The Relationship of Western Boundary Current Heat Transport and Storage to Mid-Latitude Ocean-Atmosphere Interaction

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Abstract. Much of the heat transported poleward by the ocean is carried in the midlatitude western boundary currents in the northern hemisphere, as part of the ocean's heat "conveyor belt." As these currents separate from the coastal boundaries and extend eastward into the ocean interior, the ocean steadily fluxes heat to the atmosphere. An analysis of observations shows that there are substantial interannual variations in heat transport and that much of the anomalous heat is stored locally for several years, with storage fluctuations in the Atlantic and in the Pacific Oceans in phase. The in-phase changes in heat transport are correlated with changes in wind forcing, slightly lagging the atmospheric Northern hemisphere Annular Mode. The changes in heat storage, rather than being caused by changes in air-sea fluxes, appear to be the source of interannual variations in those fluxes. The magnitude of the flux anomalies, their association with advection by the wind-forced ocean circulation, and the coherence between the two oceans all underline the importance of mid-latitude atmosphere-ocean interaction in climate variability on interannual to decadal time scales.

1. Introduction

Strong western boundary currents in the Northern Hemisphere midlatitude oceans transport heat from the warm tropical regions to 35-40°N, where much of the excess heat is fluxed to the atmosphere. Some of this heat continues on into the subpolar gyre to warm the high-latitude regions, as part of what is commonly termed the ocean's heat "conveyor belt" [*Broecker et al.*, 1989]. The convergence of the oceanic heat transport in the midlatitudes is reflected in the large annually averaged flux of heat from the ocean to the atmosphere, in excess of 100 $\mathrm{Wm^{-2}}$ [*Josey et al.*, 1999]. The transfer of heat from the ocean to the atmosphere in the midlatitudes causes an increase in the meridional heat transport of the atmosphere north of 40°N (*Trenberth and Caron* [2002], Figure 7).

Observations of sea surface height (SSH) anomalies from the TOPEX/POSEIDON radar altimeter [*Fu et al.*, 1994] since 1992 suggest that there are large interannual-to-decadal variations in the structure of these current systems [*Qiu*, 2000; *Vivier et al.*, 2002; *Dong and Kelly*, 2003]. In Figure 1 the SSH anomaly has been combined with an estimate of the mean SSH for the 10-year altimetric record to give the absolute SSH [*Kelly and Gille*, 1990; *Qiu*, 2000; *Dong*, 2003]. These maps of SSH show similar changes in the Atlantic and in the Pacific, alternating periods of positive SSH anomaly south of the current core (indicated by the closely spaced contours) in 1993 and 1999, with a period of negative SSH anomalies in 1996. Through the geostrophic relationship (altimetric SSH anomalies correspond to height changes for a constant pressure surface), changes in SSH across the current core represent changes in the strength of the geostrophic currents. Thus, the increase in the SSH difference across the boundary current, say from 1996 to 1999, represents an increase in the geostrophic surface current. Somewhat surprisingly, the variations in the SSH anomalies appear to be in phase between the North Atlantic and the North Pacific; the causes and implications of this synchronicity are discussed in Section 4.

SSH variations are also closely related to changes in heat storage, because a warming water column expands, increasing SSH, whereas a cooling water column contracts, decreasing SSH. Changes in the SSH in the Gulf Stream were shown, on seasonal time scales, to be caused primarily by seasonal variations in heat content resulting from surface heating [*Kelly et al.*, 1999]. However, as discussed below, on longer time scales, changes in the heat content are more the result of oceanic advection than of surface heating.

2. The Upper Ocean Heat Budget

To understand the causes of these fluctuations in the boundary current SSH, parallel studies of the upper ocean heat budget were conducted for the western North Pacific and North Atlantic [*Vivier et al.*, 2002; *Dong and Kelly*, 2003]. A simple upper ocean layer model, down to a depth of 800 meters, was was forced by surface heat fluxes, winds, and currents to predict temperature. Geostrophic velocity was specified from the altimeter data using a climatological vertical profile and Ekman velocity was estimated from wind stress. Sea level winds were taken from the National Center for Environmental Prediction (NCEP) Reanalysis [*Kalnay et al.*, 1996]; air-sea fluxes were derived by using the NCEP variables in the COARE bulk flux algorithm [*Fairall et al.*, 1996].

In the upper ocean heat budget, the rate of change of heat storage is balanced by surface heating, advection plus diffusion, and the vertical motion of isotherms. This motion is the result of local convergences and divergences forced by changes in the curl of the wind stress. These studies [*Vivier et al.*, 2002; *Dong and Kelly*, 2003] confirmed that changes in SSH correspond to changes in the oceanic heat content, primarily in the upper 400 meters. As expected, they showed that changes in both sea surface temperature (SST) and heat content are primarily forced by surface fluxes on seasonal time scales. However, the studies demonstrated that for longer time scales the advection of heat into the region by the currents is more important than air-sea fluxes (Figure 2).

The contribution of the isotherm motion is small relative to the other terms.

Advection can be caused either by geostrophic currents, the dominant component in the boundary currents, or by ageostrophic currents, of which the Ekman component is likely the largest part. Scaling arguments dating back to work by *Gill and Niiler* [1973] have suggested that Ekman advection dominates because this component often is nearly at right angles to the isotherms; this is the case for the western boundary currents where winds blow along the current core. On the other hand, the geostrophic current, which is in thermal wind balance, tends to flow parallel to isotherms. However, much of the poleward ocean heat transport must be accomplished by the western boundary currents, which are in geostrophic balance to a very large degree [*Johns et al.*, 1989]. Because of the large boundary current velocities (2 ms^{-1}), a slight misalignment of the currents and the isotherms will cause a large contribution to advection. This is possible because the thermal wind balance only restricts the advection of temperature by the current shear, not by the current itself.

