Chapter 1

Introduction

My soul is full of longing
For the secret of the sea,
And the heart of the great ocean
Sends a thrilling pulse through me.

Longfellow, *The Secret of the Sea*

1.1 Motivation

1.1.1 The big picture

Oceanography and meteorology would be rather dull were it not for two simple facts: the earth spins and is illuminated by the sun. These transform what could have been a quiet rock into one whose oceans and atmosphere are rich in structure, and alive with currents, waves and eddies spanning from the microscopic to the global and from seconds to millennia.

Knowing only this, a distant observer of earth would likely point out the equator as a region of special interest, since it receives the most sunlight per orbit, and is the only place on the globe where the vertical component of rotation changes sign. If the observer could see the configuration of earth's continents, he might also infer that the Pacific Ocean, which covers a third of the global surface, would be a major player in earth's climate. The tropical Pacific would seem a prime target for further study.

We residents of earth came to this conclusion less directly. Confined to the continents, we farmed the land and fished the coastal seas, growing accustomed to the march of the seasons and to local differences in winds, temperature and rainfall. When the usual climate patterns were disrupted, the impact on society was often devastating. We then yearned to understand and predict these strange fluctuations using the tools of science. As observations accrued and theory and simulations advanced, our perspective finally became that of the distant observer. We now realize that something very big indeed is happening in the tropical Pacific.

1.1.2 The importance of ENSO for climate and society

A key to global climate

The El Niño/Southern Oscillation (ENSO) is now recognized as earth's dominant climate fluctuation on interannual time scales (Anderson et al., 1998). The warm phase of ENSO, which appears irregularly every two to ten years, is associated with warming of the eastern and central tropical Pacific and a weakening of the easterly trade winds. The shift of strong convection from the western Pacific into the central Pacific also reorganizes atmospheric flows on a global scale, bringing floods to Peru, droughts and fires to Australia and Indonesia, changes in weather over the United States, and worldwide changes in agricultural productivity. The weakening of the trade winds also shuts down upwelling in the eastern equatorial Pacific, reducing the inflow of nutrients from the deep. This inhibits the growth of marine microorganisms, which propagates up the food chain to affect ecosystems, fisheries, and economies along the western coast of South America. ENSO is not a new phenomenon; coral records indicate that it is over a hundred thousand years old (Tudhope et al., 2001). It thus appears that understanding ENSO is key to understanding global climate.

Hope for long-term forecasts

Since Lorenz (1963) showed that the evolution of deterministic, turbulent systems can be sensitive to initial conditions, there has been a fair amount of pessimism regarding long-term forecasts of day-to-day weather at specific locations. Such "predictions of the first kind" (Lorenz, 1975) attempt to foretell the precise chronological order in which atmospheric states will occur. Unfortunately, stretching and stirring by weather systems rapidly amplifies initial uncertainties in the state of the atmosphere, so that useful information is rapidly lost, i.e., the set of possible atmospheric states consistent with the initial conditions soon becomes indistinguishable from the climatological set of weather states. Weather-stirring is so vigorous in the atmosphere that it appears useful forecasts of day-to-day weather may be limited to two weeks or less (AMS Council, 2001).

Climate forecasts, on the other hand, are "predictions of the second kind," which aim to foretell the large-scale and long-term *statistics* of events but not their precise chronological order. Such forecasts depend less on the uncertainty of the initial state and more on the evolution of boundary conditions like sea surface temperature (SST), which are controlled by slowly-evolving components of the climate system. Fortunately, a substantial part of the global atmospheric circulation appears to be in equilibrium with tropical heating. Since this heating is modulated by slowly-evolving processes like ENSO, there is great hope for seasonal-to-interannual prediction of climate anomalies if phenomena like ENSO can be properly simulated (Barnston et al., 1994; Goddard et al., 2001).

The ability to forecast climate several seasons in advance would be of enormous benefit to society. Farmers could plant the crops best suited to the predicted rainfall. Fishermen could target regions where ocean temperatures and plankton blooms promised an abundant catch. Governments and insurers could prepare ahead of time for droughts and floods.

