Final Report

Title: **North Pacific Mesoscale Coupled Air-Ocean Simulations Compared with Observations**

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1. Introduction

a) The overall objective of this project.

The overall objective of this study was to improve the representation of regional ocean circulation in the North Pacific by using high resolution atmospheric forcing that accurately represents mesoscale processes in ocean-atmosphere regional (North Pacific) model configuration. The goal was to assess the importance of accurate representation of mesoscale processes in the atmosphere and the ocean on large scale circulation. This is an important question, as mesoscale processes in the atmosphere which are resolved by the high resolution mesoscale atmospheric models such as Weather Research and Forecasting (WRF), are absent in commonly used atmospheric forcing such as CORE forcing, employed in e.g. the Community Climate System Model (CCSM).

We identified several mesoscale and large scale processes in the atmosphere and the ocean that haven't been emphasized before, which are playing an important role in air-sea heat exchange in the western Pacific, in the Kuroshio Extension (KE) region, which is one of the regions of strongest air-sea heat exchange in the world. Particularly strong air-sea heat exchange is in winter during outbreaks of very cold and very dry air from Asian continent into west Pacific, inducing extremely strong air-sea heat and moisture fluxes (Dorman et al., 2004). The novel result is that the ocean heat loss induced by CAOs is significantly amplified by advection from meso-cyclones forming on the southern part of the Japan Sea (Koracin et al., in preparation). Strong ocean heat loss to the atmosphere triggers strong convection in the upper ocean creating a large pool of nearly homogenized water on the equatorward side of the KE, called the North Pacific SubTropical Mode Water (NPSTMW). Individual cold air outbreak (CAO) can change MW volume by 10%, thus significantly altering the heat content of the upper ocean (Jensen et al., 2011). We analyzed processes playing an important role in formation and destruction of NPSTMW both in high resolution ocean model simulation and in the observations (Argo). Both show that change in stratification associated with changes in Pacific Decadal Oscillation (PDO) significantly affects potential vorticity (PV) distribution in the mode water low PV pool. When the PDO index is negative, westward propagating sea surface height (SSH) anomalies (Qiu and Chen, 2005) are accompanied by positive PV anomalies, which increase PV in the NPSTMW low PV pool. Consequently, some of the water in the NPSTMW low PV pool ceases to satisfy the low PV criteria, and the volume of NPSTMW decreases (Cerovečki and Giglio, submitted). At the same time volume decrease of the isopycnal layer containing NPSTMW is much more modest.

b) Scientific results.

Here we outline the main scientific questions addressed as part of this project. More details on each of them is provided in text below, Sections 2-7.

- We simulated and analyzed a case study of a severe CAO event in January 2000 using the results of the 0.1º WRF model, identified a new efficient mechanism of ocean heat loss by advection from meso-cyclones forming on the southern part of the Japan Sea. We compared WRF model results with the observations. More detail is given in ***Section 2***. This work was presented in a talk at AGU, San Francisco 2012, and at a seminar at New Mexico Institute of Mining and Technology, Socorro, NM, April 2012. A manuscript summarizing these results (Koracin et al., in preparation) is largely finished.

- The effects of the CAO in January 2000 on the upper ocean were studied in two 0.1º Parallel Ocean Program (POP) model simulations, both carried out within the Community Earth System Model (CESM) framework. In one simulation atmospheric state was represented by results of a high resolution (0.6º) WRF simulation for years 2000 – 2002. These "POP+WRF" results were compared to the results of a POP simulation for the same time period (2000-2002) forced with interannually varying CORE forcing (IAF-CORE). While IAF-CORE forcing is part of the CESM framework, the WRF model is not, thus forcing the POP model with WRF fields within CESM framework required a great deal of model development. Model development efforts are described below in ***Section 1c***. One of the most important differences between these two runs is highlighted in ***Section 3.***

- The work on air-sea interaction was extended to the effects of marine fog on air-sea interaction. The ship observations showed that the marine world's highest deep fog occurrence is in the North West Pacific due to the interaction of the Kuroshio – Ohyashio current system in June-July-August. This work describes a link between the Kuroshio and deep fog in the NW Pacific and marginal seas. The results are written up by Dorman et al. in Chapter 2.3 of the book on marine fog, edited by Koracin and Dorman (2014), the first draft was submitted to Springer Verlag. More detail in ***Section 4***.

- To have a better understanding of physical processes important for strong atmosphere-ocean interaction in the KE region, which should be accurately simulated in order to accurately represent oceanic circulation and climate, we carried out and analyzed a POP model simulation using IA-CORE forcing for 1995-2005 within CESM framework. The main feature of this model simulation was a dramatic decrease in volume of the NPSTMW at the end of a decade (***Section 5***).

