Do coastal cities have a sustainable long-term future?

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Abstract: This paper examines the literature to find a realistic forecast of sea-level change during the coming millennium. Climate change induced by greenhouse gas emissions is put into the perspective of changes in CO_2 concentrations during geological time. Global dimming is currently acting as a negative feedback but in time this effect should reduce and in conjunction with a likely high emissions scenario, temperatures will rise significantly. The resulting sea-level changes during the next millennium will have very serious implications.

Résumé : Ce papier examine la littérature pour trouver une prévision réaliste du changement du niveau de la mer au cours du millénium venir. Le changement climatique induit par les émissions de gaz effet de serre est mis en relation avec les changements de concentration en CO_2 pendant les temps géologiques. L'atténuation globale agit actuellement comme un feedback négative mais cet effet devrait diminuer avec le temps, et en conjonction avec un probable scénario de hautes émission, les températures vont augmenter significatif les changements du niveau de la mer résultants durant le prochain millenium vont avoir de sérieuses implications.

Keywords: climate change

AIM

The aim of this paper is to examine the current predictions for climate and sea level change during the next millennium. A prodigious volume of research, much of it referenced in the IPCC Third Assessment Report (Houghton *et al.* 2001) has been undertaken to predict climate and sea level changes over the next century. Such predictions are subject to uncertainty not only owing to limitations in our knowledge of the earth's climate system but are conditional on the level to which governments will control greenhouse gas emissions. The further we look forward, the greater the level of uncertainty. The predictions for the next hundred years are now quite well known but just what is being predicted for the next millennium? It can be argued that it does not matter for the current and the next one or two generations but if we take 100 years as the upper limit for an engineering design then each passing decade takes us well beyond 2100. Furthermore, a town and country planner conventionally looks much further forward than a civil engineer thinking in terms of the design life of an engineering structure. With large sea-level rises, planned retreat for rural communities is a much easier option than for coastal cities. Providing the warning comes with acknowledgement of the various kinds of uncertainty, then potentially large, and possibly accelerating, sea-level rises cannot be given too much advance notice.

GREENHOUSE GASES

Climate models have convincingly demonstrated that the warming experienced during the previous century can be ascribed to anthropogenic greenhouse gas emissions (Houghton *et al.* 2001). Future emissions are assumed to be the controlling factor in the future climate (although a proviso is warranted here in respect of the incomplete knowledge of the earth's climate system, as suggested, for instance, by Veizer *et al.* [1987]). To answer the question in our title, we need to consider the emissions and how they will influence the future climate.

Carbon dioxide

Of the various greenhouse gases (ignoring water vapour), because of the quantities being generated, CO_2 is the dominant radiative forcing agent. Figure 1 shows past, current and range of predicted atmospheric concentrations. We can examine this diagram to gain some insight into how the current and future concentrations may influence the future climate. At the bottom of the diagram are the various levels associated with the Pleistocene ice ages. Both the Holocene record at 8 ka BP and the pre-industrial level are well within the maximum concentration associated with interglacial stages. Ruddiman (2003, 2005) has suggested that the 8 ka BP and the pre-industrial levels show evidence of anthropogenic influence on the grounds that at these dates, an interglacial stage would normally be well past the peak concentration of CO_2. The current (2004) concentration at 377 ppm is well above the peak of any interglacial stage and thus gives cause for concern, Imbrie & Imbrie (1979) using the phrase "super interglacial" to describe what may be in store.

