CCSM3 simulation of Pacific multi-decadal climate variability: The role of subpolar North Pacific Ocean

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Abstract. Previous analyses of the CCSM3 standard integration have revealed pronounced multidecadal variability in the Pacific climate system. The purpose of the present work is to investigate the physical mechanism underlying the Pacific multidecadal variability (PMV) using specifically designed sensitivity experiments. A novel mechanism is advanced, characterized by a crucial role of the subpolar North Pacific Ocean. The multidecadal signal in ocean temperature and salinity fields is found to originate from the subsurface of the subpolar North Pacific, as result of the wave adjustment to the preceding basin-scale wind curl forcing. The multidecadal signal then ascends to the surface and is amplified through local temperature/salinity convective feedback. Along the southward Oyashio current, the anomaly travels to the Kuroshio Extension (KOE) region and is further intensified through a similar convective feedback in addition to the wind-evaporation-sea surface temperature feedback. The temperature anomaly in the KOE is able to feed back to the large-scale atmospheric circulation, inducing wind curl anomaly over the subpolar region, which in turn generates anomalous oceanic circulation and causes temperature/salinity variability in the subpolar subsurface. Thereby, a closed loop of PMV is established, in the form of a subpolar delayed oscillator.

1. Introduction
The Pacific multidecadal variability (PMV) is one of the most important climate phenomena over the Pacific Ocean [1-3]. However, our knowledge is limited concerning its origin and the physical mechanism because of the paucity and short duration of historical records. Fortunately, the arrival of state-of-art coupled global climate models (CGCMs) provides an unprecedented opportunity for the study of PMV. Recent increasing effort has been witnessed toward improved understanding of PMV using long integration of CGCMs [4, 5]. The CGCMs not only yield sufficient long time series of comprehensive climate variables but also present a powerful tool to help distill responsible physical mechanism.

The origin of PMV is an issue under intense debate. Numerous observational studies projected a tropical origin largely based on a substantiated tropical-North Pacific linkage [3]. In contrast, recent model studies suggested the PMV likely arises from the North Pacific [4, 5]. This discrepancy is attributable partly to a model deficiency that is common to state-of-art CGCMs, that is, a too-weak tropical-North Pacific linkage. Yet, the discrepancy may as likely result from the inconclusiveness (regarding causality) with statistical diagnostics of observational studies.

As a follow-up of [4] using FOAM, Zhong et al. [6] explicitly identified a North Pacific origin for the PMV in CCSM3, using advanced model strategies. The CCSM3 is thus consistent with the FOAM in terms of the origin of PMV. A closer inspection by Zhong et al. revealed a robust tropical-North Pacific linkage in accompany of the North Pacific originated PMV. This model linkage resembles that found in
the observation [3]. Since the model PMV is known to arise locally from the North Pacific, the associated tropical-North Pacific linkage indicates more of a climate impact on the tropical Pacific by the PMV rather than a tropical origin. This interpretation of the tropical-North Pacific linkage thus reconciles the two contradictory views regarding the origin of PMV.

The present study is intended for a more thorough investigation of the North Pacific originated PMV in CCSM3. To better understand the responsible mechanism, we perform additional appropriately designed experiments to help isolate the relevant physical processes. The paper is organized as follows. Section 2 introduces the model and the experiment design. A preliminary survey of PMV is undertaken in Section 3 for all experiments. Section 4 is devoted to depicting the life cycle of the PMV. Conclusions are given in Section 5.

2. The model and experiment design

CCSM3 is a state-of-art global climate model [7]. Under the present-day climate conditions, CCSM3 at T31x3 [8] has been integrated for 880 years without flux adjustment later than year 133, showing no apparent climate drift. Analyses of this control integration are based on the past 580 years of simulation.

Aside from the CCSM3 control integration (named CTRL), sensitivity experiments that employ modeling surgery are performed to explore the mechanism of the PMV. The modeling strategy used is partial coupling (PC) and partial blocking (PB) [4]. The PC strategy is used to deactivate atmosphere-ocean coupling in specified regions while retaining it elsewhere. In the decoupled regions, the atmosphere “sees” prescribed sea surface temperature (SST) from the seasonal climatology of the CTRL and is therefore not affected by the SST anomalies predicted by the model’s ocean component. Meanwhile, the ocean is still driven by heat flux and wind stress anomalies, rather than pure climatological fluxes. The PB strategy is used to block Rossby wave propagation by inserting a sponge wall in a specific longitudinal band of the ocean component of the coupled system. Technically, a restoring boundary of climatological temperature and salinity is inserted in the North Pacific along 180°E with a width of 10°, and from bottom to 100 meters below the surface.

