WBC Workshop Abstracts

Alphabetically by Submitting Author

The Impact of Tropical Teleconnections on WBC Regions

Michael Alexander

The integrated Arctic Ocean Observing System, conceived by the Arctic Ocean Sciences Board (AOSB) was designed to optimise the cohesion and coverage of Arctic Ocean Science during the IPY. Its main scientific focus was with Arctic change, including the fate of its perennial sea-ice and the climatic and social effects of its disappearance. Its task was to view the ocean-atmosphere-cryosphere system of high northern latitudes operating as a complete system for the first time. The rationale for this task was that understanding this system and testing its predictability seemed to be a direct way of extending our ability to mitigate for or adapt to its changes, including global change. Its means lay in the fact that for the first time we are technically able to measure almost any key variable at almost any place and time that we need to describe the ocean-atmosphere-cryosphere system of high latitudes. And the IPY provided the necessary stimulus for piecing together the available PIs, gear, ships and funding on a pan-Arctic scale. This talk aims first to describe the major advances that were made in our understanding of large-scale change in northern seas through the close international coordination that was achieved during the IPY. Second, to contribute to the debate on which of these efforts should be maintained into a post-IPY ‘legacy phase’. This exercise is necessarily one of prioritising the observational needs of climate models and ecosystem management against the technical demands and cost of meeting these on a sustained international basis.

Manifestation of the Pacific Decadal Oscillation in the North Pacific Western Boundary Current System

Magdalena Andres, Jae-Hun Park, Mark Wimbush, Xiao-Hua Zhu, and Kyung-Il Chang

Abstract

Western-boundary-current (WBC) transports in the mid-latitude North Pacific, determined using satellite altimetry calibrated with in situ data from CPIESs and ADCPs, correlate positively with PDO index. The correlations, which are highest at zero time lag, are 0.76 for the Kuroshio in the East China Sea and 0.49 for the Ryukyu Current. The combined WBC transport variation correlated with PDO index variations has a range of about 4 Sv. PDO index is strongly negatively correlated with NCEP wind-stress curl over the central North Pacific at these latitudes (24°-28°N). The magnitude and timing of the observed WBC variations suggests that they arise from a barotropic response to wind-stress curl over a region stretching from the western North Pacific through the central North Pacific. Estimated Kuroshio throughflow crossing the ASUKA-line south of Japan is not correlated with PDO index, yet the estimated recirculation strength in this region is negatively correlated at the 85% confidence level. This may arise from a misallocation of eastward transport south of Japan into throughflow and recirculation components.

The Oceanic Eddy Heat Transport

in a High Resolution Ocean GCM Simulation

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ABSTRACT

The northward eddy heat transport is calculated from a global eddy-resolved Ocean circulation model For the Earth Simulator (OFES). The northward time-mean eddy heat transport is found to be strong in the western boundary currents, the Antarctic Circumpolar Current, and the equatorial region. This feature is qualitatively consistent to the previous estimates based on the eddy-permitted ocean circulation model. Our results, however, have some new findings regarding a magnitude and spatial distribution of the northward eddy heat transport. In the North Pacific and North Atlantic the zonally integrated northward eddy heat transport associated with the western boundary currents is 0.4 PW in maximum. This corresponds to nearly 30% of the total northward time-mean transport. In the latitude band from 30˚ to 40˚N of the North Pacific our estimates of the zonally integrated northward eddy heat transport are comparable to those based on a satellite observational data by Qiu and Chen (2005). In those latitudes, the eddy heat transport is largely confined to the upper 500-m as shown in their study using Argo profiling data. Our estimates, however, are weaker than those of their estimates in the latitude band from 20˚ to 30˚N. In this region, below the northward eddy heat transport in the upper layer of 200-m, the large southward eddy heat transport is found. This result suggests an importance of 3-dimensional analysis of the eddy heat transport.

Florida Current Transport Variability: An Analysis of Annual and Longer-Period Signals

Authors:
Christopher S. Meinen, Molly O. Baringer, and Rigoberto F. Garcia

Abstract:
As the Florida Current passes through the northern Straits of Florida it carries both the bulk of the Subtropical Gyre western boundary current flow and the majority of the warm upper limb of the Meridional Overturning Circulation. More than forty years of Florida Current transport estimates are used to illustrate the difficulties in extracting annual and longer time scale variability in the presence of a large amount of higher frequency energy. It is shown that for the Florida Current the annual cycle represents less than 10% of the total variance in the long-term record, while interannual (13-42 month) variability represents only 13% of the total variance and periods longer than 42 months (out to a maximum observable period of about 12 years) represents less than 10% of the total. Given the observed variability of the Florida Current, in order to get a monthly mean value that is accurate to within 0.5 Sv at the one standard error level more than 20 daily observations are needed. To obtain an estimate of the annual cycle that is accurate to within 20% of its own standard deviation at the one standard error level at least 24 years of daily data is needed. More than 40 observations spread throughout a year are required to obtain an annual mean that is accurate to within 0.5 Sv. Despite these daunting data requirements, there is sufficient data now to evaluate both the annual cycle of the Florida Current transport with a high degree of accuracy and to begin to determine the longer period variability of the Florida Current. Comparison of the 40+ year record of the Florida Current to the North Atlantic Oscillation index and to the wind stress curl over the basin interior illustrates that a recently described Sverdrup-based mechanism explains a significant fraction of the long-period variability, although the forcing for the mechanism does not appear to be consistent over the full record.

Air-sea interactions in the Gulf Stream region from long-term in-situ observations

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As part of the CLIMODE observational program, a fixed surface mooring was deployed in the Gulf Stream (38N, 65W) for 15 months. Air-sea measurements (1 minute sampling), including radiation, and subsurface oceanographic data (5 minutes sampling) were collected. These high quality and long term measurements are the first of their kind in this region where high winds and strong currents are common. Air-sea fluxes were computed using the COARE bulk parameterization. Wintertime oceanic heat loss events in excess of 1500 W/m^2 occurred during cold air outbreaks when SST was high. We describe here the time variability of the marine boundary layer surface conditions and their evolution with respect to the relative position of the front as the Gulf Stream moved back and forth past the mooring. Very rapid and large changes in SST were observed that concurred with atmospheric conditions. Air-sea coupling such as wind intensification and cloud coverage is discussed. Comparison with NWP is also shown.

Tropical Cyclone to Extratropical Storm Transitions in the Vicinity of the Kuroshio: Sensitivity to Regional SST

N.A. Bond, M.F. Cronin, J. McCaa

Tropical cyclones are common in the western North Pacific during late summer and early fall, and many of them include a northward track over the Kuroshio east of Japan. At this stage in their lifecycle, these cyclones typically undergo a transition from tropical to extra-tropical in nature. It is hypothesized that the timing and structural evolution of these transitions is sensitive to the underlying sea surface temperature distribution. The effects of the regional SST on these storms are manifested not just locally, but through the mechanism of downstream development, have potential impacts on the atmospheric circulation over the entire North Pacific basin. The issue is being addressed through a series of case studies of previous events using high-resolution numerical weather prediction (NWP) model simulations. Control and perturbed SST runs are examined to determine the magnitude and robustness of the local and remote atmospheric response to regional SST anomalies during tropical to extra-tropical transitions.

Frontal Scale Air-Sea Interaction in High Resolution Versions of the Community Climate System Model

Frank Bryan and Bob Tomas

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Julie McClean

Physical Oceanography Research Division, Scripps Institution of Oceanography

Abstract

Multi-decade to century long global coupled climate system simulations that resolve ocean mesoscale eddies are now on the horizon. Prototype integrations in this class of models are currently underway with versions of the Community Climate System Model (CCSM) that are configured with an ocean component with 0.1˚ horizontal resolution, and an atmospheric component with resolution of 0.25˚ or 0.5˚ horizontal resolution. The emerging picture of frontal scale air-sea interaction derived from high resolution observations of surface winds and temperature provides a unique opportunity to test the fidelity of these coupled simulations. Initial analysis of the output of the CCSM experiments indicates that characteristics of frontal scale ocean-atmosphere interaction such as the organization of low level convergence and precipitation along western boundary currents, and the positive correlation between wind stress and SST is captured by the CCSM when the ocean component is eddy resolving. The results are qualitatively similar with the 0.5˚ and 0.25˚ versions of the atmospheric component model. We will present initial quantitative comparisons with observational metrics of frontal-scale air-sea interaction, and seek input from the working group on how best to utilize recent observational results from programs such as KESS and CLIMODE.

