The Impact of the 1997/98 El Niño Event on the Atlantic Ocean
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ABSTRACT
The El Niño–Southern Oscillation (ENSO) has far-reaching impacts on global climate via “teleconnections” associated with wavelike or other disturbances that are excited in the tropical Pacific. These teleconnections may influence the air–sea heat fluxes, either by altering the latent and sensible heat fluxes through a change in low-level wind speed or direction or by altering the degree of cloud cover and thus the radiation budget. The anomalous fluxes can generate sea surface temperature (SST) anomalies that can in turn feed back on the atmospheric circulation. These effects are explored for the 1997/98 ENSO event using a novel and powerful modeling technique in which a coupled ocean–atmosphere model (the U.K. Hadley Centre HadCM3 model) is forced to follow observed tropical Pacific SSTs using a strong thermal relaxation, while elsewhere the model is allowed to vary freely. This is an extension of previous studies in which the impact of ENSO was investigated using an atmospheric model coupled to an ocean mixed layer model. The authors focus on the impact of ENSO on the Atlantic Ocean. Model results are compared both with historical records of the Atlantic response to El Niño and with SST observations during the 1997/98 event. The model simulates well the warming of the tropical North Atlantic that is typical of El Niño events. In addition, it identifies a significant positive anomaly in the South Atlantic in the autumn of 1997/98 that was also observed and appears to be a feature of the Atlantic response to El Niño that has not previously been noted. The results suggest that many other large SST anomalies observed in the Atlantic during 1997/98 were not part of the response to El Niño.

1. Introduction
The development of seasonal forecasting presents an enormous challenge to the climate science community, namely, to identify and exploit the full limits of the predictability of the ocean–atmosphere system. The most important phenomenon that gives rise to useful predictability on seasonal timescales is the El Niño–Southern Oscillation (ENSO). ENSO events are associated with predictable climate anomalies both in the tropical Pacific, where the center of action lies, and in remote regions. The remote anomalies arise through atmospheric “teleconnections” associated with wavelike or other disturbances that are excited in the tropical Pacific (e.g., Trenberth et al. 1998).

Although the remote response to ENSO has been studied for many years, we are still far from possessing a complete understanding of all the factors that influence the strength and nature of the impacts on climate. One such factor is the role of remote ocean–atmosphere interactions: the atmospheric disturbances excited by ENSO events can force changes in remote ocean basins, via the so-called atmospheric bridge (Lau and Nath 1996). The remote sea surface temperature anomalies that develop in these regions may then force further changes in the atmosphere. Consequently, to understand the full implications of an ENSO event, and to fully exploit the associated climate predictability, these remote ocean–atmosphere interactions must be considered.

One of the regions that is affected by ENSO events is the Atlantic basin. Curtis and Hastenrath (1995) used a composite of observed El Niño events to study the remote effects on the tropical Atlantic Ocean–atmosphere system. They identified a common sequence of events beginning with a weakening of the northeast trade winds in boreal winter. This weakening leads to a reduction in the cooling of the ocean by surface heat fluxes and therefore to the development of a warm SST anomaly north of the equator in boreal spring. This SST anomaly has a significant influence on the atmosphere. In particular, it tends to force anomalous flow across the equator toward the north. This anomalous flow may in turn force additional changes in the ocean, further extending the chain of events.

The Curtis and Hastenrath study provides a very useful summary of some of the major features of the At-
Atlantic basin response to El Niño events. A feature of their approach, however, is that it extracts only that part of the response that is common to all El Niño events. In practice El Niño events themselves, and their remote impacts, differ from one another, and understanding the unique character of each event is an important research challenge.

In this paper we investigate further the influence of El Niño on the Atlantic basin. We focus on a particular case study: the El Niño event of 1997/98—in the future we hope to investigate the response to other El Niño events. We begin by examining the observed evolution of the Atlantic Ocean at this time. An immediate problem, however, is that there is no way on the basis of observations alone to determine whether particular changes are necessarily a response to the El Niño event rather than a result of other processes. In other words, we cannot separate signal and noise.

