Diagnosis and Sensitivity of the 200 hPa Circulation in NCAR Community Climate Models

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Wintertime 200 hPa Stationary Wave Error (10^6 m^2 s^-1)

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Preface

The purpose of this report is to determine the nature of systematic errors in several different seasonal cycle versions of the National Center for Atmospheric Research (NCAR) Community Climate Models (CCMs) and to assess the dynamical impact of such errors on climate perturbation studies. Our diagnosis focuses on the seasonal mean December-January-February (DJF) 200 hPa circulation and evaluates the sensitivity of that flow to anomalous tropical forcing. Other features of the CCM climatologies for January and July, including the mass fields and hydrologic cycle, are evaluated in Hurrell et al. (1993).

A linear barotropic stationary wave model is used to examine the sensitivity of observed and CCM climatological flows to idealized tropical forcing. The forcing consists of a mass source/sink dipole over the equatorial Pacific that mimics the horizontal structure of anomalous rainfall during El Niño. The climatological flows on which the forcing is imposed differ among the various CCMs, and these in turn differ from observations. Differences between the responses to tropical forcing imposed on each base state relative to observations then indicate the dynamical significance of the CCM climate errors.

The northern wintertime teleconnections during El Niño are particularly strong with the Northern Hemisphere (NH) flow, and our assessment of the significance of the CCM climate biases focuses on how such errors impact the NH stationary wave response. Of course, the full CCM behavior during El Niño is considerably more complicated than just the steady barotropic response to tropical forcing. As such, the approach taken herein should be viewed as only one component of a more thorough model evaluation that ultimately requires diagnosis of CCM integrations with interannual sea surface temperature (SST) anomalies.

Relationships between climate errors in CCM divergent and rotational flow components are examined in the context of the linear model. These experiments are designed to determine the link between various features of the CCM 200 hPa circulation biases, and to provide guidance for model development.

Our principal results common to all the CCM versions studied herein are:

- The zonally averaged zonal wind at 200 hPa has a westerly bias in the tropics. The error is not zonally uniform but is strong locally with a 20 m s\(^{-1}\) maximum over the equatorial central Pacific. This is associated with an erroneous westward shift of the CCMs' subtropical Pacific stationary wave troughs in both hemispheres.
Excessive divergence at 200 hPa is found over the tropical west Pacific with amplitudes up to four times greater than those observed.

With regard to the sensitivity of the CCM NH wintertime flow:

- A much larger extratropical response to tropical forcing occurs within a barotropic model linearized about the CCM wavy climatological flow than about the observed flow.

- These different climatological flow basic state sensitivities are in large part attributable to errors in the CCM asymmetric zonal flow, particularly over the Pacific basin.

- The large CCM 200 hPa westerly wind bias over the tropical central Pacific is consistent with excessive 200 hPa divergence over the equatorial western Pacific and appears to be a dynamical response to excessive model rainfall over New Guinea.

Several other important climate biases are model-dependent, and these are discussed individually.

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1. Introduction

The Community Climate Models (CCMs) in several forms at the National Center for Atmospheric Research (NCAR) are among the most extensively used general circulation models (GCMs) in climate research. Over 200 CCM-related investigations have been published in the last decade, addressing such diverse problems as paleoclimates, coupled ocean-atmosphere interactions, climate change due to carbon dioxide and aerosol effects, and tropical/extratropical interactions accompanying the El Niño/Southern Oscillation (ENSO) (a complete list of CCM-related publications is provided in Williamson 1993a). Since the inception of the first community version of NCAR's GCM (referred to as CCM0) in the early 1980s (Washington 1982), numerous modifications have been introduced that reflect both our improved understanding of the physics of the climate system and increased computer capacity. These have led to the release of versions CCM1 in 1987 and CCM2 in 1992. The modifications incorporated in CCM1 and CCM2 are described by Williamson et al. (1987) and Hack et al. (1993), respectively, while a compendium of circulation statistics documenting the climates of CCM1 and CCM2 appear in Williamson and Williamson (1987) and Williamson (1993b), respectively.

In addition, numerous research versions of the NCAR CCM have been developed. While retaining the essential architecture of the CCM, these models have typically introduced modifications to the physical parameterizations for purposes of simulating specific climatic features. Two such research versions of the CCM have been extensively used—a version of CCM0 modified for coupled model experimentation and carbon dioxide studies (e.g., Washington and Meehl 1983, 1984, 1989; Washington and VerPlank 1986; Meehl et al. 1993; Washington and Meehl 1993), and a version of CCM1 used for aerosol sensitivity studies (e.g., Thompson et al. 1987) and land surface process studies including paleoclimates (e.g., Bonan et al. 1992; Barron et al. 1993; Pollard and Thompson 1993b).

Our primary goal in this report is to diagnose the climatological wintertime 200 hPa flows of the three standard control and the two aforementioned research versions of NCAR CCMs and to assess the sensitivity of these flows to anomalous forcing. The latter objective is motivated by the fact that a major application of atmospheric GCMs is to understand the global teleconnections within the climate system. Faithful representation of such teleconnections depends sensitively on the veracity of the GCM's mean atmospheric circulation, as it plays a central role in "transmitting" information from regions of forcing to regions of response. A particular example for which the CCM has been extensively used is the tropical sea surface temperature (SST) forcing of the NH extratropical circulation...
anomalies during ENSO. We consider an idealization of the ENSO forcing in this report and examine the CCMs' ability to represent the ensuing interaction between tropical and NH extratropical latitudes.

