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Short Communication

Propagation of wind and buoyancy forced density anomalies in the North Pacific: Dependence on ocean model resolution

LuAnne Thompson *, Jordan Dawe

School of Oceanography, University of Washington, Box 355351, Seattle, WA 98195, United States

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Abstract

The response of the thermocline to changes in atmospheric forcing are explored in two 50-year hindcast North Pacific model runs. The model runs only differ in their resolution and horizontal viscosity values. The thermocline response is explored through a modal decomposition. The first baroclinic mode response is qualitatively similar in both model runs, with a somewhat smaller response in the lower resolution model. This mode is primarily wind driven. The second baroclinic mode shows a larger response at midlatitudes in the low-resolution model than in the higher resolution model. This is consistent with the presence of very large-scale baroclinic instability in the return flow of the subtropical gyre at low-resolution, and represents a spurious response of the ocean model to large horizontal viscosity. This spurious mode of decadal variability in the thermocline is maintained even when there is variability in atmospheric forcing. This result suggests that care must be taken in interpretation of the realism of mid-latitude modes of variability centered in western boundary current extensions of coupled ocean–atmosphere models.

1. Introduction

The North Pacific Ocean's response to variability in atmospheric forcing has been explored in both models and observations. The response can be separated into two primary components. The first component is governed by the first baroclinic mode Rossby wave and propagates with minor dependence on the mean flow (Schneider and Miller, 2001; Liu, 1999; Thompson and Ladd, 2004; Auad, 2003; Capatondi and Alexander, 2001). This response is primarily generated by variability in the wind-stress curl. The second component is a second baroclinic mode response generated in the central Pacific by subduction anomalies (Liu, 1999; Thompson and Ladd, 2004).

The time scale for the ocean response to reach from the eastern to the western boundary is on the order of 5–10 years, depending on latitude, which is the appropriate time scale for the mid-latitude Pacific Ocean to play a role in decadal climate variability. Latif and Barnett (1996) suggest a mechanism for oceanic contributions to decadal climate variability in which an increase in Kuroshio Transport results in a warm SST

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* Corresponding author.
E-mail address: luanne@ocean.washington.edu (L. Thompson).

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anomaly. This leads to weakening in the Aleutian Low that initially increases the warm SST anomaly. However, ocean adjustment to the changes in wind eventually causes a decrease in the Kuroshio Transport. Subsequent model analysis by Schneider et al. (2002) and Pierce et al. (2001) suggests that while there is decadal variability associated with mid-latitude coupled ocean–atmosphere interaction, it appears to originate in the Kuroshio and is focused in its recirculation and extension. They surmise that much of the decadal variability in the mid-latitude ocean can be described as an oceanic response to stochastic atmospheric forcing. The evidence for a coupled mid-latitude ocean–atmosphere mode is inconclusive, with negative feedbacks from the ocean to the atmosphere that would lead to oscillatory behavior not readily apparent.

Partly because of the limited observational record, there is currently little observational evidence for feedback from decadal SST anomalies to long term variability in the atmosphere, although it cannot be ruled out. However, because the results of coupled atmosphere–ocean models do suggest feedback from the mid-latitude ocean to the atmosphere it is important to explore the possibility of a role for the mid-latitude ocean in decadal climate variability. The coupled models are typically run at low-resolutions that do not explicitly resolve the ocean eddy field. Here we further explore the possibility that the enhancement of decadal variability in mid-latitude in models is caused by internal oceanic variability that is artificially stronger at low-resolution, even in the presence of changes in atmospheric forcing. This is despite the higher eddy kinetic energy and higher variability that one might expect at all time scales at higher resolution.

Evidence for internal variability in the ocean can be found in several modeling studies (see for instance Cox, 1987 and Hazeleger and Drijfhout, 2000). However, Dawe and Thompson (2005) demonstrate that some model internal variability can be explained as very long-wave baroclinic instability in the presence of strong friction needed for numerical stability. We argue in that paper that the results of non-eddy resolving models tend to be biased toward a large-scale propagating response in the return flow of the subtropical gyre between 20 and 30N. The high viscosity of low-resolution models smooths the short-wave baroclinic instabilities that tend to non-linearly disrupt larger-scale instabilities, allowing these long-wave instabilities to grow. Using a climatologically forced run, we show that a strong 10–15 year oscillation in a 2°-resolution simulation is spurious and goes away when resolution is increased. However, it is not resolution that is the problem; rather, it is the friction required for numerical stability that causes the spurious behavior.

