The Asia Pacific Region and major ocean currents.
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Effect of various environmental parameters on Henry’s Law Constant, of significance to climate change.

254x190mm (96 x 96 DPI)
Migration processes for POPs as modified by climate change.

Melting of polar icecaps releases POPs from air-ice interface

Migration processes for POPs as modified by climate change.

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Modelling of Diazinon concentration in soil under climate change conditions
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Schematic diagram showing possible effects of climate change on particulate-mediated transport of pollutants

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Increased levels of atmospheric CO$_2$ available for dissolution into water

Increased levels of CO$_2$ available for photosynthesis and N$_2$ fixation

CO$_2$ $\rightarrow$ N$_2$

Increased levels of atmospheric particulates deposit additional nutrients and iron upon water surface

Nutrient processes as a result of climate change (modified from Michaels et al. (2001))

254x190mm (96 x 96 DPI)
REVIEW ARTICLE

An opinion on the distribution and behaviour of chemicals in response to climate change, with particular reference to the Asia-Pacific Region

Ross Sadler\textsuperscript{a*}, Albert Gabric\textsuperscript{b}, Glen Shaw\textsuperscript{c}, Emily Shaw\textsuperscript{b} and Des Connell\textsuperscript{b}

\textsuperscript{a}School of Public Health, Griffith University, Logan Campus, University Drive, Meadowbrook, QLD, AUSTRALIA, 4131.

\textsuperscript{b}School of Environment, Griffith University, Nathan Campus, 170 Kessels Road, Nathan, QLD, AUSTRALIA, 4111.

\textsuperscript{c}School of Public Health, Griffith University, Gold Coast Campus, QLD, 4222.

\textsuperscript{*}Corresponding Author: Ross Sadler, School of Public Health, Griffith University, Logan Campus, University Drive, Meadowbrook, QLD, AUSTRALIA, 4131. ross.sadler@griffith.edu.au
Keywords
Climate change, polluant behaviour, polluant transport, environmental fate, harmful algal blooms, particulates

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ABSTRACT

There is a general lack of knowledge as regards effects of climate change on pollutant behaviour. This is particularly true of the Asia-Pacific Region. This region has major significance in terms of global pollutant emission and also displays a wide variety of environments. This review presents the authors' opinions on possible implications of climate change for pollutant behaviour in the Asia-Pacific Region. Although differing responses can be expected across the region, there are clear implications as regards the short and long-term behaviour of pollutants. Effects can be predicted through modelling, but further data are required for model calibration. Nevertheless, it can be predicted that climate change will affect processes including global distillation of POPs, airborne transport of heavy metals, half lives of readily degradable pollutants and eutrophication in water bodies. Particulates are expected to play a central role in mediating the effects of climate change and successful predictive models will need to be based on particulate-mediated transport and behaviour.

Climate change also has the potential to cause increases in the intensity and frequency of harmful algal blooms in aquatic environments throughout the region, with significant implications for supply of both food and drinking water.
1.0 INTRODUCTION

The term Asia-Pacific Region (APR) generally applies to littoral East Asia, Southeast Asia and Oceania. Although an imprecise geographical descriptor, the term Asia-Pacific became popular from the late 1980s as the economies within this heterogeneous region flourished. Figure 1 gives an illustration of the APR, along with ocean currents in the region. For the purposes of this review, the APR will be taken to include Australia, Brunei, Cambodia, People’s Republic of China, Taiwan, Fiji, India, Indonesia, Japan, Kiribati, North and South Korea, Laos, Malaysia, Marshall Islands, Federated States of Micronesia, Nauru, Nepal, New Zealand, Palau, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Tonga, Tuvalu, Vanuatu, Vietnam, and the United States Territories of American Samoa, Guam and Northern Mariana Islands. Some of the conclusions may also be applied to other comparable areas of the world, such as parts of South America, South Africa.

The science of climate change has evolved considerably over the last decade, and the possibility of future dangerous climate change is generally (although not universally) accepted by scientists (AAAS, 2007). However, our ability to detect changing climatic trends is limited by short meteorological records. This is particularly true in some parts of the Asia-Pacific, where reliable, detailed meteorological time series do not exist for longer than 100 years.

In the APR, the demonstration of deviations from the climatic norm is complex. In addition to the lack of climatological monitoring data, the APR is characterized by extremes of climate, even in so-called “normal seasons”. Events such as tropical cyclones, droughts and heavy snowfall/snow melt are common in individual parts of the APR. It follows that any pattern of climate change will be superimposed on this noisy background. For the purpose of regional climate projections, the Intergovernmental Panel on Climate Change (IPCC) divides Asia into several sub-regions: viz. North Asia, Central Asia, Tibetan Plateau, West Asia (Middle East), East Asia, South Asia and...
South-East Asia and treats Australia and New Zealand and the Pacific Islands separately (IPCC, 2007a).

An examination of the trends in these areas demonstrates considerable spatial variability. For example, there is a demonstrable increase in temperature in many areas, whereas others such as Central Siberia have recorded decreasing summer temperatures. Since 1905, temperatures in Northeast China have increased in winter but decreased in summer. It has often been hypothesized (and observed) that minimum temperatures seem to increase more than maximum temperatures. The observed trends in mean annual precipitation are similarly variable, with significant decreases in the annual range in South-East Asia, increases in NW Australia and Java, but decreases in NE Australia (IPCC, 2007b).

Many manifestations of climate change (e.g. increased incidence of droughts) are extreme in nature. Some changes may be more subtle than mere reductions/increases in annual rainfall. For example, an examination of the annual rainfall in Central India between 1951 and 2000 shows a relatively constant value, but an increase in the rainfall delivered by heavy monsoonal downpours (Goswami et al., 2006).

The objectives of this review are to present the authors’ opinions regarding the effects of climate change on dynamic chemical processes in the APR environment. Studies that have already been undertaken in terms of the effect of climate change on pollutant behaviour pertain to other geographic regions (Macdonald et al., 2003a,b; Dalla Vale et al., 2007). Because climate warming has proceeded faster in Arctic regions, than elsewhere, the most definite empirical evidence of this link to contaminants comes from this region. Hence the work of Macdonald et al. (2003a,b) is of particular overall significance to the prediction of climate change effects worldwide. The present review will consider chemical rather than ecological consequences of climate change. A recent review of the ecological consequences of climate change has appeared (Schiedek et al. 2007).
only ecological process to be considered in depth by this review will be the occurrence of harmful algal blooms, because of the obvious chemical implications. We present this review with the objective of initiating discussion in the scientific community on climate change as it specifically affects pollutant behaviour in the Asia-Pacific Region. This review also represents a further contribution to the literature on the subject in a global context.