A linear steady state barotropic model is used as the primary diagnostic tool. Barotropic models have been used for studying a wide range of problems, including the origin of wintertime stationary wave anomalies (e.g., Hoskins et al. 1977; Simmons 1982; Simmons et al. 1983; Hoskins and Sardeshmukh 1987) and the dynamics of GCM simulated responses to SST anomalies (e.g., Branstator 1985; Held and Kang 1987; Hoerling et al. 1992) and doubled carbon dioxide (Meehl et al. 1993; Robertson 1992). Although the barotropic vorticity equation is a very simple representation of the atmosphere's circulation, it nonetheless contains the essential dynamics required to explain the horizontal propagation of energy through an ambient flow containing zonal and meridional shears. Indeed, it is the strong modulation of the energy propagation, and hence the remote response, by the structure of the zonal and meridional flow that makes the barotropic model a powerful tool for quantifying the dynamical significance of circulation errors.

The results are divided into two main sections. The first is model diagnostics where we present the errors in the CCM 200 hPa zonal flow, stationary waves, and divergent circulations. In view of observational uncertainties, particularly in the divergence, two climatological datasets for identical periods are used for CCM validation. It should be noted, however, that the observations are derived from a climate system that is subjected to interannually varying boundary forcings, whereas the CCM is not. We have examined a long-term integration of NCAR's CCM0 and CCM2 with interannual SST variability and find that the 10-year mean climates differ only slightly from their parallel control runs. The second section presents various linear model sensitivity studies. Specific questions we address using the linear model are: (1) What is the dynamical impact of biases in the CCM 200 hPa flows on the sensitivity to tropical forcing? (2) What is the relative importance of errors in the zonally averaged and zonally varying flows? and (3) What is the link between biases in the CCM rotational and irrotational flows? The latter question seeks possible origins for the CCM mean stationary wave errors that may arise from errors in simulating convection over the tropical monsoon regions. Similar applications of the barotropic model have provided insight on the possible cause of systematic errors of 10-day forecasts at the European Centre for Medium-Range Weather Forecasts (ECMWF) (Sardeshmukh and Hoskins 1987) and the cause of climatological stationary wave errors in a research version of CCM1 (Hoerling et al. 1992).
2. The NCAR Community Climate Models

We diagnose the wintertime climates of six versions of NCAR CCMs. All model climatologies are based on ten years of repeating seasonal cycle integrations performed at R15 resolution. The one exception is for the standard CCM2 run which is performed at T42 resolution. A brief description of each is given in this report, whereas a more detailed description appears in Hurrell et al. (1993).

2.1 CCM0

The initial version of the NCAR CCM is based on the Australian spectral model (Bourke et al. 1977). The vertical structure is represented by nine unequally spaced sigma levels. Physical parameterizations of surface hydrology (non-interactive), large-scale stable condensation, convection, and vertical diffusion are based on schemes developed at the Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe et al. 1965; Smagorinsky et al. 1965). The parameterization of clouds and radiation is based on Ramanathan et al. (1983).

In this study, we examine a 10-year subset of a long-term integration of a seasonal cycle version of CCM0 developed by Chervin (1986). Chervin (1986) describes the modifications to CCM0 required for conducting realistic annual cycle simulations. During the integration, all surface boundary conditions evolve through identical annual cycles. The SST climatology is based on Oort's (1983) 15-year mean dataset for the period 1958-1973.

2.2 CCM0: atmospheric model for coupled simulations

A version of CCM0 has been extensively used for coupled ocean/atmosphere system experiments, including experiments to study the climatic impact of doubled carbon dioxide by the Climate Sensitivity and CO2 Research (CSCO2) group at NCAR (e.g., Washington and Meehl 1983; 1984; 1986; 1989; 1993). This research version will be subsequently referred to as CSCO2. As in Chervin's CCM0 seasonal cycle model described above, the CSCO2 model uses nine unequally spaced sigma levels. However, in this model version surface hydrology is computed (snow cover and soil moisture) and land albedos are taken from CCM1. The radiation scheme follows Ramanathan et al. (1983), but with the modification that middle and high clouds have specified emissivities of 0.9 and 0.7, respectively, whereas their emissivity varies as a function of water content in CCM0. Ramanathan et al. (1983) illustrate the sensitivity of the CCM's climate to various treatments of the cloud radiative properties. Perhaps the largest change involves the
treatment of moist convection. The CSCO2 version employs a hybrid parameterization of
the convective fluxes of heat and moisture (Albrecht et al. 1986; Meehl and Albrecht 1988;
Meehl and Albrecht 1991), in conjunction with the moist adiabatic adjustment of Manabe et
al. (1965). This most recent version of the CSCO2 model has been described by
Washington and Meehl (1993). The seasonal cycle simulation of the CSCO2 model uses
the SST climatology of Alexander and Mobley (1976).

2.3 CCM1

CCM1 is based on an adiabatic version of the spectral model developed at
ECMWF. As in CCM0, large-scale condensation, convection, and surface hydrology are
based on GFDL physics (Manabe et al. 1965), while the treatment of clouds and radiation
follows Ramanathan et al. (1983). Several modifications to the physics were introduced,
however, as described in detail by Williamson et al. (1987). Most notably, condensation
occurs at 100% relative humidity in CCM1 instead of 80% in CCM0, and vertical diffusion
in CCM1 transports moisture vertically. These two changes are believed to have
significantly impacted the vertical distribution of tropical heating in the CCM (Hoerling et
al. 1990). Additionally, CCM1 has 12 sigma levels, with the enhanced resolution
occurring near the tropopause and lower stratosphere. The CCM1 simulations use the
Alexander and Mobley (1976) SST climatology, and the runs studied herein have fixed
surface hydrology.