- Can such a dramatic decrease of the NPSTMW volume, significantly changing the stratification and the heat content of the upper ocean also be identified in the observations? The decrease of the NPSTMW, typically at the end of a decade, has been noted before in model results (Davis et al., 2011), and a limited set of observations (Qiu et Chen, 2006), but not in an extensive observational data set such as Argo. We thus analyzed Argo data for 2005 – 2012 with the goal to identify physical mechanisms at play in the dramatic decrease of the NPSTMW volume observed in 2007-2009, Cerovečki and Giglio, submitted. (***Section 6)***.

- The frequency-wavenumber spectra of the two three-year long simulations "POP+WRF" and "POP+CORE" are compared,as described in in ***Section7.***

c) Model development.

One of main modeling objectives of this project was to develop a state-of-the-art Regional Ocean-Atmosphere Climate System Model to perform high-resolution simulations using Parallel Ocean Program (POP) ocean model and WRF model as an atmospheric component. While the POP model is a standard ocean component of the global climate models (e.g., the Community Climate System Model (CCSM) and the Community Earth System Model (CESM)), WRF is not part of the standard, publically available CCSM or CESM setup. Yet WRF is state-of the art mesoscale atmospheric model, thus most suitable atmospheric model for regional modeling.

We separately configured regional (North Pacific) setup of POP model (by the Scripps team) and regional (North Pacific) setup of WRF model (by the DRI team) as independent stand-alone model components. North Pacific 0.1° POP is configured from a "sector" of the global tripole grid with 42 vertical levels and partial bottom cells used by Maltrud et al. (2009). Dr. M. Maltrud provided invaluable help with this setup. Both POP and WRF models were successfully used to obtain high resolution (0.1º POP and 0.6º and 0.1º WRF) model simulations. The simulations were performed at the National Energy Research Scientific Computing Center at Lawrence Berkeley National Laboratory.

In the next step we coupled POP and WRF models within CESM framework. Dr. W. Maslowski, Principal Investigator of "The Regional Arctic Climate Model (RACM)" project (Higgins et al., 2011; Maslowski et al., 2011), provided invaluable help and guidance in coupling WRF and POP. This work started using Community Climate System Model (CCSM4), but was switched to a more recent Community Earth System Model (CESM1.1) when it became available. We thus modified the CESM code in parallel to NCAR model development efforts, and Dr. A. Craig provided invaluable help.

We adapted the CESM flux coupling architecture CPL7 (Craig et al., 2011) for our specific regional domain as well as WRF and POP model component configurations. This was a significant model development effort as CPL7 software was originally developed for coupling the global Community Atmospheric Model (CAM), and not WRF, with POP model. Both WRF and POP use different grid resolutions, projections, and domains, which made developing the coupled regional system a significant effort. On oceanic/Scripps side we successfully forced POP model with WRF output fields within CESM framework using Coupler 7. On atmospheric/DRI side task was more complex because WRF is not a standard component of CESM, thus requiring further development of appropriate coupling schemes. Dr. A. Craig provided guidance and information on how to change the data Atmosphere in CESM to convert WRF fields for ingestion into CESM. Despite having some direct collaboration with CCSM/CESM developers, several difficulties were encountered. The biggest one was that because the WRF model is not standard part of CESM, but only incorporated for reseach purposes (e.g. Maslowski et al., 2011), many of its integrated model components have not been tested for functionality and at that time were still undergoing development and evaluations. Secondly, most of the input data and grid configurations are not easily adaptable to special cases such as ours. All cases available use a separate Land Surface Model (LSM) component, the Community Land Model (CLM) version 3.5, which requires additional expertise for adaptation, which was beyond our expertise. We looked for guidance on adapting this component to our North Pacific regional configuration, but with little success since LSM component was very much under development at the time we were developing coupling system. The WRF-CLM configuration itself required an additional grid configuration as well as an additional parameters for its setup.

Because the CESM framework was still under development, DRI team started producing our own coupling configuration. They created a coupling system that halts and synchronizes WRF and POP simulation times, exchanges information accordingly every coupling time step (~3 hours), and balances surface heat fluxes using the regional domain configuration. These configurations provide easier coupling than coupling within CESM, since WRF configurations can be changed without affecting POP setup and other configurations. This coupler development handles all communications, performs interpolations between the different grids. One months test fully coupled simulation has been obtained.