The major source of noise on seasonal-to-interannual timescales is atmospheric internal variability. To identify the remote response to a particular El Niño event we need a way of repeatedly simulating the event with multiple different realizations of the atmospheric evolution. This requirement can be accomplished straightforwardly in studies where atmosphere-only models are used: the imposed lower boundary condition provides the common El Niño forcing, while a range of atmospheric initial conditions is used to sample the atmospheric internal variability. Such models, however, are clearly not suitable for studying the ocean–atmosphere interactions of interest here. Fortunately, there is a way forward. Lau and Nath (1996) pioneered experiments in which common boundary forcing is imposed in a limited region (usually the tropical Pacific), while elsewhere the atmosphere is allowed to interact freely with an ocean model. In their experiments the ocean model consisted of a simple representation of the mixed layer. In this study we have extended the approach by using a full coupled GCM so that a more complete representation of the ocean physics is achieved.

The common forcing in our coupled GCM experiments is imposed by strongly relaxing the SST in the tropical Pacific and Indian Oceans to follow a prescribed evolution (e.g., climatology or a particular El Niño event), while elsewhere the ocean and atmosphere interact freely. As with atmosphere-only model studies we sample the atmospheric internal variability by choosing a number of different atmosphere initial conditions. Overall our approach offers a very powerful way to further understanding of the remote ocean–atmosphere response to individual El Niño events.

The remainder of this paper is divided into five sections. Section 2 describes the observed evolution of Atlantic SST during 1997/98. Section 3 introduces the model used, and the spinup procedure used to provide suitable initial conditions. Section 4 describes our experimental design, while section 5 describes the results. Last, section 6 draws conclusions from this work and highlights possible future directions for research.

2. Observed evolution of Atlantic SST during 1997/98

The 1997/98 El Niño event was unusual in being one of the largest events on record and in the fact that significant SST anomalies developed earlier in the year than is typical. Figure 1 shows the evolution of central-eastern equatorial Pacific SST during 1997/98. Positive anomalies first appeared in the spring of 1997 and had already reached several degrees centigrade by summer. The growth continued until the end of the year before a relatively rapid decay in the winter and spring of 1998.

Figure 2 shows 2-month averages of the observed Atlantic SST anomaly, obtained by optimal interpolation using the method of Smith et al. (1994), from mid-1997 to the end of 1998 (relative to the climatological mean from November 1981 to June 1999; we also calculated SST anomalies relative to the climatology derived from the U.K. Met. Office historical data that was used in our modeling studies, and, apart from some artifacts attributable to the different interpolation algorithms, found very similar patterns of anomalies). In the second half of 1997 the North Atlantic exhibited a tripoledike pattern of anomalies, with a negative anomaly off the North American coast and positive anomalies to its north and south. In the southern tropical Atlantic negative anomalies present in June–July 1997 had, by the end of the year, been replaced by positive anomalies.

In the early part of 1998 the negative anomalies off the coast of North America gradually decayed leaving positive anomalies covering almost all the Atlantic basin. Meanwhile the northern subtropical Atlantic (latitudes 0°–20°N) gradually warmed. This latter development is in line with the canonical El Niño response described by Curtis and Hastenrath (1995). A notable event in the middle of 1998 was the development of

![Fig. 1. The evolution of Pacific SST anomaly in 1997/98 averaged over the region from 5°S to 5°N and 150°W.](image-url)
sizeable positive anomalies off the west coast of southern Africa and along the equator. Also at this time a large positive anomaly became prominent in the North Atlantic. This latter anomaly persisted, with some southeastward evolution, into the autumn.

As noted in the introduction, from a simple inspection of observations there is no way we can identify with any confidence which of the observed anomalies are part of the response to the El Niño event and which are attributable to other causes (notably internal atmospheric variability). Consequently, to make further progress we turn now to our model-based investigation.

3. Coupled model and spinup

As explained in the introduction, to investigate the impact of the 1997/98 El Niño event on the Atlantic basin we employ a novel modeling strategy. We use a global coupled climate model, but modify the coupling in the tropical Pacific and Indian Oceans by applying a strong relaxation to the SST. Although the Indian Ocean is not a major area of El Niño forcing, we choose to relax the SST in this region as well as in the Pacific to avoid possible large SST gradients in the region of Indonesia, which could have adverse effects on the model’s performance, in particular the location of deep convection.

The model we use is a version of the U.K. Hadley Centre global coupled climate model known as HadCM3, which is described in Gordon et al. (1999). The atmosphere resolution is $2.5^\circ \times 3.75^\circ$, with 19 levels in the vertical, while the ocean resolution is $1.25^\circ \times 1.25^\circ$, with 20 levels in the vertical. The model uses
a new radiation scheme developed by Edwards and Slingo (1996), as well as a new land surface scheme (Cox et al. 1999) that includes a representation of the freezing and melting of soil moisture, as well as surface runoff and soil drainage. The standard version of this model requires no heat flux correction to maintain a stable climate.