2.4 CCM1 : GENESIS

The second research version of the CCM to be examined is GENESIS (Global
Environmental and Ecological Simulations of Interactive Systems) which originated from
CCM1. It incorporates several significant modifications to the physics of CCM1. The
solar radiation scheme of Thompson et al. (1987) is used, and a diurnal cycle has been
added to the model. Water vapor is advected by semi-Lagrangian transport, as described
by Williamson and Rasch (1989). Convection is treated using an explicit sub-grid plume
model (Pollard and Thompson 1993a), and the cloud parameterization is similar to that of
Slingo and Slingo (1991). A land-surface transfer model computes surface hydrology and
accounts for the physical effects of vegetation (Pollard and Thompson 1993b). The
seasonal cycle simulation of GENESIS presented here uses the SST climatology of
Alexander and Mobley (1976), although the model has often been coupled to a simple 50
meter slab ocean (Thompson and Covey 1988).
2.5 CCM2

Major modifications to the CCM architecture and to the treatment of physical processes appear in version 2. These are described in detail in Hack et al. (1993). Some of the structural changes include a hybrid vertical coordinate system consisting of 18 layers that transition from constant sigma in the low troposphere to constant pressure in the stratosphere. The horizontal resolution of the standard control version has been increased to T42 and includes a semi-Lagrangian treatment for water vapor transport. A simple mass flux scheme is used to represent all types of moist convection following Hack (1993). The cloud fraction parameterization is a generalization of Slingo (1987), while the cloud emissivity depends on liquid water path (Kiehl et al. 1993). Additional features include a diurnal cycle and an explicit prediction of the planetary boundary layer height and turbulence.

In this report, we diagnose the CCM2 climates at both T42 and R15 resolutions. The R15 version of CCM2 is otherwise identical to its higher resolution counterpart, except for the scale-dependent treatments of horizontal diffusion and changes in cloud parameters. Both models have been run in seasonal cycle mode with fixed surface hydrology and use the Shea-Trenberth-Reynolds global monthly SST climatology (Shea et al. 1990).

3. Observational Analyses

We have generated two 5-year wintertime (December, January, and February---DJF) climatologies based on the 1986/87 through 1990/91 period. The first is derived from the National Meteorological Center (NMC) global initialized analyses, and the second is derived from ECMWF global uninitialized analyses as provided in the TOGA grid-point archive (Trenberth 1992). This particular record for determining the observed climate was chosen due to the substantial revisions in both NMC and ECMWF assimilation models that took place in the mid-1980s. These had major impacts of estimates of the tropical climate (see Trenberth and Olson 1988, and Trenberth 1992). It should be recognized, however, that revisions to both assimilation models have continued during our 5-year record, and that these have led to trends in some variables, most notably water vapor and divergence (see Trenberth (1992) for analysis of recent trends in the ECMWF data).

The NMC and ECMWF data are archived at 15 mandatory pressure levels and have been converted once daily into CCM format by interpolating horizontally from a 2.5° x 2.5° grid to an R15 gaussian grid. All model comparisons are performed at the common R15 resolution using the CCM Modular Processor (Wolski 1987). Note that all the CCM
datasets studied herein are already at R15 resolution, with the exception of the standard CCM2 model output which we have subsequently truncated from T42 to R15 resolution.

4. Linear Barotropic Model

Our description of the linear barotropic model is based on the discussion in section 2b of Hoerling et al. (1992). When linearized about a basic state flow $\vec{v} = \vec{v}_\psi + \vec{v}_\chi$, the barotropic non-divergent vorticity conserving model is given by

$$\frac{d\zeta'}{dt} + \vec{v}_\psi \cdot \nabla \zeta' + \vec{v}_\psi \cdot \nabla (\zeta'f) = S' + D' + T,$$

where $\vec{v}_\psi$ and $\vec{v}_\chi$ are rotational and irrotational components of the velocity, $\zeta$ is the relative vorticity, overbars represent climatological means, and primes refer to perturbation quantities. The perturbation quantities on the left-hand side of (1) ($\zeta'$ and $\vec{v}_\psi'$) may be viewed as the response of the base state to the sum of forcings on the right-hand side.

The forcing associated with divergence is expressed as a source $S'$ (Held and Kang 1987; Sardeshmukh and Hoskins 1988), given by

$$S' = -\nabla \cdot \left[ \vec{v}_\chi (\zeta'f) \right] - \nabla \cdot (\vec{v}_x \zeta'),$$

which includes both the vortex-tube stretching effect and the advection of vorticity by the divergent flow. The effects of dissipation are represented by $D'$ according to

$$D' = -\kappa \zeta' + \nu \nabla^4 \zeta',$$

where $\kappa$ is a drag coefficient equal to 1/(7 days) as in Branstator (1985), and the biharmonic diffusion $\nu = 2 \times 10^{16}$ m$^4$s$^{-1}$ is equal to the CCM1 value. $T$ represents the transient vorticity forcing due to the vorticity flux divergence by transients for all sub-seasonal time-scales less than 90 days. The effects of transients are not considered in this study.

We spectrally transform (1) in the horizontal at rhomboidal wave number 15, and steady solutions are sought (i.e., omit the first left-hand side term) using the matrix inversion method of Ting and Held (1990). Equation (1) may then be viewed as a complete statement of the time-averaged linear vorticity balance at a level, with the only omissions being the vertical advection of vorticity and tilting terms.

In this report, the basic state flows used in (1) are derived from the CCM and observed climatological flows at R15 scale, and we consider the response to various distributions of divergence at 200 hPa. One set of experiments investigates the sensitivity to the idealized
divergence forcing shown in Fig. 1. This simple dipole attempts to reproduce the essential features of the tropical convective response to El Niño-related SST forcing. Maximum values are $4.0 \times 10^{-6}$ s$^{-1}$ which correspond to a rainfall anomaly of roughly 10 mm day$^{-1}$. A second set of experiments considers the response to errors in the CCMs' climatological 200 hPa divergence.

