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Sensitivity of the global submarine hydrate inventory to scenarios of future climate change

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ABSTRACT

The global submarine inventory of methane hydrate is thought to be considerable. The stability of marine hydrates is sensitive to changes in temperature and pressure and once destabilised, hydrates release methane into sediments and ocean and potentially into the atmosphere, creating a positive feedback with climate change. Here we present results from a multi-model study investigating how the methane hydrate inventory dynamically responds to different scenarios of future climate and sea level change. The results indicate that a warming-induced reduction is dominant even when assuming rather extreme rates of sea level rise (up to 20 mm yr^{-1}) under moderate warming scenarios (RCP 4.5). Over the next century modelled hydrate dissociation is focussed in the top $\sim$100 m of Arctic and Subarctic sediments beneath $<$500 m water depth. Predicted dissociation rates are particularly sensitive to the modelled vertical hydrate distribution within sediments. Under the worst case business-as-usual scenario (RCP 8.5), upper estimates of resulting global sea-floor methane fluxes could exceed estimates of natural global fluxes by 2100 ($>$30–50 Tg CH_4 yr^{-1}), although subsequent oxidation in the water column could reduce peak atmospheric release rates to 0.75–1.4 Tg CH_4 yr^{-1}.

1. Introduction

Hydrates are crystalline cage structures which enclose low molecular-weight gases, primarily methane. The most common types, stratigraphic deposits, form over geological timescales within sediment pore space when methane and water are in close proximity in high-pressure low-temperature environments typical of continental shelf margins. Many studies have estimated the size of the global inventory. Early work (reviewed in Milkov, 2004) estimated the inventory to be of the order of 10,000 GtC (i.e. Kvenvolden, 1999) which was subsequently *refined* to between $\sim$500 and 3000 GtC (Buffett and Archer, 2004; Archer, 2007; Wallmann et al., 2011; Piñero et al., 2012) although lower estimates exist (i.e. 50 GtC, Burwicz et al., 2011, assuming only microbial CH_4 sources) as well as optimistically large outliers (e.g. 74,000 GtC, Klauda and Sandler, 2005). Boswell and Collett (2010) concluded that this lack of clear convergence was due to poor data-availability and uncertainty in initial model assumptions.

Regardless, the dependence of methane hydrate stability on temperature and pressure and their existence around continental shelf margins mean that they are sensitive to changes in bottom water conditions and sea-level. However, while methane hydrates would likely provide a positive feedback to climate warming, the strength of this feedback is modulated by concurrent rises in the sea-level, which would provide a stabilising influence by increasing local hydrostatic pressure. How these two opposing influences combine has not previously been assessed in a temporal and quantitative manner, nor has the uncertainty in hydrate destabilisation imparted by different emissions forcing scenarios. Defining future climate scenarios from an evaluated multi-climate-model ensemble ensures that our hydrate model boundary conditions are robust and not determined by biases in a single model.

2. Methods

We use climate model experiments from the CMIP5 multi-model ensemble, evaluated against modern observations to define a series of future anthropogenic-warming climatic scenarios. Modelling the propagation of bottom water temperature change (ΔBWT) through the continental margin sediment column in combination with a series of linear sea level models allows a series of time-profiles of the change in the hydrate stability zone volume to be calculated. Using a hydrate model to derive an

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initial pre-industrial global hydrate inventory we then compute its evolution and derive rates of hydrate dissociation. This procedure allows the first-order response of the hydrate inventory to be determined through and beyond a series of anthropogenic warming scenarios.

2.1. *CMIP5*

The World Climate Research Programme (WCRP) Fifth Coupled Model Intercomparison Project (CMIP5) is a globally coordinated model-intercomparison setup to address questions raised within IPCC AR4 (Taylor et al., 2011). We conduct hydrate modelling under boundary conditions derived from a subset of the CMIP5 long-term experiments namely the pre-industrial (CMIP5 Experiment 3.1), historical (Exp 3.2) and the RCP and ECP future responses (Exp 4.1–4.4, 4.1L–4.3L), covering the climate from 1860 to 2300.

2.1.1. *Pre-industrial and historic climate model experiments*

The pre-industrial climate experiments (pre-1860; piControl) have been run with fixed atmospheric composition and unperturbed land use. The historic experiment (1860–2005) has changing atmospheric composition (anthropogenic and natural), solar forcings and land use change according to historical records. Details of boundary conditions are summarised within Taylor et al. (2011) and WCRP (2012). The pre-industrial experiments are used to determine climatic drift and to initialise the global hydrate inventory. The historical experiments are used in the evaluation of models against observations and to initialise climatic scenarios.

2.1.2. *RCP scenarios*

Representative Concentration Pathways (RCP, Moss et al., 2010) describe possible climate scenarios of future greenhouse gas emissions for the period 2005–2100. The RCPs are labeled according to their approximate global radiative forcing at ~2100. They represent the range of published emission scenarios as of 2007. They have been extended to 2300 leading to Extended Concentration Pathways (ECP, Meinshausen et al., 2011). A summary of these scenarios can be found within Table 1 and details of those modelled in Table 3.