The complexity and inertia associated with the earth's climate system is such that one cannot simply equate a given CO_2 concentration with climate state. Examination of ice core records (Fischer *et al.* 1999) suggests that increases in CO_2 concentrations did not initiate the glacial stage terminations but followed them, acting as a positive feedback to augment the warming phase. Other aspects of the climate system were responsible for the climate swings and the latter in turn, promoting the changes in CO_2 concentration, perhaps from changes in the "biological pump" (Pedersen & Bertrand 2000, Sigman & Boyle 2000) or maybe as a result of changes in sea ice (Stephens & Keeling 2000). As the CO_2 concentration rose, so there could be no return to glacial conditions until the very slow processes of the carbon cycle (Berner 2003, Sundquist 1991) gradually reduced it. It is pertinent to compare the rates of increase in CO_2 which occurred at the glacial terminations with the current rates of emission. Using the data given by Fischer *et al.* (1999), the rate of increase during the terminations was about 1 ppm per 40 years but during the 1990s the rate due to the greenhouse emissions ranged from 1 to 3 ppm per year.

Large changes in CO_2 occurred over Phanerozoic time (Berner 2004) owing to the operation of the carbon cycle as assisted by the evolution of vascular plants. Berner (2004) demonstrates that decreases in concentration of the order of several thousand ppm can provide conditions suitable for the onset of glaciation. It is evident that very large changes will exert an overall control but small changes occurring at slow rates, such as those during the Pleistocene, appear insufficient to act as a climatic mode switch from glacial to interglacial and vice versa. Similarly, we can note a general decrease in greenhouse gases during the Cenozoic (Pearson & Palmer 2000), which, in broad terms, can be related to the gradual increase in episodes of glaciation. However, there is no exact correlation as the glacial episodes were also related to other factors including the distribution of the continents and the opening and closing of seaways (Zachos *et al.* 2001).

At the high end of the scale, CO_2 concentrations in the order of 1800-3600 ppm (Pearson & Palmer 2000), can be held responsible for the geologically transient episode of extreme warmth known as the Palaeocene/Eocene Thermal Maximum (PETM). Although the major source of CO_2 in the PETM was almost certainly volcanic (Owen & Rea 1985, Zachos 2003), a significant contribution occurred from release of methane hydrate, subsequently oxidised to CO_2, (Svenson *et al.* 2004, Tripati & Elderfield 2005, Weissert 2000). Although the methane release would have made for a rapid increase in greenhouse gas concentrations, actual warming of 5 to 10° C took place over a period of about 35 ka (Bowen *et al.* 2004) giving an average rate of temperature increase that would not be noticed on a human time scale. With the very high concentrations of CO_2, a very warm world was inevitable with a climatic state that appears to have involved very high levels of humidity (Bowen *et al.* 2004).

CO_2 concentrations predicted for 2100 AD as resulting from various emissions scenarios, range from 540 to 970 ppm. Only the lower end of this range, with strictly controlled emissions (such as the B1 scenario, Houghton et al. 2001) yields stable concentrations as at 2100. As seen in Fig. 1, the predictions are located between the concentrations of the Pleistocene and the PETM. With the larger predicted values, and their associated increasing concentrations beyond 2100, the conclusion must be drawn that the atmospheric composition will be, if it is not already so, out of equilibrium with the earth's climate system. Owing to the rapidity of the climate forcing induced by anthropogenic emissions the geological past does not provide suitable analogs for the present (Crowley 1990). The inertia of the earth's climate system could ensure that the rates of equilibration will be slow on human scale terms but others warn of the possibility of unexpected changes (Broecker 1987). While careful attention should be given to results from the current generation of climate models, it is important not to lose sight of a telling phrase used in the IPCC Third Assessment Report (Houghton *et al.* 2001) which is that "*the rapid forcing of a non-linear system has a high prospect of producing surprises*". What these surprises could be, we can only speculate but it is important to keep this possibility in mind while we examine the predictions based on our current understanding of the system.

Methane

Although it is a more effective greenhouse agent than CO_2, methane exists in much smaller quantities (Dickinson & Cicerone 1986). A major fear has been expressed that it could be dramatically increased from melting permafrost (Smith 2004, Pearce 2005b), burning peat (Pearce 2002) or by release of methane hydrate from rising ocean temperatures (Nisbet 1990, Weissert 2000). On the long-term time scales we are considering here, methane itself is not a problem owing to its limited atmospheric residence time. The concern is more that rapid release, by the before mentioned mechanisms, could act as a trigger for non-linear responses from the climate system (such as occurred during the PETM, Bowen *et al.* 2004, Dickens 2004). Currently there is a decrease in the rate of methane accumulation in the atmosphere (Khalil 2000) of unknown origin but which could relate to changing industrial and /or agricultural practices.

