ENSO Diabatic Heating in ECMWF and NCEP–NCAR Reanalyses, and NCAR CCM3 Simulation

SUMANT NIGAM, CHUL CHUNG,* AND ERIC DEWEAVER†

Department of Meteorology, University of Maryland at College Park, College Park, Maryland

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ABSTRACT

Diabatic heating associated with El Niño–Southern Oscillation (ENSO) variability is residually diagnosed from the European Centre for Medium-Range Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) atmospheric reanalysis datasets during the overlapping 1979–93 period. Quantitative characterization of the horizontal and vertical structure of ENSO heating anomalies, including estimates of uncertainty, provides observationally constrained validation targets for GCM physical parameterizations.

The diagnosed ENSO heating anomalies have similar horizontal structure, but the vertically averaged ECMWF heating is stronger and in better agreement with the Xie–Arkin precipitation anomalies, particularly with respect to precipitation reduction over the western tropical Pacific. Comparison of heating vertical structures in the central equatorial Pacific shows ECMWF heating to be considerably stronger in the lower troposphere, where it exhibits a local maximum.

The ENSO covariant tropospheric temperature in the two reanalyses was also examined along the equator and found to have an intriguing vertical structure, with sizeable amplitude in the lower and upper troposphere and vanishing amplitude in between. The largest temperature anomalies in the lower troposphere are at the surface, and the ECMWF one is about 50% stronger.

The three-dimensional heating anomalies diagnosed from the reanalyses are used to evaluate the ENSO heating distribution produced by NCAR’s Community Climate Model, version 3 (CCM3) atmospheric GCM, when integrated in a climate simulation mode. At least, in context of ENSO variability, the differences in ECMWF and NCEP heating anomalies are small in comparison with CCM3’s heating departures from either of these anomalies, allowing characterization of the CCM3’s ENSO heating structure: horizontally, as a more meridional redistribution (“Hadley-like”), and vertically, as a substantially “bottom-heavy” profile, relative to the reanalyses anomalies.

In a companion paper, deficiencies in the simulated ENSO surface winds are related to specific features of the CCM3’s heating error, from diagnostic modeling.

1. Introduction

This research was motivated by our interest in establishing the three-dimensional (3D) structure of the principal forcing of the tropical circulation—diabatic heating—from the recent atmospheric reanalysis datasets. An accurate parameterization of diabatic heating associated with both deep and shallow convection still eludes atmospheric general circulation models (GCMs), and it is hoped that availability of the observationally constrained heating targets will facilitate refinement of the GCM physical parameterizations.

Atmospheric diabatic heating has been diagnosed before (e.g., Hoskins et al. 1989; Nigam 1994; Schaack and Johnson 1994; Li and Yanai 1996) but such diagnosis was typically produced from the operational circulation analyses. As the operational analyses are impacted by changes in the forecast center’s weather prediction model, analysis and data assimilation techniques, and observation usage, the diagnosed heating record can be compromised for climate variability studies. Recently, Yanai and Tomita (1998) have diagnosed diabatic heating from the reanalysis fields produced at the National Center for Environmental Prediction (NCEP), but their focus was on the seasonal heating distribution over landmasses.

The goal of this study, on the other hand, is to diagnose the three-dimensional structure of the atmospheric diabatic heating anomaly associated with El Niño–Southern Oscillation (ENSO) climate variability.
The heating structure is diagnosed from both NCEP and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses during the overlapping 1979–93 period in order to ascertain robustness. An estimate of the uncertainty, obtained from the difference of two diagnosed加热s, should be useful in gauging the significance of the departure of GCM’s heating from these targets. Given the importance of 3D heating in forcing tropical circulation, including surface winds over the oceans, it is somewhat surprising that the ENSO covariant heating anomalies remain undiagnosed from the reanalysis datasets.

Our focus on ENSO variability, of course, stems from the rather large modifications of tropical precipitation and circulation during this period, which provide a robust signal for climate simulation. Improving the simulation and prediction of this signal is an important objective of current climate dynamics research, and a quantitative characterization of the horizontal and vertical structure of ENSO heating anomalies should help advance these efforts.

Another important goal of this research is to promote the dynamical diagnosis strategy, whose modeling analysis component is illustrated in a companion paper (Nigam and Chung 2000). In the context of GCM diagnosis, this strategy would begin with a quantitative comparison of both simulated circulation (e.g., tropical surface winds) and its forcing (e.g., diabatic heating) with the observed counterparts—the heating intercomparisons described in this paper are part of this step. The follow-up error attribution phase, in which the deficiencies in simulated circulation are related to specific features of the GCM’s heating error from diagnostic modeling, are reported in the companion paper. Such a double-pronged approach consisting of diagnostic analysis and modeling should facilitate GCM development.

The atmospheric GCM whose ENSO simulation is analyzed here is the Community Climate Model version 3 (CCM3) developed by the National Center for Atmospheric Research (NCAR). This model was forced by the observed 1950–94 SST, and Hurrell et al. (1998) and Meehl and Arblaster (1998) have compared the simulated interannual variability with the corresponding period observations, including the Xie–Arkin precipitation (Xie and Arkin 1997). The ENSO surface-wind and diabatic heating anomalies produced by the model were however not examined in these studies, although such an examination would appear to be pertinent in understanding the causes of ENSO simulation deficiencies, particularly, in a more interactive modeling environment (e.g., coupled ocean–atmosphere modeling).