2.0 SIGNIFICANCE OF THE APR AS A GLOBAL SOURCE OF CHEMICAL POLLUTANTS

Growth in global greenhouse gas emissions since 2000 has exhibited a sharp rise. There have been significant increases in the energy intensity of gross domestic product (GDP) (energy/GDP) and the carbon intensity of energy (emissions/energy), coupled with continuing increases in population and per-capita GDP. Nearly constant or slightly increasing trends in the carbon intensity of energy have been recently observed in both developed and developing regions. The growth rate in emissions is strongest in rapidly developing economies, particularly China. Together, the developing and least-developed economies (forming 80% of the world's population) accounted for 73% of global emissions growth in 2004 (Raupach et al., 2007).

New consumers in developing economies possess over one-fifth of the world's cars, a proportion that is rising rapidly. Global CO$_2$ emissions from motor vehicles, of which cars make up 74%, increased during 1990-1997 by 26% and at a rate four times greater than the growth of CO$_2$ emissions overall (Myers and Kent, 2003) The situation is exacerbated by the relatively high proportion of two-stroke engines in the APR (Kojima et al., 2000). Throughout the year, the largest source of particulate PAHs in the APR is gasoline and diesel vehicle emissions (cf. Lee and Kim (2007).

The APR is of global significance as a source of persistent organic pollutants (POPs). The available information on the occurrence of POPs in the Asia Pacific Region, has been reviewed by Tanabe 6
(2007). He concluded that there were hot spots of POPs pollution in areas of heavy use. Elevated levels of HCH were found in India and South China, while DDTs were high in China and Vietnam. PBDEs were found to be increasing substantially in Hong Kong coastal waters. Tanabe concluded that the East Asia region is probably a global source of these contaminants. The APR constitutes the only current source of production of DDT. In 2005, total global production was estimated at 6,269 t (a.i.), of which some 4,250 t (a.i.) were produced in India alone. China is also a major producer, about 55% being used as an intermediate in the production of dicofol and the remainder sold for direct use. North Korea is thought to produce about 300 t (a.i.) per year (UNEP, 2007).

The increasing heavy industry (Fang et al., 2004), domestic fossil fuel consumption throughout the region (Park et al., 2002) as well as high volume motor traffic (Hien et al., 2006) are all significant sources of polycyclic aromatic hydrocarbons (PAHs). A rather complex situation prevails in the Asian environment and some initiatives have been undertaken to determine the relative contributions of the sources. The subject of PAH behaviour is subsequently discussed in the section on particulates.

A similar situation exists with inorganic chemicals. For example, China is one of the major global sites of production and use of mercury compounds, with coal combustion being the major source (cf. Pacyna et al., 2003). A number of countries in the APR (viz. Philippines, Indonesia, Vietnam, China, Papua New Guinea, Russia and Mongolia) are reported to use mercury for the extraction of gold. Generally, these operations are small and dispersed. It has been estimated that as much as 95% of the mercury used in these operations is lost to the environment and that these emissions comprise about 10% of the global total (UNEP, 2003). The United Nations Environment Program (UNEP) is currently reviewing the global situation as regards cadmium and lead. Japan and China are the largest producers of cadmium worldwide (Nordic Council of Ministers, 2003). In view of the fact that Australia, China, Russia and North Korea are amongst the most significant producers
of lead on a global scale, a similar situation can be expected to pertain to lead (US Bureau of Mines, 1993).

3.0 IMPACTS OF CLIMATE CHANGE ON CHEMICAL BEHAVIOUR

3.1 Distribution of POPs and other Organics
In terms of chemical behaviour, the underlying physical processes are governed by physicochemical properties of the pollutants, such as the octanol-water partition coefficient ($K_{\text{OW}}$), octanol-air partition coefficient ($K_{\text{OA}}$) and Henry’s Law Constant. In terms of global warming, the effect on these parameters will vary. $K_{\text{OW}}$ shows only a weak dependency on temperature (Connell, 2005) and $K_{\text{OA}}$ has a somewhat more pronounced one, increasing log-linearly with the reciprocal of temperature (Harner and Mackay, 1995). Temperature dependence of the Henry’s Law Constant varies amongst different classes of chemicals, being maximal with compounds that are polar or have significant hydrogen bond interaction capacity (Staudinger and Roberts, 2001, Kühne et al., 2005). A number of other environmental factors are known to affect Henry’s Law Constants and the significance of these on climate change is identified in Figure 2. It is clear that in addition to temperature, suspended solids, salinity and dissolved organic matter can all be expected to affect the observed Henry’s Law Constant, under conditions of climate change. The observed effect will therefore depend upon which of these factors comes into play, in the environment under consideration.

Of particular significance to climate change effects on chemicals is the influence that climate perturbations will have on global transport of chemicals (i.e. movement from one part of the APR to another or movement from the APR to other parts of the world). In terms of polar migration potential, Wania (2006) divided environmental organics into four categories, which could be distinguished by any two out of three of the parameters: octanol-water partition coefficient; octanol-air partition coefficient and air-water partition coefficient:
(a) ‘Fliers’, which have a log $K_{OA} < 6.5$ or log $K_{AW} >0$ and are so volatile that they are unlikely to deposit on the Earth’s surface, even at the Poles.

(b) ‘Single Hoppers’, which have $K_{OA} > 10$ and hence will readily sorb to particles, their overall transport being in this form, between the point of sorption and the poles.

(c) ‘Multiple Hoppers’, which have $K_{AW}$ between $-4$ and $0$ and will be subject to transport by global distillation (Wania and Mackay, 1995).

(d) ‘Swimmers’, which have $K_{AW} < -2$, which undergo significant meridional transport in the oceans.

The demarcations amongst these groups are not absolute and some chemicals (Particularly those whose physicochemical properties are at the border between one group and another) can exhibit both types of behaviour (Wania, 2006).

Climate change will have at least some influence on behaviour of all groups. Substances in the group (d) are dealt with in a subsequent section. Increased temperatures resulting from climate change (especially significant rises caused by extreme weather events) would be likely to favour ‘flier’-type behaviour amongst chemicals at the border of groups (a) and (c). Because group (a) chemicals are not sorbed onto particulates, the expected prevalence of cloud-free days could lead to higher photodegradation.

In the case of climate change effects, groups (b) and (c) will be the most susceptible to changes in behaviour. The expected rise in particulates and prevalence of dust storms as a result of climate change (see below), will tend to favour transport of ‘single hoppers’ and will also reduce their potential for atmospheric degradation.

The potential climate change effects on ‘multiple hoppers’ is more complex, especially as applied to the APR. Although there has been ample evidence produced of global distillation effects in the Northern Hemisphere, the situation in the Southern Hemisphere is far less defined. The so-called “grasshoppering” process which underpins global distillation is mediated by successive cycles of
suspension and deposition (Wania and Mackay, 1995). It is noteworthy that the atmospheric condensation step may involve deposition onto particulates (Wania and Mackay 1997) and on reaching the Earth’s surface, these substances could again find their way into the atmosphere through evaporation. (The particulates could include precipitation).