Global dimming

The seemingly confident prediction of increased global warming in the near future leads to the question of why is there not more evidence for a markedly rising trend? The answer is that global dimming is to an extent counteracting the warming trend. Global dimming is the reduction in direct solar radiation at ground level due to a build-up of haze composed of aerosols and particulates (Anderson *et al.* 2003). Observations in different regions have shown that the haze is not only concentrated within large conurbations but is worldwide (Liepert 2002, Roderick & Farquhar 2002, Pinker *et al.* 2005, Wild *et al.* 2005). Increased condensation as clouds has also been noted as a consequence of the reduction in arctic sea ice and acting to offset temperature rise at low levels (Wang & Key 2005). Climate models confirm that clouds can act as significant negative feedbacks during global warming (Mitchell *et al.* 1989). Haze consisting of aerosols and particulates is a health hazard and we can assume that smoke laden emissions will be significantly reduced within a short-term time scale. Thus it is to be expected that as the global dimming phenomenon is gradually reduced, the climate will begin to show marked increases in temperature (Andrae *et al.* 2005, Wild *et al.* 2005).

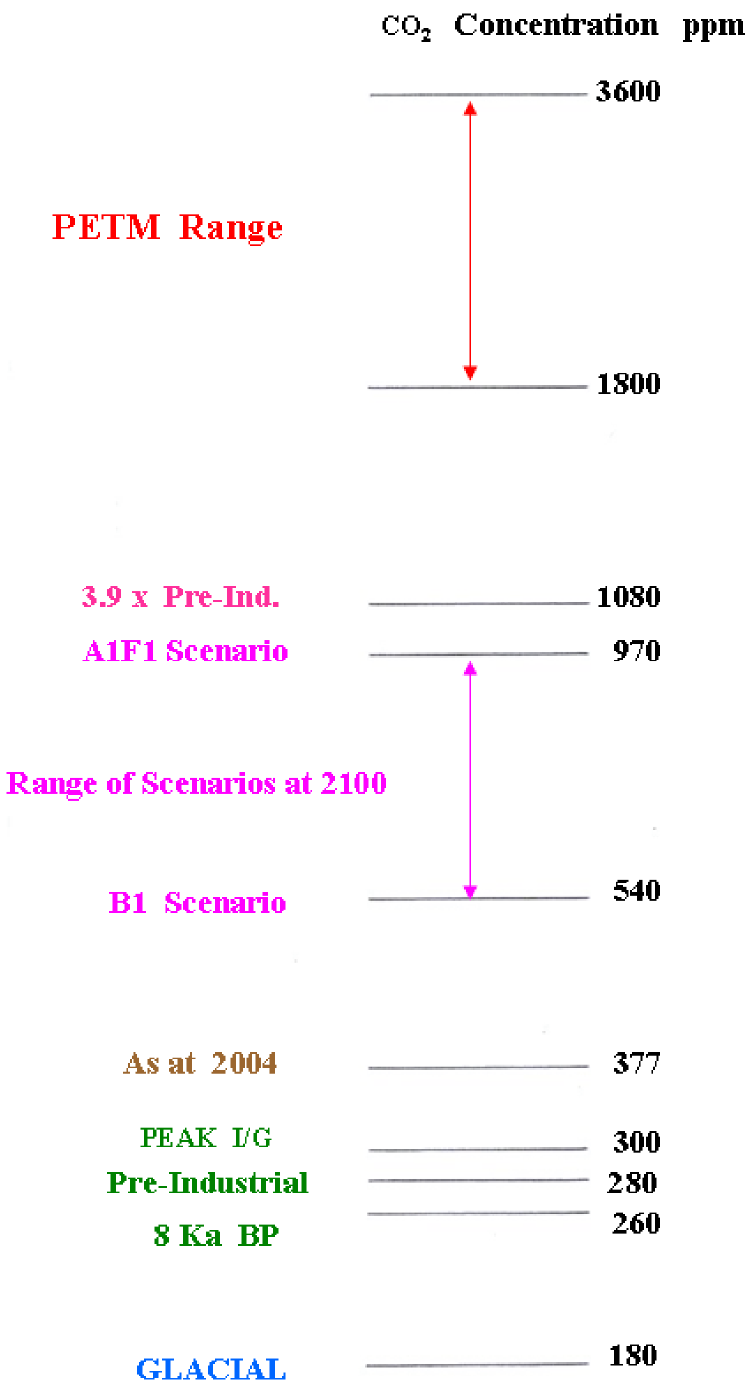

Figure 1. Past, present and possible future atmospheric concentrations of CO_2 ppm. The vertical scale is plotted on a logarithmic basis in accordance with the radiative effect of increased concentrations.

SEA LEVELS

Sea level changes are subject to the same uncertainty as greenhouse gas emissions; namely they are dependant upon the operative emissions scenario. Uncertainties also arise in respect of the response of the various sources to global warming so we will proceed to examine each of the sources of sea level change in turn.

Thermal expansion

Thermal expansion of ocean water has a long time scale owing to the weak diffusion and slow circulation processes which transport heat to the deep ocean. With the current global warming this process has now been set in motion and can be expected to take many centuries to a few millennia for completion (Wigley 2005, Meehl *et al.* 2005). The IPCC Third Assessment Report offers two sets of predictions according to whether CO_2 emissions eventually stabilise at concentrations of either 540 or 1080 ppm. These correspond to approximately 2X or 4X pre-industrial CO_2 respectively. Varying results are obtained from the different climate models employed. A concentration of 540 ppm seems unduly optimistic, being at the maximum control end of the emissions scenarios. The conservative estimate of 1080 ppm is more realistic and may provide a margin of error on the safe side. For the first 1,000 years, the various models give a range of eustatic sea-level rises of 1 to 3.3 m. With our aim of obtaining an estimated rise for the end of the coming millennium (3000 AD), we can take the average value of 2.15 m.