Here, we extend Dawe and Thompson's analysis of a climatologically forced run to one that is forced by a 50 year time series of atmospheric variability. As in Dawe and Thompson, we examine the model ocean at two different resolutions. We evaluate thermocline variability through examination of the relative contribution of the first and second baroclinic modes to isopycnal displacements, and examine the relationship between atmospheric forcing and the thermocline response. We conclude with a discussion of the possible consequences for evaluation of coupled modes of variability in ocean–atmosphere coupled models.

2. Models

The model used here is the Hallberg Isopycnal Model (see Ladd and Thompson, 2002; Thompson and Ladd, 2004, and references therein). The model is run in the North Pacific sector on a domain spanning 20S to 60N and 90E to 70W. The boundaries in the east, south and north are nudged towards Levitus values. The model has 16 layers in the vertical, composed of a 2 layer bulk mixed-layer model and 14 isopycnal layers (see Ladd and Thompson, 2002 for details). The model is run at two-degree and one-degree resolution.

The forcing is NCEP monthly winds, DaSilva monthly long- and short-wave radiation, sensible and latent heat fluxes calculated using bulk formulae as discussed in Dawe and Thompson (2005), and relaxation of sea surface salinity to Levitus climatology. Both model runs show reasonable climatologies of SST and SSS. The model was spun up for 50 years using climatological forcing fields then run with variable forcing from 1948 to

Table 1
Biharmonic viscosity m^4/s value for each model run

	One-degree	Two-degree
Climatologicaly forced run	4×10^{13}	1.5×10^{15}
Hindcast run	5×10^{13}	4×10^{14}

1999. Monthly averages of all fields were saved for the analysis that follows. The horizontal viscosity is biharmonic for all model runs with values given in Table 1.

3. Results of a modal decomposition

We use the technique of vertical modal decomposition developed by Thompson et al. (2002) and Thompson and Ladd (2004) to separate the energy and propagation characteristics of the first and second baroclinic modes. The first baroclinic mode reflects the propagation of anomalies in thermocline depth and the second baroclinic mode reflects the expansion and contraction of the thickness of the thermocline. The respective baroclinic modes propagate at the same speed in both models, with the first baroclinic mode propagating faster than the second, as demonstrated by Thompson and Ladd (2004). However, distinct differences can be seen in mode amplitude between the two model runs.

The energy of the first baroclinic mode in the one-degree model is consistently higher than in the two-degree model, in both the midlatitudes and the tropics (Fig. 1). Since the first baroclinic mode is not influenced to first order by the mean flow, the suppression of the response in the two-degree model must result from the higher viscosity of that run. The tropical response (south of 20N) shows a similar suppression of the second baroclinic mode in the two-degree model. The response for both baroclinic modes is primarily wind-driven in the tropics (Thompson and Ladd, 2004), with significant wind driven energy in both the first and second baroclinic modes. In contrast, the midlatitude second baroclinic mode energy is lower in the one-degree model than in the two-degree model. A swath of maximum energy emanates from the dateline in the Kuroshio Extension and moves southwest toward the western boundary (see also Fig. 4 of Thompson and Ladd, 2004). These results are summarized in Table 2.

