in their physiology, however subtle, will probably cause a very dramatic change in the overall ecology of the reef (Reimer 1975). Oil pollution is one threat in the long list of threats to coral reefs.

Our literature review concerning oil spills on coral reefs reveals that the majority of the research has been conducted in the 1970's and 1980's. Very little research on this subject has been done after 1990 and an almost negligible amount after 1995. Results of the earlier studies were often contradictory. The discrepancies in these research findings result from the different types of corals, oils and dispersants studied; the wide range of exposure times, environmental conditions, and dosage concentrations used; the methods used to measure stress; and the length of time corals were monitored for recovery. Most of the research has been done in the Caribbean and in the Red Sea. Different types of corals and corals from different regions have been found to vary greatly in their response to oils and dispersants. It is therefore difficult to apply the results of these studies to predict the effects of oil spills and dispersant clean-up operations in the Indo-Pacific (Harrison *et al.* 1990).

Confusing results, the lack of new research, and the wide array of oils and dispersants available on the market call for a need to do further research on thresholds of damage of these new products to coral physiology. Research conducted in field conditions is important, because the extrapolation to natural populations from laboratory-based physiological data or small-scale, short-term perturbations have proven to be dangerous.

All efforts should be made in order to prepare the best clean-up methods for the reef environment in case of an oil spill. Studies confirm the toxicity of dispersants to corals and their use is not recommended (e.g. Harrison *et al.* 1990). During the last few years, earlier generations of oil dispersants were replaced by newly developed, "environmentally friendly" third generation compounds which were claimed to be less toxic. However, as Epstein *et al.* (2000) point out, these new products have serious negative impacts on coral larvae behaviour and recruitment. Ward *et al.* (2003) point out following the TROPICS experiment case in Panama that the use of dispersants is often a trade-off between the impact on corals and mangroves. In this particular case, efficient dispersant use saved the mangroves, but was harmful in shallow water where they were in contact with corals.

The most suitable clean-up method on shallow fringing reefs and reefs with high energy is considered to be natural clean-up. In order to act rapidly and effectively in case of an oil spill, thorough contingency plans are needed in coral reef countries. This is a challenging task considering that the majority of them are Third World countries with limited infrastructure and resources at their disposal.

So far, there has been no major oil pollution incidents on the world's coral reefs, but chronic pollution from small day-to-day spills in coastal waters is large in total volume (Guzmán 1991). Sublethal effects from this chronic pollution are extensive and may be more important in the long-term than initial mortality (Loya & Rinkevich 1980, Southward 1982).

The most extensively documented case study on the impacts of oil pollution on corals is that of Bahía las Minas, Panama, following the oil spill in 1986. The TROPICS experiment, also in Panama, has so far been the most extensive field study of the impacts of oil and dispersants on several biological habitats. As a result from this spill, an enormous amount of oil was locked in the mangrove sediments and chronic pollution due to the original oil spill is likely to last for many years. However, the chemical composition and toxicity of the oil is likely to have changed considerably over time, so that chronic effects may be less than were observed after the oil spill (Guzmán *et al.* 1991). Although petroleum released to the sea in tropical environments generally suffers rapid degradation, petroleum contaminants reaching intertidal sediments may exhibit long-term persistence (Corredor *et al.* 1990). Loya & Rinkevich (1977) pointed out the need for base-line biological studies in regions with a high probability of future subjection to oil pollution. This will lead to better evaluation and quantification of long-term effects of hydrocarbons on animal and plant communities. Various features of the life history of species composing such communities should be quantified and when possible, coupled with controlled experiments in the laboratory.

The responses of organisms to an oil spill, or any other major disturbance will depend on the conditions in which they normally live (e.g. Woodley *et al.* 1981). Moreover, the suite of organisms able to survive under conditions of chronic pollution, and their resistance to further stress, is typically different from that in similar unpolluted habitats (Southward 1982, Bak 1987). The exposure to chronic oil pollution of corals in the Arabian Gulf area may therefore explain the lack of impacts on corals observed after the world's biggest oil spill resulting from the Gulf War. Observations in the Gulf indicate that coral communities exist at their ecological limits with respect to low temperature (Coles & Fadlallah 1990) and high salinities (Coles & Jokiel 1991), a fact that further increases the stress tolerance of corals in this region.