Small glaciers and ice caps

It is estimated that melting of all the small glaciers and local ice caps would raise sea levels by 0.5 m (Houghton *et al.* 2001). Although some have been monitored, particularly in the Northern Hemisphere, their widely scattered distribution with many occurring within areas not subject to systematic surveys, provision of a reliable estimate of the *average total* rate of change presents considerable difficulties. An attempt to overcome this problem was undertaken by Meier (1984) by using a hydrometeorological mass balance model. His results indicated a sea level rise of 0.46 mm per year over the period from 1900 to 1961. Serious depletion of high-level glaciers is now in progress (Barnett *et al.* 2005). With the warming envisioned by the upper range of climate scenarios, we expect serious retreat to continue but with a reduction in water volume as the glacier margins retreat to higher altitudes. We may assume a 60 % decrease in the total ice volume over the next millennium with a consequent total eustatic sea level rise of 0.3 m.

Greenland

The Greenland ice sheet is the most vulnerable of the two major ice sheets. Coupled atmosphere and ocean global climate models show that the largest temperature changes are located in the high latitudes of the northern hemisphere (where the temperature increases could be between 1.2 to 3.1 times the global average). As well as being within the zone of maximum temperature change, Greenland is also exposed to ocean current changes in the North Atlantic and adjacent seaways, the coastal climate then influencing the ablation rate of the ice sheet margins. A reduction in the volume of the Greenland ice sheet is believed to have occurred during the penultimate (Ipswichian) interglacial (Cuffey & Marshall 2000). Gregory *et al.* (2004) calculate that the critical annual temperature marking the threshold between stability and net depletion is 2.7 °C (± 0.5 °C) and that most projected CO_2 concentrations exceed this value. Huybrechts and De Wolde (1999) predict eustatic sea level change from depletion of the Greenland ice sheet for three warming scenarios during the coming millennium. Taking the middle of these as representing the likely emissions scenario, we obtain a figure of 3.2 m by the year 3000 AD.