The North Pacific Gyre Oscillation Drives Ocean Decadal Variations in the Western and Eastern Boundaries

Lina Ceballos, Emanuele Di Lorenzo, Carlos Hoyos, Niklas Schneider, Bunmei Taguchi

Using ocean model hindcasts, satellite data and simple dynamical models we show that decadal variations in the western and eastern boundaries are coherent and driven by a common atmospheric forcing pattern – the North Pacific Oscillation (NPO). In the central/eastern Pacific the oceanic expression of the NPO corresponds to the North Pacific Gyre Oscillation (NPGO), which reflects the strengthening/weakening of the eastern and central branches of the subtropical gyre. We show that Rossby waves dynamics excited by the NPO propagate the NPGO signature from the central North Pacific into the Kuroshio-Oyashio Extension (KOE), and trigger changes in strength of the KOE with a lag of 3 years. This suggests that the NPGO index can be used to track changes in the entire northern branch of the North Pacific sub-tropical gyre. These results also provide a physical mechanism to explain coherent decadal climate variations and ecosystem changes between the North Pacific eastern and western boundaries.

Modification of Air-Sea Heat Fluxes by Ocean Eddies in the North Pacific

Julie McClean1,2, Ivana Cerovecki**1** (presenter), and the
"CCSM Ultra High Resolution Simulation Team"
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The ocean is known to significantly influence the atmosphere in regions where sea surface temperature (SST) fronts are large; hence these frontal regions should be investigated within a fully coupled ocean-atmosphere model. One such system is the Kuroshio Extension Region, characterized by the strongest air-sea heat exchange in North Pacific. The knowledge of ocean-atmosphere heat exchange and the mechanisms governing it are crucial for understanding the coupling between the ocean and the atmosphere over a wide range of timescales, from those associated with the passage of storms to those of global climate change.

A new fine-resolution configuration of the Community Climate System Model Version 4 (CCSM4) consisting of coupled 0.25° atmosphere/land and 0.1° ocean/sea-ice components is currently being executed on Lawrence Livermore National Laboratory's Atlas Linux Cluster. Here we present analyses of the role of ocean mesoscale processes in modifying air-sea heat fluxes and North Pacific Subtropical Mode Water (STMW) formation. STMW formation is estimated using Walin type analysis. We also draw on results from an earlier standard coarse resolution CCSM3 simulation to reflect on the role of eddies. Finally, both sets of results are compared to those from a fine resolution (0.1°) stand-alone ocean simulation using the Parallel Ocean Program (POP), the ocean component of CCSM. In all cases formation rates obtained from the Walin analysis are compared to STMW volume changes in the ocean interior. The results suggest that STMW formation cannot be explained solely in terms of overlying atmospheric conditions but also strongly depends on oceanic lateral advection.

Beyond KESS and CLIMODE

Meghan F. Cronin[1], Hiroshi Ichikawa[2], and Bob Weller[3]

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During the Kuroshio Extension System Study (KESS) and the CLIvar Mode water Dynamic Experiment (CLIMODE) intensive process studies, full water column and tropospheric sounding measurements were made in conjunction with flux measurements at the air-sea interface. As a consequence, these process studies were able to observe active (two-way) interaction between the ocean and atmospheric boundary layers and also active (two-way) interactions between the upper and deep ocean. These intensive measurements challenge our understanding and models of these systems. Intensive field studies, however, are typically limited in duration, and thus cannot capture the decadal variability in the climate system. Likewise, intensive process studies are not designed to monitor the changing state in near real-time, which is crucial for accurate long-term re-analyses time series. For this we rely upon the sustained climate observing system that comprises a constellation of satellite remote sensing and in situ measurements from ARGO floats, drifters, ship based measurements and an array of moorings. Improved quantification of the role of western boundary currents, their variability, and their coupling to atmosphere is essential to better understand and predict basin-scale climate variability. Strong currents, typhoons and winter storms make western boundary current regions extremely challenging regimes for sustained measurements. As proven, however, during the KESS and CLIMODE studies, many of these challenges can be overcome. In this talk we will discuss the sustained climate observations within the Gulf Stream and Kuroshio Extension Systems.

Comparisons Between KESS Data and the OCAA Assimilation Results

Elizabeth Douglass

Data from the Kuroshio Extension System Study (KESS) from 2004 to 2006 in the western Pacific Ocean are compared with output from a one-degree data-assimilating model estimate. Hydrographic measurements of temperature and salinity are used to examine the formation and decay of the summer thermocline in the region of the Kuroshio. During 2004 and 2006, the wintertime deep mixed layer is formed earlier in the data than in the model estimate, and decay occurs later, leading to a bias of generally warmer temperatures in the model estimate. Model estimates are most similar to the data in 2005, the year most similar to the average of the time series, indicating that the model simulates the basic physical principles well but does not respond to changes on shorter time scales. Comparisons with altimetry show that the model simulates broad-scale changes in the location of the Kuroshio well, but smaller-scale perturbations are not resolvable with one-degree horizontal resolution. Overall, the model estimate is instructive in examining processes in this region on a climatological time scale, but the spatial and temporal resolution are not well suited to analysis of shorter time and length scales.

Momentum, Heat and Mass Exchange in Extreme Conditions during CLIMODE

James Edson
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The NSF sponsored CLIvar MOde Water Dynamic Experiment (CLIMODE) is designed to investigate the formation, evolution, storage, and dispersal of Eighteen Degree Water (EDW), the subtropical mode water of the North Atlantic. The Gulf Stream region of the North Atlantic is a very attractive region for air-sea interaction research as the region experiences the largest net wintertime heat loss over the global ocean. Near surface winds averaged 14 m/s during the first leg of the 2007 field program with a maximum winds speed of approximately 25 m/s. These high wind events drove surface stresses that exceeded 1.0 N/m2. The combined values of the latent and sensible heat fluxes reached 1300 W/m2 during the second leg of the 2007 field program.

An overall objective of the CLIMODE program is to improve our estimates EDW formation through air-sea exchange by accurate measurement of the heat, mass and momentum fluxes. This was accomplished using three highly instrumented platforms during the field program to provide surface fluxes using the direct covariance technique: a moored 3-m discus buoy, a research vessel for surveys, and a drifting Air-Sea Interaction Spar (ASIS). The ship and ASIS packages included Direct Covariance Flux Systems (DCFS) used in the development of the COARE bulk algorithm. A low-power version of the DCFS was deployed on the discus mooring and operated successfully for over a year.

The extreme conditions provide an excellent data set to improve bulk formulae. Specifically, the fluxes from these platforms are being used to validate and improve the COARE 3.0 bulk algorithm. Direct estimates of the drag coefficient are in good agreement with COARE 3.0 over moderate wind conditions. However, there are differences at the lowest and highest wind speeds where COARE 3.0 overestimates and underestimates the drag, respectively. Fairly simple modifications to the COARE 3.0 parameterization provide excellent agreement with our data. Similarly, estimates of the transfer coefficients for sensible and latent heat show differences with COARE 3.0 at high winds. Of particular interest are the extreme conditions encountered during cold air outbreaks that drive combined latent and sensible heat fluxes exceed 1200 W/m2. These enormous heat fluxes are driven by a combination of high winds are significant air-sea temperature and humidity differences. The data is now being used to reduce the uncertainty in the Stanton and Dalton number at wind speeds greater than 15 m/s.

Air-sea Interactions and Variability of the Gulf Stream in a High-resolution Climate Model

R. Farneti, T. Rosati and T. L. Delworth

Climate simulations with a high-resolution CGCM are presented. The model is derived from the GFDL CM2.1 and consists of a 1/4 degree ocean model coupled to a 1 degree atmosphere with several improvements in ocean physics.
We focus our analysis on the Gulf Stream region and its role in basin-scale climate variability. Air-sea interactions over the western boundary current (WBC) regions are analyzed in terms of local correlations and subsequent remote responses; a discussion on the feedbacks and their role in setting a basin-wide response will also be presented. The results are compared with a hierarchy of coupled models that differ only on the spatial resolutions of their oceanic and atmospheric components, thereby modifying the ability of representing oceanic mesoscale features and their influence on the coupled air-sea response.
Finally, climate change scenarios as well as idealized freshwater forcing experiments are used to test the response and sensitivity of the system to the WBC variability and vice versa.

