Future Projection of Wave Climate by Multi-SST and Multi-Physics Ensemble Experiments

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1 Introduction

Concerns about impact of long-term change in oceanographic phenomena related with climate change, have been increasing. Changes in ocean surface gravity waves (denoted as waves hereafter) produce impacts on variety fields. Waves is one of key components of beach morphology (Short, 1999), and wave energy can be promising as renewable energy source (Cruz, 2008). Actually, impact of long term variability or change in wave climate on shoreline (Kuriyama et al., 2012) and wave energy (Sasaki, 2012) has been reported based on in situ observations. Furthermore, sea level extreme (inundation) has occurred across the western tropical Pacific which were caused by waves and recent accelerated sea level rise contributed to the severity of the impact (Hoeke et al., 2013).

In order to assess the future change in wave climate, several future projections of global wave climate have been conducted (Wang and Swail, 2006; Mori et al., 2010; Dobrynin et al., 2012; Hemer et al., 2012; Fan et al., 2013; Semedo et al., 2013). Consequently, multi-model ensemble projection of global wave climate has been carried out in the Coordinated Ocean Wave Climate Project (COWCLIP, Hemer et al., 2013), based on the results of independent five studies (Wang and Swail, 2006; Mori et al., 2010; Hemer et al., 2012; Fan et al., 2013; Semedo et al., 2013), showing the consistent future change in wave climate among models, such as future increase in wave height over the Southern Ocean and decrease in wave height at subtropics. However, there is small discussion of cause of variation in wave climate projections across models. Confidence in model projection does not come from the sheer amount of data (Knutti et al., 2013). It is necessary for more reliable projection to take scientific insight to the variation in projections across models.

General approach of dynamical wave projection (used in Mori et al., 2010, Hemer et al.,

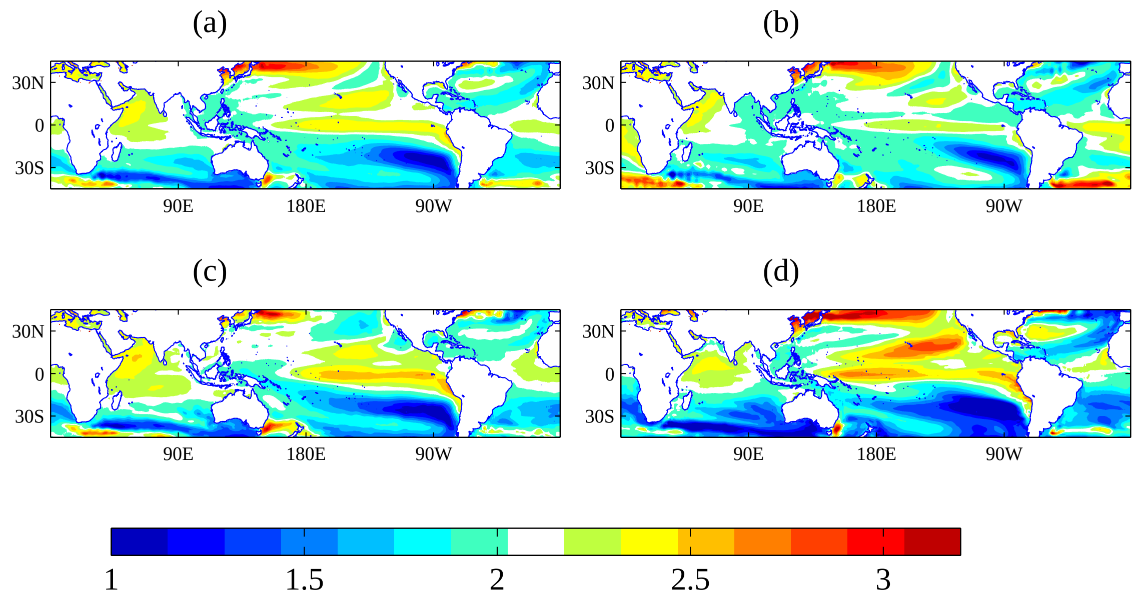

Figure 1: Future changes in SST for (a) cluster 0, (b) cluster 1, (c) cluster 2 and (d) cluster 3. (unit: K)