The theory and also practical observations regarding global distillation suggest that compounds such as HCHs and HCBs will migrate preferentially to the Polar Regions, whilst others such as DDT will be deposited preferentially at mid-latitudes (Wania and Mackay, 1996). If global warming occurred uniformly across the region, then there should be relatively little effect on the pattern of pollutant deposition. But as the pattern of global warming tends to be accentuated in Polar Regions, there will be a shift in the area of deposition of chemicals. Temperature differentials however are not the only factors to be considered in the movement of organics. Precipitation plays an important part in removing particulates from the atmosphere. As is apparent from the foregoing comments, the general trend throughout the APR is toward decreased rainfall, albeit with an increase in heavy rains delivered through monsoon and other extreme events. A modified delivery pattern such as has been observed in Central India (Goswami et al., 2006) could actually enhance distribution of persistent organic pollutants, by increasing the time available for pollutant volatilization between rainfall events.

Long-term regional monitoring data that could support these trends are fairly rare and may be complicated by local emissions. For example, Macleod et al. (2005) employed a global mass balance model (BETR-Global) to determine the effects of the North Atlantic Oscillation (NAO) on atmospheric PCB concentrations. Using historical data from 11 Northern Hemisphere sites, they were able to obtain satisfactory correlations in a number of cases. The authors predicted that the maximum variability in atmospheric PCB concentrations likely to be ascribable to NAO would be a factor of 2. At other sites, such as Hazelrigg (UK), the monitoring data did not support the model
predictions, probably as a result of local emissions. Generally, the most significant correlations were found during winter and spring. This underlines the difficulties encountered with monitoring data of this kind – difficulties that are likely to be even more accentuated in the APR. To date, no comparable study has been performed with the Southern Oscillation Index. Wurl et al. (2006) reported a study of PCB congeners in the Indian Ocean area. Unlike the trend observed with many organochlorine pesticides, where levels have decreased since the 1990s (as a result of banning), PCBs are still present at significant concentrations in the air column. The authors believed that military dumping and unregulated waste combustion are responsible for some of the observed elevated concentrations. Some POPs (e.g. Lindane) were still in use in certain countries (viz. Malaysia) during the study period. The climate change predictions that are in place for the APR offer some clear possibilities for disruption of the global distillation pattern. For example, it has been postulated that the existing Hadley cell could undergo equatorial drift and the normal tropical winds would be replaced by a westerly super rotation (Pierrehumbert, 2000). Figure 3 summarizes the aspects of global distillation as they will be affected by climate change.

It has been suggested that alpine ecosystems may provide a model for global transport of POPs (Daly and Wania, 2005). Glaciers are known to be a dominant source of persistent organic pollutants in other parts of the world (cf. Blais et. al., 2001) and it is unlikely that this would not be true for the APR as well. The APR possesses some major mountain systems, such as the Himalayas. There has been very little work defining the situation with persistent organic pollutants in these systems. It is known that the Himalayas are showing marked effects of climate change as indexed by snowmelt and of the retreat of glaciers (Cyranoski, 2005). They will therefore be an important site of activity as regards climate change, particularly the release of contaminants across the air-ice interface.

Although somewhat less studied than the Arctic, the Antarctic has the potential to be a major site at which climate change effects will be manifest. Clear evidence of ice melt has already been
produced and Lenton et al., 2008 consider that rapid sea-level rise (>1 m per century) is more likely to come from the West Antarctic Ice Sheet than from the Greenland Ice Sheet. Such a loss of the sorption interface would cause a major redistribution of POPs in the Antarctic environment, with a renewed potential for bioaccumulation and exchange with the atmosphere.

There are other transport pathways for POPs, apart from global distillation. Macdonald et al. (2003b) noted that climate change scenarios in the arctic regions could result in changes from air to sea transport for particle-bound POPs. The consequences of this would be expected to differ in the Asia-Pacific region than in the Atlantic, because of the strong coupling between the Antarctic Intermediate Water and the tropical Pacific processes (Pierrehumbert, 2000).

Krümmel et al. (2005) described the deposition of PCBs in North American lakes. This distribution appeared to be correlated with the return to those lakes for spawning of salmon, which subsequently die and release their pollutant load to the lakes. It is possible that other fish which exhibit similar behaviour could also perform a similar function. Climate change may influence their choice of different river systems for spawning and hence a modified pollutant distribution may be a consequence. The entire subject of biovector transport has been examined by Blais et al., (2007) and could extend well beyond the realm of fish to include migratory birds and even marine mammals. It is clear that climate change has the ability to affect this form of transport significantly although the relative contribution of biovector transport, particularly to the APR has yet to be determined.

These effects will be generally long-term in nature and will reflect the prolonged influence of climate change. But climate change will also be reflected in the behaviour of organic pollutants at a more local level with consequences of a more short-term nature. Perturbations of climate such as two or three particularly hot and dry summers, severe monsoons, etc will exert a major influence over effects of this kind. The organic pollutants that will be most clearly affected by such changes
will be those whose behaviour and persistence are most directly affected by environmental parameters. Thus, climate change effects at this level have the potential to affect pesticides currently in use, as well as POPs. Figure 4 shows a modelling scenario in which diazinon in soil is exposed to an average night temperature increase of 5°C and an average day temperature increase of 3°C (Wu and Nofziger, 1999). Although such increases are above long-term projections for climate change, there is abundant evidence of local increases of this magnitude over the period of the model prediction (less than 2 years). The result is clearly a shorter half-life for diazinon in soil, which may result in scenarios of increased application.

Temperature is only one of the climate change factors that could change the behaviour of organic pollutants in environmental matrices. Phenomena such as extreme weather events, rises in sea level etc. also have the potential to change the behaviour of organic pollutants, particularly at a local level. For example, increased sediment loads are associated with the runoff from tropical rainfall events. It is well known that in Australia at least, the highest erosion and runoff of pesticide-containing material occurs during intense, short duration rainfall events (Connolly et al., 2002). This is almost certainly the case with most countries of the APR. Given the fact that such events will almost certainly increase in some areas as a result of climate change, then increased export of particle-bound organics can be expected to occur. Connolly et al., 2002 have noted that agricultural soils are particularly vulnerable to erosion by heavy rainfall events following prolonged dry periods. This effect is most pronounced with shrink-swell soils that have not been cropped for some time – precisely the situation that would arise in the case of predicted climate change scenarios. Degradation of filter strips and riparian zones in general would be another consequence of climate change in areas where there is a significant decrease in rainfall and this would exacerbate the situation described. The organic pollutants carried by particulates include not only pesticides (Ghadiri and Rose, 1991) but also endocrine disrupting substances (Zhou et al., 2007).
Changes in environmental conditions, such as may result from climate change can also influence environmental behaviour of pesticides through effects on biotransformation. For example, aldrin, applied to the soil surface will, given time, epoxidize and the pesticide transported to lower layers of the soil will consist of a mixture of aldrin and its epoxidation product dieldrin. Under relatively dry conditions, the epoxidation will be able to proceed to a greater extent before transport out of the aerobic layer of the soil occurs. In contrast, under comparatively wet conditions, the aldrin and dieldrin will be transported out of the surface layer before conversion has proceeded to such a significant extent. The effect is most noticeable with clay soils, (Figure 5) where pesticide transport is relatively slow, compared to sandy soils (Sadler et al., 1997).

