

# Formation of subtropical westerly jet core in an idealized GCM without mountains

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**Abstract.** In boreal winter, subtropical westerlies in the upper troposphere reach maxima in speed over the eastern edges of the Asian and North American continents. The zonal variations in the westerlies are generally attributed to large-scale orography and thermal forcing, but the latter mechanism remains largely unsubstantiated. Here we conduct general circulation model (GCM) experiments without orography to identify the most important thermal forcing for generating zonal asymmetries in subtropical westerlies. By changing sea surface temperature (SST) distribution in the GCM, we find that the tropical SST distribution plays a decisive role in producing a subtropical jet core to the north of the tropical warm water pool, while the effects of extratropical continent-ocean heating contrast on upper-level zonal wind speed distribution are secondary. The results from Aqua Planet runs further support this conclusion.

## 1. Introduction

The upper tropospheric subtropical westerlies are locally enhanced over the western Pacific and the western Atlantic during the boreal winter season. The large deviations from zonal symmetry in the extratropical circulation are associated with planetary-scale quasi-stationary waves forced by large-scale orography and zonally asymmetric heat source (Smagorinsky, 1953). Several numerical experiments have been carried out to evaluate the quantitative contribution of orographic and thermal forcings. Based on general circulation model (GCM) experiments with and without mountains, Held (1983) suggested that they are complementary to each other, each contributing about one half of the observed stationary wave amplitudes.

The orographical forcing of stationary waves is relatively simple to examine because it can be externally specified in terms of surface boundary conditions. On the other hand, the effects of the thermal forcing are not as straightforward because it is composed of several ingredients, such as continent-ocean heat contrast, SST distribution, and latent heat release and heat flux convergence associated with extratropical transient eddies (Valdes and Hoskins, 1989).

Among others, extratropical continent-ocean contrast is widely believed as a major thermal forcing for the zonal asymmetry in westerly speed (e.g. Holton, 1992). The land-sea heat contrast can induce a number of zonal variations

in the lower atmosphere. First, meridional temperature gradient reaches a maximum over the eastern continent, which has an effect of enhancing local westerly winds through thermal wind relation. Second, near surface static stability drops and hence baroclinicity reaches a maximum off the east coast of the continent, which may modulates the development of baroclinic eddies. Such direct response to an extratropical land-sea distribution is confined to the lower atmosphere in winter time, and it is not clear how such near-surface asymmetries can lead to large zonal variations in upper tropospheric westerly jet.

The present study conducts a series of GCM experiments that are specifically designed to investigate the atmospheric response to extratropical land-sea heat contrast with a focus on its role in the formation of subtropical jet.