ENSO variability in observations and CCM3 simulation is extracted from a rotated principal component analysis (RPCA) of combined interannual variability of SST and 1000-mb winds. ENSO covariant anomalies in all other fields (e.g., diabatic heating) are obtained from regression with the principal component of the ENSO mode. Determination of ENSO variability in this manner focuses attention on the surface-wind anomalies, whose correct simulation is a necessary condition for coupled ocean–atmosphere modeling.

The ECMWF and NCEP reanalyses, CCM3 simulation, and the Xie–Arkin precipitation datasets are all briefly described in section 2. The analysis tools—residual diagnosis of 3D diabatic heating and the rotated principal component analysis technique—are briefly discussed in section 3. The structure of ENSO diabatic heating and precipitation anomalies during the overlapping period (1979–93) of the ECMWF and NCEP reanalyses, and CCM3 simulation is examined in section 4. Specifically, the 400-mb heating, vertically averaged heating, precipitation, and the heating vertical structure are intercompared. As residual diagnosis of diabatic heating does not provide information about the constituent components, the NCEP model-generated heating components (from the 6-h forecasts starting from NCEP reanalysis) linked with ENSO are shown in section 5. Discussion and concluding remarks follow in section 6.

2. Datasets

a. ECMWF reanalyses

The initialized ECMWF reanalyses are obtained from NCAR where the 6-h fields are archived on a 2.5° × 2.5° global grid and at 17 pressure levels from January 1979 to December 1993. The fields are produced from intermittent statistical (optimum interpolation) analysis with 6-h cycling, 1D variational physical retrieval of TIROS (Television and Infrared Observation Satellite) Operational Vertical Sounder cloud-cleared radiances, and diabatic, nonlinear normal mode initialization of five vertical modes, using a T106 spectral model with 31 vertical hybrid levels. Other model features include a prognostic cloud scheme and a mass flux convection scheme (Tiedtke 1989); additional details can be found in the ECMWF Re-Analysis Project Report Series (ECMWF 1997).

b. NCEP–NCAR reanalyses

The NCEP–NCAR reanalyses (Kalnay et al. 1996) are produced from spectral statistical interpolation using a T62 resolution (~210 km) spectral model with 28 vertical sigma levels. The 6-h fields are available on a 2.5° × 2.5° global grid and at 17 pressure levels from January 1958, but only the 1979–93 subperiod is analyzed here.1 The model uses a diagnostic scheme for

1 The pressure-level geopotential, winds, temperature, and vertical velocity (ω) fields are generated from the leading T36 spectral amplitudes. This spatial smoothing of the pressure-level reanalyses was brought to our attention by Glenn White, and can be found noted at ftp://wesley.wwb.noaa.gov/pub/reanal/random_notes/smooth.ing (as pointed out by Muthuvel Chelliah).
clouds, and a simplified Arakawa–Schubert cumulus convection scheme (Pan and Wu 1994).

The diabatic heating generated during a 6-h model forecast starting from each time step’s reanalysis circulation is available partitioned into six components: large-scale condensation, deep convective, shallow convective, longwave and shortwave, and vertical diffusion heating rates. White and Saha (1996) have documented the vertical structure of the heating components and their variability during the 1982–93 period. However, in view of potential differences between the model-produced and the reanalysis-consistent heating (Ebisuzaki 1996), and in order to directly compare with the heating diagnosed from ECMWF reanalyses, diabatic heating was residually diagnosed from the NCEP reanalyses as well.

c. CCM3 simulation

The 45-yr simulation analyzed in this study (January 1950–December 1994) was generated using the prototype CCM3 model forced by the NCEP monthly SST. The model was integrated from 18 December 1949 to 2 May 1995, after a 4.5-month spinup run. The spectral model was run at T42 resolution with 18 hybrid sigma-pressure vertical levels, and the monthly averaged output was available on a regular longitudinal grid (Δλ = 2.8125°) and the T42 Gaussian latitude grid. The model output was linearly interpolated in ln(p) to the following 17 pressure levels: 1000, 925, 850, 775, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, and 10 mb—the ECMWF reanalysis pressure levels. Besides horizontal winds, wind stresses, and precipitation, the following fields from the CCM3 master field list (Kiehl et al. 1996) were also extracted in order to assemble diabatic heating: temperature tendency (T-tendency) due to horizontal diffusion (DTH), T-tendency due to vertical diffusion (DTV), solar heating rate (QRS), longwave heating rate (QRL), and the T-tendency from adjustment physics (DTCOND), which presumably represents the heating resulting from shallow, deep-convective, and the large-scale condensation processes. The diabatic heating rate (Q) should thus equal DTH + DTV + QRS + QRL + DTCOND.

d. Xie–Arkin precipitation

The Climate Prediction Center’s merged analysis of global monthly precipitation produced by Xie and Arkin (1997) on a 2.5° x 2.5° global grid for the 1979 onward period was obtained from NCEP. The merged precipitation is generated by combining gauge observations with the satellite estimates derived from infrared, outgoing longwave, and microwave scattering- and emission-based precipitation indices; for additional algorithm details and comparisons with gauge data, see Xie and Arkin (1997).

