Session 1
Keynote Talks

Bo Qiu (University of Hawaii)
Shuiming Chen, Niklas Schneider, and Bunmei Taguchi

Decadal variability, impact, and prediction of the Kuroshio Extension system

The Kuroshio Extension is an eastward-flowing, inertial jet in the subtropical western North Pacific Ocean after the Kuroshio separates from the coast of Japan. Being the extension of a wind-driven western boundary current, the KE has long been recognized as a turbulent current system rich in large-amplitude meanders and energetic pinched-off eddies. An important feature emerging from recent high-precision satellite altimeter measurements and eddy-resolving ocean model simulations, is that the KE system exhibits clearly-defined decadal modulations between a stable and an unstable dynamic state. The decadally-modulating KE dynamic state not only exerts a great impact on the regional sea surface temperature, heat content and water mass properties, it also brings about significant changes in marine ecosystems and fisheries in the western North Pacific Ocean. In this presentation, we review our current knowledge about the KE variability from mesoscales to sub-basin scales. The focuses will be on the interactions among various length scales and the prediction of the KE dynamical state.

Ichiro Yasuda (Univ. Tokyo)

Variability and mixing in the Kuroshio and impact on ecosystem and climate

In the Kuroshio where spawning grounds of many kinds of fish are formed, physical environment controls the survival of larvae and juveniles, and subsequent recruitment. One example is the Japanese sardine. Winter temperature and mixed layer depth in the frontal zone and current axis changed by current intensity and atmospheric cooling change the recruitment and long-term drastic stock variability. Pacific Decadal Oscillation (PDO) is a cause of the variability. Locally intensified vertical mixing possibly controls such long-term ocean and climate variability as PDO. Long-term records of PDO show that 18.6-year period tidal oscillation yields the rhythm of the PDO bi-decadal and its related variabilities. Climate model experiments show that tide-induced vertical mixing around the Kuril Straits is a possible driver amplified by air-sea interactions between Kuroshio-Oyashio Extension SST and the Aleutian Low. Locally intensified mixing in the Kuroshio as well as in the Kuril Strait possibly also yields great impact on ecosystem and fisheries through nutrient supply. Such mixing related 5-year project entitled “Ocean Mixing Processes: Impact on Biogeochemistry, Climate and Ecosystem
Session 2
Observation of the Kuroshio and Kuroshio extension

Meghan Cronin (NOAA PMEL)
Andrea Fassbender, Christopher Sabine

Applying diffusivity from the KEO mixed layer heat balance to determine the biological sinks of organic and inorganic carbon

Data from the Kuroshio Extension Observatory (KEO) surface mooring, combined with satellite Sea Surface Temperature (SST) data, are used to evaluate the residual diffusive flux of heat across the base of the mixed layer from the surface mixed layer heat budget. The diffusion coefficient (i.e., diffusivity) is then computed by dividing the diffusive flux by the temperature gradient in the 20-m transition layer just below the base of the mixed layer. During summer, KEO diffusivity had values of ~ 3×10⁻⁴ m²/s, while during winter, values were more than an order of magnitude larger, although wintertime errors are large. These large diffusivity values appear to be due to the increased turbulence associated with the summertime typhoons, and weak wintertime stratification. These diffusivity values are then applied to the dissolved inorganic carbon budget, the residual of which represents sources and sinks of carbon due to biological processes. By also considering the Total Alkalinity budget (using estimates based on a regional salinity relationship), the export of organic carbon (net community production) and inorganic carbon (calcification) from the surface mixed layer could be quantified. Preliminary results indicate that ~4.5 ± 2.2 mol C m⁻² yr⁻¹ is exported as organic carbon and ~0.4 ± 1.1 mol C m⁻² yr⁻¹ is exported as calcium carbonate, with maximum export occurring during the spring bloom. These estimates are based on seven years of in situ, mooring observations coupled with satellite and repeat hydrography data sets, providing a much needed modern baseline for the biological carbon pump in this dominant carbon sink region of the North Pacific Ocean.

Toshio Suga (JAMSTEC)
The region around the Kuroshio Extension as a ventilator of the North Pacific pycnocline: A review

The wintertime mixed layer to the south and the north of the Kuroshio Extension develops to the greatest depth in the North Pacific. Part of the large volume of water with properties renewed in this deep mixed layer spreads widely and ventilates the substantial part of the North Pacific pycnocline. Mostly observational studies in recent years are reviewed to summarize characteristics of the region as a ventilator of the pycnocline, highlighting issues to be addressed for better understanding of past and future changes in the ocean interior and their impacts.
Variability of the Kuroshio in the upstream region

In the Kuroshio upstream region northeast of Taiwan, variations of position and speed of the Kuroshio axis had been described from 2001 to 2010 with high temporal and spatial resolutions by the long-range HF ocean radar system operated by NICT, Japan. When the axis speed is higher (or lower), the Kuroshio is found to move southward (northward) and its width becomes narrower (broader). With the aid of satellite altimetry data, those variations are revealed to be associated with

Decadal variability of the Kuroshio Extension jet and its relation to coastal sea level along Japan

This study examines interannual to decadal variability of the Kuroshio Extension (KE) jet and its relation to coastal sea level changes along Japan using satellite and tide-gauge sea-level data. The first empirical orthogonal function mode of sea level in the KE region indicates meridional shifts of the KE jet on decadal timescales. These shifts of the jet result from wind induced signals in the eastern North Pacific, which propagated westward along the jet axis as a jet-trapped Rossby wave. During the propagation, the meridional scale of the sea level anomalies gradually narrows, and their amplitude increases. In addition, northward (southward) shifts of the KE jet accompany the coastal sea level rise (fall) in the early 2000s and 2010 (in the late 1990s and the late 2000s). The resultant sea level variability along the Japanese coast is quite large in the regions that are under the direct influence of the jet-trapped Rossby waves. Our results suggest that a large part of recent sea level rise in the KE region and along the coast of Japan can be explained by wind-driven circulation changes.

