MOCA: Methane Emissions from the Arctic OCean to the Atmosphere: Present and Future Climate Effects

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1 Relevance relative to the call for proposals

Methane hydrates (MHs) in ocean seabed sediments are a potential source of methane (CH_4) to the atmosphere, where CH_4 acts as a powerful greenhouse gas. MHs are unstable and potentially susceptible to ocean warming, which could trigger an important positive feedback resulting in rapid climate warming. MHs can be found in several areas on the ocean floor, but one of the globally most important MH regions is the seabed west of Svalbard. Norway has a special interest in the polar areas ("*Nordområdesatsingen*[1]") and it is therefore Norway's responsibility to carefully analyze the current state of MHs in this region and detect any early warning signs of significant changes. The proposed research project **MOCA** addresses this responsibility by investigating the stability of MHs, and potential oceanic CH_4 emissions around Svalbard, and the implications for global climate. Emissions of CH_4 from hydrates at the shallow seabed and the associated contribution to atmospheric CH_4 will be investigated and combined with modelling to estimate the current and future climate impact. According to Maslin et al (2010), there are several areas of gas hydrate reserves close to Svalbard and in the Russian Arctic Ocean, and emission of CH_4 from seabed has been observed west of Spitsbergen (e.g. Westbrook et al, 2009) and in the Kara Sea (Shakova et al., 2010). The climate effect of future CH_4 emissions from MHs is particularly uncertain (Ruppel, 2011; Shakova et al. 2012).

MOCA is an interdisciplinary project that will utilise the national established infrastructures at Svalbard and in surrounding sea areas, for measurements in the atmosphere, the ocean and at seabed, in a new integrated and coordinated way for the first time. This will be supported with campaigns and powerful modelling tools, and involves collaboration with several international experts. The project is expected to generate new knowledge about the climate using Svalbard as an experimental test bed to study central polar processes that have potential to impact the entire Earth system and change climate. Since uncertainties are large, it is of utmost importance to quantify the vulnerability of MH stores to Arctic climate changes. Results from **MOCA** may have widespread implication for future research on this topic in relation to climate change and for predictions of future temperature changes.

MOCA is closely linked to Svalbard and within the core of the POLARPOG program. **MOCA** will address 3 out of 4 thematic areas in the call and focus primarily on the interaction between the atmosphere and hydrosphere, but will also improve knowledge of inter-related processes in the biosphere and geosphere. Improved "***Understanding of processes"*** and **"*Understanding of state"*** will be gained by improved characterisation of MH stability under conditions on the continental shelf west of Svalbard, main influencing factors and current and potential CH_4 emissions from this region. The new knowledge from in-depth understanding of the processes at Svalbard will be up-scaled for the Arctic region and used to investigate "***The role of the polar regions in the Earth system"*** with an atmospheric chemistry transport model, combined with radiative forcing calculations and climate model simulations.

[1] http://www.regjeringen.no/en/dep/ud/campaigns/the-high-north.html?id=450629

2 Aspects relating to the research project

CH_4 is an important climate gas. CH_4 present in the atmosphere has both direct radiative impacts on climate and indirect effects through influences on atmospheric chemistry (e.g., ozone formation). CH_4 has an atmospheric lifetime of around 10 years, thus changes in atmospheric concentration may have a global impact. There are huge reservoirs of CH_4 in the Arctic (Vonk et al. 2012): MH in seabed sediments (Shakova et al., 2010) and organic material in land- and marine-based permafrost which can be partly converted to CH_4 after permafrost thaw, which are both vulnerable to destabilization in a warming climate (O'Connor et al, 2010). The Arctic Ocean surface waters may also represent a potentially important source of CH_4, which may be sensitive to changes in sea-ice cover (Kort et al 2012).

The overall objective of **MOCA** is to "***Quantify the present atmospheric effects of methane from gas hydrates at the seabed, and future potential climate impacts on decadal to centennial timescales***."

The driving questions for **MOCA** are:

I. *What is the status and current release of methane from marine seep sites and methane hydrates in the Arctic Ocean, and specifically around Svalbard?*
II. *How are these processes depending on trends in sea temperature and annual variations?*
III. *Where are the most important areas in the Arctic Ocean which could constitute a possible source of atmospheric methane, now and in the future?*
IV. *What is the present CH_4 emission from the seabed to the atmosphere?*
V. *What is the most likely change in flux, the next 50 and 100 years under realistic climate scenarios? And what is the global effect of this?*
VI. *What is the ocean temperature threshold for large changes in emission of methane from hydrates?*

Based on the driving questions the following sub-objectives are defined. MOCA intends to:

- Quantify the present-day CH_4 emissions from the seabed west of Prince Carl Forland (Svalbard) and identify main influences on the processes.
- Improve the knowledge about the overall activity of the marine seep sites offshore Svalbard.
- Identify main areas where seabed CH_4 emissions are likely to take place in the Arctic region.
- Produce estimates of CH_4 emissions to the atmosphere related to MHs and other sources in the Arctic Ocean.
- Describe the climate impact and radiative forcing (direct and indirect effects) of CH_4 release from the seabed under:
    - Present-day atmospheric composition
    - Realistic future atmospheric composition scenarios

2.1 Background and status of knowledge

Arctic atmospheric CH_4 emissions from submarine and terrestrial permafrost pools have contributed to past global change (Nisbet and Chappellaz, 2009) and in the future may again provide a positive feedback within the global climate system. MHs are the largest Arctic carbon pool, but the amount and spatial distribution of deposits is highly uncertain. Recent estimates range from $7 \cdot 10^2$ - $1.27 \cdot 10^4$ Gt Carbon (Gt C) (Ruppel, 2011 and references therein) to be sequestered in marine gas hydrates alone, while Shakova et al. (2010) estimate $3.75 \cdot 10^2$ Gt C of MHs are present within sediments of the East Siberian Arctic Sea alone. Compared to current total annual emissions of CH_4 to the atmosphere these are giant numbers.