According to Ramade & Roche (2006), a number of unsolved questions are still pending in the field of ecotoxicology of coral reefs. An effective monitoring program and standardised analytical processes for assessing the exposure of scleractinian corals to xeniobiotics should be put into place. There have been very few studies on accumulation and biomagnification processes in the coral reef trophic web and these studies should be undertaken as soon as possible. Coral planulae, amphipods, larval stages of crustaceans and echinoderms could be used for assessing the toxicity of different pollutants. These young life stages have been proven to be very useful in monitoring pollution because of their high sensitivity to pollutants. Studies on biomarkers in coral reefs have been rare and should be equally put into place (Ramade & Roche 2006).

When considering the possible risks of an oil pollution accident on a coral reef, the life cycle of the corals on site is crucial. Detrimental effects would follow if a spill occurs during an annual coral spawning event, but also if it occurs during the subsequent 1-3 week period during which most larval metamorphosis and recruitment occurs (Harrison *et al.* 1984).

The estimated reef recovery time of 10-20 years in Panama in 1986 was based on the assumption that no other event would further depress coral populations (Brown 1997). In the light of the current health of corals worldwide and the array of problems facing this ecosystem (e.g. Pandolfi *et al.* 2003), a major oil spill might mean a point of no return for corals. The risk of oil pollution should therefore be taken seriously.

ACKNOWLEDGEMENTS.- We are very grateful for M Flavell's comments on the manuscript.

REFERENCES

Antonius A 1981. Coral reef pathology: a review. *In* Proceed 4th Intern Coral Reef Sympos 2: 7-14.

Bak RPM, Elgershuizen JHBW 1976. Patterns of oil-sediment rejection in corals. *Mar Biol* 37: 105-113.

Bak RPM 1987. Effects of chronic oil pollution on a Caribbean Coral Reef. *Mar Poll Bull* 18: 534-539.

Ballou TG, Hess SC, Dodge RE, Knap AH, Sleeter TD 1987. Effects of a Dispersed and Undispersed Crude Oil on Mangroves, Seagrasses, and Corals. API Publ N° 4460. Washington, D.C: American Petroleum Institute, Health and Environmental Sci Dept, 198 p.

Ballou TG, Hess SC, Dodge RE, Knap AH, Sleeter TD 1989. Effects of untreated and chemically dispersed oil on tropical marine communities: A long-term field experiment. *In* Proceed 1989 Intern Oil Spill Conf, San Antonio, Texas. Am Petroleum Inst, Washington, DC: 447-454.

Benson AA, Muscatine L. 1974. Wax in coral mucus: Energy transfer from corals to reef fishes. *Limnol Oceanogr* 19: 810-814.

Blenkinsopp S, Sergy G, Doe K, Wohlgeschaffen G, Li K, Fingas M 1997. Evaluation of the toxicity of the weathered crude oil used at the Newfoundland Offshore Burn Experiment (NOBE) and the resultant burn residue. *In* Proceed 20th Arctic and Marine Oil spill Program (AMOP) Technical Seminar, Vancouver, British Columbia, June 11-13, 1997: 677-684.

Blumer M, Sanders HL, Grassle JF, Hampson GR 1971. A small oil spill. *Environment* 13: 1-18.

Brown BE, Howard LS 1985. Assessing the effects of 'stress' on reef corals. *Adv Mar Ecol* 22: 1-63.

Brown BE 1997. Disturbances to reefs in recent times. *In* Birkeland C ed, Life and death of coral reefs: 373-374.

Burns KA, Knap AH 1989. The Bahia Las Minas oil spill: hydrocarbon uptake by reef building corals. *Mar Poll Bull* 20: 391-398.

Capone DG, Bauer JE 1992. Microbial processes in coastal pollution. *In* R Mitchell ed, Environmental microbiology, John Wiley and Sons, New York: 191-238.

Chia FS 1973. Killing of marine larvae by Diesel oil. *Mar Poll Bull* 4: 29-30.

Cohen Y, Nissenbaum A, Eisler R 1977. Effects of Iranian crude oil on the Red Sea Octocoral *Heteroxenia fuscescens*. *Environ Poll* 12: 173-186.

Coles SL, Fadlallah YH 1990. Coral survival and mortality at low temperatures in the Arabian Gulf: New species-specific lower temperature limits. *Coral Reefs* 9: 231-237.

