Impact of Atlantic sea surface temperatures on the warmest global surface air temperature of 1998

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[1] The year 1998 is the warmest year in the record of instrumental measurements. In this study, an atmospheric general circulation model is used to investigate the role of sea surface temperatures (SSTs) in this warmth, with a focus on the role of the Atlantic Ocean. The model forced with the observed global SSTs captures the main features of land surface air temperature anomalies in 1998. A sensitivity experiment shows that in comparison with the global SST anomalies, the Atlantic SST anomalies can explain 35% of the global mean surface air temperature (GMAT) anomaly, and 57% of the land surface air temperature anomaly in 1998. The mechanisms through which the Atlantic Ocean influences the GMAT are likely different from season to season. Possible detailed mechanisms involve the impact of SST anomalies on local convection in the tropical Atlantic region, the consequent excitation of a Rossby wave response that propagates into the North Atlantic and the Eurasian continent in winter and spring, and the consequent changes in tropical Walker circulation in summer and autumn that induce changes in convection over the tropical Pacific. This in turn affects climate in Asia and Australia. The important role of the Atlantic Ocean suggests that attention should be paid not only to the tropical Pacific Ocean, but also to the tropical Atlantic Ocean in understanding the GMAT variability and its predictability.


1. Introduction

[2] Global mean surface air temperature (GMAT) is an important indicator of global climate. The year 1998 was the warmest year for GMAT, setting a new record by a wide margin for the period of instrumental measurements [Bell et al., 1999; Folland et al., 2001]. The GMAT shows a clear interannual and interdecadal variability [Kang, 1996]. A strong positive interannual anomaly, in conjunction with the trend of global warming, may cause a considerable impact on the global climate in a particular year.

[3] The period of 1997–1998 was also characterized by a major cycle of the El Niño-Southern Oscillation (ENSO) with a record breaking El Niño in 1997 and a modest La Niña in 1998 [McPhaden, 1999]. The Pacific is the largest ocean on the globe, and its tropical part is approximately three times that of the Atlantic. Most attention has been paid to the influence of sea surface temperatures (SSTs) in the Pacific, especially in the tropical eastern Pacific, on the global air temperatures [e.g., Kang, 1996; Wu and Newell, 1998; Cai and Whetton, 2001; Trenberth et al., 2002]. Besides the Pacific SST anomalies, there are also SST anomalies in other ocean basins, for example, in the Atlantic Ocean. In fact, 1998 was the year with the largest ocean heat content for the Atlantic [Levitus et al., 2000]. There is growing evidence which suggests that the tropical Atlantic Ocean plays an important role in the climate in the Atlantic European sector in boreal winter based on observations [e.g., Czaja and Frankignoul, 2002], and model studies [e.g., Sutton et al., 2000; Drevillon et al., 2003; Mathieu et al., 2004]. However, the role of Atlantic SSTs on the global surface air temperatures has been overlooked. The main purpose of this paper is to demonstrate that the Atlantic Ocean exerted a significant influence on global surface air temperature in 1998 and further try to elucidate the mechanisms.

2. Observational Evidence

[4] Figure 1 shows the surface air temperature anomalies in the 1998 meteorological year (from December 1997 to November 1998), based on the NCEP-NCAR reanalysis data set [Kalnay et al., 1996]. The 30-year average from 1961 to 1990 is used as the climatology, since the control simulation (described in the following section) was forced with climatological SSTs during these 30 years in this study. The estimated global mean temperature is 0.5°C above normal over land and marine areas combined and 0.7°C above normal over land.

[5] The dominant feature of annual mean surface temperatures over the land areas is the average temperatures over most of North America (1.0°–2.0°C), and southern Eurasian continent (0.5°–1.0°C). Over the northern Eur-
Asian continent, temperatures are 0.5–1.0°C below normal. The annual temperatures are 0.5–1.0°C above normal over Australia and the majority of Africa and South America (see also Table 1).