MH is an ice-like substance composed of water and gas which is only stable under conditions of high pressure and low temperature (O'Connor et al, 2010). Such conditions are found in continental margin marine sediments at water depths of >300 m. Temperature changes may cause the hydrate to become unstable and break down and release CH_4 into the ocean water column

(O'Connor et al, 2010, Shakova et al. 2010). Studies indicate that such CH_4 releases from shallow seabed in the Arctic Ocean have a high probability of reaching the atmosphere (Shakova et al., 2010), and one known area in the Arctic with MHs and emissions from the seabed into the ocean is west of Svalbard (Rajan et al., 2012; Ferre et al., 2012 Greinert et al., 2011). Several studies indicate that sub-sea permafrost and hydrates are potentially more vulnerable to thawing than terrestrial permafrost (Shakova et al., 2010; Isaksen et al., 2011; Vonk et al., 2012).

2.1.1 Arctic Ocean, methane hydrates and emissions to atmosphere

Dissociating Arctic marine gas hydrates have been considered as a potentially strong source of CH_4 for the atmosphere in future warming scenarios (Semiletov et al., 2004; Shakhova et al., 2005, 2010). To date, a direct link between gas hydrate decomposition and CH_4 seepage has only been identified in one area, offshore western Svalbard (Figure 1). Release of CH_4 from the seafloor as streams of gas bubbles was observed in 2008 and repeatedly after that during yearly monitoring cruises (Greinert et al., 2011), although this activity has almost certainly been going on for some time. Most of the bubbling activity in this region is focused on two depth intervals; one at about 240 m at the shelf edge and a second in a rather narrow water depth interval, between 360 and 396 m. This second clustering coincides with the depth of the top of the gas hydrate stability zone (GHSZ), at present-day bottom water temperatures (396 m) and at bottom water temperatures some 30 years ago, which were about 1°C colder (Westbrook et al., 2009). There has been a warming of the northward-flowing West Spitsbergen current by 1°C over the last thirty years, and this might have increased the release of CH_4 from the seabed (Westbrook et al, 2010,). A recent study showed that bottom water warming offshore Prins Karls Forland may have triggered the GHSZ to retreat towards upper continental slope areas, potentially increasing CH_4 release due to gas hydrate dissociation (Ferré et al., 2012).

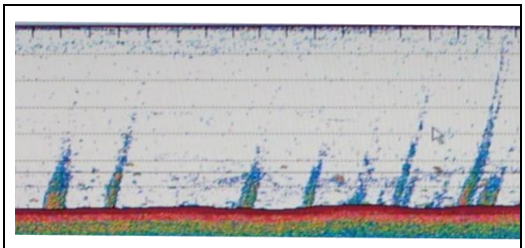

Figure 1: Sonar image the field of ~250 gas plumes, rising from the edge of the gas hydrate stability zone, west of Svalbard (Westbrook et al., 2009)

Methane from hydrates can only influence climate once in the atmosphere, but oxidation within the ocean might add to local acidification. In the seafloor sediments CH_4 oxidizing archaea and sulfate reducing bacteria rather effectively block a large percentage of the dissolved CH_4 via anaerobic oxidation (Boetius et al., 2000) at the seabed before it reaches the aerobic oxidation zone in the water column and finally the sediment-seawater interface. Dissolved CH_4 that manages to escape the sediments is sometimes rapidly oxidized in the water column and distributed by currents which cause a general quick decrease of CH_4 concentrations away from the actual release site. However, our knowledge is very limited when it comes to the situation in shallow Arctic waters.In particular the efficiency of CH_4 oxidizers in the water column and the effects of ice cover are still at an infant stage. At deeper CH_4 seep areas (< 100 m), dissolved CH_4 is not thought to play a major role in current and future atmospheric CH_4 increase but gas bubble transport is assumed to be a significant source of CH_4 to the atmosphere under certain conditions (e.g. Solomon et al., 2009). Detecting and mapping the distribution of gas bubbles in conjunction with seafloor and sub-seafloor studies, is therefore imperative if we are to understand whether the Arctic marine environment is a CH_4 source, and whether it is vulnerable to increase in the future. It is also likely that there are other processes leading to oceanic CH_4 emissions in the Arctic (Kort et al. 2012).

2.1.2 Status of recent atmospheric development of CH_4

Interestingly, and contrary to most other greenhouse gases, the growth rate of atmospheric CH_4 has experienced a slowdown from the 1980s to the early 2000s. However, after a decade of near-stable global concentrations, the atmospheric growth rate started to increase again in 2006. This is probably due to a combination of tropical and Arctic increases of the CH_4 emissions (Dlugokencky et al., 2009, Rigby et al., 2008, Fischer et al., 2011). Also NILU's observations at the Zeppelin Observatory at Svalbard reveal a recent growth in CH_4 of around 12 ppb/year from 2006-2009, but

less after (Myhre at al. 2012). This is significantly larger than the average yearly increase for the two previous decades. Source discrimination of CH_4 emissions is possible thorough measurement of $\delta 13\text{-}CH_4$ and $\delta D\text{-}CH_4$ (Figure 2). There is considerable evidence that Arctic sources of CH_4 to the atmosphere are changing from year to year (Rigby et al., 2008, Dlugokencky et al., 2009, Fisher at al. 2011). Enhanced emissions from wetlands due to unusual high Arctic temperatures may be one of the explanations for the recent increase (Dlugokenchy et al., 2009, Fischer 2011), but this is uncertain. A recent study analysing flight observations of CH_4 above the Arctic Ocean indicates a prevalence of CH_4 surface ocean emission over open leads and areas of fractional sea ice (Kort et al., 2012). The measurements were performed over deep water far away from shallow continental shelves that hold vulnerable CH_4 hydrates which may highlight transport from source in the oceanic water column and in-situ production of CH_4 in the upper water layers. They report layers of increased CH_4 as far north as 82° near the surface ocean, with no indications of combustion sources (from simultaneous CO measurements).

