The Simulation of Peak and Delayed ENSO Teleconnections

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Abstract

There is much evidence that El Niño and La Niña lead to significant atmospheric seasonal predictability across much of the globe. However, despite successful predictions of tropical Pacific SSTs, atmospheric seasonal forecasts have had limited success. This study investigates model errors in the Hadley Centre Atmospheric Model version 3 (HadAM3) by analyzing composites of similar El Niño and La Niña events at their peak in December–January–February (DJF) and through their decay in March–April–May (MAM).

The large-scale, tropical ENSO teleconnections are modeled accurately by HadAM3 during DJF but the strongest extratropical teleconnection, that in the North Pacific during winter, is modeled inaccurately. The Aleutian low is frequently observed to shift eastward during El Niño but the modeled response always consists of a deepening of the low without a shift. This is traced to small errors in the sensitivity of precipitation to SST in the tropical Pacific, which does not display enough variability so that the precipitation is always too high over the warmest SSTs. This error is reduced when vertical resolution is increased from 19 to 30 levels but enhanced horizontal resolution does not improve the simulation further.

In MAM, following the peak of an El Niño or La Niña, atmospheric anomalies are observed to decay rapidly. The modeled ENSO response in DJF persists into MAM, making the extratropical anomalies in MAM too strong. This inaccuracy is again likely to be due to the high modeled sensitivity of tropical Pacific precipitation to SST, which is not significantly improved with enhanced vertical or horizontal resolution in MAM.

1. Introduction

A number of observational studies (e.g., Halpert and Ropelewski 1992; Klein et al. 1999; Pan and Oort 1990), modeling studies (e.g., Cassou and Terray 2001; Kumar et al. 1996; Peng et al. 2000; Rowell 1998; Shukla et al. 2000; Graham et al. 2000), and the review paper by Palmer and Anderson (1994) have shown that there may be scope for extended predictability of seasonal climate anomalies in years of anomalous tropical Pacific sea surface temperature (SST). Brankovic et al. (1994) showed that this predictability is mainly due to the correct boundary conditions at the sea surface, rather than memory of the atmospheric initial conditions. This paper forms part of a larger modeling study to investigate the role of the response by the remote oceans and land surface in modifying and possibly extending the predictability associated with ENSO.

Seasonal prediction requires sufficiently accurate atmosphere, land surface, and ocean models and a sufficiently nonchaotic system. The focus here will be on assessing the accuracy of an atmosphere and land surface model, the Hadley Center Atmospheric Model version 3 (HadAM3), at reproducing ENSO teleconnections when forced by observed SSTs. The effect of the response of the remote ocean basins on atmospheric predictability is examined by Spencer et al. (2002, manuscript submitted to Climate Dyn.).

Composite events are calculated in order to ascertain, with statistical significance, the influences of ENSO. This technique has been used by Cassou and Terray (2001), Kumar et al. (1996), Renshaw et al. (1998), and Straus and Shukla (2000) and is based on the assumption that the events in the composite share a number of similar features. These authors based their composites on various ENSO indices and included both strong and weak events. This has the desirable effect of increasing statistical significance due to the large number of events in the composite. However, the signal for different sized events can be quite variable due to the nonlinearities of the atmospheric response (Hoerling et al. 2001; Molteni and Brankovic 2002). [The nonlinear response more commonly discussed is the difference between the El Niño and La Niña response (Hoerling et al. 2001; Molteni and Brankovic 2002).] Therefore, if strong and weak events are included together to make the composite bigger, statistical significance may, in fact, decrease as the response differs between events.