Prior to beginning any experiments, a two-stage spin-up procedure was followed. First, the standard version of the model with no flux correction was integrated for 700 yr. At the end of this period, the model had reached a stable state with very small drift. In the second stage of the spinup the SST relaxation was introduced in the tropical Pacific and Indian Oceans. The SST was relaxed to a climatology calculated from the Met. Office historical data (based on monthly data going back to 1856), using a relaxation coefficient that is illustrated in Fig. 3. Note that the very strong relaxation (5000 W m\(^{-2}\) K\(^{-1}\)) has the effect of anchoring the SST to the prescribed climatology. With this relaxation in place, the coupled model was integrated for a further 10 yr.

It was not known whether the model climate would start to drift during this period, since there were some significant differences between the observed climatology and the model climatology. One might expect that the sudden change in SST in large parts of the Tropics would cause large changes in the atmospheric circulation and subsequent changes in the SST in other regions. Fortunately, this did not occur. Figure 4 illustrates, for example, the tropical Atlantic temperatures at four depths during this spinup period. At all depths any drift is very small.

An indication of how well the flux-corrected model simulates the observed climate is given in Fig. 5, where the annual mean SSTs from the final year of the 10-yr spinup are differenced from observed climatological SSTs. The errors are very similar to the errors from the full coupled model (Gordon et al. 2000). As discussed above, adding the relaxation to prescribed climatological SSTs in the tropical Pacific does not significantly change the model climatology outside the relaxation region. Although the model errors are large in some places, over most of the Atlantic Ocean errors are no worse than 1°C.

The final state of the coupled model after the second phase of the spinup is the state that was used as initial conditions for our experiments to investigate the effect of El Niño on the Atlantic Ocean. The design of these experiments is described in the next section.
4. Experimental design

To create a control Atlantic climate, an ensemble of eight integrations, all forced with the Met. Office historical climatology, was performed. Each integration lasted 2 yr, starting on 1 December. The initial conditions consisted of an oceanic state taken from the end of the 10-yr spinup described in the previous section, and different atmospheric conditions sampled from consecutive days of the same spinup run.

Having created the control ensemble, a second ensemble (again of eight members) was created in which the Pacific Ocean SSTs were strongly relaxed to the observed values (taken from the Reynolds optimal interpolation) for the period December 1996–December 1998. We refer to this ensemble as the ENSO ensemble.

5. Results

As discussed earlier, Curtis and Hastenrath (1995) found that the most robust feature of the Atlantic response to El Niño events was a significant positive SST anomaly in spring in the tropical North Atlantic. We thus focus our attention first on this region. We form averages of the SST over the shaded region in the lefthand panel of Fig. 6 for both the control ensemble and the ENSO ensemble. The evolution of these averages for the members of both ensembles is shown in the righthand panel, with solid lines corresponding to the control ensemble and dotted lines to the ENSO ensemble.

The slightly different atmospheric initial conditions of the different ensemble members lead to diverging atmospheric fields that force the ocean differently in each integration of the ensemble. This results very quickly (within about one month) in different SSTs, and on longer timescales will result in different density and circulation anomalies throughout the ocean. The separation of ensemble SSTs can be seen in the right-hand panel of Fig. 6, which shows that the ensemble spread increases rapidly at first, but saturates after around 3 or 4 months, the typical lifetime of mixed layer temperature anomalies. We can thus expect the eight ensemble members to give reasonably independent realizations of the Atlantic SST fields beyond this initial period of about 4 months. In the subsequent analysis of SST anomalies, the first 6 months of the integrations are ignored.

It can be seen that in the ENSO ensemble, with El Niño SSTs prescribed in the Pacific, the Atlantic SST develops in a quite different way from the control ensemble. In the early part of 1998, the SSTs in the ENSO ensemble are all higher than the SSTs in the control. This is not only a statistically significant signal but is also strong in the sense that the difference in the ensemble means is large relative to the spread within the ensembles, and is clearly indicative of the influence of tropical Pacific SSTs on the tropical North Atlantic SST. As mentioned in the introduction, it has been argued that such a teleconnection occurs through the weakening of northeasterly trade winds and the consequent reduction in evaporative cooling over the tropical North Atlantic (Curtis and Hastenrath 1995; Enfield and Mayer 1997). The signal from our model broadly agrees with
the findings of Curtis and Hastenrath, and is of a similar magnitude (approx 1 K), showing that the model is performing well in this region.