Previous heat budget analyses have shown the importance of the Ekman component in heat advection [*Miller et al.*, 1994; *Deser et al.*, 1996], relative to the geostrophic component, outside the boundary current region. However, underestimates of geostrophic advection in the boundary current likely occur because coarse ocean circulation models and hydrographic data underestimate the boundary current speeds [*Miller et al.*, 1994]. The North Atlantic heat budget of *Dong and Kelly* [2003] and the North Pacific estimates of *Qiu* [2000] both show that advection by the geostrophic current is substantially larger than advection by the Ekman component, consistent with previous studies by *Qiu and Kelly* [1993] and *Kelly and Qiu* [1995], using geostrophic currents derived from altimeter data.

Why is it important to distinguish which velocity component is causing the advection? Identification of the mechanism responsible for advection is critical to predicting the changes in ocean heat content. The Ekman current component is a local and rapid response to the wind field, whereas the geostrophic current represents the ocean's response to ocean-basin-scale forcing and may be either rapid (days for a barotropic response) or slow (years for a baroclinic response). In addition, a lag in the ocean's response to forcing, such as that associated with Rossby waves, may be the source of a coupled oscillating response [*Marshall et al.*, 2001] or the lag may allow prediction of climate variations [*Schneider and Miller*, 2001].

3. Heat Content as a Description of Ocean State

Although many climate studies use SST to designate the state of the ocean or its contribution to climate variations, we choose here to describe the ocean state in terms of its heat content. While SST is readily available and is needed to compute an instantaneous estimate of the air-sea flux in a bulk algorithm, it is not a reliable indicator of the potential contribution of the ocean to climate variations, nor is it easily predictable. In the wintertime, when mixed layers are deep, the SST anomaly is a good indicator of anomalous heat storage, the result of anomalous surface or lateral fluxes. However, in the summertime the shallow mixed layer depth greatly affects the SST changes, for the same surface heating rate. In the fall, the seasonal deepening of the mixed layer entrains the water below and SST is strongly affected by the subsurface temperature.

The problem in using SST as an indicator of the ocean state has been quantified by *Deser et al.* [2003], who showed that SST anomalies decorrelate seasonally, whereas upper ocean heat content retains its memory over the seasonal cycle. Changes in the ocean mixed layer temperature (which differs slightly from SST owing to skin effects), depends on the air-sea flux, the mixed layer depth, the entrainment of subsurface waters, and advection. All of these terms need to be accurate to make a good prediction of SST, a heavy burden on an ocean model.

On the other hand, the vertically integrated heat budget requires less accuracy for ocean models: the heat storage rate is balanced (as described in the previous section) by surface heating, advection, and isotherm motion. The vertically integrated temperature anomaly (down to the wintertime mixed layer depth) is a measure of the total amount of heat that could be fluxed to the atmosphere or that has been fluxed into the upper ocean over time periods longer than seasons. Therefore, for time scales longer than a season, the heat content anomaly is a more robust and more predictable measure of the ocean's contribution, or response, to air-sea fluxes.

4. Interannual Variations in Heat Content

The large contributions to oceanic heat storage variations by ocean transport reflected in the heat budgets using the altimeter (Figure 2) are an intriguing indication of the ocean's role in climate; however, the altimeter record is too short to draw inferences about the climate contributions of western boundary currents on decadal time scales. The robustness of the vertically integrated heat budget suggests that it is possible to infer heat transport variations as a residual between heat storage changes and surface fluxes.

To extend the heat budget results to more than the 10-year period of the altimeter data, *Kelly* [2003] estimated heat transport convergence (lateral fluxes) from the upper ocean temperatures for 1970–2000 in the western North Pacific (the region shown in Figure 1 right panels). Assimilating upper ocean temperatures into a simple one-dimensional model, lateral fluxes were inferred from the necessary temperature adjustments, using the "unknown control" method of assimilation, as outlined in *Wunsch* [1996]. This analysis showed large changes in the oceanic heat transport convergence with periods of about five years, consistent with the estimates of *Vivier et al.* [2002] from the 1990s (Figure 3). Interannual variations in heat transport from 1970-2000 are as large as the variations in surface fluxes, with the largest heat transport convergence occurring in the 1990s. With the exception of the 1970s, when advection is weak, lateral fluxes make large contributions to the heat storage rate. During the mid

1970s and the latter part of the 1990s, the relationship between surface fluxes and lateral fluxes was particularly clear: weak (strong) lateral fluxes corresponded to anomalously small (large) heat loss to the atmosphere in the 1970s (1990s).

Keeping in mind the heat budget analyses showing that variations in heat content are in large part the result of variations in heat transport by the western boundary currents, we examine the available heat content data for the northern hemisphere mid-latitude ocean. We compute the principal components (PCs) or empirical orthogonal functions (EOFs) of heat content for both the SSH from the altimeter from 1992-2002 and for heat content data from the Joint Environmental Data Analysis Center (JEDAC) for 1955-2001.

For the SSH the fraction of variance was 39, 14, and 9%, respectively, for the first three modes. The first mode of SSH (Figure 4a) describes variations in the North Atlantic and North Pacific that are out of phase, with the pattern in the Pacific resembling that of the Pacific Decadal Oscillation (PDO) [*Hare and Mantua*, 2000]. The second mode (Figure 4b) describes variations that are in phase between the Atlantic and the Pacific, with pronounced maxima in the vicinity of the western boundary currents.