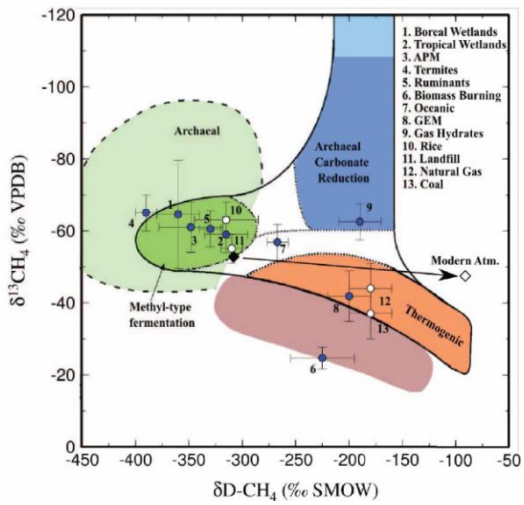

Figure 2: Sources of CH_4 to the atmosphere identified through isotopic discrimination (Melton et al., 2011). The modern CH_4 stable isotope atmospheric value is indicated by the diamond. A typical value for gas hydrates is indicated by data point 9

2.1.3 The climate implications of enhanced Arctic greenhouse gas emissions

Estimates of current global CH_4 emissions range between 400-500 Tg/year. CH_4 is mainly oxidised in the troposphere through the reaction with the hydroxyl radical (OH). Small fractions of CH_4 are deposited at the Earth's surface, or broken down after being transported to the stratosphere (approximately 5%). CH_4 is relatively well mixed in the troposphere, with current mixing ratios of 1.6-1.7 ppm. Since CH_4 influences the atmospheric lifetime of OH, there is a significant non-linear relation between CH_4 and OH (Isaksen, 1988). With current global emissions the CH_4 levels increase with as much as 1.4-1.5% per 1.0% increase in emissions. Shakhova et al. (2010) have estimated that potential Arctic CH_4 emissions could reach 50 Gt, either abruptly over 1-5 years, or gradually increasing over a 50 year time period. This is more than 10 times the current CH_4 content of the atmosphere, and such emission would strongly increase the atmospheric CH_4 lifetime. It would also lead to large enhancements of ozone and stratospheric water vapour, and could result in a substantial climate impact (Isaksen et al., 2010), possibly pushing the climate system across a tipping point. Models of the global CH_4 emissions from hydrates and trapped CH_4 bubbles suggest that a global 3°C warming could release between 35-940 GtC, which could result in an increase of 0.5°C in global mean temperature (Meslin et al., 2010). The present knowledge of current and future CH_4 emissions from MHs that may occur as a feedback to climate warming is limited of several reasons; the uncertainties in the existence and occurrence of hydrates, the amount of CH_4 stored in them, and the extent of future climate and, in particular, Arctic Ocean warming and how MHs reacts to temperature changes.

During recent decades the observed warming in the Arctic region has been twice as large as global warming (Hansen et al., 2007) and amplification of CH_4 emissions has already been observed (Walter et al., 2006; Shakova et al., 2010), and reduced sea ice extent might also influence this (Kort et al, 2012). Uncertainty in the future atmospheric burden of CH_4 represents an important challenge to the development of realistic climate projections.

2.2 Approaches, hypotheses and choice of method

MOCA consists of four complementary Work Packages (WP) to organise the work:

WP1: Improved process understanding and description of the present state of the ocean and atmosphere around Svalbard (NILU)
WP2: Understanding of present and future methane release from ocean (UiT)
WP3: Present and future projections of climate effects (CICERO)
WP4: MOCA management and coordination (NILU)

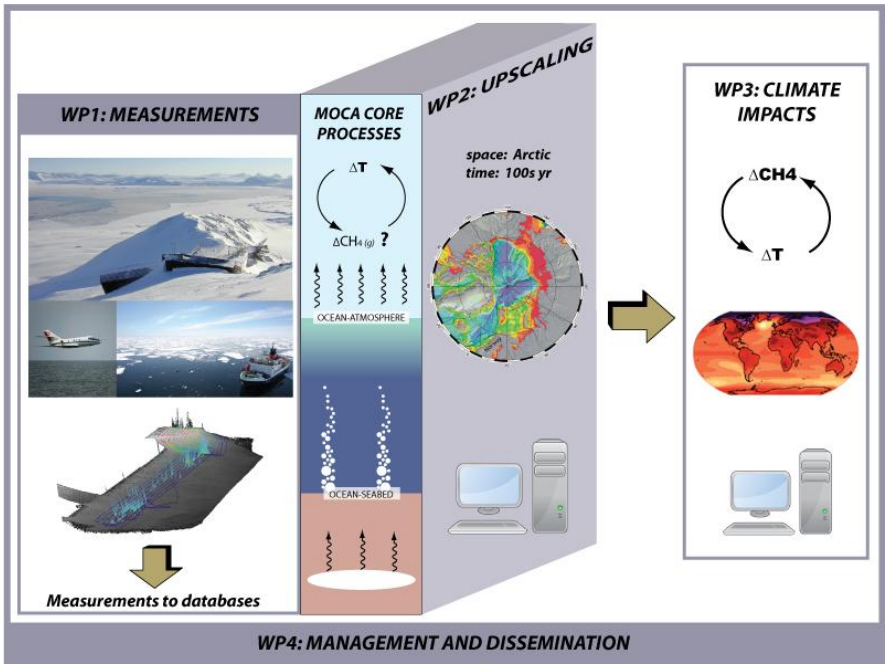

Figure 3: The MOCA core processes under investigation are in the centre of the Figure. WP1 includes measurements in the ocean, ocean interface and atmosphere to improve process understanding and quantify CH_4 emission to the ocean and atmosphere. WP2 is concerned with the upscaling based on process understanding in WP1 over the Arctic region, and as response to temperature change. WP3 includes calculation of the potential climate impacts of these emissions over timescales of 10s to 100s of years.

MOCA aims to improve the description of the current environmental state of the Svalbard region with particular focus on changes in CH_4 emissions from the ocean, and the ocean–atmosphere fluxes of CH_4. Figure 1 shows the relation between the process-based measurements and modelling activities. In WP 1 **MOCA** will combine the well established measurement infrastructure at land and in the ocean in the Svalbard region with ship- and airborne measurements coordinated in campaigns. The detailed observation and process studies in WP1 will be used as the input for up-scaling of Arctic regions in WP2. The up-scaling will be done both with respect to spatial emissions and for future time periods. This will serve as the input for WP3. The improved knowledge of the processes will be used in climate model studies to provide new knowledge about the influence of Arctic emissions on climate at present and in the future. The potential of the biogeochemical cycle as a strong feedback mechanism will also be investigated in WP3. The following section describes the approaches to the research activities in the scientific WP 1-3.

