Q. J. R. Meteorol. Soc. (2002), **128**, pp. 1–xx

Is the Gulf Stream responsible for Europe's mild winters?

By R. SEAGER[1],* D. S. BATTISTI[2], J. YIN[2], N. GORDON[1], N. NAIK[1], A. C. CLEMENT[3] and M. A. CANE[1]

[1] *Lamont Doherty Earth Observatory of Columbia University, Palisades, New York, USA*
[2] *University of Washington, Seattle, Washington, USA*
[3] *Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida, USA*

(Submitted July 18th, 2001, revised January 10, 2002, April 16 2002)

SUMMARY

Is the transport of heat northward by the Gulf Stream and North Atlantic Drift, and its subsequent release into the mid-latitude westerlies, the reason why Europe's winters are so much milder than those of eastern North America and other places at the same latitude? Here, it is shown that the principal cause of this temperature difference is advection by the mean winds. South-westerlies bring warm maritime air into Europe and North-westerlies bring frigid continental air into northeastern North America. Further, analysis of the ocean surface heat budget shows that the majority of the heat released during winter from the ocean to the atmosphere is accounted for by the seasonal release of heat previously absorbed and not by ocean heat flux convergence. Therefore the existence of the winter temperature contrast between western Europe and eastern North America does not require a dynamical ocean. Two experiments with an atmospheric general circulation model coupled to an ocean mixed layer confirm this conclusion. The difference in winter temperatures across the North Atlantic, and the difference between western Europe and western North America, is essentially the same in these models whether or not the movement of heat by the ocean is accounted for. In an additional experiment with no mountains the flow across the ocean is more zonal, western Europe is cooled, the trough east of the Rockies is weakened and the cold of northeastern North America is ameliorated. In all experiments the west coast of Europe is warmer than the west coast of North America at the same latitude whether or not ocean heat transport is accounted for. In summary the deviations from zonal symmetry of winter temperatures in the Northern Hemisphere are fundamentally caused by the atmospheric circulation interacting with the oceanic mixed layer.

KEYWORDS: Gulf Stream European winters Climate

1. INTRODUCTION

It is widely believed by scientists and laypeople alike that the transport of warm water north in the Gulf Stream and North Atlantic Drift, and its release to the atmosphere, is a major reason why western Europe's winters are so much milder (as much as $15 - 20°C$) than those of eastern North America (Fig.1). The idea appears to have been popularized by M. F. Maury in his 1855 book *The Physical Geography of the Sea and its Meteorology* which went through many printings in the United States and the British Isles and was translated into three languages. In the book Maury says:

> One of the benign offices of the Gulf Stream is to convey heat from the Gulf of Mexico, where otherwise it would become excessive, and to disperse it in regions beyond the Atlantic for the amelioration of the climates of the British Isles and of all Western Europe.

Maury says that were this not to occur:

> the soft climates of both France and England would be as that of Labrador, severe in the extreme, and ice-bound.

He continues:

---

* Corresponding author: Lamont Doherty Earth Observatory of Columbia University, Palisades, New York, NY 10964, USA. email: rich@maatkare.ldeo.columbia.edu

> Every west wind that blows crosses the stream on its way to Europe, and carries with it a portion of this heat to temper there the northern winds of winter. It is the influence of this stream upon climate that makes Erin the "Emerald Isle of the Sea", and that clothes the shores of Albion in evergreen robes; while in the same latitude, on this side, the coasts of Labrador are fast bound in fetters of ice.

The idea that the poleward ocean heat transport helps make western Europe's winters the mildest of their latitude has gained wide currency with the subtle difference that the poleward flow of warm water is now more likely to be ascribed to the thermohaline circulation (THC) than the Gulf Stream *per se.* For example, in a recent paper about the possible impact of rising greenhouse gases on the THC, Latif et al. (2000) state:

> In the North Atlantic the Gulf Stream transports enormous amounts of heat poleward (1PW) as part of the THC, thereby warming western Europe.

In a prior paper on the same subject Broecker (1997) states:

> One of the major elements of today's ocean system is a conveyor-like circulation that delivers an enormous amount of tropical heat to the northern Atlantic. During winter, this heat is released to the overlying eastward moving air masses, thereby greatly ameliorating winter temperatures in northern Europe.

These statements are somewhat ambiguous (warming and ameliorating relative to what? - the ambiguity is consciously echoed in the title of this paper), but both imply that the ocean heat transport preferentially affects temperatures in parts of Europe, increasing the zonal temperature asymmetry. Hartmann (1994) explicitly appeals to the ocean heat transport as one factor needed to explain why winters in western Europe are milder than those in eastern North America:

> It appears that some of the heat carried northward by the Gulf Stream is picked up by the Norwegian Current and carried into polar latitudes. As a result, at middle and high latitudes the eastern Atlantic is much warmer at the surface than the western Atlantic Ocean. This asymmetry in the Atlantic sea surface temperature contributes to the milder winter climates of western Europe land areas compared to eastern North American land areas at the same latitude. Another major contribution to this climate asymmetry is the eastward advection of temperature in the atmosphere.

As suggested by Hartmann (1994), the contrast between American and west European winters is largely explained by the difference between a continental climate and a maritime climate. Although this is widely accepted, and few researchers would ascribe to the ocean heat transport the dominant role attributed to it by Maury, existing explanations of the contrasting winters still generally appeal to the additional influence of the poleward ocean heat transport. However, we are unaware of a quantitative demonstration of the relative importance of the three processes that contribute to the east-west asymmetry across the North Atlantic Ocean: northward heat transport by the ocean, the seasonal and local release of heat previously stored by the ocean and advection within the winter stationary waves.

In the current paper we demonstrate that transport of heat by the ocean has little influence on the contrast between the mild winters of western Europe south of $60^\circ N$ and the harsh ones of eastern North America. North of $60^\circ N$ the ocean heat transport accounts for about a quarter of the contrast by restricting winter sea ice cover. The dominant

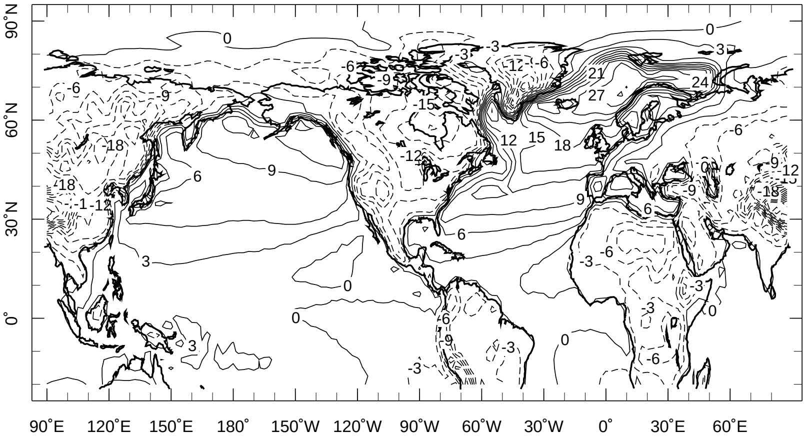


Figure 1. Departure from the zonal mean of January surface air temperature ($^\circ C$) from NCEP-NCAR Reanalysis. Parts of Western Europe (taken to mean the part of Europe west of the longitude that joins the Adriatic and the Baltic), are $15^\circ C - 20^\circ C$ warmer than parts of eastern North America and are also warmer than western North America at the same latitudes. The contrast is greatest in the maritime regions of northwest Europe (The British Isles and Scandinavia).

cause of the contrast, at both latitudes, is atmospheric advection around the Icelandic Low and the simple maritime-continental climate distinction. The exact positioning and strength of the Icelandic Low is important to the climate contrast and is shown to be greatly influenced by the orographic forcing of the Rocky Mountains. Therefore the difference in the winter climates arises fundamentally through atmospheric processes and the seasonal storage and release of heat by the ocean mixed layer. This is also all that is required to establish the difference in winter climates between the west coast of Europe and the west coast of North America at the same latitudes.

In the next section we consider the role of ocean heat transport using observational estimates of poleward heat transports, the ocean surface heat flux balance and an analysis of the heat budget of the lower levels of the atmosphere. We then proceed to describe in Section 3 results from integrations of coupled atmospheric general circulation-mixed layer ocean (AGCM-ML) models with and without specified ocean heat transports. It will be shown that the ocean heat transport does not alter the relative severity of winter climates on either side of the North Atlantic except for regions of northern Norway where it restricts the winter sea ice cover. We then show results of numerical integrations of one of the AGCM-ML models in which the mountains are removed. We briefly consider the causes of the different winter climates of the Pacific coast of Canada and Alaska and the Atlantic coast of Europe and conclude that this difference too is not the result of the greater poleward heat transport in the Atlantic Ocean. Sensitivity of the results is discussed in Section 4 and the final section summarizes our conclusions.

2. Observational analysis of North Atlantic winter climate

(*a*) *The relative roles of atmosphere and ocean in poleward heat transport*

If the atmosphere and ocean did not move heat from the tropics to mid-latitudes both North America and Europe would be much colder than they are. First, we look at how this heat transport is partitioned between atmosphere and ocean.

