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Interdecadal climate regime dynamics in the North Pacific Ocean: theories, observations and ecosystem impacts

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Abstract

Basin-scale variations in oceanic physical variables are thought to organize patterns of biological response across the Pacific Ocean over decadal time scales. Different physical mechanisms can be responsible for the diverse basin-scale patterns of sea-surface temperature (SST), mixed-layer depth, thermocline depth, and horizontal currents, although they are linked in various ways. In light of various theories and observations, we interpret observed basinwide patterns of decadal-scale variations in upper-ocean temperatures. Evidence so far indicates that large-scale perturbations of the Aleutian Low generate temperature anomalies in the central and eastern North Pacific through the combined action of net surface heat flux, turbulent mixing and Ekman advection. The surface-forced temperature anomalies in the central North Pacific subduct and propagate southwestwards in the ocean thermocline to the subtropics but apparently do not reach the equator. The large-scale Ekman pumping resulting from changes of the Aleutian Low forces western-intensified thermocline depth anomalies that are approximately consistent with Sverdrup theory. These thermocline changes are associated with SST anomalies in the Kuroshio/Oyashio Extension that are of the same sign as those in the central North Pacific, but lagged by several years. The physics of the possible feedback from the SST anomalies to the Aleutian Low, which might close a coupled ocean–atmosphere mode of decadal variability, is poorly understood and is an area of active research. The possible responses of North Pacific Ocean ecosystems to these complicated physical patterns is summarized. © 2000 Elsevier Science Ltd. All rights reserved.

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Contents

1. Introduction

Variations of oceanic physical variables are clearly involved in many aspects of the variability of biological populations on seasonal and interannual timescales. But there is great uncertainty of the mechanisms by which decadal variations of physical variables influence biological populations (e.g., Beamish & McFarlane, 1989; Beamish, 1995; Holloway & Muller, 1998). While physical variables are known to change on decadal timescales, their preferred frequencies, their characteristic patterns and their relative temporal phasing are still being sorted out. In order to determine the influence of physical ocean climate variations on North Pacific biological populations better, it is useful to outline what processes are likely to control these variations on decadal timescales.

The decadal variations in the physics can take the form of gradual drifts, smooth oscillations or step-like shifts such as those of 1976–77 (Ebbesmeyer, Cayan, McLain, Nichols, Peterson & Redmond, 1991; Trenberth & Hurrell, 1994; Miller, Cayan, Barnett, Graham & Oberhuber, 1994b; Wu & Hsieh, 1999) and of 1989 (Hare & Mantua, 2000). Many theories have recently been proposed to explain the decadal variations of the midlatitude North Pacific Ocean (e.g., see the recent review by Latif, 1998), often predicting oscillatory behavior in the presence of a stochastic component. Related observational studies have sought to uncover the characteristic signatures of these decadal variations, but the temporally and spatially limited observations preclude definitive characterizations of oscillatory, step-like or random behavior.

The biological variability may not linearly mimic the decadal variations in the physical forcing. Attention is often focussed on identifying whether or not a ‘regime shift' has occurred, that is, a change from a persistent and relatively stable period of biological productivity that accompanies a change after a similarly stable period in physical oceanographic variables. Our presently imprecise understanding of the physical mechanisms of decadal variations and the even greater obscurity of the biological response mechanisms, makes it difficult to define 'regime' precisely. Nonetheless, statistical techniques designed to detect step-like behavior may provide useful regime-change indicators. Examples include interversion analysis (Hare & Francis, 1995), interfering patterns of two or more decadal-scale periodicities (Minobe, 1999), and compositing techniques that posit step functions (Ebbesmeyer et al., 1991; Hare & Mantua, 2000). However, the presently limited observations cannot be used to discriminate confidently oscillatory from step-like models. For the purposes of this paper, any physical or biological state that persists over decadal timescales is considered to exhibit 'regime-like' characteristics.

Our first task here is to determine the consistency between oceanic observations and the physical processes of the various theoretical models for North Pacific decadal variability. Our second task is to summarize the proposed linkages between these physical processes and decadal changes in North Pacific oceanic ecosystems. Overall we hope that this discussion will aid in reconciling many aspects of the observations and theories of oceanic physical decadal variations and their consequent impact on biology.

2. Theoretical arguments of North Pacific decadal variations

2.1. Stochastic atmospheric forcing

The simplest theories suggest that stochastic variations in atmospheric forcing (e.g., James & James, 1989) drive the long-term ocean variations. This concept was first proposed by Hasselmann (1976) and Frankignoul and Hasselmann (1977) as a thermodynamic explanation of low-frequency sea-surface temperature (SST, hereinafter) anomaly variations. A white-noise surface heat flux forcing results in a red SST spectrum, the details of which are controlled by a feedback parameter that by balancing the random forcing at low frequencies limits the variance.

This idea has recently extended in two directions. Firstly, Barsugli and Battisti (1998) incorporated air temperature as an additional variable to explore better the local feedback processes. Their model provides an important interpretative tool for understanding the influences of specified SST anomaly experiments in atmospheric general circulation model hindcasts. Their model shows that midlatitude ocean–atmosphere coupling increases the variability in and decreases the energy flux between the atmosphere and the ocean. Second, Frankignoul, Müller and Zorita (1997) treated the dynamic problem of ocean currents driven stochastically by wind stress curl on decadal time scales, and showed that the resulting ocean velocity spectral levels are comparable to those of observations.

Stochastic models can also explain decadal-scale spectral peaks without invoking ocean–atmosphere feedback. For example, Saravanan and McWilliams (1998) proposed an advective resonance that postulates a preferred atmospheric spatial pattern (necessarily having at least one zero crossing in the ocean basin) and white noise atmospheric forcing in time (cf. Tsonis, Roebber & Elsner, 1999). If mean oceanic currents produce a preferred direction for the phase propagation of the oceanic response, a spectral peak can occur in the oceanic response without ocean–atmosphere feedback. Neelin and Weng (1999) propose that a similar stochastic resonance happens if oceanic waves provide the preferred direction of propagating oceanic response. Note that Jin (1997) and Frankignoul et al. (1997) outlined this uncoupled resonance effect in their earlier work.

The striking comparability of the spectral shapes and levels predicted by stochastic theories with observations give a zeroth order view of the way the North Pacific ocean behaves on decadal time scales. Temporal spectra of various observed oceanic variables are generally red but also exhibit weak spectral peaks at decadal timescales (e.g., Mann & Park, 1996). However, it remains unclear if these peaks are associated with random processes or the preferred frequencies of coupled modes of variability (e.g., Wunsch, 1999). The observed characteristic spatial patterns (Fig. 1) seen in SST (e.g., Tanimoto, Iwasaka, Hanawa & Toba, 1992) or in the thermocline (Miller, Cayan & White, 1998; Tourre, White & Kushnir (1999)) also may be indicative of preferred natural modes in the oceanic response or simply a passive response to the atmospheric forcing functions.

2.2. *Atmospheric teleconnections to the North Pacific*

Effects external to the midlatitude North Pacific may also directly force part of its decadal variability. For example, if there are decadal oscillations intrinsic to the tropical Pacific, they are likely to teleconnect to the midlatitudes (Bjerknes, 1966; Alexander, 1992; Lau, 1997) and produce decadal variations there which resemble the interannual patterns associated with El Niño (e.g., Zhang, Wallace & Battisti, 1997; Zhang, Sheng & Shabbar, 1998b). Such a teleconnection process was invoked by Trenberth (1990), Graham (1994) and Graham, Barnett, Wilde, Ponater and Schubert (1994) to explain aspects of the 1976–77 climate shift in the North Pacific (Trenberth & Hurrell, 1994). Indeed, some coupled models are found to be capable of generating decadal oscillations intrinsic to the tropics (e.g., Tziperman, Cane & Zebiak, 1995; Yukimoto et al., 1996; Knutson & Manabe, 1998; Schneider, 2000) these may teleconnect through the atmosphere to the midlatitudes forcing changes in SST and ocean currents.

This atmospheric teleconnection view was supported by Miller, Cayan, Barnett, Graham and Oberhuber (1994a) and Miller et al. (1994b) who showed that the modeled SST pattern associated with the 1976–77 shift can be viewed as a response to local surface forcing by the atmosphere without ocean feedback. As the Aleutian Low strengthens and westerly winds increase in the central North Pacific, the SST cools in response to enhanced surface heat–flux cooling, southward Ekman current advection of cool SST and increased turbulent mixing of underlying cooler water. In the eastern North Pacific, SST warms because the strengthened Aleutian Low results in increased southerly winds which are warmer and moister than normal and