A principal component analysis, like any statistic, becomes a better representation of the data when derived from a longer time series; therefore the EOFs of heat content should give a more accurate indication of the importance of each mode than SSH, although with poorer spatial resolution (2 × 5 °). For the JEDAC data the fraction of variance in the first 3 modes was 26, 16, and 10%, respectively (Figure 5). The first mode of heat content resembles the second mode of SSH, with the Atlantic and Pacific anomalies in phase; whereas the second mode of heat content resembles the first mode of SSH, with variations out-of-phase between the two oceans. The reversal of the mode order in the SSH analysis, relative to the JEDAC analysis, suggests that the out-of-phase mode contained larger variations during the 1990s than was typical for the longer period.

The time series (principal components) reveal similarities with climate indices: the first mode of heat content resembles the Arctic Oscillation (AO) Index [*Thompson and Wallace*, 1998], whereas the second mode of heat content resembles the PDO. The SSH modes also resemble these climate indices, with the in-phase mode (EOF 2) resembling the AO and EOF 1 resembling the PDO.

The AO, defined originally by *Thompson and Wallace* [1998] has been re-examined by *Wallace and Thompson* [2002]; in the latter article zonally coherent fluctuations in the sea level pressure (SLP) fields have been described by the name "Northern Annular Mode" (NAM); the index of these variations is the first principal component of SLP anomalies. A positive NAM corresponds to anomalously strong westerlies throughout the northern hemisphere. *Wallace and Thompson* [2002] argue that the NAM is not necessarily an oscillation or a particular process, but simply describes those fluctuations that are zonally coherent. That is the sense in which we describe the corresponding heat content variations also, using the first mode of heat content.

The fact that the in-phase component of heat content variance resembles the Arctic Oscillation index (correlation of 0.49, significant at 95%, with AO leading the heat content mode by 13 months) suggests that the heat content anomalies are somehow connected with the changes in the strength of the midlatitude westerly winds.

Changes in the heat content corresponding to changes in the SLP fields can be seen in the observations, despite the relatively low fraction of variance described by the in-phase mode of heat content. For a period of weak AO (Figure 6a, 1985-1987) heat content anomalies are negative in both oceans; for a period of strong AO (Figure 6b, 1989-1991), heat content anomalies are positive. Note that the SSH principal component more closely resembles the AO than the heat content principal component (Figure 6c); we believe this problem results from poor North Atlantic heat content data, as discussed in Section 5.

The simplest connection, that changes in the westerlies cause corresponding changes in the air-sea fluxes, and therefore in heat content, can be ruled out by both the heat budget analyses and by the sign of the anomalies. One would expect strong westerlies (strong AO) to produce large heat losses from the ocean and, consequently, negative heat content anomalies. On the contrary, the heat content anomalies are positive for a strong AO. Based on the heat budget studies, we hypothesize instead that the observed changes in heat content reflect changes in heat transport caused by changes in ocean circulation, not air-sea fluxes.

The obvious next question is: what is causing the changes in the circulation in the North Atlantic and in the North Pacific and why is a large fraction of those variations in phase between the oceans? We will address that question in Section 5, but first we digress somewhat to examine the nature of the regions of large heat storage near the western boundary currents.

5. Mode Water

The analysis of heat content variations reveals large anomalies of heat storage with times scales of several years or more in the vicinity of the western boundary currents. The heat budget analyses suggest that these heat storage anomalies are primarily the result of anomalous (geostrophic) advection. Although the JEDAC data have rather coarse resolution, the altimeter data (Figure 1) show distinctive heat content variations just to the south of both the Kuroshio Extension and the Gulf Stream. This region is also the location of a thick vertically homogeneous water mass, known as "subtropical mode water" (or "18-degree water" in the Gulf Stream) [*McCartney and Talley*, 1982; *Suga and Hanawa*, 1995]. Mode water is thought to be formed during the late winter, when the mixed layer deepens and surface cooling causes deep convection. This mode water is then "subducted" under warmer waters and moves southwestward as part of the large-scale circulation [*Schneider et al.*, 1999].

The association of cooling and mode water formation suggests that an increase in the thickness of the mode water layer may be associated with a decrease in the upper ocean heat content. A recent study of the Gulf Stream region showed that the thickness of the 18-degree layer is indeed negatively correlated with heat content variations [*Dong et al*, 2003] (Figure 7). This analysis suggests that the mode water is relatively cool and the existence of a large volume of this water mass therefore corresponds to a deficit of heat. The cool mode water formed in a given year affects SST in the fall and winter of subsequent years when it is entrained into the surface mixed layer as part of the seasonal cycle. A similar relationship between the mode water layer thickness and fluctuations in the Kuroshio Extension has been found by *Yasuda and Hanawa* [1997].

Given the prevailing ideas about mode water being formed by surface fluxes, the relationships between heat content, mode water layer thickness, and advection appear contradictory. Clearly, the interaction of the mode water with the overlying atmosphere, and the largest heat losses, must occur in the late winter. However, if lower heat content implies more mode water, then the heat budget suggests that the anomalous thickness of the mode water layer is more closely related to advection than to surface fluxes. One resolution of these issues is to see advection of warm water into the boundary current region as "preconditioning" the water column for mode water formation. During periods in which the boundary current has anomalously large advection, the water column is warm and stratified and normal wintertime surface heat loss will be inadequate to form mode water; conversely, during periods of weak advection, the water column is relatively cool and unstratified and the same wintertime heat loss will cause the formation of mode water.

6. Wind forcing

We now turn to the question of the causes of the changes in ocean circulation. Within each ocean, the heat content anomalies of the western boundary current region are significantly correlated (0.40 for the Pacific and 0.50 for the Atlantic) with the variations in the (negative) wind stress curl, with curl variations leading the heat content by about one year (Fig. 8b and c). The atmosphere forces circulation changes through changes in the curl of the wind stress, which cause both a relatively rapid depth-independent (barotropic) and a slower, depth-varying (baroclinic) ocean response, usually characterized as a change in the Sverdrup transport. These correlations are consistent with stronger westerlies spinning up the midlatitude Sverdrup circulation and transporting more heat into the western boundary current regions.