The linearity of the ENSO response in the North Pa-
specific has received much attention. An eastward shift of the Aleutian low response in the North Pacific in comparison with La Niña is sometimes observed during El Niño. Hoerling et al. (1997) attributed this observed shift during El Niño to the eastward shift in the tropical Pacific heating. However, DeWeaver and Nigam (2002) attributed this shift to decadal variability and the non-linearity due to ENSO was found to be much smaller. Sardeshmukh et al. (2000) also found the change in geographical location of the observed North Pacific response between El Niño and La Niña to be small in comparison with the internal variability observed and in comparison with the shift in the tropical heating. Ensembles of atmospheric GCM simulations clarify the ENSO signal and often show a more linear response (e.g., Sardeshmukh et al. 2000; Peng et al. 2000). It is therefore not clear whether this is due to sampling error of the observations or model error. Hoerling et al. (2001) found the observed North Pacific response to El Niño to be much stronger than that to La Niña and the El Niño response to be shifted 30° east of the La Niña response. However, four different atmospheric GCMs produced a response with a smaller phase shift but retaining the stronger response to El Niño. This paper diagnoses more precisely model errors in the North Pacific response and how these impact the modeled linearity of the teleconnections.

Seasonal means during strong ENSO events simulated by HadAM3 with observed SSTs are compared with reanalysis and observed datasets. The seasons of December–January–February (DJF) at the peak of an ENSO event and the following March–April–May (MAM) as the event decays are being studied because, for forecasting purposes, it is important to be able to predict the response and memory of the system during and after a strong forcing event.

A description of the evaluation method is given in section 2, including a description of the model, the model integrations used, the observational and reanalysis data, and the method of constructing the El Niño and La Niña composites. The results are presented in section 3, which describes the SST composites and the atmospheric response to these SSTs in HadAM3 and in the evaluation data for both DJF and MAM. Reasons for some of the model errors described are also discussed. In section 4, the analysis of the model errors is corroborated by an analysis of some higher resolution model results that show some reduction of these errors. Finally, conclusions are drawn on both the accuracy of the model at calculating ENSO teleconnections and the usefulness of the techniques used in section 5. Some of the modeled linearity between El Niño and La Niña teleconnections in the North Pacific is attributed to model error rather than sampling error.

2. Method

a. Description of the model

The HadAM3 atmospheric GCM is described by Pope et al. (2000) and is shown to reproduce the observed mean climate reasonably well. The standard climate version of the model has a horizontal grid of 2.5° latitude by 3.75° longitude and 19 vertical levels. The model is hydrostatic and uses the Arakawa B grid and Eulerian advection. Moist and dry convection are parameterized with a mass flux scheme (Gregory and Rowntree 1990) and clouds only form in grid boxes with relative humidity greater than a critical value of 70%. A parameterization of convective momentum transport is included that was found to improve the model in several ways but at the expense of slightly overactive Hadley and Walker circulations (Pope et al. 2000).

Pope and Stratton (2002) studied horizontal resolution dependence in a version of HadAM3 with 30 vertical levels; they found that many systematic model errors did not improve with increased horizontal resolution but they did not look at ENSO variability. Note that the model parameterizations are tuned for the standard climate resolution and not the higher resolution. Neale and Slingo (2003) showed that much of the accuracy of the climate prediction does not improve with higher resolution in the area of the maritime continent, a key region for modeling ENSO teleconnections. Renshaw et al. (1998) showed that an earlier version of the model, HadAM1, reproduced teleconnections of ENSO well at standard climate resolution.

b. Model integrations

The model data analyzed in this paper are taken from an ensemble of six integrations of HadAM3 using observed SSTs from 1870 to 1998, run by the Hadley Centre. The observed SSTs imposed are from the Global Sea Ice and SST dataset (GISST dataset version 2.3b: Parker et al. 1995) which contains monthly sea ice and sea surface temperature data from 1870 to the 1998 on a 1° × 1° grid. It was created using EOF reconstruction of ship SST measurements.