2012, Fan et al., 2013, Semedo et al., 2013, hereafter MO10, HE12, FA13, SE13, respectively) can be described simply as follow. (1) Global climate simulation by Atmosphere-Ocean Coupled Global Climate Model (AOGCM) under emission scenario, (2) Atmospheric climate simulation by Atmospheric GCM (AGCM) using Sea Surface Temperature (SST) data of AOGCM as boundary condition, (3) Global wave simulation by wave model forced by sea surface wind of AGCM. At level of (2), previous studies used arbitrary model's SST or multi-model ensemble SST. The choice of SST as boundary condition can lead to fundamental variation of wave climate projection. Therefore, it is important to estimate the variation in wave climate projection originating from different SST conditions. Even if AOGCM is used as input for wave climate projection (Dobrynin et al., 2012), analysis with SST is important because SST gives major impact on global climate. The objectives of this study are to conduct wave climate projection, and estimate the variation by changing SST with single AGCM. Finally, the results are compared with COWCLIP results (MO10, HE12, FA13 and SE13. Wang and Swail (2006) is not included because it is based on statistical approach). HE12 and FA13 have 2 members each changing SST forcing (HE12(1),(2) and FA13(1),(2), hereafter).

2 Methodology

2.1 Atmospheric climate projection

The AGCM used in this study is the Meteorological Research Institute Atmospheric General Circulation Model version 3.2 (MRI-AGCM3.2; Mizuta et al., 2012). The spatial resolution is 60km. Time slice experiments are conducted, referring to simulated climate under observed condition as present climate, and global warming condition as future climate. Period of present climate is defined as 1979 to 2009 and that of future climate is 2075 to 2099. Lower boundary condition of MRI-AGCM in the present climate is monthly mean observed sea ice concentration and SST of Hadley Centre Global Sea Ice and Sea Surface Temperature dataset (HadISST1; Rayner et al. 2003). As for future climate, four future climate simulations are forced by four different SST future change patterns (Murakami et al., 2012). One of the SST patterns is ensemble mean SST projected by 18 models of Coupled Model Intercomparison Project Phase 3 (CMIP3; Meehl et al., 2007), under the Special Report on Emission Scenarios A1B scenario. The others are three clustered future SST derived from 18 CMIP3 models, applying cluster analysis to future change pattern of SST in tropical area (30°S to 30°N). The detail of the clustering method is described in Murakami et al. (2012). Interannual variation of SST in future climate is same as that of present climate. Four different SSTs are denoted as cluster 0 to 3, and **Figure** 1 shows future changes in SST of cluster 0 to 3. All the clusters show that SST increase at almost the entire ocean up to about 3 ℃ and the increase at the North Pacific is higher than the other area. Warming at the tropical Pacific of cluster 3 is the highest and cluster 1 is the lowest in the clusters. Warming at the tropical Indian Ocean of cluster 2 is the highest. The spatial standard deviations of warming at tropical area (30°S to 30°N) are 0.24, 0.21, 0.27, 0.38 ℃ for cluster 0 to 3, respectively.

In addition, multi-physics ensemble simulations are conducted with three different cumulus convection schemes (denoted as YS, AS and KF, see Murakami et al., 2012).

2.2 Wave climate projection

Global wave climate projection is carried out by WAVEWATCH III version 3.14 (Tolman, 2009), forced by surface wind of MRI-AGCM 3.2. Global domain is latitudes 90°S-67°N and entire longitudes with $1° \times 1°$ grids. Directional resolution is 15° and frequency space is 0.04 to 0.5 Hz which is discretized 25 increments logarithmically. WAVEWATCH III can represent unresolved islands (Tolman, 2009). WAVEWATCH III is implemented with the basic parameterization and