**IDEALIZED DIVERGENCE PERTURBATION**

Fig. 1. Idealization of the tropical Pacific 200 hPa divergence anomalies typically observed during a mature El Niño. Maximum values are $3.9 \times 10^{-6}$ s$^{-1}$ and correspond to a surface rainfall anomaly of about 10 mm day$^{-1}$.

These two sets of experiments can be summarized by considering a schematic representation of (1)

$$L(\bar{X})\psi' = F',$$  \hspace{1cm} (4)

where $L$ is the linear operator, $\bar{X}$ is the base state, $F'$ is the forcing, and $\psi'$ is the response of $\bar{X}$ to $F'$. For the complete wavy state, the base state flow is given by

$$\bar{V} = [\langle u \rangle + u^*, \langle v \rangle + v*],$$  \hspace{1cm} (5)

where $u$ and $v$ are the zonal and meridional velocities, respectively, angle brackets denote zonal means, and asterisks denote departures from zonal means.

The error in the response can be expressed schematically as

$$\delta\psi' = \delta\bar{X} + \delta F',$$  \hspace{1cm} (6)
where the right side denotes contributions due to errors in the base state and to errors in the forcing.

In the first set of experiments, we consider the response of observed and CCM base states to identical forcings $F'$ as given in Fig. 1. Differences in the responses are due entirely to errors in $\bar{X}$, and, through various choices in base states, we can isolate which flow components in (5) are responsible. In the second set of experiments, we consider the response of an observed base state to errors in divergence, the latter being computed as the difference between the CCM and observed 200 hPa divergence. The stationary wave response to this forcing is then compared to the CCM's climatological stationary wave error.

5. Diagnosis of the Wintertime Climate of NCAR CCMs

Both NMC and ECMWF observed climatologies are used for model validation. For all relevant fields, we first intercompare NMC and ECMWF analyses to provide a measure of uncertainty in the observed climate (see Trenberth and Olson (1988) for a more complete intercomparison). All model-minus-observed difference fields are computed with respect to the NMC analyses, and the resultant figures are provided sequentially in section 7.

5.1 Evaluation of the CCM 200 hPa circulation

There is a high degree of confidence in the observed estimates of the zonal mean zonal wind (Fig. 2, top), whereas greater uncertainty exists in the estimates of the zonal mean meridional wind (Fig. 2, bottom). A maximum difference in the meridional wind of about 0.3 m s$^{-1}$ occurs near 10°N. It should be noted that even larger differences occur between NMC and ECMWF analyses for individual years of the 5-year record, in part due to the non-uniform evolution of the two centers' assimilation models.

A common error in all CCM versions is the westerly bias of 5-10 m s$^{-1}$ in the zonal mean zonal wind between 15°N-15°S (Fig. 3). Simulations of the Southern Hemisphere (SH) extratropical westerlies are also poor and are plagued by large phase and/or amplitude errors in all the CCMs. In contrast, simulations of the NH extratropical westerlies have shown consistent improvement in successive versions of the NCAR model. A critique of the model's zonal mean meridional wind (Fig. 4) is more problematic due to observational uncertainties. It is clear, however, that CCM2 exhibits the strongest poleward branch of the Hadley cell at 200 hPa. A poleward flow of 3.1 m s$^{-1}$ near 5°N in the T42 CCM2
version is 50 percent larger than either observational analysis and double the intensity in the R15 CCM0 version.

We next consider regional features of the 200 hPa flow. The zonal wind is well observed at this level, with a maximum difference between ECMWF and NMC analyses of only 2 m s$^{-1}$ (Fig. 5). All major features of the 200 hPa zonal wind are qualitatively reproduced in the CCMs (Fig. 6), including distinct westerly maxima along the east coasts of Asia and North America, an easterly regime in the tropical eastern hemisphere, and a westerly regime in the tropical western hemisphere. However, a quantitative evaluation of the models' 200 hPa zonal wind reveals major regional biases, many of which are evident throughout the CCMs' evolution (Fig. 7). For example, westerly biases of large amplitude are consistently found over the central equatorial Pacific. The error in this region represents both an in-phase westerly bias and a westward shift of the CCMs' tropical westerly flow regime relative to that observed. Note that the zero wind line over the equatorial Pacific is located near 150°E in the CCMs but near 170°W in observations. In the extratropics, the Middle East and East Asian westerly jets are shifted poleward of their observed latitude in all the CCMs except the GENESIS model. The extratropical errors tend to be largest over the North Pacific, with easterly biases near 30°N, 180°W reflecting a tendency for the Asian jet to be too contracted in the CCM, and westerly biases to the north reflecting the erroneous southwest-northeast orientation of the models' jet. Biases over the SH extratropics are also quite regional in character with a tendency for maximum errors downstream and poleward of South Africa, Australia, and South America. This pattern is associated with the CCMs' preference to simulate three separate SH westerly jets whereas observations suggest a more uniform distribution of westerly flow over the Southern Ocean.

The wintertime stationary wave patterns, as described by the departure from zonal symmetry of the 200 hPa streamfunction, are shown in Figs. 8 and 9 for observations and CCMs, respectively. As for the CCM simulations of the zonal flow, the wintertime features of the stationary eddy flow are all qualitatively reproduced. However, climatologically important phase shifts of the centers of action and sizeable amplitude errors lead to major regional biases (Fig. 10). A recurring bias is the westward shift of the subtropical Pacific stationary wave troughs in the CCMs relative to observations, and this is consistent with the models' large equatorial central Pacific westerly wind error. In the extratropics, the Hudson Bay trough is consistently too weak in the CCMs, as is the associated ridge over western Europe. Note also the incorrect tilt of the west North American ridge in the CCM0, CSC02, and the two CCM2 versions. In this regard, it is intriguing to note that the stationary wave error for CCM0 and both CCM2 versions over
the Pacific/North American sector is suggestive of a reverse PNA pattern whose origins appear to be the equatorial central Pacific. We examine this possible link further in section 5.3 using the linear barotropic model.