To produce simultaneous increases in advection in the North Atlantic and in the North Pacific, there must be simultaneous anomalies in ocean circulation. This suggests forcing by an anomalous atmospheric circulation that is relatively uniform around the globe, such as that characterized by the NAM and discussed in Section 4. Although wind stress curl variations in the North Atlantic and in the North Pacific are far from uniform, when averaged over the region that forces the western boundary currents (Fig. 8a), the correlation between them is 0.29, which is significant at the 95% level. For comparison, the Arctic Oscillation Index is also shown. Apparently, the oceanic heat content anomalies are related to changes in the basin-scale winds, and to the extent that the winds are zonally uniform, the oceanic response is coherent between the two ocean basins.

The analyses here are limited by the accuracy of the available ocean data. As in Figure 6c, the SSH time series (green line, Figure 8b and c) more closely resembles the wind stress curl than does the JEDAC heat content. A separate estimate of the heat content (Figure 8c, dashed line) in the North Atlantic from the Levitus Atlas [*Conkright et al.*, 2002] more closely resembles SSH in the 1990s. The two heat content estimates were computed from different ocean data bases, but much of the data in those data bases are undoubtedly the same.

The short lag between wind stress curl forcing and the heat content variations is surprising, in light of numerous studies that suggest that the climatically important ocean response to wind forcing is the baroclinic response (e.g., *Marshall et al.* [2001]). The baroclinic response would lag the wind forcing by several years, longer in the wider Pacific Ocean than in the Atlantic, because Rossby waves, which propagate the adjustment to wind forcing changes, take longer to cross the Pacific. A recent study by *Schneider and Miller* [2001] showed that SST anomalies in the North Pacific could be predicted using a simple Rossby wave equation and wind stress curl anomalies. Another study, also in the North Pacific, showed that SSH anomalies could be predicted using a wind-forced baroclinic ocean model [*Qiu*, 2002]; this model was, however, unable to describe the SSH variations just south of the Kuroshio Extension (B. Qiu, personal communication, 2003), in the subtropical mode water formation region. *Gallego and Cessi* [2001] formulated a coupled ocean-atmosphere model that showed the North Atlantic and North Pacific Oceans varying in phase; the ocean response was baroclinic and, unlike what is observed here, the differences in lag time in the two oceans caused the oceans to go in and out of phase.

Alternative explanations for the ocean's response include advection by the barotropic ocean response, a coupling between baroclinic and barotropic responses, or a nonlinear response associated with the recirculation gyre dynamics [*Dewar*, 2001].

7. Heat Content and Heat Fluxes

Interannual variations in the heat storage rate in the western boundary currents are primarily caused by advection by the wind-driven gyres (Figure 2). During periods of advection, heat accumulates near the boundary currents. Excess subsurface heat decreases the generally cooling effect of entrainment into the ocean mixed layer, causing anomalously high SSTs. This, in turn, appears to cause an anomalously large heat loss to the atmosphere. Note that this scenario is entirely reversed from that of the ocean interior where heat storage is relatively small and seasonal, and heat content H is determined by the net surface flux Q_{net}, as

$$\partial H/\partial t = Q_{net} \tag{1}$$

[*Cayan*, 1992; *Bretherton and Battisti*, 2000]. In the boundary currents the predominant relationship is that of the feedback term [*Frankignoul*, 1985], as

$$H = -Q_{net} \tag{2}$$

During the 1990s, when the heat budgets could be computed directly using altimetric data for advection [*Vivier et al.*, 2002; *Dong and Kelly*, 2003], net surface fluxes appear to be negatively correlated with heat content as in (2).

In the study by *Kelly* [2003], this relationship was examined more explicitly for the 30-year period 1970-2000 in the western North Pacific. In this study, surface fluxes and heat content were found to be negatively correlated south of the axis of the Kuroshio Extension at 35°N, where heat storage appears to be related to the mode water thickness. In addition to establishing the correlation between heat content and fluxes, this study also demonstrated the usefulness of heat content anomalies for understanding climate variations: heat content was found to have a small, but significant, skill (20%) for predicting air-sea flux anomalies up to a year in advance. SST anomalies in the Kuroshio Extension region had no such predictive skill.

To examine the zonally coherent effect of the heat content anomalies on air-sea fluxes, we regress the NCEP net surface fluxes onto the first (in-phase) mode of the heat content anomalies. This regression also shows that positive heat content anomalies are associated with anomalous fluxes of heat from the ocean to the atmosphere. To demonstrate the magnitude of this flux, we use the regression coefficients to compute the flux anomalies associated with the anomalous heat content for the year 2000 (Figure 9). Heat fluxes from ocean to the atmosphere exceed 20 $\mathrm{Wm}^{-2}$for a year in which heat content is high; these values are approximately 20% of the annual mean heat loss in these regions.

These results support our assertion that heat content variations are the primary cause of air-sea flux anomalies in the western boundary current regions, rather than the result of those anomalies.

8. Atmosphere-Ocean Coupling

The association of larger heat losses to the atmosphere with increased oceanic heat storage, caused by advection, suggests that the ocean may be forcing changes in the atmosphere in the vicinity of the western boundary currents on interannual time scales. The idea that the western boundary currents force an atmospheric response has been raised by numerous authors (e.g., *Rodwell et al.* [1999]; *Nakamura et al.* [1997]; *Joyce et al.* [2000]), particularly in regard to changing the wintertime "storm tracks." However, until recently, most modeling efforts failed to show a consistent or significant atmospheric response to the boundary current variations.