Climate change also has the potential to affect behaviour of organic pollutants through effects on biomagnification. Macdonald et al., 2002 suggested that environmental processes could be classed as either solvent switching or solvent depletion, depending upon whether or not they involve a change in fugacity. It was further hypothesized that solvent depletion processes, which involve a fugacity change are more likely to be affected by climate change through alterations to trophic structure or by changing efficiencies of fat transfers (i.e. extent of solvent depletion (Macdonald et al., 2003a). Because biomagnification is a solvent depletion process in contrast to bioconcentration, it will be the more susceptible to climate change. Some evidence in support of this has been produced particularly in Arctic regions. The trophic magnification factors for \( p,p' \)-DDE are consistently positive and vary by a factor of 2 from tropical to polar latitudes in freshwater food webs (Kidd et al., 2005,)

### 3.2 Distribution of Heavy Metals

Many of the observations regarding the effects of climate change on the behaviour of organic pollutants will have parallels as regards heavy metal distribution. Although in their inorganic form, most heavy metals (with the important exception of mercury) are probably not subject to global distillation, long-range atmospheric transport is an important phenomenon. Lee et al. (2007)
studied the content of the air masses in Hong Kong and Guangzhou and produced evidence of long-range transport of heavy metal contaminants from the northern inland areas of China to the South China coast. Using back trajectory analysis, Lee et al. were able to identify three separate air masses that would transport different heavy metal pollutant loads to the study areas. Winter months were characterized by higher $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{208}\text{Pb}/^{207}\text{Pb}$ ratios, indicating the influence of northern inland areas of China and the Pearl River delta, whilst the lower ratios observed during the summer months indicated the South Asian region and marine sources.

Clearly, climate change has the potential to alter these transport patterns through effects upon prevailing winds and currents. For example, wind shifts on one of these days produced enhanced levels of Cd, Cu, Mn, Pb, V and Zn at one of the Hong Kong monitoring stations. This resulted from a modified trajectory in which the air mass picked up significant vehicle and industrial emissions from China and Taiwan.

Climate change stressors also have the potential to alter the behaviour of heavy metals in water, soils and sediments and these effects will predominantly be manifest in the “local” as opposed to the regional environment. One of the most important climate change effects influencing the behaviour of heavy metals will be a change in frequency of extreme weather events. This has particular relevance to the APR in terms of heavy metal export from agricultural land (Ongley, 1996) urban areas (Al-Mamun et al., 2006) and mine sites (Jones et al., 1999). It is generally agreed that the transport of heavy metals from these non-point sources will occur almost exclusively as particulates and the details of this process are further considered in the following section. The result is an increase in levels of heavy metals in sediments. As with the air emission study in Hong Kong, (described above) lead isotope ratios have been used to trace the origin of heavy metals deposited in sediments (Vicente-Beckett et al., 2006). Even in areas where climate change projections are for decreased rainfall, overall stormwater runoff resulting from more intense extreme weather events is seen as the major process by which climate change will affect the
transport of heavy metals in the environment (Bridgewater, 1999). In addition to export from agricultural and other lands, extreme weather events will also cause increased pollutant loads through their effects on improperly stored chemicals. This would be of particular significance to some countries of the APR, where chemical storage standards are rather lax.

Moreover, it should be noted that some contaminants such as mercury scale with river flow. Even if an average annual river flow remains constant, a river may shift to more episodic peak and low flows as a result of climate change. In such a situation, the river could be expected to transport more mercury. The phenomenon, which has been demonstrated with respect to snowmelt in Vermont (cf. Stanley, et al., 2002) would also be applicable to climate change-induced perturbations of this kind.

Rises in sea level, which have been predicted to accompany climate change and are already being observed in some South Pacific Islands, provide a significant pathway by which the environmental behaviour of heavy metals may be altered. Considerable effort has been devoted to understanding the situation that may exist in the case of mangrove communities (cf. Gilman et al., 2006).

Mangrove forest sediments can provide a sink for trace metals because the mangroves create a baffle that promotes the accumulation of fine-grained organic matter-rich sediment, which is usually sulfidic due to the presence of sulfate-reducing bacteria. Direct adsorption, complexing with organic matter, and the formation of insoluble sulphides all contribute to the trapping of metals. The concentration and chemical speciation of the metals are influenced by the distribution of geochemically distinct horizons within the sediment. In horizons with a pH > 7 and an Eh < - 150 mV (reduction horizons), metals are largely present as sulphide-bound species, whereas in horizons with a pH < 7 and an Eh > + 100 mV (oxidation horizons), most metals are present as exchangeable or oxide-bound species (Clark et al., 1998). Mangrove soils in the intertidal zone provide a convenient sink for anthropogenic inputs of heavy metals (Tam and Wong 1996).
Of the various climate change factors that could potentially affect the growth of mangroves viz. increased temperatures, increased levels of CO$_2$ and rise in sea level, the latter is considered to be probably the most significant (Field, 1995). Studies with mangroves in pot culture have revealed a decrease in mangrove growth with increased water levels (Ellison and Farnsworth, 1997). If translated into the mangrove ecosystem, the resulting changes in the community could be accompanied by expression of the acid producing potential of mangrove soils (Mackey and Mackay, 1996), with a concomitant redistribution of heavy metals sorbed to this matrix.

Rising water levels associated with global climate change may also have implications for the methylation of mercury and its accumulation in fish. There are indications of increased formation of methyl mercury in small, warm lakes and in many newly flooded areas (UNEP, 2003). Although no data are available for the Asian or Southern Pacific region, a recent study by Sunderland et al., 2009 has suggested a rise in the observed mercury concentrations of the Northern Pacific probably results from lateral transport of Asian anthropogenic deposits. Moreover, the authors demonstrated a positive relationship between increasing rates of organic carbon remineralization and methylated Hg concentrations, pointing to a link between organic carbon utilization and mercury methylation in the open ocean. It was therefore concluded that settling particulate organic carbon could provide a source of inorganic mercury to microbiially active subsurface waters and by furnishing a substrate for microbial activity, facilitate water column methylation. Thus, the increased primary productivity that can be expected to occur from increased temperatures and nutrient inputs as a result of climate change in the APR could be expected to result in increased mercury methylation and to have consequences for other parts of the world as well.