To explore the sensitivity to horizontal and vertical resolution, a number of AMIPII integrations of HadAM3 are studied. AMIP II integrations are run with prescribed SSTs from 1979 to 1996 and are compliant with the Atmospheric Model Intercomparison Project II (Gates 1992; Gates et al. 1999). Therefore they have slightly different SST fields imposed from the ensemble with GISST. These integrations were also run at the Hadley Centre (Pope and Stratton 2002).

c. Evaluation data

A number of observational and reanalysis datasets are used to evaluate the model. Comparisons are made with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data provided by the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences Climate Diagnostics Center, Boulder, Colorado,
Fig. 1. The Niño-3 and Niño-3.4 indices from the GISST dataset compared with the composites of five El Niños and five La Niñas. [The Niño-3 index is the monthly SST anomaly in the Niño-3 area of the tropical Pacific (5°S–5°N, 90°–150°W) and the Niño-3.4 index the anomaly in the Niño-3.4 area (5°S–5°N, 120°–170°W).]

(Kalnay et al. 1996), on a 2.5° × 2.5° grid for 1948–98. However, the accuracy of the reanalysis data is dependent on the accuracy of the model used to create it. Therefore comparisons are also made with the Climate Prediction Center Merged Analysis of Precipitation (CMAP) observational dataset (from rain gauges and satellites, Xie and Arkin 1996) for 1979–99 also on a 2.5° × 2.5° grid and the Comprehensive Ocean–Atmosphere Data Set (COADS) marine observational data of sea level pressure (Woodruff et al. 1993) for 1945–93 on a 1° × 1° grid. These datasets will jointly be referred to as observations, although they are in fact derived in different ways from observations.

d. Construction of ENSO composites

The five El Niño events of 1957/58, 1965/66, 1972/73, 1982/83, and 1997/98 and the five La Niña events of 1955/56, 1970/71, 1973/74, 1975/76, and 1988/89 are composited based on their size, duration, and timing. The Niño-3 and Niño-3.4 indices (SST anomalies in the areas 5°S–5°N, 90°W–150°W and 5°S–5°N, 120°W–170°W, respectively) peak close to December and the events last for approximately one year. These observed monthly mean indices for the past 50 years from the GISST dataset are shown in Fig. 1. The El Niño and La Niña composites are plotted alongside each of the selected events for comparison.

Composite El Niño and La Niña normally contain more events over the same period (e.g., Sardeshmukh et al. 2000) and therefore include more variability of size and timing. These smaller composites, including very similar events in the tropical Pacific, are hoped to increase the statistical significance of the observed teleconnections in the extratropics.

3. Results

a. Sea surface temperature composites

The spatial SST patterns for DJF at the peak of the El Niño and La Niña composites, and MAM after the peaks, are shown in Fig. 2. The total fields show the spread of the warm waters of the western tropical Pacific into the central tropical Pacific during El Niño and the contraction of these waters during La Niña. The anomaly fields show substantial linearity between El Niño and La Niña with a horseshoe of cool (warm) water centered in the western tropical Pacific in El Niño (La Niña) in DJF, warm (cool) water along the coasts of North and South America in the Pacific and remote tropical ocean basin warming (cooling).

b. Atmospheric response in DJF

The sea level pressure ENSO composite anomalies in DJF for the COADS observational dataset (over the ocean), NCEP–NCAR reanalysis data, and the HadAM3 ensemble are shown in Fig. 3 for the Pacific and surrounding areas. Values significantly different from zero at the 95% confidence level based on a t-test are shaded. The COADS and NCEP–NCAR fields are broadly sim-
COADS is a noisier dataset because it is not constrained by assimilation into an atmospheric model. Also plotted in Fig. 3 are the differences between the NCEP–NCAR and HadAM3 ENSO responses and their significance. Plotting the significance of the differences between these composites resolves the issue of attributing these differences to random variability or model error.

The largest differences between NCEP–NCAR and the HadAM3 ensemble ENSO responses are in the North Pacific. The model reproduces the observed stronger response to El Niño than La Niña described well by Hoerling et al. (2001), although the forcing is stronger for the El Niño composite. A particular error that will be investigated is the observed high pressure anomaly in the west of the North Pacific during El Niño marked by an “H” in the NCEP–NCAR El Niño composite. This high pressure, combined with the stronger low pressure anomaly farther east, constitute an eastward shift and deepening of the Aleutian low. The 500-mb height is more commonly plotted when studying this teleconnection, but sea level pressure is plotted here because the differences between the model and reanalysis are more pronounced at this level. This observed