## 2. Model

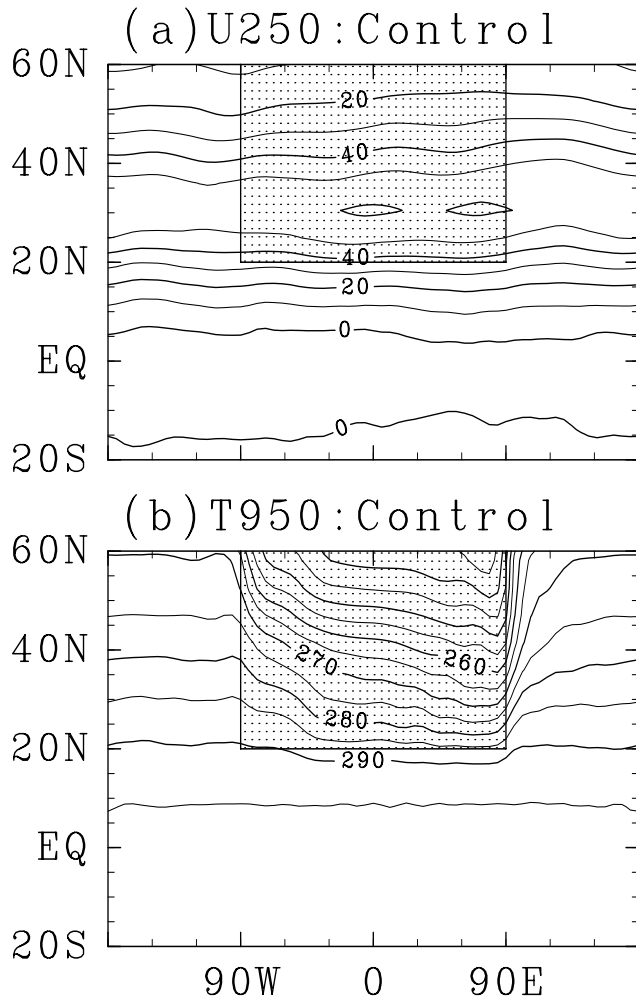
We use the CCSR/NIES AGCM, which is a community model for Japanese universities and has been widely used for realistic and idealized simulations (Shen et al., 1998; Xie and Saiki, 1999). This is a global spectral model with a triangular truncation at zonal wavenumber 21 and 20 sigma levels. The physical package of this model includes standard parameterizations for radiation, cumulus convection, large-scale condensation with prognostic cloud water, vertical diffusion, and gravity-wave drag. See Numaguti (1999) for a more detailed description of the model physics and its application to atmospheric hydrological cycle study.

For simplicity, we set the land surface at the sea level and all land surface parameters such as albedo zonally uniform. All experiments are performed under the perpetual January conditions, and the twice-daily dataset for 235 days after a spin-up period is used.

## 3. Extratropical land-sea forcing

First we set sea surface temperature (SST) zonally uniform and consider the forcing by extratropical land-sea heat contrast. An idealized Eurasian continent spans from 90°W to 90°E between 20°N and the North Pole. This experiment is referred to as the control run.

As discussed in the introduction, there are large zonal asymmetries near the surface in response to the land-sea distribution. Because of warm advection, subtropical surface air temperatures (SATs) are much higher in the western than in the eastern continent (Fig. 1b). With SAT over the ocean to the south staying relatively constant, the meridional gradient of continental SAT between 20°N and 40°N increases eastward. Despite the large zonal variations near



**Figure 1.** (a) Time-averaged zonal wind speed at 250 hPa, and (b) temperature at 950 hPa in the control run with the continent shaded. Land surface is flat at the sea level.

the surface, the upper westerly wind velocity is largely zonally uniform (Fig. 1a) in the control run. As expected, both the model baroclinicity (Linzen and Farrel, 1980) and the eddy heat flux display a local maximum east of the continent (not shown). The GCM has been run at a higher T42 resolution to improve its representation of transient eddies, but the westerly winds in the upper troposphere remain nearly constant in the zonal direction (not shown).