It may also be inferred from studies of arctic lakes that climate change has the ability to affect mercury fate (Outridge et al., 2007; Stern et al., 2009). High Arctic lakes such as those studied by Outridge and co-workers are ideal for investigating the effects of climate change on contaminant cycling, because their carbon sources and biological communities are simplified compared to those...
other areas. From studies of sediment cores in two arctic lakes, these workers concluded that
around 78% of the observed mercury increases in these study sites were due to autochthonous
primary productivity increases, via scavenging by algae and/or suspended detrital algal matter.
Only the remaining 22% could be attributed to long-range atmospheric transport.

It is clear that both algal scavenging and transport processes would be positively influenced by
climate change. Algal scavenging would be a particularly important process for food webs and the
increase in primary productivity within the arctic has been implicated as a causal factor for
increases in mercury levels of Ringed Seals (Gaden et al., 2009).

The significance of these processes to the wider APR is less clear. But of the factors identified by
Outridge et al., (2008), the following could be expected to be positively affected by climate change
in the more general areas of the APR: Coastal erosion; Marine primary productivity and mercury
scavenging; Mercury methylation. As pointed out by Outridge et al., (2008), far less is understood
in terms of the process of mercury demethylation and particularly the extent of the process at lower
latitudes. A further investigation of this factor is required before definite predictions can be made
for tropical and sub-tropical waters.

Ocean acidification has the potential to release metals from sediments. As regards most elements in
normal aquatic environments, significant shifts in speciation generally do not occur close to the pH
that is usually encountered. Hence, the magnitude of the changes projected in ocean pH as a result
of climate change (see section on coral reefs below) is unlikely to cause significant changes in any
but the most sensitive elemental equilibria. Around pH 8 however, cadmium exhibits a transition
from the insoluble carbonate to soluble ions (USEPA, 2007). Thus, decreases of ocean pH could
cause a significant liberation of cadmium existing in the carbonate form. Cadmium exists as a
carbonate both in minerals and also coral skeletons (Matthews et al., 2006). It is of significance that
cadmium has also been identified as the prosthetic group in diatom carbonic anhydrase (Lane et al.,
18
Another possible pathway for entry of a specific heavy metal into the environment as a result of climate change is the use of copper as an algicide. The potential for increase in harmful algal blooms as a result of climate change is discussed in a subsequent section and similar comments also apply to aquatic macrophytes. Copper sulfate dosing is frequently used as a means of controlling growth of nuisance plant species in water bodies and this practise will almost certainly become more prevalent, in areas where climate change results in a proliferation of this kind. Because of the relatively rapid sorption of copper ions onto sediments, the effects of such dosing will generally be limited to an area close to the point of application, although copper ions sorbed to suspended particulates may be transported further. Both sedimentary and suspended particulate copper will be subject to re-release phenomena.

Finally, it is possible that other effects of climate change may exert an influence on the environmental behaviour of heavy metals. For example, an increased delivery of plant nutrients, is a likely consequence of climate change (see below). This process has been shown to reduce metal uptake by certain aquatic plants which are an important part of the Asian ecosystem (Göthberg et al., 2004).

### 3.3 The Role of Particulates

It is clear from the previous discussion that changes in the transport and distribution of particulates in all sectors of the environment will be one of the key consequences of climate change. Particulates can interact with the so-called “global distillation” phenomenon. But the sorption of
organics, heavy metals and other environmental agents onto particulates (cf. Kookana et al., 2002) will afford a means of transport through a number of alternative pathways.

The same process will have consequences for nutrient transport, through the movement of bound nitrogen and phosphorus forms (Hunter et al., 2001). In terms of the sorption of chemicals by soils and sediments, key factors identified include organic matter and clay contents, soil pH, water content and temperature (Ahmad and Kookana, 2002). Amongst these parameters, those most likely to be affected by climate change are organic matter content, water content and soil temperature. It is well known that organic matter plays a major part in the process (Karickhoff, 1981). Hence, any process with the potential to alter the soil organic matter component will have the ability to change the extent to which chemicals are sorbed to organic phases in soils and sediments. Soil organic matter is more rapidly mineralized under tropical rather than temperate conditions (Grisi et al., 1998). Hence, increased temperatures associated with climate change (particularly those arising from short-term perturbations, particularly in daily minima) would lead to more rapid metabolism of soil organic matter. It is interesting to note that there is some evidence for control of soil organic matter properties by the temperature:precipitation ratio (Zech et al., 1989).

Soil organic matter may be roughly broken down into the categories of humic and non-humic components, the humic matter generally being a stronger sorbent for non-ionic compounds. Aromaticity of soil organic matter is a key factor in the sorption of non-ionic pesticides as are the lignin and charcoal contents (Ahmad and Kookana, 2002).

Soil temperature is known to influence the sorption behaviour of chemicals, although the effects are compound-specific or at least specific to particular groups of chemicals. In some cases, elevation of temperature leads to greater sorption of certain types of pesticides and in other cases, it results in decreased sorption (Ahmad and Kookana, 2002). Thus, increases in mean temperature associated

with climate change can be expected to change pesticide sorption characteristics, but it is not possible to make general predictions.

In the case of inorganic contaminants, many of the processes described above will again be operative. The association of metals with particulates is a product of the effect of complexing ligands, ionic strength, pH and the competition of solutes for the surface sites (Strawn and Sparks, 1999). Clearly, all of these parameters may be altered in a climate change scenario. In addition, the equilibrium constants for the reactions vary as a function of temperature. Hence, increased water temperatures associated with climate change will also affect these complexation reactions.

Evidence has also emerged that the particle concentration (or at least apparent particle concentration) can affect the particle association constant. This may reflect aggregation of particles or bridging of particles by species such as phosphate. Either way, it is clear that the climate change-induced increase of particle concentration also has the potential to affect sorption behaviour of metals. The magnitude of the observed effect varies depending on conditions and the specific heavy metal involved.

Whilst most attention as regards particulate-mediated transport of sorbed contaminants has concentrated on movement of suspended sediments by water, this is by no means the only pathway available. Sorbed contaminants can be moved by transport of fine particulates through the air. Australia and China are just two countries in the APR to record an increased frequency of dust storms in recent years. This pathway has particular significance in the case of desertification, associated with climate change. Erel et al. (2006) have noted the importance of this pathway for the transport of pollutants by desert dust storms in the Middle East. Evidence has also been obtained suggesting the transport of various compounds with African dust to the Caribbean (Prospero and Nees, 1986). Although the origin of the particulates is soil, they are commonly found to be enriched in heavy metal pollutants such as mercury. Unfortunately, much less information is available.
available regarding the mechanisms for sorption of inorganic or organic pollutants to airborne particulates than for the corresponding situation with sediments.

Contaminants in soil may be mobilised as a result of colloid-facilitated processes (cf. Grolimund and Borkovec, 2005). It is likely that climate change will increase colloid-mediated transport in soils, through the operation of several processes. Longer periods of dry weather will tend to increase cracking of soil, and allow channelling of particulate-containing aqueous phases. In addition, extreme weather events will have the effect of causing sudden decreases in divalent cation concentration on the surface layer, hence promoting colloid release.