Coles SL, Jokiel PL 1991. Effects of salinity on coral reefs. *In* Connell DW & Hawker DW eds, Pollution in Tropical Systems. CRC Press, Florida: 147-166.

Cook CB, Knap AH 1985. Effects of crude oil and chemical dispersants on the photosynthesis of the brain coral *Diploria strigosa*. *Mar Poll Bull* 78: 21-27.

Cormack D 1983. Response to oil and chemical pollution. Applied Science Publishers, London.

Cormack D 1999. Response to marine oil pollution – review and assessment. Kluwer Academic Publishers , 345 p.

Corredor JE, Morell JM, del Castillo CE 1990. Persistence of spilled crude oil in a tropical intertidal environment. *Mar Poll Bull* 21: 385-388.

Dodge RE, Wyers SC, Frith HR, Knap AH, Smith SR, Sleeter TD 1984. The effects of oil and oil dispersants on the skeletal growth of the hermatypic coral *Dilporia strigosa*. *Coral Reefs* 3:191-198.

Dodge RE, Knap AH, Wyers SC, Firth HR, Sleeter TD, Smith SR 1985. The effect of dispersed oil on the calcification rate of the reef-building coral *Diploria strigosa*. *In* Proceed 5th Intern Coral Reef Sympos 6: 543-457.

Dodge RE, Baca BJ, Knap AH, Snedaker SC, Sleeter TD 1995. The effects of oil and chemically dispersed oil in tropical ecosystems: 10 years of monitoring experimental sites. MSRC Tech Rep Ser 95-014. Washington, DC: Marine Spill Response Corporation, 93 p.

Downing N, Roberts CM 1993. Has the Gulf War affected coral reefs of the northwestern Gulf? *Mar Poll Bull* 27: 149-156.

Ducklow HW 1977. Influence of sublethal pollutant concentrations on the microbial ecology of living corals. PhD thesis, Harvard Univ, Cambridge, Massachusetts.

Ducklow HW, Mitchell R 1979. Bacterial populations and adaptations in the mucus layers on living corals. *Limnol Oceanogr* 24: 715-725.

Eakin CM, Feingold JS, Glynn PW 1993. Oil refinery impacts on coral reefs: health, hazards and history. Rosenstiel School of Marine and Atmospheric Sci, Univ Miami, Coral Gables: 43-49.

Eisler R 1975. Toxic, sublethal and latent effects of petroleum of Red Sea macrofauna. *In* Proc 1975 Conf Prevention and Control of oil pollution. Am Petroleum Inst, Washington, DC: 535-540.

Elgershuizen JHBW, De Kruijf HAM 1976. Toxicity of crude oils and a dispersant to the stony coral *Madracis mirabilis*. *Mar Poll Bull* 7: 22-25.

Epstein N, Bak RPM, Rinkevich B 2000. Toxicity of third generation dispersants and dispersed Egyptian crude oil on Red Sea coral larvae. *Mar Poll Bull* 40 (6): 497-503.

Fadlallah YH 1983. Sexual reproduction, development and larval biology in scleractinian corals. A review. *Coral Reefs* 2: 129-150.

Farrington JW 1989. Bioaccumulation of hydrophobic organic pollutants compounds. *In* Ecotoxicology: problems and approaches. Levin SA, Harwell MA, Kelly JR, Kimball KD eds. Springer: 279-313.

Friaz-Lopez J, Zerkle AL, Bonheyo GT, Fouke BW 2002. Partitioning of bacterial communities between seawater and healthy, black band diseased and dead coral surfaces. *Appl Environ Microbiol* 68: 2214-2228.

Fucik KW, Bright TJ, Goodman KS 1981. Restoration of habitats impacted by oil spills Symposium, Blacksburg, VA (USA) 9-11 Nov 1981. Restoration of habitats impacted by oil spills, Cairns J, Buikema AL eds: 115-134.

Garrett P, Ducklow H 1975. Coral diseases in Bermuda. *Nature* 253: 349-350.

Green A, Burgett J, Molina M, Palawski D, Gabrielson P 1997. The impact of a ship grounding and associated fuel spill at Rose Atoll National Wildlife Refuge, American Samoa. Honolulu: US Fish Wildlife Serv, Pacific Islands Ecoregion, 60 p.