#### 4. Tropical forcing

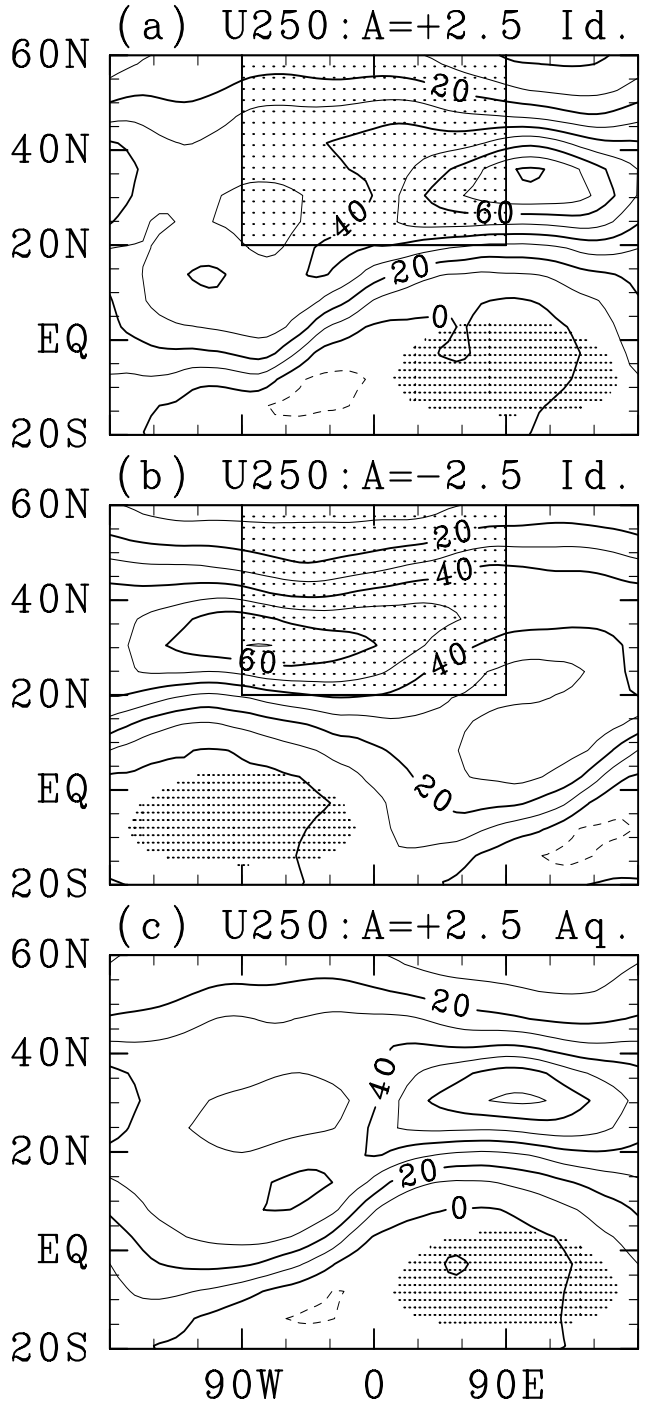
In the real world, SST varies quite substantially in the zonal direction. In the tropics, highest SSTs are found in the so-called warm water pool south of the eastern Eurasian continent, which can locally enhance the subtropical westerlies as suggested by experiments under the realistic land-sea distribution (Appendix). We add a zonally varying component

$$T'(\lambda, \phi) = A \sin \lambda \exp \left\{ -\frac{1}{2} \left( \frac{\phi - \phi_0}{10} \right)^2 \right\}, \quad (1)$$

to the tropical SST field. Here,  $\lambda$  is longitude,  $\phi$  is latitude,  $\phi_0 = 8^\circ\text{S}$ , and  $A$  is 2.5 K. In this case, a warm pool is located to the south of continent's east coast as in observations.

The GCM now generates substantial zonal variations in upper-level westerlies (Fig. 2a), while the SAT field is similar to that in Fig. 1b (not shown). Therefore, the control run rules out extratropical land-sea distribution as a major component of thermal forcing for subtropical jet core. Instead, it implicates the tropical forcing.

To further demonstrate the controlling effect of tropical SST forcing, we shift the tropical warm water pool onto the western side of the continent by setting  $A = -2.5\text{K}$ . The