It is more difficult to speculate on the effects that climate change may have with respect to organic pollutants sorbed to atmospheric particulates. A limited amount of work has been undertaken with regard to the effect of seasons on the sorption of PAHs to particulates in the APR and the results are conflicting. Panther et al. (1999) identified the factors that would be expected to influence atmospheric levels of PAHs as: (1) increased photolytic degradation during the summer, (2) transport of pollutants from other sources, (3) removal of PAH via wet deposition and in-cloud scavenging mechanisms and (4) volatilisation of lower molecular weight species during periods of high temperature. Similar results were obtained by investigators who studied benzo(a)pyrene levels in the atmosphere of three New Zealand cities (Khanal and Shooter, 2004). Park et al. (2002) identified temperature and humidity as the most important environmental factors controlling the levels of the more volatile PAHs in Seoul’s atmosphere. Hien et al. (2006) believed that changes in wind direction and speed were the major causative factor of the observed seasonal differences in Vietnam.

Thus, higher temperatures associated with climate change might lead to increased loss of volatile PAHs from particulates, and altered large-scale wind patterns (cf. Pierrehumbert, 2000) could lead to a global redistribution of PAHs increasing levels in some areas. Photolytic degradation could be
increased during the relatively cloud-free periods associated with lengthy dry weather, while the relative importance of wet deposition and cloud scavenging mechanisms would decrease.

Particulates and Ecological/Public Health Effects.

Particulates can exert an effect upon public and/or ecological health in a number of ways. Firstly, through direct effects of the particles themselves and their sorbed contaminants. The situation is far more complex than is reflected by gross metrics such as PM$_{2.5}$ (Samet et al., 2005). Correlations between levels of air particulates and public health effects have already been implied by studies of the effects of forest fires in South-East Asia. Moreover, it has been shown that the majority of PAHs sorbed to roadside dust in Asian cities are correlated with the respirable (<0.5 µm) fraction (Hien et al., 2006).

The concept of sorbed contaminants and public health effects has received some attention, but far less consideration has been given to the possibility that particulates themselves may have a direct effect. Clearly, this is the case with aerosols, such as those containing acidic components (Gwynn et al., 2000). General increases in such aerosols are predicted as a result of climate change, although given the affinity of acid aerosols for particles, it is quite likely that they will exert their effect as sorbates rather than as acidic aerosols per se (IPCC, 2007a).

An increase in harmful algal blooms is another possible consequence often linked with climate change in at least some areas of the Asia-Pacific region (Garnett et al., 2003). The so-called ‘red tide’ events (resulting from dinoflagellate blooms in ocean waters) are associated with the
production of a variety of toxic compounds, which often exert their public health effects through accumulation in the muscle tissue of edible seafood. But it has also been shown that aerosols arising from red tides also carry toxins. Cheng et al. (2005) observed brevitoxin-containing aerosols from a red tide of *Karenia brevis* in the Gulf of Mexico. The toxin was associated with particles of diameter 6-12µm and the workers speculated that the aerosol may have been produced by a breakup from whitecap waves.

Secondly, it has been shown that dust particles are effective vectors for the transport of marine diseases (Harvell et al., 1999) and there can be little doubt that the same is true of human diseases as well (Griffin et al., 2001).

It can safely be assumed that this pathway of transport for both pollutants and diseases will increase as a result of climate change events.

### 3.4 Acidification of Oceans

The topic of ocean acidification and climate change has been the subject of a recent review (Doney et al., 2009). Since the beginning of the industrial era, the oceans have absorbed 127 ± 18 billion metric tons of carbon as carbon dioxide from the atmosphere. Although this absorption has some positive benefits on the reduction of global warming, it can potentially have a deleterious effect on marine systems. It has been estimated that about half of the carbon dioxide arising from fossil fuel combustion and cement manufacture has found its way to the oceans and resides in the upper 400m (Thacker, 2005).

A prediction of the expected shifts in chemical species can be made from Eh-pH diagrams (Snoeyink and Jenkins, 1980). The concentration of calcium carbonate present in the water column has been shown to have a direct relationship to the growth rate of corals and hence any process that reduced the concentration of the carbonate species (e.g. a fall in pH) would potentially decrease
calcification (Hoegh-Guldberg et al., 2007). This has been observed in at least some laboratory studies. The possibility also exists that acidification of the oceans could lead to calcium carbonate dissolution, as would be predicted by equilibrium diagrams (Buddemeier et al., 2004, Kleypas et al., 2005).

Compounding the effects of acidification and temperature changes on coral bleaching and reef degradation are the effects of agricultural and urban runoff. These could reasonably be expected to contain herbicides and other pesticides, plus elevated levels of sediments (WHO, 2000, AAS, 2003). The presence of photosystem II herbicides in runoff has the potential to inhibit photosynthesis by organisms that live in symbiosis with coral reefs (Shaw et al., 2008,). This in turn is predicted to act synergistically with elevated temperature in causing coral bleaching and reefal degradation.

Two different forms of calcium carbonate are produced by marine organisms. Corals and molluscs secrete aragonite, whereas foraminifera and calcifying macroalgae secrete calcite. The few studies that exist suggest that increased carbon dioxide levels in oceans will also reduce calcification rates amongst these organisms (Kleypas et al, 2005, Doney et al., 2009). There can be expected to be particular sensitivity in areas with shallow aragonite horizons, such as the North Pacific. The uptake of anthropogenic carbon dioxide has caused these horizons to shoal by 50 to 100 m since preindustrial times so that they are particularly subject to upwelling processes (Feely et al., 2008). Such regions will be hotspots for ocean acidification effects on coral reefs.

The translation of atmospheric CO₂ levels into ocean pH is a more difficult operation than it might seem. It has been estimated that atmospheric emissions of 5000 Pg C and 20,000 Pg C would produce global ocean surface pH reductions of 0.8 and 1.4 units, respectively, by the year 2300. At the lower level, the surface ocean would be undersaturated with aragonite and at the higher level, it would become undersaturated with respect to calcite as well (Caldiera and Wickert, 2005).
When predicting the effect of climate change on corals or any other calcifying organisms, it is important to realize that these organisms will also be subjected to other stresses, in addition to those resulting from increased carbon dioxide. Although accurate predictions can be made of the effects of acidification by the use of modelling, the role played by temperature increases and other effects of climate change need to be taken into account. Claims have been made for both antagonistic and synergistic effects of acidification and temperature with respect to coral growth (Thacker, 2005).

### 3.5 Nutrients in Aquatic Systems

It is clear that nutrients will be affected significantly by the climate change scenarios described. A long-held cornerstone of describing the behaviour of nutrients in the oceans has been the co-called Redfield ratio – i.e. that C:N:P will lie in the ratio of 106:16:1. This ratio has been established as a fairly universal parameter. However the situations induced by climate change may not satisfy these criteria and hence Redfield ratios may not apply under such conditions. This has been observed in at least some instances (Thacker, 2005).