3. Diagnostic analysis tools

a. Residual diagnosis of diabatic heating

The 3D diabatic heating Q is diagnosed as a residual in the thermodynamic equation (e.g., Hoskins et al. 1989; Nigam 1994) using the analyzed vertical velocity (ω) in the ECMWF and NCEP reanalyses:

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Q = \frac{\Delta T}{\Delta t} + \nabla \cdot \nabla T + (p/p_0)R \frac{\partial \theta}{\partial p} \\
+ (p/p_0)R \left[ \nabla \cdot \left( \nabla \theta \nabla T \right) + \frac{3(\omega \partial \omega)}{\partial p} \right],
\]

Here, the overbar denotes the monthly average and prime represents the departure of the 6-h analysis from the monthly average. The residual diagnosis however does not provide information about the constituent sensible, latent, and radiative heating components, but as noted earlier in section 2b, partitioned heating components are available from 6-h NCEP model forecasts starting from each time step’s reanalyses.

In the absence of an observational counterpart, the credibility of a heating estimate can be gauged only by the extent of its dynamical consistency with the large-scale circulation, that is, through diagnostic modeling. Such an assessment shows the uninitialized ECMWF analyses–based heating (diagnosed using the mass-balanced ω; Nigam 1994, 1997), and even more, the one diagnosed from ECMWF reanalyses (Nigam and Chung 2000) to be reasonably consistent estimates.

b. Rotated principal component analysis

ENSO variability is extracted from the RPCA of combined interannual variability of SST and the 1000-mb zonal and meridional winds. The RPCA technique extracts recurrent modes of combined variability by simultaneously analyzing the structure of autocovariance and cross-covariance matrices. The method’s efficacy in extracting the truly coupled modes increases with the number of variables in the combination (Nigam and Shen 1993). In case of a three-variable combination, as in this study, the number of cross-covariance submatrices equals the number of autocovariance submatrices; while it would be desirable for the former to outnumber the latter in the interest of extraction of coupled patterns, the leading-mode structure is robustly extracted even in the present analysis, as shown later.

3 The evaluations were performed using a steady global primitive equation model having high horizontal and vertical resolution: Δθ = 2.5°, zonal Fourier truncation at wavenumbers 15 or 30, and 18 vertical sigma levels.
In combined analysis of variables in different domains, as in this study, the individual variables are put on par by dividing each of them by the square root of the sum of temporal variances over that variable’s spatial grid; furthermore, an equal-area representation of regular gridded data was ensured by weighting with a \((\cos \theta)^{1/2}\) factor (Chung and Nigam 1999). Eigenvectors and eigenvalues of the associated covariance matrix were obtained from singular value decomposition.

The results presented in this study are obtained from orthogonal rotation of eight loading vectors using the varimax criterion (e.g., Horel 1981), which destroys spatial orthogonality but leaves the temporal orthogonality among the vectors intact; rotation of 6, 8, or 10 vectors led to virtually identical structure of the leading mode. The temporal orthogonality allows us to conveniently obtain the covariant anomalies in other fields from linear regression with the mode’s principal component.

4. ENSO diabatic heating and precipitation anomalies

The structure of ENSO diabatic heating and precipitation anomalies during 1979–93 is analyzed in this section. In this 15-yr period, both ECMWF and NCEP reanalyses, and the Xie–Arkin precipitation data are available; the availability of multiple observational datasets was considered important in developing a robust description of the ENSO heating anomalies. The CCM3 simulation is also available for this period, thus allowing an assessment of the modeled ENSO heating anomalies in a state-of-the-art atmospheric GCM.

ENSO variability in each dataset (ECMWF, NCEP, and CCM3) was extracted by analyzing the combined interannual variability of the 1000-mb winds and NCEP SST anomalies over the Pacific (20°S–40°N; 125°E–75°W) in all calendar months, using the RPCA technique; the anomalies were defined using the 1979–93 monthly climatologies. Figure 1 shows the ENSO principal components extracted from the ECMWF, NCEP, and CCM3 datasets, as well as the Niño-3.4 index, the latter is defined as the SST anomaly average in the 5°S–5°N and 170°–120°W sectors (e.g., NOAA 1999), and is a widely recognized marker of ENSO variability. The evolution of principal components and the Niño-3.4 index is rather similar as the SST anomalies in various combined analyses and the Niño-3.4 index definition are the same. Not surprisingly, the El Niño episodes of 1982–83, 1986–87, 1987–88, and 1991–92, and the La Niña events of 1984–85 and 1988–89 are well captured in all principal components.

ENSO covariant anomalies in other fields, such as diabatic heating and precipitation, were obtained from regression with the ENSO principal component of that dataset. However, in view of the insignificant differences among principal components and the Niño-3.4 index (cf. Fig. 1), the latter could as well have been used for all regressions, and this has been verified.

a. 400-mb heating anomalies \( (Q_{400}) \)

The diabatic heating anomalies are first displayed at 400 mb as the heating anomalies are generally largest at/near this level (e.g., Reed and Recker 1971; Nigam

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4 In order to compare with principal components, the Niño-3.4 index was normalized so that its norm, \( \Sigma \text{index}^2 \), during 1979–93 was the same as theirs \( \Sigma \text{index}^2 \); there are 180 months in the analyzed record.