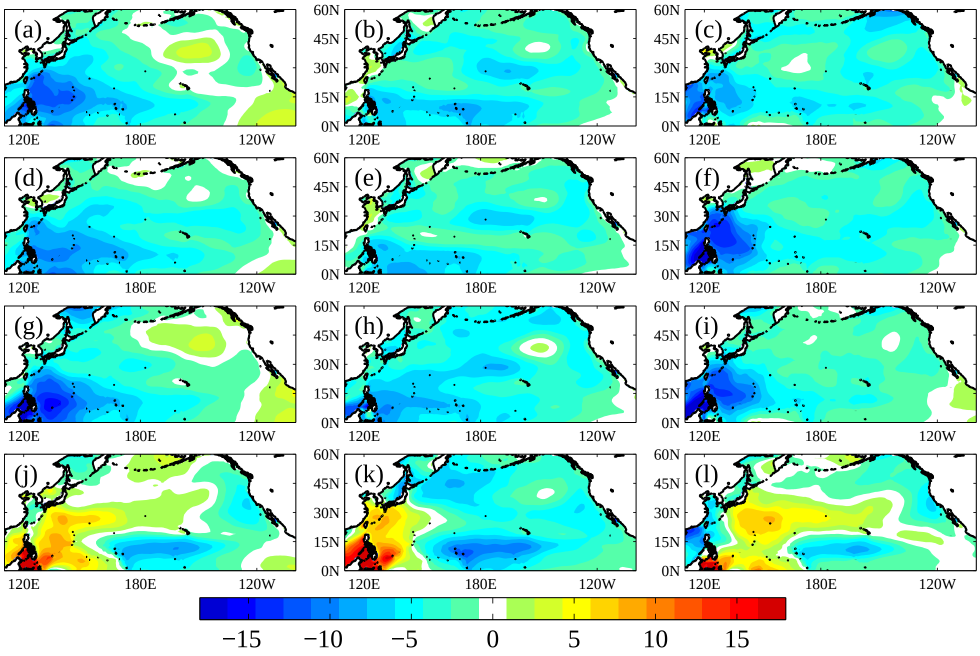

Figure 2: Future changes in MSWH in summer. First to fourth rows are for SST cluster 0 to 3. First to third columns are for physics YS, AS and KF. (100(Future - Present)/Present; [m])

numerical schemes.

3 Results and Discussions

Future changes in wave climate of the North Pacific (NP) in summer (June to November), are discussed in this present study. **Figure** 2 shows the future changes in mean significant wave height (MSWH) by multi-SST and multi-physics ensemble projections. It is noticeable that future changes in MSWH under SST cluster 0 to 2 (**Figure** 2 except for (j)(k)(l)) are negative (-20% of present climate ∼) at lower latitudes (0-30°N) of the western NP, on the other hand, those under SST cluster 3 (**Figure** 2 (j)(k)(l)) are positive (∼+20%). **Figure** 4(a) shows the maximum difference of future changes in MSWH across 12 ensemble members, indicating the differences at lower latitudes of the western NP are larger comparing other region. Wave climate at the western NP in summer is affected by typhoon, and it is shown below that the future changes in wave height can be well associated with that in typhoon characteristics. The contribution of typhoon change to future change in MSWH is estimated quantitatively as follow. MSWH is represented as

$$MSWH = MSWH_{tc} \cdot r_{tc} + MSWH_{no} \cdot (1 - r_{tc}) \tag{1}$$

where $MSWH_{tc}$ is MSWH under typhoon condition, $MSWH_{no}$ is MSWH under non typhoon condition and r_{tc} is ratio of the period under typhoon condition per all the period. Waves within $40° \times 40°$ box whose center is typhoon center are defined as waves under typhoon condition. Future change in MSWH ($\triangle MSWH$) is represented as

$$
\begin{aligned}
&\triangle MSWH \\
&= (MSWH_{tc} - MSWH_{tc}) \cdot \triangle r_{tc} + \triangle MSWH_{tc} \cdot r_{tc} \\
&+ \triangle MSWH_{no} \cdot (1 - r_{tc}) + (\triangle MSWH_{tc} - \triangle MSWH_{no}) \cdot \triangle r_{tc} \\
&= C_r + C_{Htc} + C_{Hno} + C_{\triangle}
\end{aligned} \tag{2}
$$