Such predictions have been realized with some success since 1987, when Cane et al. (1986) issued the first experimental forecasts of ENSO using a fairly simple ocean-atmosphere model. Since then, ever more complex models, including comprehensive general circulation models (GCMs) and sophisticated statistical models, have been employed for operational seasonal prediction (Latif et al., 1998). The growth of this seasonal forecasting capability has gone hand-in-hand with the deployment of more comprehensive and accurate observing systems (McPhaden et al., 1998), and the continued development of more realistic coupled GCMs (Delecluse et al., 1998).

1.1.3 The modeling challenge

Why ENSO is difficult to simulate

Despite recent progress, El Niño has proved devilishly hard to simulate and forecast. There are many reasons this is so. First, ENSO is a fundamentally *coupled* ocean-atmosphere phenomenon. Coupled air-sea interactions are partly a blessing, since they lend seasonal predictability to the atmosphere. But they are also a curse, since coupled feedbacks make the climate system highly sensitive to errors in the formulation of a forecast model. Current coupled GCMs have trouble maintaining realistic climatologies beyond a year or so; this "climate drift" arises from inadequate resolution, incomplete model physics, or mis-tuned parameterizations and can be very difficult to diagnose and fix given the complexity and computational cost of most GCMs. As will be shown in this thesis, misrepresentation of the time-mean state can then affect the simulation of ENSO.

A second reason that ENSO is difficult to model is that it involves a very wide range of spatial and temporal scales. Processes important to ENSO occur throughout the tropical Pacific, so a model must encompass at least this region. To the extent that extratropical weather or the globe-circling Madden-Julian Oscillation (MJO) trigger ENSO events, a fully global model may even be required. The model must then run for years (to forecast a single event) or even many decades (to characterize long-term statistics). With present computational resources, such large-scale models cannot adequately resolve many important processes that occur at small scales, including mixing, surface heat fluxes, and cloud formation. Such processes must be parameterized in terms of the large-scale fields, and uncertainties in these parameterizations can lead to problems in simulating the tropical climatology and ENSO variability.

A third reason El Niño is so difficult to describe, understand and model is its irregularity in time. Although many robust features of ENSO have been identified (Rasmusson and Carpenter, 1982; Harrison and Larkin, 1998), no two events look alike, and the time between events can vary from 2 to 10 years. The behavior of the phenomenon also seems to change from decade to decade (Gu and Philander, 1995; Wang and Wang, 1996; Torrence and Compo, 1999; Torrence and Webster, 1998, 1999). It is therefore unclear just what ENSO is: a linear mode modulated by climate change, a chaotic system, a series of stochastic events, or some combination of these? This uncertainty has in turn led to disagreements over just what constitutes a good model of the system and how to approach the forecast problem.

Forecast surprises

The difficulty of simulating ENSO has been revealed by several forecast surprises over the past few decades. In 1982, forecasters were caught completely off guard by a severe El Niño that wreaked havoc with ecosystems and economies worldwide. This spurred a decade of intense research into ENSO and led to the development of sophisticated monitoring and forecasting systems. While many of the new models were successful at "hindcasting" the 1982–1983 warm event and showed good skill for the rest of the 1980s, they began having trouble in the early 1990s when an unusual sustained series of warm events occurred. These secular changes in forecast skill have now been documented in several models (Kerr, 1993; Latif et al., 1998; Kirtman and Schopf, 1998) and have confounded researchers for more than a decade.

With further development, many models did anticipate the strong 1997 warm event (Barnston et al., 1999a,b), but none successfully forecast its unusually rapid onset, severity, and sudden demise (Landsea and Knaff, 2000). For this event and its aftermath, most state-of-the-art models failed to achieve even a modest standard of forecast skill (Kerr, 2000b; Landsea and Knaff, 2000). Fig. 1.1 shows the skill of operational forecasts of the 1997–98 event, relative to that of a simple statistical model called ENSO-CLIPER (Knaff and Landsea, 1997) which is based on historical data. No model, statistical or dynamical, was able to exceed this benchmark of skill at forecast lead times of two seasons or less. At longer leads, some of the predictions outperformed ENSO-CLIPER, but by that time their absolute errors were so large that they would have been of little use to forecasters (Landsea and Knaff, 2000).