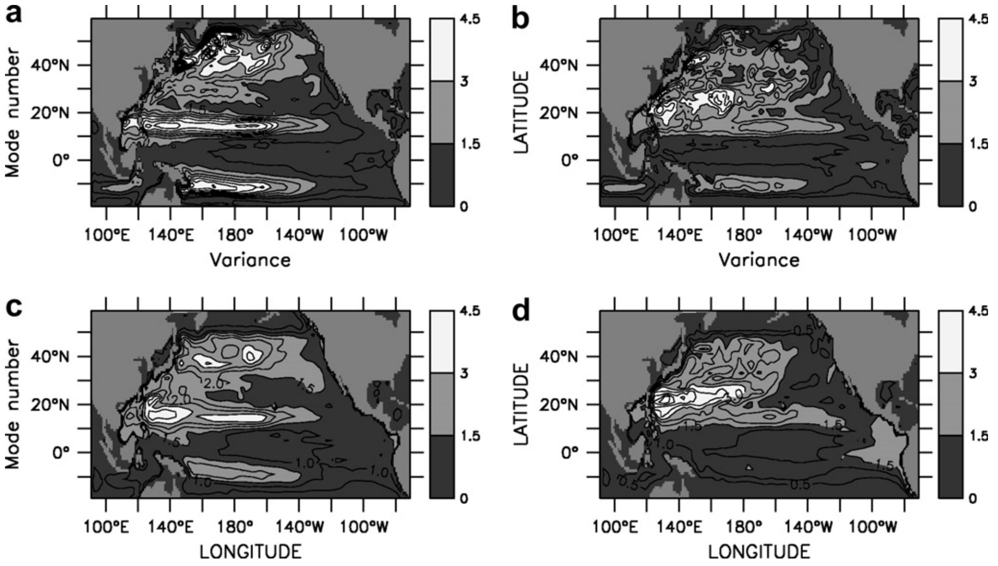

Fig. 1. Amplitude of thermocline response in first and second baroclinic modes. (a) First baroclinic mode for the one-degree model, (b) second baroclinic mode for one-degree model, (c) first baroclinic mode for the two-degree model, and (d) second baroclinic mode for two-degree model.

Table 2
Model run with larger baroclinic mode response

	Mid-latitude	Tropical
First baroclinic mode	1 degr.	1 degr.
Second baroclinic mode	2 degr.	1 degr.

There are several possible reasons for the differences seen in the second baroclinic mode in the two model runs. First, in low-resolution models, mode water production tends to be enhanced. The enhancement is caused by the overshoot of the western boundary current that results in too much warm water in the subpolar gyre and a large flux of heat to the atmosphere because of a mismatch between the model SST and the surface air temperature. We argued in Thompson and Ladd (2004) that the second baroclinic mode is primarily diabatically forced in the Kuroshio Extension, in the mode water formation region. The enhancement of the heat flux results in large diabatic forcing of the second baroclinic mode (as suggested by Liu, 1999). Anomalies then form that propagate as a second baroclinic mode following an advective pathway towards the western boundary. This effect occurs in both model runs, since the western boundary current tends to overshoot in all ocean models with resolution coarser than about one tenth of a degree, but the effect is strong in the lower resolution run. This response is reflected in the mean flow as well, with the Kuroshio Extension broader with larger heat flux out of the ocean in the Central Pacific and larger production of Central Mode Water in the two-degree ocean model.

Second, as described by Dawe and Thompson (2005), long-wave baroclinic instability (with wavelengths of 1000 km or more) in the return flow of the subtropical gyre is enhanced in low-resolution models, due to viscous suppression of short-wave disturbances. In the forced model, this preference for long-wave disturbances to survive and propagate continues. To confirm this, we performed the modal decomposition on the two-degree run of Dawe and Thompson (2005) which was climatologically forced, but still had significant decadal variability. The model is run in a slightly different domain than the hindcast results discussed here, but this should not unduly affect the results of this analysis. The modal decomposition shows that the internal mode of variability projects most on the second baroclinic mode with enhanced energy in the same region as seen in Fig. 1 (Fig. 2). The second baroclinic mode amplitude is as much as eight times bigger than the first baroclinic mode in this internal mode of variability. The variance as a function of mode number in the two hindcast model runs shows that, averaged over the whole model domain, the one-degree model has larger amplitude for all baroclinic modes. However, in the Kuroshio Extension, the two-degree model has larger amplitude than in the one degree model in mode 2 and 3, similar to the climatologically forced model of Dawe and Thompson (2005) (Fig. 3). For pure baroclinic instability, the larger the viscosity, the more enhanced the energy is at longer wavelengths over that for shorter wavelengths.