There are two possible causes for the difficulty in obtaining a robust atmospheric response, corresponding to the two basic modeling strategies used. These strategies have been dictated by the overwhelming computational problem associated with modeling the atmosphere-ocean system.

Early modeling efforts examined the response of an atmospheric model to a fixed SST anomaly (e.g., *Kushnir and Held* [1996]; *Palmer and Sun* [1985]). These experiments have generally produced weak or ambiguous results, in part because fixing the SST eliminates the ocean's ability to force surface fluxes. As we have discussed here, the SST (or heat content anomaly) is associated with oceanic advection. For a fixed (positive) SST anomaly, the model air temperature will rise to nearly eliminate the air-sea fluxes. However, the real ocean will continue to transport heat into the region, forcing SST even higher, unless the atmosphere continues to absorb the heat. A more accurate way to specify the forcing by the ocean is to specify the advection or heat transport convergence. More recent studies [*Yualeva et al.*, 2001; *Sutton and Mathieu*, 2002] have specified anomalies in the ocean's heat transport convergence (albeit only within the upper ocean mixed layer). *Yualeva et al.* [2001] found that heat transport convergences of up to 40 Wm^{-2}produced statistically significant changes in the 500-mb geopotential height fields in the model atmosphere. *Sutton and Mathieu* [2002] found that the specified heat transport convergence produced large anomalies of latent heat flux, and that the regions of largest oceanic heat loss did not have correspondingly large SST anomalies. These latter studies emphasize the importance of specifying the ocean forcing properly in climate studies.

The solution would seem to be to use coupled-ocean models, as in *Latif and Barnett* [1996]. Ideally, the coupling would solve the problem of correctly specifying the ocean's contribution to the fluxes; however, an exceedingly high spatial resolution is required to adequately resolve the western boundary currents. Ocean modelers have found [*Metzger and Hurlburt*, 2001; *Garraffo et al.*, 2002] that a spatial resolution of approximately 1/12 degree is required to obtain a realistic western boundary current.

But is this resolution necessary to properly model advection? One could imagine that a broader, slower boundary current would be sufficient for this problem, providing that the transports are realistic. This would likely be the case if there were no heat losses from the boundary current as it transported heat from the tropics poleward. However, a given water parcel is constantly losing heat to the atmosphere; therefore the longer it takes to transit the approximately 20° of latitude, the more heat that is lost to the atmosphere en route. Therefore, to accurately model the heat transport and storage, as well as the intense heat losses at 35-40°N, the ocean model must simulate the 2ms^{-1} currents within the approximately 100km-wide boundary current core.

9. Conclusions

The strong western boundary currents of the mid-latitude North Pacific and North Atlantic Oceans have been shown to have relatively large anomalies in heat transport. Much of that anomalous heat is stored near the boundary currents in the region where subtropical mode waters are formed.

About 25% of the heat content variations in the western boundary currents regions are coherent between the Atlantic and the Pacific Oceans, and are correlated with zonally uniform changes in the wind, characterized by the Northern Annular Mode (or as it is more commonly known, the Arctic Oscillation). Although it would be tempting to attribute the ocean heat content variations to changes in the surface fluxes associated with changes in wind speed, the sign and phase of the correlations is inconsistent with this idea. Instead the heat budgets in the boundary current regions show that the heat content variations are primarily the result of anomalies in advection.

Variations in advection appear to be caused by changes in the mid-latitude winds. The heat content variations lag the changes in negative wind stress curl (strength of the westerlies) by about one year. This relatively short lag suggests that the response may be, at least in part, barotropic, rather than baroclinic, as assumed in many simple coupled models. The accumulation of heat in the region from advection results in a anomalous losses of heat to the atmosphere, suggesting that the boundary current anomalies force atmospheric anomalies in the mid-latitudes.