5 ENSO variability was extracted from RPCA rather than simply from Niño-3.4 regressions because heating associated with the non-ENSO modes was also of interest, although its discussion is beyond the scope of this paper.
Fig. 2. ENSO covariant diabatic heating at 400 mb during 1979–93 from: (a) ECMWF reanalysis, (b) NCEP reanalysis, and (c) CCM3 simulation with observed SST. Contour interval and shading threshold is 0.2 K day$^{-1}$ in all panels, and the zero contour is omitted.

In addition to the zonal redistribution, a meridional redistribution in $Q_{400}$ is also evident, but mainly in the southern Tropics (w.r.t. SPCZ heating). ENSO heating anomalies also contain features beyond the Pacific basin, including diabatic cooling over the Amazon.$^6$

$^6$ The diabatic cooling over Congo likely results from the presence...
ENSO heating anomalies diagnosed from the NCEP reanalyses are shown in Fig. 2b. While the structure is broadly similar, the NCEP $Q_{400}$ anomalies are weaker, particularly, in the equatorial date line, SPCZ, and the western Pacific sectors. The NCEP $Q_{400}$ anomalies are weaker also over Nordeste.

ENSO heating in the CCM3 simulation is shown in Fig. 2c. At first encounter, it appears similar to the other heating distributions. Closer inspection however reveals that diabatic cooling, or rainfall reduction, in the off-equatorial latitudes is stronger in CCM3, whereas the cooling over the Maritime Continent and the western Pacific is considerably weaker than in the reanalysis based heating (Figs. 2a,b). In the eastern Pacific too, the CCM3 anomalies represent equatorward migration of the ITCZ, but the reanalysis heating anomalies indicate merely an expansion into the Tropics. In view of such differences, the CCM3 ENSO heating anomaly can be broadly characterized as being more of a meridional redistribution ("Hadley-like"), than a zonal one ("Walker-like").

The ENSO heating difference between reanalysis anomalies, and between the CCM3 and reanalysis anomalies is shown in Fig. 3. The ECMWF–NCEP difference (Fig. 3a) shows the ECMWF $Q_{400}$ anomaly to be somewhat stronger everywhere except over the off-equatorial northern Pacific where diabatic cooling is marginally stronger in the NCEP anomaly. The difference provides an estimate of the uncertainty in diagnosed heating, stemming largely from the divergent circulation differences in the two reanalyses.

The CCM3–ECMWF difference (Fig. 3b) shows the CCM3 ENSO heating to be stronger over the Pacific, by over 0.5 K day$^{-1}$ across large sectors of the equator. The CCM3 diabatic cooling, on the other hand, is substantially weaker over the western Pacific and eastern Indian Ocean, as indicated by the positive difference, particularly, over Borneo, Philippines, and the South China, Sulu, and Celebes Seas. The reduction in the GCM’s deep convection here is quite small, suggesting that this region is not as responsive in CCM3 as it is in the reanalyses, at least in context of ENSO variability. The CCM3–NCEP heating difference is shown in Fig. 3c, and is quite similar to the difference displayed in Fig. 3b.

Given the uncertainty in validation targets (Fig. 3a), how should one characterize the CCM3 heating departures from these targets? Should the CCM3 departures be construed as serious errors in need of urgent fixes? These questions are answered in this study, but after gathering supporting evidence from analysis at other vertical levels and from the analysis of thermodynamic fields (e.g., precipitation) for which validating data is independent of the reanalyses.

Although the 400-mb analysis does not allow for a convincing claim, largely because the CCM3 departures (Figs. 3b,c) are not much larger than the reanalysis difference (Fig. 3a), the sign of the differences does indicate the CCM3 ENSO heating to be an outlier, both in the weakness of cooling over the western Pacific and in the excessive heating (and off-equatorial cooling) in the central Pacific—a claim buttressed in subsequent sections.

b. Vertically averaged heating anomalies

The vertically averaged ENSO heating anomalies are computed in order to assess the robustness of the differences between diagnosed and modeled heating anomalies; the mass-weighted vertical averaging is over a column extending from 1000 to 10 mb. These anomalies are also computed in view of their linkage to precipitation anomalies—the linkage is strong when condensation heating dominates other components of diabatic heating, as can be the case in the deep Tropics. The vertically averaged anomalies are shown in Fig. 4, while their differences are displayed in Fig. 5.

The vertically averaged heating anomalies are structurally similar to the $Q_{400}$ anomalies except for the stronger diabatic cooling in the northern equatorial latitudes (relative to other features) in the ECMWF (Fig. 4a) and, particularly, CCM3 (Fig. 4c) anomalies.

The differences in vertically averaged ENSO heating anomalies (Fig. 5) are also similar to the $Q_{400}$ differences (Fig. 3) except that the CCM3 heating departures (Figs. 5b,c; “signal”) are now significantly larger than the ECMWF–NCEP difference (Fig. 5a; “noise”), particularly, over the Maritime Continent and the western and central tropical Pacific—an assertion, not possible from analysis of the $Q_{400}$ differences. The CCM3 anomaly is an outlier in the vertically averaged heating fields as well, and its characterization as a Hadley-like heating redistribution is on firmer ground.

c. Precipitation anomalies

ENSO precipitation anomalies during 1979–93 are shown in Fig. 6. It is important to note that precipitation in ECMWF and NCEP reanalyses is produced from 6-h model forecasts, and as such, its consistency with reanalysis circulation, including diagnosed heating, is not assured. As noted earlier, inconsistency between precipitation and vertically averaged diabatic heating can also arise when the noncondensational heating components are significant.