Fig. 3. Sea level pressure anomalies for five-event ENSO composites in DJF for the NCEP–NCAR reanalysis data, COADS observational dataset (1997/98 not included), and the HadAM3 ensemble. The contour interval is 1 mb and negative contours are dashed and start at −0.5 mb. Values significantly different from zero at the 95% confidence level are shaded.
teleconnection is only just significant at the 95% confidence level since only three of the five El Niño events project strongly onto the composite (not shown). However, whenever low pressure anomalies are observed in the east of the North Pacific during El Niño, high pressure anomalies are always observed to the west at sea level for seasonal means. This behavior is not reproduced by any of the six ensemble members for any of the five El Niños (not shown). Instead, the model produces a very reliable deepening of the Aleutian low across the width of the North Pacific at sea level during El Niño. This model error will be investigated further.

The La Niña model errors in the North Pacific are similar to those for El Niño but less pronounced since the observations have a more zonally symmetric response to La Niña, more similar to the modeled response to both events.

It is common to plot tropical Pacific precipitation anomalies when studying the forcing of the extratropics from the Tropics (e.g., Hoerling et al. 1997; Sardeshmukh et al. 2000) due to the Rossby wave source associated with the upper-level divergence above the convection (Sardeshmukh and Hoskins 1988). Observations of precipitation were not assimilated into the NCEP–NCAR reanalysis, so the NCEP–NCAR calculated values are not very reliable (Kalnay et al. 1996; Newman et al. 2000). Therefore model comparisons are also made with the shorter CMAP precipitation dataset. However, only two of the chosen El Niño events (1982/83 and 1997/98) and one of the La Niña events (1988/89) occur within this dataset timescale. Total and anomalous precipitation for these events from CMAP and NCEP–NCAR are compared with HadAM3 in Fig. 4. Even though only two El Niños are included in the composite, almost all of the anomalies plotted are significant at the 99% confidence level. The HadAM3 precipitation El Niño anomalies are more similar to the CMAP observations than are the NCEP–NCAR reanalysis. This is an encouraging feature of this model but a difficulty when trying to compare with the longer NCEP–NCAR precipitation dataset. However, there are differences in detail in the tropical Pacific between CMAP and HadAM3, which are clearer when looking at the total El Niño precipitation fields. The observed maximum of total precipitation moves into the central tropical Pacific during El Niño whereas the modeled maximum remains in the southwest of the tropical Pacific, despite the apparent realism of the climatology and El Niño anomalies.

The NCEP–NCAR total precipitation fields plotted in Fig. 4 do reveal the observed eastward shift and intensification of the tropical Pacific precipitation maximum during El Niño. This feature is also evident in the NCEP–NCAR five event composites of precipitation and the model errors remain the same for the five event composites (not shown).

The 1988/89 La Niña total and anomalous precipitation fields also show model errors. Significance is not calculated for this single event, but it is assumed to be high based on the observed reproducibility of tropical Pacific precipitation. These show that the model fails to produce the required suppression of precipitation along the equator and the enhanced precipitation in the western Pacific.

The causes of these errors will be discussed in sections 3d and 4.

The impact of the tropical convection on the large-scale circulation and hence the link with the extratropics can be seen in the 200-hPa velocity potential. The climatologies and five-event ENSO composites in DJF are shown in Fig. 5 for NCEP–NCAR and the HadAM3 ensemble. Large-scale features of the climatological divergent circulation are similar for the two datasets. In particular, the west Pacific velocity potential minimum has the same location in NCEP–NCAR and HadAM3. In the NCEP–NCAR El Niño composite this minimum moves eastward, whereas in the HadAM3 ensemble composite it remains in the west Pacific, over the maximum precipitation. In the NCEP–NCAR La Niña composite, the west Pacific minimum is intensified and confined to the west of the basin so that it extends farther northward. In the HadAM3 composite, the west Pacific intensification is simulated, but the minimum is not confined to the west of the basin, again following the precipitation. This demonstrates that the anomalies in the NCEP–NCAR reanalysis are large enough to modify the basic state sufficiently and hence shift the North Pacific response, whereas the modeled anomalies do not alter the pattern of the basic state sufficiently.