A couple of new experiments (table 1) are specifically designed to assess the significance of Rossby waves in the subtropical/subpolar Pacific for the generation of PMV. In experiment BLKNP, the PB surgery is applied to the latitudinal band 10°N–60°N to block wave propagation from the middle of the basin. In another experiment BLKSTP, the PB is applied to the latitudinal band 10°N–35°N only. For both experiments, the tropical region equatorward of 20° is decoupled using the PC surgery, similar to the experiment PC-ET from previous work of Zhong et al. [6]. A 400-year annual time series is used for the diagnostics.

### Table 1. List of the sensitivity experiments.

| Case   | Experiment Design                                                                 |
|--------|----------------------------------------------------------------------------------|
| CTRL   | Standard integration of CCSM3.                                                    |
| PC-ET  | PC surgery is applied to the global tropics equatorward of 20°.                   |
| BLKNP  | PC surgery is applied to the global tropics equatorward of 20°; PB surgery is    |
|        | applied to the North Pacific at 10°–60°N.                                        |
| BLKSTP | PC surgery is applied to the global tropics equatorward of 20°; PB surgery is    |
|        | applied to the Subtropical North Pacific at 10°–35°N.                            |

3. PMV in sensitivity experiments

Spatial distribution of multidecadal SST variability in the North Pacific is given in figure 1 for new sensitivity experiments in comparison to the CTRL and PC-ET. The BLKSTP shows similar features to the CTRL and PC-ET, exhibiting heaviest loading (over 0.3°C) along the KOE. They also show comparable variability in the western subpolar North Pacific. Differently in the BLKNP (panel c), the activity center in the subpolar North Pacific is missing for the wave blocking there; associated, the other center in the KOE appears considerably weaker.
Figure 1. Spatial distribution of standard deviation of 25–80-year band filtered SST in (a) CTRL, (b) PC-ET, (c) BLKNP, and (d) BLKSTP. Contour Interval (CI) is 0.05 °C. The western-central North Pacific (140°E-140°W, 35°N–45°N) is delineated with the dashed rectangular box in (a). The dashed track line in (b) represents the vertical section on which figure 3 is based.

A power spectrum analysis is made for unfiltered SST anomalies averaged over the western-central North Pacific as denoted by the dashed rectangular box in figure 1. The BLKSTP captures the multidecadal peak (quasi-50-year period) that is evident in the CTRL and PC-ET, whereas no similar peak shows up in the BLKNP (figure 2). It is inferable the PMV hinges on the wave propagation in the North Pacific Ocean. As wave propagation is blocked at all latitudes of the North Pacific along the middle of the basin, the PMV is virtually suppressed in the BLKNP. However, as the blocking is applied to the subtropical region only, the PMV is essentially retained in the BLKSTP. Thus the wave propagation at mid-to-high latitudes of the North Pacific is crucial to the generation of the PMV, whereas that at subtropical latitudes is irrelevant at large.

Figure 2. Power spectra of unfiltered SST averaged over the western-central North Pacific in (a) CTRL, (b) PC-ET, (c) BLKNP, and (d) BLKSTP; 95% and 90% confidence levels are indicated. The quasi-50-year frequency band is highlighted with shading.

