

## 堆積物記録に基づく瀬戸内海の過去150年にわたる低次生産量の変動—外洋・陸起源の栄養塩はどんな影響を与えてきたか—

### Temporal variations of productivity at low trophic levels over the past 150 years in the western Seto Inland Sea, Japan, revealed by sedimentary records

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We examined fossil pigments in a <sup>210</sup>Pb-dated sediment core to document the temporal variations in phytoplankton biomass over the past 150 years in a semienclosed bay, Beppu Bay, in the western Seto Inland Sea, Japan. The flux of fossil pigments was used as an index of phytoplankton biomass, which we reconstructed after removing the effect of post-burial degradation on the concentrations of fossil pigments.

The flux doubled from the 1960s to the early 1970s, decreased or remained stable in the early 1980s, and increased again from the late 1980s to the early 1990s. The first increase in phytoplankton biomass during the 1960s was likely caused by eutrophication due to an increase in terrestrial nutrient fluxes from watersheds. The decreasing phytoplankton biomass in the early 1980s was likely related to the establishment of a sewage treatment system that reduced the terrestrial nutrient fluxes to the sea. However, the terrestrial nutrient fluxes could not explain the second increase from the late 1980s to the early 1990s. Intensification of the influx of nutrients from the shelf slope to the sea was likely the cause of the second increase in phytoplankton biomass. This is supported by the inverse relationship between phytoplankton biomass and sea level at the shelf slope, the latter being an index of the intensity of the influx of oceanic nutrients from the shelf slope to the sea. The supply of oceanic nutrients may be therefore a critical factor in the determination of primary production in the western Seto Inland Sea.

キーワード：基礎生産、色素、瀬戸内海、黒潮、古海洋学、富栄養化

Keywords: Primary production, fossil pigment, Seto Inland Sea, Kuroshio current, Palaeoceanography, Eutrophication

## Evidence for multiple redox zones in early Cambrian ocean

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Ocean redox state is basically controlled by the balance between oxidizers and reductants. In theory, in addition to conventional oxygen and sulfate, Mn-Fe oxides and nitrate can serve as the oxidizer, whose reductions have been hypothesized to have generated manganous-ferruginous and nitrogenous zones between oxic and sulfidic zones in a highly stratified ocean of early Earth (>520 Ma; Li et al., 2015). To test this hypothesis, we conducted a high-resolution Fe-S-C-N and trace-element geochemical study of the early Cambrian Qingxi Formation in a deep-water setting at Silikou, Guangxi Province, South China. Integrated Fe-Mo-S-C-N data demonstrate an overall marine redox transition at Silikou from euxinic to oxic conditions up section, which is consistent with the gradual oxygenation of early Cambrian ocean observed widely in South China (Jin et al., 2016). However, our data also clearly reveal the developments of manganous-ferruginous and nitrogenous conditions during the transition as suggested by higher sedimentary Mo concentrations relative to U due to the adsorption to Mn-Fe oxides and subsequent reductions (i.e., the activity of Mn-Fe shuttle) and the abrupt increase of the organic N isotope from +2 ‰ to +5 ‰. The occurrence of these redox zones reflects the successive use of oxygen, nitrate, Mn-Fe oxides and sulfate as the oxidizers in early Cambrian oceans. Thus our study for first time provides direct evidence for the existence of these hypothesized redox zones in early Earth's oceans, which is of significance to our understanding of elemental biogeochemical cycles in early Earth's oceans and their impacts on biological evolutions.