WP 1: Improved process understanding and description of the present state of the ocean and atmosphere around Svalbard and North Siberia (NILU)
Objective: *Quantify the present emissions of methane from ocean to the atmosphere around Svalbard and in North-East Siberia. Identification of other possible CH_4 sources*

The aim of this WP is to (1) quantify present-day CH_4 emissions from the ocean to the atmosphere; (2) identify seasonal perturbations on atmospheric CH_4 composition related to sea-ice break-up; and (3) characterise ocean-based processes that may lead to hypothesised large releases of CH_4 gas. CH_4 gas from hydrates at the seabed along the West Spitsbergen continental margin may accumulate under the sea ice during late winter. Thus the ice break-up season is of particular interest for investigation of the ocean-atmosphere interface, and will be the focus time for ship, aircraft and isotopic sampling campaigns in **MOCA**. The various approaches and selection of methods for each of these steps are described here, and Table 1, Page 7 summarise the essential contributions from the international collaboration.

Understanding seabed-ocean methane release: Little is known about the extent of gas migration towards the upper continental slope and episodic gas releases, and whether or not the gas originates from dissociating gas hydrates. At the seabed, four MASOX (Monitoring Arctic Seafloor

– Ocean Exchange) devices will be installed over a 10 km^2 region of the seabed offshore from Prins Karls Forland to measure ocean current vectors, temperature, salinity and CH_4 gas emission characteristics. In combination, four buoys will measure the CH_4 concentration of released CH_4 plumes at the seabed-ocean interface, within the water column and at the ocean-atmosphere interface. These devices were developed under the framework of FP6-ESONET (European Seas Observatory Network) and have been active since 2010. Each MASOX lander includes a seismometer, two Recorded Current Meters (RCM9) to measure ocean currents, conductivity, temperature and depth (CTD) sensors, and a flow meter to measure the rate of gas venting and apparent pulsating behaviour of bubble plumes. Using these devices, CH_4 gas will be sampled to determine isotopic proportions of δ13-CH_4 and possibly δD-CH_4 for source attribution (**Figure 2**). Annual cruises during the project will be carried out using the RV Helmer Hanssen (UiT). Seismic surveys will be performed to identify the base of the GHSZ in sediments based on characteristic seismic returns (e.g. Shipley et al., 1979; Bünz et al., 2012). Bubble size distributions will be measured using a remotely operated vehicle (ROV) to identify bubble dissolution and to identify the potential transport capacity of CH_4 via free transport up through the ocean column. Bubble releas in the ocean column will be mapped using sonar. Water samples collected through the ocean column will be analysed to determine the amount of dissolved CH_4 and isotopic abundances; the latter will be used to determine the extent of microbial CH_4 oxidation based on identification of δ13C fractionation in the residual CH_4 (Faure et al., 2010). The total rate of gas release will be determined from the distribution of vents, and the type and source of gas in WP2, in cooperation with GEOMAR, USGS and RHUL.

Oceanic emissions to the atmosphere; Atmospheric CH_4 measurements will be made at Svalbard, Kara and Laptev Sea from a number of platforms: continuous *in situ* measurements at the Zeppelin Observatory, campaign measurements at ships, and aircraft. The Zeppelin Observatory is located at 79°N on the Zeppelin Mountain, 474 m a.s.l., close to Ny-Ålesund, Svalbard. This is an atmospheric supersite which provides continuous long-term measurements of CH_4, CO_2 and CO, and more than 20 other trace gases, valuable as traces for biomass burning and industrial pollution.

In **MOCA** isotopic samples collected at Zeppelin will be analysed by RHUL for isotopic information to gain information about regional CH_4 sources, see Figure 2. Through the partner RUHL the project will also have access to CH_4 measurements at Kjølnes Lighthouse (70°N, 29°E), and probably also CH_4 from Tiksi at the mouth of the Lena River, Russia. Observations at Zeppelin, from ship and aircraft campaigns from previous years will also be utilised. This includes isotopic samples from campaigns (see e.g. Fisher at al, 2011) and measurements from GAME project http://game.nilu.no, lead by Lund Myhre and funded by NFR.

Collaboration will be established to do ship-based atmospheric measurements over existing seabed installations to identify emissions from the ocean surface on campaign basis. This will be based in voluntary collaboration with GEOMAR and USGS (See Table 1). At the sea surface, an equilibrator sampling system coupled to a cavity ring-down spectrometer (CRDS) will be used to map sea surface CH_4 and CO_2 concentrations. Together with atmospheric measurements this will allow direct calculation of the flux of CH_4 and CO_2 across the ocean-atmosphere interface. Samples will be collected to determine isotope abundances for source attribution (USGS and GEOMAR).

There will be two aircraft campaigns in April-May 2014. One utilising the DLR Falcon jet research aircraft (collaboration with H. Schlager) measuring atmospheric CH_4 mixing ratios using fast cavity ring-down spectrometers (Picarro CO_2/CH_4/H_2O) at Svalbard. Additionally, flask samples will be collected for isotopic analysis. Sampling at several height levels in the marine boundary layer will be performed both upwind and downwind of suspected regions of CH_4 release from MHs west of Svalbard and in coordination with the ship measurements. Wind speeds will be taken into account to allow a quasi-Lagrangian sampling between up- and downwind areas. The CH_4 measurements with high time resolution will allow a detailed budget analysis; the isotopic samples will allow an independent attribution of eventual elevated downwind concentration enhancements to MH emissions. Since the aircraft can cover long distances, extensive sampling over large regions can be made, which may detect any active CH_4 sources to the atmosphere west of

Svalbard. The aircraft will also perform vertical profiles throughout the depth of the troposphere, which will allow quantifying other sources of CH_4 to the atmosphere in the Svalbard region, for instance long-range transport from wetlands. Collaboration with Prof. Pyle and the MAAM[2] project will be established for data sharing, and to benefit from experiences from their work (see accompanying letter).

The second aircraft campaign is in Siberia. As part of an ongoing French-Russian-Norwegian collaboration, a Russian research aircraft has been equipped with extensive instrumentation for measuring trace gases (e.g., O_3, CO, NO_x, CO_2) and aerosols (e.g., Paris et al., 2008; 2010). Campaigns have been carried out annually since 2006 and two campaigns (2008, 2013) are also part of NILU-led projects (POLARCAT, CLIMSLIP). Since 2012 a new aircraft, a Tupolew-134, is available and a Picarro instrument has been added to measure CH_4 mixing ratios. Within the framework of **MOCA**, a YAK-AEROSIB campaign will be carried out just off-shore the Siberian coastline, over the Kara and Laptev Seas, during spring 2014. We will aim to collect air samples for isotopic analysis, but this has not yet been approved by Russian authorities. Even without isotopic analysis, the sources of detected CH_4 plumes can be identified using calculations with an atmospheric transport model, and this will allow clarifying whether MHs in the Kara or Laptev Seas cause any substantial CH_4 emissions. This will give a broader picture on CH_4 emissions to the atmosphere from MH seepage locations than is possible with a campaign around Svalbard only.

