Relationship between 18.6-year period lunar tidal cycle and ENSO

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Bi-decadal variability is known to be a major component in the inter-decadal ocean and climate variability over the Pacific. Variations in vertical mixing induced by 18.6-year period nodal tidal cycle (18.6-yr cycle) are suggested as one of the causes of this bi-decadal variation. Previous studies showed that the north Pacific mid-high latitude SSTs and air temperature, surface and intermediate water masses in the subarctic North Pacific, the Aleutian Low Pressure, PDO (Pacific Decadal Oscillation) index etc. are synchronized with the 18.6-yr cycle (Yasuda et al., 2006; Osafune and Yasuda, 2006; 2010; Yasuda, 2009). Numerical climate model experiments with vertical mixing modulated with the period of 18.6 year near the Kuril Islands also suggested that the 18.6-yr cycle affects low-latitude Pacific and climate as PDO (Tanaka et al., 2012) and El Niño Southern Oscillation (ENSO) (Hasumi, et al. 2008). Although climate impacts from tropical variability as ENSO is large, there has been only one observational study that suggested relationship between intense El Niño and the 18.6-yr cycle; however the result (Cerveny and Shaffer, 2001) is not reliable because the analysis method used was inadequate. In the present study, long-term time series of ENSO indices (Southern Oscillation Index (SOI), NINO3-index, Cold Tongue Index (CTI) etc.) reconstructed from tree rings, etc. are analyzed to clarify the relationship between tropical climate and the 18.6-yr cycle. Furthermore, on the basis of ocean and atmosphere datasets, spatial structures of the 18.6-yr variability are examined to discuss mechanisms how the 18.6-yr cycle affects the tropical ocean and climate. Variations synchronized with the 18.6-yr cycle are detected by using “calendar composite analysis” in which the mean and its confidence interval are evaluated at each tidal year from the maximum diurnal tide in the 18.6-yr cycle. We here found 3.72 (=18.6/5)-year period variability based on a proxy record of December-February Southern Oscillation Index (SOI) reconstructed from tree-rings (Stahle et al., 1997), and showed that El-Nino (La-Nina) tends to occur in the 1st, 10th, 13th and 17th (3rd, 7th and 16th) year after the maximum diurnal tide in the 18.6-year cycle.
In the low-passed (5-year running mean) long-term time-series of ENSO indices during 1700s-1970s, statistically significant +SOI and –NINO3 is found to occur at the 4-5th tidal year from the maximum diurnal tide suggesting La Niña, and –SOI and +NINO3 at the 11-12th tidal year suggesting El Niño. These are consistent with the PDO-18.6yr cycle relationship (Yasuda, 2009). In the 10-30yr period band-passed SST/SLP during 1910-1997, low (high) SST in the tropical Pacific, high (low) SST in the mid-latitude central North Pacific, almost simultaneously weak (strong) Aleutian Low Pressure, high (low) SLP in the western tropics, and low (high) SLP in the eastern Pacific occurs at the 3-4th (12-13th) tidal year after the maximum diurnal tide in the 18.6-yr cycle.

Keywords: 18.6-year period lunar nodal cycle, ENSO, interdecadal ocean climate variability

Intensive mixing along the Kuril island chain controls upward micro-, and macro-nutrient supply in the western subarctic North Pacific