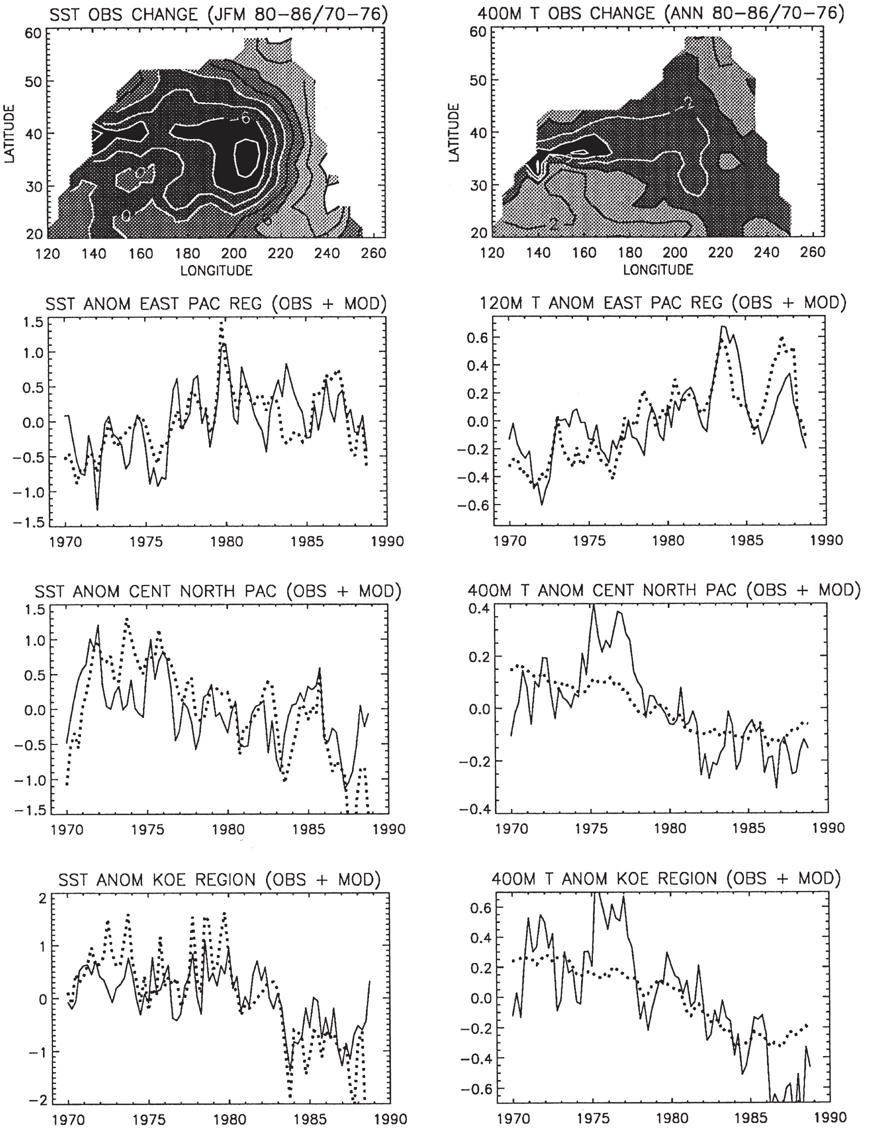

Fig. 1. Difference maps of the 7-year periods 1980–1986 relative to 1970–1976 for (a) observed winter (January–February–March) SST and (b) observed annual 400 m temperature (based on the White, 1995, objective analysis of XBT observations). Contour intervals (CI) are 0.3°C for SST and 0.2°C for 400 m with darker (lighter) shading negative (positive). Time series of observed (solid) and modeled (dotted) (c) SST and (d) 120 m temperature in the Eastern North Pacific region 135°W-coast, 25°N–45°N, (e) SST and (f) 400 m temperature in the Central North Pacific region 180°W–150°W, 30°N–40°N, and (g) SST and (h) 400 m temperature in the Kuroshio–Oyashio Extension region 150°E–180°W, 35°N–40°N. The depths 120 m and 400 m are representative of the local depths of the thermocline. The model (Miller et al., 1994a) is a coarse resolution primitive equation model (isopycnal coordinates with surface mixed layer) driven from 1970–88 by observed anomalies of surface wind stresses and heat fluxes.

hence reduce surface heat loss (Cayan, Miller, Barnett, Graham, Ritchie & Oberhuber, 1995). The southerly winds during the 1976–77 winter also resulted in eastward Ekman currents that advected warmer open ocean SST towards the climatologically cooler region near the coast. During other time intervals, however, variations in horizontal advection and mixing are usually much smaller than the dominant heat–flux forcing in the eastern North Pacific. This SST pattern, with opposite polarity in the central and eastern North Pacific (Fig. 1a), occurs so commonly on seasonal, interannual and decadal timescales (Tanimoto et al., 1992) that we refer to it below as the 'canonical SST pattern'.

Associated with the canonical SST pattern of the 1976–77 shift was a pattern of altered mixed-layer depth (MLD, hereinafter). Modeled MLD changes indicate that there was a deepening in the central North Pacific but a shallowing in the northeastern Pacific (Fig. 2; Polovina, Mitchum, Graham, Craig, DeMartini & Flint, 1994), consistent with the temperature observations by Polovina, Mitchum and Evans (1995); Deser, Alexander and Timlin (1996). However, salinity effects (which were not contemporaneously observed) may have contributed strongly to density and the determination of MLD in those regions (Freeland, Denman, Wong, Whitney & Jacques, 1997; Royer, 1981; Overland, Salo & Adams, 1999)). On the other hand, unpublished ocean model hindcasts of MLD by the authors that also include anomalous fresh-water fluxes specified from NCEP reanalyses, do not differ appreciably from hindcasts that only include wind stress and heat flux anomalies.

Recent studies (Deser & Blackmon, 1995; Nakamura, Lin & Yamagata, 1997; Miller et al., 1998; Enfield & Mestas-Nuñez, 1999; Xie, Kunitani, Kubokawa, Nonaka & Hosoda, 2000) suggest there are two complementary modes of decadal SST variability in the North Pacific Ocean. One is consistent with the tropical teleconnection forcing, i.e., the cold central and warm eastern North Pacific canonical SST pattern of Fig. 1a. The second is associated with the Kuroshio/Oyashio Extension

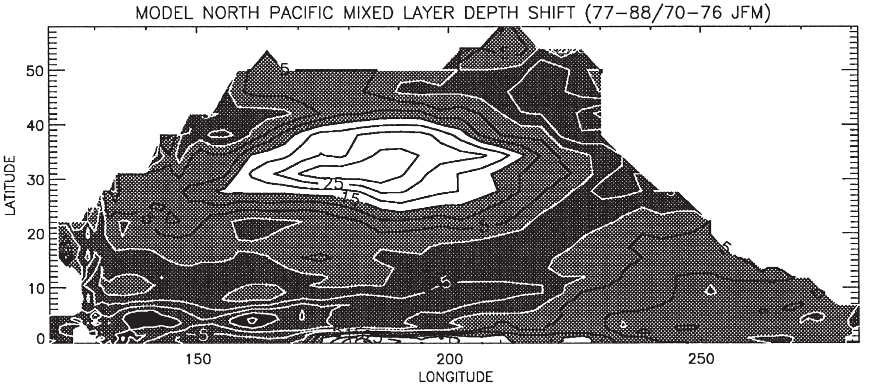

Fig. 2. Difference map of the 10-year averaged period 1977–1988 less the 6-year averaged period 1970–76 of the mixed-layer depth change from the model of Miller et al. (1994a). This can be compared directly with the observed change computed by Deser et al. (1996) using only temperature observations. (Effects of fresh-water fluxes on surface stability may be significant, however, as discussed by Freeland et al., 1997.)

(KOE, hereinafter), i.e., the cold anomaly seen Fig. 1a in the western North Pacific. The SST anomalies in the KOE region lag the central Pacific canonical SST pattern anomalies by roughly five years (Fig. 3). This distinction will be elaborated later in the context of midlatitude ocean–atmosphere feedback processes.

Decadal variations originating in other regions may also teleconnect via the atmosphere to the North Pacific. The Arctic region may support decadal oscillations as a result of ice–ocean–atmosphere feedbacks (e.g., Bitz, Battisti, Moritz & Beesley, 1996; Mysak & Venegas, 1998) and these could drive a subarctic oceanic response via the Arctic Oscillation's footprint on the high-latitude North Pacific (Thompson and Wallace, 1998), but links to the North Atlantic Ocean sector are more direct. Variations in direct solar irradiance also have been associated with decadal timescale changes of the upper-ocean heat content of the global ocean (White, Lean, Cayan & Dettinger, 1997).

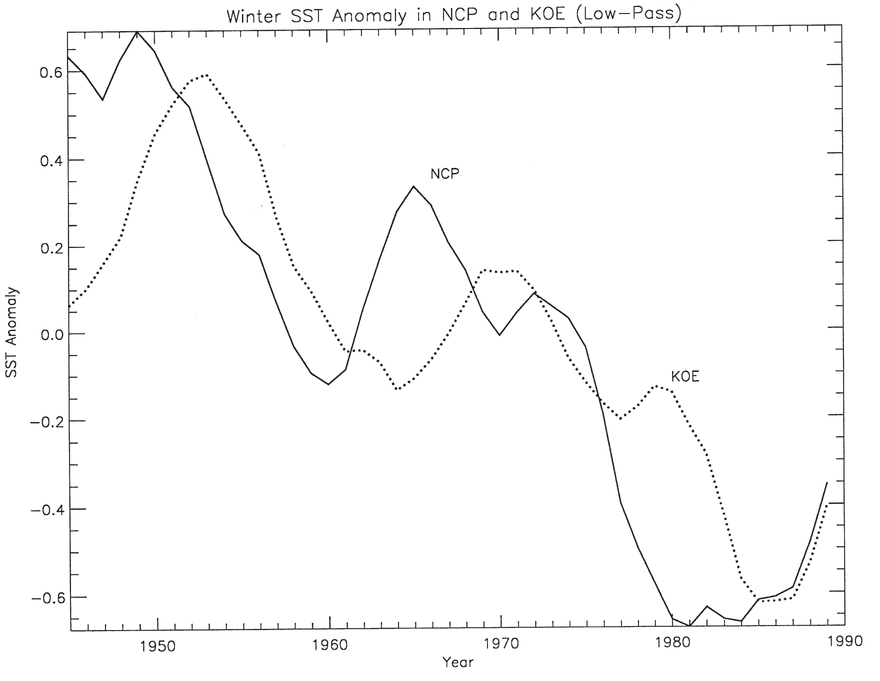

Fig. 3. Time series of the SST anomalies in the central North Pacific (180°W–150°W; 30°N–40°N; solid line) and the Kuroshio/Oyashio Extension region (150°E–180°E; 35°N–40°N; dotted line) from the Da Silva, Young and Levitus (1994) analysis of COADS showing the approximately five-year lag of of the KOE SST anomalies with respect to the central North Pacific canonical pattern of SST anomalies. The anomalies are low-pass filtered with a nine-year triangular running mean. The maximum correlation occurs at a five-year lag.

2.3. Midlatitude ocean–atmosphere interactions

On sufficiently long time scales significant thermal feedback from the midlatitude ocean to the overlying atmosphere must occur. However, the strength of the midlatitude ocean-to-atmosphere feedbacks as a function of time scale is unknown. Several models have suggested these feedbacks are important on decadal timescales.

Latif and Barnett (1994, 1996) proposed a midlatitude ocean–atmosphere feedback mechanism to explain a coupled ocean–atmosphere model that exhibits oscillations with roughly 20-year period. They interpreted that oscillation as follows. An initial, say, cold SST anomaly in the Kuroshio Extension grows via some ocean–atmosphere feedback process (e.g., Palmer & Sun, 1985; Miller, 1992). The atmospheric pressure pattern excited during this feedback process is associated with wind-stress curl changes (Ekman pumping) which force Rossby waves. These Rossby waves arrive at the western boundary many years later and subsequently enhance the poleward transport of the subtropical gyre western boundary current. This enhances the heat transport into the Kuroshio Extension, eventually reversing the sign of the originally cold SST anomaly. Robertson (1996) showed that a subtropical gyre advective effect that is balanced by surface heat fluxes into the atmosphere leads to decadal variations in another coupled model.