The Xie–Arkin precipitation anomalies are obtained from regression with the Niño-3.4 index, while the others are diagnosed using their own ENSO principal component, as in the heating case. Given that the Xie–Arkin...
Fig. 3. ENSO heating differences at 400 mb: (a) ECMWF – NCEP, (b) CCM3 – ECMWF, and (c) CCM3 – NCEP. Contouring and shading as in Fig. 2.

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precipitation (Fig. 6a)\(^7\) is diagnosed without any input from either of the reanalyses, its structural correspondence with the vertically averaged reanalysis heating anomalies (Figs. 4a,b), particularly the ECMWF one, is impressive: The maximum positive anomalies are located near the date line and slightly southward of the equator in both fields. The negative features in Figs. 4a and 6a are also quite similar, specially, over the north equatorial Pacific.

The Xie–Arkin anomalies depict a largely zonal redistribution of rainfall during ENSO, with the meridi-

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\(^7\) If the vertically averaged heating rate (in K day\(^{-1}\)) is all attributed to condensational heating, then the equivalent precipitation rate (mm day\(^{-1}\)) is obtained by scaling the heating rate by \([p C_p/(g L_c)]\), where \(C_p\) is 1004, \(L_c\) is \(2.5 \times 10^6\), and surface pressure \((p_s)\) is 101, all in S.I. units; the scaling factor is computed to be 4.09. The precipitation anomalies in Figs. 6 and 7 are thus contoured using four times the interval used in the vertically averaged heating plots (Fig. 4).
onal redistribution being comparatively modest, and focused primarily in the SPCZ—in considerable agreement with the structure of ECMWF heating anomalies. ENSO precipitation anomalies from the ECMWF and NCEP 6-h forecasts are shown in Figs. 6b and 6c, while those from the CCM3 simulation are shown in Fig. 6d. Not surprisingly, the precipitation anomalies from model forecasts exhibit substantial differences from the Xie–Arkin anomaly: The NCEP anomaly, in particular, is only half as strong as the others and depicts a mostly meridional rainfall redistribution; the ECMWF anomaly compares more favorably with the Xie–Arkin anomaly, but not over the Maritime Continent, which appears to be a problematic region in all the model precipitation fields (Figs. 6b–d). Intercomparison of these fields, in fact, suggests that state-of-the-art atmospheric GCMs are, to an extent, insensitive in the Maritime Continent region, and that this insensitivity may produce a more
Hadley-like rainfall redistribution during ENSO—at variance with the ENSO structure of Xie–Arkin precipitation and the diagnosed heating anomalies (specially, from ECMWF reanalyses).

The insensitivity of NCEP precipitation over the Maritime Continent is, to an extent, evident also in Kalnay et al.’s (1996) comparison of 1988–1987 summertime model precipitation with the Microwave Sounding Unit derived rainfall (see their Figs. 6a and 6b). In case of CCM3, Hurrell et al.’s (1998) rainfall analysis based on correlations with the Southern Oscillation index (their Fig. 38) also shows a rather diminished response over the Maritime Continent, much as in our Fig. 6d.

Recently, Houze (1997) has discussed the occurrence of both convective and stratiform precipitation in convection-generated cumulonimbus in the Tropics. It is thus of interest to examine the relative contribution of convective and large-scale condensation processes in the generation of ENSO precipitation anomalies. Such a decomposition is however possible only in case of mod-
Fig. 6. ENSO covariant precipitation during 1979–93 from: (a) Xie and Arkin (1997), (b) ECMWF reanalysis (6-h model forecasts), (c) NCEP reanalysis (6-h model forecasts), and (d) CCM3 simulation. Contour interval and shading threshold is 0.4 mm day$^{-1}$ in all panels, and the zero contour is omitted.
el-generated precipitation, and the ECMWF anomaly is chosen in view of its considerable similarity to the Xie–Arkin precipitation anomaly (cf. Fig. 6).

ENSO covariant anomalies in the ECMWF model-generated convective and large-scale precipitation fields are shown in Fig. 7. The convective part evidently determines the structure of the total anomaly (Fig. 6b), but large-scale condensation is clearly an important contributor in the Niño-3.4 sector, where it is, at least, half as large as the convective part. It thus appears that successful parameterization of tropical convection will likely involve a careful treatment of both the vigorous and the older and “spent” convective zones.

d. Vertical structure of diabatic heating anomalies

The vertical distribution of heating anomalies is examined in this section because the tropical circulation is sensitively dependent on the vertical gradient of heating: the horizontal divergence \(-\partial Q/\partial p\) is proportional to \(-\partial Q/\partial p\) in the Tropics, linking the divergent circulation, directly, and the rotational circulation, indirectly (through vortex stretching), with the vertical heating gradient. Examination of vertical structure will also reveal the extent of differences between the various ENSO heating anomalies at other tropospheric levels. The central Pacific (180°-150°W) anomalies are displayed as a function of latitude and pressure in Fig. 7; this longitudinal sector was chosen as it includes the heating maxima in Figs. 2 and 4. ENSO heating anomaly diagnosed from the ECMWF reanalyses is shown in Fig. 7a, while the one obtained from NCEP reanalyses is displayed in Fig. 7b.