Evidence of enhanced double-diffusive convection below the main stream of the Kuroshio Extension

In this study, a Navis-MicroRider microstructure float and an EM-APEX float were deployed along the Kuroshio Extension Front. The observations deeper than 150 m reveal widespread interleaving thermohaline structures for at least 900 km along the front, presumably generated through mesoscale stirring and near-inertial oscillations. In these interleaving structures, microscale thermal dissipation rates $\chi$ are very high $O(10^{-7} \text{K}^2\text{s}^{-1})$, while turbulent kinetic energy dissipation rates $\varepsilon$ are relatively low $O(10^{-10} - 10^{-9} \text{Wkg}^{-1})$, with effective thermal diffusivity $\theta$ of $O(10^{-3} \text{m}^2\text{s}^{-1})$ consistent with the previous parameterizations for double-diffusion, and, $K_\theta$ is two orders of magnitude larger than the turbulent eddy diffusivity for density $K_\rho$. The average observed dissipation ratio $\gamma$ in salt finger and diffusive convection favorable conditions are 1.2 and 4.0, respectively, and are larger than that for turbulence. Our results indicate that
mesoscale subduction/obduction and near-inertial motions catalyze double-diffusive favorable conditions, and thereby enhancing the diapycnal tracer fluxes below the Kuroshio Extension Front.

Session 3
Ocean Dynamics in the Kuroshio and KE, including multi-scale ocean processes

Xiaopei Lin (Physical Oceanography Lab, Ocean University of China)
Jiayan Yang, Ping Chang and Lixin Wu

The Kuroshio decadal variability and its climate impact

The Kuroshio plays a crucial role in the North Pacific climate system due to the intense mass and heat transport and complex air-sea interaction along the sharp oceanic front of the Kuroshio. Interactions between the Kuroshio and the Pacific Decadal Oscillation (PDO) that occur on decadal timescales are still unclear and we do not fully understand the ocean response to decadal climate change, such as the fast warming before the 2000s and the following hiatus. Previous studies and observations show that the warm pool in the tropical Western Pacific Ocean is in a cold state and warm water flows eastward during the fast warming period, while the Kuroshio transport and its SST increase. In the recent warming hiatus, more warm water accumulates in the warm pool but the Kuroshio transport and its SST decrease. This anti-phase change of warm pool water and the Kuroshio variability is mainly caused by the ocean adjustment process. The long Rossby waves, which link the Kuroshio variability to the open ocean climate change, are propagating from east to west in the open ocean and from north to south near the shelf region. So the Kuroshio decadal variability is more related with higher latitude wind changes rather than its upstream forcing. Since the IPO/PDO mechanisms are still under debate and the Kuroshio should play a key role, continuous and enhanced observations are needed in the Kuroshio regions.

Fangli Qiao (First Institute of Oceanography)

The Kuroshio and its effects on regional climate

The seven years cooperation between China and Japan on Kuroshio expedition started in 1986 much improved our scientific understanding on this strong western boundary current. However, there are still several key issues are not clear. What is the main process of the interaction between Kurushio and the East China Sea? What are the regional climate effects of this strong current under climate change? The observation equipments including satellite remote sensing and numerical models are much more advanced than 30 years ago. It should be the time to initiate cooperation on Kuroshio’s effects on regional climate.

Hideyuki Nakano (Metrological Research Institute)

Water mass transport associated with the oceanic fronts in the
northwestern Pacific Ocean

There are several oceanic fronts in the northwestern Pacific, such as the Kuroshio Extension (KE), the Subarctic Boundary (SAB), the Kuroshio Extension Northern Branch (KENB), and the Subarctic Front (SAF). These fronts are less notable to the east of the dateline. To investigate how the tracers are distributed in the frontal system, four virtual tracers are released in an eddy-resolving OGCM, which realistically simulates these oceanic fronts. Each virtual tracer corresponds to the Kuroshio Current (KC), the East Kamchatka Current (EKC), the Okhotsk Sea Mode Water (OSMW), and the Tsugaru warm Current (TC), respectively. To the west of the dateline in the upper layer, the virtual tracer concentration shows a stair-like structure that reflects the fronts, indicating that the mixing is suppressed not only across the KE but also across other fronts. It is also shown that substantial contribution of the OSMW and the TC between the KE and the SAF. To the east of the dateline, such a stair-line structure disappears, indicating that significant water mass exchange occurs. However, the signals of the OSMW and the TC still remain between those of the KE and the EKC. The distribution of the virtual tracers are consistent with characteristic water mass structures in the North Pacific.

Naoki Sato (Tokyo Gakugei University/JAMSTEC)
Masami Nonaka, Yoshikazu Sasai, Hideharu Sasaki, Yoichiro Tamimoto, Ryuichi Shirooka

Contribution of sea-surface wind curl to the maintenance of the SST gradient along the upstream Kuroshio Extension in early summer

The seasonal cycle of the meridional sea-surface temperature (SST) gradient in the upstream Kuroshio Extension (KE) region was examined using satellite observation data and model simulations. In general, the meridional SST gradient is small in summer. However, in early summer (June and July), the SST front is sustained or intensified on the northern side of the KE near the coast of eastern Japan. This observed seasonal cycle was successfully simulated in the North Pacific Ocean model for the Earth Simulator (NP-OFES). Analysis of the simulation data revealed that the vertical profiles of temperature and salinity are shifted upward along the KE in early summer. As a result, the permanent thermocline depth is shallowest during summer, causing relatively small SST tendency. In addition, significant cyclonic vorticity in the lower atmosphere related to the southwesterly sea-surface wind was found to the south of the KE, associated with the Baiu frontal zone (BFZ). It was inferred that the positive vorticity causes Ekman upwelling over the KE region, resulting in suppressed SST warming on the northern side of the KE. These results suggest that the BFZ contributes to maintaining or strengthening the SST front.