We have noted that the tropical North Atlantic warming is common to all (or at least most) El Niño events. We now turn to discuss the specific response to the 1997/98 event. Figure 7 shows the evolution of model SST anomalies (mean of the ENSO ensemble minus mean of the control ensemble) in the Atlantic Ocean from mid-1997 to the end of 1998—the anomalies are only shown where a t test indicates statistical significance at the 99% confidence level. In the North Atlantic, positive anomalies develop off the east coast of the United States in early 1998, peaking in the middle of that year. The positive anomalies in the tropical North Atlantic (which have already been discussed) can be seen peaking in April–May 1998 and then decaying. In the South Atlantic, a positive anomaly develops off the east coast of South America in late 1997, and decays toward the end of that year, while negative anomalies develop off the west coast of Africa toward the end of 1998.

We now make detailed comparisons between the model SST anomalies and the observed SST anomalies shown in Fig. 7. The first point to note is that many of the large SST anomalies seen in the observations, for example, the positive anomaly that develops in the North Atlantic toward the end of 1998, are not seen in the ensemble mean model response. Assuming (for now) that the model is perfect, this result indicates that most of the SST anomalies present in the North Atlantic in 1997/98 were not part of the response to El Niño, instead, as mentioned in section 2, they probably arose as part of the ocean’s response to internal atmospheric variability.

We now examine the difference between model and observed SST anomalies in specific regions of the Atlantic, and return first to the tropical Atlantic region. Our El Niño–forced model shows a strong positive SST anomaly in the spring of 1998, and we see clear evidence of a similar signal in the observed SST anomalies. There is a suggestion that the SST anomaly seen in the model is closer to the equator than in the observations, perhaps indicating some systematic error. A somewhat similar feature has been noted in other studies with HadCM3 (R. Neale 1999, personal communication). Another interesting feature in the observations is the equatorial SST anomaly off the west coast of Africa that develops in April–May 1998, and peaks in June–July. There is some indication of a similar signal in the model, but a poor simulation may be attributable to the fact that equatorial upwelling is poorly resolved.

In the North Atlantic region, the model shows positive SST anomalies off the east coast of North America during most of 1998, and especially in February–March and April–May. A similar signal (albeit displaced slightly to the northeast) is seen in the observed SST anomalies, indicating that it is likely to be part of the ENSO response. Later in the year, and farther to the east, the observations show the development of a large positive SST anomaly off the west coast of Spain. Since there is no evidence of a counterpart to this feature in the model, it is probably part of the response to internal atmospheric variability, rather than a response to ENSO.

For the South Atlantic region, a particularly interesting feature is the significant positive anomaly that develops off the South American coast in the El Niño–forced ensemble toward the end of 1997, peaking in October–November 1997. A positive anomaly in a similar position at the same time is seen in the observed SST anomalies, strongly suggesting that it is part of the ENSO response rather than a consequence of internal variability. Whether this feature is common to all El Niño events remains to be discovered in follow-up investigations.

It is interesting and informative to consider how SST anomalies are formed and destroyed in the model. As a case study, we now examine the evolution of the anomaly off the South American coast. For this purpose, Fig.
Fig. 7. Two-month means showing the evolution of the model SST anomaly (ensemble forced by El Niño minus control ensemble) in the Atlantic Ocean. The anomaly is only shown in regions where it is statistically significant (reaching a 99% confidence level in a $t$ test).

8b shows the evolution of the anomaly, averaged in the region from $40^\circ$S to $10^\circ$S and from $40^\circ$W to $0^\circ$ (shown by Fig. 8a). Figure 8c shows the SST tendency in this region (the dashed line) compared with the tendency expected from the net surface flux anomalies (the solid line) in the absence of advective effects. The fact that the two curves are so similar shows that the advective terms are relatively small, and a simple mixed layer ocean would probably suffice in this case. In Fig. 8d, the net surface flux is decomposed into individual constituents, namely, the net shortwave radiation (dotted line), the net longwave radiation (dashed line), the latent heat flux (dot–dashed line), and the sensible heat flux (dot–dot–dot–dashed line). This shows that the main contributor to the growth of this particular anomaly is reduced cooling by surface evaporation (associated with a reduction in the surface wind speeds), while the main contributor to its destruction is a reduction in the net shortwave radiation (associated with an increase in the cloud cover in this region). Klein et al. (1999) have carried out studies of anomalous heat fluxes associated with ENSO events by regressing ship observations onto the ENSO index; they found modest increases in cloud cover north and south of the equator during the same period, consistent with this interpretation.