We believe that our model development efforts will facilitate focused regional studies to resolve the role of small (meso) scale critical details of the KE region and its effect on extratropical storm tracks by improved representation of feedbacks and local physical processes.

2. Ocean-to-Atmosphere interaction over the KE during winter cold air outbreaks (CAO). Large scale synoptic patterns with anomalously strong anticyclone over Siberia and Mongolia, deep Aleutian Low, and the Pacific subtropical ridge are crucial for the development of an CAO. Analyzing WRF model results and the observations we found that the onset of the CAO is related to the breaking of atmospheric Rossby waves and vertical transport of vorticity that facilitates meridional advection (Koracin et al., in preparation). The comparison with the observations revealed that intrinsic parameterization of the surface fluxes within the WRF model needs more evaluation and analysis.

The main novel result of this work is that the ocean heat loss induced by CAOs is significantly amplified by advection from meso-cyclones forming on the southern part of the Japan Sea. Thus strong wintertime ocean heat loss in the North Pacific is not simply due to a CAO, as commonly described. Instead, as a surface atmospheric low moves to the E/NE near Japan and then far to the East of Japan, the western portion of the low pulls colder air from the north across the Kuroshio SST gradient, resulting in large heat loss for a period of a few days. It is thus possible to have appreciable heat losses over the Kuroshio extension that are not directly associated with winter winds from Siberia that are part of an CAO.

3. The comparison of the simulation of the CAO in January 2000 in two model simulations, "POP+WRF" and "POP+CORE". The most interesting result of this study is that POP+WRF successfully captures and represents atmospheric mesoscale cyclones that have been identified in our study described in Section 2 as an efficient but until now overlooked mechanism of ocean heat loss, while POP+CORE fails to represent this feature (Fig. 1).

Koracin et al., in preparation, describes: on JAN 23 dominant southwesterly flow over the Japan Sea retreats to the south due to encroachment of the stronger northerly and northwesterly flow, which intensifies and extends over the islands of Japan and the KE region. This interaction forms flow convergence zones that extends to the southeast. The northerly and northwesterly flow over the Japan Sea becomes blocked and channeled by the Korean Peninsula's coastal mountains and attains a cyclonic rotation near the gap between the southern tip of Korea and Japan.

During this event, the rotation resulted in formation of transient mesocyclones which travel from the southern side of the Japan Sea eastward over Japan and the KE region. Additional convergence is generated due to the interaction of the outbreak advection (north and northwesterly) with the southwesterly flow from the subtropical ridge in the southern Pacific. Consequently, two mechanisms are at work during the CAO – the straightforward northerly and northwesterly advection of cold continental air and the additional southwesterly and westerly transport by poleward mesocyclones. QuikSCAT wind fields also reveal convergence zones and formation and evolution of the transient mesoscyclones.

Over the Japan Sea, sensible fluxes calculated using atmospheric observations from a buoy were in excess of 1000 Wm^{-2}, while the WRF model parameterizations yielded a maximum of 400 W m^{-2}. Buoy latent heat fluxes approached 1000 W m^{-2} while the WRF modeled fluxes again reached a maximum of 400 W m^{-2}. However, in "POP+WRF", using WRF atmospheric variables, combined with POP sea surface temperature as input in POP bulk formulae, the net air-sea heat flux is much closer to the observations, up to 800 W m^{-2}, whereas the net air-sea heat flux estimated by POP+CORE is significantly lower.