Whereas the rotational component of the 200 hPa flow is well observed during the recent climate record, there is considerably less agreement among the two assimilation centers' analyses of the irrotational component. Although regional centers of climatic mean 200 hPa divergence and convergence agree among the two analyses (top two panels of Fig. 11), differences in amplitude locally exceed the estimated divergence itself (bottom panel of Fig. 11). Maximum differences are found in the tropics with values up to $3 \times 10^{-6}$ s$^{-1}$. Despite this unsatisfactory situation with regard to observations, the CCM-simulated 200 hPa divergence is sufficiently different from either analysis to leave little doubt about the deficiencies. Figure 12 shows the CCMs' winter mean divergence at 200 hPa, while differences between the CCM and NMC observations are shown in Fig. 13. In the tropics, the CCM divergence centers tend to be considerably more localized than in observations. Over the tropical Pacific, in particular, this may be due to the absence of interannual SST variations in the CCM which act to zonally extend the rainfall regime (and hence the 200 hPa divergence) farther toward the dateline during warm episodes. Nevertheless, there exists a pronounced tendency in the CCM to concentrate precipitation in the vicinity of steep orography such as the African highlands, New Guinea, and the Andes during northern winter. Similar problems occur near the Tibetan plateau during summer (see Hurrell et al. 1993). The situation over New Guinea appears especially recurrent and severe in the CCMs, where the simulated 200 hPa divergence exceeds observed values by a factor of 2-4. In contrast, there is very little evidence of a South Pacific Convergence Zone (SPCZ) southeast of New Guinea, although the T42 version of CCM2 generates a modest convective band that extends southeastward across the dateline. An important issue that we address later in this report is the extent to which these errors in simulating the monsoonal outflow over the Pacific are dynamically related to the aforementioned errors in the rotational flow over both the tropical and extratropical Pacific sector.

5.2 Sensitivity of the CCM 200 hPa circulation

We examine in this section the sensitivity of the CCM 200 hPa flow to the tropical ENSO-type forcing (see Fig. 1). The results are sequentially displayed in section 8. We emphasize the NH sensitivity in the current study. This is motivated by the considerable use of the CCM (and other GCMs) to study the NH stationary wave response during mature ENSO winters, a time when such features acquire large amplitude.
The idealized forcing is first imposed on the observed climatological flows in order to provide a benchmark against which to critique the CCMs. Figure 14 shows the steady linear response of the NMC and ECMWF full wavy base states. Very similar patterns evolve on both climatological flows attesting to the close agreement between those flows. These consist of a subtropical anticyclone (solid contours) across the central Pacific, extending northwestward to a larger amplitude anticyclone east of Japan, and cyclonic circulations (dashed contours) centered in the Gulf of Alaska, the North Atlantic, and extending across southern Asia.

Responses of the full wavy CCM base states (Fig. 15) exhibit much larger amplitudes and, for some model versions, significant phase differences compared with the responses of the observed base states. Over the North Pacific sector as a whole, the steady linear responses of the CCM base states are more than double the amplitude of that occurring on the observed base states. The position of the North Pacific cyclonic responses varies considerably with centers over the Aleutians in CCM0, British Columbia in the CSC02 version, and central Canada in the GENESIS version. It is clear that the degree to which the sensitivities of CCM and observed base states differ is related to the degree to which their climatological flows differ. For example, the North Pacific response on the CCM1 base state is in closer agreement with observations than are the responses of the other CCM base states. This is consistent with the somewhat better simulated climatological flow in CCM1 over the Pacific sector. In contrast, the response of the GENESIS model's flow over the Atlantic and Middle East is particularly poor and is undoubtedly related to its poor simulation of the climatological Atlantic jet (see Fig. 7).

In order to assess which CCM circulation biases account for the different sensitivities, we have performed a hierarchy of linear experiments that successively increase the complexity of the base state upon which the forcing in Fig. 1 is imposed. The first involves linearization about the zonal mean zonal flow only, the results from which are shown for observed and CCM base states in Figs. 16 and 17, respectively. Note that the observed symmetric flows yield a considerably larger response over the PNA region than the full wavy base states (see Fig. 14). Responses of CCM zonally symmetric flows are nearly in phase with those observed and possess amplitudes differing less than 50 percent from observations. One exception is over the North Pacific where the response of CCM zonally symmetric flows is nearly double that observed, which accounts for an important fraction of the discrepancies in the full wavy base state responses. For the extratropics as a whole, a larger response is excited on all the CCM symmetric base states relative to the NMC and ECMWF observed counterparts. It is useful to recall, from our diagnosis of the zonally averaged zonal wind (see Fig. 3), that the CCMs possess a 5-10 m s\(^{-1}\) tropical
westerly bias. The stronger extratropical response of the CCM base states is then consistent with the results of Simmons (1982) and others who found a larger amplitude remote response to a tropical forcing embedded in ambient westerlies versus easterlies.

We increase the complexity of the climatological base states by including a zonal mean divergence. The inclusion of a Hadley cell increases the amplitude of the responses for both observed (Fig. 18) and CCM (Fig. 19) flows in a manner consistent with earlier findings of Watterson and Schneider (1987). However, there is no detectable change in the phase of the forced wavetrains. It is interesting that the differences of over 50 percent in CCM and observed 200 hPa meridional velocities (see Fig. 4) do not lead to corresponding differences in steady state responses. Indeed, the sensitivity of the CCM symmetric base states, as shown in Fig. 19, is not appreciably different from the observed sensitivities in Fig. 18. Of course, some of the agreement is fortuitous since it masks compensation between the dynamical effect of errors in the zonal mean u and v wind components.

