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Effect of global warming on sea level rise: A modeling study

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ABSTRACT

Global mean sea level has been rising in response to global warming since the past few decades and is anticipated to potentially affect the coastal population. The main driver of global warming is the enhanced concentration of the heat-trapping gas carbon dioxide in the atmosphere. In this paper, we propose a nonlinear mathematical model to study the effect of an increase in the anthropogenic carbon dioxide emissions on sea level rise and its effect on the human population. The long-term behavior of the proposed system is analyzed using stability theory of differential equations. The model analysis shows that an increase in the anthropogenic emission rate of carbon dioxide leads to increase in the equilibrium levels of surface temperature and sea water level. Further, it is found that the increase in anthropogenic emission rate of carbon dioxide and melting rate of ice sheets lead to decrease in the equilibrium level of human population as a result of crowding caused by the decrease in the total inhabitable land area due to sea level rise. Numerical simulations are carried out to illustrate the effect of key parameters on the dynamics of the system.

1. Introduction

Global warming is affecting all of us in many ways. Sea level rise is one of the direst impacts of global warming which is affecting the coastal population of many countries. Global warming is a result of the increase in radiative forcing of climate system due to the enhanced anthropogenic emissions of greenhouse gases, primarily carbon dioxide (CO_2). Human activities, between 1750 and 2011, have caused nearly 40% increase in the atmospheric concentration of carbon dioxide. This upsurge in carbon dioxide concentration has caused a radiative forcing of 1.82 watts per square meter, which is nearly 64% of the total radiative forcing of all the well-mixed greenhouse gases (Stocker et al., 2013). The positive radiative forcing created by carbon dioxide and other greenhouse gases has increased the Earth's energy budget, leading to increase in the global surface temperature. The global mean surface temperature has risen by nearly 0.84 °C since pre-industrial times and is expected to rise in future with the increase in atmospheric concentration of CO_2 and other greenhouse gases. A doubling of carbon dioxide concentration is estimated to bring nearly 1.5–4.5 °C rise in global mean surface temperature in comparison to pre-industrial level (Lindsey, 2014). The rise in global mean temperature leads to melting of glaciers and ice caps, resulting in sea level rise. It is found that the global mean sea level has risen approximately 0.19 m between 1900 and 2010 with a rate of nearly 1.7 millimeter per year (Church et al., 2013). The rate of sea level rise is expected to increase in future with the further increase in atmospheric temperature. The fifth assessment report of IPCC (Intergovernmental Panel on Climate Change) projects that the global mean sea level may rise by 0.52–0.98 m by the end of 21st century. The NOAA (National Oceanic and Atmospheric Administration) projection of sea level rise is up to 2 m by 2100. The ice sheets across the world hold sufficient water to raise the sea level by several meters. Antarctica and Greenland ice sheets are the two largest ice sheets containing nearly 99% of the freshwater ice on the Earth. It is estimated that if the Greenland ice sheet melts completely, sea level may rise about 6 m, while the melting of Antarctic ice sheet may cause a sea level rise of about 60 m. It is estimated that Antarctica ice sheet alone can contribute more than a meter of sea level rise by the year 2100 and more than 15 m by the year 2500 (DeConto and Pollard, 2016).

Sea level rise has potentially harmful consequences, such as coastal flooding, erosion, saltwater contamination of fresh water supplies, increase in salinity of agricultural soil, hurricane storm surge, etc. Nearly 625 million people residing in low-elevation coastal zones are at risk of exposure to these hazards of sea level rise (Neumann et al., 2015). Hazards of sea level rise may force a

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portion of the coastal population to migrate from coastal zones to inland zones, affecting the coastal population dynamics. Sea level rise affects not only the dynamics of regional population, but also the global population by affecting the net carrying capacity of human population due to the reduction in inhabitable land area. The elevated sea level has already begun to wipe out many coastal areas. For instance, nearly half of Bhola Island in Bangladesh has become permanently flooded due to sea level rise, leaving 500,000 climate refugees (Penna and Rivers, 2013). As most of the global population is residing in coastal zones and many of the world's major cities, such as New York, Los Angeles, California, Sydney, etc., are located in low-lying coastal zones, the future sea level rise is likely to potentially influence the population dynamics.

From the above, it is pointed out that the global warming caused by an increase in anthropogenic carbon dioxide emissions may affect the sea water level, which in turn may affect the human population levels. To address the problem of sea level rise, it is crucial to comprehend the role of anthropogenic carbon dioxide emissions and the associated temperature rise behind the sea level rise. For this purpose, mathematical modeling is an effective tool. The effect of climate change on sea level rise is usually evaluated by using the process-based numerical models (Gregory et al., 2006; Meehl et al., 2007) and semi-empirical models (Gornitz et al., 1982; Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Grinsted et al., 2010). These models are either numerical or statistical models and use quantitative methods to assess the response of sea level to the temperature change and rely completely on data. Apart from these numerical and semi-empirical models, dynamical models that utilize qualitative methods may also be used to gain an in-depth understanding of the effect of temperature change on sea level rise. In recent years, various differential equation models have been proposed to address the dynamics of greenhouse gases and pollutants in the atmosphere (Tennakone, 1990; Naresh and Sundar, 2007; Naresh et al., 2007; Caetano et al., 2011; Sundar, 2013; Misra and Verma, 2013, 2014; Misra et al., 2015; Shukla et al., 2015; Verma and Misra, 2016). In these studies, qualitative analysis of the proposed models is carried out to assess the long-term effect of various crucial factors on the dynamics of greenhouse gases and pollutants. In the present study, we formulate a nonlinear mathematical model comprising a set of differential equations to study the effect of the enhanced concentration of carbon dioxide and the associated temperature rise on the sea level rise, and the effect of sea level rise on the human population. The qualitative analysis of the proposed model is performed to assess the long-term behavior of the system using stability theory of differential equation.