The propagation characteristics (the phase speed and its dependence on longitude) of the second baroclinic mode in both forced model runs are very similar to that in the Dawe and Thompson (2005) two-degree run, suggesting that the internal mode represents a preferential mode of variability when the model is run with variable forcing (Fig. 4). In the second baroclinic mode, the two- and one-degree model hindcasts show some propagating features in common that are likely forced by subduction anomalies (e.g. the feature that starts near the eastern boundary at 36 years and reaches the western boundary towards the end of the record), but for the most part, they look quite different. In contrast, the first baroclinic mode looks very similar in the two hindcast runs (not shown), which is consistent with this mode being primarily a linear wind-driven response (as seen in Thompson and Ladd, 2004), although there are quantitative differences owing to the differences in friction and resultant damping. In an examination of the frequency response of each of the model runs, we found that at 23N there is a maximum in the spectrum at about 12.5 years in both the climatolog-

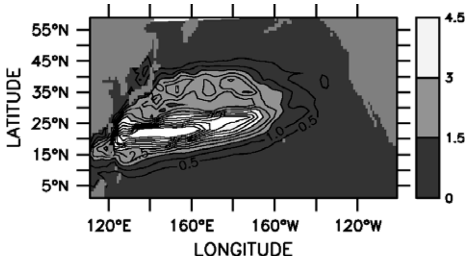

Fig. 2. Amplitude of second baroclinic mode in model forced by climatology as discussed in Dawe and Thompson (2005) in a two-degree model.

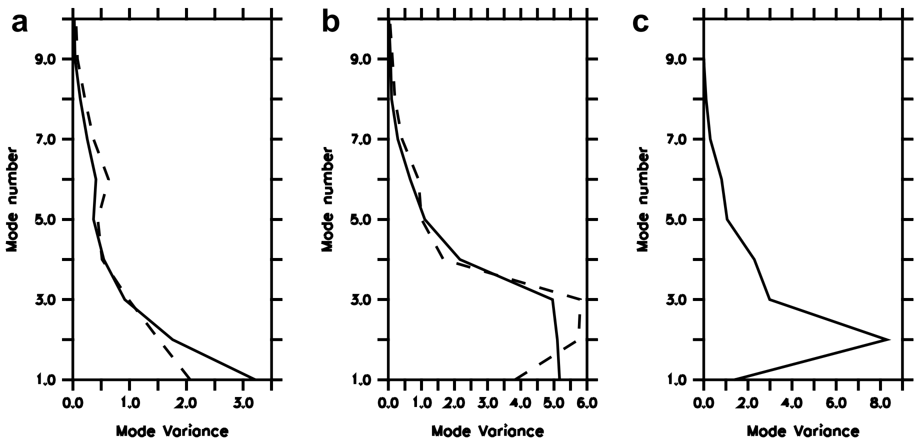

Fig. 3. Average variance as a function of mode number of the one-degree (solid line) and two-degree (dashed line) models. (a) Area averaged variance over whole the model domain, (b) averaged over the Kuroshio extension from 120E to 180E and 15N to 40N, (c) variance in two-degree climatologically forced run of Dawe and Thompson (2005).

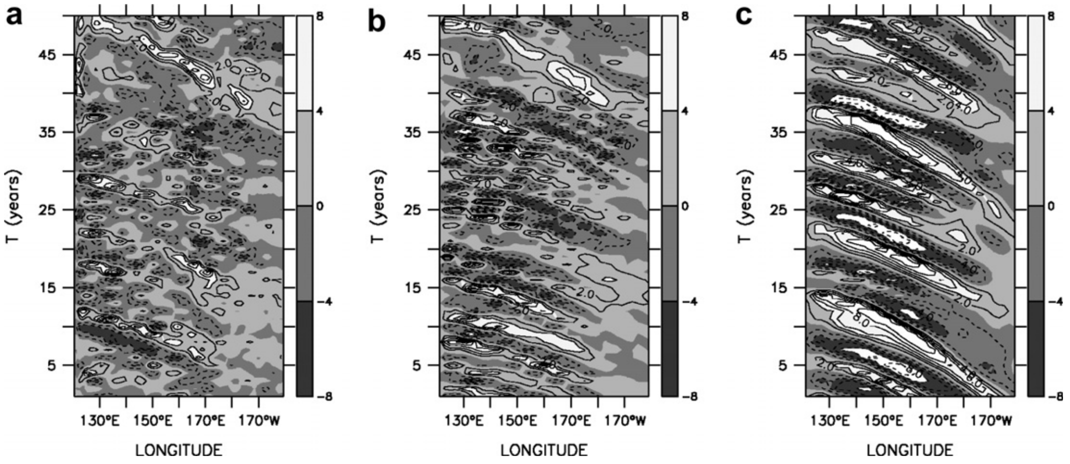

Fig. 4. Second baroclinic mode amplitude at 23N as a function of time for one-degree, two-degree, and climatologically forced models.

ically forced run and in the two-degree hindcast simulation, with a response in this frequency band about half as big in the one-degree run. This frequency is close to the oscillatory frequency found in the analysis of Dawe and Thompson, and it is in this lower frequency band that the two-degree model more closely resembles the internal mode of variability. We conclude that the enhancement of energy in the second baroclinic mode in the lower resolution model is related to the long-wave instability described by Dawe and Thompson (2005) especially in the lower frequency bands, even in the presence of variable forcing.