Simpler versions of this type of feedback mechanism have been analyzed by many authors (Jin, 1997; Xu, Barnett & Latif, 1998; Goodman & Marshall, 1998; Talley, 1999; Neelin & Weng, 1999; Münnich, Latif, Venzke & Maier-Reimer, 1998; Watanabe & Kimoto, 2000). These simpler models usually rely on two questionable approximations: specifying direct relationships between thermocline depth and SST anomalies, which is not generally valid in midlatitudes; and between SST anomalies and the overlying atmospheric response, the mechanisms for which are still unclear (e.g., Lau, 1997). Cessi (2000), on the other hand, derives a consistent approximation for the non-linear effects of synoptic-scale variability of the atmosphere in her model that exhibits decadal oscillations as a result of gyre-scale processes affecting oceanic heat transport and SST. These theoretical models allow a simple and quantitative estimation of possible feedbacks loops in the midlatitude system. They suggest that the thermocline adjustment process (especially its time-lagged response) is essential to determining the period of oscillations and that the strength and nature of the ocean-to-atmosphere feedback is central in determining whether oscillations are self-sustaining or exponentially damped.

The observed subsurface temperature fluctuations (e.g., Fig. 1b) indeed exhibit a westward intensified structure in the KOE region of the subpolar gyre consistent with Sverdrup-like dynamics resulting from an increase in wind stress curl forcing from the 1970s to the 1980s. Miller et al. (1998) separated the decadal anomalies of subsurface temperature from the westward propagating ENSO-time scale anomalies (Miller, White & Cayan, 1997) in the North Pacific for the time period 1970–88. They then compared the observations to decadal temperature anomalies from a numerical hindcast forced by observed heat flux and wind stress anomalies. The model physics indeed show that wind stress curl drives the model vorticity equation yielding simulated thermocline variations similar to those observed (Fig. 1d,f,h).

Deser, Alexander and Timlin (1999) directly computed decadal changes in the zonal geostrophic current in the KOE using the subsurface temperature dataset. They showed KOE currents are consistent with wind stress curl forcing the ocean gyre but with a 4–5 year phase lag in the response of KOE currents. These complementary results give a directly observed basin-scale perspective to the previous studies of observed changes in western boundary current transport and inferences of transport changes deduced from wind stress curl (Sekine, 1988; Trenberth, 1991; Tabata, 1991; Qiu & Joyce, 1992; Watanabe & Mizuno, 1994; Hanawa, 1995; Lagerloef, 1995; Yasuda & Hanawa, 1997; Schwing, 1998).

An interesting aspect of these results is that the westward intensified thermocline changes are nearly stationary without any obvious propagating component. As the Aleutian Low wind stress curl changes on the 20-year time scale, the subpolar gyre adjusts in place with no evident westward phase propagation associated with Rossby waves which ubiquitously provide the delayed response in the simple coupled models. The subtropical gyre behaves similarly with a stationary response to overlying wind stress curl variations which lags the subpolar wind stress curl forcing by several years (Tourre et al., 1999; Miller et al., 1998). An additional oceanic signal that does propagate gives the appearance of linking the stationary western-intensified subpolar and subtropical gyre responses, but that signal is associated with anomalous subduction (to be discussed next) and thus has different physics than the adiabatically forced thermocline adjustment. The combination of these results is the appearance of a circumbasin transit of temperature anomalies, interpreted by Zhang and Levitus (1997) as an advective process (mean circulation advecting subsurface temperature anomalies). But that advection process only appears to be occurring over a short path (Schneider et al., 1999b), while the rest of the signal is wind-stress curl forced.

Returning to the oceanic surface response, the SST in the KOE region decreases approximately five years after the 1976–77 shift cooling of the the central North Pacific canonical SST pattern (Deser et al., 1996; Miller et al., 1998) as shown in Fig. 3. This is in contrast to the Latif–Barnett scenario that calls for warming in the KOE region after cooling in the central North Pacific. The cooling in the KOE is clearly associated with the gyre-scale response to wind-stress curl forcing, but it is unclear whether this KOE SST pattern results from changes in thermal structure at the base of the mixed layer, from anomalous advection by geostrophic or Ekman currents or from yet another process.

It is interesting to speculate on a possible feedback loop that differs from the Latif–Barnett interpretation as follows. An anomalously strong Aleutian Low initially forces the canonical pattern with cold central North Pacific SST as described in Section 2.2 above. This is associated with increased Ekman upwelling over the subpolar gyre and increased Ekman downwelling over the subtropical gyre, spinning up both gyres and their western boundary currents. If the heat transport of the subtropical gyre dominates, the KOE SST should warm after a few years. But this is not observed (Fig. 3). If heat transport by the subpolar gyre dominates, the KOE SST should cool after a few years, as is observed (Fig. 3). Preliminary analyses by the authors of the coupled model that contains the Latif–Barnett mode (Barnett, Pierce, Saravanan, Schneider, Dommenget & Latif, 1999) show that the canonical SST pattern leads the like-signed KOE SST by roughly five years as in Fig. 3. The subpolar may therefore be more important than the subtropical gyre in the observed decadal variation associated with the 1976–77 shift (Miller et al., 1998).

The feedbacks associated with midlatitude SST anomalies are uncertain (Lau, 1997). However, SST anomalies in the KOE region, rather than in the central North Pacific, have recently been associated with generating a significant atmospheric response that depends sensitively on the background state (e.g., Peng, Robinson & Hoerling, 1997). Continuing our speculation on the decadal feedback loop, if the cool SST in the KOE leads to a strengthened Aleutian Low (as in the equivalent barotropic response of the Palmer & Sun, 1985 model) a positive feedback results and persistent states may be established. If the cool SST in the KOE leads to a weakened Aleutian Low, a negative feedback results and decadal oscillations may follow.

If the cool SST in the KOE leads to a regional atmospheric response that does not influence the Aleutian Low, the feedback loop does not close. In that case, spectral peaks can only result from stochastic resonances (e.g., Neelin & Weng, 1999). However, Pierce et al. (personal communication) argue against such an explanation for the 20-year spectral peak in the Latif–Barnett coupled model. They show that the time sequence of the surface forcing is critical to existence of the peak since randomizing the monthly mean forcing of an ocean-only hindcast of the coupled model run causes the disappearance of the 20-year peak in the KOE. These results suggest a decadal feedback is indeed operating in the coupled model. In summary, the sensitivity of the atmosphere to KOE SST is clearly the key issue to determining whether natural decadal variability can be explained by deterministic midlatitude coupled modes or as a stochastic response (as in Section 2.1).

2.4. Tropical–extratropical interactions

Different ideas to explain midlatitude decadal variations involve tropical–extratropical interaction. Gu and Philander (1997) proposed a mechanism whereby atmospheric teleconnections from, say, warm tropical SST drive cool anomalous SST in the central North Pacific or South Pacific; this changes the temperature of water that is subducted into the thermocline and follows the mean circulation to the tropics. Once the anomalously cool subducted water reaches the tropical strip many years later it is presumed to upwell to the surface and cause the SST to cool along the equator resulting in oppositely signed teleconnection patterns.

The Gu–Philander mechanism was motivated by the analysis of Deser et al. (1996) who showed a vertical section of temperature anomalies in the North Pacific that migrate southward and downward. Schneider, Miller, Alexander and Deser (1999a) studied the same dataset (White, 1995) and examined the full three-dimensional structure of these anomalies using isotherm displacements as a surrogate for temperature. To determine if thermal anomalies can be better followed to the equator using isopycnals rather than isotherm displacements, Fig. 4 displays this subduction process by showing the anomalous depths of the σ_θ=25.5 surface estimated from time-dependent temperature and time-averaged salinity observations. The results are consistent with the isothermal framework of Schneider et al. (1999a), simple Sverdrup theory,

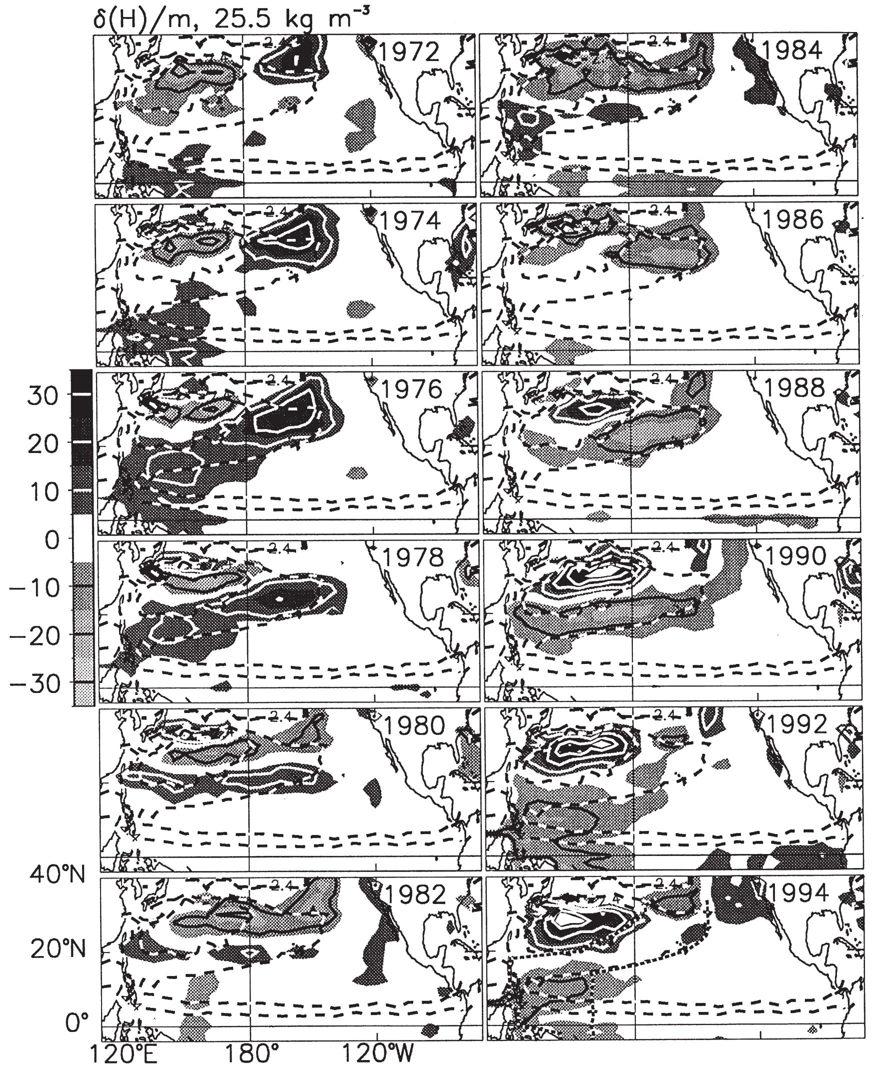

Fig. 4. Decadal anomalies in the North Pacific of the observed depth of the 25.5 kg m^{-3} isopycnal surface for years 1972 to 1994. Isopycnal depth was estimated from the White (1995) XBT data and the mean distribution of salinity (see Schneider et al., 1999b). Annual average anomalies were smoothed with a 1–2–3–2–1 filter over a 5-year interval. Dark shaded areas mark positive anomalies larger than 5 m (warm conditions) and light grey shading indicate negative anomalies larger then −5 m (cold conditions). Contour interval is 10 m, with the grey scale changing at ±5, 15 and 25 m. Overlaid as dashed lines are the 2.4×10^{-10} and 4.5×10^{-10} m^{-1} s^{-1} isolines of the potential vorticity obtained from the mean difference of depths of the 25.3 and 25.7 kg/m^3 isopycnals. The dotted lines in the lower right hand panel denote the region of zonal average used to produce Fig. 5. The anomalies follow the isolines of potential vorticity poleward of 14°N in this corridor.

more complicated ventilated thermocline theory, and full-physics ocean model hindcasts (Schneider et al., 1999a,b). Depth anomalies follow paths of the mean potential vorticity contours from north of Hawaii in the subtropical subduction zone southwestward towards 140°E, 20°N and downward from the mixed layer to 200m. Speeds of the propagation are consistent with advection by the mean subsurface currents (Fig. 5). Forcing by surface heat fluxes, Ekman advection and anomalous vertical mixing are consistent with the observed sign of the anomalies generated in the subduction source region north of Hawaii (Schneider et al., 1999a).