Bunmei Taguchi (Application Laboratory, JAMSTEC)
Niklas Schneider, Masami Nonaka, Hideharu Sasaki

Low-frequency Variability of Upper Ocean Heat Content Associated with
Meridional Shifts of the North Pacific Western Boundary Current Extensions

Generation and propagation processes of upper ocean heat content (OHC) in the North Pacific are investigated using oceanic subsurface observations and an ocean general circulation model hindcast simulation. OHC anomalies are decomposed into two physically distinct components: (1) dynamical component (OHC\(\rho\)) due to temperature anomalies that are associated with density anomalies and (2) spiciness component (OHC\(\chi\)) due to temperature anomalies that are density-compensated with salinity. Analysis of the observational and the model data consistently shows the following. OHC\(\rho\) variability represents heaving of thermocline yielding westward propagation and intensification along the Kuroshio Extension as consistent with jet-trapped Rossby waves while OHC\(\chi\) variability is eastward-propagating along subarctic frontal zone, suggesting advection by mean eastward currents. OHC\(\chi\) variability tightly corresponds in space to horizontal mean spiciness gradient, whereas area-averaged OHC\(\chi\) anomalies in the western subarctic frontal zone closely corresponds in time to meridional shifting of the subarctic frontal zone, the latter known to possibly influence on the atmospheric storm track and basin-scale circulations. Regression coefficient of the OHC\(\chi\) time series on the frontal displacement anomalies quantitatively agree with the area-averaged mean spiciness gradient in the region, which confirms a hypothesis previously proposed by the authors on OHC generation mechanism via anomalous spiciness advection. These results suggest a crucial role of Western Boundary Current Extensions for decadal variability of OHC and its interaction with the atmosphere.

Kunihiro Aoki (Department of Earth and Planetary Science, Graduate School of Science, U. Tokyo)
Yukio Masumoto, Atsushi Kubokawa, Ryo Furue, Hideharu Sasaki

The momentum balance over the Kuroshio Extension

It is well known that the mesoscale variability such as mesoscale eddies causes the momentum fluxes consisting of the Reynolds stress and interfacial form stress, which can feedback the background mean flow. This study explores the role of these fluxes for the maintenance of the Kuroshio Extension (KE) jet, analyzing the zonal momentum budget in a high resolution ocean general circulation model. The KE jet generally decelerates to the east, which can be well explained by the sum of the zonal Reynolds stress and the Coriolis force by the mean ageostrophic flow. The mean ageostrophic Coriolis force is, however, partially balanced with the horizontal gradient of eddy kinetic energy, which is an isotropic component of the Reynolds stress. Therefore, the residual between these terms and the anisotropic component of the Reynolds stress governs the dynamics of the KE jet. The deceleration of the KE jet to the east is accounted for by the latter in the upstream, but by the latter in the downstream. As the aforementioned partial balance suggests, the mean ageostrophic flow tends to be parallel to the contours of the eddy kinetic energy with the large energy to the right, like the relation between the velocity and pressure under the geostrophic balance. This partial balance can
be interpreted as a consequence of the fact that any potential in the momentum equation such as eddy kinetic energy does not affect the dynamics because the curl of its horizontal gradient is zero. We will give a physical interpretation of that balance on the Workshop.

Mio Terada (Graduate School of Science, Hokkaido Univ.)
Shoshiro Minobe
Regional Sea Level Rise over the North western Pacific until the end of 23rd century in CMIP5 models

Sea-level rise due to the global warming can have substantial impacts on society. Relatively large sea-level rise is expected to occur in the western North Pacific as shown in a future projection at the end of 21st century in IPCC’s fifth assessment report, and the regional sea level change in this region is related to ocean circulation changes such as the Kuroshio Extension [Bouttes et al., 2012; Sueyoshi and Yasuda, 2012]. Although the global sea-level will continue to rise for a few centuries after the air temperature rise will have stabilized, regional sea-level in the western North Pacific after the end of 21st century is not investigated in the previous studies. Therefore, we analyze the regional sea-level changes over the North Pacific in relation with atmosphere circulation changes until the end of 23rd century by analyzing outputs from CMIP5 models. The spatial pattern of the regional sea-level change in the 21st century (2071-2100 minus 1971-2000) is different from that in the 22nd–23rd century (2271-2300 minus 2071-2100). The difference is related to the changes of the Kuroshio Extension. The Kuroshio Extension intensifies from the 20th century to the end of 21st century, but become stationary after that. On the other hand, the Kuroshio Extension almost monotonically moves northward until the end of 23rd century. These temporal evolution of regional sea-level rise and Kuroshio Extension changes are the most likely to be caused by the temporal evolution of dominant atmospheric circulation modes.

Session 4
Development of ocean modeling: high-resolution modeling and reanalysis

Masao Kurogi (JAMSTEC)
Yukio Tanaka, and Hiroyasu Hasumi
Effects of deep bottom topography on the sea surface height field in the Kuroshio Extension region studied by a nested-grid OGCM

Effects of deep bottom topography on the sea surface height (SSH) field in the Kuroshio Extension (KE) region is investigated by using a two-way nested-grid model based on the COCO ocean model. The horizontal resolution of the model is about 10km around the KE region. Results from experiments with different bottom topography are compared. In the first case, the bottom topography deeper than about 5500m is not represented; ocean floor is flat at
this depth. In the second case, deeper bottom topography is represented. In this case, the amplitude of KE quasi-stationary meander is roughly two times larger than the former. Root-mean-square of SSH anomaly (RMS SSHA) is also 10% larger in horizontal average (141-160°E, 32-38°N). Both RMS SSHA and the amplitude of KE stationary meander are more realistically reproduced in this case with deep bottom topography.

Recent development of a nested-grid OGCM with higher horizontal resolution (about 400 m around Japan) will be also introduced.

Tsuyoshi Wakamatsu (JAMSTEC)
Norihisa Usui, Yosuke Fujii, Yusuke Tanaka, Nariaki Hirose, Yoichi Ishikawa

**Observability of long term Kuroshio variability through four dimensional ocean data assimilation**

Eddy resolved (1/10 degree), long term (1982-current) ocean reanalysis data, FORA-WNP30, covering the Western North Pacific Ocean (117E-160W, 15N-65N) is newly produced using cycled 4DVar data assimilation system with quasi 10 day assimilation period. The reanalysis project was led by joint research group of Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Meteorological Research Institute, Japan (MRI). Validation studies against independent data indicate that temporal variation of Kuroshio meandering path off the southern coast of Japan is well reproduced throughout the entire analysis period. Observation sensitivity experiment (OSE) conducted in parallel to the main reanalysis calculation reveals geographical region where the meso-scale features can be reproducible without altimeter data in our reanalysis system. Due mainly to relatively dense hydrographic data sampled off the southern coast of Japan, the Kuroshio path can be well reconstructed without altimeter data up to the first crest after its separation. In this presentation, detail analysis on the observability of Kuroshio variability under the current and future observation network from inverse modelling point of view will be discussed.