The ENSO heating anomalies in the central Pacific are generally largest at the equator but they are not symmetrically distributed, particularly, in the upper troposphere where heating extends farther into the Southern Hemisphere, until \(-10^\circ\)S; note that in the ECMWF case, the upper-level heating maximum is also located in the Southern Hemisphere. The diagnosed heating anomalies are in agreement regarding the level of maximum equatorial heating (~400 mb), but disagree on the vertical structure of diabatic cooling, particularly, in the northern equatorial latitudes. The heating vertical structure in the equatorial lower troposphere is different as well, with the ECMWF anomalies being strong near
850 mb, leading to a local maximum there—a feature not present in the NCEP distribution.

The CCM3’s ENSO heating is shown in Fig. 8c. At first glance, this anomaly appears to be broadly similar to the ECMWF one, particularly, in the southern latitudes and at the equator. The CCM3 heating at the equator contains an absolute maximum near 400 mb and a local maximum near 800 mb, much as in the ECMWF case, but closer inspection reveals the CCM3 anomaly to be too strong near 800 mb, where heating is nearly as large as at 400 mb. The CCM3 anomaly also contains strong and extended diabatic cooling zones, particularly in the northern Tropics, indicating stronger meridional redistribution of heating and rainfall during ENSO, as noted earlier.

Differences in the vertical structure of ENSO heating anomalies in the central Pacific sector are shown in Fig. 9 using the same contour interval as in the individual fields (Fig. 8). The ECMWF–NCEP difference (Fig. 9a) is as large as 0.5 K day$^{-1}$ near 850 mb because of the
local maximum in ECMWF heating here; the difference is clearly noteworthy as it is larger than the NCEP heating itself at this level. Significant differences occur at upper levels too, but mainly from the robustness of ECMWF heating in southern equatorial latitudes, reflected in the greater equatorial asymmetry of the ECMWF heating (cf. Fig. 8a).

The CCM3 departures from the diagnosed ECMWF and NCEP heating (Figs. 9b,c) are rather similar, and much larger than the reanalysis heating difference (Fig. 9a) in most regions. The CCM3 ENSO heating is evidently at greater variance with the reanalysis heating in the lower troposphere (600–850 mb) than at 400 mb: The 700-mb differences are greater than 0.7 K day$^{-1}$ at the equator (excessive heating) and 0.5 K day$^{-1}$ in the northern Tropics (excessive diabatic cooling)—both larger than the 400-mb differences, and even the diagnosed 700-mb anomalies (Figs. 8a,b) themselves!

The robustness of CCM3 differences relative to the ECMWF–NCEP difference and the fact that CCM3
heating remains an outlier support the characterization of CCM3’s ENSO anomalies as a Hadley-like redistribution. The CCM3 heating is additionally portrayed as “bottom heavy.”

The vertical structure of ENSO heating anomalies is intercompared in Fig. 10 using the traditional display of heating profiles over the central equatorial Pacific. In addition to the previous anomalies, ENSO covariant anomalies in the heating generated during 6-h NCEP model forecasts (starting from NCEP reanalysis; see section 2B for more details) is also shown. The most striking feature in this display is the strength of CCM3 heating (shown by “Δ” marks) in the middle-to-lower troposphere, where departures from the diagnosed profiles are notably large (e.g., near 700 mb)—almost as large as the diagnosed heating itself!

The heating profiles diagnosed from NCEP and ECMWF reanalysis (shown by “□” and “●” marks, respectively) are comparatively closer, except in the lower troposphere ($p \geq 700$ mb), where the ECMWF profile has a local maximum, as noted earlier. The NCEP model heating (shown by “■” marks) is evidently in considerable agreement with the diagnosed NCEP profile; while this is reassuring for heating diagnosis, the agreement confirms the discrepancy between the two leading reanalyses in their implicit representation of ENSO diabatic heating in the lower troposphere.

5. Analysis of CCM3’s ENSO heating error

The reason why CCM3’s western Pacific region, encompassing Borneo, Philippines, and the South China, Sulu, and Celebes Seas, is not responsive during ENSO is investigated in this section. The seasonal variability of CCM3’s $Q_{400}$, ECMWF’s $Q_{400}$ (diagnosed from reanalyses), and the Xie–Arkin precipitation is compared over the western Pacific (110°–130°E) in Fig. 11 to examine if this region’s unresponsiveness is more pervasive. The validation targets—seasonal cycles of ECMWF $Q_{400}$ (Fig. 11b) and Xie–Arkin precipitation (Fig. 11c)—are evidently in remarkable agreement both at the equator and in the off-equatorial latitudes.