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In the subarctic North Pacific, physical processes that transport macro- and micro-nutrients from the meso-pelagic layer to the surface have not been clearly identified. *Sarmiento et al.* [2004] used the combined distributions of silicic acid and nitrate to trace the main nutrient return path from deep water to above the thermocline (approximately 26.8 $\sigma_\theta$in the subarctic Pacific) and pointed out the existence of a return process in the northwest corner of the Pacific where there is enhanced vertical mixing, perhaps driven by tidal mixing at the Kuril Islands chain (KIC). Therefore, detailed investigation of material fluxes in water flowing through the KIC is important for understanding macro- and micro-nutrient supply to the surface.
In 2006, 2007, 2010, we conducted direct observation around the KIC during R/V *Professor Khromov* cruise, and chemical measurements were carried out for clarifying vertical distribution of micro-(dissolved-Fe (Fe)), and macro-(nitrate + nitrite (N)) nutrients. From the results, we estimate the vertical fluxes of dissolved Fe and N from the subsurface to the surface at Bussol' Strait (the deepest strait along the KIC) using the equations,
Dissolved-Fe Flux = - K_ρ ×(dFe/dz), Nitrate + nitrite Flux = - K_ρ ×(dN/dz),
where K_ρ is vertical diffusivity and dFe/dz and dN/dz are the vertical gradients of dissolved-Fe and N concentrations, respectively. Our measured vertical profiles of dissolved-Fe and N in Bussol' Strait display the influence of strong mixing in their disrupted gradients. Therefore, these gradients are not suitable for estimating material flux from intermediate to surface waters. Instead, we used the vertical profile obtained at station in the Kuril Basin to approximate the state of the water before the mixing process. The vertical gradients of dissolved-Fe (dFe/dz) and N (dN/dz) at station in the Kuril Basin are 0.0052 μmol m^{-4} and 0.073 mmol m^{-4}, respectively. Combining these gradients with 1-day average vertical diffusivity for depths of 100–500 m in Bussol' Strait reported by *Yagi and Yasuda* [2012] (K_ρ = 1 $\times 10^{-3}$ m^2 s^{-1}), the estimated fluxes are 0.45 μmol m^{-2} day^{-1} for dissolved-Fe and 6.3 mmol m^{-2} day^{-1} for N. These fluxes are two orders of magnitude greater than that estimated in the open ocean in the western subarctic Pacific, indicating strong upward vertical transport around the Bussol' Straits.
Our results provide observational evidence that strong vertical tidal mixing in the KIC at the margin of the Pacific Ocean plays a pivotal role in transporting Fe and nutrients from deep water to the surface.
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Keywords: Kuril Strait, iron/nutrients, tidal mixing, biogeochemical cycle

Evaluation of the biogeochemical impact of iron-rich shelf water to the Green Belt in the southeastern Bering Sea

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The Green Belt (GB) in the southeastern Bering Sea lying along the continental slope is a biological hotspot where summertime high primary production is sustained by continuous input of nutrients and iron. To understand the mechanisms to sustain the GB, we need to know how dissolved iron (D-Fe), which regulates the GB production, is drawn from the abundant source in the adjacent shelf should be clarified, but no quantification has ever done yet. In the present paper, using hydrographic and D-Fe data taken by a cruise and hydrographic database, we estimate horizontal D-Fe flux from the outer-shelf along 25.4 $\sigma_\theta$and 26.2 $\sigma_\theta$density surfaces, which are proposed as possible pathways by previous studies. The hydrographic data shows that the cold outer-shelf water is distributed in the slope region, and we estimate that 10 % (65 %) of the water-mass in the slope is originated from the outer-shelf at 25.4 (26.2) σ_θ. Assuming that this portion of the along-slope geostrophic transport is derived from the shelf through horizontal isopycnal mixing, and using the observed D-Fe concentration, we estimate the D-Fe flux of $O(10^3)$ molFe/day at 25.4 $\sigma_\theta$and $O(10^4)$ molFe/day at 26.2 σ_θ. The large flux at 26.2 $\sigma_\theta$is consistent with the vertical maximum of D-Fe concentration previously observed off the shelf break at this density range, and the flux provides sufficient iron into the euphotic zone via the subsequent enhanced vertical mixing off the shelf break, which is estimated to be $O(10^3)$ molFe/day based on our prior studies. Since our estimated D-Fe flux through horizontal mixing at 25.4 $\sigma_\theta$and the vertical mixing off the shelf break altogether are comparable to the minimum D-Fe requirement by phytoplankton in the GB, which is estimated as $O(10^3 - 10^4)$ molFe/day, we suggest that both processes could play important roles in providing D-Fe to the euphotic zone in the GB.

Keywords: Bering Sea, Green Belt, Mixing, Dissolved iron flux

Missing source of nutrients -Mechanism of nutrients’ supply in the oligotrophic region –