In contrast to the Gu–Philander hypothesis, the anomalies were extinguished

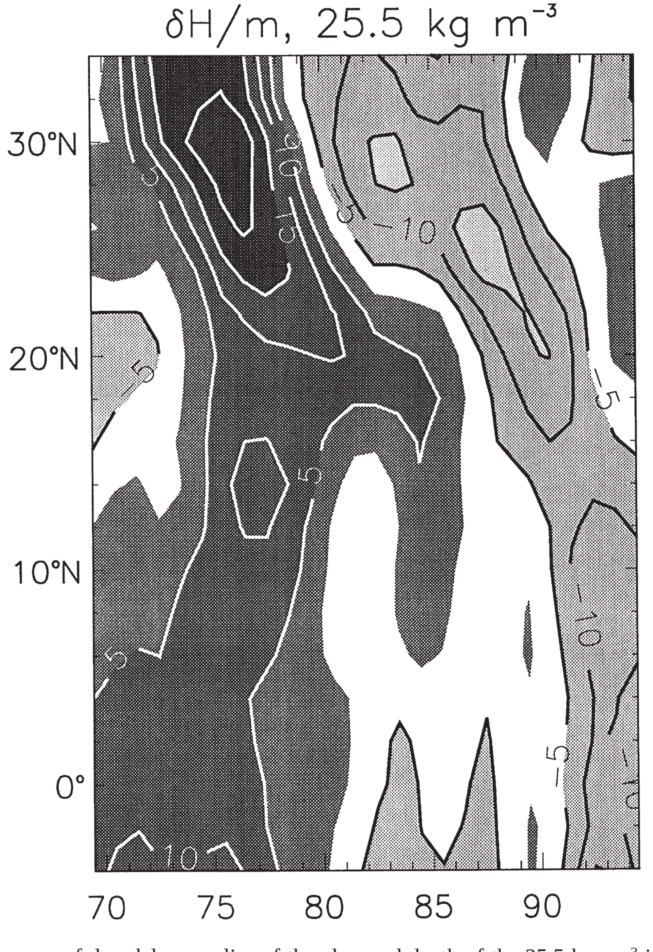

Fig. 5. Zonal average of decadal anomalies of the observed depth of the 25.5 kg m^{-3} isopycnal surface as a function of year and latitude over the region demarcated by the lines in the lower right panel of Fig. 4 (a corridor which parallels lines of constant potential vorticity). The temperature anomalies move southwestwards at a speed consistent with the zonally averaged meridional speed predicted by the model of the ventilated thermocline forced by observed mean winds from 1969 to 1993 as in Schneider et al. (1999b).

before moving south of 18°N. This is likely to be the result of vertical turbulent diffusion because three-dimensional EEOFs of temperature (discussed by Schneider et al., 1999a) reveal that temperature anomalies in this region spread downward and diminish with time. Forcing by basinwide wind stress curl anomalies was instead shown to be consistent with the thermocline variability south of 18°N.

The interpretation of the observed temperature anomalies in the undulating isopycnal framework assumes that all temperature anomalies result in density anomalies and are therefore governed by planetary baroclinic wave dynamics (Liu, 1999; Yang, personal communication). Alternatively, temperature anomalies may be accompanied by salinity anomalies such that no perturbation in density occurs. In this case the anomalies are termed spiciness anomalies (Munk, 1981) and behave in the ocean as a passive tracer rather than as baroclinic waves (e.g., Liu & Shin, 1999). The undulating isopycnal framework is supported by the explanation of observed subsurface temperature variance by forcing caused by changes of the surface wind stress and surface heat flux, but without consideration of surface fresh-water flux anomalies. Mapping temperature anomalies to a fixed time-mean σ_θ grid (Zhang & Liu, 1999) assumes that all temperature anomalies are spiciness anomalies. This interpretation of observed temperature anomalies does not account for the subsurface growth of the temperature anomalies and is therefore unlikely to be correct. However, this does not preclude the possibility that a small fraction of the temperature variance is associated with spiciness anomalies and can reach the tropics while begin advected along isopycnal surfaces.

The mean subduction pathways on isopycnal surfaces that link the midlatitudes to the tropics are indicated by the observed tritium and potential vorticity distributions (Fine, Peterson & Ostlund, 1987; Johnson & McPhaden, 1999) and ocean general circulation model studies (McCreary & Lu, 1994; Liu, Philander & Pacanowski, 1994; Rothstein, Zhang, Busalacchi & Chen, 1998; Lu, McCreary & Klinger, 1998). The two hemispheres have very different mean flow patterns. Subduction paths in the Northern Hemisphere pass mainly through low-latitude western boundary currents, regions that are not resolvable by the present temperature observations. The Southern Hemisphere, on the other hand, has a mid-oceanic and shorter subduction path from the midlatitudes to the tropics. Thus, a hypothesized coupled mode a la Gu and Philander (1997) would likely have a commensurately shorter oscillation timescale than a North Pacific analogue. Yet even with the direct mid-ocean subduction route to the tropics in the Southern Hemisphere, the scant temperature observations reveal no consistent migration of temperature anomalies towards the equator at any depth. Anomalous oceanic subduction resembling Northern Hemisphere observations does occur in uncoupled and coupled models (e.g., Venzke, 1999; Inui & Takeuchi, 1999; Pierce, Barnett & Latif, 2000), but decadal coupled modes relying on midlatitude subduction have not yet been found to occur in full-physics coupled ocean–atmosphere models. Schneider (2000) speculated that a 10-year spectral peak in a coupled ocean–atmosphere model was the result of advection of spiciness anomalies from the off-equatorial tropics to the equatorial upwelling zones.

Changes in the subduction pathways may be more important than advection along the time-mean pathways in governing the variability of spiciness anomalies. Concurrent long-term observations of salinity and temperature are only available at select longitudes. At 165°E, these indicate that the spiciness anomalies are not moving coherently from the southern hemisphere subduction regions to the equator; rather, anomalous advection dominates the variability of low-latitude spiciness variability (Kessler, 1999). Similarly, subsurface changes of the circulation as indicated by layer thickness and velocity variations partly explain spiciness variability in the northern hemisphere at 137°E between 10°N and 20°N (Suga, Kato & Hanawa, 2000); the equatorial spiciness variability for this dataset has not been explained. Thus passive tracers following the circulation may be significantly influenced by the subsurface processes of anomalous advection across mean tracer gradients and anomalous mixing; tritium subduction may therefore differ significantly from spiciness subduction because of different mean gradients.

Other types of tropical–extratropical interactions have also been proposed as mechanisms for decadal variability. Lysne, Chang and Giese (1997) noted that tropical teleconnections can force thermocline fluctuations in the midlatitudes, which propagate westward to the western boundary. If these Rossby waves can couple to equatorward propagating coastally trapped Kelvin waves, the tropical strip can be influenced by this process. Models tend to exhibit this behavior, albeit very weakly (e.g., Venzke, 1999; Shin & Liu, 2000), but it has not yet been observed in nature. Kleeman, McCreary and Klinger (1999) suggest the adjustment of the subtropical current system to wind stress anomalies teleconnected from the tropics causes a decadal signal that modulates the speed of the equatorward transports in the thermocline and provides a feedback to the tropics. White and Cayan (1998) propose that upper ocean mean currents of the eastern subtropical Pacific advect SST anomalies from the midlatitudes to the tropics to complete an atmospheric teleconnection and oceanic heat advection decadal feedback loop. Wang and Weisberg (1998) develop a simple model of interactions between the Hadley and Walker cells and upper-ocean tropical and midlatitude circulation, similar to the Gu and Philander (1997) model but including a novel (albeit postulated) Hadley cell sensitivity to middle latitude SST anomalies that has scant observational support.

2.5. Oceanic teleconnections to the midlatitudes

The oceanic wave guide along the eastern boundary of ocean basins can support Kelvin-like waves that communicate information from the tropical strip to the midlatitude eastern boundaries. These waves can radiate baroclinic Rossby waves into the ocean interior. Jacobs et al. (1994) proposed that large El Niño events such as the 1982–83 El Niño can exert an influence on the evolution of western boundary currents and KOE SST up to 10 years after the event (although Miller et al., 1997 suggest it is closer to a 5-year lag). Meyers, Johnson, Liu, O'Brien and Spiesberger (1996) suggested that a preponderance of warm tropical events after 1976–77 may have lowered the thermocline along the North American coast, and contributed to the occurrence of the observed warm state of the eastern Pacific upper ocean associated with the 1976–77 climate shift. Clarke and Lebedev (1999) argued that decadal tropical thermocline fluctuations impose a strong boundary condition on the midlatitude thermocline and could drive midlatitude decadal variations. Considering the major influence of atmospheric forcing found in the midlatitudes, it seems unlikely that these theoretical tropical ocean teleconnections have a dominant effect on midlatitude decadal variability. However, the impact of these tropical Pacific influences along the North American coast can be locally important, especially nearshore and in the thermocline where organisms are concentrated.