Table 1: Brief overview of contributions from international collaborators

People and institutions involved	Contribution
Dr. Jens Greinert, Helmholtz Centre for Ocean Research Kiel, (GEOMAR), Kiel, Germany	Ship-based measurements of bubble size distributions and CH_4 in water column and surface water; MH emissions. Timing not finally decided, depending on other funding sources.
Dr. Carolyn Ruppel, Gas Hydrates Project, U.S. Geological Survey, USA (USGS)	Directly quantify ocean-atmosphere methane flux through ship-based measurements of real-time (~1 Hz) CH_4 and CO_2 concentrations and carbon isotopes in near-surface waters and greenhouse gas concentrations in the overlying atmosphere. Also depending on other funding sources.
Prof. Euan Nisbet, Royal Holloway, University of London, Egham, UK (RHUL)	Isotopic analysis of gas samples collected in atmosphere from various platforms (ship, aircraft, Zeppelin)
Dr. Jean-Daniel Paris Laboratoire des Sciences du Climat et l'Environnement, Gif-sur-Yvette, France (LSCE)	Atmospheric measurements of CH_4, CO, CO_2 and others at a Tupolew-134 research aircraft in 2014. (piggy-back on YAK-AEROSIB (Airborne Extensive Regional Observations in SIBeria) project, *https://yak-aerosib.lsce.ipsl.fr*)
Dr. Boris Belan V.E. Zuev, Institute of Atmospheric Optics, Russian Academy of Sciences, Tomsk State University, Novosibirsk, Russia	
Dr.rer.nat. Hans Schlager Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen-Wessling, Germany (DLR)	Atmospheric measurements of CH_4, CO, CO_2 with DLR Dassault Falcon 20-E5 research aircraft in 2014. (piggy-back on MERLIN (Methane Remote Sensing Lidar Mission) project *http://www.dlr.de/pa/en/desktopdefault.aspx/tabid-2342/6725_read-26662/*)
Prof. John Pyle, Centre for Atmospheric Science, University of Cambridge, Department of Chemistry, Cambridge, UK (UCAM)	Access to atmospheric measurement data from 2011-2013 MAAM campaign collected by FAAM BAe-146 research aircraft (*http://www.faam.ac.uk/index.php/current-future-campaigns/354-mamm-methane-mapping*)
Dr. Renato Spahni, Physics Institute, and Oeschger Centre for Climate Change Research, University of Bern, Switzerland (BERN)	Access to simulated CH_4 emissions from circumpolar wetlands and peatlands using the LPX global dynamical vegetation model including WHyMe (*Biogeosciences*, 8, 1643–1665, 2011, doi:10.5194/bg-8-1643-2011)

The Lagrangian particle dispersion model FLEXPART (http://transport.nilu.no/flexpart) (Stohl et al., 1998, 2005) will be used as a campaign planning tool to predict arrival of CH_4 plumes via long-range transport to allow measurements in specific CH_4-rich air masses (e.g., from Siberian wetlands), especially with the aircraft. Forecasts will also be made by releasing a tracer from

[2]Methane and other greenhouse gases in the Arctic – Measurements, process studies and Modelling http://www.arctic.ac.uk/mamm/

regions of suspected ocean-atmosphere transfer of CH_4 for advance planning of upwind/downwind flight patterns.

WP2. Understanding of present and future methane release from ocean (UiT)
Objective: *Produce methane emission estimates for the Arctic Ocean over various time scales*

The measurements and analysis performed in the focussed studies around Svalbard and Eastern Siberia in WP1 will be compiled and used in WP2 for up-scaling, both spatially and temporally. The up-scaling will provide CH_4 emissions for present-day, and future emissions as response to climate change, and by this link WP1 and WP3. WP2 will aim to identify the main areas where emissions from the seabed are happening now or are likely to happen in the Arctic within 100 year time-scale. This is important both for **MOCA** work, but also for development of future monitoring in critical areas. Due to the large uncertainties in the future emissions of MH it is crucial with initiation of various approaches of up-scaling.

Source attribution and generation of emission maps. Inverse modelling is a mathematical-statistical technique for deriving unknown quantities that cannot be measured directly from other quantities that can be measured. In our case, CH_4 air concentrations will be measured on a ship, by aircraft and at stations (Zeppelin, plus other high-latitude sites). Direct measurements of CH_4 emission fluxes will be done at single spot stations and also during transit using sea-air gas exchange equilibration techniques (USGS, GEOMAR). These data can be used to extrapolate over a larger area. To further upscale, FLEXPART will be used to establish the corresponding source-receptor relationships. NILU's inverse modelling system (Stohl et al., 2009) has recently been used for such diverse applications as estimating the halocarbon emissions for East Asia (Stohl et al., 2010), volcanic ash emissions during a volcanic eruption (Stohl et al., 2011), or the release of radionuclides from the damaged Fukushima nuclear power plant (Stohl et al., 2012). It is well suited for estimating CH_4 emissions and in WP2 we will use it for determining CH_4 emission fluxes in the northern high latitudes. In a first step, long-term monitoring data from high-latitude stations (e.g., Barrow, Zeppelin, Kjølnes, Birkenes, Norunda, Puijo-Koli, Pallas, Hyytiälä, Tiksi, Zotino pending permission) will be used. This step shall serve two purposes: A) Identification of possible Arctic MH emissions into the atmosphere for assessing the current overall situation; B) Provision of an optimized emission data set for the campaign periods. In the second step, CH_4 fluxes for the campaign domains and periods will be determined, with all other emissions fixed to values obtained in step 1.