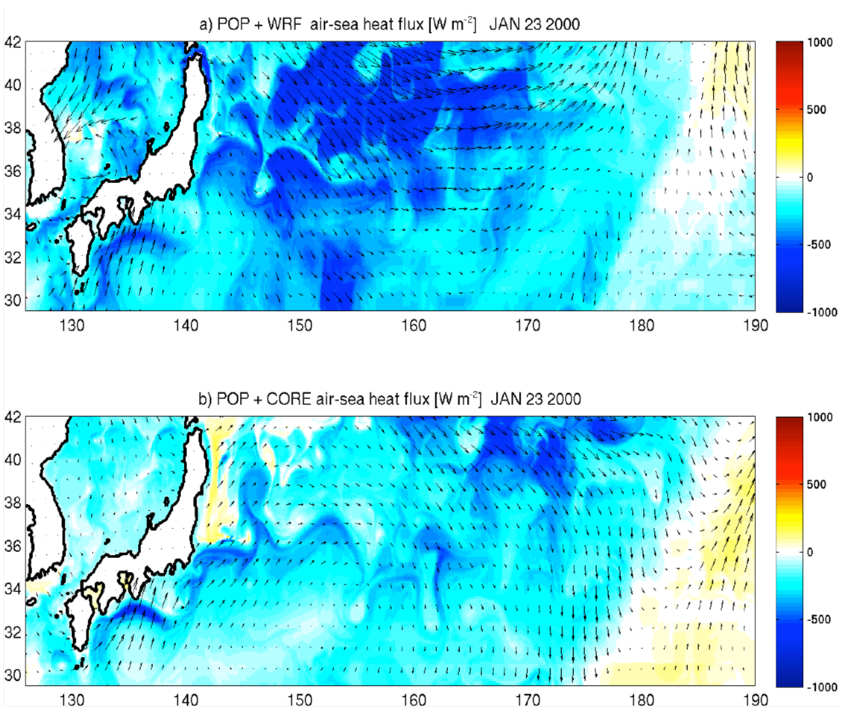

FIG. 1. Daily snapshot of the net air-sea heat flux (color) and wind stress vectors on JAN 23 2000, during a CAO for (a) POP+WRF and (b) POP+CORE. While POP+WRF accurately simulates mesoscale cyclone centered at approximately 37° N, 130°E, the cyclone is not captured by POP+CORE. POP+WRF net air sea heat flux estimate is much closer to the estimates obtained using observations from two buoys in Japan Sea and south of Japan than POP+CORE, although both use the same bulk formulae.

4. Marine Fog in the Northwest Pacific. While carrying out the work on air-sea interaction in the North Pacific, we examined closely related aspects of air sea interactions, such as the marine fog. The analysis of ICOADS ship weather observations revealed a link between the Kuroshio and deep fog in the NW Pacific and marginal seas. These results showed that the marine world's highest deep fog occurrence is in the NW Pacific and is due to the interaction of the Kuroshio – Ohyashio current system in June-July-August, as described in Koracin and Dorman (2014).

The marine world's highest deep fog occurrence is in the NW Pacific and is due to the interaction of the Kuroshio – Ohyashio current system in June-July-August. Mean poleward surface air is hydrated and warmed over the Kuroshio, and then moves over a generally negative SST gradient to form a deep fog occurrence maximum centered over the Kuril Island chain between Hokkaido and Kamchatka. This deep fog maximum disappears during winter when the mean air flow is cold and dry, Koracin and Dorman (2014).

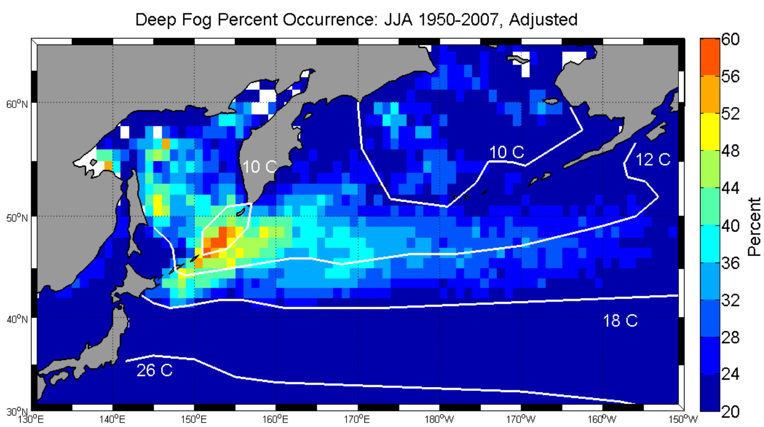

Figure 2. JJA observed percentage of deep fog observations in each 1° square from NW Pacific, averaged for 1950-2007 from ship observations. Three SST isotherms averaged for the same period are in white.

5. Interannual NPSTMW variability in the model KE. We analyzed the results of 0.1° POP model simulation forced by IAF-CORE forcing for years 1995 - 2005.

The NPSTMW region is characterized by energetic variability on a broad range of time scales. One manifestation of this variability, shown in Fig. 3 is a strong variability of the NPSTMW volume. The upper plot employs a rather restrictive definition of NPSTMW, while the lower employs a looser characterization. Both show a dramatic NPSTMW volume decrease in 1999. Which physical process play an important role in this variability is still an open question. In particular the role of atmospheric and oceanic variability in generating the large NPSTMW volume variability is still not clear.

We have shown that the interannual variability in surface NPSTMW formation contributes, but does not by itself explain the observed strong variability in low PV NPSTMW volume. We therefore considered other processes that might have contributed to such a large observed volume change of low PV NPSTMW volume: variations in the NPSTMW outcrop area, variations in the buoyancy flux averaged over the outcrop area, and variations in outcrop latitude. The most important conclusion is that interannual variations in buoyancy flux have greater influence on interannual variability in water mass transformation than do interannual variations in outcrop area.