Review of Observed Influence of SST Anomalies in Western Boundary Current Regions on the Large-scale Atmospheric Circulation

Claude Frankignoul

Various statistical methods have been used to detect the observed influence of SST anomalies on the large-scale atmospheric circulation, but they have limitations that will be discussed. In early winter, the North Atlantic Oscillation has been shown to be influenced by SST anomalies in the North Atlantic, with a main center of action in the Gulf Stream / North Atlantic Current region. The signal appears to be robust, but the SST anomalies may not be much influenced by the variability of boundary currents, and attempts have failed at directly linking the atmospheric signal to previous meridional shifts of the Gulf Stream. In the North Pacific, SST anomalies with a main center of action in the Kuroshio Extension region have been found to significantly affect the atmospheric circulation in summer. Since these SST anomalies are affected by anomalous geostrophic advection, the Kuroshio Extension changes appear to influence the large-scale atmospheric circulation. Whether these seasonal atmospheric responses are sufficiently strong to be seen in year-round data will be discussed, as well as their possible feedback on the mid-latitude oceanic circulation.

Air Sea Interaction over the Gulf Stream

Ralf Hand, Nour-Eddine Omrani, Noel S. Keenlyside, Mojib Latif

Off the east coast of Northern America, the Gulf Stream produces a strong meridional gradient in the sea surface temperatures. The sharp SST front causes distinct convergences and divergences in the wind field and enhanced upward motion over the warm water masses, combined with strong evaporation and enhanced upward flows of air and latent heat in this region. Recent studies show, that these processes influence the whole troposhere (e.g. Minobe et. al., Nature, 2008). The impact of the Gulf Stream on the troposhere is studied in observations and high resolution atmospheric model (ECHAM5) simulations. The model is able to reproduce the main circulation features over the Gulf Stream. SST and sea level variability in the region of the Gulf Stream are studied using satellite data with high temporal and spatial resolution. The relationship between variability in this region and large scale atmospheric variability using the reanalysis data are studied with EOF and regression analysis. The result will form the basis of future high resolution atmospheric experiments.

Ocean model representation of western boundary currents and frontal systems: How good are the strongly

Matthew Hecht

Ocean model representation of western boundary currents and frontal systems: How good are the strongly eddying models? The study of ocean-atmosphere interaction over western boundary currents can rely in part on modeling, with prognostic models on either oceanic or atmospheric sides, or alternatively in a "fully-coupled" context. Western boundary currents are much better represented in strongly eddying models, yet some of the important frontal systems, notably that of the Gulf Stream and its extension, retain significant sensitivities to model parameters, discretization and forcing. A brief survey is made of the state of the art, with emphasis on the relevance to ocean-atmosphere interaction.

Recent Progress in Chinese Study on Ocean Circulation in the Western Pacific and its Role in Climate

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Abstract

In the last three years a number of research projects on ocean circulation in the western Pacific and its role in climate were funded by MOST (Ministry of Science and Technology of China) as its 973 projects, NSFC (National Natural Science Foundation of China) as its major project and CAS (Chinese Academy of Sciences) as its major project. In the present talk, based on research results available some key scientific issues on ocean circulation in the western Pacific and its role in climate will be brought up, and Chinese projects related to the western Pacific Ocean, such as 973 projects, NSFC major project and an international NPOCE (Northwest Pacific Ocean Circulation Experiment) project will be introduced.

On the relationship between synoptic wintertime atmospheric variability and path shifts in the Gulf Stream and Kuroshio Extension

Terrence Joyce

Coherent, large scale shifts in the paths of the Gulf Stream (GS) and the Kuroshio Extension (KE) occur on interannual to decadal time scales. Attention has usually been drawn to causes for these shifts in the overlying atmosphere, with some built in delay of up to a few years due to propagation of wind-forced variability within the ocean. Yet these shifts in the latitudes of separated western boundary currents can cause substantial changes in SST, which may influence the synoptic atmospheric variability with little or no time delay. We have chosen to examine various measures of wintertime atmospheric variability in the synoptic band (2:8 days) using a relatively new data set for air sea exchange (OAFlux) and subsurface temperature indices of Gulf Stream and Kuroshio path that are insulated from direct air-sea exchange and therefore preferable to SST. We find significant changes in the atmospheric variability following changes in the paths of these currents, sometimes in a local fashion such as meridional shifts in measures of local storm tracks, and sometimes non-local, broad regions coincident with and 'downstream' of the oceanic forcing. Differences between the N. Pacific (KE) and N. Atlantic (GS) may be in part related to the stronger SST signals of the GS, as well as the more zonallity of the KE. Because of the long time scales present in the oceanic path changes, It is likely that there might be some skill in predicting changes in the atmospheric storm tracks on seasonal to interannual time scales.

Ocean convection within the wintertime Gulf Stream and interannual changes in the N. Atlantic storm track: some early results from CLIMODE

Terrence Joyce

A recent study of Eighteen Degreee Water (EDW), the principal mode water of the subtropical N. Atlantic Ocean, was conceived as one of the major process studies of US CLIVAR. The NSF project; CLIvar MOde water Dynamics Experiment (CLIMODE) focuses on the processes of air-sea exchange, mixing, and advection/subduction as fundamental to Subtropical Mode Water formation process globally. Ocean mode waters provide a climate flywheel because the renewal times for their volume and heat content can be of order several years. With the field experiment only recently completed, results thus far are emerging in the areas of air-sea exchange and water mass formation within the eastward-flowing Gulf Stream (GS). While CLIMODE has thus far focused on the atmosphere forcing of the ocean, data have been collected that will permit an examination of the ocean's affect on the atmosphere. The region of EDW formation is arguably the most intense area of net wintertime heat exchange on the planet, and it is coincident with location of the N. Atlantic storm track for synoptic wintertime atmospheric variability. Two aspects of the program will be explored in this early overview of CLIMODE: the nature of the EDW formation process that occurs within the GS, and the effect of GS path location on interannual changes in the wintertime storm track. The wintertime shipboard observations illustrate that a significant amount of EDW formation occurs within the southern portion of GS where both vertical and meridional shear of the eastward flow alter the 1-D convection process and introduce inertial and slantwise convection/symmetric instabilities as important processes in the EDW formation. And a 22 year-long data set on the Marine Atmospheric Boundary Layer (MABL) is examined to show that synoptic atmospheric variability in the MABL over the GS changes in concert with path shifts in the GS front, pointing out a new coupling between the ocean and atmosphere that could play a important role in interannual/decadal climate variability.

TITLE: Variability of mixed layer depth in Kuroshio/Oyashio Extension region: 2005–2006

Authors: Shin'ichiro Kako and Masahisa Kubota

Abstract:

In December 2005, the winter monsoon was abnormally strong around Japan. Therefore, it was expected that the cooling effect on the upper layer of the ocean would be very strong. However, the mixed layer depth (MLD) in the Kuroshio/Oyashio Extension region was not as deep as those observed during the last four winters. We investigated the reason for the shallow MLD by using a one-dimensional turbulent closure model and the temperature and salinity data obtained using Argo floats. We found that summer heating plays an important role in the determination of the maximum MLD. In 2005, the heat storage rate was very high from July to October since summer heating was significantly stronger than those during the other summers. Consequently, a large vertical density gradient existed at the bottom of the mixed layer and prevented the deepening of the mixed layer.

Comparison of Western Boundary Currents: Gulf Stream and Kuroshio Extension

Kathryn A. Kelly and Co-Authors from the WBCWG Working Group

In the northern hemisphere mid-latitude western boundary current systems there is a complex interaction between dynamics and thermodynamics and between atmosphere and ocean. Their potential contribution to the climate system motivated major parallel field programs in both the North Pacific (KESS) and in the North Atlantic (CLIMODE) and preliminary observations and analyses from these programs highlight that complexity. The 15-yr satellite altimeter data record provides a rich source of information with which to compare the two current systems. Satellite and in situ analyses are combined here to compare and describe the current systems. While many important similarities have been noted on the dynamic and thermodynamic aspects of the time-varying Gulf Stream (GS) and Kuroshio Extension (KE), some not-so-subtle differences exist in current variability, mode water properties, and recirculation gyre structure. This study provides a comprehensive comparison of these two current systems from both dynamical and thermodynamical perspectives with the goal of developing and evaluating hypotheses about the physics underlying the observed differences, and exploring the western boundary current's potential to influence midlatitude sea-air interaction and climate predictability.