4. Life cycle of PMV
The evolution of multidecadal temperature and salinity anomalies is shown in figure 3 along the vertical section that crosses both the subpolar and KOE activity centers, as represented by the dashed track line in figure 1b. It is derived as lagged regression of temperature and salinity upon the KOE SST (140°E-170°E, 35°N–45°N), which exhibits the strongest multidecadal signal in figure 1. To show the life cycle more clearly, all data have been 25–80-year band filtered before regression. The multi-decadal signal appears to originate in the subsurface of subpolar North Pacific. A cold anomaly develops first in the subpolar subsurface at lag -12yr (figure 3a2). It grows (figure 3a3-a5), expands to the surface at lag +4yr (figure...
3a6), and further intensifies at the surface (see figure 3a1, but with the sign reversed). This cold anomaly from the subpolar region is being advected southward by the Oyashio current and turns the KOE into anomalously coldness eventually (figure 3a3, but with the sign reversed). Similarly, a fresh anomaly emerges in the subpolar subsurface (figure 3b4). It intensifies and upwells to the surface (figure 3b6). At the surface, the fresh anomaly is further amplified while being transported southward to the KOE (figure 3b3, but with the sign reversed). Thus, the multidecadal signal forms in the subsurface of subpolar North Pacific, then ascends to the surface, and travel southward to the KOE afterwards. Herein, three key regions have been identified: the subsurface, surface of the western subpolar North Pacific Ocean, and the KOE. Further insight into the physical interactions among the three key regions is provided in [9, 10] and leads us to a novel mechanism of PMV that is detailed in the next section.

\[\text{Figure 3. Lagged regression of (a1)-(a6) temperature and (b1)-(b6) salinity upon the normalized SST in the KOE based on output from PC-ET. The vertical section is along the dashed track line in figure 1b. All data are 25-80-year band filtered before regression. Lags are (a1), (b1) -16yr, (a2), (b2) -12yr, (a3), (b3) -8yr, (a4), (b4) -4yr, (a5), (b5) 0yr, (a6), (b6) +4yr respectively. CI = 0.1 °C/°C and 0.05 psu/°C for temperature and salinity, respectively. Also shown in vector is the mean meridional and vertical current with the latter multiplied by 1e4. Unit length of vector represents 3cm/s.}\]

5. Schematic diagram of PMV

The physical processes involved in a multidecadal cycle of PMV are illustrated with the schematic diagram in figure 4. During the mature cold phase of the PMV (figure 4a), the KOE undergoes maximum coldness and freshness. The atmosphere responds to the cold anomaly in the KOE with a cyclonic wind curl anomaly over the subpolar region, which in turn induce Ekman suction and dynamic low pressure anomaly propagating westward across the subpolar North Pacific Ocean in form of first baroclinic Rossby waves. As a result, the subsurface of the western subpolar North Pacific shows substantial warm and saline anomaly owing to the mean halocline stratification (i.e., cold fresh water on top of warm saline water). At the same time, the surface is in a near-normal state, while the mean upwelling carries the warm saline anomaly from subsurface to surface. After a quarter of cycle (figure 4b), the warm saline anomaly maximizes at surface via local temperature/salinity convective feedback that is preconditioned by the mean halocline stratification. To be more specific, once the warm saline anomaly ascends to the surface, the warm anomaly damps quickly and leaves the saline anomaly behind, which makes the surface water denser and thus weaker stratification. Consequently, convective activity gets more intense and entrains more warm saline water from below. The warm saline anomaly is then advected southward along the
Oyashio current, working to neutralize the cold fresh anomaly in the KOE. Concomitantly, the dynamic low-pressure anomaly proceeds into the western basin of subpolar North Pacific, and the associated geostrophic current starts to diminish heat and salt convergence in the subsurface. It has cooling and freshening effect. As another quarter of cycle goes by (figure 4c), the KOE enters a mature warm saline state, due to the enduring growth via the temperature/salinity convective and WES feedback that follows the initial influx of warm saline anomaly from the subpolar North Pacific. The corresponding anticyclonic wind curl anomaly over the subpolar region generates a new wake of Rossby waves producing a cold fresh anomaly in the subsurface. Notably, the cold fresh anomaly is substantially enhanced by the aforementioned cooling and freshening that results from the previous passage of the dynamic low-pressure anomaly. Ascending of the cold fresh anomaly meanwhile, neutralizes the foregoing warm saline anomaly in the surface of subpolar North Pacific, as seen in figure 4b. Thus, a mature warm phase of the PMV (figure 4c) is established, featured by a maximized warm saline anomaly in the KOE and substantial cold fresh anomaly in the subpolar subsurface. The converse occurs during the other half cycle of PMV.

Figure 4. Schematic picture of a full cycle of PMV. Explanation is given in the text.

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