The various elements of local and remote atmospheric forcing also interact with intrinsic variability of KE and NPSTMW. Qui and Chen (2005) suggested that the KE is destabilized by the arrival of first mode baroclinic waves generated in the central Pacific Ocean three years earlier by a PDO related wind stress anomaly.

Novel result is that during 1995-1999 negative SSH anomaly propagated westward, yielding PV increase, so that some water in the NPSTMW low PV pool ceased to satisfy the low PV requirement and the volume of NPSTMW decreased. This highlights the importance of the PV constraint in identifying the mode water, a point emphasized by Deremble and Dewar (2013), as our results show that the pool constrained by PV nearly vanishes in mid decade whereas the total amount of water in the defining density range decreases more modestly. One cannot understand the evolution of the pool from a density budget alone, without simultaneously considering the PV budget.

We are finishing up the manuscript summarizing these results (Cerovečki et al., in preparation).

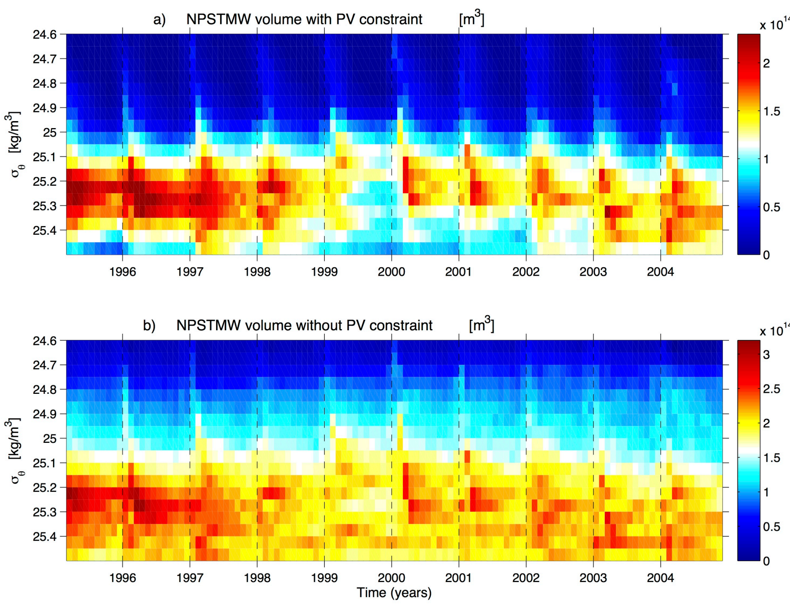

FIG. 3. Monthly averaged NPSTMW volume (m^3) in POP North Pacific ocean model simulation for the years 1995-2004 in the NPSTMW region (20°-40°N, 125°E-160°W, east of Japan) as function of the potential density and time with (a) the imposed constraint PV< 2 x 10^{-10} /(m-s) and (b) without the imposed low PV constraint.

6. Observational (Argo) study of North Pacific SubTropical Mode Water (NPSTMW) in the KE. Summary of these results, as given in the abstract of Cerovečki and Giglio, submitted, is given below.

"Analysis of monthly averaged temperature and salinity observations from Argo profiling floats, on 0.5º x 0.5º grid, for the 2005 - 2012 period shows a strong North Pacific Subtropical Mode Water (NPSTMW) volume and density decrease in years 2007 – 2009, due to the upper ocean temperature and stratification increase, causing some water that was initially in the NSTMW density range to be transformed in lighter water, while the increase in upper ocean stratification increased potential vorticity (PV) in the NPSTMW low PV pool, so that volume of water satisfying the low PV criteria decreased.

During the time when KE jet was in unstable state 2006 – 2009, mixing with high PV water poleward of Kuroshio Extension (KE) jet additionally increased PV, destroying the homogeneous low PV in the entire density range 25.0-25.5 σ_θ. Only lighter variety of NPSTMW (approximately < 25.3 σ_θ) was replenished by formation by air-sea buoyancy fluxes, so that both volume and density of the NPSTMW pool decreased reaching a minimum in 2009.

The upper ocean temperature and stratification increase in the NPSTMW formation region is linked to the shift in the PDO from neutral to a negative phase starting in 2007 and lasting until 2009, followed by westward propagating anomalously high upper ocean heat storage in the western Pacific. As the water density in the pool decreased, lighter isopycnals outcrop on the equatorward side of the KE jet, resulting in surface formation of water lighter than water formed either before (2005 – 2006) or after (2010 – 2012)."