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Keywords: Early Cambrian, Redox Condition, Early Animals, Oceanic Stratification

## Chukchi and Bering Sea shelves contribution to Mn enrichment in the Arctic deep basin

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A key role of the Siberian Arctic shelves has been suggested to play in the enrichment of Mn over all Arctic deep basins. On the orbital timescale, Mn records from the Alpha Ridge core 08B85-D displayed a close correlation to the Relative Sea Level changes on the independent age model. A threshold of -60 m sea level seems to be able to shift the Mn transportation from shelves to deep basins. This phenomenon in the core records was supported to some extent by the Mn distributions in the surface sediments with extremely low values over the Chukchi Sea and Bering Sea shelves and with relatively high values over the areas deeper than 60 m water depth. Another independent proxy Ce anomaly also shown the similar distributions as the Mn both in the core and the surface sediments, and suggested that the main transportation of Mn might occurred at the Chukchi Sea and Bering Sea shelves, rather than the Eastern Siberian Sea and Laptev Sea shelves. Especially the Contributions from the Bering Sea shelf should be considered to account for the Mn enrichment in the Arctic deep basins.

Keywords: Mn enrichment, Chukchi Sea shelf, Bering Sea shelf, Ce anomaly

## Capturing extreme river runoff events from oceanic sediment distribution

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A significant amount of the freshwater discharges around Japan occurs through extreme weather events. Capturing the event in the ocean, however, has been observationally difficult because of the strong currents and its random occurrence. Moreover, the low salinity signal often disappears after a few days since the majority of the rivers in Japan are directly connected to the open ocean and thus is strongly affected by its circulation. Regional-scale numerical oceanic models are becoming capable of resolving the dynamics of freshwater discharges but we have so far lacked a tool to test them from observations. We will introduce an observational project based on the Ariake Sea that aims to investigate the dynamics of the extreme freshwater discharges from oceanic sediments. The discharge following the Kumamoto Earthquake is likely associated with sediments that entered the rivers through the various landslides and thus contain a detectable record compared to previous years. The Ariake Sea is one of the few estuaries that is large to capture the discharge signal and not directed altered by the open oceanic circulation.

Keywords: river runoff, sediment, earthquake

## 完新世の気候変動に対する北西太平洋のイワシ類の応答

## Response of Japanese sardine and anchovy abundances to orbitally driven climate changes during the Holocene

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完新世の気候変動に対して、浮魚類はどのように応答してきたか？これを知ることは、長期的な温度変化に対する浮魚類の応答について貴重な情報をもたらすかもしれない。世界で最も漁獲されるイワシ類を対象に、完新世における個体数の長期変動を魚鱗堆積量によって明らかにした。その結果、日本マイワシの魚鱗堆積量は7000年前から3500年前に増加トレンド、3500年前から現在まで減少トレンドを示した。カタクチイワシは3500年前以前は魚鱗堆積量は少なく、それ以降徐々に増加し、マイワシとカタクチイワシの間で逆のトレンドを示した。マイワシとカタクチイワシの成長速度は、それぞれの最適水温16°Cと22°Cのユニモーダルな水温応答を示すことが報告されており、最適水温より数°Cの高水温あるいは低水温による成長速度の低下が再生産を悪化させ、マイワシとカタクチイワシの個体数の劇的な資源崩壊や魚種交替を引き起こす。これを'optimal growth temperature'仮説(Takasuka et al., 2007)という。実際、1980年代後半以降太平洋十年規模振動に代表される気候変動によって生じる水温変動によってマイワシ個体数が約90分の1にまで低下し、カタクチイワシへの魚種交替が起こったことが知られている。