2.6. Intrinsic ocean variability

Intrinsic nonlinear variability of western boundary current systems with steady wind forcing have been known to generate long-time variations in currents in eddy-resolving models. For example, Holland and Haidvogel (1981) discussed vacillation cycles with periods near 480 days in the eddy field of simple flat bottom quasigeostrophic models. Spall (1996) demonstrated that a primitive equation eddy-resolving model can produce decadal variations in eddy activity through interaction with deep steady inflow/outflow boundary conditions. Other recent studies (e.g., Meacham, Dewar & Chassignet, 1998; Hazeleger, 1999; De Verdiere & Huck, 1999) have shown that simplified coupled and uncoupled eddy-resolving models also can produce interesting decadal variations that rely on the eddy effects in the recirculation zone. Theoretical multiple equilibria of currents (e.g., Jiang, Jin & Ghil, 1995) may also help to explain those long-time scale model vacillations. If these types of decadal eddy-process oscillations can occur in nature they may influence the SST distribution in the region around the atmospherically sensitive KOE region. But it is unclear if the SST anomalies would have adequately large amplitude or broad spatial scale to influence the overlying atmospheric flows. Tests of these hypotheses require studies using coupled ocean–atmosphere models that allow oceanic eddy variations to be compared with much more viscous non-eddy-resolving runs that are identical in all other respects.

3. Biological impacts

The most important physical oceanographic variables that influence biology are SST, MLD, thermocline depth, upwelling velocity, upper-ocean current fields and sea ice. Correlations between these variables and long-term changes in ecosystems can been identified but the specific mechanisms involved are usually unclear (e.g., Beamish & Bouillon, 1993; Hollowed & Wooster, 1995; Francis & Hare, 1994; Hayward, 1997; Sugimoto & Tadokoro, 1997; Francis, Hare, Hollowed & Wooster, 1998; McGowan, Cayan & Dorman, 1998; Weinheimer, Kennett & Cayan, 1999; Smith & Kaufmann, 1999; Sydeman & Allen, 1999; Brodeur, Mills, Overland, Walters & Schumacher, 1999). This is because the ecosystem can be contemporaneously influenced by many physical variables, the ecosystem is sensitive to the seasonal timing of the anomalous physical forcing, and the ecosystem itself can generate intrinsic variability on long timescales. Therefore, only the guiding influences of physical forcing rather than precise linkages are normally invoked in explaining decadal ecosystem variations (e.g., Hayward, 1997).

SST, which is strongly correlated to atmospheric sea level pressure, is the best observed oceanic physical variable over decadal timescales. Partly for this reason, studies often attempt to link SST directly to ecosystem changes. But the direct influence of SST on ecosystems is obscured by the fact that many physical processes cause SST to change (e.g., direct surface heating, horizontal current advection, upwelling, changes in mixing) so that SST anomalies can be symptomatic rather than causal.

For example, Baumgartner, Soutar and Ferreira-Bartrina (1992) used sediment records in the Santa Barbara Basin to show that sardine and anchovy populations varying on decadal and longer timescales, tend to be out of phase and are linked to SST variations over the observational record (allowing for effects of overfishing), because warmer temperatures are preferred for sardine spawning and growth in eastern boundary current systems (Lluch-Belda, Lluch-Cota, Hernandez-Vazquez & Salinas-Zavala, 1992). But it remains unclear if other physical factors that may be correlated with SST, such as horizontal current, upwelling, or mixed-layer depth variations, are involved in changing the ecological conditions (e.g., nutrient supply or primary production) in which the small pelagic fisheries oscillations are embedded. Numerical simulations of changing ocean conditions in the Santa Barbara Basin (Miller, Auad, Baumgartner and Cayan, personal communication) are underway to diagnose these processes. SST variations are also linked to sea ice distribution changes which can affect the grazing patterns of fish and their predators (e.g., Wyllie-Echeverria & Wooster, 1998). Long-term ice variations will also influence surface buoyancy and MLD during subsequent melting seasons.

The oceanic MLD can influence primary production variations on decadal timescales (Venrick, McGowan, Cayan & Hayward, 1987; Polovina et al., 1994). Primary production in the mixed layer can be limited by nutrients, as in the central North Pacific, or by light, as in the northeastern Pacific. Thus, Polovina et al. (1995) could explain increased production in both those regions after the 1976–77 regime shift because the mixed layer deepened in the central North Pacific and shallowed in the northeastern Pacific, as seen both in nature (Deser et al., 1996) and in an ocean model hindcast (Fig. 2 and Polovina et al., 1994). Mid-Pacific microbial community structures and nutrient cycling mechanisms may also be influenced by decadal variations in upper-ocean mixing conditions (Karl, 1999).

Physical oceanographic forcing of ecosystems has been linked to salmon stock variations along the North American west coast (e.g., Beamish & Bouillon, 1993; Beamish, Riddell, Neville, Thomson & Zhang, 1995; Adkison, Peterman, Lapointe, Gillis & Korman, 1996) as a means to explain the covariations of salmon species (e.g., Mantua, Hare, Zhang, Wallace & Francis, 1997). Stocks in Alaska tend to vary in phase with each other but out of phase with northwestern U.S. salmon stocks (e.g., Hare, Mantua & Francis, 1999). Many ideas have been advanced to explain this linkage (e.g., as summarized by Hare & Francis, 1995); these include direct influences of temperature anomalies on fish migration routes and concomitant predation factors, the influence of regional zooplankton productivity differences on feeding conditions (Brodeur & Ware, 1992; Brodeur, Frost, Hare, Francis & Ingraham, 1996; McGowan et al., 1998) and early life history effects on populations (Beamish & Bouillon, 1993).

This latter point was quantified by Gargett (1997), who proposed that light and nutrient limitations in the mixed layer can counterbalance to result in an optimal stability window by favoring or suppressing primary production during the near-coastal first year growth of salmon. However, the details of how the poorly-observed variables of fresh-water fluxes, streamflow, temperatures, salinity and mixing rates modulate stability along the North American boundary can affect the success of fitting such a model to the observations (Gargett, Li & Brown, 1998). Full physics ocean model hindcasts including the effects of nearshore streamflow forcing (Royer, 1981) may provide a long-term perspective to this mechanism.

Long-term decreases in macrozooplankton in the Southern California Bight and California Current System (Roemmich & McGowan, 1995; Mullin, 1998; Lavaniegos, Gomez-Gutierrez, Lara-Lara & Hernandez-Vazquez, 1998) have drawn considerable attention as being fundamental to the health of the entire ecosystem (e.g., Veit, McGowan, Ainley, Wahls & Pyle, 1997; Holbrook, Schmitt & Stephens, 1997; Sagarin, Barry, Gilman & Baxter, 1999). The long time series of the California Cooperative Fisheries Investigations (CalCOFI) surveys give a unique long-term perspective to physical forcing of biological systems on decadal timescales. Long-term warming of the CalCOFI region is usually cited as a determinant of decreased productivity through weaker upwelling, but estimates of upwelling changes are the opposite of expected (Schwing & Mendelsohn, 1997). Interpentadal and interannual changes in CalCOFI horizontal currents can amount to 30% of the mean (Bograd, Chereskin & Roemmich, 2000) and estimates of interannual geostrophic current anomalies from TOPEX sea level are an even larger percentage of the mean (Strub and James, personal communication). But decadal-scale changes in horizontal currents simulated with models (Miller et al., 1994a) and deduced from ocean analyses (Giese & Carton, 1999) are not very large in this region and hence may not provide the dominant driving mechanism for these ecosystem changes. Instead, the dominant sources of long-term SST warming in the California Current System as diagnosed in ocean model hindcasts (Miller et al., 1994a; Auad, Miller & White, 1998) are anomalous surface heat fluxes (Section 2.2), that concomitantly cause the mixed layer to thin as a result of the increased stability of the upper ocean.

Decadal changes in thermocline depth along eastern North Pacific boundaries can be established by some combination of large-scale wind-stress curl forcing, cross-shore Ekman transport, or by poleward wave propagation from the tropics. For example, the observed deepening of the thermocline (a warming of 120 m temperature diagnosed as being driven by basin-wide wind stress curl forcing, Fig. 1d) along the boundary of the northeastern Pacific after the 1976–77 shift may have counteracted the cooling of SST expected from increased magnitudes of upwelling favorable winds during spring and summer (Schwing & Mendelsohn, 1997). Long-term changes in thermocline depth along boundaries can directly influence the preferred habitats of benthic fauna (e.g., Hollowed & Wooster, 1992; Holbrook et al., 1997) or change the characteristics of mesoscale eddy and filament formation to fundamentally affect upwelling processes and near-surface nutrient enrichment.

4. Summary

The basic features of the two observed components of decadal variability in the North Pacific Ocean are illustrated schematically in Fig. 6. The dominant pattern in the decadally varying midlatitudes is the canonical SST pattern (Fig. 1a) driven and maintained by commensurate anomalous patterns of surface heat fluxes, Ekman advection of mean SST gradients, and turbulent vertical ocean mixing, organized by the large-scale structure of the Aleutian Low. Surface-forced temperature anomalies subduct and propagate southwestward from the region north of Hawaii into the thermocline but fade out before moving south of 18°N. The large-scale Ekman pumping resulting from changes in the Aleutian Low also forces western-intensified thermocline depth anomalies that are nearly consistent with Sverdrup theory and are associated with a secondary (and lagged) pattern of decadal SST anomalies in the KOE. Possible feedbacks of this KOE SST to the North Pacific atmospheric circulation are poorly understood.