Over the oceans, the surface air temperature anomalies are in good agreement with SST anomalies (not shown). The annual mean SST anomalies in the meteorological year of 1998 exhibit an El Niño pattern. The El Niño event in 1997 persisted into spring 1998, and a La Niña event started in the summer of 1998. Concurrent with the 1997–1998 ENSO cycle there were also SST anomalies over other ocean basins, for example, the Indian Ocean and Atlantic Ocean. The SSTs in the tropical Atlantic and North Atlantic are above average in each season of 1998. In fact, in 1998, the annual mean of the Tropical North Atlantic (TNA)...

Table 1. Observed and Simulated Surface Air Temperature Anomalies Averaged Over the Specified Areas in the 1998 Meteorological Year

<table>
<thead>
<tr>
<th>Area</th>
<th>Mean Surface Air Temperature Anomalies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>0.60  0.88  0.74  1.56  0.56</td>
</tr>
<tr>
<td>Forced by</td>
<td>0.12  0.95  1.28  0.45  1.46</td>
</tr>
<tr>
<td>global SSTs</td>
<td></td>
</tr>
<tr>
<td>Implied by</td>
<td>0.61  0.31  0.73  −0.07  −0.07</td>
</tr>
<tr>
<td>Atlantic SSTs</td>
<td></td>
</tr>
</tbody>
</table>

*Eurasia, Africa, Australia, North America, and South America are defined as the lands in (0°−140°E, 30°N−50°N), (0°−60°E, 30°S−15°N), (110°E−160°E, 40°S−10°S), (150°W−20°W, 40°N−80°N), and (80°W−30°W, 20°S−10°N), respectively. These specified areas are determined according to the strong positive anomalies of observed surface air temperatures (Figure 1). Units are °C.

Figure 1. The anomalies of surface air temperature in the 1998 meteorological year, based on the NCEP-NCAR reanalysis data set. The anomalies are obtained with respect to the 1961–1990 base period. Contours are plotted at ±0.5°C, ±1.0°C, ±2.0°C, and ±4.0°C, using solid lines for positive values and dashed lines for negative values. The values larger than 0.5°C and 2.0°C are lightly and heavily shaded, respectively.

Figure 2. Simulated surface air temperature anomalies in the 1998 meteorological year. (a) Forced with the global SSTs. (b) Implied by the Atlantic SSTs. The setting of contour lines and shadings is the same as Figure 1.
Table 2. Global Mean Surface Air Temperature Anomalies Forced With the Global SSTs and Implied by Atlantic SSTs

<table>
<thead>
<tr>
<th></th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global SST</td>
<td>0.399</td>
<td>0.449</td>
<td>0.522</td>
<td>0.508</td>
<td>0.470</td>
</tr>
<tr>
<td>Atlantic SST</td>
<td>0.156</td>
<td>0.147</td>
<td>0.174</td>
<td>0.184</td>
<td>0.165</td>
</tr>
</tbody>
</table>

*Units are °C. The Atlantic SST anomalies can explain 46.0% (DJF); 32.7% (MAM); 33.3% (JJA); 36.2% (SON), and 35.1% (annually) of the global mean surface air temperature anomalies forced with the global SSTs.

Table 3. Same as Table 2 But for Land Mean Surface Air Temperature Anomalies

<table>
<thead>
<tr>
<th></th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global SST</td>
<td>0.355</td>
<td>0.504</td>
<td>0.706</td>
<td>0.635</td>
<td>0.550</td>
</tr>
<tr>
<td>Atlantic SST</td>
<td>0.327</td>
<td>0.240</td>
<td>0.321</td>
<td>0.367</td>
<td>0.314</td>
</tr>
</tbody>
</table>

*Units are °C. The Atlantic SST anomalies can explain 92.1% (DJF); 47.6% (MAM); 45.5% (JJA); 57.8% (SON), and 57.1% (annually) of the global mean surface air temperature anomalies forced with the global SSTs.

index, which is defined by the anomaly of the average of the SST from 5.5°N to 23.5°N and 15°W to 57.5°W [Enfield et al., 1999], is highest since 1948, and its anomaly is greater than 2 standard deviations. Were the SST anomalies over the Atlantic Ocean important? A specially designed experiment allows us to separate and assess the influence of Atlantic SSTs on the GMAT of 1998.