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It is well known that the northwestern Pacific subtropical region is oligotrophic: its nutrient in upper sun-lit layer of this region is very low or deficient all the year around. However it is recently reported that its primary productivity is comparable to or larger than that in the northwestern Pacific subarctic eutrophic region. In order to verify the mechanism of nutrients supply to the oligotrophic upper layer, time-series sediment trap was deployed at 5000 m near National Ocean and Atmospheric Administration (NOAA) time-series station KEO, where meteorological and physical oceanographic observation has been conducted with surface buoy (NOAA-KEO buoy), and temporal variability in settling particles deeply associate with surface primary productivity was observed between July 2014 and July 2015. Total mass flux clearly increased three times: (1) first half of October 2014, (2) first half of January 2015, (3) last half of April 2015. In September 2014, two typhoons passed near station KEO. Based on analysis of satellite data, it was verified that SST decreased and chlorophyll-a increased after typhoons along typhoons’ tracks. This was supported by temporal variability in vertical profile of water temperature upper 500 m observed by NOAA-KEO buoy: during typhoon passage, a few days’ scale upwelling of subsurface cold water occurred. On the other hand, time-series observation of vertical profile of water temperature revealed that a month’s scale upwelling also occurred in July and November 2014. It is suspected that these upwelling were attributed to pass of meso-scale eddy near station KEO. In addition, winter upwelling (winter cooling mixing) was also observed, centering February and March 2015. Taking into account for the time lag, temporal variability in upwelling and total mass flux was generally synchronized. Thus upwelling caused by meteorological disturbance and meso-scale eddy likely supplied nutrients to upper sun-lit layer resulting increase of primary productivity and sequentially increase in settling particles. In future, by simultaneous time-series observation of meteorology, physical oceanography and biogeochemistry, mechanism of nutrients’ supply to oligotrophic region (not only upwelling, but also eolian input) will be quantified.

Keywords: Oligotrophic region, primary productivity, nutrients, meso-scale eddy, meteorological disturbance, Time-series observation

Seasonal variations in the nitrogen isotopic composition of settling particles at station K2 in the western subarctic North Pacific

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Intensive observations using hydrographical cruises and moored sediment trap deployments during 2010 and 2012 at station K2 in the North Pacific western subarctic gyre (WSG) revealed seasonal changes in δ^{15}N of both suspended and settling particles. Suspended particles (SUS) were collected from depths between the surface and 200 m; settling particles by drifting sediment traps (DST; 100-200 m) and moored traps (MST; 200 and 500 m). All particles showed higher δ^{15}N values in winter and lower in summer, contrary to the expected by isotopic fractionation during phytoplankton nitrate consumption. We suggest that these observed isotopic patterns are due to ammonium consumption via light-controlled nitrification, which could induce variations in δ^{15}N(SUS) of 0.4-3.1 ‰in the euphotic zone (EZ). The δ^{15}N(SUS) signature was reflected by δ^{15}N(DST) despite modifications during biogenic transformation from suspended particles in the EZ. δ^{15}N enrichment (average: 3.6 ‰) and the increase in C:N ratio (by 1.6) in settling particles suggests year-round contributions of metabolites from herbivorous zooplankton as well as TEPs produced by diatoms. Accordingly, seasonal δ^{15}N(DST) variations of 2.4-7.0 ‰showed a significant correlation with primary productivity (PP) at K2. By applying the observed δ^{15}N(DST) vs. PP regression to δ^{15}N(MST) of 1.9-8.0 ‰, we constructed the first annual time-series of PP changes in the WSG. Moreover, the monthly export ratio at 500 m was calculated using both estimated PP and measured organic carbon fluxes. Results suggest a 1.6 to 1.8 times more efficient transport of photosynthetically-fixed carbon to the intermediate layers occurs in summer/autumn rather than winter/spring.

Keywords: nitrogen isotopes, suspended and settling particles, nitrogen recycling, biological pump

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Eddy transport in upper 1000 m observed by Argo floats

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Mesoscale eddies which account for most of oceanic kinetic energy plays important roles in turbulent mixing in the ocean. One of the crucial roles is horizontal transport. Because quantitative observation of eddy transport requires velocity and hydrographic measurements, at a eddy-resolving resolution, in the middle of water column, they have been estimated only from results of numerical simulations. With recent increase in number of Argo floats, fuelled by vibrant efforts of the community, it is now possible to estimate the eddy statistics using the Argo data. Here, I report horizontal eddy transport estimated using the drift and hydrographic data from the Argo floats based on the formulation by McDougall and McIntosh (2001). Eddy transport is large in the western boundary current regions in the Northern Hemisphere, the mid-latitude Indian Ocean and along the Antarctic Circumpolar Current in the Southern Hemisphere. Locally, upgradient (in thickness) transports are found, which cannot be explained by baroclinic instability per se and thus showing negative thickness diffusivity.