The West Antarctic Ice Sheet (WAIS)

The recognition that the WAIS, which holds a volume equivalent to a eustatic rise of 6 m, consisted largely of grounded ice raised serious concerns about its stability but later studies suggested that its collapse would be very long term rather than a catastrophic event (Mercer, 1978, Thomas *et al.* 1979). Comparison has been made with the Barents Sea ice sheet which was also grounded ice and which disappeared in the late Devensian (Siegert *et al.* 2002). Although it is re-assuring to note that this took an estimated 3,000 years to break-up, the deglaciation was not taking place at a time of accelerated global warming. Recent studies by Conway *et al.* (1999) indicate that grounding-line retreat of the WAIS has been proceeding steadily since the LGM and that current observations merely fit into this pattern rather than being an acceleration. Nevertheless, observations indicating collapse took place during at least one of the interglacial stages (Scherer *et al.* 1998) provides fresh cause for concern, augmented by the recent spectacular break-up of the Larsen B ice shelf around the Antarctic Peninsula (Domack *et al.* 2005). Further studies involving ice sheet dynamics and melting rates, have given widely varying results (Houghton *et al.* 2001). The model of Warner and Budd 1998 shows that for moderate global warming, the rate of basal melting is the dominant factor. For the first few centuries, the major change is a reduction in the volume of the protecting ice shelves but after this the WAIS is progressively reduced. The sea level rise is to some extent offset by increased accumulation elsewhere, leaving a net rise of 1.5 m by 3000 AD.

East Antarctic Ice Sheet

This has been a continuous feature since at least the mid-Miocene (Zachos *et al.* 2001). While most emissions scenarios indicate that this ice sheet will remain in mass balance, some indicate that because of increased snowfall, the ice sheet may grow. The latter results have received some confirmation from recent satellite radar altimetry measurements which indicates some ice sheet growth and considered to be slowing sea-level rise by 0.12 mm / year (Davis *et al.* 2005). For a conservative estimate of sea level rise by 3000 AD, we will assume a mass balance during the next millennium.

Estimated sea level rise during the next Millennium

The figures we have taken from the various sources are summed in Table 1 with the rate of rise shown in Figure 2. These figures represent a eustatic rise, but it must be noted that because of both the changing climate and the increasing heat within the oceans, there will be substantial regional differences, especially in relation to thermal expansion. The large value obtained by 3000 AD will also engender a hydro-isostatic response so again there will be further regional differences. The value shown represents an average eustatic change, to be summed according to local land movements to give the relative sea level change at any location. Eustatic changes may also be involved with changes in hydrological regimes, melting permafrost, reservoir impounding and land drainage but no reliable estimates of these can be given for the next millennium and they are therefore ignored.

The totals given in Table 1 are derived from the various references quoted above, and where faced with conflicting predictions, those selected can be taken to represent a fairly high but still realistic, emissions scenario. A rather more pessimistic prediction for the next millennium was given by Lowe *et al.* (2005) who suggested a figure of 6.5 m for the rise of sea level, without taking into account any contribution from small glaciers and the WAIS. Clearly, these totals will be subject to revision as knowledge of the earth's climate system, and the models used for its analysis, improves. That being said, we will use Table 1 for a preliminary answer to the question in our title.

Table 1. Estimated contributions from four main sources to eustatic sea-level rise during the next millennium, based on the references given in the text.