where $\triangle$ means future change, and C_r, C_{Htc}, C_{Hno} and $C_{\triangle}$ are contributions of $\triangle r_{tc}$, $\triangle MSWH_{tc}$, $\triangle MSWH_{no}$ and the rest to $\triangle MSWH$. **Figure** 3 shows $\triangle MSWH$, C_r, C_{Htc}, and C_{Hno} under SST cluster 0 to 3 of physics YS. $\triangle MSWH$ under cluster 3 is totally different to the other experiment (**Figure** 3(a)(b)(c)(d)) as described above. C_r at lower latitudes is negative value for all the experiments due to typhoon frequency reduction, but C_r under cluster 3 is relatively moderate (**Figure** 3(e)(f)(g)(h)), which follow the moderate reduction of typhoon frequency under cluster 3. Furthermore, C_{Htc} under cluster 3 is larger than the other experiments (**Figure** 3(i)(j)(k)(l)). As the results, although C_{Hno} under cluster 3 is different to those under cluster 0 to 2, the differences in typhoon characteristics change between cluster 3 and cluster 0 to 2 read to the differences in MSWH future change. Consequently, variation of future change in SST reads to large variation of wave climate at lower latitudes of the western NP in summer through typhoon characteristics.

Although COWCLIP six members have complex differences with each other such as different SST, scenario, AGCM and wave model (**Table** 1), but the maximum difference of future changes in MSWH across COWCLIP members (**Figure** 4(b)) shows the similar spatial distribution to that of this study (**Figure** 4(a)). Future changes in MSWH of multi-SST, multi-physics ensemble and COWCLP models within the box of **Figure** 4 (10-30°N, 110-150°E) were compared (not shown, details will be presented at the conference). As the result, COWCLIP study supports that future change in MSWH at lower latitudes of the western NP forced by cluster3-like SST

Table 1: Model description of COWCLIP

	HE12(1)	HE12(2)	FA13(1)	FA13(2)	MO10	SE13
Scenario	A2		A1B		A1B	A1B
SST	MPI's ECHAM5	CSIRO's MK3.5	GFDL's CM2.1	CMIP3 mean	CMIP3 mean	ECHAM5
AGCM	CSIRO's CCAM		GFDL's HiRAM and WW3 coupled		MRI-AGCM3.1S	ECHAM5 AGCM
Wave model	WW3				SWAN	WAM

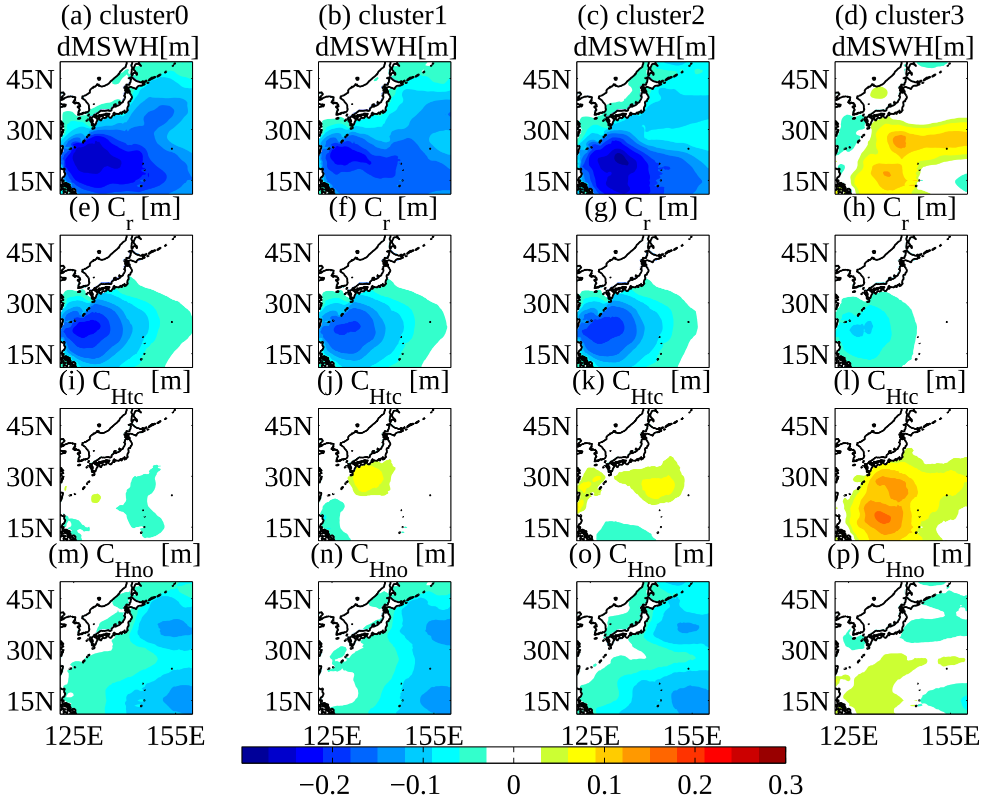

Figure 3: Future changes in MSWH at the West North Pacific under (a)cluster0, (b)cluster1, (c)cluster2 and (d)cluster3. C_r under (e)cluster0, (f)cluster1, (g)cluster2 and (h)cluster3. C_{Htc} under (i)cluster0, (j)cluster1, (k)cluster2 and (l)cluster3. C_{Hno} under (m)cluster0, (n)cluster1, (o)cluster2 and (p)cluster3. (unit: m)