Gupta RS, Kureishy W 1981. Present state of oil pollution in the Northern Indian Ocean. *In* UNEP/IUCN (1988). Coral Reefs of the World. Vol 2: Indian Ocean, Red Sea and Gulf. UNEP Regional Seas Directories and Bibliographies. IUCN, Gland, Switzerland and Cambridge, U.K./UNEP, Nairobi, Kenya. 1+389 p, 36 maps.

Guzmán HM, Jackson JBC, Weil E 1991. Short-term ecological consequences of a major oil spill on Panamanian subtidal reef corals. *Coral Reefs* 10: 1-12.

Guzmán HM, Holst I 1993. Effects of chronic oil-sediment pollution on the reproduction of the Caribbean reef coral *Siderastrea siderea*. *Mar Poll Bull* 26 (5): 276-282.

Guzmán HM, Jackson JBC, Holst I 1993. Changes and recovery of subtidal reef corals. *In* Keller BD, Jackson JBC eds, Long-term assessment of the oil spill at Bahia Las Minas, Panama, synthesis report, Vol. II, tech rep U.S. Depart Interior, Minerals Manag Serv, Gulf of Mexico OCS Region, New Orleans: 361-446.

Guzmán HM, Burns KA, Jackson JBC 1994. Injury, regeneration and growth of Caribbean reef corals after a major oil spill in Panama. *Mar Ecol Prog Ser* 105: 231-241.

Harrison PL, Babock RC, Bull GD, Oliver JK, Wallace CD, Willis BL 1984. Mass spawning of reef corals. *Science* 223: 1186-1189.

Harrison PL, Collins JC, Alexander CG, Harrison B 1990. The effects of fuel oil and dispersant on the tissues of a staghorn coral *Acropora formosa*: a pilot study. *In* Proceed 2nd Nat Workshop on the role of scientific support co-ordinator. 26-30 March 1990.

Harrison PL 1994. The effects of oil pollutants on fertilization and larval settlement in the scleractinian reef coral *Acropora tenuis*. *In* Proceed of Joint Scientific Conf Sci management and Sutainability of Marine Habitats in the 21st century. Townsville, Australia.

Haynes D, Johnson JE 2000. Organochlorines, heavy metals and Polycyclic aromatic Hydrocarbons in the great barrier reef (Australia) environment: a review. *Mar Poll Bull* 41: 267-278.

International Maritime Organization (IMO) 1997. Field Guide for Oil Spill Response in Tropical Waters. IMO 1997, 54 p.

International Petroleum Industry Environmental Conservation Association (IPIECA) 1992. Biological Impacts of oil pollution: coral reefs. IPIECA Report Series, Vol. 3. 1992.

International Tanker Owners Pollution Federation (ITOPF) 2006. Historical Data. http://www.itopf.org/stats.html

International Tanker Owners Pollution Federation (ITOPF) 2006. Clean-up techniques. http://www.itopf.org/clean-up.html

Jackson JBC 1986. Dispersal and distribution of clonal and aclonal benthic invertebrates. *Bull Mar Sci* 39: 588-606.

Jackson JBC, Cubit JD, Keller BD, Batista V, Burns K, Caffey HM, Caldwell RL, Garrity SD, Getter CD, Gonzalez C, Guzmán HM, Kaufman KW, Knap AH, Levings SC, Marshall MJ, Steger R, Thompson RC, Weil E. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243 (4887): 37-44.

Johannes RE 1967. Ecology of organic aggregates in the vicinity of a coral reef. *Limnol Oceanogr* 12: 189-195.

Johannes RE, Maragos JE, Coles SL 1972. Oil damages corals exposed to air. *Mar Poll Bull* 3: 29-30.

Knap AH, Solbakken JE, Dodge RE, Sleeter TD, Wyers SJ, Palmork KH 1982. Accumulation and elimination of (9-14C) Phenanthrene in the reef-building coral (*Diploria strigosa*). *Bull Environ Contam Toxicol* 28: 281-284.

Knap AH, Wyers SC, Dodge RE, Sleeter TD, Frith HR, Smith SR, Cook CB 1985. The effects of chemically and physically dispersed oil on the brain coral *Diploria strigosa*. 1985 Oil Spill Conf, Publ 4385. Am Petroleum Inst, Washington, DC: 547-551.

Knudsen JW 1967. *Trapezia* and *Tetralia* (Decapoda, Brachyura, Xanthidae) as obligate ectoparasites of Pocilloporid and Acroporid corals. *Pacif Sci* 21: 51-57.