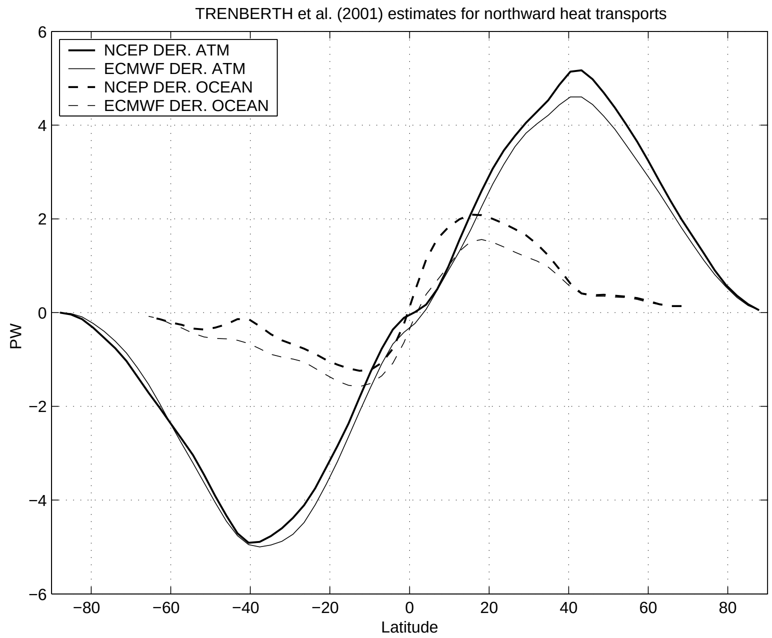


Figure 2. Estimated zonally averaged atmospheric (solid lines) and oceanic (dashed lines) northward heat transports as computed from NCEP (heavy lines) and ECMWF (light lines) reanalyses (see Trenberth et al. (2001) for more details and http://www.cgd.ucar.edu/cas/catalog/tn430 where the data resides). The heat transports are in petawatts.

Trenberth et al. (2001) have used recent reanalysis products from the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium Range Weather Forecasts (ECMWF) to derive new estimates of the atmospheric and oceanic energy transports. They directly computed the atmospheric transports from the reanalyses and used these, in combination with satellite estimates of the net radiation at the top of the atmosphere, to derive the implied surface fluxes and zonally and annually averaged ocean heat transports. The estimates are shown in Fig. 2. The ocean and atmosphere poleward transports are equal at about $15°N$ and S, with the ocean moving more in between, and an increasingly small proportion poleward of those latitudes. In the mid-latitudes the annual mean atmospheric heat transport exceeds the ocean transport by a factor of five or so. The dominance of the atmosphere is far greater than earlier estimates (e.g. Peixoto and Oort 1992) which gave more weight to the ocean. Trenberth and Caron (2001) have compared their results to direct estimates in the ocean and those derived using an inverse method by Ganachaud and Wunsch (2000) and show that the NCEP-derived estimates fall within the error bars of those estimates in the subtropics while the ECMWF-derived estimates are clearly too low. North of $40°N$, NCEP and ECMWF estimates agree with each other and with independent direct estimates. Interestingly, these recent estimates are in quantitative agreement with the early estimates of Houghton (1954) and Sverdrup (1957) as presented by Bjerknes (1964).

Clearly, the atmosphere is doing the lion's share of the poleward heat transport required to ameliorate climates at mid-latitudes. This will be even more so in northern winter when the atmospheric heat transport is greater than its annual mean while the ocean heat transport appears to be less than its annual mean (see below) *.

(*b*) *Maintenance of the zonal asymmetries of Northern Hemisphere winter temperatures*

To look more closely at the causes of the zonal asymmetries of temperature in the lower atmosphere during Northern Hemisphere winter we turned to an analysis of the balance of terms in the thermodynamic energy equation:

$$-\left(\frac{\bar{u}}{acos\theta}\frac{\partial\bar{T}}{\partial\lambda}+\frac{\bar{v}}{a}\frac{\partial\bar{T}}{\partial\theta}\right)-\bar{\omega}\left(\frac{\partial\bar{T}}{\partial p}-\frac{R\bar{T}}{pc_p}\right)-\frac{1}{acos\theta}\left(\frac{\partial\left(\overline{u'T'}\right)}{\partial\lambda}+\frac{\partial\left(\overline{v'T'cos\theta}\right)}{\partial\theta}\right)$$

$$-\left(\frac{\partial\left(\overline{\omega'T'}\right)}{\partial p}-\frac{R}{pc_p}\left(\overline{\omega'T'}\right)\right)=-\bar{Q}. \tag{1}$$

The budget is then integrated from 70000Pa to 100000Pa and then averaged over December to February. The overbars denote the monthly mean and primes denote departures from the monthly mean. Hence the transient terms include everything on sub-monthly timescales. u, v and ω are the zonal, meridional and vertical pressure velocities, respectively, T is temperature, a is the radius of the Earth, θ is latitude, λ is longitude, p is pressure, R is the gas constant and Q is the diabatic heating.

The first two terms are the stationary advection, including the zonal mean, by the horizontal flow and the stationary vertical advection. The third term is the horizontal transient eddy heat flux convergence and the fourth term is the vertical transient eddy heat flux convergence. Q, the diabatic heating, is evaluated as the residual. All terms were multiplied by c_p/g, where c_p is the specific heat capacity of dry air and g is the gravitational acceleration, to convert the units to Wm^{-2}. Calculations were performed using the NCEP Reanalyses from 1949 to 2000 (Kalnay et al. 1996). Horizontal derivatives were evaluated using centred differences and the vertical integrals were approximated using data at 1000, 925, 850, 700 and 600mb assigning each level value to a layer.

Figures 3 through 5 show the terms in the temperature equation. The stationary horizontal advection (Fig. 3a) creates the America-NW Europe contrast. Horizontal transient heat fluxes (Fig. 3b) act to oppose the asymmetry by warming northeastern North America and cooling western Europe. The cooling of northeastern North America by the stationary advection appears as a stronger feature than the warming of western Europe. Similar asymmetries also appear across the Pacific Ocean. The term involving the mean vertical velocity (Fig 4a) is a cooling in the region of the Pacific coast of North America opposing the warming by horizontal advection. The transient vertical fluxes (Fig. 4b) act to cool the North Atlantic and North Pacific Oceans and in both cases by more in the west than in the east. The diabatic heating (Fig. 5) of the lower levels of the atmosphere is strong in the Gulf Stream and Kuroshio regions and is positive over most of the North Atlantic and North Pacific Oceans. East of North America the diabatic heating, which reaches $150Wm^{-2}$, is partly balanced by stationary advective cooling and partly by transient eddy heat flux divergence. Consequently release of some of the heat converged by the ocean into the Gulf Stream region is used by transient eddies to dissipate the east-west climate asymmetry. Immediately west of western Europe the net diabatic heating

---

* In the model experiments described below the surface temperatures of the area north of $35°N$ varied as the ocean heat transport changed according to a climate sensitivity of about $2Wm^{-2}K^{-1}$. Given this sensitivity, the winter atmospheric heat transport across $35°N$ of about $6PW$ (equivalent to $54Wm^{-2}$ for the area north of there) warms the area to the north by about $27°C$. The global ocean heat transport across the same latitude (about 1.3 PW) would warm the area to the north by about $6°C$.

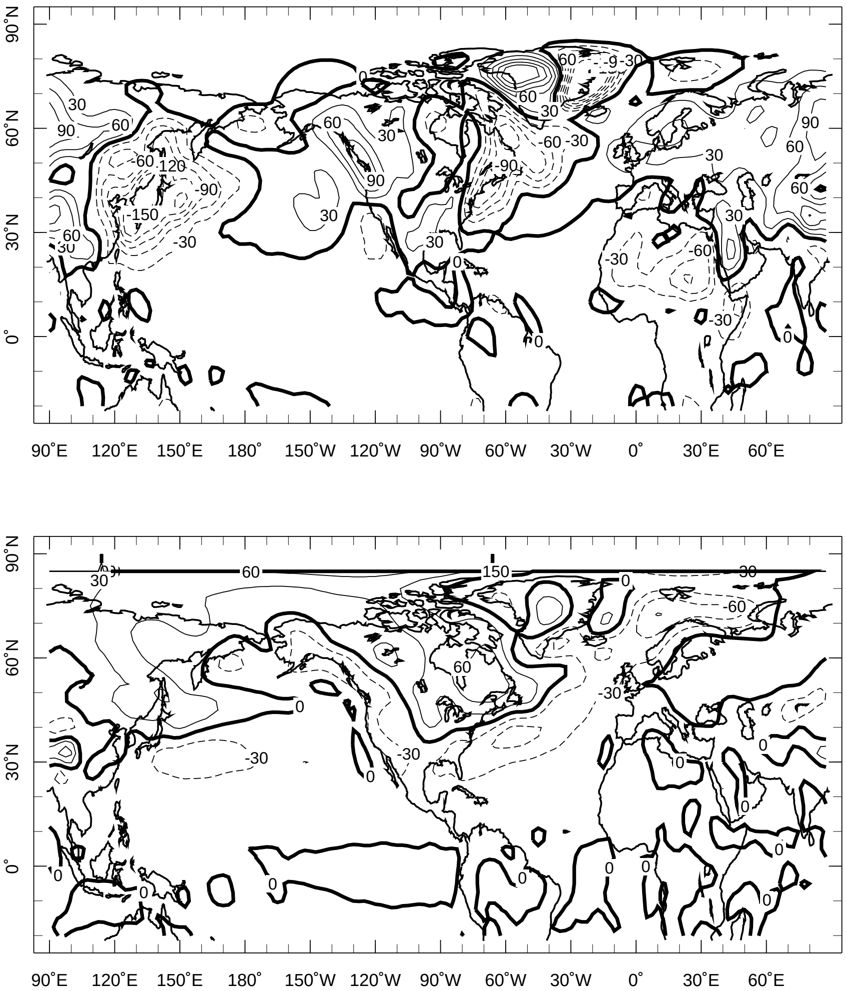


Figure 3. Terms in the temperature equation, vertically integrated from $700mb$ to $1000mb$ and averaged from December to February. (a) The stationary horizontal advection of temperature and (b) the convergence of transient eddy horizontal sensible heat flux. Terms are evaluated from NCEP Reanalyses for the 1949 to 2000 period. All terms are in Wm^{-2} and the contour interval is $30Wm^{-2}$

of the lower part of the atmosphere is about $30 - 60Wm^{-2}$ indicating that the surface sensible and radiative heating plus condensational heating is more closely balanced by radiative cooling of the layer.