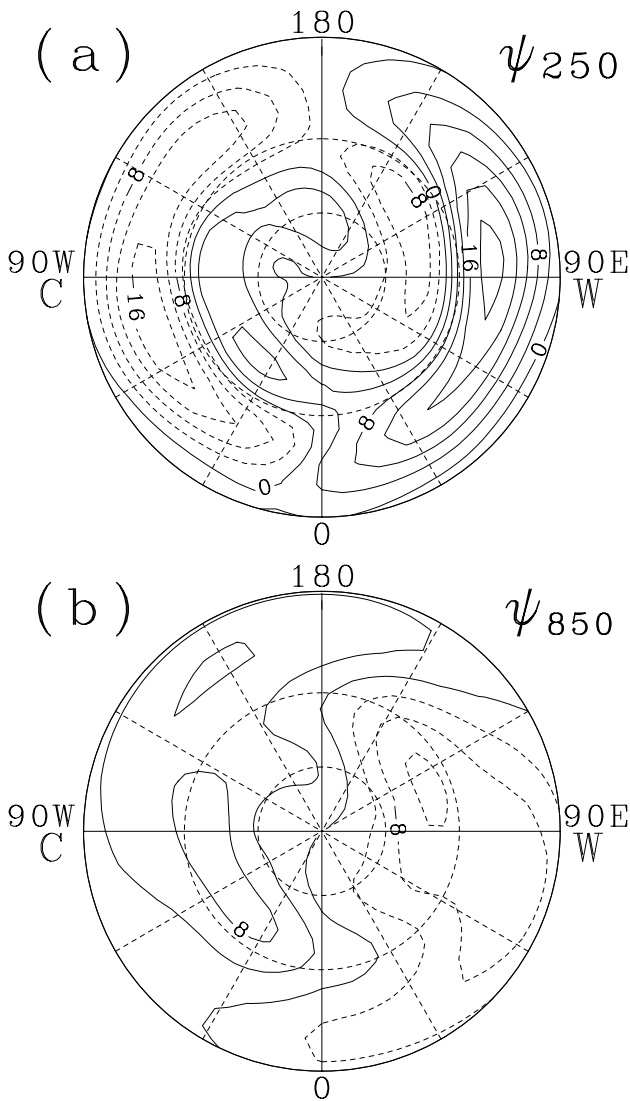
**Figure 2.** Same as Fig. 1a but for (a) the eastern and (b) western equatorial warm water pool runs, and (c) the Aqua Planet run. The heavy shade in the tropics denotes SST  $\geq 301.5\text{K}$ .

GCM responds to this western warm pool by locating the subtropical jet core on the west coast (Fig. 2b), lending further support for the tropical forcing mechanism.