The NPSTMW volume minimum, occurring in 2009, is shown in Fig. 4a. The volume and density decrease in the same region and isopycnal range, but without the PV constraint is not nearly as dramatic (Fig. 4b), very similar to our model results shown in Fig. 3., again highlighting the importance of the PV constraint in identifying the mode water (a point emphasized recently by Deremble and Dewar, 2013).

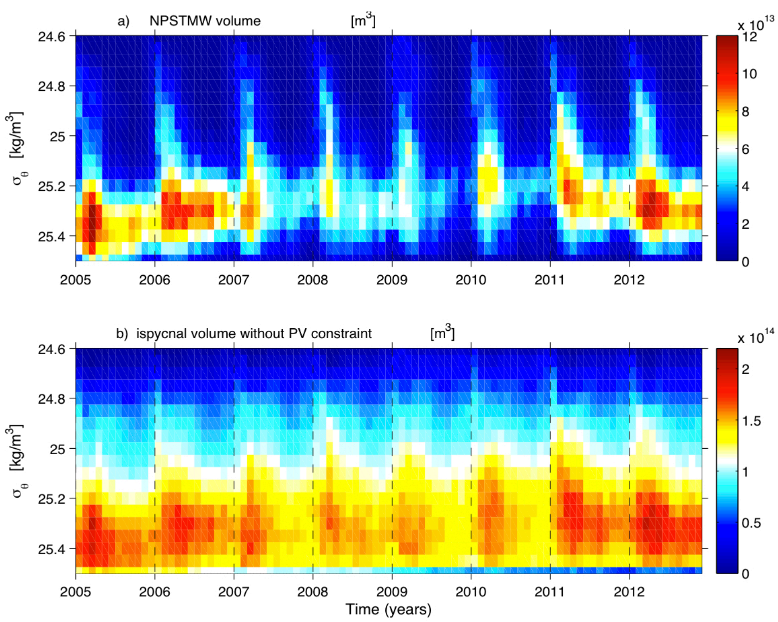

FIG. 4. Monthly averaged NPSTMW volume (m^3) estimated from gridded Argo data for 2005-2012 (a) with and (b) without PV < 2 x 10^{-10} /(m-s) constraint. Both for the region 20°-40°N, 125°E-160°W, east of Japan.

Although an eight year long observational record certainly does not allow us to address the question of decadal variability, it provided a case study to diagnose and describe physical processes that are playing an important role in changing the NPSTW volume and properties during these eight years, which span both the unstable (2006-2009) and stable (2002-2005, 2010) KE dynamical state (e.g. Oka and Qiu, 2012).

This study clearly revealed the need to separate forced and intrinsic North Pacific variability to examine and fully understand processes such as dramatic decrease of the NPSTMW from 2007 to 2011.

7. The comparison of the wavenumber frequency spectra of sea surface height in in two model simulations, POP+WRF and POP+CORE. Both climate models and eddy resolving ocean models often use coarse resolution atmospheric forcing fields such as CORE, which do not resolve mesoscale atmospheric processes. One of the questions we wanted to address is to which degree resolving the atmospheric mesoscale structures influences the oceanic response, both at large- and mesoscales. To address this question, we analyzed the two numerical simulations, one forced by the low-resolution atmospheric forcing (CORE) and the other by a high-resolution atmospheric forcing (WRF). The sea surface height (SSH) from the two simulations were analyzed and compared.

Fig. 5 shows the time-mean SSH from the two simulations. The large-scale patterns of time-mean SSH from the two simulations are roughly the same: SSH is high in the subtropical gyre, low in the subpolar gyre, separated by a strong KE front. The magnitude of the time-mean SSH is also roughly the same in the two simulations. To compare eddies, defined as the deviation from the time mean, we examined the frequency-wavenumber spectra of SSH in four selected regions (Fig. 5). Region 1 includes location of mooring arrays in the KESS experiment; Region 2 is at the downstream part of the KE; Region 3 and Region 4 are located in the eastern quiescent part of the gyre, in the low (3) and mid- (4) latitudes. These four regions have been chosen to contrast the oceanic response in the energetic versus quiescent regions and in low-latitude versus mid-latitudes.

The frequency-wavenumber spectra of SSH in the four selected regions is shown in Fig. 6. The overall structures of spectra from two model simulations are roughly the same (left and midcolumns of Fig. 6): the spectra in the KE region (Regions 1 and 2) is more isotropic compared to the quiescent areas (Regions 3 and 4). In Region 3 and 4, dominant energy is on two lines: one is around k=0 and the other is tilted representing the westward propagating eddies.