All of these features of the stationary advection, transient heat flux and diabatic heating have their analogues over the Pacific Ocean and explain why winters in eastern Asia are so much colder than those in western North America.

All the patterns are very similar to those presented by Lau (1979) and the results appear to be robust: stationary advection creates the situation whereby winters in western Europe are warmer than those in northeastern North America while transient heat fluxes attempt to damp this asymmetry (see also Hoskins and Valdes (1990)).

The zonal and meridional contributions to the stationary horizontal advection are shown in Figs. 6a and 6b. Cold air resides over North America and, over the North At-

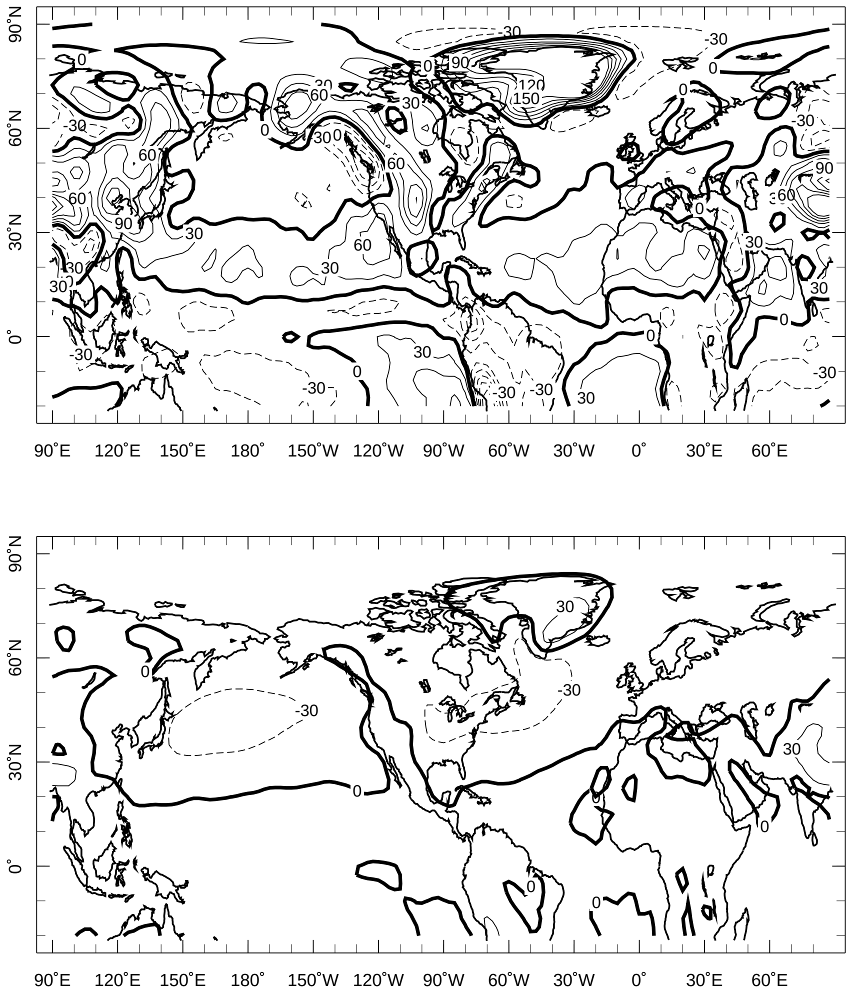


Figure 4. As for Figure 3 showing (a) the stationary vertical advection of temperature and adiabatic heating and (b) the convergence of transient eddy vertical advection and adiabatic heating. The contour interval is $30 W m^{-2}$.

lantic, the isotherms tilt from southwest to northeast, with cool air on their northwestern side. Zonal advection by the mean westerlies therefore cools eastern North America and the Atlantic Ocean until quite close to the European coast. The air temperature has a longitudinal maximum just west of the European coast and east of here the zonal advection warms western Europe. Meridional advection cools central North America but warms the central North Atlantic where the mean flow has a southerly component. The meridional advection is therefore creating the southwest to northeast tilt of the isotherms that allows the zonal advection to adopt its particular pattern and, in sum, provide the pattern of net stationary heating and cooling seen in Fig. 3a.

In summary, the east-west asymmetry of winter climates on the seaboards of the North Atlantic is created by northwesterly advection over eastern North America and by zonal advection into Europe. The Pacific Ocean has an analogous arrangement with meridional advection being an especially strong cooling over Asia. Since western Europe

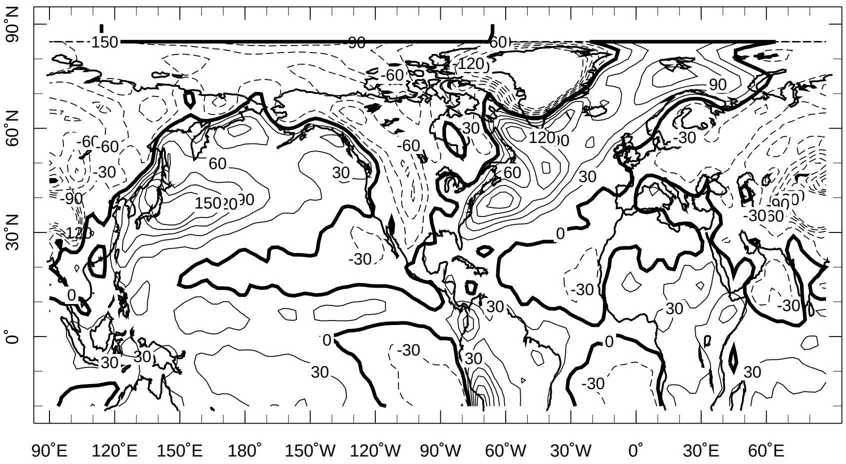


Figure 5. As for Figure 3 but showing the diabatic heating. The contour interval is $30 W m^{-2}$.

is indeed warmed by westerly advection off the Atlantic we next assess how the surface fluxes over the Atlantic are maintained.

(*c*) *Relative contribution of ocean heat flux convergence to seasonal release of heat over the North Atlantic Ocean*

Large amounts of heat are released to the atmosphere from the North Atlantic Ocean during winter. Of primary interest here is how the maintenance of this winter heat release divides up between release of heat converged by the ocean and release of heat stored locally by the ocean in summer months. We are still a long way from knowing the seasonal and latitudinal and longitudinal distribution of ocean heat flux convergence accurately because our knowledge of the surface fluxes and the seasonal changes in ocean heat storage is incomplete. However Hsiung et al. (1989) have used surface observations and U.S. Navy temperature profile data to compute the monthly and latitudinal distribution of zonally averaged poleward heat transports*. Hsiung et al. show that, for the North Atlantic, at $40°N$ for example, the ocean moves 1PW of heat north during March through October but only 0.5PW during winter (their Figure 8). This seasonal distribution is not unreasonable given that when the mid-latitude westerlies are blowing in full force during winter they drive a southward Ekman drift that cools the ocean while, in summer, the northward heat transport by the geostrophic gyres and the thermohaline circulation is relatively unopposed. The same seasonal cycle, with considerably stronger northward heat transport in the Atlantic Ocean during summer between $10°$ and $50°N$, has been found in wind-forced ocean general circulation models (Boning and Herrmann 1994, Chassignet et al. 1996). These models show that there is larger ocean heat flux convergence in the Atlantic north of $40°N$ in summer than in winter. In the annual mean the net surface heat flux must be very nearly balanced by the ocean heat flux convergence. By the reasoning above, the annual mean ocean heat flux convergence should be an upper bound on the wintertime ocean heat flux convergence, as is true in the extratropics of the model studies cited. This wintertime ocean heat flux convergence is responsible for a portion of the

---

* Our own attempts to do this with the independent data of Levitus and Boyer (1994) led to very noisy estimates presumably due to dubious heat storage data that Hsiung et al.'s analysis procedures were able to overcome.

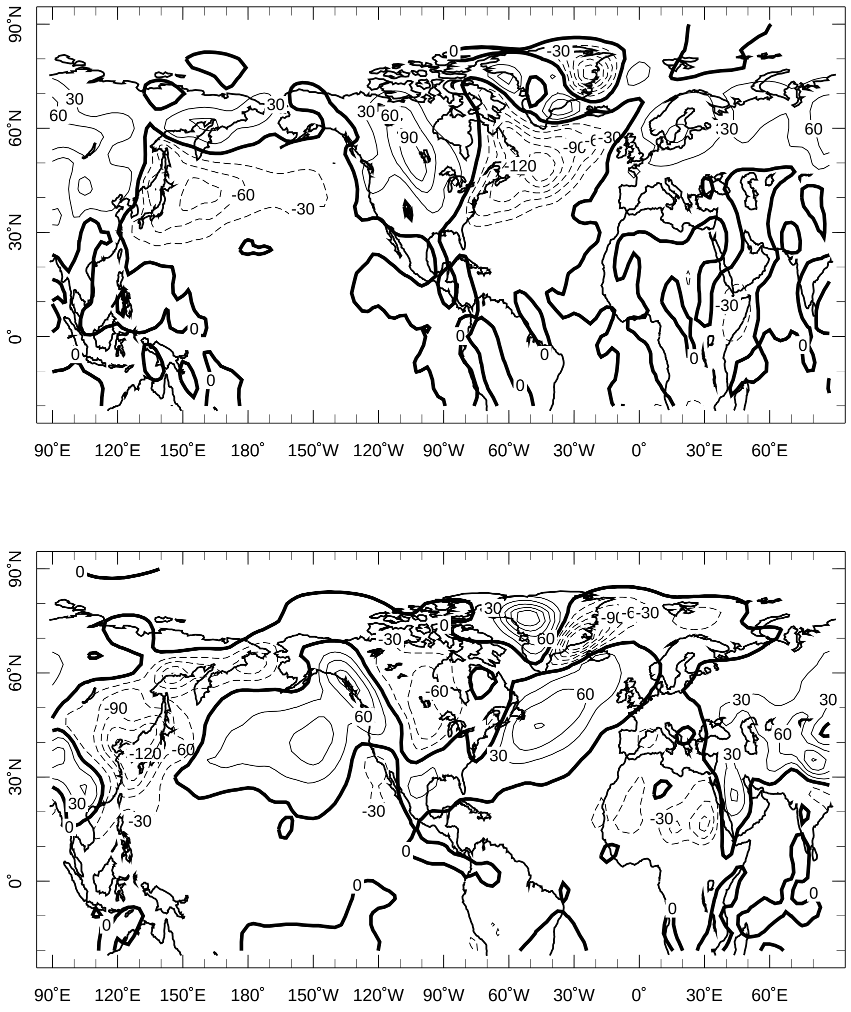


Figure 6. Stationary advective terms in the temperature equation, vertically integrated from $700mb$ to $1000mb$. (a) The zonal advection of temperature and (b) the meridional advection of temperature. The contour interval is $30Wm^{-2}$.