Helene Hewitt (Met Office)
Malcolm Roberts, Pat Hyder

**The impact of eddy resolving resolution in coupled climate models**

There is mounting evidence that mesoscale features in the ocean can play an important role in coupled climate simulations. We discuss the role of resolution and eddies in leading to both improved representation of the ocean circulation and enhanced air-sea interaction. We show results from coupled climate experiments changing atmosphere resolution, ocean resolution and coupling frequency. At the resolutions we explore, moving to eddy-resolving resolution is shown to be one of the key factors in changing the mean climate. Our results show that the circulation and air-sea fluxes in western boundary current regions play a key role in modifying the resulting climate. The implications of these results for coupled modelling from short range forecasting to climate projections are discussed.
Analysis of the Kuroshio Extension decadal variability as simulated by an eddy-permitting model

The Kuroshio Extension (KE) decadal variability, often denoted as bimodal because of the existence of two main modes of circulation [1-3], is suggested to be due to intrinsic mechanisms of oceanic origin. This is not in contradiction with the observed synchronization of the KE oscillations with the main decadal time-scale modes of the sea level pressure variability in the North Pacific region. In fact, a recent model study interprets this phenomenon as a case of intrinsic climate variability paced by external forcing, and suggests that its simulation may be very sensitive to model implementation. To this respect, it is important to assess the ability and sensitivity of high-resolution state-of-the-art ocean general circulation models to correctly simulate the KE cycles. In this presentation the hindcasts from 1993 to present obtained from an eddy-permitting global configuration of the NEMO ocean model, with or without assimilation of hydrographic profiles and sea level anomalies, are compared with altimeter data. To reveal the main features of the variability, indices such as the KE path length $L_{KE}$ and mean KE latitudinal position $F_{I_{KE}}$ are computed for both altimeter and model data. In addition, a combined index (based on $F_{I_{KE}}$ and on $L_{KE}$ modified through the application of the wavelet transform) is used as well. The results show a good performance of the model and suggest possible future sensitivity studies.

Impact of horizontal resolution (1/12 to 1/50 degree) on Gulf Stream separation and penetration

The impact of horizontal resolution (1/12 to 1/50 degree) on Gulf Stream separation and penetration is analyzed in a series of identical North Atlantic configurations. The 1/50 degree simulation shows a significantly improvement in the Gulf Stream representation (surface and interior) when compared to observations. The results will also be discussed in terms of power spectra with comparisons to the Kuroshio.

Session 5
Air-sea interaction in the Kuroshio and Kuroshio extension and its climate impact

Shoshiro Minobe (Graduate School of Science, Hokkido Univ.)
Climate Dynamics Panel and mid-latitude ocean’s influence on the atmosphere

Climate Dynamics Panel has started in 2015, having the first panel meeting in
April 2015. The panel fosters increased understanding of the dynamical processes that control circulation variability and change in the atmosphere and ocean on synoptic to centennial timescales. The focus is on large-scale phenomena, processes, and mechanisms of coupled climate variability/modes, teleconnections and change on seasonal to centennial time-scales, in particular i) storm tracks, jet streams and weather systems, ii) tropical-extratropical interactions, and iii) long-term coupled atmosphere-ocean circulation. The first point includes mid-latitude ocean's influence to the atmosphere, which is especially strong along western boundary currents, such as the Kuroshio and the Gulf Stream, which provide vast heat and moisture to the atmosphere. The studies of mid-latitude ocean's influence to the atmosphere have rapidly developed in the last one and half decade, exploiting high resolution observational data and numerical modellings. The high-resolution observation data analysis can allows one to detect atmospheric patterns coherent with oceanic structures, such as fronts and currents. Such detection indicates that oceanic forcing play an important role in the atmosphere, because scales of free-atmospheric variations are one order larger than oceanic ones. The strategy can be, therefore, referred to as “scale-separation strategy”. Intrinsic limitation of this strategy exists for possible atmospheric responses on atmospheric spatial scales. For these more general problems, therefore, numerical experiments play essential roles.

Ping Chang (Texas A&M Univ.)
Ocean Mesoscale Eddy-Atmosphere (OME-A) Feedback: Kuroshio Eddies, Pacific Storm Track and Climate Variability

Eddy-rich western boundary current regimes, such as the Kuroshio and Gulf Stream Extension regions, have been identified as key locations in the extratropics where SST variability may provide an important source of energy for driving atmospheric variability. In this talk, we present high-resolution regional climate modeling results, supported by observational analyses, that meso-scale SST variability, largely confined in the Kuroshio-Oyashio confluence region (KOCR), can exert an influence on the Pacific storm track. The presence of meso-scale SST anomalies enhances diabatic conversion of latent heat energy, intensifying winter cyclogenesis via moist baroclinic instability, which in turn affects storm activity and precipitation downstream. We further show that the ocean mesoscale eddy-atmosphere (OME-A) feedback plays an important role in maintaining the sharp SST gradient along the Kuroshio Extension. These findings point to the need to improve the representation of ocean mesoscale eddies and their interactions with the atmosphere in climate models.

Sergey Gulev (IORAS)
Natalia Titlinina
Cyclone activity and its interaction with the Kuroshio current system

We consider synoptic variability of surface turbulent heat fluxes in the Northwestern Pacific with the emphasis on extreme fluxes quantified using...
probability density distributions of surface fluxes. Surface turbulent flux PDFs were approximated by Modified Fisher-Tippett (MFT) distribution whose parameters put more light on the nature of differences between different surface flux products. Furthermore, this concept allows for robust estimation of extreme flux values which can amount to several thousands W/m². Finally, using this concept we can account for the fractional contribution of fluxes exceeding a given percentile to the total flux integrated over long time (e.g. month, year). We further focus on understanding the mechanisms of synoptic variability of surface turbulent fluxes and particularly on the origins of extreme turbulent fluxes and their further impact on the atmospheric and oceanic dynamics. The main questions addressed in this study are (i) what are the large scale atmospheric conditions associated with extreme ocean surface fluxes and to what extent they are related to cyclones, (ii) what is the role of extreme surface fluxes in the variability of oceanic heat content, and (iii) which characteristics of atmospheric cyclones are most sensitive to the surface ocean flux signals? To answer these questions, we analyse statistical characteristics of surface turbulent heat fluxes and cyclone characteristics over the mid-latitudinal North Pacific. Further we investigate links of cyclones and surface fluxes with each other focusing on cyclone life cycle characteristics such as deepening rates, propagation velocities, life time and clustering. We argue that the presence of the high pressure system following to the rare part of propagating cyclone is a critical condition for the formation of extreme surface ocean fluxes which are associated with the cyclone-anticyclone interaction zone rather than with cyclone per se.