The 200-hPa streamfunction describes the rotational part of the upper-level flow. It has a dominant zonal component, so the zonal mean is removed and displayed separately from the remaining asymmetric component in Fig. 6, which shows the NCEP–NCAR and HadAM3 ENSO composite anomalies. Anomalies are plotted for the asymmetric streamfunction rather than total values as plotted for precipitation and velocity potential because the streamfunction emphasizes the anomalous wave propagation into the extratropics whereas the precipitation and velocity potential were plotted in order to investigate the forcing of these waves from the Tropics.

Both datasets show anomalous anticyclones straddling the equator during El Niño above the region of the tropical heating with Rossby waves arcing poleward and eastward from these anticyclones. In the Northern Hemisphere during El Niño, much of the modeled response is shifted westward in comparison to the reanalysis. This is related to the modeled peak in precipitation during El Niño, which is in the southwest of the tropical Pacific during El Niño rather than shifting eastward. This shift is not so evident in the weaker, Southern Hemisphere, summer response during El Niño but there are significant model errors in this hemisphere (not shown).

The North Pacific model errors, connections with the
Fig. 4. DJF precipitation climatologies, 1982/83 and 1997/98 El Niño composites and 1989 La Niña for the NCEP–NCAR reanalysis data, CMAP data, and the HadAM3 ensemble.
Tropics and linearity of the modeled response will be discussed further in section 5.

c. Atmospheric response in MAM after an ENSO peak

The ENSO composite sea level pressure anomalies in MAM after the peak of an ENSO event for the COADS observational dataset (over the ocean), NCEP–NCAR reanalysis data, and the HadAM3 ensemble are shown in Fig. 7. The main difference between the HadAM3 ensemble and the other datasets is again in the North Pacific for El Niño and La Niña. During this season, HadAM3 still has a strong response in the North Pacific, whereas the response has decayed to almost insignificant levels in NCEP–NCAR and COADS. This difference between NCEP–NCAR and HadAM3 is significant at 98% confidence based on a t test (not shown) and possible causes will be discussed.

Composites of the MAM precipitation fields after the 1982/83 and 1997/98 El Niños and after the 1988/89 La Niña are shown in Fig. 8 for the CMAP dataset, NCEP–NCAR, and the HadAM3 ensemble and are compared with the climatological fields. The positive anomalies during El Niño in the central Pacific are actually stronger in CMAP than the model even though the model’s North Pacific response is stronger. However, again, looking at the total precipitation fields reveals that there is still a sharp peak during El Niño modeled in the southwest of the tropical Pacific that is not observed in CMAP or NCEP–NCAR. This could be forcing the strong, reproducible North Pacific response modeled. In both the North Pacific and Tropics, the DJF El Niño conditions appear to be persisting into MAM in the model, even though observed SSTs are imposed. During the 1988/89 La Niña, both the total and anomalous modeled precipitation show the central and western equatorial Pacific to be too dry as modeled by HadAM3, which again could be forcing the North Pacific too strongly.
The 200-hPa velocity potential ENSO composites in MAM after the peak of the ENSO event for NCEP–NCAR and the HadAM3 ensemble are shown in Fig. 9. The model climatology shows some slackening of the gradients in the west Pacific in MAM as opposed to DJF (Fig. 5) but not as much as observed. Additionally, the observed west Pacific minimum has moved north of the equator whereas the HadAM3 minimum is on the equator. These differences in the climatologies carry through into the El Niño and La Niña absolute fields. Therefore the meridional gradients remain strong in the northern subtropics, conditions conducive to Rossby wave propagation into the extratropics and a strong North Pacific response, as erroneously modeled.