The CCM3’s seasonal cycle of $Q_{400}$ is indeed anemic in the northern Tropics (5°–15°N) of the western Pacific sector where ENSO heating and precipitation variability was notably weak. In contrast, the model’s $Q_{400}$ seasonal cycle in southern latitudes is simulated reasonably well in both phase and amplitude. On account of the simulation deficiency in northern latitudes, the seasonal northward migration of deep convection during the northern spring-to-summer months is not well captured in CCM3. The comparisons suggest that CCM3’s unresponsiveness in deep convection and precipitation over the northern Tropics of the western Pacific during ENSO—which contributes to the Hadley-like heating redistribution—is likely rooted in the same causes that lead to notably weak seasonal variability over this region.

The reasons for the bottom-heavy structure of CCM3’s ENSO heating anomalies are also investigated in this section. The distribution of leading heating components in the Tropics—latent and the longwave radiative heating—is examined in the CCM3 simulation and in NCEP’s 6-h model forecasts (initialized from reanalysis); note that diabatic heating from the ECMWF model forecasts is unavailable. The CCM3’s

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* Seasonal variability is obtained by removing the climatological annual mean from the climatological monthly means.
Fig. 11. Seasonal cycle of heating and precipitation in the western Pacific (110°–130°E), from departures of the climatological monthly means from the climatological annual mean: (a) $Q_{400}$ from CCM3, (b) $Q_{400}$ diagnosed from ECMWF reanalyses, and (c) Xie–Arkin precipitation. The contour interval and shading threshold is 0.5 K day$^{-1}$ for heating and 1.0 mm day$^{-1}$ for precipitation, and the zero contour is omitted as before.

ENSO heating produced from all condensation process (shallow, deep-convective, and large-scale; DTCOND) is shown in the central Pacific in Fig. 12a, while the ENSO covariant longwave radiative heating (QRL) is shown in Fig. 12b. An inspection of these figures, and comparison with the CCM3 heating differences (Figs. 9b,c) indicates that the differences arise primarily from the DTCOND component. The longwave heating is quite modest (<0.5 K day$^{-1}$) and moreover peaks at ~800 mb, and as such, cannot be directly implicated
FIG. 12. ENSO covariant heating components in the central Pacific (180°–150°W): (a) CCM3 heating from all condensation processes (DTCOND; see section 2c for details), (b) longwave radiative heating in CCM3, (c) sum of deep and shallow convective, and large-scale condensation heating from NCEP reanalysis (6-h model forecasts), and (d) longwave radiative heating from NCEP reanalysis (6-h model forecasts). Note that (c) is the counterpart of (a). The contour interval and shading threshold is 0.1 K day$^{-1}$ in all panels, and the zero contour is omitted as before.
in the generation of the CCM3 heating differences. In this diagnostic assessment, both the bottom-heavy structure and excessive diabatic cooling in the northern Tropics in CCM3’s ENSO heating have their origin in the condensation component (DTCOND).

ENSO covariant heating components from the NCEP model forecasts are shown in Figs. 12c,d: Condensation heating, obtained by summing the large-scale condensation (LRGHR), deep-convective (CNVHR), and shallow convective (SHAHR) components, is shown in Fig. 12c, while the longwave heating (LWHR) is shown in 12d. Given the large differences between the NCEP and CCM3 diabatic heating anomalies (Fig. 9c), it is not surprising that heating components differ as much as they do. The longwave differences are primarily in amplitude, with NCEP’s being about half of CCM3’s and notably weak at the equatorial tropopause. Condensation heating, on the other hand, exhibits substantial differences, particularly, in the equatorial lower troposphere and the northern extratropics, which were manifest in the total diabatic heating fields, and discussed earlier.

It is noteworthy that the latitudinal distribution of longwave and convective heating anomalies is very similar over the tropical Pacific, both in CCM3 and NCEP heating (Fig. 12); examination of the longitudinal distribution (not shown) supports this to be true as well. The longwave heating anomalies occur as if in the ‘‘shadow’’ of convective heating anomalies, perhaps, because of their dependence on cloud anomalies: for example, in the equatorial convective zones containing cumulus/ cumulonimbus clouds, longwave heating occurs beneath the clouds due to the trapping of longwave radiation, and anomalous cooling occurs near the cloud tops from longwave emission to space.

6. Summary and concluding remarks

This study has sought to establish the three-dimensional structure of diabatic heating anomalies associated with ENSO climate variability. Monthly heating was first diagnosed from the recent (1979–93) ECMWF and NCEP reanalysis datasets, as a residual in the thermodynamic equation; ENSO covariant anomalies were then obtained from regression with an ENSO index. In the deep Tropics, the heating diagnosis depends critically on the analyzed vertical velocity, that is, on the representation of divergent flow in the reanalyses, and as such, the residually diagnosed heating anomalies are expected to exhibit some differences. The key question is whether these differences are modest or substantial relative to the ENSO heating anomalies themselves, as robust targets for GCM heating distributions can be established only in the former case. The validation of GCM heating distributions is important as diabatic heating is the principal forcing of tropical and subtropical circulations, including surface winds over the tropical oceans, and because accurate parameterization of the diabatic heating components still eludes many atmospheric GCMs.

The analysis begins with a comparison of the ECMWF and NCEP heating anomalies. The horizontal intercomparisons show remarkable phase agreement, but stronger amplitudes in the ECMWF case; the largest difference over the Pacific is near the equatorial date line, where the vertically averaged ECMWF heating is stronger by \( \sim 0.3 \) K day\(^{-1} \), whereas the anomaly itself is \( \sim 0.5 \) K day\(^{-1} \). Of the two, the ECMWF heating is in better accord with the Xie–Arkin precipitation, particularly, with respect to precipitation reduction (or diabatic cooling) over the western Pacific. Examination of the heating vertical structure in the central equatorial Pacific reveals notable variance in the lower troposphere, where the ECMWF anomaly is stronger, having a local maximum near 850 mb.