condition is positive or at least larger than that forced by the other SST cluster condition.

It has become clear that variation of SST is major uncertainty source of summertime wave climate in NP based on the results by multi-SST, multi-physical ensemble projection and multi-model ensemble projection (COWCLIP). However there is the robust relationship between future change pattern of SST and summertime wave climate in NP, such as relative growth of mean wave height under cluster3-like SST condition through change in typhoon characteristics. Although the physical mechanism of the relationship has not been addressed in this study, which is future work, insight into the cause of variation in projections can provide the better understanding of climate change. This study indicates that a reduction of uncertainty in the SST under global warming condition will reduce uncertainty in wave climate significantly.

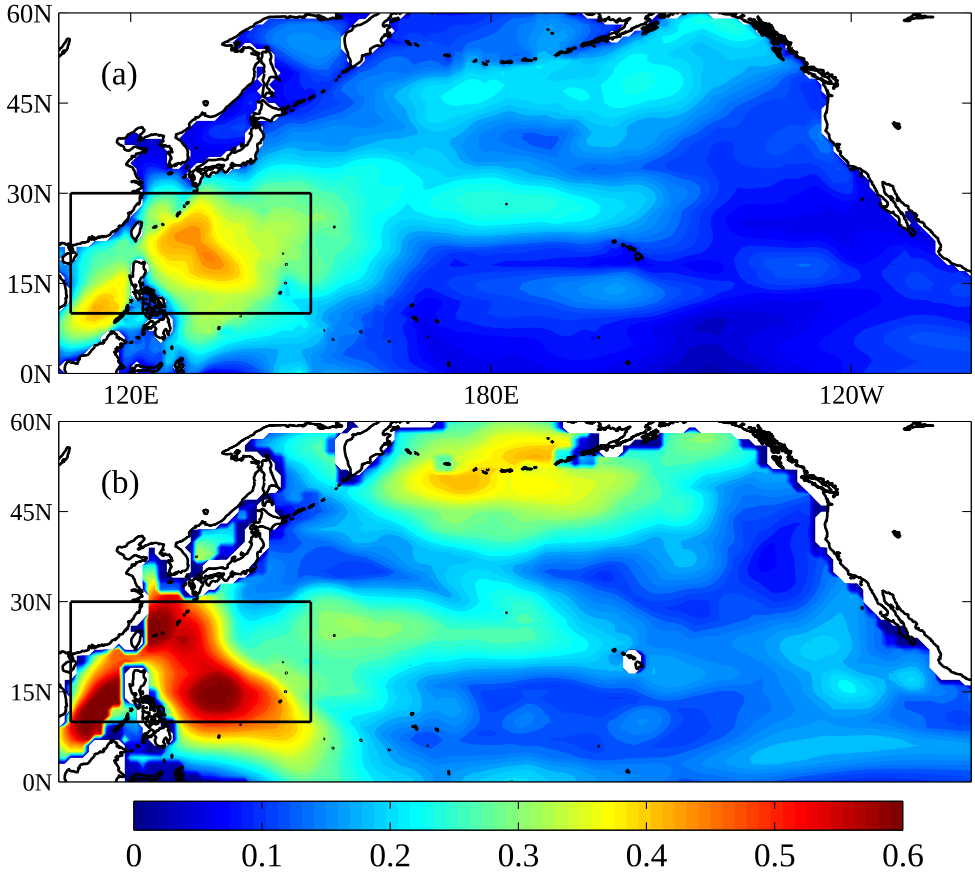

Figure 4: Maximum difference of future changes in MSWH in summer across ensemble members. (a)12 members of multi-SST and multi-physics ensemble. (b)6 members of COWCLIP. (unit:m)

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