The 200-hPa asymmetric streamfunction ENSO composite anomalies in MAM for the NCEP–NCAR data and HadAM3 ensemble are shown in Fig. 10. For both El Niño and La Niña events the model zonal mean and extratropical wave train responses are too strong, consistent with the high tropical precipitation and steep meridional gradients of velocity potential during this season.

d. The tropical Pacific precipitation response

The model errors in the response to El Niño and La Niña in the North Pacific in DJF and MAM have been attributed to errors in the modeled tropical Pacific precipitation. In this section, the tropical Pacific precipitation errors will be investigated further and the El Niño event of 1982/83 will be studied in greater detail. This event is chosen since all datasets include this event, including the high-resolution model runs that will be analyzed in section 4.

The SST and SST anomalies and precipitation anomalies for CMAP, NCEP–NCAR, and each member of the HadAM3 ensemble with GISST are shown in Fig. 11 for DJF during the El Niño of 1982/83. This confirms that none of the members resemble the CMAP or NCEP–NCAR precipitation but they do show substantial similarities between themselves. The reason for the errors appears to be that the modeled precipitation follows the SST too closely. The SST field contains small-scale structures in the tropical Pacific that are not evident in the observed (CMAP) or renalyzed (NCEP–NCAR) precipitation. For example, within the region of the Maritime Continent and out to the Solomon Islands (10°S, 160°E), the SST anomalies show considerable spatial variability, there being positive and negative SST anomalies here. However, the observed precipitation is suppressed over almost this entire area during this El Niño, as is frequently observed during El Niño. This indicates an influence of the dynamics on the precipitation as well as just the SST, that is,
Fig. 7. Sea level pressure anomalies for five-event ENSO composites in MAM after the peak for the NCEP–NCAR reanalysis data, COADS observational dataset, and the HadAM3 ensemble. The contour interval is 1 mb and negative contours are dashed and start at \(-0.5\) mb. Values significantly different from zero at the 95% confidence level are shaded.

scale anomalous descent is forced by the anomalous ascent farther east. The model ensemble members show more spatial variability of precipitation over this area of the Maritime Continent and west Pacific, often following the SST more closely.

This model error is confirmed by plotting precipitation as a function of local SST for one month of each year of the period and at each grid point in the area shown in the box in Fig. 11. The probability density functions (pdfs) of monthly, January, and April precipitation as a function of local SST are shown in Fig. 12 for CMAP, NCEP–NCAR, and the HadAM3 ensemble. The pdf is constructed using a two-dimensional Gaussian kernel estimator (Marshall and Molteni 1993) for every grid box in the area between 10°S and 5°N, 160°E and 120°W in the western and central tropical Pacific. This area encompasses the main precipitating regions in both the observations and the model. The CMAP and HadAM3 pdfs are broadly similar, with suppressed precipitation at low SST and exponentially increasing precipitation with increasing SST. However, in January the model precipitation follows this exponential distribution too closely, with less variability of precipitation as a function of SST than observed. The observations also show some low values of precipitation over the highest SST, as seen in the Maritime Continent region during
El Niño. The NCEP–NCAR January pdf is very different to both CMAP and HadAM3, showing an almost linear increase in precipitation with SST.

The close relationship between the HadAM3 modeled precipitation and SST could be due to the formulation of the convection scheme. The Gregory and Rowntree (1990) scheme is closed on the buoyancy of the near-surface air rather than moisture convergence, as in the NCEP–NCAR model (Kanamitsu et al. 1991). The buoyancy of the near-surface air is closely controlled by evaporation and SST whereas the moisture convergence is more controlled by the large-scale circulation which is less tightly linked with SST.