3. Model and Experimental Design

[7] The numerical model used in this study is the Met Office Hadley Centre atmospheric general circulation model known as HadAM3. The model use a 2.5° latitude by 3.75° longitude grid and 19 model levels. It includes the new land surface scheme developed by Cox et al. [1999]. This new land surface scheme includes a representation of the freezing and melting of soil moisture leading to better simulations of surface temperatures, and a new formulation of evaporation which includes the dependence of stomatal resistance to temperature, vapor pressure deficit and CO2. A detailed description of the model formulation and its performance is documented by Pope et al. [2000].

[8] Three experiments, where only SSTs and sea ice extent differ, have been performed. The control simulation was forced with climatological SSTs and sea ice extent, averages over the 30 years from 1961 to 1990 [Smith and Reynolds, 1998]. The “global” experiment was forced with global observed SSTs and sea ice extent, as described by Reynolds and Smith [1994]. The “without Atlantic” experiment was forced with observed SSTs and sea ice extent except in the Atlantic (latitude band 30°S–75°N) where the climatological SSTs and sea ice extent were used. The first step of this study is to determine if the model reproduces the main features of land surface air temperature anomalies when forced with the global observed SSTs. The second step is to investigate the role of just the Atlantic Ocean.

[9] In order to separate externally forced variability from internal variability, an ensemble of 10 integrations was performed for each experiment. These integrations were different only in their initial conditions, which were taken from the end of spin-up integrations. For the control integration, the spin-up was forced with climatological SSTs and sea ice extent, and lasted 1.5 years. Then the control experiment was run for 1 year beginning on 1 December. For the sensitivity experiments, the spin-up was forced with observed SSTs and sea ice extent from 1 June to 31 December, 1996. Then the sensitivity experiments were integrated from 1 January 1997 to 30 November 1998. The initial conditions for spin-up were taken from the model output of the Atmospheric Model Intercomparison Project (AMIP) simulations. Since the atmospheric response time is a few weeks, and since the land surface response time is a few months, the spin-up in this study is adequate. The response to SST anomalies was estimated as the difference between the ensemble means of a pair of experiments. The Student’s t-test is used to determine if the ensemble means are significantly different between experiments.

[10] The model and experimental design are identical to those given by Dong et al. [2000], who investigated the
cause of winter climate anomalies in the North Atlantic sector during the 1997–1999 ENSO cycle. In addition, this model was found capable of producing the observed collapse of the Walker circulation and the east/west cloud structure changes during the 1997/98 El Niño [Lu et al., 2004].

4. Simulated Results

[12] The model forced with the global SSTs captures the pattern of annual surface air temperature anomalies (Figure 2a; see also Table 1) with a pattern correlation of 0.41 with observed anomalies over land globally between 60°S and 70°N. The model simulates the positive surface air temperature anomalies of 0.5°–1.0°C over the southern Eurasian continent, central and southern Africa, and northern parts of North and South America, 1.0°–2.0°C over Australia, and cold anomalies of 1.0°–2.0°C over the northern Eurasian continent.

[13] It should be noted that the pattern correlation between observed and simulated air temperature anomalies over land are not very high. The current climate models have a limited capability of simulating well the climate anomalies in the extratropics. The HadAM3, at least qualitatively, captures the main pattern of annual surface air temperature anomalies over global land, which provides a base for the present study.

[14] The global mean features of the model simulated surface air temperature are summarized in Tables 2 and 3. The model forced with the global SSTs simulates an anomalous GMAT of 0.47°C, very close to the value of observed GMAT anomaly (0.5°C). The simulated global land mean surface air temperature (LMAT) shows a season-to-season change similar to GMAT, being largest in summer and smallest in winter (Table 3). The model forced with the global SSTs reproduces well the phenomenon that the land warmth is stronger than the SST warmth.

[15] Figure 2b illustrates the difference between the global experiment and the “without Atlantic” experiment, which implies the role of Atlantic SSTs. It demonstrates that the Atlantic SST anomalies induce positive anomalies of surface air temperature in Africa, a major portion of the Eurasian continent, Australia, tropical North America, and Greenland (see also Table 1). The Eurasian continent is the region where the Atlantic SST anomalies contribute most to the global land warmth in the 1998 meteorological year. Without the role of Atlantic SSTs, the surface air temperatures would be lower than or near to normal in the central and eastern parts of the Eurasian continent and Australia.