wintertime heat release from the ocean to the atmosphere; the remainder is maintained by the balance between reduction of heat stored in the ocean and absorption of solar radiation. Hence we can write:

$$Q^{winter}_{O\to A} = OHC + Q^{local}_{O\to A}. \tag{2}$$

Here, $Q^{winter}_{O\to A}$ is the wintertime heat release from ocean to atmosphere and equals the sum of sensible, latent and longwave radiative heat loss, OHC is the ocean heat flux convergence and $Q^{local}_{O\to A}$ is the release of heat due to local processes of reduction of heat storage and absorption of solar radiation. Figure 7 shows these three quantities estimated from the surface marine data of DaSilva et al. (1994). The total winter heat release has a maximum in the Gulf Stream region, west of $35°W$, where it can reach $400Wm^{-2}$. The heat release is much less elsewhere. The annual mean ocean heat flux convergence also has a maximum in the Gulf Stream region where it is about 50% of the total heat release. The ocean heat flux convergence also accounts for up to 50% of the winter heat release in the subpolar North Atlantic north of Norway. Outside of these two regions the winter heat release is largely accounted for by the local release of absorbed solar radiation and heat previously stored. These comparisons indicate that, for most of the North Atlantic the processes of ocean heat flux convergence play a secondary role to local processes in maintaining the wintertime heat release from ocean to atmosphere. This is consistent with the early estimates of Gill and Niiler (1973, pp. 147-8). The partitioning of the winter heat release between ocean heat flux convergence and seasonal storage appears very similar in other surface flux data (from NCEP reanalyses (Kalnay et al. 1996) as well as the Southampton Oceanography Centre (Josey et al. 1998) and Oberhuber (1988), both of which, like DaSilva et al., are based on ship reports but use different analysis procedures). It is noticeable that the ocean heat flux convergence is more localized in the Gulf Stream and Norwegian Sea than the seasonal heat release.

If the Atlantic Ocean heat transport across $35°N$ is $0.8PW$ (the value used in the models described below and consistent with observational estimates), then it sustains a mean net surface heat flux out of the Atlantic Ocean north of there of $37Wm^{-2}$. This is small compared to the area average of the seasonal heat release (net surface heat flux minus the contribution by ocean heat flux convergence) which is $135Wm^{-2}$. The seasonal heat release from both the Pacific and the Atlantic north of $35°N$, weighted to account for the partial area of ocean, is $53Wm^{-2}$. This should be compared to the $11Wm^{-2}$ contributed by the $1.3PW$ heat transport by the Atlantic and Pacific Oceans across $35°N$. Given the typical climate sensitivity the seasonal heat storage and release warms winters, in the zonal mean, by about $27°C$ (equal to the warming due to atmospheric heat transport calculated in Section 2a). This warming will be greatest over the ocean giving rise to the obvious land-sea temperature contrast. Thus according to these simple estimates, the absolute zonal mean temperatures are maintained by the seasonal heat release from the ocean, the atmospheric heat transport and ocean heat transport in the ratio $4.5 : 4.5 : 1$.

It is interesting to note that the total heat release from ocean to atmosphere is a maximum east of North America, where the atmosphere is cold, and much less west of western Europe, where the atmosphere is warm. This is explained in terms of the low level atmospheric circulation. The Icelandic Low brings cold dry air off the North American continent and over the relatively warm ocean causing large surface fluxes. To the east circulation around the low brings warm, moist air from the southwest toward western Europe and reduces the heat flux from the ocean to the atmosphere. This arrangement of winds, surface fluxes and SSTs is consistent with the atmosphere forcing the ocean's temperature distribution. The position of the Icelandic Low is consistent with the idea of a thermally forced stationary wave whereby the atmospheric heating east of North America is balanced by advective cooling which requires low pressure to the east (Smagorinsky 1953, Hoskins and Karoly 1981). However, as we shall see in Section 3c, the location of the surface low pressure system is also influenced by the net effect of forcing of stationary waves by the Rocky Mountains.

In summary, the observational data indicate: in midlatitudes the atmospheric heat transport greatly exceeds the oceanic heat transport; east-west differences in surface air temperature and the southwest-northeast tilt of isotherms of SST appear to be driven by advection of the mean temperatures by the mean atmospheric flow and the winter surface heat release from the Atlantic Ocean is primarily due to the release of heat stored locally and, to a much lesser extent, ocean heat transport.

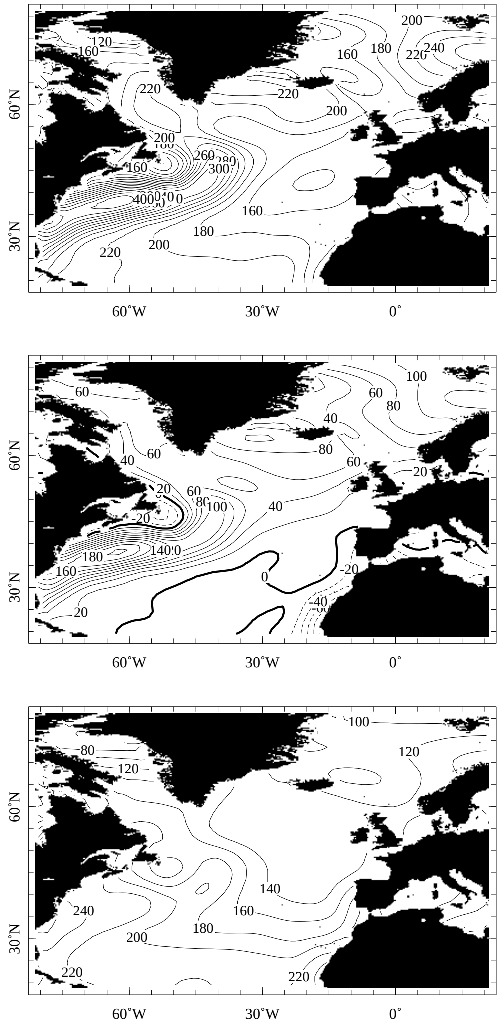


Figure 7. (a) The total release of sensible, latent and radiative heat from the ocean to atmosphere, averaged over December to February. (b) The annual mean net surface heat flux, taken to equal the annual mean ocean heat flux convergence which is assumed to be an upper bound on the wintertime ocean heat flux convergence. (c) The difference between (a) and (b) which is the heat released from the ocean to atmosphere due to reduction of heat storage and absorption of solar radiation. All terms are in Wm^{-2}. Data are from the surface marine analysis of DaSilva et al. (1994).

3. Model results

The observational analyses suggest that ocean heat transport (OHT) should have only a modest impact on both absolute temperatures and the zonal asymmetries of temperatures in the wintertime mid-latitude Northern Hemisphere. To test this we performed a pair of experiments with an atmospheric general circulation model (GCM) coupled to a uniform depth mixed layer ocean. In one experiment we specify a seasonally and spatially varying ‘q-flux’ which has been diagnosed as that required for the model to reproduce the observed SST. The annual mean q-flux equals the annual mean implied OHT. However, because the ocean mixed layer depth is held fixed, the seasonally varying part of the q-flux accounts for not just the seasonal variations of OHT but also exchange of heat with water below that occurs in nature as the mixed layer depth changes. In the other experiment we set the q-flux to zero so that the SST is determined by surface heat fluxes alone and, in equilibrium, the annual mean net surface heat flux must be zero. In both experiments the sea ice cover was held fixed at its annual mean value in order to eliminate feedbacks between ocean heat transport and sea ice and allow comparison with the results obtained from a different model that includes this feedback. Results are for the average of the last 8 years of 15 year integrations by which time the SSTs are in equilibrium.

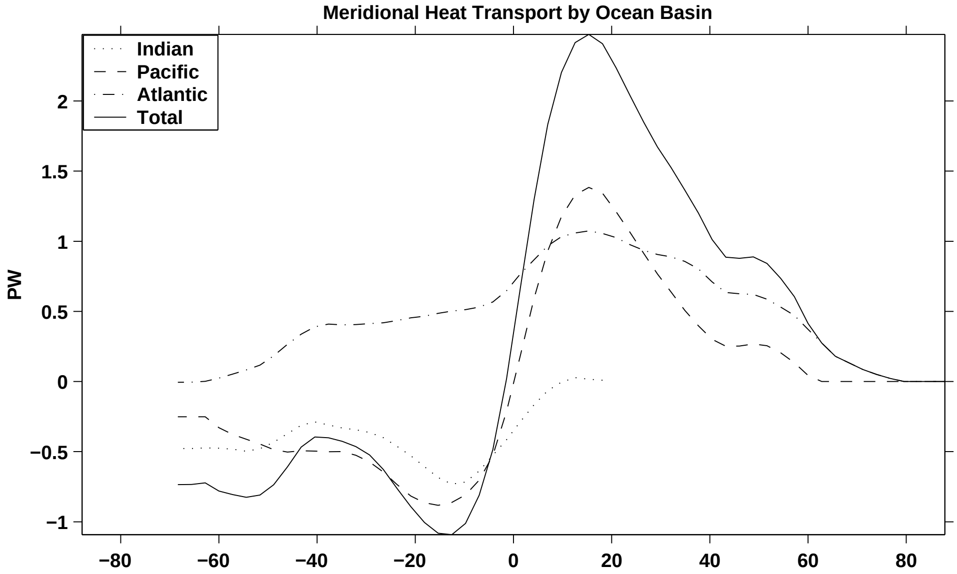


Figure 8. The northward ocean heat transport for the three ocean basins, and their sum, as implied by the annual mean of the CCM3 model q-flux.