Step 1: The inverse modelling method of Stohl et al. (2009) incorporates *a priori* information on the CH_4 sources as well as information on the uncertainties in the *a priori* fluxes, the measurement data and the model calculations. For the *a priori* CH_4 fluxes, emission information such as from EDGAR, the ECLIPSE EU project, or RCP for emissions related to anthropogenic activity, and eco-system models, such as ORCHIDEE[3] or LPX[4] with wetland hydrology and methane (WHyMe; Spahni et al., 2011; Zürcher et al., 2012) for CH_4 emissions from wetlands, peatlands and permafrost soils for wetland emissions will be used. Regarding the MH source, we will probably assume *a priori* that the emissions to the atmosphere are zero, but we will assign large uncertainties to the emission fluxes in areas where MH emissions seem possible (see Task 2.1) to give the inversion the freedom to detect eventual CH_4 fluxes. Using the station measurement data, monthly CH_4 fluxes at high Northern latitudes will be determined. While emissions from wetlands, and anthropogenic sources are needed in step 2, emphasis will be given to possible MH emissions, by carefully testing the inversion system with respect to variations of *a priori* uncertainties, demarcation of candidate MH emission regions, etc. It will also be tested whether incorporating existing isotopic information from Zeppelin and previous ship campaigns into the inversion system can improve the derived CH_4 emissions by providing constraints on the source type.

[3] http://orchidee.ipsl.jussieu.fr
[4] Land surface Processes and eXchanges

Step 2: The large-scale CH_4 emissions for the specific campaign periods will be constrained by the results from the first step for the campaign-period month. Eventual CH_4 emissions around Svalbard and in the Kara/Laptev Seas during the campaign periods will then be determined by using FLEXPART to derive high-resolution source-receptor relationships. As meteorological input data, we would either use data at the highest available resolution (currently 16 km) from the European Centre for Medium-Weather Forecasting (ECMWF) or from even higher-resolution simulations with the Weather Research and Forecasting (WRF) model. The FLEXPART results and all campaign-period data (ship, airborne, station) will be jointly used to determine the ocean-air fluxes during the measurement campaign via inverse modelling. Isotopic information will be incorporated into the inversion system and will strongly constrain the source type. We will also investigate whether local land-based sources on Svalbard, specifically coal-mining, is a substantial source of CH_4 to the atmosphere.

Seabed-Ocean-Atmosphere fluxes over various time scales. The uncertainty in the future CH_4 emission from the seabed is large (Ruppel, 2011; Shakova et al., 2010) not due to missing methodology, rather to short and localised observations, thus estimates are highly uncertain. First, there are uncertainties in the current emissions from the seabed to ocean with regard to temporal variability, magnitude and extent, but observations show dissolved and free gas emissions (Westbrook et al, 2009; Fisher at al., 2011). Secondly, the sensitivity of CH_4 emissions to changes in the ocean temperature is highly uncertain. Methane emissions from the seabed might have a potential to enhance the warming (Isaksen et al., 2011). Therefore, improved estimates and knowledge are urgently needed with methods that can provide upper and lower bounds on the emissions. In WP2 the quantification of future emissions for two regions will be emphasized with particular focus on upper and lower bounds given the lack of a well established methodology for upscaling the future emissions.

Starting with visual and hydro-acoustic surveys to map and monitor seep location and seabed activity, geochemical studies in the water column/sea surface complement CH_4 flux and overall budget calculations. We concentrate on areas where the seabed is shallow enough for CH_4 to reach the ocean-atmosphere boundary. Under the assumption that the key areas that emit CH_4 today will be a major emitter also in the future, an up-scaling will be done for the shallow Svalbard margins and the shallow Kara Sea region.

Building on existing work (Rajan et al., 2012), and work in progress, UiT plans to carry out 3-D seismic surveys routinely from 2013 to 2015. The results will be used in conjunction with planned long-term observatories at the site of CH_4 release activity. Repeated seismic surveys provide the actual database for a proposed time-lapse 3-D seismic study, where target areas encompass gas hydrates and active fluid leakage zones on the West-Svalbard margin. Each area covers up to 10 km^2 so that 3-D seismic surveying will only take between 2-4 days in each of the areas. The time-lapse analysis will encompass a total time period of 4 years.

Based on the measurements of CH_4 release activity in WP1 and temperature data combined with current knowledge of CH_4 stored as hydrates in the two locations (Svalbard and Kara Sea) a parameterization will be developed. The development of the schemes must be seen in light of the current large uncertainty and range in initial estimates. Due high complexity of this, the international experts listed in Table 1 will be involved in this work. The results will also be compared to estimates provided in the literature e.g. Bhattacharyya et al, 2012). Sensitivity to various factors influencing the CH_4 release activity will be investigated. The scheme will be combined with projections for ocean temperature change in the middle and towards the end of this century for various scenarios of future climate changes.

Simulations with the NCAR Community Earth System Model (CESM) combined with data from CMIP5 (http://cmip-pcmdi.llnl.gov/cmip5/) (Taylor et al., 2012) will be used for temperature changes (and for uncertainties in temperature changes) in the relevant regions for different time periods.

WP3 . Present and future projections of climate effects
Objective: *Quantify climate effects of direct and indirect emissions of methane from ocean under various climate scenarios*

In WP3, **MOCA** estimates of CH_4 emissions from the seabed and ocean as derived in WP2 will be used in global models to simulate the impact on the atmospheric composition and the global climate effect. Also the climate changes from CH_4 emissions from the ocean, and how much additional temperature rise and CH_4 emissions this may cause will be investigated.

The approach is to use the present-day emissions from WP2 for quantification of the CH_4 emissions from the seabed on the CH_4 budget and atmospheric chemistry. It is expected that this impact is currently quite modest. Thereafter, the CH_4 emissions from the upscaling in WP2 will be used to simulate climate changes with focus on surface temperature and partly precipitation for various scenarios. The impact of CH_4 emissions on the CH_4 concentration and indirect effect such as ozone and stratospheric water vapour will be simulated with a detailed chemistry transport model (OsloCTM3) (Søvde et al. 2012). The radiative forcing will thereafter be quantified and finally simulations with the NCAR CESM model will be performed. The simulations will be performed for various future temperature scenarios and time periods, with most focus on 2050 and 2100. The Arctic temperature rise, and in particular the temperature change around Svalbard will be investigated. The additional warming will be used in combination with results from WP2 to investigate the strength and potential of the biogeophysical cycle on hydrates with feedback between emissions and temperature. The simulations will be performed for various CH_4 emission scenarios.