[16] The annual mean of the LMAT anomaly implied by the Atlantic SST anomalies is 0.31°C, more than half of that forced with the global SSTs (Table 3), indicating that the Atlantic SST anomalies play an important role in influencing the land surface air temperatures in 1998. Particularly, the Atlantic SSTs cause a 0.33°C December-January-February (DJF) mean LMAT anomaly, being 92.1% of that forced by the global SSTs, mainly due to the considerable warmth in the Eurasian continent induced by the Atlantic SSTs (Figure 3, first panel).

[17] Figure 3 shows the seasonal mean surface air temperature anomalies implied by the Atlantic SSTs. In all seasons, the Atlantic SST anomalies result in warmer surface air temperatures in most areas of the Eurasian
continent and colder air temperatures in northern Europe. The air temperature anomalies tend to be zonally oriented in the Eurasian continent in summer and autumn. The Atlantic SST anomalies also lead to warmer surface air temperatures in Africa, Australia, and tropical North America, although they are somewhat seasonally dependent. The positive anomalies become stronger and more significant from winter 1997/98 to autumn 1998 in the African continent.

Figure 4 shows the seasonal mean precipitation anomalies implied by the Atlantic SSTs. In all seasons, there is enhanced precipitation in the tropical Atlantic. It is likely that the precipitation anomalies arise as a direct local response to the warm SST anomalies in the tropical Atlantic. In addition, enhanced precipitation appears in the extratropical Atlantic, particularly in the North Atlantic in DJF and SON. In DJF and MAM, significant negative precipitation anomalies appear in the Gulf of Mexico, and extend northeastward into the North Atlantic.

In JJA and SON, enhanced precipitation in the tropical Atlantic extends westward into the tropical northwest Pacific. In addition, there are many more significant and well-organized precipitation anomalies in the Pacific in comparison with those in DJF and MAM. In the western and central Pacific, there are strong and significant precipitation anomalies extending into the high latitudes in both the Northern and Southern Hemispheres. These precipitation anomalies are oriented in the zonal direction in the Tropics. In the extratropics, they are oriented in the southwest-northeast direction in the North Pacific and in the southeast-northwest direction in the South Pacific, similar to the orientation of subtropical convergence zones.

In the Indian Ocean, there are significant negative precipitation anomalies in all seasons, which appear in the southern Indian Ocean in DJF and shift northward into the northern Indian Ocean and even over the Indian continent in the subsequent seasons.

Some critical questions, of course, are what are the mechanisms through which Atlantic SST anomalies influence the GMAT? Are different mechanisms operating in different seasons? In the following, the anomalies of atmospheric circulation induced by Atlantic SST anomalies are used to illustrate these mechanisms.

Figure 5 shows the seasonal mean 200-hPa velocity potential anomalies implied by the Atlantic SSTs. The shading shows the 95% significance level using the Student’s t-test. Solid lines are for positive values and dashed lines are for negative values. Units are in \( 10^6 \text{ m}^2 \text{s}^{-1} \). The contour interval is 0.5, and the zero line is not shown.
ity potential anomalies suggest that the stationary disturbances extend into the Pacific, and likely lead to the significant and well-organized precipitation anomalies in the western Pacific and Indian Ocean. These precipitation anomalies and associated diabatic heating anomalies may in turn influence the climate in the Eurasian continent and Australia.

In DJF and MAM, velocity potential anomalies are much smaller than those in JJA and SON, particularly in the central and western Pacific, Indian Ocean, and the Eurasian continent (Figures 5a and 5b). This suggests the weakness of stationary tropical wave patterns in DJF and MAM, and thus implies different mechanisms operating in DJF/MAM and in JJA/SON.