Kushmaro A, Henning G, Hofman DK, Benayahu Y 1997. Metamorphosis of *Heteroxenia fuscescens* planulae (Cnidaria: Octocorallia) is inhibited by crude oil: a novel short term toxicity bioassay. *Mar Env Res* 43 (4): 295-302.

LeGore S, Marszalek DS, Danek LJ, Tomlinson MS, Hofmann JE, Cuddebak JE 1989. Effect of chemically dispersed oil on Arabian Gulf corals: A field experiment. *In* Proceed 1989 Intern Oil Spill Conf, San Antonio, February 13-16, 1989: 375-381.

Lewis JB 1971. Effects of crude oil and oil spill dispersant on reef corals. *Mar Poll Bull* 2: 59-62.

Lewis JB 1978. Feeding mechanisms in black corals (Antipatharia). *J Zool* 186: 393-396.

Littler MM, Littler DS 1996. Black band disease in the South Pacific. *Coral Reefs* 15: 20.

Loya Y 1976. Recolonization of Red Sea corals affected by natural catastrophes and man-made perturbations. *Ecology* 57: 278-289.

Loya Y, Rinkevich B 1977. Effects of oil pollution on coral reef communities. *In* DR Stoddart, RW Grigg eds. Coral reef ecosystem under stress. Academic Press, London.

Loya Y, Rinkevich B 1979. Abortion effect in corals induced by oil pollution. *Mar Ecol Prog Ser* 1: 77-80.

Loya Y, Rinkevich B 1980. Effects of oil pollution on coral reef communities. *Mar Ecol Prog Ser* 3: 167-180.

Loya Y, Rinkevich B 1984. Effects of petroleum hydrocarbons on corals. *In* Human Impacts on Coral Reefs: facts and recommendations. Salvat B ed. Antenne Museum EPHE, French Polynesia, 1987.

Maragos JE 1994. Reef and coral observations on the impact of the grounding of the longliner Jin Shiang Fa at Rose Atoll, American Samoa. Honolulu: US Fish and Wildlife Serv, Pacific Island Office, 27 p.

Mercurio P, Negri AP, Burns KA, Heyward AJ 2004. The ecotoxicology of vegetable versus mineral based lubricating oils: 3-Coral fertilization and adult coral. *Environ Poll* 129: 183-194.

Merlin FX ed. 2005. Traitement aux dispersants des nappes de pétrole en mer. Guide opérationnel du CEDRE.

Mitchell R, Chet I 1975. Bacterial attack of corals in polluted sea water. *Microb Ecol* 2: 227-233.

Negri AP, Heyward AJ 2000. Inhibition of fertilization and larval metamorphosis of the coral *Acropora millepora* by petroleum products. *Mar Poll Bull* 41 (7-12): 420-427.

NOAA 2001. Oil spills in coral reefs: planning and response considerations. http://response.restoration. noaa.gov./oilaids/coral/reports.html. National Oceanic and Atmospheric Administration ed, report 2001 (revised in 2003).

Oil Spill Intelligence Reports (OSIR) 1999. Oil Spill risks in Latin America and Caribbean Region. White Paper Ser, Techn Statist Anal Cutter Information Corp, September 1999.

Palmork KH, Solbakken JE 1980. Accumulation and elimination of radioactivity in the Norway Cobster (*Nephrops norvegicus*) following intragastric administration of [9-^{14}C]phenanthrene. *Bull Environ Contam Toxicol* 25: 668-671.

Palmork KH, Solbakken JE 1981. Distribution and elimination of [9-^{14}C]phenanthrene in the horse mussel (*Modiola modiolus*). *Bull Environ Contam Toxicol* 26: 196.

Pandolfi JM, Bradbury RH, Sala E, Hughes TP 2003. Global trajectories of the long-term decline of coral reef ecosystems. *Science* 301: 955-958.

Peters EC, Philip AM, Yevich PP, Blake NJ 1981. Bioaccumulation and histopathological effects of oil on a stony coral. *Mar Poll Bull* 12 (10): 333-339.

Price ARG 1998. Impact of the 1991 Gulf War on the coastal environment and ecosystems: current status and future prospects. *Environ Int* 24 (1/2): 91-96.

Ramade F 1995. Eléments d'écologie : écologie appliquée, 5th ed, Ediscience International, Paris, 1995.