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Figure Captions

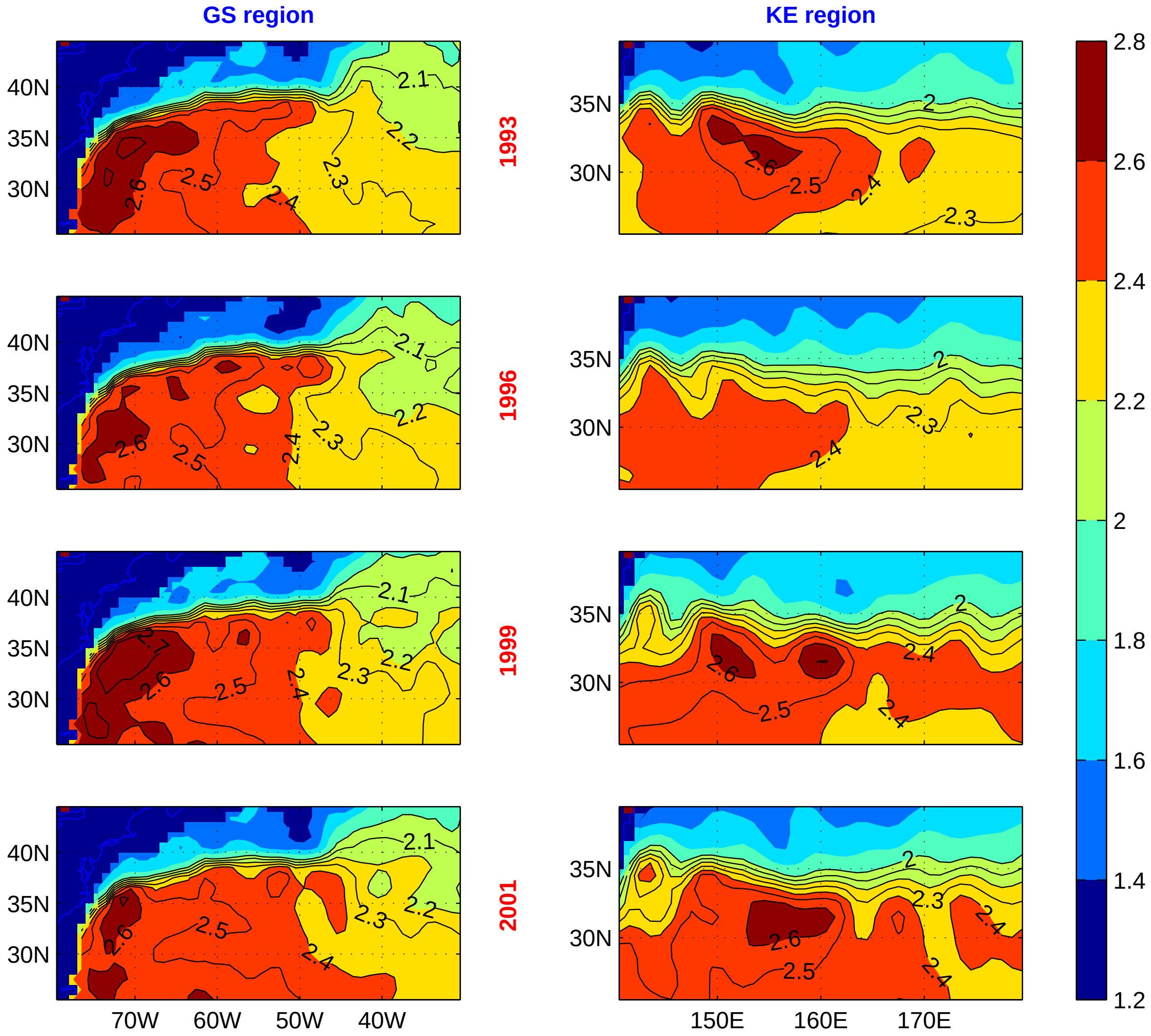
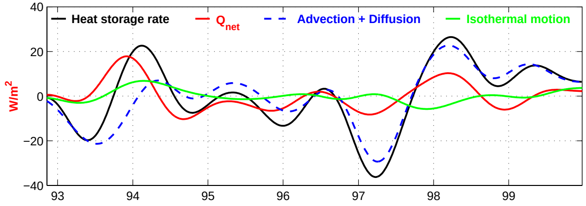
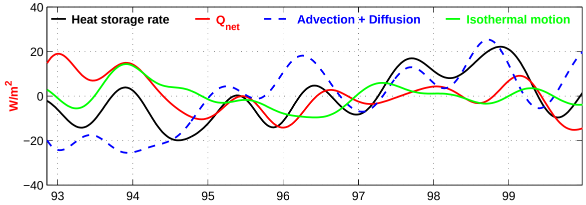


Figure 1. Sea surface height maps from the TOPEX/POSEIDON altimeter. (left) Gulf Stream region in the North Atlantic and (right) in Kuroshio Extension region in the North Pacific and for years 1993, 1996, 1999, and 2001. Units are meters. More positive SSH indicates more heat stored in the ocean.



(a) Gulf Stream



(b) Kuroshio Extension

Figure 2. Heat storage rate for the western boundary current regions. (a) Gulf Stream and (b) Kuroshio Extension. The heat storage rate (black) is the sum of the surface heating (red), the advection and diffusion (blue dashed), and the vertical motion of isotherms (green). The heat storage rate is more highly correlated with the advection-diffusion term than with either of the other terms. *After Dong and Kelly* [2003]; *Vivier et al.* [2002].

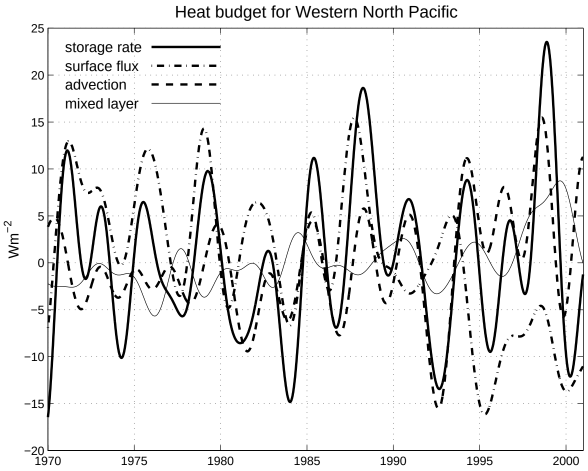


Figure 3. Heat budget of the western North Pacific: 1970-2000. The heat storage rate (black) is the sum of the surface heating (red), lateral (geostrophic) fluxes (blue dashed), and the sum of Ekman advection and a surface flux correction (green). *After Kelly [2003].*

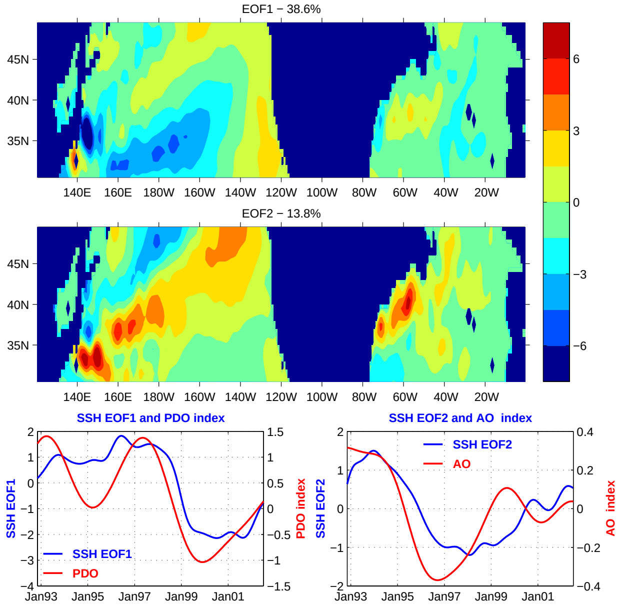


Figure 4. Empirical Orthogonal Functions of SSH. The (a) first and (b) second EOFs of SSH from the altimeter and (c) and (d) their respective time series. The first EOF describes SSH anomalies that are negative in the Pacific and positive in the Atlantic. The second EOF describes SSH anomalies that are in phase in the two oceans and have their maxima in the western boundary currents. Indices of the Pacific Decadal Oscillation and the Arctic Oscillation are shown for comparison.