The model used is the National Center for Atmospheric Research Community Climate Model Version 3 (NCAR CCM3) with a triangular truncation at wavenumber 42 and 18 vertical levels. The model has an extensive suite of physical parameterizations of the type that are often referred to as 'state-of-the-art'. The ability of the model to simulate the current climate is extensively documented in papers by Kiehl et al. (1998) and other authors in the same issue of the *Journal of Climate*.

Figure 8 shows the northward OHTs for the three ocean basins, and for the total, implied by the model q-flux. The maximum northward transport at about 15°N is about 10-20% too large. Compared to Trenberth and Caron's (2001) estimates the implied northward heat transport is also too large in the mid-latitude North Atlantic. Differences occur because the errors in the modeled surface fluxes are absorbed into the q-flux. This means that in the control run, with the q-flux, the ocean is accounting for a larger proportion of the poleward heat flux than is probably the case in nature and the difference between that experiment and the case without the q-flux should bound the upper range of the possible impacts of OHT for the case of fixed sea ice cover.

Clement and Seager (1999) performed the same experiments with the Goddard Institute for Space Studies (GISS) GCM, a grid point model described by Hansen et al. (1984) and DelGenio et al. (1996). The resolution is 4° latitude by 5° longitude with 9 vertical levels. The model has an ocean mixed layer with a specified seasonally and spatially varying depth as in Russell et al. (1985). The mixed layer exchanges heat with a layer below such that, in this model, the q-flux accounts for the implied OHT alone. The GISS model also includes a thermodynamic sea ice model so the sea ice extent was allowed to adjust when the specified OHT was removed. The experiments were run for 30 years by which time the SSTs and sea ice were in equilibrium and results are shown for averages over the last five years.

(*a*) *Contribution of ocean heat transport to winter temperatures in the Northern Hemisphere*

Figure 9 shows the difference in January surface temperature for the case without OHT minus the case with, as simulated by CCM3. (Surface temperature is shown here, allowing us to see the SST, but the same conclusions follow from looking at lower tropospheric temperatures). Removing the OHT warms the equatorial regions but cools everywhere else, as expected. The cooling is already large (about $3°C$) in the subtropics but there are regions of stronger cooling in the Gulf Stream and Kuroshio regions and in the far North Atlantic near Iceland where it is above $6°C$.

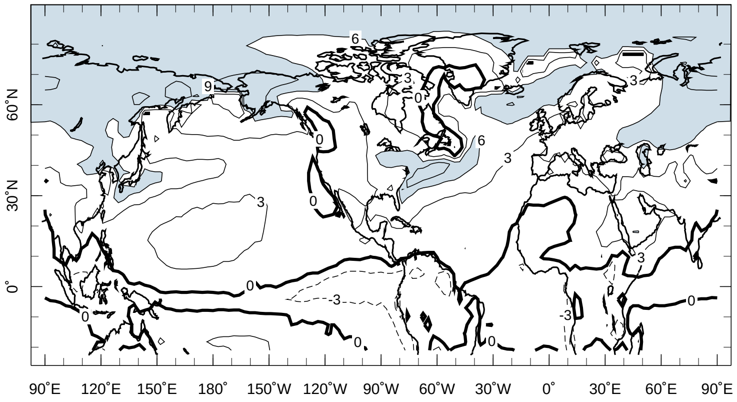


Figure 9. The difference in January surface temperature as simulated by the CCM3 AGCM-ML model for the case with a specified OHT minus the case with no OHT. Values greater than $6°C$ are shaded.

The temperature change is quite zonally uniform. In the North Atlantic sector removing the global OHT cools much of Western Europe (the British Isles, Scandinavia, France, Germany) by an average of $3°C$ and by over $6°C$ in parts of Russia between the Black Sea and the Arctic. However eastern North America also cools by about $3°C$. The zonal mean cooling north of $35°N$ is $4.5°C$. The temperature change in western Europe is due to cooler air advecting in with the mean winds, while the change over Russia is more likely caused by a change in circulation around the Icelandic Low (see Section (c)). The cooling in eastern North America is probably caused by a weakening of the pattern, seen in the observations in Fig. 3b, of transient eddy heat flux divergence over the Gulf Stream region and convergence over eastern North America. This occurs because the winter ocean heat loss in the Gulf Stream region reduces when the OHT is removed.

Thus the OHT warms Northern Hemisphere winters by a few °C in an essentially zonally uniform way while the temperature *contrasts* across the basins must be explained by other processes.

Figure 10 shows the change in surface air temperature for the case with OHT minus the case without OHT as simulated by the GISS model. The pattern of temperature change is similar to that in the CCM3 model: OHT causes a warming of a few °C that is quite zonally uniform. The remarkable exceptions are that, in the GISS model, where sea ice cover is allowed to vary, removal of OHT causes an expansion of winter sea ice near Kamchatka and in the Norwegian and Barents Seas that, in turn, causes dramatic cooling (as much as $20°C$) of the air temperature immediately above and to the east. Nonetheless it is noticeable how little this subsequently impacts temperatures in Europe to the south of Norway where the changes are comparable to those simulated by CCM3. The zonal mean cooling north of $35°N$ is $6°C$.

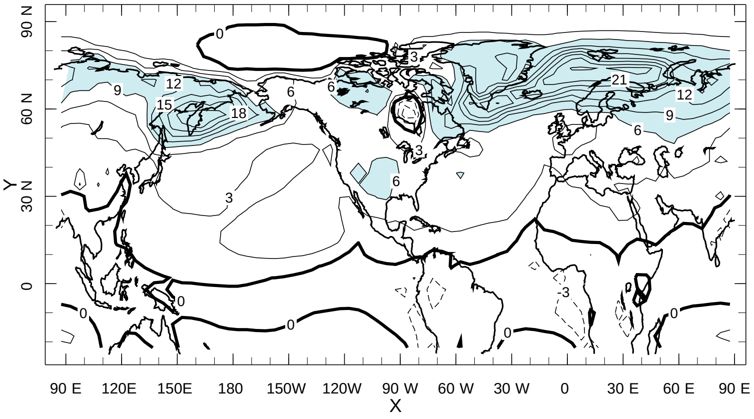


Figure 10. The difference in January surface air temperature as simulated by the GISS AGCM-ML model for the case with a specified OHT minus the case with no OHT. The GISS model allows sea ice cover to vary.

The zonal mean cooling of $4.5°C$ due to removal of OHT in CCM3 is less than anticipated by the simple calculation in the previous section. This is because the atmosphere heat transport partially compensates for the removal of OHT. Figure 11 shows the annual and zonally averaged ocean and atmosphere heat transports for the CCM3 experiments with and without OHT. In the case without OHT the total and atmospheric heat transport are equal. Without OHT, the atmosphere increases its poleward heat transport in the tropics and subtropics trying to make up for the loss of the ocean contribution. In mid-latitudes north of $40°N$ the atmospheric poleward heat transport changes little when the OHT is removed. Within the GISS model (not shown) the atmosphere also fully compensates in the tropics, but only partially compensates in mid-latitudes, for the loss of OHT.

(*b*) *Contribution of ocean heat transport to the differences in winter temperatures across the North Atlantic*

Next we turn our attention to the impact of OHT on the zonal asymmetries of winter temperatures. Figures 12a and 12b show the deviation from zonal symmetry of the surface temperature for the two experiments with CCM3. The contrast between European and

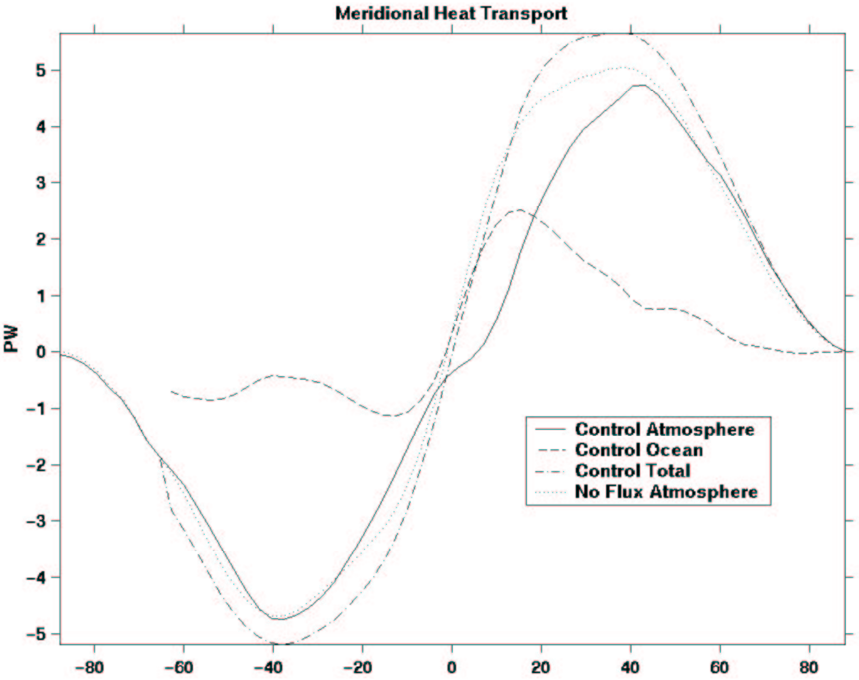


Figure 11. The atmosphere and ocean poleward heat transports, zonally and annually averaged, for the CCM3 AGCM-ML model experiments with and without OHT. Values are in petawatts.

eastern North American winter temperatures only very slightly weakens when the OHT is removed. When sea ice is allowed to vary the ocean heat flux convergence contributes at most $2°C$ out of the total contrast of about $15°C$ south of $60°N$ and about $3-6°C$ of the larger $25°C$ contrast between $60°N$ and $70°N$. Figures 13a and 13b show the departure from zonal mean of the surface air temperature derived from the GISS model runs with and without ocean heat transport. As expected, the zonal variations of surface air temperature are weaker than those of surface temperature (shown for the CCM3 experiments). Nonetheless, the results of the GISS experiments are remarkably similar to those derived from the CCM3 model. Some differences are due to the lower horizontal resolution of the GISS model. The more fundamental difference is that in the GISS model expansion of sea ice when the OHT is removed causes the surface air northwest and north of Scandinavia to cool by many $°C$ more than in the CCM3 experiment. Clearly OHT restricts the sea ice cover in the Norwegian and Barents Seas keeping winters in northern Scandinavia much warmer than they otherwise would be. However this impact is localized and has little impact on the remainder of Europe to the south.