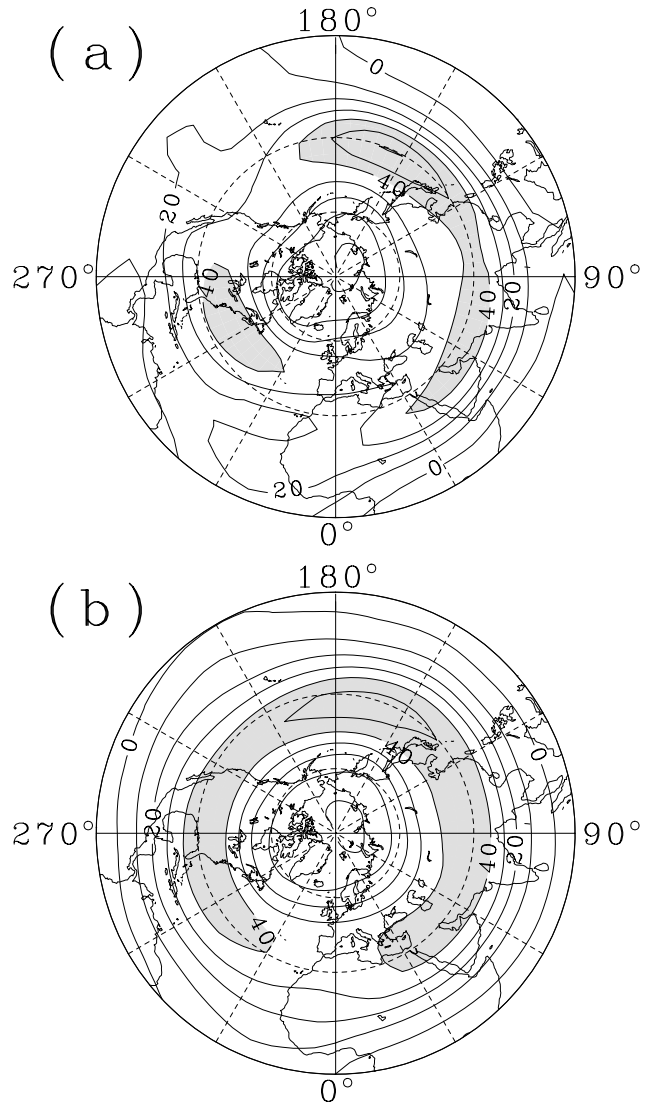
**5. Aqua Planet runs**

Given that extratropical land-sea distribution has little impact on the zonal variations in upper westerlies, we further simplify the GCM by running it under the so-called Aqua Planet conditions. Now SST is the only externally imposed zonal asymmetry. As in the previous experiments, the westerly jet forms north of the equatorial warm pool (Fig. 2c). The zonal asymmetry in the wind speed of upper-level subtropical westerlies is about the same as in the runs with extratropical land-sea distribution.

In the stationary eddy fields, baroclinic structure dominates the tropics. On the upper-level surface, a baroclinic anticyclonic vortex resides immediately north of tropical warm SST anomaly and a barotropic cyclonic vortex exists



**Figure 3.** Stationary wave component of the stream function ( $10^6 \text{ m}^2/\text{s}$ ) at (a) 250 hPa and (b) 850 hPa in the Aqua Planet experiment. The longitudinal positions of prescribed equatorial warm/cold water pool are denoted by W/C, respectively.



**Figure 4.** (a) Time-averaged zonal wind speed at 250 hPa in a perpetual January GCM run with observed SST and land-sea distributions. Values greater than 40 m/s are shaded. (b) Same as (a) except for zonal-mean SST. Land surface is flat at the sea level with all the orography removed.

further north of this baroclinic anticyclone (Fig. 3). The upper-level subtropical jet core is located in a high gradient zone between the baroclinic anticyclone and the barotropic cyclone. The excitation mechanism for these vortices, however, needs further investigations.

**6. Concluding remarks**

Our GCM experiments suggest that the extratropical land-sea distribution plays a secondary role in forming locally enhanced westerly jets. Sharp SAT gradient off the eastern continent does not seem to affect the upper-level flow field, despite that transient eddies tend to occur over this high baroclinicity region and develop downstream.

Tropical SST distribution is found to largely determine the longitudinal position of the subtropical jet cores. The upper-level westerly velocity reaches a maximum to the north of the equatorial warm water pool, consistent with

previous studies (Geisler et al., 1985; Ting and Held, 1990; Valdes and Hoskins, 1989). The GCM experiments under the realistic land-sea distribution (Appendix) corroborate the notion that the tropical SST distribution is the most important thermal forcing for the subtropical jet. Zonal variation in transient eddy activity and extratropical diabatic heating can be viewed as a response to the tropical forcing, at least in the model without mountains. Detailed analysis of transient eddy fluxes and their relationship with the mean flow will be reported elsewhere.

Finally, we note that the dominance of the tropical SST forcing has been demonstrated here only in the context of no-mountain experiments. Pre-existing meanders mechanically forced by surface topography in the extratropics may reduce the effect of the tropical SST distribution, which will be a subject of our next study.

## Appendix — Realistic experiment

We conduct a GCM experiment with the realistic continents and observed SST distribution but with all the orography removed. Subtropical westerlies (Fig. 4a) have enhanced jet cores over the western Pacific and the western Atlantic much as the observed ones (Holton, 1992). With the zonal SST variation removed, however, the subtropical westerlies become almost zonally uniform (Fig. 4b). The small zonal asymmetries are partially an artifact of low-frequency variability and partially due to tropical land-sea distribution. In an experiment that removes zonal SST variation only in the tropics, the result is almost the same as in Fig. 4b (not shown).

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