Sources and Predictability of Anomalies in North Atlantic Subtropical Mode Water Formation and Transformation Using the Walin Framework

Kathryn A. Kelly

University of Washington, Seattle, Washington

While the mean rates of mode water formation and transformation remain elusive owing to the difficulty of estimating each of the terms, the relative contribution of some of the processes can be determined by comparing the forcing in different years. Estimates of any quantity near the highly variable Gulf Stream front require high spatial resolution for accuracy. The calculation of the formation and transformation forcing functions using the Walin framework requires SST and net surface heat flux fields that are well-matched in spatial resolution, because the heat fluxes must be integrated over each SST outcrop. Great improvements have been made in the spatial resolution of these fields in recent years from microwave SST and scatterometer winds, but the high resolution fields span only a short period. Using microwave SST and turbulent fluxes that combine QuikSCAT winds, microwave SST and ECMWF fields in the COARE bulk formulas, a simple method is presented to extend the current high resolution to earlier years and to create matched fields.

Monthly estimates of formation and transformation are used to quantify interannual variability and to determine the relative contributions of outcrop area (stratification) and heat flux to mode water transformation anomalies. Correlations between net surface heat flux and outcrop area clearly show the influence of the ocean temperature on the air-sea fluxes. Transformation is shown to depend more critically on outcrop area than on heat flux anomalies. The influence of preconditioning on transformation is examined using early winter values of outcrop area and is shown to have predictive skill for wintertime transformation anomalies.

An observational analysis of the variability of the sea surface heat flux in the Kuroshio Extension region

Masanori Konda1 2, Hiroshi Ichikawa2, Hiroyuki Tomita2, Akira Nagano2 and Meghan F. Cronin3

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3. NOAA/PMEL

Abstract

We analyzed the winter and autumn surface heat flux variability in synoptic timescales in the Kuroshio Extension (KE) region, as the Kuroshio Extension Observatory (KEO) and JAMSTEC KEO (JKEO) buoys. The former is moored in the Kuroshio recirculation gyre south of the KE, and the latter is in the mixed water region north of the KE. It is suggested from the relationship between the sea surface temperature (SST) and the turbulent heat flux that the north-south contrast of the air-sea coupling processes across the KE front changes seasonally. In winter, large latent and sensible heat fluxes are observed both at JKEO and KEO. The SST at JKEO can change up to several degrees within a week, whereas SST at KEO is hardly changed possibly because of the deep mixed layer. In the autumn season, SST at JKEO decreases much faster than at KEO, although the evaporative cooling at JKEO is slightly smaller than at KEO. Further investigation of the relationship between the turbulent heat flux at JKEO and KEO shows that the strong wintertime northerly wind causes extremely large turbulent heat flux both north of, and south of, the KE, despite the marked temperature front in the sea and the air. This is attributable to the atmospheric adjustment to the sea surface thermal condition, as the northerly winds blow across increasingly warm water. Although there are some differences in the turbulent heat flux when winds are from the south, the amplitude of such variation is usually small. In contrast, there is a significant difference between the evaporative cooling in the north and the south of the KE in autumn. The surface heat flux on seasonal timescales and its spatial distribution should depend in part on the frequency of occurrence of these flux patterns in synoptic timescales. This result shows the importance of the high frequency monitoring of the air-sea interaction parameters on both sides of the KE front in order to analyze the role of the KE front in the mid-latitude climate variability.

Western Boundary Current SST anomalies and their Interaction with the Atmosphere

Yochanan Kushnir, Richard Seager, and John Sawicki

Lamont-Doherty Earth Observatory, The Earth Institute at Columbia University

and

Walter A. Robinson

Department of Atmospheric Sciences University of Illinois at Urbana-Champaign and Climate Dynamics Program National Science Foundation

Western boundary currents are regions of intense air-sea heat exchange and large SST anomalies on a broad range of time scales. In this talk we revisit the nagging question regarding the role of these anomalies in climate, particularly their effect on the atmospheric circulation. We focus on the Atlantic Gulfstream extension region and examine the time-dependent relationship between observed SST variability in this region and anomalies in the overlying atmospheric circulations. Results suggest the presence of a positive feedback between SST anomalies and the atmosphere during winter. The air-sea interaction involves baroclinic-eddy/mean-flow interaction, which contributes to the persistence of large-scale atmospheric anomalies in the North Atlantic.

Atmospheric response to the Gulf Stream in an AGCM

Akira Kuwano-Yoshida[1*], Shoshiro Minobe[2], and Shang-Ping Xie[3]

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3. International Pacific Research Center and Department of Meteorology,

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Abstract

Sensitivity experiments for sea surface temperature (SST) gradient associated with the Gulf Stream are conducted using an atmospheric general circulation model. Precipitation, surface convergence, and evaporation are trapped over the Gulf Stream similar to satellite observation in the result of a simulation with observed SST, while they do not concentrate over there with horizontally smoothed SST irrespective of the season. It is the cumulus precipitation that is sensitive to the SST gradient rather than large-scale precipitation. Composite analysis for cumulus precipitation suggests that larger surface evaporation over the Gulf Stream basically maintains larger specific humidity near surface, and surface moisture convergence induced by the SST front through the pressure adjustment mechanism anchors convection by sustaining larger convective available potential energy. Narrow structure of vertical velocity is found in upper troposphere in summer, while it is limited lower troposphere in other seasons, because, in summer, cumulus height and updraft associated with cumulus convection are larger, and in winter updraft associated with synoptic scale disturbances is relatively larger than one of cumulus convection.

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Winter Atmosphere – Mixed Layer Ocean Response to Geostrophic Ocean Heat Transport Variations along the Kuroshio Current Extension

Young-Oh Kwon

Abstract

The winter response of the coupled atmosphere-ocean mixed layer system to anomalous geostrophic ocean heat flux convergence (OHFC) in the Kuroshio Extension is investigated by means of experiments with an atmospheric general circulation model coupled to an entraining ocean mixed layer model. In addition to the direct response, interaction with the tropics and the role of the extra-tropical ocean mixed layer are addressed. The direct coupled ocean mixed layer - atmospheric circulation response to a positive OHFC anomaly in the Kuroshio Extension consists of anomalous positive SST along the Kuroshio Extension and a baroclinic atmospheric response characterized by a low-level trough and upper-level ridge over the north Pacific. The low-level component of this atmospheric circulation response is weaker in the case without coupling to an extratropical ocean mixed layer compared to the case with coupling, especially in late winter. The inclusion of an interactive mixed layer in the tropics modifies the direct coupled atmospheric response as a result of a northward displacement of the Pacific Inter-Tropical Convergence Zone which drives an equivalent barotropic anomalous ridge over the north Pacific. Although the tropically-driven component of the north Pacific atmospheric circulation response is comparable to the direct response in terms of sea level pressure amplitude, it is less important in terms of wind stress curl amplitude due to the mitigating effect of the relatively broad spatial scale of the tropically-forced atmospheric teleconnection.

Ocean-atmosphere Coupling over Mid-latitude Ocean Fronts

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The Agulhas and Kuroshio Extensions have strong horizontal current shears and temperature gradients in their meanders. The spaceborne scatterometer, QuikSCAT, observes that, over these meanders, the variability of surface stress (momentum flux) is very different from those of surface wind. The geophysical product of QuikSCAT, the equivalent neutral wind, rotates in opposition to the surface current, which is a clear characteristic of turbulent stress generated by vertical shear; stress is the vector difference between wind and current. The ubiquitous spatial coherence between sea surface temperature and the equivalent neutral wind, found under a variety of atmospheric conditions, including the two ocean fronts, is a characteristics of turbulent stress generated by buoyancy. At the small scales of turbulence, the differences in large-scale factors, such as pressure gradient force, Coriolis force, and large-scale advection, are not important. There was no continuous and large-scale stress measurement over ocean until the launch of the scatterometers and our knowledge of stress variability is largely based on wind. Scatterometer measurement has been used as the actual wind, particularly in operational weather applications. The difference between the variability of stress and wind is assumed to be negligible on the justification that the marine atmosphere has near-neural stratification, and the magnitude of ocean current is negligible compared with wind. Such assumption has to be vigorously examined over the ocean fronts, as they should be examined under the high wind conditions when flow separation occurs. Most studies using atmospheric general circulation models fail to generate systematic response to prescribe midlatitude sea surface temperature anomalies. The lapse rate is believed to be too weak to support deep convection and the ocean effect is confined to the atmospheric boundary layer. We found strong spatial coherence among sea surface temperature and surface stress convergence at the surface, and cloud top temperature and cloud optical thickness provided by the International Satellite Cloud Climatology Project. Atmospheric Infrared Sounder temperature profiles show that the high and low temperatures penetrate from the ocean all the way up to 300 mb. The surface and cloud top temperatures are also spatially coherent with rainfall from the Tropical Rain Measuring Mission over the southern branch of the Kuroshio Extension, and TRMM radar confirms that rainfall anomalies up to 5 km, way above the top of the atmospheric boundary layer. The AIRS and TRMM data contradict the prevailing notion among atmospheric modeling community and present a challenge to model dynamic and the spatial versus temporal scale parameterization.