Niklas Schneider (University of Hawaii)
B. Taguchi, M. Nonaka
Characterization of frontal air-sea interaction by spectral transfer functions

We test a linear model for the response of the atmospheric boundary layer to variations the sea surface temperature associate with the ocean mesoscale. The model includes the impact of sea surface temperature fronts on vertical mixing and on pressure gradients, and includes advection by a background Ekman spiral. Model dynamics are governed by transfer function in wave-number space between sea surface temperature, and frontally boundary layer variables. Using output from the atmospheric general circulation model AFES, we evaluate the spectral transfer functions for frontally induced wind speed and direction. For the Southern Ocean results show encouraging agreements and suggest that the linear model captures the underlying physics. In contrast, the Kuroshio region is more challenging.

Justin Small (NCAR)
F. Bryan, R. Tomas, S. Bishop, J. Booth, Y.-O. Kwon
Atmospheric variability associated with western boundary currents in high-resolution climate models

It has been suggested that including mesoscale ocean features (fronts, eddies) in atmosphere-only or coupled models can lead to significant changes
in the storm tracks, and in local interannual variability of the atmosphere. Here we investigate this possibility using the Community Earth System Model with a high-resolution atmosphere model (0.25deg) and ocean model of either 1deg or 0.1deg, the latter resolving the ocean mesoscale. The results will be discussed in the context of previous studies.

Hisashi Nakamura (RCAST, Univ. Tokyo)
R. Masunaga, S. Okajima, H. Kamahori
Impacts of frontal SST gradients in the Kuroshio-Oyashio Extension on the atmosphere as revealed in a new Japanese reanalysis, a legacy of the “hot-spot” project

Impacts of frontal SST gradients in the Kuroshio-Oyashio Extension (KOE) on the overlying atmosphere are assessed through comparison of two products of a new Japanese reanalysis (JRA55). One is JRA55C in which all the observational data but satellite data have been assimilated in a forecast system with horizontal resolution of ~60km and the COBE SST data on 1-degree resolution prescribed over 55 years. The other is JRA55HS, which is the same as JRA55C but with MGDSST data with a quarter-degree resolution only over 28 recent years. This data set prepared jointly between the Meteorological Research Institute and University of Tokyo as a legacy of the Japanese “hot-spot” project, which was concluded in March 2015. The comparison reveals substantial differences in midlatitude atmospheric processes around SST fronts in the KOE region. As in satellite observations, enhancement of cloudiness and precipitation in the mixed-water region east of Japan during the unstable regime of KE relative to its stable regime is represented well in JRA55HS but not in JRA55C. The enhancement arises from augmented heat/moisture release from the warmer ocean with more active warm-core eddies. This oceanic thermal forcing onto the atmosphere is manifested as positive correlation in anomalies between SST and heat/moisture release, which is represented only in the high-resolution MGDSST but not in the COBE SST. As another example, stormtrack response to meridional displacement of the Oyashio front is examined. Again, the positive correlation between anomalous SST and heat/moisture release is much stronger in JRA55HS, and so is the enhancement of convective precipitation over warm SST anomalies. Convective diabatic heating may be essential for the development of synoptic-scale cyclones, which may enhance the sensitivity of a stormtrack to the variability of the SST front. Note that the main JRA55 product, in which satellite data are incorporated with the COBE SST, exhibits almost the same characteristics as the JRA55C.

Masami Nonaka (JAMSTEC)
Bunmei Taguchi, Niklas Schneider
Dynamical response of the North Pacific Ocean to the tropical variability and its decadal modulation

While teleconnections from the tropical Pacific to the North Pacific sea surface temperature are well known, the dynamical response of the North Pacific
Ocean to the tropical atmosphere-ocean variability is not well investigated. Based on observed and reanalysis data, we investigate this link through a correlation analysis using the indices of Nino3, Nino3.4, and El Nino Modoki Index (EMI). The simultaneous correlation maps of the wind-stress curl indicate that the signal associated with EMI in the eastern North Pacific is stronger than the counterparts with Nino3 and Nino3.4. Responding to these signals in wind-stress curl, sea surface height (SSH) anomalies develop following EMI, but almost no SSH responses are found to Nino3 and Nino3.4. As El Nino Modoki lasts for a longer period than canonical El Nino, the stronger wind-stress curl signal to EMI drives the ocean more persistently, and induces substantial SSH signals. The induced SSH signals propagate westward to the western boundary region around 35N, affecting variability in the Kuroshio Extension, which might feedback atmosphere aloft. The teleconnection from EMI to the North Pacific, however, was not found before the 1990s, indicating its clear decadal modulation.

Tomoki Tozuka (Univ. Tokyo)
Hiroyuki Tomita, Meghan F. Cronin

Role of mixed layer depth in surface frontogenesis: the Kuroshio Extension front

The sea surface temperature (SST) front in the Kuroshio Extension region plays an important role in the air-sea interaction over the North Pacific. In this study, we examine how meridional variations in the mixed layer depth across the SST front in the Kuroshio Extension region affects the frontogenesis/frontolysis. Based on mixed layer heat budget analysis, we show that the surface heat flux term tends to strengthen the SST front despite the stronger net surface heat loss on the equatorward side. Since the mixed layer is much deeper on the equatorward side, the SST there is less sensitive to the surface heat loss. In contrast, the oceanic term contributes to the frontolysis.