Michaels et al (2001) discussed possible models for nutrient behaviour in ocean ecosystems, with particular reference to climate change. They considered input of nutrients from dust storms to be of particular significance to this process and noted that, in contrast to the classical Redfield model, at least some components of the C, N, P system would not be at steady state conditions, under the influence of climate change. Associated with such conditions would be increased uptake and fixation of CO$_2$ and probably nitrogen, in addition to deposition of organic nitrogen-containing particulates. In terms of transport of nutrients, dust has been shown to be a significant factor as regards both Asian and African systems (Garrison et al., 2003).

Because of the involvement of ferredoxin in nitrogen fixation, this process has a high requirement for iron. The possibility exists that some of the iron requirement will be satisfied via dust
deposition (Boyd et al., 2004). Through this pathway, climate change may result in enhanced nitrogen fixation. In a study conducted in the North Pacific, Young et al. (1991) suggested that the arrival of an atmospheric dust plume gradually converted the ocean phytoplankton ecosystem from a situation of iron limitation to one of limitation by other nutrients.

In assessing the overall effects of climate change on nutrient behaviour in aquatic environments, it is important to consider not just the static pool sizes of the substances involved, but also the dynamic situation. The data required for successful operation of these models will therefore represent an increase in sophistication over the relatively simplistic “total” parameters currently used to represent nitrogen and phosphorus. Figure 7 summarizes some of the processes that would lead to changes in the Redfield Ratio, outlined above (cf. Michaels et al (2001)).

Not a great deal is known regarding the bioavailability of the nitrogen and phosphorus fractions associated with particulate matter and the situation is likely to be complex (cf. Sigleo and Shultz, 1993). The value of the available information is limited by the chaetotropic conditions generally used in pre-digestion during laboratory analysis to liberate the molecules from their combined state. The agents employed would release not only bioaccessible fractions but also more firmly bound forms.

4.0 IMPACT OF CLIMATE CHANGE ON BIO-SYNTHESIS OF TOXIC CHEMICALS

Climate Change can be expected to have an effect on harmful algal blooms (HABs). Whilst HABs are a natural phenomenon, the frequency, intensity and distribution of HABs has increased globally in recent decades (Van Dolah, 2000; GEOHAB 2001; Hayes et al., 2001). In the future, there will be increasing interaction between humans and coastal areas. Thus, HABs will likely be an important human health and environmental concern into the future (GEOHAB 2001). Scarcity of water in inland areas as a result of desertification will also mean that supplies may have to be drawn
from sources that were traditionally avoided because of problems with HABs. The main factors affecting the distribution of HABs are nutrients and physical conditions, such as temperature and mixing (Smayda, 1997). Owing to the diversity of HABs, these factors will have different impacts on individual species and will be further discussed.

The increase in HABs in recent decades is believed to be largely due to anthropogenic increases in nutrients (Zingone and Enevoldsen, 2000; Fristachi and Sinclair, 2008). For example, cultural eutrophication is believed to be the main cause of blooms of the toxic dinoflagellate Karenia brevis (Brand and Compton 2007), the toxic diatom Psuedo-nitzschia calliantha (Spatharis et al., 2007) and the toxic cyanobacterium Nodularia spumigena (Sellner 1997). In a study dealing with a specific part of the APR (viz. Queensland Australia), Garnett et al. (2003) observed that increased night temperatures produced increased growth of the toxic cyanobacterium, Cylindrospermopsis raciborskii. At low light intensities, there was a slight negative correlation with toxin production and a slight positive one at high light intensities. Microcystis aeruginosa on the other hand, only exhibited increases in growth rate with increasing temperature at higher light intensities. Mesocosm studies demonstrated the ability of cyanobacteria (particularly Cylindrospermopsis raciborskii to respond quickly to inputs of phosphorus and to a lesser extent, nitrogen). They concluded that Cylindrospermopsis raciborskii could increase its geographical range and/or dominance to more temperate areas of Queensland.

Whilst enhanced nutrient conditions often do lead to increases of HABs, it has also been demonstrated that they may favour the competitors of HAB organisms (Zingone and Enevoldsen 2000). The ratio of nutrients may also be an important factor in determining whether harmful algal species will dominate in a community. For example, Hodgkiss and Ho (1997) attributed HABs in Tolo Harbour, Hong Kong, to a reduction in the N:P ratio. Furthermore, different nutrient ratios would be expected to have varying affects on each taxonomic group of HABs, due to differences in
their physiological attributes (Zingone and Enevoldsen, 2000). For example, toxic cyanobacteria are favoured in high iron and phosphorus conditions, but not in high nitrogen conditions (Hood et al. 2001). These variations in response to nutrients between different taxa of HABs make predicting the response of HABs to changes in nutrients a complex process.

Whilst the diverse range of harmful algal species will have adaptations to different physical conditions, there are some common conditions that are associated with a majority of HABs. Firstly, most HABs have been observed to occur when the waterbody is stratified and thus has limited vertical mixing (eg. Tang et al., 2003; Trainer et al. 2007). This is likely to be because stratification favours dinoflagellates and cyanobacteria, which are the dominant HAB organisms in marine and freshwater environments, respectively (Sherman et al. 1998; Smayda 1997).

The second physical condition common to a number of observed HABs is increased temperatures at the time of the bloom (eg. Tang et al. 2003; Yang and Hodgkiss 2004; Tang et al. 2006). Furthermore, the toxicity of a HAB may be higher at high temperatures, as is the case with blooms of the dinoflagellate *Pfiesteria piscida* (Burkholder and Glasgow, 1997). However, due to the diversity of harmful algae this trend is not always seen. For example, the toxic dinoflagellate, *Alexandrium catenella*, has its distribution limited to temperate waters and has been found to be more toxic at low temperatures (GEOHAB 2001; Sekiguchi et al. 2001).

Climate change involves shifting precipitation patterns with respect to both space and time. Thus, future climate change scenarios will involve both increased precipitation as a result of extreme weather events and also desertification, through perturbation of natural seasons (IPCC 2007a,b). Increased precipitation intensity as a result of global climate change is expected to increase the amount of continental runoff (Labat et al., 2004). Increased runoff leads to an increase in the fluvial supply of nutrients into coastal environments (Ringuet et al., 2003). Therefore it would be expected that HABs would increase in the future due to further increases in nutrients. In the case of harmful
algal species that are favoured in low nutrient conditions, these species may bloom less frequently or become limited in their distribution. However, overall it would be expected that the frequency and intensity of HABs will increase with increased nutrients and that HABs may occur in areas in which they were previously limited by low nutrient levels, therefore expanding their distribution.