Keywords: eddy, parameterisation

The effect of diurnal cycle of surface heat flux on the temperature structure in the ocean surface boundary layer

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It is well known that solar radiation at the surface induces diurnal variation in both atmospheric and oceanic boundary layers. Despite of this evident feature, however, little attention has been paid to the diurnal cycle of upper ocean and its impact on longer-scale atmospheric and oceanic variability through the interaction between them. Recently, Large and Carbon (2015) performed atmospheric general circulation model and showed that diurnal cycle of SST affects the longer time scale variability of sea surface heat flux and basin scale climate. This demonstrates significance of the diurnal cycle in upper ocean on longer time scale variability. However, detailed processes of upper ocean response to the diurnal cycle is not well investigated. In this study, we performed Large-eddy simulation of upper ocean under the diurnal cycle of the surface heat flux in order to understand the diurnal cycle effects on the upper ocean variability. Here two sets of simulations; one with diurnal cycle of solar radiation and the other without it, are performed for spring season. While heat gained at surface was distributed over the whole of wind-driven mixed layer in the experiment without the diurnal cycle, in experiment with the diurnal cycle, heat was trapped near the surface in daytime and it was distributed over mixed layer in night time. This induces the diurnal cycle of SST and increases daily mean SST. The diurnal cycle of the surface heat flux also affects the mixed layer depth. Noteworthy is that this effect depends on latitude; the diurnal cycle makes MLD deeper (shallower) at lower (higher) latitude. The dependence on the latitude will also be discussed.

Keywords: Diurnal Cycle, Mixed Layer, Sea Surface Heat Flux

Response of upper ocean cooling off northeastern Taiwan to typhoon passages

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In this study, all upper ocean responses to typhoons striking Taiwan from 2005 to 2013 were simulated based on Regional Oceanic Modeling System to provide a comprehensive investigation on the process of typhoons induced upper ocean responses off northeastern Taiwan. Previous study indicates that the strong northeast wind, accompanied by a typhoon, could trigger a Kuroshio intrusion (KI) event that would promote the upwelling of the Kuroshio's subsurface water onto the shelf and thus causing cooling off northeastern Taiwan. In addition to this scenario, this study indicates another mechanism of wind-current resonance (WCR) over the continental shelf of East China Sea that can also trigger a distinct cooling (through entrainment mixing) within this region. Besides, statistic results based on 17 typhoon cases indicate that the processes of typhoon passage leading to distinct cooling NET are not as common as expected. Actually, they are conditional phenomena. By executing a series of sensitivity experiments and systematic analysis on the behaviors and background conditions (in both atmospheric and oceanic frames) of 17 typhoon cases, key criteria determining the occurrences of cooling NET through both mechanisms (KI and WCR) were elucidated individually. Once the rotation rate of local sensed wind forcing (depending mainly on moving track, translation speed, and RMWs of typhoons) off northeast Taiwan over the continental shelf of ECS is comparable to the turning rate of wind-driven local inertial motions (it is about 27.4 hours off northeast Taiwan), TCNET will be triggered through WCR. Occurrence of TCNET through the mechanism of KI is determined mainly by intensity/strength of northeast wind within local NET. Both processes are dominated by wind forcing rather than oceanic conditions. Finally, according to the possible dynamic linkage between local SST off NET and regional weather system raised in recent studies, the results elucidated in this study are believed to provide a possible advancement on improving regional weather prediction surrounding NET.

Keywords: air-sea interaction, typhoons, modeling, remote sensing

Variabilities of currents and turbulence in the Tokara Strait

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Tokara strait is a site through which the Kuroshio Current enters the deep western north Pacific from the shallow East China Sea, and considered to be an important region for the water mass modification of the Kuroshio water due to strong mixing. Although numerical studies have indicated the Tokara Strait is a hot spot of internal tide generation and mixing, observational works of internal tide and turbulence in the strait are only a few. In this study, results of turbulence measurements around the Tokara Strait are presented from a 7-day cruise in November 2015. We performed a survey of current velocity and microstructure along two sections across the Kuroshio Current using shipboard Acoustic Doppler Current Profiler (ADCP) and a free-falling microstructure profiler, TurboMAP-L. In addition, a mooring array with an upward-looking 75-kHz ADCP was deployed beneath the pathway of the Kuroshio for about 6 days to capture temporal variabilities of the Kuroshio Current as well as tidal currents. Elevated vertical shear ($S^2 > 10^{-4}$ s^{-2}) and dissipation rate of turbulent kinetic energy (epsilon > 10^{-7} Wkg^{-1}) were obtained near abrupt topographies and in the downstream side of the strait. The depth-averaged shear and dissipation rate were well correlated (R^2~0.8). Current data from the moored ADCP showed that the vertical shear is dominated by baroclinic tidal currents while mean flow at the site is dominated by the eastward Kuroshio Current (~1 ms^{-1}), indicating turbulent mixing in the strait was mainly induced by internal tide processes. We discuss the relation between enhancement of internal tide shear and the Kuroshio.