Stuart Bishop (North Carolina State University)
Frank Bryan and Justin Small

Bjerknes-like compensation in the wintertime North Pacific

Observational and model evidence has been mounting that mesoscale eddies play an important role in air–sea interaction in the vicinity of western boundary currents and can affect the jet stream storm track. What is less clear is the interplay between oceanic and atmospheric meridional heat transport in the vicinity of western boundary currents. It is first shown that variability in the North Pacific, particularly in the Kuroshio Extension region, simulated by a high-resolution fully coupled version of the Community Earth System Model matches observations with similar mechanisms and phase relationships involved in the variability. The Pacific decadal oscillation (PDO) is correlated with sea surface height anomalies generated in the central Pacific that propagate west preceding Kuroshio Extension variability with a ~3–4-yr lag. It is then shown that there is a near compensation of O(0.1) PW (PW (10^15 W)
between wintertime atmospheric and oceanic meridional heat transport on decadal time scales in the North Pacific. This compensation has characteristics of Bjerknes compensation and is tied to the mesoscale eddy activity in the Kuroshio Extension region.

Akira Kuwano-Yoshida (JAMSTEC)
Shoshiro Minobe

Storm track response to SST front in the northwestern Pacific region in an AGCM

The NICT radar sites were unfortunately terminated in 2010, but a new radar observation network covering the whole Kuroshio upstream region has recently started, as an international cooperative study between Kyushu University, Japan, and Taiwan Ocean Research Institute, whose data will be soon open to public.

Ryusuke Masunaga (Research Center for Advanced Science and Technology, Univ. Tokyo)
H. Nakamura, T. Miyasaka, K. Nishii, B. Qiu

Interannual modulations of mesoscale oceanic imprints on the wintertime atmospheric boundary layer under the changing dynamical regimes of the Kuroshio Extension

The Kuroshio Extension (KE) fluctuates between its different dynamic regimes on decadal timescales. In its stable (unstable) regime, the KE jet is strengthened (weakened) and less (more) meandering. The present study investigates wintertime mesoscale atmospheric structures modulated with the changing KE regimes based on the ERA-Interim atmospheric reanalysis data for 2002-2014, during which the resolution of sea surface temperature (SST) data prescribed is high enough to represent the KE regime fluctuation. In the unstable KE regime, positive anomalies in SST to the north of the climatological-mean KE jet accompany positive anomalies in upward heat fluxes from the ocean, surface wind convergence and cloudiness. Furthermore, these positive anomalies coincide with local lowering of sea level pressure, warming and thickening of the marine atmospheric boundary layer (MABL), anomalous ascent and convective precipitation. In the stable KE regime, by contrast, the corresponding imprints of sharp SST gradients across the KE and subarctic fronts on the wintertime MABL are separated more distinctly. These results are overall consistent with high-resolution satellite observations.

Hidenori Aiki (Institute for Space-Earth Environment Research, Nagoya University)

Wind stress for ocean circulation as given by the dissipation rate of surface waves

Recent studies have shown that mesoscale eddies and recirculation around western boundary currents are better simulated with a moderate magnitude in
high-resolution OGCMs when relative wind speed (difference between the speeds of wind and surface circulation) is used in the bulk formula for wind stress. However the drag coefficient for wind stress might be better parameterized using quantities associated with surface gravity waves, such as significant wave height, wave age, and the direction of waves. Many studies in the surface wave community suggest that the net momentum flux from air (i.e. wind) to water (i.e. ocean circulation and surface waves) is given by the sum of skin stress and wave stress, the latter of which is associated with the generation of surface waves. Meanwhile, the net momentum flux to ocean circulation is given by the sum of the skin stress and dissipation-induced stress, the latter of which is associated with the breaking of surface waves. In order to investigate the utility of this mechanism, we have developed a coupled atmosphere ocean surface-wave model and performed sensitivity experiments associated with three types of wind stress. The first type of wind stress is given by the traditional formula with absolute wind speed. The second type of wind stress is given by the traditional formula with relative wind speed. The third type of wind stress is given by the surface wave model based on the dissipation rate of surface waves. The sensitivity experiments have been performed to examine the strength of mesoscale eddies in the Kuroshio Extension region, the small Kuroshio meander south of Japan, and the interaction between the Kuroshio Current and coastal upwelling associated with the landing of tropical cyclones.

Session 6
Marine ecosystems in the Kuroshio and Kuroshio Extension

Hiroaki Saito (Atmosphere and Ocean Research Institute, Univ. Tokyo)
Kuroshio Paradox: High fisheries production in oligotrophic Kuroshio ecosystem

Kuroshio is an oligotrophic western boundary current of the North Pacific flowing along continental shelf of Taiwan and the Japanese archipelago. Although Kuroshio transports oligotrophic subtropical water, various fisheries target species use the Kuroshio ecosystem as spawning and nursery ground. These Kuroshio species contribute to 58% of fisheries landing in Japanese water. I named this inconsistency of high fisheries production in oligotrophic water as Kuroshio paradox. To resolve the Kuroshio paradox, interdisciplinary research project “The Study of Kuroshio Ecosystem Dynamics for Sustainable Fisheries” (SKED) was launched in 2011. In the presentation, I will show obtained results in SKED and remaining issues to solve the Kuroshio Paradox

Keith Rodgers (AOS Program, Princeton Univ.)
Maricela Coronado, Sarah Schlunegger, Thomas Frölicher, Ivy Frenger, Masao Ishii, Daisuke Sasano
Interannual modulations of mesoscale oceanic imprints on the wintertime atmospheric boundary layer under the changing dynamical regimes of the Kuroshio Extension
Interannual modulations of mesoscale oceanic imprints on the wintertime atmospheric boundary layer under the changing dynamical regimes of the Kuroshio Extension.

Potential marine ecosystem stressors, such as acidification and de-oxygenation, are expected to impact ocean biology over the course of the 21st century. Detection of acidification and de-oxygenation is complicated by elevated natural background variability of the climate system. This presents a challenge for inferring secular trends from repeat hydrographic measurements. This is expected to be particularly pronounced in regions such as the Kuroshio Extension.