The methodology will be based on our previous work in Isaksen et al. (2011), but extended with long term simulations with CH_4 emissions to calculate the influence on the atmospheric composition and climate model simulations to simulate the climate effect. OsloCTM3 with a detailed atmospheric chemistry will be used to simulate changes in CH_4 and its lifetime, ozone and stratospheric water vapour. The changes in distribution will be quantified in terms of radiative forcing. These changes will also be implemented in the NCAR climate model system to calculate temperature changes with focus on global Arctic changes. Ocean temperature changes will be particularly investigated for analyses of the strength of the biogeophysical cycle of hydrates from the sea bed. Since uncertainties will be significant in the emission scenarios several sensitivity simulations will be performed. In particular, the duration of the CH_4 emissions is crucial for the climate effect especially for substantial CH_4 emissions, and will be investigated with several sensitivity simulations.

2.3 The project plan, project management, organisation and cooperation

The **MOCA** project work plan is set up for a 3-year from and the start is set to 1. October 2013, optimised with respect to the organisation of campaigns. Four work packages (WPs) are defined. An overview of the relations between the WPs is illustrated in Figure 3, page 5. The work is in close collaboration with several international partners that have essential contribution, both scientifically and with respect to financial support. This is described detail in accompanying letters. Table 1 at page 7 summarises their contributions. This section describes the scientific work based the on the description in section 2.2, the relations between WPs and the milestones planned.

WP 1. Understanding and description of present state of system around Svalbard (leader Adam Durant, co-leader Jürgen Mienert, UiT)

Partners: NILU (lead), *UiT, GEOMAR, USGS,, DLR, CEA, UCAM*

Task 1.1: Understanding seabed-ocean methane release (UiT)

- Installation and analysis of measurements from four MASOX landers and accompanying buoys with measurement instrumentation within a 10 km^2 area targeting CH_4 bubble release aerea offshore of Prins Karls Forland.

Task 1.2: Determination of MH and oceanic emissions to the atmosphere (UiT)

- Ocean-atmosphere interface CH_4 mixing ratios, fluxes and isotope abundances (USGS, GEOMAR).
- Ocean column profile sampling for dissolved and free CH_4 and isotope abundances (GEOMAR).

Task 1.3: Vertical profile and extended time-series measurements of atmospheric CH_4 (NILU).

- *In situ* CH_4 mixing ratios and isotopic abundances at Zeppelin Observatory
- Aircraft-based vertical profiles of CH_4 concentration and isotope abundances over the ocean around Svalbard and Siberia (collaboration between DLR, LSCE and UCAM).

Task 1.4: Coordination of campaigns and measurements, dataflow and management (NILU)

- Detailed overview of all measurement activities will be set up and discussed regularly.
- Coordination of collaboration with the external partners in the campaigns
- A data sharing policy document will be established to ensure availability of **MOCA** data also after the project is completed. All atmospheric data will be submitted to EBAS (Tørseth et al, 2012). EBAS is the data base for the long-term program EMEP also hosting atmospheric in situ data in the EU research infrastructure ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure Network, http://www.actris.net) and others. Dr. Lund Myhre is coordinating the data centre in ACTRIS. The project and metadata from the project will also be registered in the RiS database of the Svalbard Science Forum (SSF) and if the Svalbard Integrated Arctic Earth Observing System (SIOS) is implemented during the project, the metadata will be linked to SIOS.

Milestone 1.1: Joint WS with MAAM[5] on coordination of campaigns (M3)
Milestone 1.2: Organisation of 2014 campaign (M4)
Milestone 1.3: Deployment of MASOX landers and buoys (M6)
Milestone 1.4: Completion of potential 2014 ship campaign (M10)
Milestone 1.5: Completion of 2014 aircraft campaign, Svalbard and Siberia (M10)
Milestone 1.6: Field campaign report, 2014 (all activities, including isotopic analysis) (M12)
Milestone 1.7: Organisation of 2015 campaign (M18)
Milestone 1.8: Completion of potential 2015 ship campaign (M21)
Milestone 1.9: Final field campaign report (all activities, including isotopic analysis) (M24)
Milestone 1.10: All measurement data to EBAS and other databases (M30)

WP 2. Understanding of present and future methane release from ocean (leader Jürgen Mienert, UiT, co-leader Andreas Stohl, NILU)

Partners: *UiT (lead), NILU, CICERO, GEOMAR, USGS*

Task 2.1: MH regions in Arctic (UiT)

- Synthesis of available information about all MH areas in the Arctic and detailed description areas where MH emissions are known and seem possible

[5] http://www.arctic.ac.uk/mamm/

Task 2.2: Detailed CH_4 emissions at present time for the Arctic (NILU)

- Source attribution and generation of emission maps by use of inverse modelling using FLEXPART and all observations from WP1 and other observations of CH_4 in the Arctic.

Task 2.3: Upscaling of CH_4 emissions for two regions with time (CICERO)

- Develop parameterization of CH_4 emissions for MH as a function of temperature and other key parameters
- Use an Earth System Model (NCAR CESM) combined with CMIP5 results for future temperature changes and its uncertainty for scenarios in 2050 and 2100 without CH_4 emissions from MH.
- Estimate upper and lower bounds of CH_4 emissions from MH for 2050 and 2100 in 2 Arctic regions.

Milestone 2.1: Synthesis of available information about all MH areas in Arctic (M12)
Milestone 2.2: Methane budget from individual seeps and seep areas (M20)
Milestone 2.3: Ocean-seabed and ocean-atmosphere emission estimates, (M24)
Milestone 2.4: Inverse modelling step 1 completed (M15)
Milestone 2.5: Inverse modelling step 2, completed (M24)
Milestone 2.6: Preliminary estimate of CH_4 emissions from MH for 2050 and 2100 (M18)
Milestone 2.7: Parameterisation of CH_4 emissions from MH (M18)
Milestone 2.8: Ocean temperature scenarios in 2050 and 2100 (M12)
Milestone 2.9: Estimate upper/lower bounds of CH_4 emissions from MH for 2050 and 2100 (M30)

WP 3. Present and future projections of climate effects (Leader: Gunnar Myhre, co-leader Ivar Isaksen, CICERO**)**

Partners: CICERO, *UCAM*

Task 3.1: Current influence of methane emissions from the seabed (CICERO)

- OsloCTM3 will be used simulate the influence on the atmospheric composition from the current emissions of CH_4 from the seabed as derived in WP1 (all tasks) and WP2, task 2.2.

Task 3.2: Future impact of methane emissions from the seabed (CICERO)

- Methane emissions from the seabed as derived in WP2 task 2.3 will be used to calculate changes in the CH_4 distribution and indirect effect of CH_4 and its radiative forcing and temperature changes.
- Simulations will be performed for different time periods in particular 2050 and 2100 and CH_4 emission scenarios.
- Sensitivity simulations on the time duration of CH_4 emissions will be performed.