Influence of the Gulf Stream on the troposphere

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ABSTRACT

The impacts from the Gulf Stream to the marine atmospheric boundary layer and troposphere are investigated using high-resolution datasets and numerical model outputs including satellite-derived surface winds, precipitations, and OLRs, horizontal and vertical winds and pressures from ECMWF operational data, and AGCM for the Earth Simulator for a period from 2002 to 2006. In addition to previously known convergences and divergences of surface winds somewhat off-shore of the Gulf Stream, the wind convergences almost along the Gulf Stream current axis (to the south of the SST front) and divergences to the near-shore side of it (to the north of the SST front) are observed. A good correspondence between the wind convergence and Laplacian of SLPs strongly suggests that pressure adjustments to SSTs play an important role. Just above the wind convergences, a narrow strengthened precipitation band is commonly found in satellites, ECMWF data, and AGCM. In addition, ECMWF data indicates upward winds in the middle and lower troposphere and associated horizontal wind divergence in the upper troposphere. All these features exhibit meandering consistent with the Gulf Stream, suggesting a close linkage of the atmospheric responses in the troposphere to the Gulf Stream. Frequencies of high-level clouds derived from OLRs exhibit a signature over the Gulf Stream, though the concentration to the Gulf Stream of this feature is weaker than those in other parameters. These results indicate that the Gulf Stream gives the impact to the atmosphere in a systematic manner not only in the boundary layer but also in the troposphere (Minobe et al. 2008, Nature). In this presentation, we will also discuss relating problems such as relative contribution of vertical mixing and pressure adjustment mechanisms in this region, a relation to climate variability such as the Atlantic Multidecadal Oscillation, uncertainties of parameters that are desirable to be obtained by field observations, and a future strategy of effective use of the hierarchy of numerical models.

Inter-annual Variability of the Kuroshio Transports South of Japan Derived from Satellite Altimetry Data

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The heat transported by the Kuroshio is considered to be one of the important elements in a global climate variation system. However, its inter-annual variation is not clear due to fluctuations caused by recirculation eddy to the south of Shikoku and mesoscale eddies from the east. One-year long measurements by inverted echo sounders (IES) and current meters along the ASUKA (south of Shikoku) and 30˚N lines from October 2004 permitted us to obtain eddy-removed Kuroshio transports by practically separating the eddy components from the Kuroshio transports. In this study, using satellite altimetry data, we expanded the period of the time series of the eddy-removed transports to 15 years from 1992 by an empirical formula for the minimum residual between the IES- and altimeter-derived volume transports. The time series shows a quadrennial variation, which originates in the region of 180˚E-160˚W, 20˚N-25˚N, propagates along the North Equatorial Current and the Kuroshio in the East China Sea, and reaches around Japan.

Decadal variability in the Kuroshio and Oyashio Extension fronts simulated in an eddy-resolving OGCM

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For the North Pacific decadal variability, the potential importance of ocean-to-atmosphere feedback in the western North Pacific (WNP) region has been emphasized as well as the importance of remote influence from the tropics and that of the midlatitude atmospheric stochastic forcing. To understand the ocean-to-atmosphere feedback it is necessary to improve our knowledge for oceanic variability in the WNP Ocean, which is characterized by two prominent fronts, the subarctic (Oyashio Extension) and the Kuroshio Extension (KE) fronts. Through analysis of a hindcast integration of an eddy-resolving quasi-global ocean general circulation model, we have investigated decadal variability in the WNP region, with particular emphasis on those fronts.

As a decadal-scale change from a warm period around 1970 to a cool period in the mid-1980s, those fronts in the model migrate southward as observed, and the associated pronounced cooling is confined mainly to those frontal zones. Reflecting distinctive vertical structures of those fronts, the mixed layer (subsurface) cooling is the strongest along the subarctic (KE) front.

The cool sea surface temperature anomalies (SSTAs) in the frontal zones associated with the southward migration of the fronts are accompanied by anomalous downward surface heat flux as observed, indicating that the SSTAs are caused not by atmospheric thermal forcing but by oceanic dynamics. Further, this suggests the ocean induced SSTAs can have feedback to the overlying atmosphere.

Large meridional scale portion of decadal sea surface height variability in the KE frontal zone seems to be explained by propagation of baroclinic Rossby waves driven by large-scale wind anomalies in the North Pacific. This process alone, however, can fully explain neither strong frontal-scale variability in the KE frontal zone, nor the corresponding variability in the subarctic frontal zone. Advection of anomalous potential vorticity by the KE and Oyashio currents, respectively, may have impacts for these, but further investigations are necessary to fully understand mechanisms for decadal variability in these frontal zones.

The Character of North Atlantic Subtropical Mode Water Potential Vorticity Forcing

Otmar Olsina

The input of potential vorticity (pv) over the North Atlantic is estimated from observations to produce a climatological map of pv flux and to study the interannual forcing variability. Particular attention is paid to the North Atlantic subtropical mode water potential temperature range from 17 to 19C. The sea surface PV flux is estimated through buoyancy and wind stress contributions and using a climatological mixed layer depth product. Wind forcing of pv is found to be weak. A major observational subtropical mode water program named CLIMODE was conducted during the winters of 2004 to 2006. These years appear to be slightly stronger in their forcing than climatology, although the difference is comparable to the uncertainty. Attempts are made to relate the fluctuations to the NAO, a major mode of North Atlantic atmospheric variability.

Distribution of deep near-inertial waves observed in the Kuroshio Extension

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Wind-induced near-inertial waves (NIWs) are considered to be a major energy source for ocean mixing. They radiate from the mixed layer to the deep ocean and provide kinetic energy that stirs the deep ocean. The mesoscale velocity field can dramatically influence NIW vertical propagation by trapping or reflecting NIW energy. We investigate deep NIW energy distribution in the Kuroshio Extension using data from an array of instruments comprised of 46 pressure-sensor-equipped inverted echo sounders and near-bottom acoustic current meter sensors that spanned a 600 km x 600 km region as part of the Kuroshio Extension System Study (KESS) during 2004−2006. The deep NIW distribution is interpreted in the context of both upper and deep layer mapped circulation. Our results demonstrate that the NIW energy distribution in the deep ocean under the Kuroshio Extension is affected by both upper and deep mesoscale velocity fields. The wintertime-mean NIW energy input from the wind to the mixed layer determined by a damped slab-like model predicts relatively homogeneous distribution over the KESS domain. Yet, the winter-time-mean NIW energy map shows a sharp factor-5 decrease south of the Kuroshio Extension suggesting that the Kuroshio Extension blocks NIWs from further equatorial propagation. Furthermore, the time-varying NIW energy distribution south of the Kuroshio Extension indicates that the deep mesoscale circulation traps NIW energy in deep anticyclones.

Interannual Variability of the North Pacific Subtropical Mode Water: New Insights from the KESS Profiling Float Program

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Forty-eight profiling floats were deployed in the Kuroshio Extension region since May 2004 as part of the Kuroshio Extension System Study (KESS) project. By combining the float temperature-salinity measurements with satellite altimetry data, this study investigates the role played by mesoscale eddies in controlling the property changes in North Pacific Subtropical Mode Water (STMW). Following a 3-yr period of low eddy activity in 2002-04, the KE transitioned to a high eddy kinetic energy state in 2005. This transition is the result of delayed oceanic response to the 2002 shift in the basin-scale surface wind forcing in connection with the Pacific decadal oscillation. By transporting northern-origin, high potential vorticity KE water into the recirculation gyre, the enhanced eddy activity affects STMW in two ways: first, it hinders the formation of deep winter mixed layer (hence the source for STMW) by modifying the upper ocean stratification and, secondly, it provides a direct high-PV source to mix with the surrounding low-PV STMW. The eddies's influence upon STMW is observed to be both significant in magnitude and efficient in time. Compared to 2004, the PV signal in the core of STMW was reduced by half in 2005 and this weakening of STMW's intensity occurred within a period of less than 7 months.