One possible reason for the small HadAM3 errors that do exist is the lack of two-way coupling between the atmosphere and the ocean surface. Observational studies (e.g., Bony et al. 1997) have shown that the warmest SSTs are generally associated with regions of descent and suppressed convective activity as also indicated in Fig. 12. Kitoh and Arakawa (1999) showed that the lack of feedback from the atmosphere back to the ocean may lead to an overestimation of precipitation over the warmest SSTs in an AGCM. Woolnough et al. (2001) showed that the sea surface heats up during the suppressed phase of the Madden–Julian oscillation, when the skies are clear. This may contribute to some of the low values of precipitation over high SSTs in the observations. However, even for an atmosphere-only model, the reaction of the convection scheme to increasing SST is critical. If a positive SST anomaly is imposed in an area of subsidence and dry atmosphere, it takes some time for the atmosphere to moisten before deep, precipitating clouds can be formed (Woolnough et al. 2001; Tompkins 2001). This timing is dependent on the entrainment calculated by the convection scheme as this affects the time it will take for shallow, nonprecipitating convection to moisten the free atmosphere and allow deep, precipitating convection (Tompkins 2001).

This pattern of tropical Pacific precipitation errors also carries through into MAM but is more pronounced.
as can be seen from the precipitation versus SST plots for April in Fig. 12. This shows that, in April, the HadAM3 precipitation over the ocean is generally too strong, especially over the warmest SSTs. The DJF precipitation patterns tend to persist into MAM during El Niño in the model, as shown in Fig. 13 for the zonally averaged tropical Pacific precipitation during the 1982/83 El Niño for CMAP and HadAM3. This strong modeled precipitation in spring after El Niño, especially in the Southern Hemisphere, could be due to the high precipitation over warm SSTs associated with the model’s excessive sensitivity to SST discussed above.

Again, the relationship between SST and precipitation in April is more realistic in HadAM3 than NCEP–NCAR, which consists of weak precipitation over all values of SST (also shown in Fig. 8). In April as well as January, the HadAM3 convection scheme closed on buoyancy is producing a nonlinear increase in precipitation with SST whereas the NCEP–NCAR scheme, closed on moisture convergence, is more linear. However, neither model captures the instances of low values of precipitation that occur over the whole range of SST in April.

4. Sensitivity to model resolution

When discussing model errors, it is important to identify whether errors are due to insufficient horizontal or vertical resolution, inaccurate physical parameterizations, or physical mechanisms that are not included or not coupled correctly. To this end, the observations are compared with three integrations with observed SSTs run at the Hadley Centre as part of AMIP II (Pope and Stratton 2002) with different resolutions, run from 1979 to 1996. Again the El Niño of 1982/83 is studied. These AMIP II integrations have slightly different SSTs to GISST imposed, conforming to the AMIP II standard (Gates 1992; Gates et al. 1999); GISST includes smaller scale variability than AMIP II SSTs, which are smoother.

AMIP II integrations with three different resolutions are studied. The first has the same resolution as the HadAM3 ensemble with GISST SSTs. That is, 19 vertical levels and 96 × 73 grid points in the horizontal (2.5° latitude by 3.75° longitude). The second has the same horizontal resolution but 30 vertical levels and the third has 30 vertical levels and three times the horizontal resolution. The physical parameterizations in the 30-level versions of the model were not tuned for this resolution but for the standard 19-level resolution.

The sea level pressure anomalies, total precipitation, and total 200-mb velocity potential for the three AMIP II integrations are shown in Fig. 14 and compared with NCEP–NCAR and CMAP (for precipitation). The 19-level AMIP II integration has the same model error as the HadAM3 ensemble with GISST (Fig. 3) in the west.
Fig. 11. SST and precipitation total and anomalous values for DJF 1982/83 El Niño from GISST, CMAP observations, NCEP–NCAR reanalysis, and the HadAM3 ensemble with GISST.
of the North Pacific as marked by an “H” for NCEP--NCAR. However, both the 30-level AMIP-II integrations correctly predict high pressure anomalies here. Increased resolution does not appear to lead to improvements in tropical Pacific precipitation, with all three resolutions producing too much precipitation north of the equator and too much spatial variability. However, the absolute maximum does shift eastward for both 30-level integrations, as observed, whereas the absolute maximum remains in the southwest for the 19-level integration. This is reflected in the 200-mb velocity potential. The two 30-level integrations show the minima in the center of the tropical Pacific, as observed during El Niño. However, the 19-level integration also has a minimum in the west, forced by the high precipitation here. This will lead to inaccurate Rossby wave propagation into the extratropics.