On the other hand, it is striking that the spectra values in the two numerical simulations are different in almost the entire available frequency-wavenumber space here (right column in Fig.6). In Region 3, more energy is at high frequencies in the POP+WRF simulation compared to the POP+CORE (Fig. 6c3).

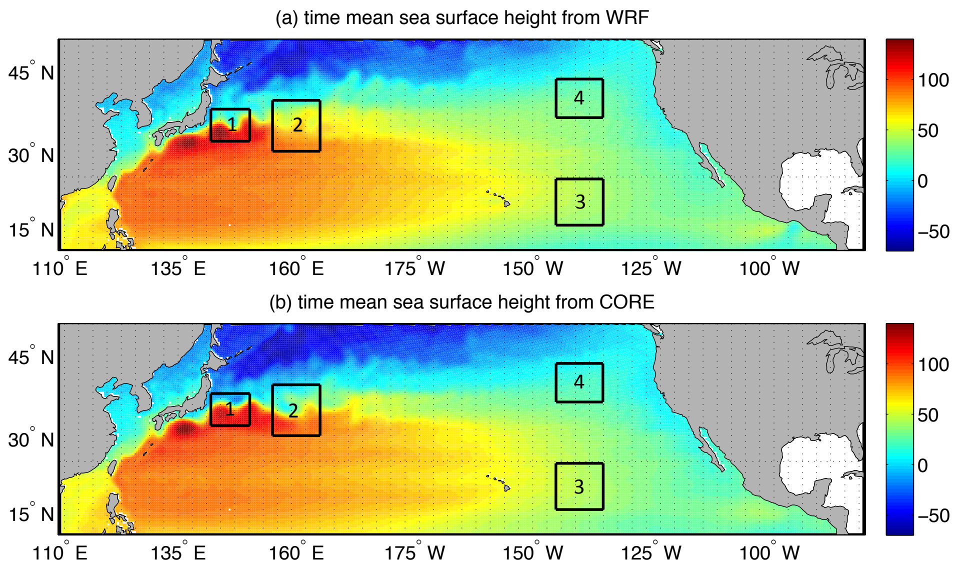

Figure 5: The temporal average of SSH (cm) over the year 2000-2002 in the (a) POP+WRF and the (b) POP+CORE. Black boxes show the four regions for which the spectral analysis was carried out. Region 1 has 83 (65) grids in the zonal/meridional direction. The other three regions have 101 grids in both zonal and meridional directions.

The WRF forcing has more energy at high-frequencies. This high-frequency atmospheric forcing probably predominantly excites the high-frequency, not low-frequency oceanic motions in Region 3, as this low-latitude quiescent area is approximately linear. Region 4 is at a higher latitude than Region 3, and oceanic motions are thus more nonlinear. In this region, the POP+WRF simulation is more energetic only at some high-frequency areas (Fig. 6d4). We hypothesize that this is because the atmospheric input at high frequencies is transferred to some low-frequency oceanic motions through energy cascades in the frequency domain in Region 4. The model difference is more striking in the highly nonlinear KE region, where eddies are mostly generated through baroclinic and barotropic instabilities, not from atmospheric forcing (Figs. 6a3, ab3). In the upstream Kuroshio Though the difference between the two spectra is complicated, varying from region to region. One key feature is that the differences are large and they are prevalent in the entire available frequency-wavenumber space. This suggests that using high resolution atmospheric forcing may increase ocean model fidelity not only at meso-scales, but also at large scales.

These results are still preliminary. To examine the effect of mesoscale atmospheric processes on the ocean response, we will analyze kurtosis and skewness of SSH, the 1-D, 2-D and 3-D SSH spectra. The SSH statistics from the POP+CORE and POP+WRF will be compared to the altimetry to identify the source of the differences. These result may also shed some light on the limitations of altimetric observations due to their course spatial and temporal resolution.