The changes observed in the thermocline in the North Pacific Ocean in the 1970s and 1980s can thus be viewed as having two distinct physical components, a part forced by wind-stress curl another part resulting from subduction. The gyre-scale thermocline anomalies and the subducted temperature anomalies then result in an

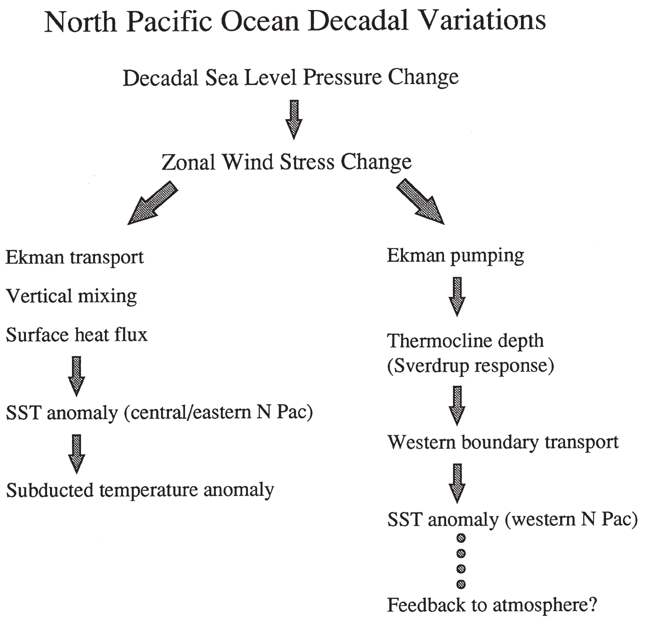

Fig. 6. Schematic diagram of the two basic components of observed decadal variations in the upper ocean of the North Pacific, each driven by the large-scale changes of the Aleutian Low atmospheric pressure system. The left panel describes SST anomalies in the central North Pacific that are driven by perturbations of the surface heat budget and subducted into the main thermocline. The right panel depicts the generation of SST anomalies in the western boundary region through a Sverdrup-like response to changes in Ekman pumping. The possible feedbacks to the atmosphere are poorly understood.

apparent propagation of temperature from the KOE eastwards to 150°W and southwestwards towards the western boundary (Tourre et al., 1999). Since different physics controls the subsurface temperature anomalies in different regions, a gyre-scale circuit of temperature anomalies advected by the mean flow does not provide an accurate description of the variability (cf. Zhang & Levitus, 1997). Moreover, the connection between the tropics and the midlatitude by anomalous subduction cannot be identified in the available dataset (Gu & Philander, 1997; Zhang, Rothstein & Busalacchi, 1998a).

Since anomalies of the central North Pacific canonical pattern lead KOE SST anomalies by roughly five years, the decadal feedback mechanism suggested by Latif and Barnett (1994) must be re-evaluated. Determining the details of the response of the gyres (subpolar or subtropical) to the wind-stress curl forcing, the response of the SST to the gyre changes and the response of the atmosphere to the KOE SST anomalies are now the key tasks for closing an intrinsic midlatitude decadal feedback loop. A mixture of stochastic forcing by the atmosphere, direct forcing from tropical atmospheric teleconnections and a weakly coupled gyre-circulation mode appear to be the most consistent theoretical explanation for the observed decadal variability of the midlatitude Pacific Ocean during the 1970s–1990s. Determining the influence of these complicated patterns on ecosystem dynamics is a major scientific goal for future decades.

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References

Adkison, M. D., Peterman, R. M., Lapointe, M. F., Gillis, D. M., & Korman, J. (1996). Alternative models of climatic effects on sockeye salmon, *Oncorhynchus nerka*, productivity in Bristol Bay, Alaska, and the Fraser river, British Columbia. *Fisheries Oceanography*, *5*, 137–152.

Alexander, M. A. (1992). Midlatitude atmosphere ocean interaction during El Niño. 1. The North Pacific Ocean. *Journal of Climate*, *5*, 944–958.

Auad, G., Miller, A. J., & White, W. B. (1998). Simulation of heat storages and associated heat budgets in the Pacific Ocean — 2. Interdecadal timescale. *Journal of Geophysical Research*, *103*, 27621–27636.

Barnett, T. P., Pierce, D. W., Saravanan, R., Schneider, N., Dommenget, D., & Latif, M. (1999). Origins of the midlatitude Pacific decadal variability. *Geophysical Research Letters*, *26*, 1453–1456.

Barsugli, J. J., & Battisti, D. S. (1998). The basic effects of atmosphere–ocean thermal coupling on midlatitude variability. *Journal of the Atmospheric Sciences*, *55*, 477–493.

Baumgartner, T. R., Soutar, A., & Ferreira-Bartrina, V. (1992). Reconstruction of the history of Pacific sardine and Northern anchovy populations over the past 2 millennia from sediments of the

Santa-Barbara Basin, California. *California Cooperative Oceanic Fisheries Investigations Reports*, *33*, 24–40.

Beamish, R. J. (1995). Climate change and northern fish populations, Canadian Special Publication, *Fisheries and Aquatic Sciences*, *121*, 739 pp.

Beamish, R. J., & Bouillon, D. R. (1993). Pacific salmon production trends in relation to climate. *Canadian Journal of Fisheries and Aquatic Sciences*, *50*, 1002–1016.

Beamish, R. J., Riddell, B. E., Neville, C. E. M., Thomson, B. L., & Zhang, Z. Y. (1995). Declines in Chinook salmon catches in the Straight of Georgia in relation to shifts in the marine environment. *Fisheries Oceanography*, *4*, 243–256.

Beamish, R. J., & McFarlane, G. A. (1989). Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. Canadian Special Publications, *Fisheries and Aquatic Science*, *108*, 379 pp.

Bitz, C. M., Battisti, D. S., Moritz, R. E., & Beesley, J. A. (1996). Low-frequency variability in the arctic atmosphere, sea ice, and upper-ocean climate system. *Journal of Climate*, *9*, 394–408.

Bjerknes, J. (1966). A possible response to the atmospheric Hadley circulation to equatorial anomalies of temperature. *Tellus*, *18*, 820–829.

Bograd, S. J., Chereskin, T. K., & Roemmich, D. (2000). Transport of mass, heat, salt and nutrients in the California Current System: annual cycle and interannual variability. *Journal of Geophysical Research* (in press).

Brodeur, R. D., & Ware, D. M. (1992). Interannual and interdecadal changes in zooplankton biomass in the subarctic Pacific Ocean. *Fisheries Oceanography*, *1*, 32–38.

Brodeur, R. D., Frost, B. W., Hare, S. R., Francis, R. C., & Ingraham, W. J. (1996). Interannual variations in zooplankton biomass in the Gulf of Alaska, and covariation with California current zooplankton biomass. *California Cooperative Oceanic Fisheries Investigations Reports*, *37*, 80–99.

Brodeur, R. D., Mills, C. E., Overland, J. E., Walters, G. E., & Schumacher, J. D. (1999). Evidence for a substantial increase in gelatinous zooplankton in the Bering Sea, with possible links to climate change. *Fisheries Oceanography*, *8*, 296–306.

Cayan, D. R., Miller, A. J., Barnett, T. P., Graham, N. E., Ritchie, J. N., & Oberhuber, J. M. (1995). Seasonal–interannual fluctuations in surface temperature over the Pacific: effects of monthly winds and heat fluxes. Natural Climate Variability on Decadal-to-Century Time Scales, National Academy Press, Washington, DC, 133–150.

Cessi, P. (2000). Coupled dynamics of ocean currents and midlatitude storm tracks. *Journal of Climate*, *13*, 232–244.

Clarke, A. J., & Lebedev, A. (1999). Remotely driven decadal and longer changes in the coastal Pacific waters of the Americas. *Journal of Physical Oceanography*, *29*, 828–835.

Da Silva, A., Young, A. C., & Levitus, S. (1994). Atlas of Surface Marine Data, Volume 2: Anomalies of Directly Observed Quantities. NOAA Atlas NESDIS 7, U.S. Department of Commerce, U.S. Gov. Printing Office, Washington, D.C. 416 pp.

Deser, C., & Blackmon, M. (1995). On the relationship between tropical and North Pacific sea surface temperature variations. *Journal of Climate*, *8*, 1677–1680.

Deser, C., Alexander, M. A., & Timlin, M. S. (1996). Upper ocean thermal variations in the North Pacific during 1970–1991. *Journal of Climate*, *9*, 1840–1855.

Deser, C., Alexander, M. A., & Timlin, M. S. (1999). Evidence for a wind-driven intensification of the Kuroshio Current Extension from the 1970s to the 1980s. *Journal of Climate*, *12*, 1697–1706.

De Verdiere, A. C., & Huck, T. (1999). Baroclinic instability: an oceanic wavemaker for interdecadal variability. *Journal of Physical Oceanography*, *27*, 893–910.

Ebbesmeyer, C. C., Cayan, D. R., McLain, D. R., Nichols, F. H., Peterson, D. H., & Redmond, K. T. (1991). 1976 step in the Pacific climate: forty environmental changes between 1968–75 and 1977–1984. In: *Proc. 7th Ann. Pacific Climate Workshop, California Department of Water Resources, Interagency Ecol. Stud. Prog*. Report 26.

Enfield, D. B., & Mestas-Nuñez, A. M. (1999). Multiscale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns. *Journal of Climate*, *12*, 2719–2733.

Fine, R. A., Peterson, W. H., & Ostlund, H. G. (1987). The penetration of tritium into the tropical Pacific. *Journal of Physical Oceanography*, *17*, 553–564.

Francis, R. C., & Hare, S. R. (1994). Decadal scale regime shifts in the large marine ecosystems of the Northeast Pacific: a case for historical science. *Fisheries Oceanography, 3,* 279–291.

Francis, R. C., Hare, S. R., Hollowed, A. B., & Wooster, W. S. (1998). Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. *Fisheries Oceanography, 7,* 1–21.

Frankignoul, C., & Hasselmann, K. (1977). Stochastic climate models. Part II. Application to SST anomalies and thermocline variability. *Tellus, 29,* 289–305.

Frankignoul, C., Müller, P., & Zorita, E. (1997). A simple model of the decadal response of the ocean to stochastic wind forcing. *Journal of Physical Oceanography, 27,* 1533–1546.

Freeland, H., Denman, K., Wong, C. S., Whitney, F., & Jacques, R. (1997). Evidence of change in the winter mixed layer in the Northeast Pacific Ocean. *Deep-Sea Research I, 44,* 2117–2129.

Gargett, A. E. (1997). The optimal stability window: a mechanism underlying decadal fluctuations in North Pacific salmon stocks? *Fisheries Oceanography, 6,* 109–117.

Gargett, A. E., Li, M., & Brown, R. (1998). Testing the concept of an optimal stability window. Biotic Impacts of Extratropical Climate Change in the Pacific. Aha Huliko'a Hawaiian Winter Workshop, University of Hawaii, SOEST Special Publication, 133–140.

Giese, B. S., & Carton, J. A. (1999). Interannual and decadal variability in the tropical and midlatitude Pacific Ocean. *Journal of Climate, 12,* 3402–3418.

Goodman, J., & Marshall, J. (1998). A model of decadal middle-latitude atmosphere–ocean coupled modes. *Journal of Climate, 12,* 621–641.

Graham, N. E. (1994). Decadal scale variability in the 1970s and 1980s: observations and model results. *Climate Dynamics, 10,* 135–162.

Graham, N. E., Barnett, T. P., Wilde, R., Ponater, M., & Schubert, S. (1994). Low-frequency variability in the winter circulation over the Northern Hemisphere. *Journal of Climate, 7,* 1416–1442.

Gu, D. F., & Philander, S. G. H. (1997). Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science, 275,* 805–807.