4. Relationship between forcing and thermocline motions

In Thompson and Ladd (2004), we established that a qualitative relationship between the forcing fields and the anomaly fields in the thermocline can be found using quasi-geostrophic theory. We argued that the first baroclinic mode is forced primarily by the wind, while the second baroclinic mode is forced primarily by diabatic forcing. The response can then be traced along wave pathways. At midlatitudes, the first baroclinic mode travels dominantly to the west, while the second baroclinic mode, because of its smaller propagation speed in the absence of mean flow, follows an advective pathway that tracks the general circulation.

Investigation of the forcing of the second baroclinic showed that it was dominantly forced by subduction anomalies in the Central North Pacific (Thompson and Ladd, 2004), and thus, one might want to define a subduction index as an indicator of the forcing of thermocline anomalies. However, while subduction anomalies are easily defined in the model, they are difficult to determine from observations. The PDO index, as an indicator of North Pacific SST is a common index for characterizing longer term climate variability in the region and is a representation of the state of the upper ocean that will be reflected in subduction anomalies. To confirm this, and Ladd and Thompson (2002) showed that the 1976 climate shift is strongly reflected in subduction anomalies in the central Pacific, and the 1976 climate shift is easily identified by the PDO.

To investigate how changes in the state of the atmosphere and surface ocean relate to thermocline changes, we use the Pacific Decadal Oscillation (PDO) index (Mantua et al., 1997) as a regression index. Averaged over the tropics (equatorward of 20°), both model runs show a lagged correlation in the first baroclinic mode, with maximum correlation of 0.6 in the one degree model and 0.4 in the two-degree model (both maximums occur in broad peaks between 6 and 15 years lag). In both cases, the correlation of the second baroclinic mode is slightly lower than the first baroclinic mode, with its maximum correlation occurring about five years later owing to its slower propagation speed. The tropical response appears to be quite robust since its characteristics are so similar in the two model runs. Thompson and Ladd (2004) argued that the wind driving explains nearly all of the variability there, with diabatic (buoyancy) forcing playing only a very minor role. Of course, the second baroclinic mode is also forced by the wind with its amplitude scaled by the inverse of its mode number, and thus we expect that it would have reduced amplitude relative to the first baroclinic mode. In the tropics, the model second baroclinic explains 22–23% of the area averaged isopycnal displacement variance, while the first baroclinic mode explains 30% and 42% of the area averaged variance of isopycnal displacements in the two- and one-degree models, respectively. This suggests that the second baroclinic mode evolution should be included in analysis of equatorial wave dynamics, especially within 10–20 degrees of the equator. Because of the slower propagation speed, the second baroclinic mode may allow a longer time scale delayed response by the oceans to changes in wind forcing.

However, in midlatitudes the results are quite different between the two model runs. First, the maximum lag correlations are much smaller (∼0.2–0.3). In the one-degree model, the maximum lag correlation is about 0.2 and occurs at about 20 years lag in both baroclinic modes. In the two-degree model, the correlation is smaller for the first baroclinic mode than for the second baroclinic mode. This again suggests that the forcing is projecting onto a preferred mode of variability in the ocean model in the two-degree model, but not in the one-degree model. The lag correlation maps confirm this result (Fig. 5). The correlation to the PDO index at 8 years lag is quite high in the tropics, with the one- and two-degree simulations showing very similar results, including high correlations between 15N and 20N, and along the eastern boundary at mid-latitudes. These patterns are a projection of the familiar PDO pattern onto the thermocline variability. However, there are striking differences near the western boundary current extension. The two-degree model shows a much larger-scale response, with a swath of high correlation emanating from the central Pacific at 165W, 35N and extending to the western boundary at about 15N. This pattern is not reproduced in the one-degree model. In the one degree model, the whole response shrinks back to the western boundary with smaller scales in evidence. The first baroclinic mode pattern (not shown) shows a much larger-scale correlation pattern, similar to what is seen in the tropics in the second baroclinic mode.