Outside of the limited regions influenced by changes in sea ice cover the similarity of the results of the two models suggests that mixed layer depth variations are not important to establishing the zonal climate asymmetries. The two models have nothing in common in their physics or numerics. The reproducibility reassures us that the lack of dependence of the zonal asymmetry on OHT is unlikely to be a model artifact.

(*c*) *The shape of the Icelandic Low and the contribution of mountains to the difference in winter temperatures across the North Atlantic*

So far the results are consistent with the difference in winter temperatures across the

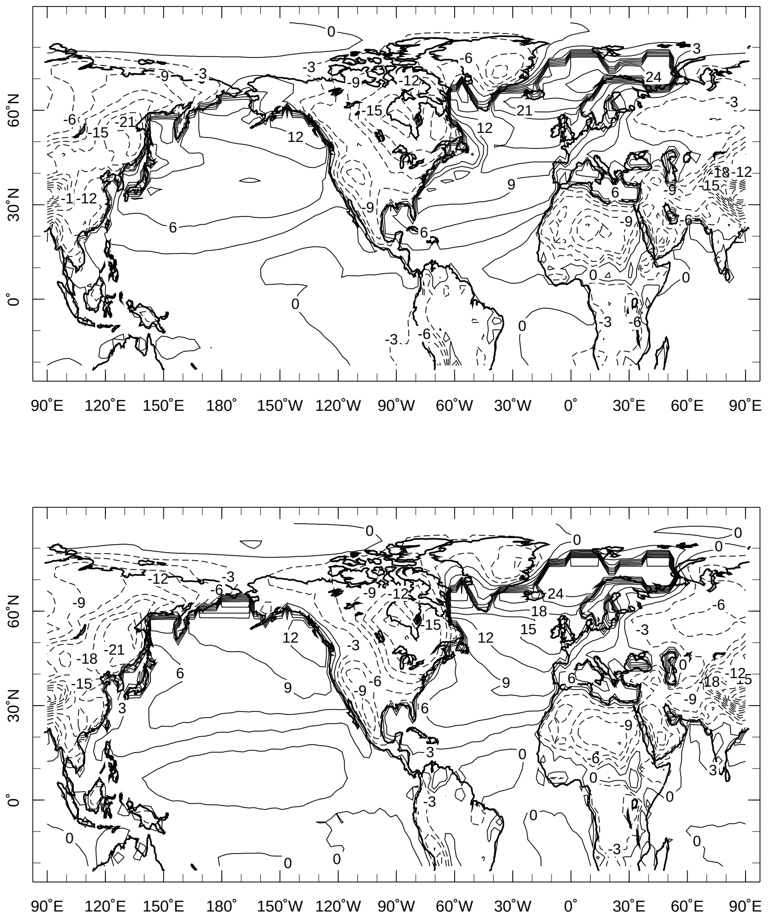


Figure 12. The departure of January surface temperature from the zonal mean as simulated by the CCM3 AGCM-ML model for (a) the case with a specified OHT and (b) the case with no OHT.

North Atlantic being determined by the simple contrast between a continental climate in eastern North America and a maritime climate in western Europe. However it is likely that the exact position and strength of the Icelandic Low, which brings a northerly component to the winds over America and a southerly component over western Europe, is important.

Forcing by orography, asymmetries in the heating of the mid-latitude atmosphere at the surface, transient eddy fluxes and tropical diabatic heating are the principal causes of stationary eddies (see Held 1983 for a review). Held (1983) showed that when mountains were removed in a GCM the flow across the North Atlantic became more zonal. This might be expected to influence the temperature asymmetry. We performed another experiment with the CCM3 AGCM-ML model in which we used the specified q-flux but removed the mountains. (The influence of mountains on surface temperature was the same whether or not we included the q-flux.)

Figure 14 shows the sea level pressure and the deviation of surface temperature from the zonal mean for the three model experiments with CCM3. In the absence of mountains (Fig. 14c), the equivalent barotropic trough over the eastern North American seaboard is

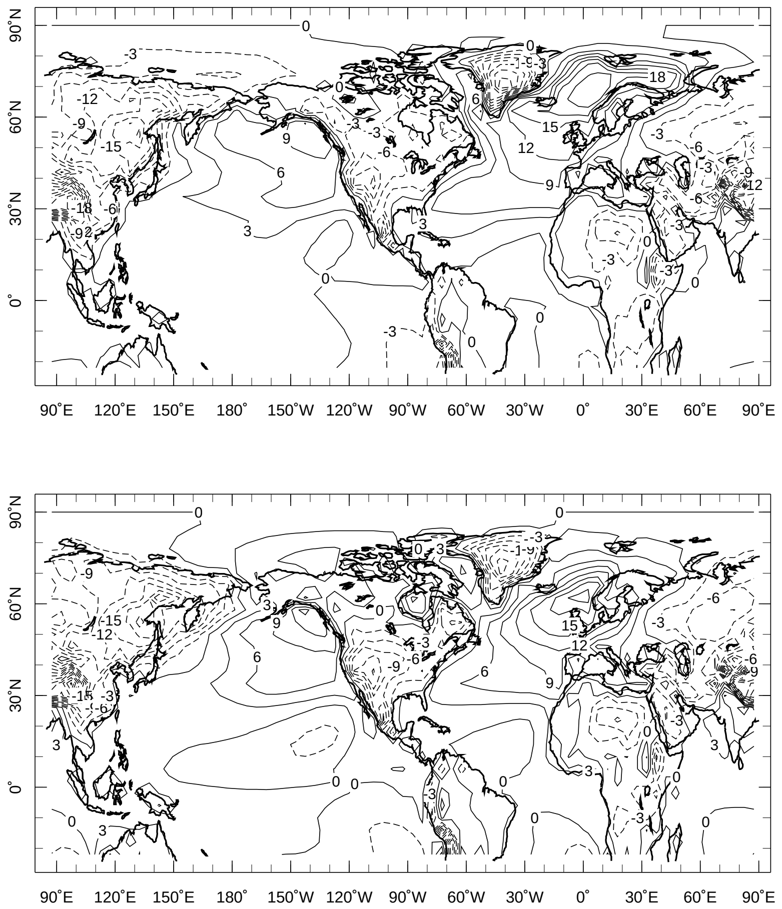
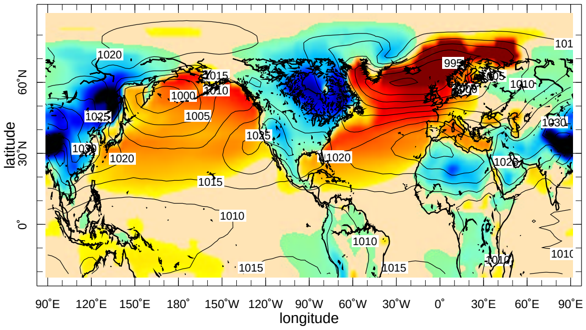


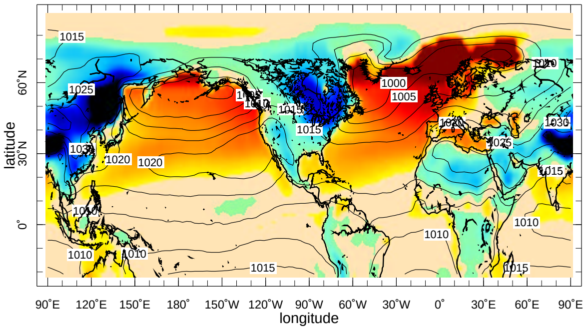
Figure 13. The departure of January surface air temperature from the zonal mean as simulated by the GISS AGCM-ML model, which allows for variations in sea ice cover, for (a) the case with a specified OHT and (b) the case with no OHT.

considerably weakened compared to the case with mountains (Fig. 14a). Consequently the flow is more zonal over North America, the North Atlantic Ocean and western Europe than when the mountains are present. The weakened northerlies over North America lead to a large warming, while the reduced southerlies over the North Atlantic Ocean and northern Europe cause cooling. The part of the Icelandic Low east of Iceland retains its full strength when the mountains are removed. The difference between Figs 14a and 14b show the impact of the ocean heat transport. In this case the trough over eastern North America remains but the portion of the Icelandic Low east of Iceland is weakened. The flow over western Europe also weakens but becomes more southerly maintaining the strength of the warm advection. The Icelandic Low comprises an orographically forced trough over eastern North America and a thermally and transient eddy forced low northeast of Iceland (e.g. Hoskins and Valdes (1990)). The weakening of the eastern part of the Icelandic Low when OHT is removed is consistent with our estimate that ocean

(A) Control



(B) No Flux



(C) No Mountains

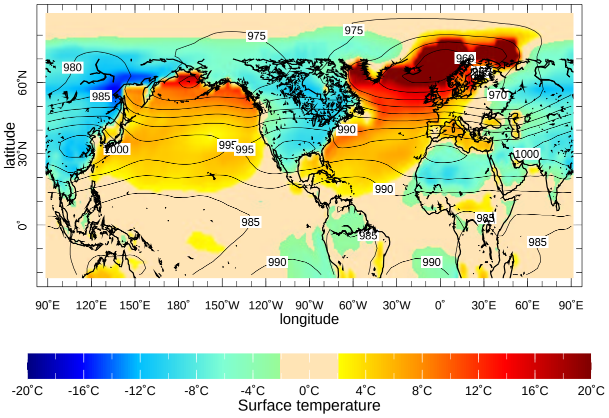


Figure 14. Sea level pressure (mb) and zonal eddy surface temperature in $^\circ C$ (colours) for January for (a) the case with mountains and q-flux, (b) the case with mountains and the q-flux set to zero and (c) the case without mountains but with the q-flux.

heat flux convergence accounts for about half of the winter heat release from ocean to atmosphere in this region (Fig. 7). The same weakening occurred in the GISS model (not shown).