An increase in drought frequency from global climate change would be expected to lead to an increase in major dust storm events in a number of countries (eg. Prospero and Nees, 1977; Goudie and Middleton, 1992). The implications of dry deposition in terms of nutrient and iron availability have been described in the previous section. Aeolian deposition of dust is a major source of iron in the global ocean and therefore is believed to a major environmental factor controlling cyanobacterial blooms (Boyd et al., 2004; Michaels et al., 1996; Karl et al., 2002). Thus increased dust deposition as a result of global climate change may be expected to result in increased cyanobacterial blooms. New nitrogen introduced during cyanobacterial blooms through dinitrogen fixation may then allow succession of other phytoplankton species. For example, this was seen to be the case in Florida where blooms of the toxic dinoflagellate *Gymnodinium breve* followed a large bloom of the cyanobacterium *Trichodesmium* (Lenes et al., 2001).

Warming of the oceans and freshwater systems as a result of global climate change would be expected to alter the distribution, frequency and intensity of HABs. Species that are currently limited to warm waters, such as the highly toxic dinflagellate, *Pyrodinium bahamense*, may be expected to increase their range into higher latitudes as a result of global warming. Indeed fossilised cysts of *P. bahamense* reveal that in the past they were also distributed in temperate regions, presumably when temperatures were warmer than they are at present (Zingone and Enevoldsen 2000). Conversely, some species, such as *A. catenella*, that are limited to temperate waters may be expected to have their distribution reduced as a result of increasing sea surface temperatures. Overall, however, there appears to be the general trend that HABs occur during periods of increased temperature (eg. Tang et al. 2003; Yang and Hodgkiss 2004; Tang et al. 2006)
and therefore it would be expected that HABs would increase in the future as a result of global climate change. Historical records support this prediction as it has been found in geological records that HABs were more prevalent in periods of warm sea surface temperatures (Mudie et al. 2002).

Freshwater runoff induces stratification in denser, higher salinity environments (Smayda, 1997). Therefore an increase in runoff as a result of global climate change would be expected to increase stratification in water bodies that did not previously stratify. In the future, stratification may be expected to occur more frequently and to occur in water bodies that did not previously stratify resulting in an increase in the frequency and distribution of HABs.

Ciguatera fish poisoning is an example that has been well studied and is predicted to become more abundant due to the effects of climate change. Ciguatera fish poisoning is produced by the presence of ciguatoxins at the microgram per kilogram level in the flesh of a variety of tropical reef fish (Bagnis, 1993, Pierce and Kirkpatrick, 2001, Chinain et al., 1999, Lewis, 2001). Ciguatoxin precursors are produced by marine dinoflagellates, notably *Gambierdiscus toxicus*, and these precursors are accumulated by herbivorous fish, biomagnified through carnivorous fish species and oxidised to ciguatoxins (Lewis and Holmes, 1993; Backer and McGillicuddy, 2006; Villareal et al., 2006). Usually considered of importance to the Pacific nations, ciguatera is now of considerable significance to Asian countries such as Hong Kong through the import of live reef fish species for human consumption (Wong et al. 2005).

The potential of climate change to result in coral deaths has been described in a previous section. Colonisation of dead corals by filamentous and calcareous macroalgae is common after coral bleaching events and this produces a favourable environment for benthic dinoflagellates such as *G. toxicus* (Backer and McGillicuddy; Villareal et al., 2006; Lehane and Lewis, 2000). It is therefore predicted that an increased incidence and severity of coral bleaching events as a result of global
warming and its secondary effects, will result in an increased frequency of ciguatera fish poisoning episodes (Hall et al., 2007).

In addition it has been reasonably suggested that the range of toxic marine dinoflagellates will extend to higher latitudes, thus producing ciguatoxic fish in locations previously considered to be outside the range of *G. toxicus* colonisation (Patz et al., 2006). Recently ciguatera fish poisoning has been shown to occur from consumption of pelagic carnivorous fish from the Northern Rivers area of New South Wales, Australia (Safefood NSW, 2002). This region has not previously been associated with ciguatera poisonings. Recent research in French Polynesia has identified significant correlations between ciguatera incidence rates and local sea surface temperature increases (Chateau-Degat et al., 2005).

The role of climate change in the expansion of HABs is difficult to test, because of the complexity of overlying issues (e.g. inputs from the increased activity of aquaculture) and a general lack of reliable long-term historical data (van Dolah, 2000). Edwards et al. (2006) examined long-term spatial variability in a number of Harmful Algal Blooms (in the northeast Atlantic and North Sea) using data from the Continuous Plankton Recorder. Over the last four decades, some dinoflagellate taxa showed pronounced variation in the south and east of the North Sea, with the most significant increases being restricted to the adjacent waters off Norway. This was one of the areas, identified through consideration of North Atlantic Oscillation data as being highly vulnerable to effects of harmful algal bloom formation. There currently being no parallel studies in the Southern Hemisphere, a need exists for work in this area, particularly in relation to the Southern Oscillation Index.
CONCLUSIONS

It is clear that climate change has the potential to create a variety of effects within the APR and this review has presented the authors’ opinions on possible changes that may occur. In our view, these effects are not simple or uniform and different effects will be observed across the region. Climate change has implications for both the short and long term behaviour of pollutants at a region-specific level across all environmental media. For example, effects can be predicted in terms of processes including global distillation of POPs, airborne transport of heavy metals, half lives of readily degradable pollutants and eutrophication in water bodies. In terms of HABs, there is the potential for increases in the intensity and frequency of both marine and freshwater species. In particular, it is now becoming apparent that ciguatera fish poisoning will become an increasing health issue in a warming world, as will the presence of certain cyanobacterial toxins in drinking water reservoirs. The central role of particulates in mediating the effects of climate change has been clearly demonstrated and the most successful models in terms of predicting environmental effects of climate change will be those that are centred around particulate-mediated transport and behaviour. Modelling is a useful tool in prediction of effects, but is presently limited by the absence of data required for the model calibration. There thus exists an urgent need for the development of region-specific models, to predict the behaviour of chemicals of concern in the Asian environment. A corollary of this requirement is the collection of data relevant to the development of models and their ultimate calibration.
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FIGURE CAPTIONS

1305 Figure 1. Global map of major ocean currents.

Figure 2. Effect of various environmental parameters on Henry’s Law Constant, of significance to climate change.

Figure 3. Migration processes for POPs as modified by climate change.

Figure 4. Modelling of Diazinon concentration in soil under climate change conditions, showing how small changes in the range of daily temperatures can affect the organism’s persistence.

Figure 5. Effect of prevailing conditions on transformation and soil transport of aldrin. Wet/dry regimes have maximum effect in regions with clay soils and are of less significance in sandy soils.

Figure 6. Schematic diagram showing possible effects of climate change on particulate-mediated transport of pollutants.

Figure 7. Nutrient processes as a result of climate change (modified from Michaels et al. {2001}). Increased inputs of nutrients and iron will be experienced as a result of atmospheric deposition and extreme weather events.