チャクチ海バロー沖におけるフラジルアイス生成と海底堆積物の上方輸送の観測

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Observations of frazil ice formation and sediment upward transport off Barrow in the Chukchi Sea

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Sediment-laden sea ice, called “dirty ice”, is well known in the Arctic Ocean. Particles which are incorporated into sea ice are transported horizontally by drift of pack ice and finally released to a water column as sea ice melt. Some in-situ observations have revealed that such sediment export by sea ice potentially has great impacts on deep-sea sedimentation, its redistribution, dispersal of pollutants and biological productivity (e.g. Kanna et al., 2014). Sediment inclusions into sea ice contribute significantly to the surface energy balance of the ice cover due to the absorption of short-wave radiation. As a likely process for sediment entrainment into sea ice, some laboratory experiments suggested the direct interaction between frazil ice and re-suspended sedimentary particles and anchor ice formation/growth on the ocean bottom (e.g. Reimnitz et al., 1993). From in-situ observations in the Arctic Ocean, large amount of sedimentary particles were found inside of grease ice and of layer of granular ice in perennial ice, which indicates that sediment incorporation into sea ice occurs in association with newly ice formation (e.g. Eicken et al., 2005). However, the entrainment process in the real ocean has not been clarified because of logistical challenges in polar oceans and few methods of frazil ice and sedimentary particles detection in the marine water column. During from August 2009 to June 2010, two moorings were deployed off Barrow in the Chukchi Sea at 71.3°N, 156.9°W and 71.3°N, 156.9°W in a water depth of 43 m and 55 m, respectively. These moorings were equipped with an Acoustic Doppler Current Profiler (ADCP), an Ice-Profiling Sonar (IPS) and a conductivity-temperature sensor. Ito et al. (2015) reported the occurrence of supercooling in the depth of 40 m during polynya activities in association with strong offshore-ward winds, based on these mooring measurements. In this study, we analyzed acoustical backscatter data obtained by these moored ADCPs and IPSs, focusing on the frazil ice formation and upward transport of ocean-bottom sediment, along with analyses of the satellite and meteorological data. Some recent in-situ observations reported that an ADCP is potentially able to detect suspended frazil crystals or sedimentary particles in the water column. According to our mooring data, frazil crystals were detected from ocean surface down to at least depths of 30 m (above the IPS) in association with supercooling events in December (Fig. 1a). These facts suggest a possibility that frazil ice captures sedimentary particles through the interaction between frazil ice and sea floor. On the other hand, another strong signals, intensified near the bottom, were detected in the whole water column (Fig. 1a) in association with strong bottom currents (Fig. 1c). These signals are considered to be sedimentary particles which are dispersed upward from the bottom and transported up to near the ocean surface. At these timings, frazil ice was not detected even in the ocean surface, although satellite and IPS data show open water with turbulent conditions around the mooring sites. These facts suggest a possibility that sedimentary particles are transported up to ocean surface, and then incorporated into sea ice, owing to re-freezing of ocean surface or flooding of sea ice by the ocean wave and swell.

北極海では“dirty ice”と呼ばれる、多量の海底堆積物を取り込んだ海氷がしばしば観測されている。海氷内に取り込まれた物質は、海氷の漂流によって運ばれ、融解時に再び海中へと放出される。北極海やオホーツク海で行われたいくつかの現場観測より、このような海氷による物質の輸送は、海底地質の再形成や、汚染物質の輸送、生物生産に深く関係することが明らかとなってきた (e.g. Kanna et al., 2014; Eicken et al., 2005)。また、海氷内部に取り込まれた堆積物粒子は海氷のアルベドを著しく低下させることから、海氷域の表面熱収支に大きく影響を与