Coupled Decadal Variability in the North Pacific: An Observationally-Constrained Idealized Model

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Air-sea coupled variability is investigated in this study by focusing on the observed sea surface temperature signals in the Kuroshio Extension (KE) region of 32-38N and 142E-180. In this region, both the oceanic circulation variability and the heat exchange variability across the air-sea interface are the largest in the midlatitude North Pacific. SST variability in the KE region has a dominant timescale of ~10 yr and this decadal variation is caused largely by the regional, wind-induced sea surface height changes that represent the lateral migration and strengthening/weakening of the KE jet. The importance of the air-sea coupling in influencing KE jet is explored by dividing the large-scale wind forcing into those associated with the intrinsic atmospheric variability and those induced by the SST changes in the KE region. The latter signals are extracted from the NCEP-NCAR reanalysis data using the lagged correlation analysis. In the absence of the SST feedback, the intrinsic atmospheric forcing enhances the decadal and longer timescale SST variance through oceanic advection, but fails to capture the observed decadal spectral peak. When the SST feedback is present, a warm (cold) KE SST anomaly works to generate a positive (negative) wind stress curl in the eastern North Pacific basin, resulting in negative (positive) local SSH anomalies through Ekman divergence (convergence). As these wind-forced SSH anomalies propagate into the KE region in the west, they shift the KE jet and alter the sign of the pre-existing SST anomalies. Given the spatial pattern of the SST-induced wind stress curl forcing, the optimal coupling in the midlatitude North Pacific occurs at the period of ~10 yr, slightly longer than the basin crossing time of the baroclinic Rossby waves along the KE latitude.

Oceanic response to atmospheric forcing in the Kuroshio Extension

Luc Rainville (APL/UW), Steve Jayne (WHOI), Tom Farrar (WHOI), Nick Bond (UW), Meghan Cronin (NOAA/PMEL), Jae Hun Park (URI).

We are currently using an extensive set of oceanic and atmospheric observations, collected as part of the Kuroshio Extension System Study (KESS) and the Kuroshio Extension Observatory (KEO) programs, to investigate the upper and deep ocean response to atmospheric forcing in the Kuroshio region. Specifically, we focus on the generation of near-inertial motions from the wind, how and where they propagate and dissipate, and how they directly affect the mass and heat budget of the mixed layer and subtropical mode water (STMW).

The KESS array, deployed during May 2004--June 2006, comprised subsurface moorings with moored profilers and current meters, and inverted echo sounders equipped with near-bottom pressure and current sensors. KEO, a moored surface buoy, was first deployed in 2004 as part of KESS and is now part of the sustained ocean climate observing system. Because of to its combination of vertical, horizontal, and temporal resolution and extent of spatial coverage, the KESS array is uniquely suited to to better understand the role of strong wind events (tropical cyclones, winter storms) for the erosion of seasonal thermocline and in the overall heat balance of the region.

NUMERICAL AND THEORETICAL INVESTIGATIONS OF NORTH PACIFIC SUBTROPICAL MODE WATER WITH IMPLICATIONS TO PACIFIC CLIMATE VARIABILITY

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An investigation using a combined numerical modeling and theoretical approach is followed to better resolve the role of Subtropical Mode Water (STMW) in the exchange of information between the atmosphere and the ocean linked to climate variability in the North Pacific Ocean. In this, a High resolution MIT General Circulation Model (MITgcm) simulation is analyzed to study the formation, isolation, dispersal of STMW and identify correlations between STMW variations and established climatic signals in the Pacific basin. During a 171-month time period (from January 1992 to March 2006), the seasonal variability is the dominant temporal variation observed. From climatological model fields, STMW exhibits distinct features in time and space. This can be seen more clearly by dividing the cycle into three distinct time periods: the formation, the isolation and the dissipation periods. In addition to seasonality there is also an interannual signal observed in STMW variability. This interannual variation pattern is connected closely to the climate shifts of North Pacific with further investigation showing that there is a high correlation between the STMW variability and the Pacific Decadal Oscillation index. Dynamics mechanisms behind this interannual variability is further explored in a planetary geostrophic ocean model (PGOM). Results from this indicate that the amplitude of seasonal and interannual variability of STMW volume is primarily dominated by the variability in the air-sea heat flux.

Decadal Variability of the Kuroshio Extension Jet in a Global Eddy-resolving Ocean Model Hindcast

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Decadal variability of the Kuroshio Extension (KE) jet is investigated using a hindcast simulation of an eddy-resolving Ocean general circulation model For the Earth Simulator (OFES). The first empirical orthogonal function mode of sea level anomalies of OFES in the KE region exhibits the narrow and zonally elongated sea level anomalies along the KE jet. The corresponding principal component of this mode indicates prominent decadal variability with rapid phase change in the early 1980s. Because this principal component is quite well correlated with meridional fluctuations of the KE jet axis in the upstream region, the first mode corresponds to the southward shift of the KE jet in the upstream region in the early 1980s. This decadal change is consistent with past observational studies. We reveal that the meridional shift of the KE jet in the downstream region leads that in the upstream region by a few years, and propagates to the upstream along the jet with a phase speed about 2.80 cm s^{-1}. This phase speed is comparable to that of linear long Rossby waves, but linear long Rossby waves cannot account for the propagation of the jet displacement, because the jet displacement propagates not along the same latitude but along the KE jet. The authors hypothesize that the propagation of the meridional shift of the KE jet can be explained by the thin-jet theory (e.g. Cushman-Roisin et al., 1993). The basic assumption of the thin-jet theory is variations along the jet are small compare to variations normal to the jet. Under this assumption, the meridional shift of the jet can propagate to the upstream along the jet.

Interaction of large scale climate fluctuations with the western boundary currents in the North Pacific

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In the western boundary currents the slow evolution of the thermocline circulation effectively interacts with the surface heat budget and the atmosphere. As such, these regions have been hypothesized to be players in the formation of decadal climate variations. In the North Pacific, changes in the Kuroshio and its extension are modulated on decadal time scales in response to North Pacific wind stresses partially associated with the large scale climate modes such as the Pacific Decadal Oscillation, and the recently described North Pacific Gyre oscillation. The associated oceanic Rossby waves act as a low pass filter and couple the eastern and western basins. In case of the North Pacific Gyre Oscillation decadal undulations in the California current and Alaskan gyre are lag correlated with undulations of the Kuroshio extension jets. The framework of linear waves, however, is deficient in explaining the sharp meridional scales of the oceanic responses in the Kuroshio extension, and other processes have to be invoked. The atmospheric response to the perturbations in the Kuroshio Extension has been a contentious issue. Recent developments indicate that this feedback involves the ocean meso-scale, and that it be viewed as response of the coupled oceanic surface boundary layer - atmosphere system to perturbations of the oceanic geostrophic circulation and heat transports. Pertinent recent studies will be reviewed.

Mesoscale air-sea interaction and feedback in the western Arabian Sea

Hyodae Seo, R. Murtugudde, M. Jochum, and A. J. Miller

Observations of the western Arabian Sea over the last decade have revealed a rich filamentary eddy structure, with large horizontal SST gradients in the ocean, developing in response to the southwest monsoon winds. This summertime oceanic condition triggers an intense mesoscale coupled interaction, whose overall influence on the longer-term properties of this ocean remains uncertain. In this study, a high-resolution Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model is employed to explore this feedback effect on the long-term dynamical and thermodynamical structure of the ocean.

The observed relationship between the near-surface winds and mesoscale SSTs generate Ekman pumping velocities at the scale of the cold filaments, whose magnitude is the order of 1 m/day in both the model and observations. This additional Ekman-driven velocity, induced by the wind-eddy interaction, accounts for approximately 10-20% of oceanic vertical velocity of the cold filaments. This implies that Ekman pumping arising from the mesoscale coupled feedback makes a nontrivial contribution to the vertical structure of the upper ocean and the evolution of mesoscale eddies, with obvious implications for marine ecosystem and biogeochemical variability.

Furthermore, SST features associated with cold filaments substantially reduce the latent heat loss. The long-term latent heat flux change due to eddies in the model is approximately 10-15 W/m2 over the cold filaments, which is consistent with previous estimates based on short-term in situ measurements. Given the shallow mixed layer, this additional surface heat flux warms the cold filament at the rate of 0.3-0.4°C/month over a season with strong eddy activity, and 0.1-0.2°C/month over the 12-year mean, rendering overall low-frequency modulation of SST feasible. This long-term mixed layer heating by the surface flux is approximately ±10% of the lateral heat flux by the eddies, yet it can be comparable to the vertical heat flux. Potential dynamic and thermodynamic impacts of this observed air-sea interaction on the monsoons and regional climate are yet to be quantified given the strong correlation between the Somalia upwelling SST and the Indian summer monsoons.