In view of the above results, the dramatic differences between sensitivities of the full wavy base states must originate in large part from errors in the CCMs' zonally asymmetric flow. Indeed, further calculations using the dynamical model suggest the important role of errors in the CCMs' zonally asymmetric zonal flow (not shown). These results suggest that the PNA sector response to equatorial Pacific forcing may be significantly distorted by errors in the CCMs' regional zonal flow (presumably over the Pacific sector). As noted in section 5.1, these errors include excessive equatorial central Pacific westerlies, and a northward displaced East Asian jet. The relative importance of these two biases has yet to be determined with certainty, but several additional calculations not shown here strongly suggest the importance of the CCMs' equatorial westerly wind bias. The situation for the GENESIS model is somewhat different. Note in Fig. 7 that the GENESIS model yields the best simulation for the 200 hPa zonal flow over the equatorial Pacific. However, it has significant meridional flow errors over the subtropical central Pacific (Fig. 10), which evidently play a major role in distorting the stationary wave response over the PNA region (see Fig. 15).

In summary, the linear one-level calculations have demonstrated that all the CCM climatological flows considered herein are more sensitive to equatorial Pacific forcing than observed. This stems in part from the CCMs' zonal mean westerly bias in tropical latitudes and, more importantly, from asymmetric zonal wind biases which are particularly large over the Pacific basin. The conclusions are not particularly dependent on our choice of the 200 hPa level; similar behavior is noted when the barotropic model is linearized about the 150 hPa and 300 hPa levels (not shown). Of course, the barotropic response to a mass source at a single level may not be an adequate proxy for the baroclinic response to a
vertically distributed heat source. For example, the vertical profiles of heating in the various CCM versions are known to differ (e.g., Hoerling et al. 1990), and this may be an important consideration when evaluating the sensitivities of a GCM's base state (Ting and Sardeshmukh 1993). Nonetheless, our purpose here is not to reproduce the full GCM sensitivity to ENSO-like forcing, as this would ultimately require integration of the GCM. Instead, the simple model analyses are designed to offer guidance on the possible dynamical importance of errors in the GCM's unperturbed climate and draw implications for sensitivity studies.

5.3 Dynamical link between CCM 200 hPa circulation biases

It was emphasized in section 5.1 that all CCM versions studied herein are plagued by excessive 200 hPa divergence over the tropical west Pacific and a westerly wind bias over the equatorial central Pacific. While analysis uncertainties due in part to sparse observations over the tropical Pacific make it difficult to quantify these errors with confidence, we are nonetheless interested to determine whether the model biases are dynamically linked. An additional systematic bias was noted in the CCM0 and CCM2 simulated eddy streamfunctions over the PNA region which resembled a large amplitude Rossby wavetrain of the type noted in numerous observational and modeling studies. The extent to which this bias is remotely linked to the tropics is also addressed in this section. Each of the remaining three CCM versions (CSCO2, CCM1, and GENESIS) exhibits different stationary wave biases over the PNA region, and their origins are not assessed in this study.

We use the T42 CCM2 version to illustrate the dynamical relationships between the aforementioned climate errors. Similar analyses have been done for CCM0 and the R15 CCM2 that are in agreement with the results shown below. For convenience, the estimated CCM2 eddy streamfunction and horizontal divergence errors at 200 hPa are repeated in Figs. 20 and 21, respectively. The top (bottom) panels illustrate differences computed relative to NMC (ECMWF) analyses.

We first determine the degree to which the "error" vorticity budget is balanced at 200 hPa using the linear barotropic model. The divergence differences in Fig. 21 are treated as forcings and are imposed on the observed full wavy climatological flow. In all these calculations, the zonal mean divergence is first removed in each latitude band. The resulting divergence patterns differ only slightly from those in Fig. 21. Recall from section 4 that this is not a complete statement of the steady linear vorticity balance, having ignored the errors in transients, vertical advection, tilting, and also the impact of errors in the zonal
mean zonal flow. Nonetheless, many of the qualitative features of the CCM2 eddy streamfunction error are reproduced in the linear model forced by the divergence differences between 25°S-60°N\(^1\) (compare Fig. 22 and Fig. 20). In particular, the negative phase of the PNA error pattern is well reproduced as are the tropical Pacific cyclonic circulation errors. Several other features of the linear response, particularly over North Africa and southeast Asia, have no counterparts in the CCM2 eddy streamfunction error. Even where the phase of the linear response agrees with that in Fig. 20, considerably less agreement is noted in the amplitude. In this regard, however, it is important to note the large differences in amplitudes between responses to the NMC- and ECMWF-derived divergence errors. These indicate the dynamical significance of uncertainties in climatological estimates of the 200 hPa divergence. The ECMWF-derived divergence errors excite a response that is in closer agreement with the amplitude of the CCM2 stationary wave biases, although this may be fortuitous in view of the aforementioned omissions in the vorticity budget.

Figure 23 shows the eddy streamfunction predicted by the barotropic model when forced with the divergence errors between 25°S-25°N only. Nearly all features noted in the previous figure are still present, although with reduced amplitude. Note particularly that the reverse PNA-type pattern is effectively forced by the tropical divergence errors alone. We have further isolated the source of this response as being due to tropical Pacific sector forcing, as demonstrated in Fig. 24 where the tropical forcing consists of the divergence errors between 110°E and 90°W only.