The example given in the previous paragraph of an SST anomaly produced by anomalous heat fluxes could have been reproduced by an atmospheric model coupled to a mixed layer ocean model, since the advective effects in that particular case were small. However, our model also simulates significant changes in ocean dynamics in response to ENSO. Figure 9 shows the anomalous sur-
Fig. 8. This plot shows the evolution of a particular Atlantic SST anomaly. (a) The model SST anomaly averaged over the months of Oct–Nov 1997 with the rectangle highlighting the anomaly. (b) The evolution of the SST anomaly averaged over this rectangle, while (c) compares the actual trend in SST (in units of 0.01 K month$^{-1}$), shown by the dashed line, with that derived from the total heat flux at the surface (the solid line). (d) The individual terms that make up the total heat flux, namely, the net shortwave radiation (dotted line), the net longwave radiation (dashed line), the latent heat flux (dot–dashed line), and the sensible heat flux (dot–dot–dot–dashed line).

face ocean velocity (the mean of the ENSO ensemble minus the mean of the control ensemble) averaged over March, April, and May of 1998 (Fig. 9a), and the corresponding anomalous wind stress (Fig. 9b). Arrows are only shown where the anomalies are statistically significant at the 99% level. The most significant features seen in the anomalous ocean velocity are a westward current at the equator, driven by the anomalous westward wind stress, and, off the equator, Ekman flows perpendicular to the anomalous wind stress. The anomalous wind stresses are associated with the enhanced northward flow across the equator seen by Curtis and Hastenrath (1995) in the canonical ENSO response. Figure 9 shows that by using a full ocean model it is possible to capture the remote response to ENSO more completely than is possible with a mixed layer model alone.

For most of the preceding discussion we have assumed our model is perfect. In reality there are of course model errors, such as the poor representation of equatorial upwelling that we mentioned previously. It is likely that these errors are a factor in explaining some of the differences between our model results and the observations, especially in the equatorial region. Consequently, it would be useful to repeat our study with other models to assess any model dependence of the conclusions. That said, our conclusion that the major source of differences between the model ensemble mean and the observed Atlantic SST anomalies indicates the important role of atmospheric internal variability is almost certainly robust.

6. Conclusions

We have carried out numerical studies using the U.K. Met. Office Unified Model (with HadCM3 physics) to investigate the impact of the 1997/98 El Niño event on the Atlantic Ocean. We have chosen not to take the path of using a globally coupled model, owing to the difficulty of investigating the response to a particular El Niño event within that framework, but have opted instead to use a partially coupled model, forced in the Pacific with observed SSTs but fully coupled elsewhere. This is an extension of the work of Lau and Nath (1996), who pioneered the use of an atmospheric model partially coupled to an ocean mixed layer model.

Our results show a strong response to El Niño in the tropical Atlantic Ocean, with almost complete separation of SST between our control and ENSO ensemble. We have investigated the patterns of SST anomaly produced by our experiment and compared them with observed SST anomalies from Reynolds analyses—
some cases the correspondence is weak, pointing to the role of stochastic atmospheric variability in forcing SST anomalies, while in other cases there is strong correspondence, suggesting that we are looking at part of the Atlantic response to El Niño. In particular, the interesting South Atlantic SST anomaly described in the previous section is, insofar as we are aware, a newly identified feature of the Atlantic response to El Niño. By analyzing the contributions to the surface heat flux that were responsible for its creation and subsequent destruction, we have found that it was created by anomalous evaporation and destroyed by anomalous shortwave radiation. Such analyses permit us to study the physical mechanisms by which SST anomalies are formed.

Future work will include more detailed studies of individual SST anomalies with greater attention to physical mechanisms responsible for their creation, and experiments to investigate in detail the role of atmosphere–ocean coupling in the Atlantic. We intend to extend our studies to other ENSO events to find out which features of the response are unique and which are common to all events. We also hope to investigate the influence on our results of the initial state of the Atlantic Ocean, which could have important implications for predictability. The work described here may be seen, at least in part, as a proof of concept, demonstrating the viability of the partially coupled ocean–atmosphere model in investigating the response to events such as El Niño.

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