5. Discussion

The results of the two model runs demonstrate that forced low-resolution ocean model simulations tend to show enhanced propagation of large-scale wind and buoyancy driven signals in the thermocline. This enhancement occurs primarily in the second baroclinic mode; that is, in the expansion and contraction of the thermocline thickness. The diabatically driven signal is strengthened by the enhancement of diabatic forcing in the central Pacific owing to the overshoot of the western boundary current extension that results in an unrealistically large ocean heat loss. The signal is further strengthened by the suppression of baroclinic instability at short length scales and enhancement at long length scales, owing to the large viscosity required for numerical stability. This is displayed by the difference responses in the one- and two-degree models. In the one-degree model, the midlatitude interannual wind-driven response is larger than the diabatically-driven response, while

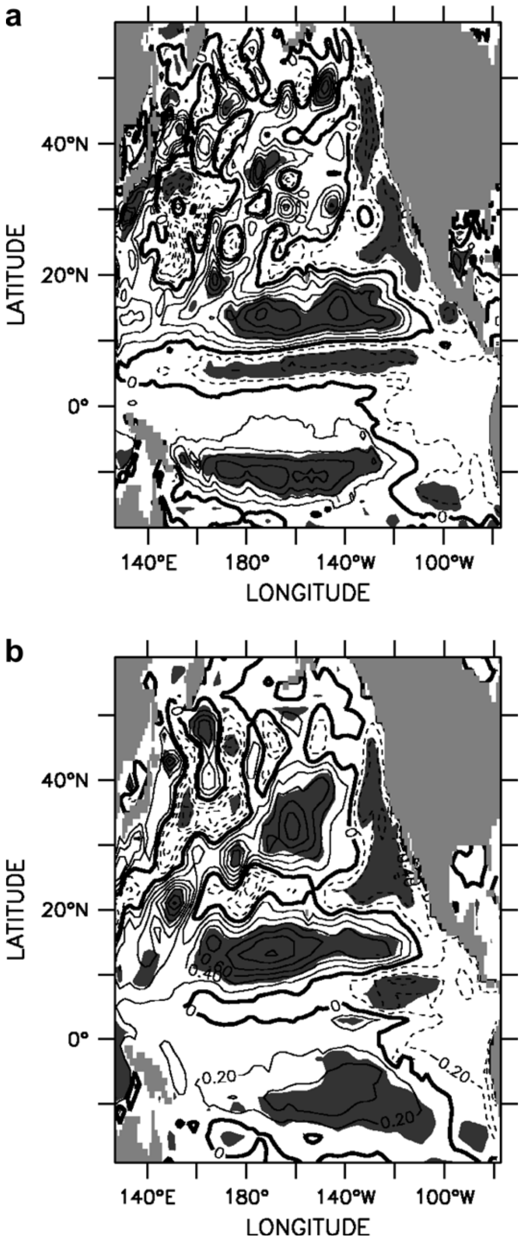

Fig. 5. Lag correlation maps between PDO index and second baroclinic mode amplitude. Shown is the 8-year lag correlation for one-degree model (a) and two-degree model (b). The shaded areas are significant at the 75% confidence level.

the opposite is true for the two-degree model. The reason for the enhancement of the low-frequency in the forced model at lower amplitude runs may result because anomalies forced by interannual changes in atmospheric may disrupt the phase relationships needed for very long-wave baroclinic instability to grow. The results of this modeling study suggest several things. First, the second baroclinic mode should be considered in simple models and analysis of decadal variability in the ocean. In the tropics, the wind-driven response in the second baroclinic mode can give a decadal time scale in the ocean owing to its slow propagation. This has also been suggested by Liu et al. (2002), where they find that in fully coupled models, changes in tropical wind-stress can be linked to decadal variability in the coupled system that is mediated by higher baroclinic modes. Our results support the idea that higher baroclinic modes in the tropics may indeed be present with relatively large amplitude. Second, low-resolution models appear to overestimate the capacity of the ocean to carry propagating signals all of the way across the basin at midlatitudes, especially at decadal time scales. In the runs of Dawe and Thompson (2005), the temperature anomalies associated with the internal mode of variability have amplitude of about 1 °C, a significant anomaly on decadal time scales.

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