A further decomposition of the tropical Pacific divergence forcing is performed in order to determine the role of errors north and south of the equator separately. Such a decomposition is clearly artificial in that the excessive divergence over New Guinea is undoubtedly related to suppressed convection and convergence north of the equator due to local Hadley-type overturning. Nonetheless, it is instructive to assess the direct dynamical effect of each feature individually. Figure 25 shows the steady linear response to tropical Pacific divergence forcing located approximately between 25°S and the equator (the divergence forcing extends slightly into the NH so as to incorporate the entire region of excessive divergence over the west Pacific). The response reproduces much of the tropical pattern seen in Fig. 24 including the on-equatorial westerlies over the central Pacific. We

\(^1\)The divergence differences north of 60°N are excessively noisy and have been excluded. As we are interested in the PNA sector response, we have omitted divergence differences south of 25°S, and these have negligible impact on the NH response.
have repeated this particular experiment using the divergence errors derived from the other five CCM versions, and for each case we find an on-equatorial westerly response that is in qualitative accord with the CCM zonal wind bias. Common features of the CCM divergence errors found to be important in forcing this response are the excessive divergence centered over New Guinea and the absence of divergence over the region of the SPCZ.

In contrast, the extratropical response including the reverse PNA pattern is excited primarily by the divergence errors in the northern tropics (Fig. 26). Note that the wavetrain appears to originate from the tropical western Pacific, where a large-scale upper level convergence error in the CCM2 is associated with a pronounced lack of rainfall over the Micronesian region. Indeed, forcing from this sector alone (110°E-180°W) excites a significant portion of the reverse PNA-type response (Fig. 27). This result is consistent with several earlier studies (e.g., Simmons et al. 1983) that demonstrate a large sensitivity of the extratropical stationary waves to forcing from the tropical west Pacific.

6. Concluding Remarks

Our diagnosis of a wide class of NCAR CCMs developed over the past 10 years has, on the one hand, revealed several improvements in the model's wintertime 200 hPa climate, particularly the zonally averaged zonal flow over the northern extratropics. This has been associated with a substantial improvement in the zonal mean thermodynamic structure of the most recent CCM2 version, as shown in Hurrell et al. (1993). On the other hand, we noted a stubborn persistence of several climate biases, despite drastic revisions in CCM physics and architecture during the past decade. The most recurring 200 hPa circulation biases include a zonal mean westerly bias in the tropics, excessive divergence over the tropical west Pacific, and a large equatorial westerly bias over the central Pacific. In the extratropics, the model's East Asian jet is too contracted and is shifted north of the observed climatological position.

A series of steady linear calculations was performed to provide insight on the relative importance of various CCM biases most frequently of concern to the atmospheric modeler and diagnostician, such as in the zonally symmetric and asymmetric winds. The CCM climatological flows were considerably more sensitive to forcing located in tropical latitudes than the observed flow, a difference attributable to the CCMs' tropical westerly wind error.

Possible origins of CCM circulation biases were also sought. When forcing a linear barotropic model with the CCM2 200 hPa divergence errors, a qualitative agreement
was found between the linear model's eddy streamfunction response and CCM2's stationary wave error in both tropical and NH extratropical latitudes. To the extent that the rotational flow evolves in response to convective forcing, the results are quite suggestive of the local and remote influence of errors in simulating convection over the Indonesian monsoon region.

The sensitivity studies were conducted with two practical purposes in mind. First, the simple model experiments are intended to provide guidance in interpreting the veracity of the CCM, particularly where tropical-midlatitude interactions are important. To the extent that the CCM derived datasets are used as proxies for understanding nature, the limitations of the model must be carefully considered. Of course, our steady linear diagnoses represent only a partial assessment of the CCM's overall fidelity. It is quite clear, for example, that the extratropical response to tropical forcing is more complicated than just the barotropic dispersion of energy from a steady tropical source and sink. There are also numerous other perturbations of importance operating in the climate system, and the CCM's sensitivity to these has not been treated herein.

Second, the dynamical relation between CCM circulation errors, as measured with the aid of the barotropic model, provides some clue about possible causes for model failure. The task of model development is becoming increasingly difficult due to the intimate coupling between numerous physical parameterizations. A statement such as "The simulated extratropical stationary waves are too weak," while helpful to a model user, is of little assistance to the model developer owing to multiple possible causes. However, the suggestion that a spurious extratropical stationary wave may be excited by spurious tropical convection as provided herein, offers the hope for more immediately curing the model deficiency. It is with this intent that the experiments in section 5.3 were conducted, and we hope they provide useful information to developers of future NCAR CCMs. Even here the situation is complicated by the fact that uncertainty remains as to whether errors reside in the convective scheme itself or in the inputs (e.g., temperature and moisture) to that scheme. Further experimentation using baroclinic models or the full GCM will be required to sort out these issues.
References


7. Circulation Statistics
Fig. 2. Observed climatological DJF zonally averaged zonal wind (top) and zonally averaged meridional wind (bottom) at 200 hPa. Units are m s\(^{-1}\).
Fig. 3. NCAR CCM simulated climatological DJF zonally averaged zonal wind at 200 hPa overlaid with the same field from NMC observations. Units are m s$^{-1}$. 
Fig. 4. NCAR CCM simulated climatological DJF zonally averaged meridional wind at 200 hPa overlaid with the same field from NMC observations. Units are m s$^{-1}$. 