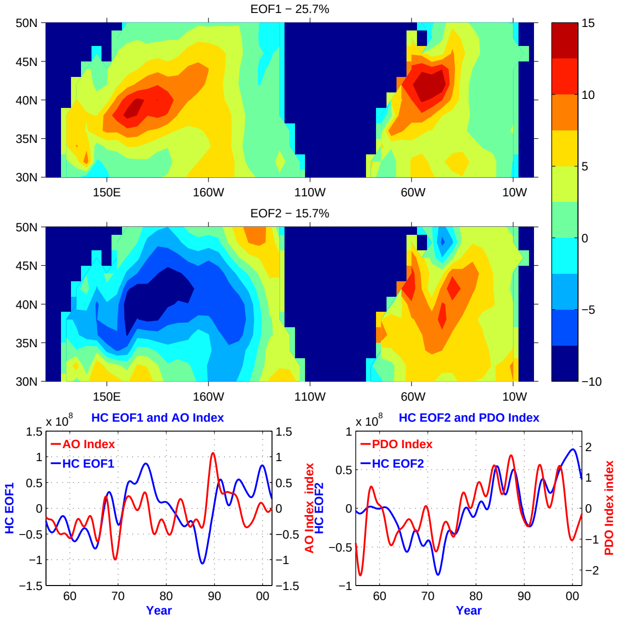


Figure 5. Empirical Orthogonal Functions of Heat Content. The (a) first and (b) second EOFs of JEDAC heat content and (c) and (d) their respective time series. The first EOF describes heat content anomalies that are in phase in the two oceans and have their maxima in the western boundary currents. The second EOF describes SSH anomalies that are negative in the Pacific and positive in the Atlantic. Indices of the Pacific Decadal Oscillation and the Arctic Oscillation are shown for comparison.