***Task 3.3: Investigation of the strength of the bio geophysical cycle of methane emissions from* the seabed (CICERO)**

- The temperature changes in Task 3.2 will be used to derive whether the change is sufficient to change the CH_4 emissions from the seabed as investigated in WP2. The potential strength of the cycle will be investigated.

Milestone 3.1: Impact on current atmospheric distribution of CH_4 emissions from the seabed (M24)
Milestone 3.2: Future radiative forcing of direct and indirect effect CH_4 emissions from the seabed (M30)
Milestone 3.3: Future temperature changes from effect CH_4 emissions from the seabed (M33)
Milestone 3.4: Quantification of potential of the bio-geochemical cycle of CH_4 emissions (M33)

WP 4 Management and outreach (Cathrine Lund Myhre, NILU)

Partners: *NILU*

Task 4.1: MOCA Management

- Coordinate the project and ensure internal communication of the results for national and international **MOCA** partners
- Official correspondence with the Norwegian Research Council.
- Established **MOCA** webpage and include intranet with preliminary results available to project participants to facilitate easy communication, access to all levels of data and results

Task 4.2: Outreach

- Scientific publications will be a central and integrated part of the WP 1-3. Conference participations will be encouraged and attempt will be made to organise dedicated CH_4 sessions at international conferences and also effort to contact TV and media will be made
- Participation in national meetings involving scientists, policy makers and other user groups
- Maintenance of webpage with project progression and results to project partners and public

Milestone 4.1: Kick off meeting and project web page established (M1)
Milestone 4.2: Reports to the Research Council (M14, M26)
Milestone 4.3: Organisation of interdisciplinary meetings/workshops/conference sessions (M36)
Milestone 4.4: Participation in conferences, symposia and workshops (M36)

2.4 Budget

The total requested budget is 23.3 mill NOK. The project will benefit largely from international contributions *in kind*, including ship, and aircraft campaigns, and isotopic analysis (see Table 1). A total of ~6.3 mill NOK is requested from NFR for purchase of isotopic analyses, contributions to aircraft and ship campaigns, instrumentation, as specified in the application form. The project will employ a PhD student for field work under supervision of UiT.

3 Key perspectives and compliance with strategic documents

3.1 Compliance with strategic documents

This project is closely linked to the strategic aims of NILU, UiT and CICERO. **MOCA** is within **NILU's** core strategic goal: "*NILU should be an internationally prominent research institute within the field of measurements, analysis and modelling activities and of relevant technology development.*" NILU was in 2011 awarded top rank (grade 5) in the evaluation of the Geosciences in Norway, and the evaluation identifies the Norwegian atmospheric research community to represent a national flagship. NILU has a strategic aim to prioritize the use of observations and focus on the integration of observations with modelling tools. **UiT is** Norway's representative for European projects such as EMSO (European Multidisciplinary Seafloor Observatory), ESONET and the leader of NOON (Norwegian Ocean Observatory Network). All these projects aim at creating a network of observatories for long-term monitoring, mainly in real-time, of environmental processes related to the interaction between the geosphere, biosphere, and hydrosphere, including natural hazards. **CICERO** was established by the Norwegian government in 1990 as an independent non-profit organization attached to University of Oslo. CICERO employs approximately 80 persons, of which more than 50 are researchers. With expertise within natural science as well as social science, the institute specializes on interdisciplinary research over a broad range of issues relevant for climate issues.

Strategic documents like the national climate research strategic "*Klima 21 Strategi for*

klimaforskning"[6] and the new EMEP Monitoring Strategy (2010-2019)[7] have emphasised the importance of CH_4. In "*Klima 21*", research focusing on improving the knowledge of CH_4 emissions from Arctic reservoirs and the possible climate feedback with accelerating climate change is recommended.

3.2 Relevance and benefit to society

More studies are required to understand connections between natural CH_4 emissions and the potential for serious climate change. This is relevant both for quantification of future temperature levels and for risks of reaching a "tipping point" of irreversible climate change (Lenton et al.2010). Measures to reduce CH_4 concentration could be efficient if a specific threshold value for temperature increase within a short time horizon is considered important (Penner et al., 2010). However, for abatement strategies to be successful, we urgently need improved understanding of recent trends and natural sources.

3.3 Environmental impact

Over the long-term the project will have indirect consequences for the environment through reducing uncertainty in climate predictions within a topic which presents one of the highest uncertainties.

3.4 Ethical perspectives

There are no ethical implications associated with the proposed project.

3.5 Gender issues (Recruitment of women, gender balance and gender perspectives)

The project leader is female; Cathrine Lund Myhre. No discrimination will take place related to pregnancy or military service. The scientists participating in the project will have equal opportunity to take part in research and dissemination. In recruitment of PhD student balance with respect to gender equality will be encouraged and relevant.

4 Dissemination and communication of results

4.1 Communication with users

There are several national and international users that will be highly interested in the results from **MOCA**. The main users of the project results are the climate scientific community, IPCC, and broad scientific disciplines e.g. atmosphere, oceanography, geology, biology, and policy makers. Attempt will be made to organize dedicated sessions at e.g. the EGU conference and other conferences. Interactions with the Earth System Modelling communities will be a part of this. Also participation in, and organization of, national symposia with scientists, and policy makers are important. Several of the **MOCA** team are routinely engage with the media, both in Norway and abroad. Cathrine Lund Myhre is regularly informing about ozone layer, UV exposure, and greenhouse gases in Norwegian broadcast as NRK (TV and radio), TV2, newspapers. Adam Durant has previously worked closely with media to report research activities including the National Geographic documentary "Earth Report: State the Planet 2009". Attempt will be made to produce documentary from the campaigns (funding for this will potentially be from other sources).

4.2 Dissemination plan

The dissemination of the scientific results of the project will be done through various channels, and scientific publications will be an integrated activity of WP1-3. The scientific findings of the project will be published in presumably 6 papers in peer-reviewed journals covering oceanography,

[6] http://www.klima21.no/
[7] http://www.emep.int/

biogeochemistry, atmospheric chemistry and climate change. Results will also be presented at national and international conferences and meetings. This is an important part of the communication with users as described in section 4.1.

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