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Fig. 5. Observed climatological DJF zonal wind at 200 hPa. Difference of middle and top panels is shown in lower panel. Contour interval is 5 m s\(^{-1}\).
Fig. 6. NCAR CCM simulated climatological DJF zonal wind at 200 hPa.
Contour interval is 5 m s$^{-1}$. 
Fig. 6. (cont.)
Fig. 7. Difference field (CCM - NMC) of climatological DJF zonal wind at 200 hPa. Contour interval is 5 m s$^{-1}$. 
CCM1 R15 - NMC

GENESIS R15 - NMC

Fig. 7. (cont.)
Fig. 7. (cont.)
Fig. 8. Observed climatological DJF eddy streamfunction at 200 hPa. Difference of middle and top panels is shown in lower panel. Contour interval is $5 \times 10^6$ m$^2$ s$^{-1}$ for top and middle panels, $2 \times 10^6$ m$^2$ s$^{-1}$ for bottom panel.
Fig. 9. NCAR CCM simulated climatological DJF eddy streamfunction at 200 hPa. Contour interval is $5 \times 10^6 \text{ m}^2 \text{s}^{-1}$.
Fig. 9. (cont.)
Fig. 9. (cont.)
Fig. 10. Difference field (CCM - NMC) of climatological DJF eddy streamfunction at 200 hPa. Contour interval is $2 \times 10^6$ m$^2$ s$^{-1}$. 
Fig. 10. (cont.)
Fig. 10. (cont.)
Fig. 11. Observed climatological DJF divergence at 200 hPa. Difference of middle and top panels is shown in lower panel. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 
Fig. 12. NCAR CCM simulated climatological DJF divergence at 200 hPa. Contour interval is 1x10^{-6} s^{-1}.
Fig. 12. (cont.)
Fig. 13. Difference field (CCM - NMC) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 
Fig. 13. (cont.)
Fig. 13. (cont.)
8. Dynamical Model Experiments
Fig. 14. Eddy streamfunction predicted by the barotropic model when forced with idealized divergence pattern in Fig. 1. The left (right) panel shows the response of NMC (ECMWF) full wavy base state. Contour interval is $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$. 
Fig. 15. Eddy streamfunction predicted by the barotropic model when forced with idealized divergence pattern in Fig. 1. The individual panels show the responses of CCM full wavy base states. Contour interval is $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$. 
Fig. 15. (cont.)
RESPONSE OF CCM2 (R15) BASE STATE \[<U>+U^*,<V>+V^*]\]

RESPONSE OF CCM2 (T42) BASE STATE \[<U>+U^*,<V>+V^*]\]

Fig. 15. (cont.)
Fig. 16. Eddy streamfunction predicted by the barotropic model when forced with idealized divergence pattern in Fig. 1. The left (right) panel shows the response of NMC (ECMWF) base state consisting of zonal mean $U$. Contour interval $2 \times 10^6 \, m^2 \, s^{-1}$. 
Fig. 17. Eddy streamfunction predicted by the barotropic model when forced with idealized divergence pattern in Fig. 1. The individual panels show the responses of CCM base states consisting of zonal mean U. Contour interval is $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$. 
RESPONSE OF CCM1 BASE STATE \[<U>\]

RESPONSE OF GENESIS BASE STATE \[<U>\]

Fig. 17. (cont.)
Fig. 17. (cont.)
Fig. 18. Eddy streamfunction predicted by the barotropic model when forced with idealized divergence pattern in Fig. 1. The left (right) panel shows the response of NMC (ECMWF) base state consisting of zonal mean U and zonal mean V. Contour interval is $2 \times 10^6$ m$^2$ s$^{-1}$. 
Fig. 19. Eddy streamfunction predicted by the barotropic model when forced with idealized divergence pattern in Fig. 1. The individual panels show the responses of CCM base states consisting of zonal mean U and zonal mean V. Contour interval is $2 \times 10^6 \text{ m}^2 \text{s}^{-1}$. 
Fig. 19. (cont.)
Fig. 19. (cont.)
Fig. 20. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF eddy streamfunction at 200 hPa. Contour interval is $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$. 
Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

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Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$. 

Fig. 21. Difference field CCM2 T42 minus NMC (top) and CCM2 T42 minus ECMWF (bottom) of climatological DJF divergence at 200 hPa. Contour interval is $1 \times 10^{-6}$ s$^{-1}$.
Fig. 22. Eddy streamfunction predicted by the barotropic model when forced by CCM2 minus NMC (top) and CCM2 minus ECMWF (bottom) 200 hPa DJF divergence between 25°S-60°N. Model linearized about NMC's DJF full wavy base state. Contour interval is $2 \times 10^6$ m$^2$ s$^{-1}$.
Fig. 23. Eddy streamfunction predicted by the barotropic model when forced by CCM2 minus NMC (top) and CCM2 minus ECMWF (bottom) 200 hPa DJF divergence between 25°S-25°N. Model linearized about NMC's DJF full wavy base state. Contour interval is $2 \times 10^6 \, \text{m}^2 \, \text{s}^{-1}$. 
Fig. 24. Eddy streamfunction predicted by the barotropic model when forced by CCM2 minus NMC (top) and CCM2 minus ECMWF (bottom) 200 hPa DJF divergence between 25°S-25°N for the Pacific sector (110°E to 90°W) only. Model linearized about NMC's DJF full wavy base state. Contour interval is $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$. 
Fig. 25. Eddy streamfunction predicted by the barotropic model when forced by CCM2 minus NMC (top) and CCM2 minus ECMWF (bottom) 200 hPa DJF divergence between 25°S-equator for the Pacific sector (110°E to 90°W) only. Model linearized about NMC's DJF full wavy base state. Contour interval 2x10^6 m^2 s^{-1}.
Fig. 26. Eddy streamfunction predicted by the barotropic model when forced by CCM2 minus NMC (top) and CCM2 minus ECMWF (bottom) 200 hPa DJF divergence between equator-25°N for the Pacific sector (110°E to 90°W) only. Model linearized about NMC’s DJF full wavy base state. Contour interval $2 \times 10^6$ m$^2$ s$^{-1}$. 
Fig. 27. Eddy streamfunction predicted by the barotropic model when forced by CCM2 minus NMC (top) and CCM2 minus ECMWF (bottom) 200 hPa DJF divergence between equator-25°N for the west Pacific sector (110°E to 180°W) only. Model linearized about NMC's DJF full wavy base state. Contour interval $2 \times 10^6$ m$^2$ s$^{-1}$. 