The zonal wind anomalies on the equator (Figure 6) confirm that the mechanisms through which the Atlantic Ocean influences the GMAT are different between DJF/MAM and JJA/SON. In all seasons, westerly and easterly anomalies respectively appear in the lower and upper troposphere in the Atlantic, which is likely induced by the warmer SSTs and the resultant enhanced precipitation in the equatorial Atlantic. These westerly and easterly anomalies extend westward into and are even centered in the eastern Pacific in JJA/SON, while they are basically concentrated in the Atlantic in DJF/MAM. The zonal wind anomalies also exhibit a clear distinction between DJF/MAM and JJA/SON in the eastern hemisphere. Easterly and westerly anomalies respectively appear in the lower and upper troposphere in JJA/SON, while poorly organized anomalies appear in DJF/MAM in the eastern hemisphere.

The elements of height and meridional velocity are used to analyze the teleconnection patterns in the extratropics induced by the Atlantic SST anomalies. Ambrizzi and Hoskins [1997] showed that for a zonally extended source, theory predicts the excitation of Rossby waves that propagate meridionally into midlatitudes and exhibit a zonal scale similar to that of the source. In DJF and MAM, the characteristics of height anomalies with a baroclinic structure in the tropical Atlantic and a barotropic structure in the extratropics (Figure 7), are in line with theoretical predictions and thus support the hypothesis concerning the mechanism of the role of the Atlantic Ocean. In both DJF and MAM, there are significant negative height anomalies at 200 hPa in North America, although the centers of these anomalies are slightly different. These height anomalies directly result in a colder temperature in North America (Figure 3, first and second panels).

In JJA and SON, there are Rossby wave trains arching poleward into high latitudes in both hemispheres from the tropical eastern Pacific (Figure 8). This suggests that in these two seasons the positive precipitation anomalies in the tropical eastern North Pacific and the tropical North Atlantic (Figure 4), which are induced by the Atlantic SST anomalies, may trigger significant extratropical circulation anomalies. There seem to be wave trains from the tropical Indian Ocean and tropical western Pacific to high
latitudes in both hemispheres, which may be induced by the zonally oriented significant precipitation anomalies in the tropical Indian Ocean and tropical western Pacific. The positive (negative) height anomalies correspond to higher (lower) surface air temperatures in the extratropical lands in JJA and SON.

In the following, we further examine the extratropical teleconnections over the Eurasian continent in DJF and MAM because the Atlantic SST anomalies contribute to the global land surface air warmth mostly through the surface air warmth in this continent in these two seasons. The anomalies of meridional velocity and wave activity flux at

**Figure 7.** Seasonal mean height anomalies at 200 and 850 hPa implied by the Atlantic SSTs. The shading shows the 95% significance level using the Student’s t-test. Solid lines are for positive values and dashed lines for negative values. The contour intervals of heights are 10 and 5 geopotential meters (gpm) for 200 and 850 hPa, respectively, and the zero line is not shown.

**Figure 8.** Seasonal mean 200-hPa height anomalies in (a) JJA and (b) SON implied by the Atlantic SSTs. The shading shows the 95% significance level using the Student’s t-test. Solid lines are for positive values and dashed lines are for negative values. The contour interval is 10 gpm, and the zero line is not shown.
500 hPa are presented in Figure 9. Here the meridional wind, which may depict zonally oriented teleconnections well [Lu et al., 2002], is used to investigate the extratropical teleconnections over the Eurasian continent. Other elements, such as height and stream function and vorticity, are closely related to zonal wind and sensitive to the variability of the extratropical westerly jet streams, and tend to show zonally elongated anomalous patterns. Actually, zonally elongated height anomalies can be found over the southern Eurasian continent in DJF and MAM (Figures 7a and 7b). On the other hand, 500 hPa is a quasi-nondivergent level, and thus the field of meridional velocity is dominated by the rotational component, which is related to Rossby waves.

[28] We present only the horizontal components of the stationary wave activity flux, $W$, rewritten from Takaya and Nakamura [1997]

$$W = \frac{1}{2\sqrt{U^2 + V^2}} \left( U(\psi_x^2 - \psi_y \psi_{xx}) + V(\psi_y \psi_x - \psi_x \psi_{xy}) \right)$$

where $U$ and $V$ are seasonal mean zonal and meridional velocities in the “without Atlantic” experiment, and $\psi$ is seasonal mean stream function anomalies implied by the Atlantic SST anomalies. In the almost-plane wave limit, $W$ represents the phase-independent wave activity flux for stationary waves on a zonally varying basic flow, and is parallel to the local group velocity.