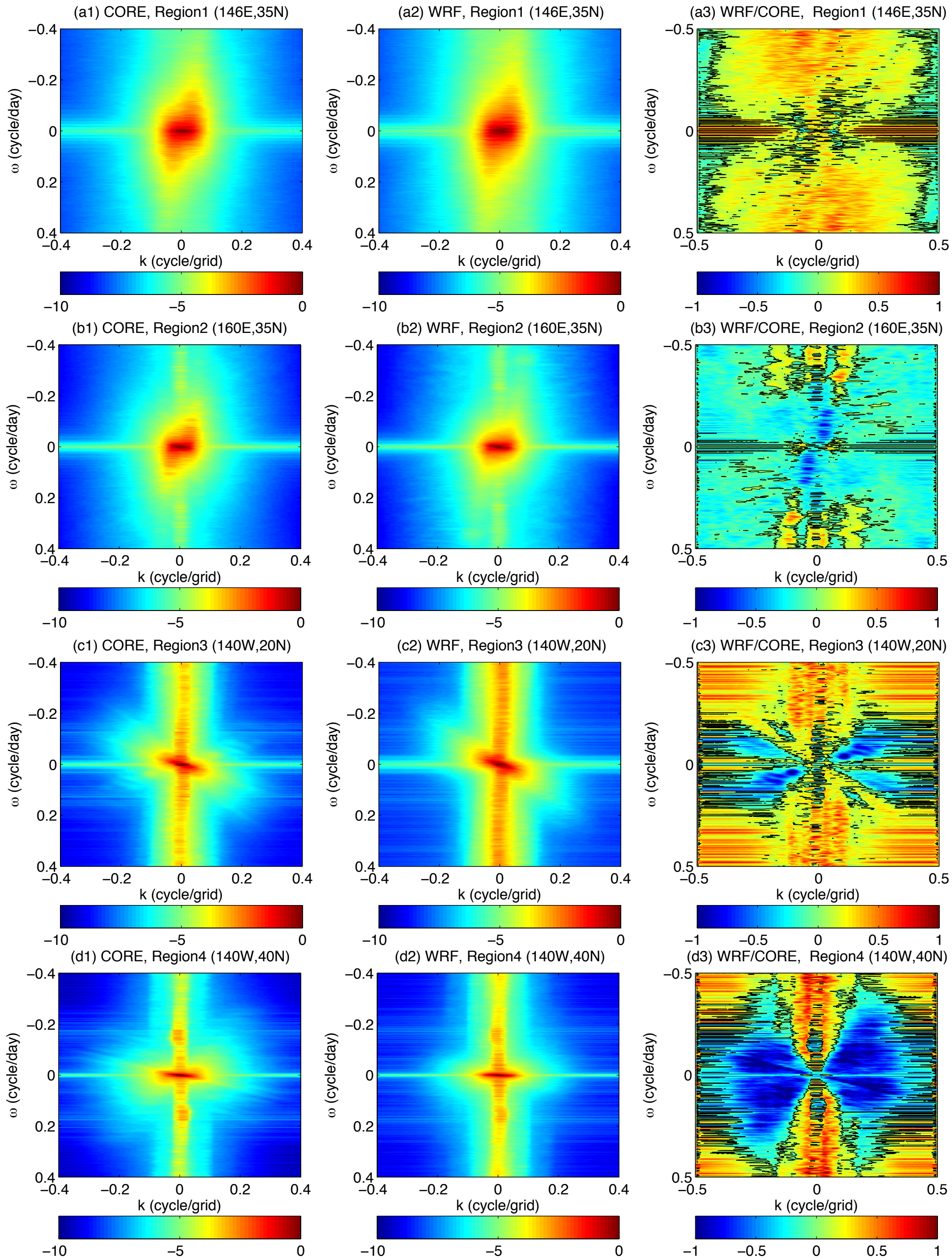

Figure 6: We use S_{WRF} and S_{CORE} to denote the omega-k spectra of SSH during years 2000-2002 from POP+WRF and POP CORE model simulation. Here ω is frequency and k is the zonal direction defined by model grid. To obtain the spectra, we remove the time-mean and spatial-mean of SSH, and then use a Hanning window before carrying out the Fourier transform. Left column: the normalized S_{WRF} in the selected four regions. Mid column: the normalized S_{CORE} in the selected four regions. Right column: black lines represent the zero contour and the color shows the base 10 logarithmic of the ratio S_{WRF}/S_{CORE}. Thus, in the area with negative values, $S_{WRF} < S_{CORE}$ and in the area with positive values, $S_{WRF} > S_{CORE}$.

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1. Cerovecki, I., and J. McClean: Modification of Air-Sea Heat Fluxes by Ocean Eddies in the North Pacific. U.S. CLIVAR Western Boundary Current Workshop, Phoenix, AZ, 2009. POSTER

2. Cerovecki, I., and J. McClean: Mesoscale eddy processes in North Pacific Subtropical Mode Water formation. CLIVAR Working Group on Ocean Model Development: Workshop on Ocean Mesoscale Eddies, UK Met Office Hadley Center, Exeter, UK, 2009. POSTER

3. Cerovecki, I., and J. McClean: Mesoscale eddy processes in North Pacific Subtropical Mode Water formation. 14th Annual Community Climate System Model Workshop, Breckenridge, CO, 2009. POSTER

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