Episodic Mode Water Formation: Atmospheric Controls and Trends

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We explore the intraseasonal variability of North Atlantic mode water formation in the CLIMODE region. We observe that wintertime sensible and latent heat fluxes from CLIMODE region surface waters are characterized by episodic high flux events due to cold air outbreaks from North America. Up to 60% of the November-March (NDJFM) total sensible heat flux and 45% of latent heat flux occurs on these high flux days. On average of 40% (33%) of the total NDJFM sensible (latent) heat flux takes place during just 17.5% (20%) of the days. Over the last 60 years, the total NDJFM sensible and latent heat fluxes over the CLIMODE region have increased, due to an increased number and intensity of high flux event days. Recent cold air outbreaks are characterized by increasingly colder surface air conditions over the eastern seaboard of North America and slightly warmer ocean SSTs, leading to increased flux rates. An increase of meridional wind variance in the CLIMODE region, indicative of more intense and rapid north-south advection of arctic air masses, is also observed over the last 60 years and may explain the surface air cooling trend over eastern North America.

Some features of atmospheric local and far-field response over the Gulf Stream

Richard Justin Small

Two aspects of the atmospheric response to the Gulf Stream and its extension are examined. Firstly, satellite scatterometer measurements show that synoptic variance of low level (10m) winds has a local maximum over the Gulf Stream. A regional numerical model is used to determine the cause of this maximum, how far extends into the atmosphere, and whether it is connected to the deeper, free tropospheric storm track. Secondly, the response of the atmosphere to the deep vertical motion and convective heat release over the Gulf Stream, reported by Minobe et al (2008, Nature, 452, 206-209), is explored using a linear baroclinic model. The relative importance of the deep heating vs shallow sensible and convective heating to far field response is discussed. Finally the weather regimes that give rise to the deep motion are described. It is proposed that future work in this field will include the joint analysis of CLIMODE and model data.

Influences of the Kuroshio/Oyashio Extensions on air-sea heat exchanges and storm track activity as revealed in regional atmospheric model simulations for the 2003/4 cold season

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Masami Nonaka (JAMSTEC), and Shang-Ping Xie (IPRC/Univ. of Hawaii)

Influences of oceanic fronts in the Kuroshio and Oyashio Extension (KOE) region on the overlying atmosphere are investigated by comparing a pair of atmospheric regional model hindcast experiments for the 2003-04 cold season, one with the observed fine-scale frontal structures in sea surface temperature (SST) prescribed at the model lower boundary and the other with artificially smoothed SST distribution. The comparison reveals the locally enhanced meridional gradient of turbulent heat fluxes and surface air temperature (SAT) across the oceanic frontal zone that acts to augment the storm track activity both in winter and spring. Distinct seasonal dependency is found, however, in how dominantly the storm track activity influences the time-mean distribution of heat and moisture supply from the ocean. In spring the mean surface sensible heat flux (SHF) is upward (downward) on the warmer (cooler) side of the subpolar SST front. This sharp cross-frontal contrast is a manifestation of intermittent heat release (cooling) induced by cool northerlies (warm southerlies) on the warmer (cooler) side of the front in association with migratory cyclones and anticyclones. The oceanic frontal zone is thus marked as the largest variability and sign reversal of the skewness in SHF. The cross-frontal SHF contrasts in air-sea heat exchanges counteract poleward heat transport by those atmospheric eddies, to restore the sharp meridional gradient of SAT effectively for recurrent development of atmospheric disturbances. Lacking this oceanic baroclinic adjustment associated with the SST front, the experiment with smoothed SST distribution underestimates storm track activity in the KOE region. In winter the prevailing cold, dry continental airflow associated with the Asian winter monsoon induces a large amount of heat and moisture release even from the cooler ocean to the north of the frontal zone. The persistent advective effect by the monsoonal wind weakens the SAT gradient and smears out the sign-reversal of the SHF skewness, leading to weaker influence of the oceanic fronts on the atmosphere in winter than in spring.

High-resolution simulation of the global coupled atmosphere–ocean system using CFES

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Abstract

To promote studies on mechanisms and predictability of high-impact phenomena especially in the mid-latitudes and their relation to the global-scale circulations, we have developed a global, high-resolution, coupled atmosphere–ocean general circulation model (GCM) which is designed to achieve ef- ficient computational performance on the Earth Simulator. The model, named CFES (Coupled Atmos- phere–Ocean GCM for the Earth Simulator), consists of AFES and OFES, atmospheric and oceanic com- ponent respectively, with MPMD (multiple program multiple data) technique and fully parallelized cou- pling schemes. Now we have two settings of CFES. The higher resolution version, called “CFES standard,” has the resolutions of T239 (about 50 km) and L48 for the atmosphere and 0.25º (about 25 km) and 54 levels for the ocean, and it takes about 20 hours for 1-year integration using 60 nodes (30 for AFES and 30 for OFES) of the Earth Simulator. The lower resolution version, called “CFES mini,” has half the horizontal resolution of CFES std. and will be used for centennial-scale and ensemble simulations. At this moment, 15-years of integration with CFES std. has been completed. Although the oceanic component is “eddy-permitting” rather than “eddy-resolving,” frontal structures and variability of western boundary currents such as the Kuroshio, Gulf Stream, Brazil, and Agulhas Currents are reproduced fairly well. In addition, the atmospheric component is fine enough to capture the steep surface temperature gra- dients and to simulate extra-tropical cyclones. These results are promising for researches on frontal-scale air–sea interactions and their role in basin- and global-scale circulations of the ocean and atmosphere.

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The mechanism of the atmospheric response to the Gulf Stream in a regional climate model

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ABSTRACT

Strong sea surface temperature (SST) fronts associated with the western boundary currents cause surface wind convergence. There are two known mechanisms to illustrate the wind speed changes: 1) vertical mixing mechanism (SST fronts unstabilize the surface layer through release of heat and moisture thus the vertical shear is weaken, so that the surface wind speed change), and 2) pressure adjustment mechanism (SST gradients induce the pressure change in atmosphere so that the wind speed change). To estimate the contribution of each mechanism, we develop a diagnostic method that represents the wind convergence in a surface layer as a linear of each mechanism. Then we apply the method to a 5 years numerical simulation of the Gulf Stream using a regional atmospheric model, with the horizontal resolution 0.5°. For the annual climatological convergence, both mechanism contribute to the response over the downstream region, however, only the pressure adjustment mechanism contribute to the upstream region. The spatial regression coefficients indicate that the pressure adjustment mechanism is major contributor: the coefficient of the vertical mixing mechanism with total convergence is 0.30, and the coefficient of the pressure adjustment mechanism is 0.69. In winter, the contribution of the vertical mixing mechanism is comparable with the pressure adjustment mechanism, while in summer, because of the northing of the westerly, the responses are almost made by the pressure adjustment mechanism.

Eighteen Degree Water from profiling floats in CLIMODE

Lynne D. Talley

As part of the CLIMODE observations of Eighteen Degree Water (EDW) formation and destruction, 9 profiling floats equipped with optical oxygen sensors as well as CTDs profiled temperature, salinity and oxygen every 5 days to 500 m and every 10 days to 1800 m during 2006 and 2007 in the Gulf Stream region. Thick (200- 450 m) late winter mixed layers with EDW properties were observed close to the Gulf Stream at about 52W, and in a separate cluster up to several hundred kilometers south of the Gulf Stream at about 62W, within the westward recirculation. Relatively thick winter mixed layers at 14C were observed north of the Gulf Stream, and also adjacent to the North Atlantic Current much farther to the east. Mixed layer oxygen saturation is a robust indicator of deep mixing: it is depressed in the thick winter mixed layers and increases abruptly upon cessation of deep mixing. EDW layers for these floats, defined by low potential density gradient, were thickest during and just after late- winter outcropping. EDW thickness declined by about 100 m when mixing ceased, with the EDW layer center also shifting physically downward. Oxygen saturation decreased in the EDW by about 10 percent from late winter to late summer, indicating annual aging of the water mass followed by renewal again in the winter. The oxygen-equipped floats provide an excellent opportunity to study the seasonal evolution of oxygen in the upper ocean in the Sargasso Sea. A well-developed oxygen minimum, centered at about 27.2 sigma theta and originating in the tropical Atlantic, underlies the EDW at about 800 m (south of the Gulf Stream). Above the EDW were the seasonally-evolving mixed layer with a thin underlying oxygen maximum layer in spring/summer and a thin oxygen minimum layer in fall/early winter, associated with photosynthesis/respiration. Although the EDW's absolute oxygen content decreased throughout the year following late winter formation, the EDW was marked by a slight vertical oxygen maximum once the overlying seasonal oxygen minimum developed.