The next question is why this small improvement in the location of the precipitation maximum occurs with 30 model levels. Inness et al. (2001) studied the organization of tropical convection in HadAM3 with 19 and 30 vertical levels. They found that, with 30 model levels, it takes longer for precipitation to occur once a warm SST anomaly is imposed. This is because the convection scheme takes longer to moisten the free troposphere before deep convection breaks through the weak inversion caused by the freezing layer. In the 19-level integration the freezing level inversion is not resolved adequately so convection breaks through this level more quickly. This could be why the 19-level version of the model produces the highest precipitation always over the warmest SSTs during El Niño; little transient suppression of precipitation can be modeled.

5. Discussion and conclusions

As described in section 1, the North Pacific response to ENSO is often assumed not to have a systematic shift
between the two phases of ENSO, possibly due to the variability in the observations and the lack of shift simulated by many atmospheric GCMs. Sardeshmukh and Hoskins (1988) explained this geographically fixed extratropical response to tropical heating solving the barotropic vorticity equation on 150 hPa with various linearization assumptions. They found that, for heating embedded in the equatorial easterlies, the Rossby wave source driving the extratropical response is located in the subtropical westerly jet. Therefore the Rossby wave emanates from the larger region of tight meridional gradients associated with this jet rather than being related to the exact location of the equatorial heating. This explains why the shift in the North Pacific response is small in comparison to the shift of the forcing in the Tropics and why total SST and precipitation rather than anomalies reveal the nature of the tropical forcing. During El Niño, the basic state is altered so the location of the subtropical westerly jet in which this Rossby wave source resides is shifted eastward (e.g., Hoerling and
Ting 1994). The smaller eastward shift in the location of the maximum total SST and precipitation in comparison to the large shift of the maximum anomalies between El Niño and La Niña explains the small shift in the extratropical response. The importance of the basic state as shown by Sardeshmukh and Hoskins (1988) indicates a dependence of the North Pacific response on the total SST and precipitation rather than the anomalies [also described by Hoerling et al. (2001)].

This also explains why the errors in the modeled North Pacific response are dependent on the tropical Pacific precipitation errors. The maximum total modeled precipitation fails to spread eastward during El Niño in DJF in the tropical Pacific, which leads to maximum modeled upper-level divergence in the western tropical Pacific during El Niño instead of an eastward shift. This leads to a Rossby wave train propagating into the northern extratropics emanating from the west of the tropical Pacific rather than the center and hence the misplacement in the extratropics. Improvements to the tropical Pacific precipitation response in DJF with enhanced vertical resolution lead to an improved North Pacific response.

This paper has demonstrated the importance of an accurate simulation of the total precipitation field over the tropical Pacific. Although the HadAM3 climatology is generally close to that observed, slight errors in the tropical climatology lead to larger errors in the tropical response to El Niño, which in turn lead to errors in the extratropical response to El Niño. The modeled tropical Pacific precipitation is too sensitive to the local SST so that the modeled maxima in precipitation remains over the very highest SST during El Niño events. These are still in the west Pacific in DJF and MAM, whereas the highest precipitation is triggered by slightly lower values of SST in the observations. Consequently the model does not capture the spread of the area of maximum precipitation into the central Pacific during strong El Niño events.

The results of this study indicate limitations in the applicability of HadAM3 for investigating the remote response to El Niño and La Niña. Tropical teleconnections are reasonably well simulated in DJF, although the precise magnitude and location cannot be relied upon. HadAM3 is less useful for studying the teleconnections of ENSO during MAM after the peak of an event because the modeled decline of anomalies from DJF is slower than that observed. The results have emphasized the importance of capturing the correct relationship between SST and precipitation, which may require an interaction between the ocean and the atmosphere.

These conclusions concerning the atmospheric modeling of ENSO teleconnections have been drawn by studying absolute fields and hence their gradients rather than anomalies of precipitation and velocity potential and by restricting the study to strong observed events with similar timings within the seasonal cycle.

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