えうる。海氷への堆積物粒子の取り込み過程に関して、いくつかの室内実験から、フラジルアイスやグリースアイスと海底から上方輸送された堆積物粒子が接触する過程や、アンカーアイスによる海底堆積物の直接的な取り込みなどが提唱されている (e.g. Reimnnitz et al., 1993)。北極海の定着氷で行われた現場観測では、フラジルアイスやグリースアイスが固化したグラニュラーアイスの層より多量の堆積物粒子が検出されており、海氷結氷期における堆積物粒子の取り込みが予想されている (e.g. Eicken et al., 2005)。しかしながら、冬季の極域海洋における現場観測が難しいこと、海中のフラジルアイスや堆積物粒子を検知する方法が確立されていないことから、実際には、どのようにして堆積物粒子が海氷内部へと取り込まれるか、つまり dirty ice の形成過程は明らかになっていない。チャクチ海バロー沖では 2009 年から 2010 年にかけて、水深 43m の岸側 (71.32N, 156.88W) と水深 55m の沖側 (71.23N, 157.65W) に係留系が設置され、各々に Ice-Profiling Sonar (IPS)、ADCP、水温塩分計が取り付けられた。これらのデータから、Ito et al. (2015) では、強風を伴うポリニヤイベント時に、40 m の水深で過冷却が観測されたことを報告している。本研究では、これら係留系の ADCP や IPS により取得されるデータを用いて、フラジルアイスの生成と海底堆積物の上方輸送に着目し、さらなる解析を行った。ADCP によるフラジルアイスや堆積物粒子の検知に関しては、北極海やサンゴ礁などで各々報告例がある。解析の結果、前述の過冷却イベント時（12 月）には、少なくとも IPS の直上である水深およそ 30 m までフラジルアイスが検知されていた（図 1a）。これはフラジルアイスが海底まで達することで、海底堆積物を捕獲する可能性を示すものである。一方で、海底に強い流れ（図 1c）が生じた際に、底ほど強いシグナルも検知された（図 1a）。これらのシグナルは海底から海面付近にまで上方輸送された堆積物粒子を検知したものと考えられる。このとき、衛星データや ISP のデータから海面は開放水面であったと推定されるが、フラジルアイスとみられるシグナルは検知されなかった。これらは海面付近まで上方輸送された堆積物粒子が、海面の再凍結や、波などの影響で海氷上に乗り上げることで、海氷内へと取り込まれる可能性を示すものである。

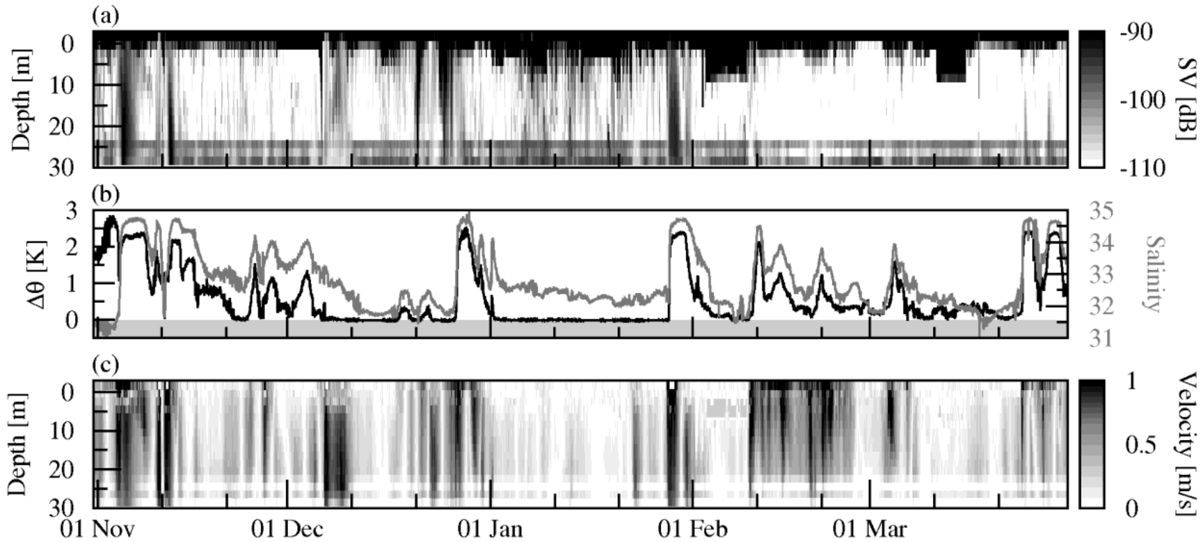

Figure 1. Time series of the mooring data at the water depth of 43 m during from 1 November 2009 to 31 March 2010. (a) Vertical profiles of acoustic echo intensities (volume backscattering strengths) calculated from the ADCP data. (b) The potential temperature relative to surface freezing point (black) and salinity (gray) at 30 m depth from the C-T recorder. (c) Vertical profiles of current speeds from ADCP.

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