Fig. 15 shows the effect of mountains on the surface temperature *. The mountains

---

* Some of the surface temperature difference is caused locally by the change in surface height (e.g., over

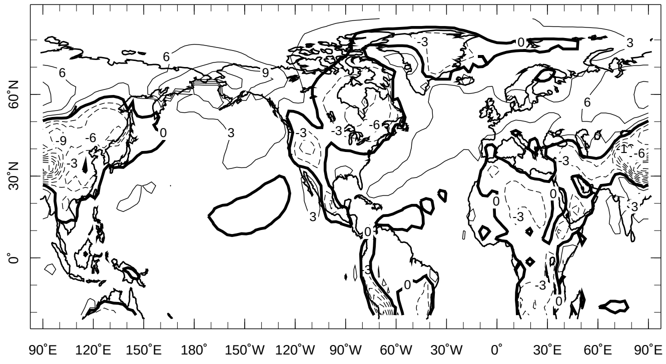


Figure 15. The difference in January surface temperature $^\circ C$ for the case with mountains minus the case without mountains, as simulated by CCM3. Both models were run with the specified q-flux.

exert a stronger influence on the temperature contrast across the North Atlantic than does the OHT (compare Fig. 15 with Fig. 9). This is because the OHT generates smaller temperature changes which have the same sign (warming) on both sides of the North Atlantic. In contrast, orography (the Rockies are the dominant influence over the Atlantic sector (Nigam et al. 1988)) creates a large zonal temperature asymmetry, warming the British Isles and parts of Scandinavia by as much as $3^\circ C$ and cooling North America by as much as $6^\circ C$. Hence, the model results indicate about half of the $15 - 20^\circ C$ difference in wintertime temperature between western Europe south of $60^\circ N$ and eastern North America is due to the *net* forcing of the atmospheric stationary waves by orography (the other half is due to the continental-maritime contrast plus advection by the thermally forced stationary waves). The net effect of orography greatly exceeds the direct mechanical forcing of the flow by the mountains and also includes the indirect effects of the reorganization of the patterns and amplitudes of the forcing of the stationary waves by transient eddies and diabatic heating.

(*d*) *The contrast between the maritime air temperatures of western Europe and western Canada and Alaska*

North of about $40^\circ N$ there is considerably more poleward ocean heat transport in the Atlantic Ocean than in the Pacific Ocean because of the contribution of the thermohaline circulation which has its sinking branch in the North Atlantic (e.g. Broecker 1997). While poleward ocean heat transport does not contribute strongly to the east-west asymmetry of winter temperatures across the oceans is it the cause of the noticeable difference in temperatures between the west coasts of Europe and North America?

Table 1 lists the difference in January surface air temperatures, Atlantic minus Pacific, at various latitudes along the west coasts of Canada and Alaska and in the British Isles and Norway, for observations and the CCM3 and GISS model runs with and without ocean heat transport. At $50^\circ N$ (Cornwall in Europe and Vancouver Island in Canada) the observed surface air temperature from NCEP is $5^\circ C$ warmer in Europe than Canada. At $55^\circ N$ (Donegal in Ireland and Prince of Wales Island in Alaska) the difference is $5^\circ C$

---

mountain ranges and plateaus such as Africa) according to a lapse rate but this does not appreciably influence the contrast between eastern North America and western Europe which both have insignificant topography in the model.

and at $60^\circ N$ (just south of Bergen in Norway and Icy Bay in Alaska) the difference is $7^\circ C$. These temperature differences are reasonably well simulated in the GISS and CCM3 model runs accounting for the ocean heat transport. In the experiments without ocean heat transport these differences between the Atlantic and the Pacific are maintained. Hence, at least in these models heat transport by the thermohaline circulation is not required for maritime Europe to be warmer than the Pacific coast of Canada and Alaska.

TABLE 1. Atlantic minus Pacific near surface coastal air temperature $^\circ C$

	observations	*GISS-ML*		*CCM3-ML*	
		OHT	no OHT	OHT	no OHT
$60^\circ N$	$7^\circ C$	$11^\circ C$	$10^\circ C$	$9^\circ C$	$10^\circ C$
$55^\circ N$	$5^\circ C$	$4^\circ C$	$7^\circ C$	$7^\circ C$	$8^\circ C$
$50^\circ N$	$5^\circ C$	$5^\circ C$	$6^\circ C$	$6^\circ C$	$5^\circ C$

So why is the Atlantic coast of northwest Europe warmer than the Pacific coast of northwest America? A full explanation of this temperature contrast is beyond the scope of the current work but our GCM experiments indicate that OHT and orographic forcing are not responsible for this asymmetry, because the asymmetry remains in the experiments with no OHT and with no mountains. The difference in SSTs between the two coasts is actually less than the difference in surface air temperature suggesting that the coastal regions of northwestern America have more continental influence than the coastal regions of northwestern Europe. The more fundamental reason must be the different geographies of the two basins. The open ocean stretching northeast north of $60^\circ N$ in the Atlantic means that the Icelandic Low is placed further north than the Aleutian Low. It also extends further into the eastern part of the ocean basin. This arrangement favours warming southwesterly winds that sweep across the maritime areas of northwest Europe and which have no counterpart on the Pacific coast of North America at the same latitudes.

4. POSSIBLE SENSITIVITY OF RESULTS TO MODEL ERRORS AND ASSUMPTIONS

We have used two independent atmospheric GCMs coupled to different mixed layer oceans and with different treatments of sea ice. In the CCM3 model the ocean mixed layer has a fixed depth and the q-flux accounts for OHT as well as the effects of heat exchange with layers below that occurs in nature as the mixed layer depth varies. In the GISS model the mixed layer depth variations are specified and the q-flux more closely accounts for OHT alone. Comparison of the results demonstrates that the treatment of the mixed layer does not substantially affect the results, except in western boundary currents where winter heat loss is opposed by mixed layer deepening. In these regions the GISS model, which better accounts for entrainment than does the CCM3 mixed layer model, cools less than CCM3 when the q-flux is removed. The next step of inclusion of a fully interactive mixed layer is unlikely to change the main results presented here.

More problematic for certain regions is the treatment of sea ice. In CCM3 we held the ice cover fixed but when it was allowed to vary in the GISS model removal of OHT caused a large expansion of seasonal ice cover in the Kamchatka region and in the Norwegian and Barents Seas, cooling the air above and to the east. The thermodynamic sea ice model in the GISS GCM probably overestimates the increase in sea ice extent. (A more reliable estimate requires a dynamic ice model that accounts for the drift of sea ice by winds.) The

GISS and CCM3 models probably bracket the influence of sea ice and demonstrate that the impact of changes in ice extent on winter temperatures is regional, not influencing temperatures in western Europe south of southern Norway.

The northeastern part of the Icelandic Low in CCM3 extends too far east into northern Europe which could, perhaps, mean that as this part weakens when OHT is removed, the impact on winter temperatures also extends too far east. The structure of the Icelandic Low is better represented in the GISS model, with strong pressure gradients parallel to the northwest European coast. Comparison of the results of the two models indicates that these differences in simulation of the Low have little impact on the main results presented here, certainly less impact that the treatment of sea ice.

Finally a comment is in order concerning the statistical significance of the results presented. The temperature changes caused by removal of OHT in the models are robust. Over the mid-latitude oceans they correspond to several standard deviations of the internal variability (estimated from the control runs). The temperature changes over land are more typically the same size as the internal variability. However, by looking at the individual years, we found that in all regions of noticeable change (more than $2°C$) removal of OHT causes a cooling, relative to the control run, in almost every single winter indicating the robustness of the results despite the relatively short periods of integration.

Together these considerations argue that the main results presented here are not sensitive to the peculiarities of the models used and that improvements in aspects of the models will change the results only locally.

5. CONCLUSIONS

We have sought to explain why winters in western Europe are much milder than those in eastern North America and other places at the same latitude. The principal findings are as follows.