この仮説は、完新世の気候変動においても魚鱗記録で見られるマイワシ・カタクチイワシの長期トレンドを説明できるだろうか。20世紀後半のマイワシ増加期における産卵場（日本南岸）の水温は17°C程度で、最適水温よりもやや高い水温であり、マイワシレジームにおける1°Cの水温低下はさらに仔魚の生残率が高くなることが期待される。ミランコビッチサイクルに伴う日射量強制あるいは日射量・温室効果ガス両方の放射強制を与えたモデル計算(Lorenz et al., 2006; Ohgaito et al., 2013)によると、仔魚が分布する黒潮続流域の海面水温は、冬季の推定で過去6000年間で0.7°C前後の増加トレンドを示しており、6千年前にはマイワシレジーム時の水温は最適水温に近かったことになる。したがって、過去6000年間、水温応答特性が変化しないと仮定すれば、個体数は6000年の間減少トレンドを示すはずだが、実際は3500年前までは増加トレンドを示し、その後減少トレンドを示している。この矛盾について幾つかの原因が考えられ、最も有力な原因の一つは、モデル計算における粗い空間解像度により、仔魚の生残にとって最も重要な黒潮続流の流軸とその北+0.5°の狭い範囲の水温の低下を過小評価している可能性が考えられる。1980年代のマイワシレジームでは17°C前後であったが、3500年前で今より1°C低下したとすれば現在よりも高い個体数を説明できる。また、6000年前に今より約2°C低下したとすれば、最適水温をさらに1°C下回るので、成長速度低下によってこの時の低い個体数を説明できる。一方カタクチイワシは現在のカタクチイワシレジームでは最適水温の22°Cよりやや低い水温環境であるが、過去の温度の低下は成長速度の低下をもたらし、個体数を減少させる原因となったと考えれば、3500年前以降からの増加トレンドを説明できる。すなわち、どちらの長期トレンドも'optimal growth temperature'仮説によって説明できることになる。いずれにしても、マイワシやカタクチイワシに見られる長期トレンドの原因は、続流域の海面水温を決定する大気海洋過程の日射量変動に対する応答を高精度で解明することによって明らかになると考えられる。今後の海洋学と古海洋学の連携を期待したい。

キーワード：マイワシとカタクチイワシ、気候変動、完新世、北西太平洋

Keywords: Japanese sardine and Japanese anchovy, climate change, Holocene, Northeast Pacific

## Multiple equilibria and overturning variability of the Aegean-Adriatic Seas

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The Eastern Mediterranean Transient (EMT) –a transition and amplification of the Eastern Mediterranean Sea deep water source from the Adriatic Sea to the Aegean Sea –was observed in the mid-90' and stimulated intense research. We demonstrate, using an oceanic general circulation model, that the meridional overturning circulation of the Eastern Mediterranean has multiple equilibria states under present-day-like conditions, and that the water exchange between the Aegean and the Adriatic Seas can drastically affect these states. More specifically, we found two stable states and a hysteresis behaviour of deep water formation in the Adriatic Sea when changing the atmospheric (restoring) temperature over the Aegean Sea. In addition, the overturning circulation in both seas exhibits large decadal variability of the deep water formation. The Aegean-Adriatic relationship can be summarized as follows: warm and saline water of the Aegean can either flow in the sub-surface to the Adriatic, switching “on” deep water formation in the Adriatic by increasing its salinity, or the Aegean water can feed the deeper layer of the Ionian and Levantine basins, turning “off” the deep water formation in the Adriatic. The “off” steady state resembles some aspects of the EMT in which the Adriatic source of deep water was weakened when the Aegean source became active. Another noticeable finding of this work is the minor to none dense water outflow from both the Aegean and Adriatic Seas in some of the simulations. When none of the seas produce dense enough water, the Levantine basin deep layers are not ventilated and a sapropel-like period is enabled, as is evident in the Eastern Mediterranean sediments record.

Keywords: Mediterranean Sea, Meridional overturning circulation, Multiple equilibria, Adriatic Sea, Aegean Sea, Eastern Mediterranean Transient

## 周辺海域の気候変動から孤立した瀬戸内海の30年水温塩分変動について 30-year variation of temperature and salinity in the Seto Inland Sea isolated from the climate change in the surrounding ocean

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Using oceanographic data archived in the Marine Information Research Center Ocean Dataset 2005, linear trends of both temperature and salinity from 1963 to 1993 were computed at each grid cell with a horizontal scale of  $1/6^\circ$  over the Seto Inland Sea, Japan. The linear trends were thereafter multiplied by 31 years to compute the increments of temperature and salinity during this period. Over the course of 31 years, summer temperatures decreased significantly both at the sea surface ( $-1.2^\circ\text{C}/31\text{y}$  averaged over the area) and the bottom ( $-1.7^\circ\text{C}/31\text{y}$ ), while salinity increased at the sea surface ( $0.46/31\text{y}$ ) and bottom ( $0.41/31\text{y}$ ). In addition, it was found that steric heights computed using temperature and salinity in summer (see Methods) mostly decreases over the Seto Inland Sea during the 31 years ( $-0.57\text{ mm}/\text{y}$ ).