We consider a large initial-condition ensemble suite of simulations with GFDL’s Earth system model ESM2M over 1950-2100. The ensemble approach provides a means to deconvolve natural variability and the forced secular trend, and this is approached in a water mass framework (Frölicher et al., 2009). The initial analysis is applied to interpret the repeat hydrographic section along 165°E reported by Sasano et al. (2015) for the emergence of oxygen and acidification trends. Emergence in this framework is defined as when the anthropogenic signal exceeds the noise level of natural variability.

The emergence of anthropogenic trends in acidification ($W_{\text{arag}}$) along 165°E emerge sooner and with greater confidence than do trends in ocean interior O$_2$ over a 30-year time frame across the major thermocline water masses of the North Pacific. The prior emergence of $W_{\text{arag}}$ relative to O$_2$ within the ocean interior over the historical period largely reflects the difference in the atmospheric boundary conditions for these two fields.

The implications for observing system design in the Kuroshio Extension region, as well as more broadly over the North Pacific, will also be presented.

Eitarou Oka (Atmosphere and Ocean Research Institute, Univ. Tokyo)
B. Qiu, Y. Takatani, K. Enyo, D. Sasano, N. Kosugi, M. Ishii, T. Nakano, and T. Suga

Decadal variability of Subtropical Mode Water subduction and its impact on biogeochemistry

Temperature and salinity data from Argo profiling floats during 2005–2014 were analyzed to examine the decadal variability of the North Pacific Subtropical Mode Water (STMW) in relation to that of the Kuroshio Extension (KE) system. The formation volume of STMW in the southern recirculation gyre of KE in the cooling season was larger during the stable KE period after 2010 than the unstable KE period of 2006–2009 by 50%. As a result, the volume and spatial extent of STMW increased (decreased) in the formation region during the stable (unstable) KE period, as well as in the southern, downstream region with a time lag of 1–2 years. The decadal expansion and contraction of STMW were also detected by shipboard observations conducted routinely in the most downstream region near the western boundary, in terms of not only physical but also biogeochemical parameters.
After 2010, enhanced subduction of STMW consistently increased dissolved oxygen, pH, and aragonite saturation state and decreased potential vorticity, apparent oxygen utilization, nitrate, and dissolved inorganic carbon, among which changes of dissolved inorganic carbon, pH, and aragonite saturation state were against their long-term trends. These results indicate a new mechanism consisting of westward sea surface height anomaly propagation, the KE state transition, and the STMW formation and subduction, by which the climate variability affects physical and biogeochemical structures in the ocean’s interior and potentially impacts the surface ocean acidification trend and biological production.

POSTERS

Shigeki Hosoda (JAMSTEC)
Masami Nonaka, Tomohiko Tomita, Bunmei Taguchi, Hiroyuki Tomita, Yoshikazu Sasai, and Hideharu Sasaki, and Naoto Iwasaka

**Sea surface temperature and net surface heat flux variability on seasonal and interannual time scales influenced by subsurface oceanic change in summer season**

We investigate sea surface temperature (SST) and net surface heat flux (Qnet) variability affected by subsurface heat condition during summer season (April-August) using Argo and other observation dataset. Many studies focused on the wintertime mixed layer and air-sea interaction for the theme of oceanic impact on climate changes because of huge heat release from subsurface ocean. While previously many researchers had considered that SST changes passively against strong downward Qnet and there may be little effect from subsurface ocean during the summer season. Focusing on the North Pacific Ocean, we clarify that temperature variability in the subsurface ocean plays important role to seasonal changes of SST even during summer season. Effect of Qnet penetrates below thin mixed layer (TML) and then SST warms to be moderate. By introducing the concept of heat penetration depth (HPD), defined as the depth to which Qnet distinctly penetrates below TML, we successfully characterized the heat capacity in terms of the heat content above the HPD with a simple, one-dimensional vertical model. The downward heat penetration into the layer below TML is widely found throughout the North Pacific (NP), and surprisingly two-thirds of Qnet penetrates below TML from May to August. Such relation in the air-sea condition can be found on interannual variability in the western NP. Interannual temperature variability in early summer is vertically coherent over a depth of 500m, appearing that the same temperature anomalies tendency as on SST’s in the western NP, while not clear in the central and eastern NP. An eddy-resolving OGCM suggest that the temperature variability is associated with changes in the oceanic frontal structures that extend below TML such as the northern branch of Kuroshio Extension, indicating that it is caused not by atmospheric thermal forcing but by oceanic structure changes. Those results suggest that subsurface temperature variability plays a crucial role in climate variations even during the warming season.
Fumiya Inoue (Hokkaido University)
Shoshiro Minobe, R. Justin Small

Summertime upper tropospheric circulations due to diabatic heating over the North Atlantic and the North Pacific

Results show that the annual average, minimum and maximum near-surface temperature all gradually increases from 1901 to 2010. And they are in the same case in wet season and dry season. Minimum near-surface temperature, with its linear trends are significant for annual, wet season and dry season means. However, the diurnal temperature range decreases in the recent 100 years, implies that the minimum near-surface temperature has increased more than the maximum. Both precipitation and wet day frequency decline from the analysis, demonstrating that Nigeria has become dryer than before by the way of rainfall. Temperature and precipitation variability has become very high during these periods especially in the Northern areas. Areas which had excessive rainfall were confronted with flooding and other related issues while area that had less precipitation were all confronted with drought. More practical issues will be presented.

Shota Katsura (U. Tokyo)

Structure and Variation of Upper Ocean Salinity in the subtropical Pacific: North Pacific Tropical Water and Barrier Layer

Formation and subduction of North Pacific Tropical Water (NPTW) and formation mechanism of barrier layer (BL) in the subtropical Pacific were investigated by using raw and gridded Argo profiling float data and various surface flux data. The sea surface salinity (SSS) maximum in the subtropical North Pacific, which corresponds to the formation region of NPTW, had a zonally bimodal structure. Mixed layer salinity variations in the western and eastern parts of NPTW formation region were significantly different. While seasonal variation was dominant in the eastern part, which is controlled by evaporation, precipitation and entrainment of fresher water below the mixed layer, interannual variation was dominant in the western part, controlled by evaporation, precipitation and Pacific Decadal Oscillation-related eddy diffusivity. After subduction, while denser NPTW formed in the eastern part dissipated quickly, the lighter NPTW formed in the western part was advected westward as far as the Philippine Sea, transmitting the interannual variation of salinity away from its formation region. Subsurface equatorward intrusion of tropical water was too deep to produce BLs in the subtropical Pacific, which is formed in winter within the SSS front located on the equator side of tropical water formation regions. Poleward Ekman advection of fresher water was dominant as the surface freshening, but cannot explain the observed seasonal variations of BL. These results strongly suggest that BLs in the subtropical Pacific are formed mainly through tilting of the SSS front. This idea is supported by dominant contribution of the meridional SSS gradient to the meridional sea surface density gradient within the SSS front and the correspondence between the seasonal variations of BL and isothermal layer depth.
Masatoshi Miyamoto (U. Tokyo)
Eitarou Oka, Daigo Yanagimoto, Shinzou Fujio, Masao Kurogi, Hiroyasu Hasumi