Source	***Rise (m)***
Thermal Expansion	2.15
Small Glaciers & Ice Caps	0.30
Greenland	3.20
West Antarctic Ice sheet	1.50
Total Rise	7.15

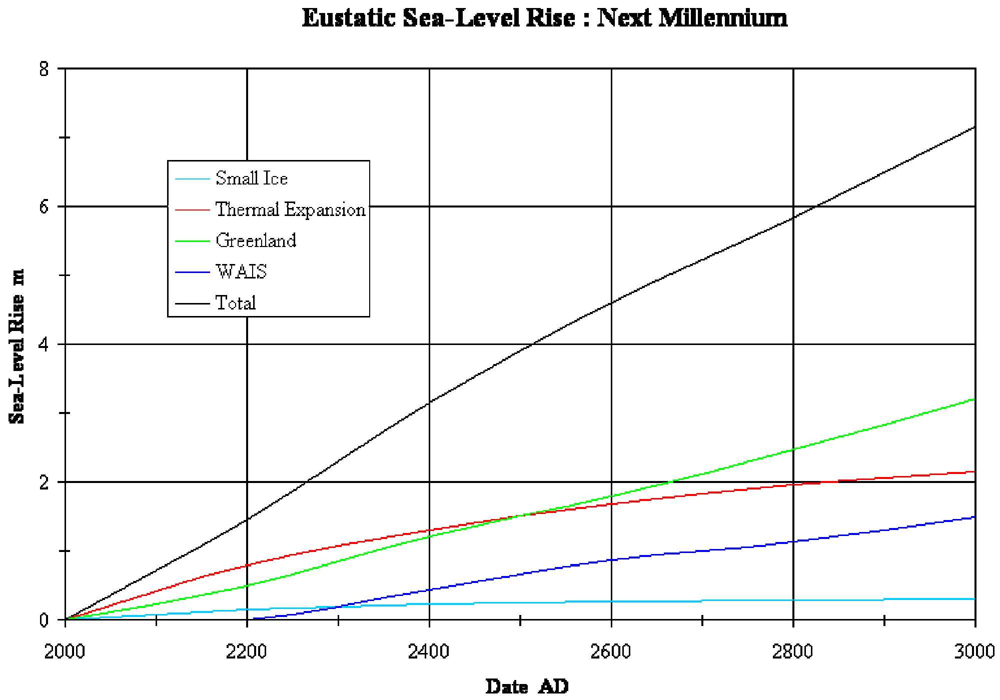

Figure 2. Possible rate of total and contributory sources to sea level rise during the next millennium based on the references given in the text.

CONCLUSIONS

1. The totals in Table 1 relate to an assumed eustatic sea-level rise. Extreme tidal levels and meteorological surge levels must be added to these with global warming also expected to increase the intensity of tropical cyclones (Emanuel 2005, Trenberth 2005, Webster *et al.* 2005) with consequent larger surge heights. Thus we obtain sea levels, which are unsustainable for large parts of many coastal cities and their associated infrastructures.

2. The problems of the world's coastal megacities and the problems they face in respect of rising sea levels has been described by Nicholls (1995) and the vulnerability of high density coastal settlements discussed in Nicholls & Lowe (2005). The costs of protection of vital areas, such as nuclear installations and architectural treasures, would need to be balanced against many competing claims. The land loss creates immense refugee problems (Gosline 2005) along with saltwater intrusion into agricultural lands (Pearce 2005a).

3. It is important to keep the time scale in mind. It is not feasible to plan centuries ahead. The problem can be brought sharply into focus by imagining how governments existing around 1000 AD, or even in 1500 AD, could possibly have planned for our modern world. We do not know anything concerning the economic, political or technical capabilities of the world several centuries ahead so that all we can say is that according to our current predictions, future generations will face serious sea level problems.

4. Table 1 confirms that two sets of actions are strongly recommended. The first is that measures to ameliorate global warming, including major reductions in greenhouse gas emissions are an urgent necessity (Nicholls & Lowe 2004). The second set includes the need to support further research to understand the earth's climate system, develop improved models to predict its future pattern and develop strategies for nations and communities to cope with greatly enhanced sea levels. The costs of both of these sets of actions will be judged by future generations as being among the best of things we will have bequeathed for their welfare.

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