Differences in the residually diagnosed ENSO heating anomalies could arise from several factors, including model resolution, initialization scheme, and the planetary boundary layer and convection parameterizations that impact the first-guess fields. Although analysis of the reasons for differences between the diagnosed heating fields is beyond the scope of this study, we compare the ENSO covariant tropospheric temperatures at the equator in Fig. 13. The large-scale circulation associated with tropical convection is usually described using vertical profiles of latent heating and horizontal divergence (or \( \omega \)), but seldom temperature. Temperature perturbations (\( \sim -\delta T/\delta \rho \)) are reckoned to be small in the Tropics because geopotential fluctuations are constrained to be smaller here owing to the diminished Coriolis parameter (e.g., Holton 1992). Moreover, the dominant balance in the thermodynamic equation—between diabatic heating and adiabatic and radiative cooling—precludes direct determination of temperature, at least where \( \omega \) is large. The temperature field, however, has a prominent role in the recent statistical equilibrium hypothesis of Emanuel et al. (1994), according to which the vertical profile of temperature rather than heating is controlled by convection.

ENSO covariant temperature anomalies in the reanalyses (Figs. 13a,b) are quite similar, and sizeable in both the upper and lower troposphere of the heating sector (see Fig. 4)—the vertical structure of the temperature anomalies is, in fact, intriguing. The largest amplitudes (\( \sim 0.6 \) K) occur near 300 mb, and the temperature anomaly during the 1987 El Niño, for example, is in the range of 1.2–1.5 K (based on principal com-

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\footnote{The spatial smoothing of NCEP’s pressure-level reanalysis fields (see footnote 1), however, is not the cause of discrepancies in the diagnosed NCEP and ECMWF heating rates, which are not only in magnitude but also structure. Given the large zonal scale of ENSO heating anomalies, truncation of vertical velocity (\( \omega \)) at T36 resolution should be inconsequential in residual diagnosis. The similarity of diagnosed heating to the NCEP model heating (a field \( \text{not subjected to spatial smoothing} \) in Fig. 10 supports this assertion.}
ponents in Fig. 1). It is interesting that the warmest anomalies appear eastward of the maximum heating anomalies in both reanalyses, but heating and temperature anomalies remain positively correlated across the heating sector (180°–90°W, approximately).\textsuperscript{10}

\textsuperscript{10} One could speculate that trapping of longwave radiation beneath the clouds and enhanced emission above can produce such upper-tropospheric temperature anomalies, except that the NCEP model's longwave heating structure (Fig. 12d) is not encouraging in this regard.

The vertical structure of ENSO temperature anomalies in the lower troposphere, particularly, surface trapping, is suggestive of the impact of vertical diffusive mixing in the planetary boundary layer; the warming is, however, too deep to arise solely from this process. The difference between the ENSO temperature anom-
alies is shown in Fig. 13c, and is evidently not insignificant in the lower troposphere; the ECMWF anomalies are about 50% larger than the NCEP ones, and could substantially impact the moistening and stability of the boundary layer.

The ENSO covariant temperature distributions in the two reanalyses do not by themselves offer insight into the reasons for differences between the diagnosed heating distributions. It is however hoped that their display will stimulate further research in the parameterization of deep and shallow convection in the Tropics.

The present study also discusses an application of the diagnosed ENSO heating distributions. ENSO diabatic heating produced by a state-of-the-art atmospheric GCM—the NCAR CCM3—is evaluated from intercomparisons. At least, in context of ENSO variability, the differences in ECMWF and NCEP heating anomalies are small in comparison with CCM3’s heating departures from either of these anomalies, allowing characterization of CCM3’s ENSO heating as an outlier:

• CCM3 anomalies reflect a more meridional redistribution of heating (Hadley-like) in comparison with the reanalysis anomalies, which are more zonally redistributed (Walker-like); a comparison of CCM3 and Xie–Arkin ENSO precipitation anomalies confirms this assessment.

• CCM3 anomalies over the eastern equatorial Indian Ocean, Borneo, Philippines, and the South China, Sulu, and Celebes Seas are quite weak; the seasonal variability of heating over this region is also suppressed in the CCM3 simulation.

• CCM3 anomalies differ from the diagnosed anomalies more in the lower troposphere (600–850 mb) than at upper levels; the 700-mb differences—greater than 0.7 K day$^{-1}$ at the equator due to excessive heating, and greater that 0.5 K day$^{-1}$ in the off-equatorial northern latitudes from excessive cooling—are larger than the diagnosed heating anomalies themselves, leading to a bottom-heavy ENSO heating profile in the CCM3 simulation.

The follow-up error attribution phase, in which the deficiencies in simulated ENSO surface winds are related to specific features of the GCM’s heating error from diagnostic modeling, is reported in a companion paper (Nigam and Chung 2000, this issue). Such a double-pronged approach consisting of diagnostic analysis and modeling should facilitate GCM development.

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