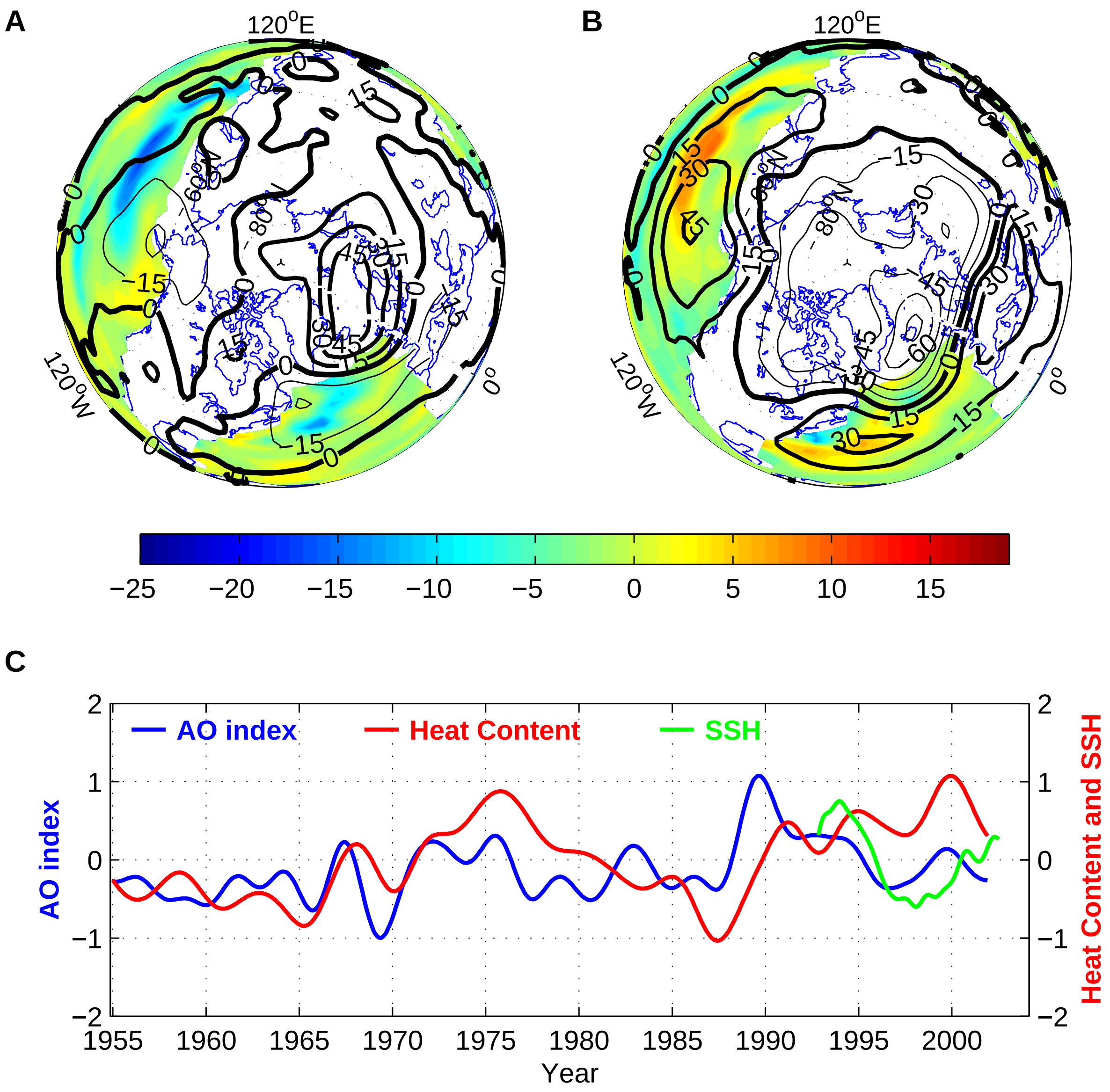


Figure 6. The Northern Annular Mode and Oceanic Heat Content. Maps of sea level pressure (contours) and oceanic heat content (color) for (a) a low index period, 1985–1987, and for (b) a high index period, 1989–1991. (c) Principal components of heat content (red) and sea surface height anomaly (green), and the Arctic Oscillation Index (blue). The correlation between the AO index and the heat content is 0.49, significant at better than 95%, with the AO leading heat content by 13 months.

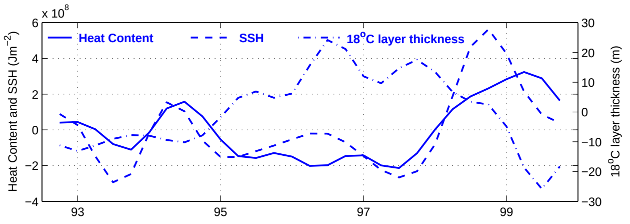


Figure 7. Heat content and mode water in the Gulf Stream region. The mean SSH (dash), heat content (solid), and the thickness of the 18°C layer (dash-dot) south of the Gulf Stream. The SSH is from the TOPEX/POSEIDON altimeter, and heat content and the layer thickness are from the GTSPP archive. *After Dong et al* [2003].

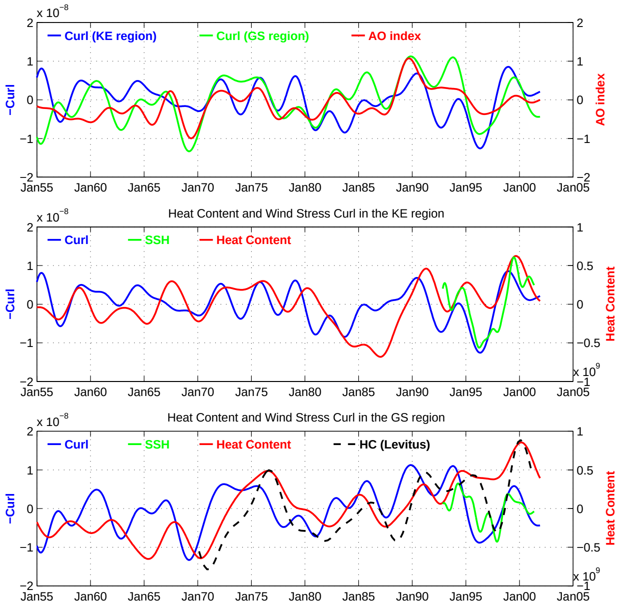


Figure 8. Wind stress curl and its relationship to heat content. (a) The negative wind stress curl in the North Atlantic [20-50°N, 10-80°W] (green), in the North Pacific [20-50°N, 140°E-130°W] (blue), and the Arctic Oscillation Index (red). Heat content (red), wind stress curl (blue), and SSH anomaly (green) in (b) the North Pacific and (c) the North Atlantic. Heat content and SSH are domain averages over 25-45°N and 140-180°E in the Pacific and 40-80°Win the Atlantic. A second estimate for the North Atlantic heat content is shown (dashed line) in (c).

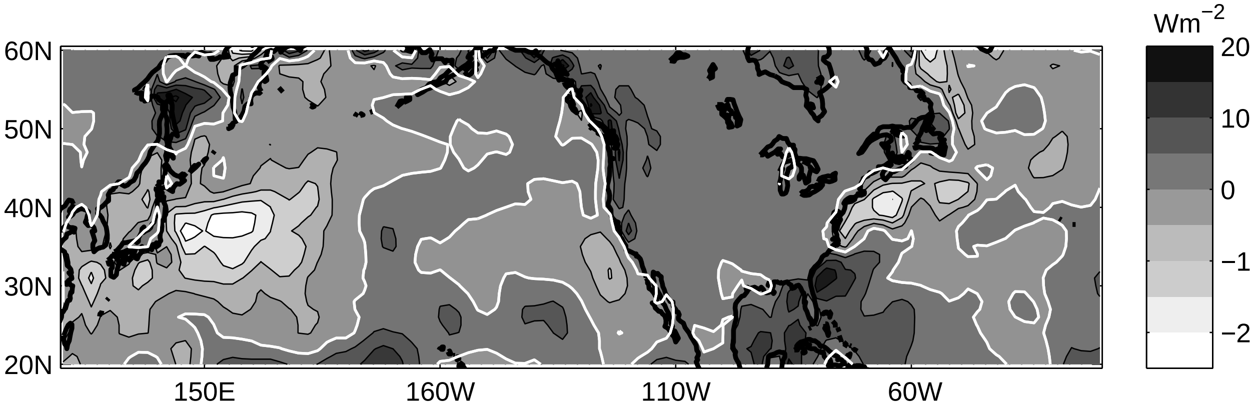


Figure 9. Relationship of net surface flux to heat content. The surface flux anomaly for the year 2000, based on a regression with the time series of the heat content in Figure 6c. Negative values indicate flux of heat from the ocean to the atmosphere. There were positive heat content anomalies in the boundary currents in 2000.