It is unlikely that these 31-year trends were caused by surface heat and freshwater fluxes through the sea surface. Of particular interest is the salinity increase, which was revealed in the bottom layer as well as the surface layer. Apparently, this is unlikely to be caused by a secular trend of freshwater flux into the upper layer (precipitation minus evaporation, and/or river runoff). The reasonable explanation is that the dense (cool and saline) Kuroshio intermediate water, uplifted near the coast over the period 1963 through 1993, intruded into the bottom layer of the Seto Inland Sea. The above-mentioned trends were restricted within the Seto Inland Sea. The temperature increment south of Japan was mostly zero during the same period in summer. Moreover, the sea surface height (SSH) within the same area in summer showed an increase of  $0.2\text{ (}2.0\text{) mm}/\text{year}$  during the same period.

In the southwestern Japan Islands, the oceanographic properties of shallow coastal waters exposed to the south are vulnerable to Kuroshio fluctuations that act as outer boundary conditions. The reconstructed SSH data (ReSSH; Hamlington et al., 201, 2112) map averaged over 10 years from 1963 to 1972 suggests that a cold eddy was located off the Kyushu and Shikoku Islands, Japan. However, in the ReSSH map averaged over the period 1984–1993, the cold eddy identified 20 years earlier had mostly disappeared, and it was replaced with a warm eddy. The transition to the warm eddy suggests that the surface speed (hence, volume transport) of the Kuroshio Current south of Japan had increased during the period 1963–1993, because of the recirculating geostrophic flow around the eddy. A geostrophic adjustment associated with the increasing Kuroshio transport results in the thermocline tilting and resultant temperature decreases (salinity increase) close to the Japan Islands. This is consistent with the temperature decrease (salinity increase) in the Seto inland Sea, potentially caused by the subsurface intrusion of the Kuroshio intermediate water. It is however a difficult task to uncover the possible cause(s) of the eddy transition south of Japan; Note that the Kuroshio meander off the Enshu Nada was apparently not a cause, because it is located far east of the Seto Inland Sea. To uncover the cause(s) of the 31-year eddy activity south of Japan, we have to investigate the secular SST/SSH variation, at least, ten times longer than the period in the present study, and it is unfortunately beyond the scope of the conventional physical oceanography.



キーワード：水温塩分30年変動、瀬戸内海

Keywords: 30-year variation of temperature and salinity, Seto Inland Sea

## 日本海における底層水の形成とその経年変動

## Formation of bottom water and its variability in the Sea of Japan

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日本海での底層水形成（陸棚水が大陸棚斜面を沈降する過程）について、その力学過程と経年変動を調べた。その結果、以下のことが分かった。冬季のピョートル大帝湾（Peter the Great Bay、以下PGB）では、低温・高塩で高密度の陸棚水が形成されている。このPGB陸棚水は、1980年以前はPGB沖の大陸棚斜面基部（3000 m深）まで時々沈降していた。ところが、1980年代に入ると、それは大陸棚斜面の半分程度（1500 m深）まで沈降することはあったものの、斜面基部（3000 m）まで沈降して底層水を形成することはなかった。しかし、2001年には、顕著に重いPGB陸棚水が作られて、再び大陸棚斜面基部にまで達する沈降が生じた。2001年に底層水形成が復活した理由は、シベリア高気圧の北部とアリューシャン低気圧が強化されて、それらが寒気を北方からPGB周辺に運んだためである。その結果、PGBで強い海面冷却が生じ、日本海での底層水形成に至ったと考えられた。すなわち、日本海底層水の形成は、大気場の経年変動に強く影響を受けている。

キーワード：日本海、底層水形成、経年変動、力学モデル

Keywords: Sea of Japan, Formation of Bottom Water, Interannual variability, Hydrodynamic Modeling