Hare, S. R., & Francis, R. C. (1995). Climate change and salmon production in the Northeast Pacific Ocean. In R. J. Beamish (Ed.), *Climate change and northern fish populations* (pp. 357–372). Canadian Special Publication of Fisheries and Aquatic Sciences, 121.

Hare, S. R., & Mantua, N. J. (2000). Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography, 47,* 103–145.

Hare, S. R., Mantua, N. J., & Francis, R. C. (1999). Inverse production regimes: Alaska and West Coast Pacific salmon. *Fisheries, 24,* 6–14.

Hanawa, K. (1995). Southward penetration of the Oyashio water system and the wintertime condition of midlatitude westerlies over the North Pacific. *Bulletin of the Hokkaido National Fisheries Institute, 59,* 103–120.

Hasselmann, K. (1976). Stochastic climate models. Part I. Theory. *Tellus, 28,* 473–485.

Hayward, T. L. (1997). Pacific Ocean climate change: atmospheric forcing, ocean circulation and ecosystem response. *Trends in Ecology and Evolution, 12,* 150–154.

Hazeleger, W. (1999). *Variability in mode water formation on the decadal time scale*. Ph.D. Dissertation, University of Utrecht. 144 pp.

Holbrook, S. J., Schmitt, R. J., & Stephens, J. S. (1997). Changes in an assemblage of temperate reef fishes associated with a climate shift. *Ecological Applications, 7,* 1299–1310.

Holland, W. R., & Haidvogel, D. B. (1981). On the vacillation of an unstable baroclinic wave field in an eddy-resolving model of the oceanic general circulation. *Journal of Physical Oceanography, 11,* 557–568.

Holloway, G., & Muller, P. (1998). Biotic impacts of extratropical climate change in the Pacific. Aha Huliko'a Hawaiian Winter Workshop, University of Hawaii, SOEST Special Publication, 156 pp.

Hollowed, A. B., & Wooster, W. S. (1992). Variability of winter ocean conditions and strong year classes of Northeast Pacific groundfish. *ICES Marine Science Symposium, 195,* 433–444.

Hollowed, A. B., & Wooster, W. S. (1995). Decadal-scale variations in the eastern subarctic Pacific: II. Response of Northeast Pacific fish stocks. In R. J. Beamish (Ed.), *Climate change and northern fish populations* (pp. 373–385). Canadian Special Publication of Fisheries and Aquatic Sciences, 121.

Inui, T., & Takeuchi, K. (1999). A numerical investigation of the subduction process in response to an abrupt intensification of the westerlies. *Journal of Physical Oceanography, 29,* 1993–2015.

Jacobs, G. A., Hurlburt, H. E., Kindle, J. C., Metzger, E. J., Mitchell, J. L., Teague, W. J., & Wallcraft, A. J. (1994). Decade-scale trans-Pacific propagation and warming effects of an El Niño anomaly. *Nature, London*, *370*, 360–363.

James, I. N., & James, P. M. (1989). Ultra-low-frequency variability in a simple atmospheric model. *Nature, London*, *342*, 53–55.

Jiang, S., Jin, F.-F., & Ghil, M. (1995). Multiple equilibria, periodic and aperiodic solutions in a wind-driven, double-gyre, shallow-water model. *Journal of Physical Oceanography*, *25*, 764–786.

Jin, F.-F. (1997). A theory of interdecadal climate variability of the North Pacific ocean–atmosphere system. *Journal of Climate*, *10*, 1821–1835.

Johnson, G. C., & McPhaden, M. J. (1999). Interior pycnocline flow from the subtropical to the equatorial Pacific Ocean. *Journal of Physical Oceanography*, *29*, 3073–3089.

Karl, D. M. (1999). A sea of change: biogeochemical variability in the North Pacific subtropical gyre. *Ecosystems*, *2*, 181–214.

Kessler, W. S. (1999). Interannual variability of the subsurface high salinity tongue south of the equator at 165°E. *Journal of Physical Oceanography*, *29*, 2038–2049.

Kleeman, R., McCreary, J. P., & Klinger, B. A. (1999). A mechanism for generating ENSO decadal variability. *Geophysical Research Letters*, *26*, 1743–1746.

Knutson, T. R., & Manabe, S. (1998). Model assessment of decadal variability and trends in the tropical Pacific Ocean. *Journal of Climate*, *11*, 2273–2296.

Lagerloef, G. S. E. (1995). Interdecadal variations in the Alaska Gyre. *Journal of Physical Oceanography*, *25*, 2242–2258.

Latif, M. (1998). Dynamics of interdecadal variability in coupled ocean–atmosphere models. *Journal of Climate*, *11*, 602–624.

Latif, M., & Barnett, T. P. (1994). Causes of decadal climate variability over the North Pacific and North America. *Science*, *266*, 634–637.

Latif, M., & Barnett, T. P. (1996). Decadal climate variability over the North Pacific and North America: dynamics and predictability. *Journal of Climate*, *9*, 2407–2423.

Lau, N. C. (1997). Interactions between global SST anomalies and the midlatitude atmospheric circulation. *Bulletin of the American Meteorological Society*, *78*, 21–33.

Lavaniegos, B. E., Gomez-Gutierrez, J., Lara-Lara, J. R., & Hernandez-Vazquez, S. (1998). Long-term changes in zooplankton volumes in the California Current System — the Baja California region. *Marine Ecology*, *169*, 55–64.

Liu, Z. (1999). Forced planetary wave response in a thermocline gyre. *Journal of Physical Oceanography*, *29*, 1036–1055.

Liu, Z., & Shin, S.-I. (1999). On thermocline ventilation of active and passive tracers. *Geophysical Research Letters*, *26*, 357–360.

Liu, Z., Philander, S. G. H., & Pacanowski, R. (1994). A GCM study of tropical–subtropical upper ocean mass exchange. *Journal of Physical Oceanography*, *24*, 2606–2623.

Lluch-Belda, D., Lluch-Cota, D. B., Hernandez-Vazquez, S., & Salinas-Zavala, C. A. (1992). Sardine population expansion in eastern boundary systems of the Pacific Ocean as related to sea surface temperature. *South African Journal of Marine Sciences*, *12*, 147–155.

Lu, P., McCreary, J. P., & Klinger, B. A. (1998). Meridional circulation cells and the source waters of the Pacific Equatorial Undercurrent. *Journal of Physical Oceanography*, *28*, 62–84.

Lysne, J., Chang, P., & Giese, B. (1997). Impact of the extratropical Pacific on equatorial variability. *Geophysical Research Letters*, *24*, 2589–2592.

Mann, M. E., & Park, J. (1996). Joint spatiotemporal modes of surface temperature and sea level pressure variability in the Northern Hemisphere during the last century. *Journal of Climate*, *9*, 2137–2162.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, *78*, 1069–1079.

McCreary, J. P., & Lu, P. (1994). Interaction between the subtropical and equatorial oecan circulation — the subtropical cell. *Journal of Physical Oceanography*, *24*, 466–497.

McGowan, J. A., Cayan, D. R., & Dorman, L. M. (1998). Climate–ocean variability and ecosystem response in the northeast Pacific. *Sciences*, *281*, 210–217.

Meacham, S. P., Dewar, W. K., & Chassignet, E. (1998). Low-frequency variability in the midlatitude coupled atmosphere–ocean system (abstract), EOS, Transactions of the American Geophysical Union, 79 Ocean Sci. Meet. Suppl., OS36.

Meyers, S. D., Johnson, M. A., Liu, M., O'Brien, J. J., & Spiesberger, J. L. (1996). Interdecadal variability in a numerical model of the northeast Pacific Ocean: 1970–89. *Journal of Physical Oceanography*, *26*, 2635–2652.

Miller, A. J. (1992). Large-scale ocean–atmosphere interactions in a simplified coupled model of the midlatitude wintertime circulation. *Journal of the Atmospheric Sciences*, *49*, 273–286.

Miller, A. J., Cayan, D. R., Barnett, T. P., Graham, N. E., & Oberhuber, J. M. (1994a). Interdecadal variability of the Pacific Ocean: model response to observed heat flux and wind stress anomalies. *Climate Dynamics*, *9*, 287–302.

Miller, A. J., Cayan, D. R., Barnett, T. P., Graham, N. E., & Oberhuber, J. M. (1994b). The 1976–77 climate shift of the Pacific Ocean. *Oceanography*, *7*, 21–26.

Miller, A. J., White, W. B., & Cayan, D. R. (1997). North Pacific thermocline variations on ENSO time scales. *Journal of Physical Oceanography*, *27*, 2023–2039.

Miller, A. J., Cayan, D. R., & White, W. B. (1998). A westward intensified decadal in the North Pacific thermocline and gyre-scale circulation. *Journal of Climate*, *11*, 3112–3127.

Minobe, S. (1999). Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: role in climatic regime shifts. *Geophysical Research Letters*, *26*, 855–858.

Mullin, M. M. (1998). Interannual and interdecadal variation in California Current zooplankton: *Calanus* in the late 1950s and early 1990s. *Global Change Biology*, *4*, 115–119.

Munk, W. (1981). Internal waves and small-scale processes. In B. A. Warren, & C. Wunsch, *Evolution of physical oceanography* (pp. 264–291). Cambridge, MA: MIT Press.

Münnich, M., Latif, M., Venzke, S., & Maier-Reimer, E. (1998). Decadal oscillations in a simple coupled model. *Journal of Climate*, *11*, 3309–3319.

Mysak, L. A., & Venegas, S. A. (1998). Decadal climate oscillations in the Arctic: a new feedback loop for atmosphere–ice–ocean interactions. *Geophysical Research Letters*, *25*, 3607–3610.

Nakamura, H., Lin, G., & Yamagata, T. (1997). Decadal climate variability in the North Pacific during recent decades. *Bulletin of the American Meteorological Society*, *78*, 2215–2225.

Neelin, J. D., & Weng, W. J. (1999). Analytical prototypes for ocean–atmosphere interaction at midlatitudes. Part I: coupled feedbacks as a sea surface temperature dependent stochastic process. *Journal of Climate*, *12*, 697–721.

Overland, J. E., Salo, S., & Adams, J. R. (1999). Salinity signature of the Pacific Decadal Oscillation. *Geophysical Research Letters*, *26*, 1337–1340.

Palmer, T., & Sun, Z. (1985). A modeling and observational study of the relationship between SST in the north-west Atlantic and the atmospheric general circulation. *Quarterly Journal of the Royal Meteorological Society*, *111*, 947–975.

Peng, S., Robinson, W. A., & Hoerling, M. P. (1997). The modeled atmospheric response to midlatitude SST anomalies and its dependence on background circulation states. *Journal of Climate*, *10*, 971–987.