Ramade F 2000. Dictionnaire encyclopédique des pollutions. Ediscience International, Paris, 1999, 640 p.

Ramade F 2005. Asie du Sud-Est: un cataclysme prémonitoire. *Courr Nat* 218: 18-26.

Ramade F, Roche H 2006. Ecotoxicological impingement of pollutants on coral reefs: a review. *Rev Ecol Terre Vie* 61 (1): 3-33.

Readman JW, Tolosa I, Law AT, Bartocci J, Azemard S, Hamilton T, Mee LD, Wagener A, Le Tissier M, Roberts C, Downing N, Price ARG 1996. Discrete bands of petroleum hydrocarbons and molecular organic markers identified within massive coral skeletons. *Mar Poll Bull* 32 (5): 437-443.

Reimer AA 1975. Effects of crude oil on corals. *Mar Poll Bull* 6: 39-43.

Richman S, Loya Y, Slobodkin LB 1975. The rate of mucus production by corals and its asimilation by the coral reef copepod *Acartia negligens*. *Limnol Oceanogr* 20: 918-923.

Rinkevich B, Loya Y 1977. Harmful effects of chronic oil pollution on a Red Sea coral population. *In* Proceed 3rd Intern Coral Reef Sympos: 585-591.

Rinkevich B, Loya Y 1979. Laboratory experiments on the effects of crude oil on the Red Sea coral *Stylophora pistillata*. *Mar Poll Bull* 10: 328-330.

Sadiq M, McCain JC 1993. The Gulf War aftermath: An environmental tragedy. Dordrecht: Kluwer Academic Publishers, 1993.

Saenger P 1994. Aftermath of an oil spill. *Search* 25 (1): 19-22.

Salvat B 2005. Les récifs coralliens: réalité et espoirs. *Courr Nat* 219:18-27.

Shinn EA 1972. Coral reef recovery in Florida and in the Persian Gulf. Report to Environmental Conservation Department, Shell Oil Comp. Houston, Texas.

Solbakken JE, Palmork KH, Neppelberg T, Scheline RR 1979. Distribution of radioactivity in coalfish (*Pollachius virens*) following intragastric administration of [9-14C] phenanthrene. *Bull Environ Contam Toxicol* 23: 100-103.

Southward, AJ 1982. The long-term effects of oil pollution on marine populations, communities and ecosystems, London, (UK), 28-29 Oct 1981. *Philos Trans R Soc Lond* Ser B 1982 297 (1087): 241-255.

Spooner M 1970. Oil spills in Tarut Bay, Saudi Arabia. *Mar Poll Bull* 1: 166-167.

Stainken DM 1975. Preliminary observations on the mode of accumulation of No. 2 fuel oil by the soft shell clam *Mya arenaria* L. *In* Proceed conf on prevention and control of oil pollution. Am Petroleum Inst, Washington, DC: 463-468.

Stirling HP 1977. Effects of a spill of marine Diesel oil on the rocky shore fauna of Lamma Island, Hong Kong. *Environ Poll* 12: 93-117.

Straughan D 1972. Factors causing environmental. changes after an oil spill. *J Petrol Technol* 24: 250-254.

Thorhaug A, McFarlane J, Carby B, McDonald F, Anderson M, Miller B, Gordon V, Gayle P 1989. Dispersed oil effects on tropical habitats: Preliminary laboratory results of dispersed oil testing on Jamaica corals and seagrass. 1989 Oil Spill Conf. Publ 4479, Am Petroleum Inst, Washington, DC: 455-458.

Vogt HP 1995. Coral reefs in Saudi Arabia: 3.5 years after the Gulf War oil spill. *Coral Reefs* 14: 271-273.

Ward GA, Baca B, Cyriacks W, Dodge RE 2003. Continuing long-term studies of the TROPICS oil and dispersed oil spill sites. 2003 Intern Oil Spill Conf.

Wilkinson C ed 2004: Status of Coral Reefs of the World: 2004. Australian Institute of Marine Science, 557 p.

Woodley JD, Chornesky EA, Clifford PA, Jackson JCB, Kaufman LS. Knowlton N, Land JC, Pearson MP, Wulff JL, Curtis ASG, Dallmeyer MD, Jupp BP, Koehl MAR, Neigel J, Sides EM 1981. Hurricane Allen's impact on Jamaican coral reefs. *Science* 214: 749-755.

Received June 19, 2006
Accepted October 26, 2006