2.1.3. *Climate models*

Twelve climate models were available within the CMIP5 database (as of Jan 2012) that had carried out pre-industrial, historical and at least one RCP scenario, these are detailed within Tables 2 and 3. These consist of Atmosphere-Ocean General Circulation Models (AOGCM) and Earth System Models (ESM), the latter incorporating additional earth system components such as biogeochemical cycles and atmospheric chemistry. Common to all models is an ocean general circulation model which we use to define bottom water conditions—the uppermost boundary condition of our hydrate model.

Native model grids were translated onto a $2\times 2^\circ$ geographic grid using a model specific weight-matrix derived from an inverse-distance weighting of nearest-neighbours, a method based upon Jones (2001). Potential temperature and salinity fields were extracted from the bottom-most layer of the 3D data. Conversion to in situ temperature was achieved using the solution of Jackett et al. (2006) which uses bottom water pressure (BWP) and salinity to uncouple potential and in situ temperature. When modelled-BWP was unavailable the bathymetry (D) and constant mean

Table 1

RCP overview. Overview of the Representative and Extended Concentration Pathway (RCP and ECP) scenarios. Descriptions derived from Moss et al. (2010) and Van Vuuren et al. (2011). Note that ECP 6.0 was not available within the Coupled Model Intercomparison Project (CMIP5) archive (as of Jan 2012) and so is not represented within this work.

Scenarios	Description
RCP 4.5	~4.5 W m^{-2} (~650 ppm CO_2 equiv) at stabilisation post-2100 (medium stabilisation scenario)
RCP 6.0	~6 W m^{-2} (~850 ppm CO_2 equiv) at stabilisation post-2100 (medium stabilisation scenario)
RCP 8.5	~8.5 W m^{-2} (~1370 ppm CO_2 equiv) at 2100 (high-baseline emission scenario)
ECP 4.5	Smooth transition from 2100 to 2150 then emissions fixed. Stabilisation at 4.5 W m^{-2}
ECP 6.0	Smooth transition from 2100 to 2150 then emissions fixed. Stabilisation at 6 W m^{-2}
ECP 8.5	Constant emissions 2100–2150 with smooth transition to 2250. Concentrations fixed post-2250. Stabilisation at 12 W m^{-2}

Table 2

GCM descriptions. Overview of the Coupled Model Intercomparison Project (CMIP5) Fifth Assessment Report (AR5) models. BCC=Beijing Climate Centre, China Meteorological Administration, CCCMA=Canadian Centre for Climate Modelling and Analysis, CNRM-CERFAC=Centre National de Recherches Meteorlogiques/Centre European de Recherche et Formation Avancees en Calcul Scientifique, CSIRO-QCCCE=Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence, NASA GISS=NASA Goddard Institute for Space Studies, MOHC=Met Office Hadley Centre, INM=Institute for Numerical Mathematics, IPSL=Institut Pierre–Simon Laplace, MIROC=Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental Studies, MRI=Meteorological Research Institute, and NCC=Norwegian Climate Centre. Model specific definitions: BL=Boundary Layer. The data was supplied as either a *Regular* cartesian or *Tripolar* grid. Vertical co-ordinates are either fixed thickness (z-coord) or isopycnal systems (ρ-coord). The *score* indicates the performance metric, specified as the product of R_m^2, R_o^2 and AMS.

Id	Name	Institute ID	Model origin, type and grid specification	Pre-industrial (years)	Score
1	BCC-CSM1.1	BCC	MOM Tripolar 360×300 z-coord	500	0
2	CanESM2	CCCMA	MOM1 Regular 256×192 z-coord	996	0.240
3	CNRM-CM5	CNRM-CERFACS	NEMO3.2 ORCA-1 Tripolar z-coord 362×292 partial-step BL	850	0.555
4	CSIRO-Mk3.6.0	CSIRO-QCCCE	MOM2.2 Regular 192×192 z-coord	490	0.392
5	GISS-E2-R	NASA GISS	MOM3 Regular 288×180 z-coord	1200	0.470
6	HadGEM2-ES	MOHC	Bryan-Cox-Semtner Regular 360×216 z-coord	240	0.514
7	INM-CM4	INM	$\text{Regular}_{modified}$ 360×340 σ-coord	500	0.369
8	IPSL-CM5A-LR	IPSL	NEMO Tripolar 182×149 z-coord partial-step	1000	0.422
9	MIROC-ESM	MIROC	Regular 256×192 8-σ 41-z and regional BBL parameterisation	531	0.270
10	MRI-CGCM3	MRI	TriPolar 360×368 surf $\sigma+z$-coord	500	0.466
11	NORESM1-M	NCC	MICOM Tripolar $320\times 384\rho$-coord	501	0.301