2. Model formulation

Human activities increase the concentration of carbon dioxide gas in the atmosphere. An increase in the concentration of carbon dioxide gas causes an increase in the global mean temperature and it causes melting of glaciers and ice caps, leading to sea level rise. As the sea level rises, the land area submerged in water increases. Due to the decrease in the inhabitable land area, carrying capacity of human population declines. To model this scenario, we consider six dynamical variables, namely, the human population '$N(t)$', the atmospheric concentration of carbon dioxide '$C(t)$', the average surface temperature '$T(t)$', the mass of ice sheets '$I_c(t)$', the mean sea level '$W(t)$' and the land area submerged in sea '$L(t)$'. It is assumed that the carbon dioxide enters in the atmosphere due to natural processes as well as due to human activities. The natural source of carbon dioxide includes volcanoes, decomposition, fire, ocean release, respiration, etc. The anthropogenic CO_2 emission consists mainly of the post-industrial CO_2 emissions from fossil fuel burning, industrial processes, deforestation and other human related activities. The carbon dioxide is uptaken by the natural sinks, such as forests, oceans, fossil fuels, carbonated rocks, etc. Prior to the industrial revolution, the atmospheric concentration of CO_2 had been relatively stable as the natural source and sinks of carbon dioxide were relatively balanced and the anthropogenic emissions were insignificant relative to natural variability (IPCC, 2007). Let C_0 be the equilibrium concentration of carbon dioxide in the absence of anthropogenic carbon dioxide emissions (or pre-industrial equilibrium concentration of carbon dioxide). Since the industrial revolution, anthropogenic emission of carbon dioxide has increased linearly with the increase in human population (Newell and Marcus, 1987; Onozaki, 2009), so the emission rate of carbon dioxide from anthropogenic sources is taken to be proportional to human population 'λN'. The emission of CO_2 from the natural sources is assumed to be a constant Q_0. The uptake rate of carbon dioxide by the natural sinks is assumed to be proportional to the atmospheric concentration of CO_2, i.e., '$\lambda_0 C$' (Nikol'skii, 2010). Let T_0 be the average surface temperature in the absence of anthropogenic carbon dioxide emissions (or the pre-industrial average surface temperature). An increase in the concentration of carbon dioxide leads to an increase in the atmospheric temperature. It is observed that the increase in global average temperature has linear correlation with the increase in CO_2 concentration (IPCC, 2014). Hence, it is assumed that the temperature increases at a rate proportional to the increase in the concentration of CO_2 due to human activities.

We have assumed that the ice sheets gain mass at a constant rate q. The increase in temperature causes melting of ice sheets, leading to sea level rise. In the study by Rahmstorf (2007), the rate of sea level rise is taken to be proportional to the increase in temperature. However, the rate of sea level rise also depends on the melting of ice sheets (Meehl et al., 2007). Hence, we assume that the ice sheets melt at a rate $\beta I_c(T-T_0)$, where β is the melting rate coefficient of ice sheets. The melting of ice sheets causes an increase in the water level at a rate $\gamma\beta I_c(T-T_0)$, where γ is a proportionality constant which represents the conversion of ice sheets into sea level rise. The surging sea level causes coastal erosion and inundation, leading to an increase in the submerged area. In some studies, it is found that the long-term shoreline retreat rate is proportional to sea level rise (Leatherman et al., 2000; Zhang et al., 2004). In view of this, it is assumed that the submerged area increases at a rate proportional to the increase in sea water level, i.e., $\phi(W-W_0)$, where ϕ is the growth rate coefficient of the submerged area and W_0 is the sea water level when the temperature is T_0. As the submerged area increases, the land inhabitable to human population decreases and this negatively affects the growth of human population, via decreasing the carrying capacity of the human population, at a rate $r_0N^2(L-L_0)$, where r_0 is the declination rate coefficient of human population due to increase in the submerged area.

Under the above considerations, the dynamics of the problem is governed by the following system of differential equations:

$$
\begin{aligned}
\frac{dI_c}{dt} &= q-\alpha_0 I_c-\beta I_c(T-T_0),\\
\frac{dW}{dt} &= \gamma\beta I_c(T-T_0)-\gamma_0(W-W_0),\\
\frac{dL}{dt} &= \phi(W-W_0)-\phi_0(L-L_0),\\
\frac{dN}{dt} &= rN\left(1-\frac{N}{K}\right)-r_0N^2(L-L_0),\\
\frac{dC}{dt} &= Q_0+\lambda N-\lambda_0 C,\\
\frac{dT}{dt} &= \theta(C-C_0)-\theta_0(T-T_0),
\end{aligned} \tag{1}
$$

where $C_0=Q_0/\lambda_0$, $I_c(0)>0$, $W(0)\geq W_0$, $L(0)\geq L_0$, $N(0)\geq 0$, $C(0)\geq C_0$ and $T(0)\geq T_0$.