Evaluation of the representation of western boundary currents in climate models at both high and low resolution

By LuAnne Thompson, Young-Oh Kwon, and Frank Bryan

The role of Northern Hemisphere Western Boundary Currents in the climate system has long been debated in the community. Biases in the ocean component of IPCC class climate models persist owing to both errors in the atmospheric component as well as errors in ocean physics owing to low resolution. Meanwhile, high-resolution ocean simulations show that many of the biases originating in the ocean model can be overcome with sufficient resolution. In this talk, we will address how biases in coupled models manifest themselves in the climate system, both for the mean climate, and for coupled modes of variability that exist on local, basin, and global scales in models. We will also address possible metrics for evaluation of western boundary currents in climate models. This presentation will provide a foundation for the consensus report that will be produced at the conclusion of this workshop to provide recommendations for both the ocean observing system and the climate modeling community.

Ocean frontal effects on the vertical development of clouds over the western North Pacific: In situ and satellite observations

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A suite of ship-board and satellite observations are analyzed and synthesized to investigate the three-dimensional structure of clouds and influences from sea surface temperature fronts over the western North Pacific. Sharp transitions are observed across the Kuroshio Extension (KE) front in the marine atmospheric boundary layer (MABL) and its clouds. The ocean's influence appears to extend beyond the MABL, with higher cloud tops in altitude along the KE front than the surroundings.

In winter, intense turbulent heat release from the ocean takes place on the southern flank of the KE front, where the cloud top penetrates above the MABL and reaches the mid-troposphere. In this band of high cloud tops, frequent lightning activity is observed. Our results suggest a sea level pressure mechanism, where temperature gradient in the MABL induces strong surface wind convergence on the southern flank of the KE front, deepening the clouds there.

In early summer, sea fog frequently occurs on the northern flank of the subtropical KE, and subarctic fronts under southerly warm advection that suppresses surface heat flux and stabilizes the surface atmosphere. Sea fog is infrequently observed over the KE front even under southerly conditions as the warm ocean current weakens atmospheric stratification and promotes vertical mixing. The KE front anchors a narrow band of surface wind convergence, helping support a broad band of upward motion at 700 hPa that is associated with the eastward extension of the Baiu rain band from Japan in June – July.

Influence of summer-time surface heat flux to the pre-condition of winter-time mixed layer observed by the Kuroshio Extension Observatory

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Abstract

The huge amount of heat loss in winter mainly by turbulent heat flux in the Kuroshio Extension region has crucial role for development of mixed layer and formation of mode water (Suga and Hanawa, 1995). However, some studies suggest that winter-time mixed layer depends on not only winter-time heat flux but also pre-condition of the ocean (Qiu and Chen, 2006, Kako and Kubota, 2007). Kako and Kubota (2007) indicates that summer-time heat flux causes anomalous pre-condition of the ocean and it affects on winter-time mixed layer by adopting 1-dimensional numerical model calculation with surface flux derived from atmospheric re-analysis as surface boundary conditions. In order to confirm their suggestion, we examined summer-time heat flux variation and its influence on the upper ocean. The present study used in-situ surface heat flux, and upper ocean temperature and salinity data above depth of 525m obtained from the Kuroshio Extension Observatory (KEO) buoy (Cronin et al., 2008).

The summer-time surface net heat flux shows anomalous surface heating in 2005 and anomalous cooling in 2004 and 2006. In 2005, the downward shortwave radiation is larger than that in 2004 and 2006. This result is different from the surface heat flux derived from NCEP/NCAR reanalysis (NRA) in which year-to-year variation of surface net heat flux is dominated by latent heat flux. In 2005, the in-situ intensity of stratification above depth of 100m is larger compared with those in 2004 and 2006. These results suggest that the year-to-year variation of summer-time surface heat flux dominated not by latent heat flux but by shortwave radiation, and it causes year-to-year variation of upper ocean stratification, the pre-condition of winter, while the length of data is only 3 years. For better understanding of variation mechanism of winter-time mixed layer the continuous time-series observation including summer-time shortwave radiation is indispensable.

Coupled Ocean-Atmosphere Response to North Pacific wind Stress Forcing

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In this paper, coupled ocean-atmosphere response to wind stress forcing over the North Pacific is studied with a series of coupled ocean-atmosphere GCM simulations. In the model, a wind stress anomaly is imposed over the North Pacific, which is different from the traditional approaches with prescribed ocean temperature anomaly or heat transport. A cyclonic wind stress anomaly over the interior ocean can force cooling in the western North and tropical Pacific. The atmospheric response over the midlatitude North Pacific displays a distinctive seasonality with a low pressure in winter and high-pressure anomaly in summer. This response is modulated by the tropical response. Without tropics, the extratropical North Pacific atmospheric response is dominated by high-pressure anomaly.

Ocean frontal effects on the atmosphere: A synthesis of observations and models

Shang-Ping Xie, Youichi Tanimoto, Hiroki Tokinaga, Hisashi Nakamura, Fumiaki Kobashi, and Bunmei Taguchi

Ocean western boundary currents and their open-ocean extensions are where subsurface ocean processes exert strong influences on sea surface temperature (SST). Recent studies show ubiquitous response of the surface atmosphere to sharp SST fronts along major ocean currents but it remains unclear whether such atmospheric signatures are confined to the planetary boundary layer (PBL). Here we attempt to synthesize recent observations and modeling results on ocean frontal effects on the atmosphere, both in and above the PBL. We will draw results from recent field experiments such as KESS.

During the CLIVAR Kuroshio Extension System Study (KESS), ship-board atmospheric soundings were carried out with GPS sondes and a laser ceilometer. The presence of ocean fronts intensifies thermal advection in the PBL by atmospheric disturbances, with sharp transitions observed across the Kuroshio Extension (KE) front in the PBL and its clouds. In early summer, sea fog frequently occurs on the northern flank of the subtropical KE, and subarctic fronts under southerly warm advection that suppresses surface heat flux and stabilizes the surface atmosphere. Sea fog is infrequently observed over the KE front even southerly conditions as the warm ocean current weakens atmospheric stratification and promotes vertical mixing. The ocean's influence appears to extend beyond the PBL, with the cloud top higher along the KE front than the surroundings during both summer and winter.

Observational and modeling evidence is emerging for deep atmospheric effects of ocean fronts in the mean state. They appear to be accomplished by the following adjustments. A sharp SST front intensifies surface evaporation and surface wind convergence on the warmer flank, anchoring a narrow rain band as seen most clearly along the Gulf Stream. The SST front also maintains a baroclinic zone that anchors the atmospheric storm track. The latter effect on the position and intensity of storm tracks has been demonstrated by model experiments under idealized and realistic conditions. This effect appears to be at work along the subtropical countercurrent, a feature produced by mode water ventilation in the North Pacific.

Frontal waves along the Kuroshio Extension and formation of distinctive salinity minimum

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Abstract

Intensive observations along the Kuroshio Extension revealed the development of frontal waves with the wavelength of about 200km propagating in the downstream direction with the speed of 0.2-0.3m/s. This frontal waves were accompanied by low-salinity Oyashio water intrusion in the intermediate layer from the upper-layer wave crest to trough, forming distinctive salinity minimum. The wave phase in the upper-layer precedes 1/4 wavelenth the intermediate layer. These wave structures are well explained through linear stability analysis as baroclinically unstable waves where upper and intermediate waves are coupled.

The Nonlinear Connection Between Labrador Sea Buoyancy Loss, Deep Western Boundary Current Strength, and Gulf Stream Path in an OGCM.

Stephen Yeager

Bulk flux forcing based on historical meteorological records together with a prognostic sea ice model results in notable improvements in the North Atlantic circulation of a non-eddy resolving ocean general circulation model when compared to an equivalent simulation with prescribed sea ice. High latitude diapycnal surface fluxes in winter are highly sensitive to the treatment of sea ice; much greater surface transformation to higher density classes is seen in the coupled ocean-ice configuration than when sea ice extent is prescribed from observations. Enhanced surface production of dense Labrador Sea water results in stronger western boundary currents, a more vigorous Northern Recirculation Gyre, a stronger North Atlantic current, and bias reduction east of the Grand Banks of Newfoundland.

The initial divergence of the solutions arises from the different thermohaline flux exhange between the ocean and cryosphere, which is more physical with a prognostic sea ice model, and is amplified by circulation feedbacks associated with the mixed surface boundary conditions. Comparison with observed fluxes shows that all experiments are characterized by excessive surface water mass transformation associated with warm, salty subpolar conditions. With sufficient surface salinity restoring, high latitude biases in temperature, salinity, ice edge, and diapycnal surface transformation are reduced, but improvements in North Atlantic circulation are lost and interannual variability is severely damped.