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Seasonal controls of methane gas solubility and transport on anaerobic oxidation of methane in shallow water marine sediments

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Sediments with free methane gas are a common occurrence in shallow water marine environments which receive high organic matter flux to the sediment surface. Methanogenesis of buried organic matter occurs below the zone of sulfate reduction and results in the formation of dissolved methane. Subsequently, free methane gas forms when dissolved methane exceeds the solubility concentration. Upward migration of dissolved and gaseous methane sustains the microbially-mediated anaerobic oxidation of methane (AOM) coupled to sulfate reduction in the sulfate-methane transition zone (SMTZ). Since pressure and temperature govern methane solubility, temporal variations in these parameters affect the location and volume of gaseous methane, and thus, biogeochemical reaction rates. In this study, a reactive-transport model is applied to investigate the transient (sub-diurnal and seasonal) dynamics of methane cycling in a marine sediment environment triggered by the individual and combined effects of temperature and pressure fluctuations. The model, which explicitly accounts for the total sediment volume occupied by gas, is calibrated with data from Eckernförde Bay, Germany, where intense AOM occurs above the gas-containing sediment. Results reveal that seasonal temperature fluctuations control the depth of gas formation and dissolution with an associated time lag related to the time of heat propagation in sediments. Typical diurnal-scale pressure variations due to tides and atmospheric conditions lead only to centimeter-scale vertical shifts in the depth of the gas horizon. Our transient simulations ultimately suggest that the seasonal coupling between the depth to the gas phase and integrated AOM rates is site specific and highly depends on the proximity of the free-gas phase to the SMTZ. Furthermore, methane is found to be efficiently oxidized within the sulfate-methane subsurface barrier, and can only escape to the water column when large and abrupt decreases in sea level reduce rapidly the gas solubility, allowing increased transport rates of gaseous methane through the sediment.