[29] The meridional velocity anomalies in Figure 9 indicate that there are teleconnection patterns in the North Atlantic and Eurasia in both DJF and MAM. The teleconnection patterns completely disappear in JJA and over the eastern extent of the Eurasian continent in SON. The wave activity flux is in good agreement with the teleconnection pattern of meridional wind for all seasons. The apparent sources of anomalous stationary wave activity are located in the North Atlantic. The wave activity flux shows that waves propagate poleward and eastward away from the North Atlantic to northern Europe and then turn equatorward and reach East Asia in DJF and MAM. In JJA, there is not any clear wave activity flux in the Eurasian continent. In SON, the wave activity flux appears clearly over the North Atlantic and the western extent of the Eurasian continent in a similar direction to that in DJF/MAM, but its eastward propagating component completely disappears over the eastern extent of the continent.

[30] Karoly et al. [1989] suggested that midlatitude processes, such as instabilities of the westerly jet stream or interaction with transient eddies, may be the major mechanisms for forcing anomalous stationary waves. The midlatitude processes may be induced by the extratropical North Atlantic SST anomalies, and may also be induced by the tropical Atlantic SST anomalies through the poleward propagating Rossby waves (Figure 7). However, this study does not distinguish the effects of tropical and extratropical Atlantic SST anomalies.

[31] The reasons for the considerable differences in the mechanisms through which the Atlantic Ocean influences air temperatures between DJF/MAM and JJA/SON remains unknown. However, the stronger and equatorward extended westerlies in the Northern Hemisphere extratropics in DJF/MAM (Figure 10), in comparison with those in JJA/SON, may be helpful to the eastward propagating quasi-stationary Rossby waves and to the stronger instabilities of the...
Figure 10. Seasonal mean anomalies of zonal mean 200-hPa zonal wind (m s\(^{-1}\)) in the “without Atlantic” experiment.

westerly jet stream or interaction with transient eddies. The
latitudinal scope of westerly is almost unchanged from DJF
to MAM, while shrinks poleward in SON and further in
JJA. Such seasonal differences, particularly the difference
between MAM and SON, is not specially for the “without
Atlantic” experiment in 1998. Climatologically, the extra-
tropical westerlies in the Northern Hemisphere are also
stronger and further equatorward extended in DJF/MAM
than JJA/SON (not shown).

5. Summary and Discussion

The HadAM3 model forced with the observed global SSTs captures the main features of land surface air temperature anomalies in 1998, which is the warmest year in the period of instrumental measurements. We have found that the Atlantic SST anomalies can explain 35% of the GMAT anomaly and 57% of the LMAT anomaly in the 1998 meteorological year forced with the global SST anomalies. The Atlantic SST anomalies contribute greatly to the positive anomalies of surface air temperature in the central and eastern parts of the Eurasian continent, Australia, Africa, and tropical North America.

The mechanisms through which the Atlantic Ocean influences the regional surface air temperature are found to be seasonally dependent. In winter and spring, the Rossby waves excited by anomalous diabatic heating in the tropical Atlantic, and their poleward and eastward propagation, are possibly responsible for the midlatitude and downstream responses. In summer and autumn, the remote role of Atlantic SSTs may be largely due to the equatorial stationary disturbances that extend westward and eastward from the Atlantic into the Pacific.

Greenhouse gases, volcanoes, and solar irradiance may play a role in causing the highest GMAT in 1998 by changing the global SSTs. On the other hand, the Atlantic SSTs may be influenced by the Pacific SSTs [e.g., Elliott et al., 2001]. This study indicates that the Atlantic SSTs, after being influenced by these factors, may play a crucial role in modifying the GMAT at least in some years. Therefore attention should be paid to both the role of Atlantic SSTs and the influences of these factors on Atlantic SSTs, in order to understand well global warming.

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References


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