- Experiments with atmospheric GCMs, coupled to mixed layer oceans in which the ocean heat transport is either accounted for or not, indicate that ocean heat transport warms winters over land in a quite zonally uniform way and warms the North Atlantic Ocean itself by much more. In the case where the sea ice cover is held fixed the area average warming of the area north of $35°N$ caused by the global ocean heat transport (1.3PW across $35°N$ in the annual mean, taken to be an upper bound on the winter value) is $4.5°C$. The warming would be larger but the atmosphere heat transport partially compensates for the imposed change in ocean heat transport. This warming contrasts with the $27°C$ area average warming due to the larger atmospheric heat transport (about 6PW across $35°N$ in winter) and another $27°C$ area average warming due to the seasonal ocean heat storage and release. When sea ice was allowed to vary in one of the models, removal of ocean heat transport caused the area average warming north of $35°N$ to increase to $6°C$ as sea ice extended in the Norwegian and Barents Seas greatly cooling the air above and to the east. However the impact on winter temperatures south of $60°N$ was small. These results are broadly consistent with prior results (e.g. Manabe and Stouffer (1988), Rind et al. (2001)) that probably also overestimated the increase in sea ice cover (see previous discussion).
- In contrast, the difference in winter temperatures between western Europe and eastern North America can exceed $15°C$ and, in the models, is hardly affected by the ocean heat transport except at the latitude of northern Norway. This contrast is explained by interactions between atmospheric advection and the seasonal storage and heat release by the ocean. This is consistent with observational evidence that the winter heat release

from the North Atlantic Ocean to the atmosphere is primarily sustained by seasonal heat release while ocean heat flux convergence contributes significantly only in the western boundary current region east of the United States and in the area north of Norway.
- Advection by the stationary waves - the Icelandic Low over the North Atlantic Ocean - adds to the effect of zonal advection of the land-sea temperature contrast by bringing cold northwesterlies to eastern North America and mild southwesterlies to western Europe.
- The Icelandic Low is forced thermally and by the net effects of orography, which are the result of a complicated interplay between the direct (mechanical) effect of orographic forcing, the transient fluxes, and diabatic heating. Further model experiments indicate that the net effect of orography intensifies the trough over the western North Atlantic that brings cold northwesterlies into eastern North America and warm southwesterlies to western Europe. This accounts for almost half of the observed winter temperature contrast between these areas. Advection by the sum of the zonal mean westerlies and the thermally forced stationary waves - as diagnosed in a model experiment with no mountains - accounts for the other half of the observed temperature contrast across the North Atlantic Ocean.
- In all the model experiments the Atlantic coast of Europe remained much warmer than the Pacific coast of Canada and Alaska when the ocean heat transport was removed as both areas cooled by similar amounts. The Atlantic-Pacific contrast ($5°C$ to $7°C$) is larger than can be accounted for by ocean heat transport and must be a consequence of the pattern of atmospheric heat transport. It probably arises because the different geographies of the two oceans allows less continental influence at European coast than at the American coast and causes the Icelandic Low to adopt a more northerly position, and extend further into the eastern part of the basin, than the Aleutian Low.

In conclusion, while ocean heat transport warms winters on both sides of the North Atlantic Ocean by a few $°C$, the much larger temperature difference across the ocean, and that between the maritime areas of northwestern Europe and western North America, are explained by the interaction between the atmospheric circulation and seasonal storage and release of heat by the ocean. Stationary waves greatly strengthen the temperature contrast across the North Atlantic and are themselves heavily influenced by the net effect of orography. In contrast, transport of heat by the ocean has a minor influence on the wintertime zonal asymmetries of temperature. Even in the zonal mean ocean heat transport has a small effect compared to those of seasonal heat storage and release by the ocean and atmospheric heat transport. In retrospect these conclusions may seem obvious, but we are unaware of any published explanation of why winters in western Europe are mild that does not invoke poleward heat transport by the ocean as an important influence that augments its maritime climate.

ACKNOWLEDGEMENT

This work was supported by NOAA grant UCSIO -10775411D/NA47GP0188 (The Consortium on the Ocean's Role in Climate) and NSF grant ATM-9986515. DSB and JY were supported by a grant from NOAA's Office of Global Programs. Jennifer Miller and Ben Kerman helped prepare the figures. We particularly want to thank Yochanan Kushnir for many excellent conversations. We also thank Martin Visbeck, Brian Hoskins, Stefan Rahmstorf and Andrew Weaver for useful conversations and the two anonymous reviewers for constructive criticisms. We thank Jim Hansen for providing us with access to the GISS model, Kenneth Lo for performing the GISS model integrations and Gary Russell for helping in interpretation of the model output. This is Lamont Doherty Earth Observatory contribution number 6322.

References

Bjerknes, J. 1964 Atlantic air-sea interaction. *Advances in Geophysics*, **10,** 1-82.

Boning, C. W. and Herrmann. P. 1994 Annual cycle of poleward heat transport in the ocean: Results from high-resolution modeling of the North and Equatorial Atlantic. *Journal of Physical Oceanography*, **24**, 91-107.

Broecker, W. S. 1997 Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the climate balance? *Science*, **278,** 1582-1588.

Chassignet, E. P., Smith, L. T., Bleck, R. and Bryan. F. O. 1996 A model comparison: Numerical simulation of the North and equatorial Atlantic oceanic circulation in depth and isopycnic coordinates. *Journal of Physical Oceanography*, **26**, 1849-1867.

Clement, A. C. and Seager. R. 1999 Climate and the tropical oceans. *Journal of Climate*, **12**, 3383-3401.

DaSilva, A., Young, A. C., and Levitus, S. 1994 *Atlas of surface marine data 1994. Volume 1. Algorithims and Procedures*, National Oceanographic and Atmospheric Administration.

DelGenio, A. D., Yao, M. -Y., Kovari, W. and Lo, K. W. 1996 A prognostic cloud water parameterization for global climate models. *Journal of Climate*, **9,** 270-304.

Ganachaud, A., and Wunsch, C. 2000 Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, **408,** 453-457.

Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R. and Lerner, J. 1984 Climate sensitivity: Analysis of feedback mechanisms. Pp. 130-163 in *Climate Processes and Climate Sensitivity*, Geophysical Monograph 29, American Geophysical Union, Washington DC.

Hartmann, D. L. 1994 *Global Physical Climatology*, Academic Press, New York.

Held, I. M. 1983 Stationary and quasi-stationary eddies in the extratropical troposphere: theory. Pp. 127-168 in *Large-scale Dynamical Processes in the Atmosphere*, Ed. B.J. Hoskins and R. P. Pearce, Academic Press, London.

Hsiung, J., Newell, R. E., and Houghtby, T. 1989 The annual cycle of oceanic heat storage and oceanic meridional heat transport. *Quarterly Journal of the Royal Meteorological Society*, **115,** 1-28.

Hoskins, B. J., and Karoly, D. J. 1981 The steady linear response of a spherical atmosphere to thermal and orographic forcing. *Journal of the Atmospheric Sciences*, **38,** 1179-1196.

Hoskins, B. J., and Valdes, P. J. 1990 On the existence of storm tracks. *Journal of the Atmospheric Sciences*, **47,** 1854-1864.

Houghton, H. G. 1954 On the annual heat balance of the northern hemisphere. *Journal of Meteorology*, **11,** 1-9.

Josey, S. A., Kent, E. C., and Taylor, P. K. 1998 *The Southampton Oceanography Centre (SOC) Ocean-Atmosphere Heat, Momentum and Freshwater Flux Atlas*, Southampton Oceanography Centre, Southampton, United Kingdom.

Kalnay, E. and 40 others 1996 The NCEP-NCAR 40-year reanalysis. *Bulletin of the American Meteorological Society*, **77,** 437-471.

Kiehl, J. T., Hack, J. J., Bonan, G. B., Boville, B. A., Williamson, D. L. and Rasch, P. J. 1998 The National Center for Atmospheric Research Community Climate Model: CCM3. *Journal of Climate*, **11,** 1131-1149.

Latif, M. J., Roeckner, E., Mikolajewicz, U. and Voss, R. 2000 Tropical stabilization of the thermohaline circulation in a greenhouse warming simulation. *Journal of Climate*, **13,** 1809-1813.

Lau, N.-C. 1979 The observed structure of tropospheric stationary waves and the local balances of vorticity and heat. *Journal of the Atmospheric Sciences*, **36,** 996-1016.

Manabe, S. and Stouffer, R. J. 1988 Two stable equilibria of a coupled ocean-atmosphere model *Journal of Climate*, **1,** 841-866.

Maury M. F. 1855 *The Physical Geography of the Sea and it's Meteorology*, Harper and Brothers, New York.

Nigam, S., Held, I. M. and Lyons, S. W. 1988 Linear simulation of the stationary eddies in a GCM: Part II, Mountain model *Journal of the Atmospheric Sciences*, **45,** 1433-1452.

Oberhuber, J. M. 1988 *An atlas based on the COADS dataset: The budgets of heat, buoyancy and turbulent kinetic energy at the surface of the global ocean*, Max Planck Institut für Meteorologie, Hamburg, Germany.

Peixoto, J. P. and Oort, A. H. 1992 *The Physics of Climate*, American Institute of Physics, New York.

Rind, D., deMenocal, P., Russell, G., Sheth, S., Collins, D., Schmidt, G. and Teller, J. 2001 Effects of glacial meltwater in the GISS Coupled Atmosphere-Ocean Model: Part I: North Atlantic Deep Water response. *Journal of Geophysical Research-Atmospheres*, **106** 27335-27354.

Russell, G. L., Miller, J. R. and Tsang, L.-C. 1985 Seasonal oceanic heat transports computed from an atmospheric model. *Dynamics of Atmospheres and Oceans*, **9,** 253-271.

Smagorinsky, J. 1953 The dynamical influence of large-scale heat sources and sinks on the quasi-stationary mean motions of the atmosphere. *Quarterly Journal of the Royal Meteorological Society*, **79,** 342-366.

Sverdrup, H. U. 1957 Transport of heat by the currents of the North Atlantic and North Pacific Oceans. Festskrift til Professor Bjorn Helland-Hansen. *Naturen*, Bergen, Norway 226-236.

Trenberth, K. E., Caron, J. M., and Stepaniak, D. P. 2001 The atmospheric energy budget and implications for surface fluxes and ocean heat transports. *Climate Dynamics*, **17,** 259-276.

Trenberth, K. E., and Caron, J. M. 2001 Estimates of meridional atmosphere and ocean heat transports. *Journal of Climate*, **14,** 3433-3443.