Pierce, D. W., Barnett, T. P., & Latif, M. (2000). Connections between the Pacific Ocean tropics and midlatitudes on decadal time scales. *Journal of Climate*, *13*, 1173–1194.

Polovina, J., Mitchum, G. T., Graham, N. E., Craig, M. P., DeMartini, E. E., & Flint, E. N. (1994). Physical and biological consequences of a climatic event in the Central North Pacific. *Fisheries Oceanography*, *3*, 15–21.

Polovina, J., Mitchum, G. T., & Evans, G. T. (1995). Decadal and basin-scale variations in mixed layer depth and the impact on biological production in the Central and North Pacific. *Deep-Sea Research I*, *42*, 1701–1716.

Qiu, B., & Joyce, T. M. (1992). Interannual variability in the mid- and low-latitude Western North Pacific. *Journal of Physical Oceanography*, *22*, 1062–1079.

Robertson, A. W. (1996). Interdecadal variability over the North Pacific in a multi-century climate simulation. *Climate Dynamics*, *12*, 227–241.

Roemmich, D., & McGowan, J. (1995). Climatic warming and the decline of zooplankton in the California Current. *Science*, *267*, 1324–1326.

Rothstein, L. M., Zhang, R. H., Busalacchi, A. J., & Chen, D. (1998). A numerical simulation of the mean water pathways in the subtropical and tropical Pacific Ocean. *Journal of Physical Oceanography*, *28*, 322–343.

Royer, T. C. (1981). Baroclinic transport in the Gulf of Alaska Part II. A fresh water driven coastal current. *Journal of Marine Research*, *39*, 251–266.

Sagarin, R. D., Barry, J. P., Gilman, S. E., & Baxter, C. H. (1999). Climate-related change in an intertidal community over short and long time scales. *Ecological Monographs*, *69*, 465–490.

Saravanan, R., & McWilliams, J. C. (1998). Advective ocean–atmosphere interaction: an analytical stochastic model with implications for decadal variability. *Journal of Climate*, *11*, 165–188.

Schneider, N. (2000). A decadal spiciness mode in the tropics. *Geophysical Research Letters*, *27*, 257–260.

Schneider, N. S., Miller, A. J., Alexander, M. A., & Deser, C. (1999a). Subduction of decadal North Pacific temperature anomalies: observations and dynamics. *Journal of Physical Oceanography*, *29*, 1056–1070.

Schneider, N. S., Venzke, S., Miller, A. J., Pierce, D. W., Barnett, T. P., Deser, C., & Latif, M. (1999b). Pacific thermocline bridge revisited. *Geophysical Research Letters*, *26*, 1329–1332.

Schwing, F. B. (1998). Patterns and mechanisms for climate change in the North Pacific: the wind did it. Biotic Impacts of Extratropical Climate Change in the Pacific. Aha Huliko'a Hawaiian Winter Workshop, University of Hawaii, SOEST Special Publication, 29–36.

Schwing, F. B., & Mendelsohn, R. (1997). Increased coastal upwelling in the California Current system. *Journal of Geophysical Research*, *102*, 12785–12786.

Sekine, Y. (1988). Anomalous southward intrusion of the Oyashio east of Japan. I. Influence of the interannual and seasonal variations in the wind stress over the North Pacific. *Journal of Geophysical Research*, *93*, 2247–2255.

Shin, S.-I., & Liu, Z. (2000). On the response of the equatorial thermocline to extratropical buoyancy forcing. *Journal of Physical Oceanography* (in press).

Smith, K. L., & Kaufmann, R. S. (1999). Long-term discrepancy between food supply and demand in the deep eastern North Pacific. *Science*, *284*, 1174–1177.

Spall, M. A. (1996). Dynamics of the Gulf Stream/Deep western boundary current crossover. Part II: low-frequency internal oscillations. *Journal of Physical Oceanography*, *26*, 2169–2182.

Suga, T., Kato, A., & Hanawa, K. (2000). North Pacific Tropical Water: its climatology and temporal changes associated with the climate regime shift in the 1970s. *Progress in Oceanography*, *47*, 227–256.

Sugimoto, T., & Tadokoro, K. (1997). Interannual–interdecadal variations in zooplankton biomass, chlorophyll concentration and physical environment in the subarctic Pacific and Bering Sea. *Fisheries Oceanography*, *6*, 74–93.

Sydeman, W. J., & Allen, S. G. (1999). Pinniped population dynamics in central California: correlations with sea surface temperature and upwelling indices. *Science*, *284*, 1174–1177.

Tabata, S. (1991). Annual and interannual variability of baroclinic transports across Line P in the northeast Pacific Ocean. *Deep-Sea Research*, *38* (Suppl. 1), S221–S245.

Talley, L. (1999). Simple coupled mid-latitude climate models. *Journal of Physical Oceanography*, *29*, 2016–2037.

Tanimoto, Y., Iwasaka, N., Hanawa, K., & Toba, Y. (1992). Characteristic variations of sea surface temperature with multiple time scales in the North Pacific. *Journal of Climate*, *6*, 1153–1160.

Thompson, D. W. J., & Wallace, J. M. (1998). The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, *25*, 1297–1300.

Tourre, Y., White, W. B., & Kushnir, Y. (1999). Evolution of interdecadal variability in sea level pressure, sea surface temperature, and upper ocean temperature over the Pacific Ocean. *Journal of Physical Oceanography*, *29*, 1528–1541.

Trenberth, K. E. (1990). Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin of the American Meteorological Society*, *71*, 988–993.

Trenberth, K. E. (1991). Recent climate changes in the Northern Hemisphere. In M. E. Schlesinger, *Greenhouse-gas-induced climatic change: a critical appraisal of simulations and observations* (pp. 377–390). Amsterdam: Elsevier.

Trenberth, K. E., & Hurrell, J. W. (1994). Decadal atmosphere–ocean variations in the Pacific. *Climate Dynamics*, *9*, 303–319.

Tsonis, A. A., Roebber, P. J., & Elsner, J. B. (1999). Long-range correlations in the extratropical atmospheric circulation: Origins and implications. *Journal of Climate*, *12*, 1534–1541.

Tziperman, E., Cane, M. A., & Zebiak, S. E. (1995). Irregularity and locking to the seasonal cycle in an ENSO prediction model as explained by the quasi-periodicity route to chaos. *Journal of the Atmospheric Sciences*, *52*, 293–306.

Venrick, E. L., McGowan, J. A., Cayan, D. R., & Hayward, T. L. (1987). Climate and chlorophyll a: long-term trends in the central north Pacific Ocean. *Science*, *238*, 70–72.

Veit, R. R., Mcgowan, J. A., Ainley, D. G., Wahls, T. R., & Pyle, P. (1997). Apex marine predator declines ninety percent in association with changing oceanic climate. *Global Change Biology*, *3*, 23–28.

Venzke, S. (1999). *Ocean–atmosphere interactions on decadal timescales*. Ph.D. Dissertation, Universität Hamburg. 99 pp.

Wang, C. Z., & Weisberg, R. H. (1998). Climate variability of the coupled tropical–extratropical ocean–atmosphere system. *Geophysical Research Letters*, *25*, 3979–3982.

Watanabe, M., & Kimoto, M. (2000). Behavior of midlatitude decadal oscillations in a simple atmosphere–ocean system. *Journal of the Meteorological Society of Japan*, (in press).

Watanabe, T., & Mizuno, K. (1994). Decadal changes of the thermal structure in the North Pacific. *International WOCE Newsletter*, *15*, 10–13.

Weinheimer, A. L., Kennett, J. P., & Cayan, D. R. (1999). Recent increase in surface-water stability during warming off California as recorded in marine sediments. *Geology*, *27*, 1019–1022.

White, W. B. (1995). Design of a global observing system for gyre-scale upper ocean temperature variability. *Progress in Oceanography*, *36*, 169–217.

White, W. B., & Cayan, D. R. (1998). Quasi-periodicity and global symmetries in interdecadal upper ocean temperature variability. *Journal of Geophysical Research*, *103*, 21335–21354.

White, W. B., Lean, J., Cayan, D. R., & Dettinger, M. D. (1997). Response of global upper ocean temperature to changing solar irradiance. *Journal of Geophysical Research*, *102*, 3255–3266.

Wu, J. Q., & Hsieh, W. W. (1999). A modelling study of the 1976 climate regime shift in the North Pacific Ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, *56*, 2450–2462.

Wunsch, C. (1999). The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. *Bulletin of the American Meteorological Society*, *80*, 245–255.

Wyllie-Echeverria, T., & Wooster, W. S. (1998). Year to-year variations in Bering Sea ice cover and some consequences for fish distributions. *Fisheries Oceanography*, *7*, 159–170.

Xie, S.-P., Kunitani, T., Kubokawa, A., Nonaka, M., & Hosoda, S. (2000). Interdecadal thermocline variability in the North Pacific for 1958–1997: a GCM simulation. *Journal of Physical Oceanography* (in press).

Xu, W., Barnett, T. P., & Latif, M. (1998). Decadal variability in the North Pacific as simulated by a hybrid coupled model. *Journal of Climate*, *11*, 297–312.

Yasuda, T., & Hanawa, K. (1997). Decadal changes in the mode waters in the midlatitude North Pacific. *Journal of Physical Oceanography*, *27*, 858–870.

Yukimoto, S., Endoh, M., Kitamura, Y., Kitoh, A., Motoi, T., Noda, A., & Tokioka, T. (1996). Interannual and interdecadal variabilities in the Pacific in an MRI coupled GCM. *Climate Dynamics*, *12*, 667–683.

Zhang, R. H., & Levitus, S. (1997). Structure and cycle of decadal variability of upper-ocean temperature in the North Pacific. *Journal of Climate*, *10*, 710–727.

Zhang, Y., Wallace, J. M., & Battisti, D. S. (1997). ENSO-like interdecadal variability: 1900-93. *Journal of Climate*, *10*, 1004–1020.

Zhang, R. H., Rothstein, L. M., & Busalacchi, A. J. (1998a). Origin of upper-ocean warming and El Niño change on decadal scales in the tropical Pacific Ocean. *Nature, London*, *391*, 879–883.

Zhang, X. B., Sheng, J., & Shabbar, A. (1998b). Modes of interannual and interdecadal variability of Pacific SST. *Journal of Climate*, *11*, 2556–2569.

Zhang, R. H., & Liu, Z. (1999). Decadal thermocline variability in the North Pacific Ocean: two pathways around the subtropical gyre. *Journal of Climate*, *12*, 3273–3296.