Keywords: turbulence, vertical shear, internal tide, Kuroshio, Tokara Strait

Availability of turbulence measurements using a microstructure profiler attached to a CTD frame

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Turbulence observations have been limited because of difficulty in microstructure measurements. In order to efficiently obtain much more turbulence data down to the ocean floor without spending extra ship-time, we propose a new method, a microstructure profiler attached to a CTD-frame. Since microstructure measurements of velocity shear are sensitive and fragile to vibration of the instruments, measurements have been performed with free-fall or free-rise instruments. The profiler attached to the CTD-frame can’t suppress vibrations. So the authors choose fast-response thermistors to measure micro temperature fields, less sensitive to vibrations than velocity fields. However, turbulence data from thermistors have not been common due to their insufficient temporal resolutions: High frequency components of a temperature spectrum are attenuated. In the present study, to overcome this deficiency, correction procedures for thermistor observations are firstly devised by comparing concurrently obtained energy dissipation rate εestimated from thermistors and velocity shear probes attached to a free-fall profiler. εestimated from thermistors by applying frequency correction assuming a single-pole low-pass filter function has bias which strongly depends on turbulence intensity. The correction with the form of double-pole low-pass filter derives less bias, and 3×10-3[s] of the time constant is found to be the best match withε from the shear probe. Next, this correction is applied to temperature spectra obtained from thermistors attached to the CTD-frame, and the turbulence intensity is compared with data from the free-fall profiler conducted at the same locations within 2 hours. Most of them are compatible, however, some εfrom the CTD-attached method overestimate when the variation of the fall speed of the CTD-frame, (dW/dz)/W, is large. Large (dW/dz)/W corresponds to violation of the shape of the temperature gradient spectrum in high wavenumber ranges, which makes spectrum peak obscure and possibly causes overestimation. This result indicates that large (dW/dz)/W collapses the Taylor hypothesis and turbulent eddies can’t be resolved. Turbulence intensity estimated from free-fall and CTD-attached thermistors reasonably agree by rejecting spectra with unclear peaks, and spectra with (dW/dz)/W>0.3, where violations of spectra expand to peaks at higher wavenumbers. In future, turbulence observations are expected to expand widely by applying the present method to ship observations and to floats equipped with thermistors.

Keywords: physical oceanography, turbulent mixing, turbulence observation, micro temperature fluctuation

Numerical investigation on effects of ocean surface turbulence on particle's sinking

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Biogenic small particles in the ocean can sink due to its own gravity. Marine-snow is a good example of the particle sinking in the ocean. Because dissolved carbon in the ocean is absorbed into the biogenic particle (phytoplankton) through photosynthesis, the particle sinking induces transfer of the carbon from the ocean surface to deeper ocean. This vertical transfer process of carbon is referred to as biological pump, and is considered as one important pathway of carbon from atmospheres into deeper oceans.
Fluid motion can accelerate and/or decelerate their sinking speed. Particle sinking in moving fluid is also found in atmosphere where aerosol-particles are the sinking particles. Several previous studies reported that effects of fluid motion on particle's sinking velocity depend largely on nature of turbulence and properties of particles (e.g., Cargnelutti and Portela 2007), but for particles with small inertia such as biogenic particles in the ocean and for steady isotropic turbulence, fluid motion does not affect the sinking velocity (Maxey 1987). On the other hand, numerical experiments for particles trapped in a ocean mixed layer (Noh et al. 2006) showed that ocean surface turbulence, particularly Langmuir turbulence, traps more particles in the mixed layer, leading to the conclusion that the turbulence decreases particle's sinking speed.
Here we performed numerical experiments of ocean surface turbulence and particle motion to investigate effects of turbulence on particle sinking in steady state. Large-eddy simulations are performed for wind-induced and Langmuir turbulence in which particles are released and tracked. In this study, particles sunk below the mixed layer base are removed and re-deployed at the surface. This approach, unlike the previous study (Noh et al. 2006), allow us to investigate effects of turbulence on the particle sinking in a steady state.
Our findings are (1) the particle's sinking speed is accelerated when a ratio of a terminal velocity (sinking speed of the particle in fluid of rest) to the RMS of fluid vertical velocity, referred to as the velocity ratio, is O(0.1), (2) the particle's sinking speed is decelerated when the velocity ratio is O(10), and (3) the deceleration is amplified for Langmuir turbulence.

Keywords: Ocean Suraface Turbulence, Particle Sinking