Mesoscale variability of deep currents south of the Kuroshio Extension

To clarify structure, origin and propagation of mesoscale variability with timescales of 20–150 days in the deep ocean, we are conducting high-resolution mooring observations at St. B (30°N, 147°E) since May 2014. We deployed nine moorings in a 3×3 diamond shape, whose zonal and meridional widths are both 100 km. As a preliminary analysis for this observation, we analyzed past mooring observations obtained around St. B during 1978–1985. At two mooring sites that were zonally 100 km apart, power spectral density at 5000-m depth had a peak at 45–70 days. Based on the phase lag at 47-day period at which coherence between the two sites was highest, the zonal wavelength and westward phase speed were estimated to be 250 km and 6.1 cm s⁻¹, respectively. We also analyzed a 10-year output of an eddy-resolving ocean general circulation model. At 5000-m depth, power spectral density at the dominant period of 54-day had a maximum in the region of 30–32°N, 146–148°E. Furthermore, 45–60 day band-pass filtered variability component propagated westward with a phase speed about 6 cm s⁻¹ and a wavelength about 250 km and was intensified in this region. Based on distributions of energy flux, the energy needed for this intensification was considered to originate from the Kuroshio Extension. And the variability was considered to be propagated via barotropic topographic Rossby waves.

Hideharu Sasaki (JAMSTEC)
Patrice Klein, Yoshikazu Sasai

Seasonal variations of meso/submesoscale dynamics in a high-resolution simulation of the North Pacific Ocean

Several high-resolution simulations have recently highlighted the seasonality of oceanic submesoscales - highly (poorly) energetic in winter (summer) – but only in two regions: in the NorthWestern Atlantic Ocean including the Gulf Stream (Menza et al. 2013) and in the NorthWestern Pacific Ocean including the Kuroshio Extension (Sasaki et al. 2014) and Subtropical Countercurrent (Qiu et al., 2014). Energetic submesoscales in winter in these regions are explained by the baroclinic instability of deep winter mixed-layers (or mixed-layer instability (MLI)). High resolution in-situ observations within the Gulf Stream region have confirmed this seasonality (Callies et al. 2015). The future altimetry missions (COMPIRA and SWOT) are expected to observe high-resolution SSH and therefore to capture oceanic features over a wide scale range, not only in the Gulf Stream and the Kuroshio Extension, but in the Global Ocean. In advance, we highlight the impact of submesoscales on ocean dynamics in several regions of the whole North Pacific Ocean by comparing two OFES simulations, at 1/30th and 1/10th degree resolutions.

In the regions of the Kuroshio Extension, Subtropical Countercurrent, Mid-
latitude Eastern Pacific and Subtropical Eastern Pacific, submesoscales are much more energetic in winter than in summer in the 1/30th degree simulation. Emergence of these submesoscales is again explained by MLIs. In addition, the spectral kinetic energy (KE) fluxes indicate an inverse KE cascade, i.e. a significant transfer of KE from submesoscales to larger ones. These mechanisms lead to a seasonality of, both, submesoscales and larger scales. In the 1/10th degree simulation, these MLIs are not resolved and as a consequence (1) total KE (including small and large scales) is significantly weaker (by a factor 1.5 to 3!) and (2) no seasonality is observed. An exception about seasonality concerns the SubTropical CounterCurrent where the seasonal variation of the isopycnal slopes triggers a large-scale instability in winter (Qiu et al., 2014) leading to a KE seasonality even in the 1/10th simulation.

In the Subarctic regions, the impact of submesoscales revealed by the 1/30th degree simulation is not so significant. A seasonality of submesoscales is still observed in the Subarctic Western Pacific but not in the Subarctic Eastern Pacific. The total KE is significantly enhanced in both regions in the 1/30th simulation (compared with the 1/10th simulation), but this concerns only the 10km-200km scale band. The scale of MLIs in these regions, certainly too small to be resolved even in the 1/30th degree simulation, requires to perform simulations at higher resolution. This is our future work.

Nobumasa Komori (JAMSTEC)

Bunmei Taguchi, Akira Kuwano-Yoshida, and Masami Nonaka

Influence of the Gulf Stream on the hemispheric-scale coupled atmosphere-ocean-sea ice system

In this study, we artificially changed the path of the Gulf Stream in a global coupled GCM by slightly modifying the bottom topography around the Florida Peninsula and investigated the response of the hemispheric-scale coupled atmosphere-ocean-sea ice system.

When the narrow channel east of the Florida Peninsula is deep enough in the model, the Gulf Stream takes a realistic path around the peninsula (otherwise the Antilles Current is enhanced unrealistically), but it overshoots northward in comparison to the case with the shallower channel. As a result, positive sea surface temperature (SST) anomalies are found around the Gulf Stream “Extension” (after it separates from the east coast of the North America) and in the Barents Sea. This is consistent with the observed fact that northward shift of the Gulf Stream Extension induces positive SST anomaly in the Barents Sea. On the other hand, SST around Japan increases as opposed to the previous studies that warm anomaly in the Barents Sea brings cold anomaly over Eastern Eurasia. In our model, decrease of sea ice in the Arctic Ocean caused by the modification of bottom topography creates negative sea-level pressure anomaly that elongates along the entire Arctic rim, which may induce northward shift of the atmospheric circulation in the lower Troposphere and the subtropical gyre in the North Pacific, and hence, positive SST anomaly around the Kuroshio Extension.