ENSO differences among coupled GCMs

Given these recent forecast surprises, it is clear there is still room for improvement in the models used to forecast ENSO. A useful initial exercise is to compare different simulations and look for relative strengths and weaknesses. From the efforts now underway (Latif et al., 2001; AchutaRao and Sperber, 2002; Davey et al., 2002) it has become apparent that there is a wide variety of ENSO simulations in different models, and that no single coupled model affords a completely realistic simulation compared to observations (Figs. 1.2–1.3).

Although every model is different, most models tend to simulate ENSO SST variability that is too weak, too variable in the western Pacific and not variable enough along the eastern boundary, has too short a period, is too regular in time, and is too weakly phase-locked to the annual cycle compared to the observations. Interannual fluctuations of GCM wind stresses are generally weaker than observed (Davey et al., 2002) and simulated SSTAs and SOIs are less correlated than observed (AchutaRao and Sperber, 2002), suggesting that the simulated atmospheres are either too weakly coupled to SST or have too little internal variability. The zonal propagation of SST anomalies can also differ from observed; this is especially the case in models with coarse oceanic resolution, where SSTAs tend to propagate westward instead of developing in place like most observed events (Latif et al., 2001).

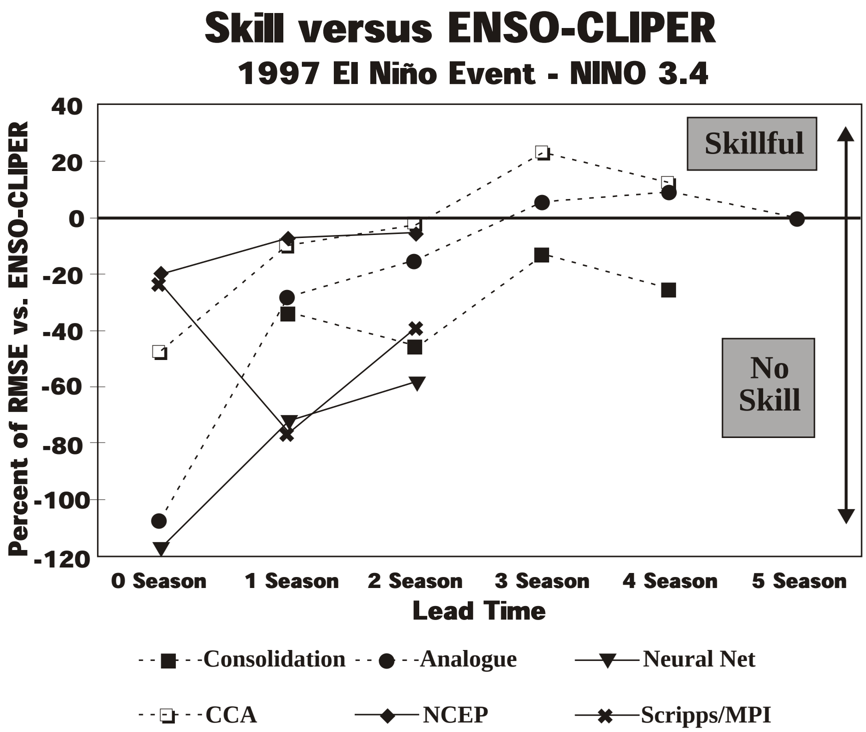

Figure 1.1: Skill assessment of operational SST anomaly forecasts of the 1997–98 warm event and its aftermath. ENSO-CLIPER, a simple statistical model, provides the benchmark of skill. Denoting the root-mean-square error relative to observations as RMSE, the relative forecast skill of a given model at a given forecast lead time is plotted as [1-RMSE(model)/RMSE(ENSO-CLIPER)] $\times$ 100%. Panel shows the relative skill of SST anomaly forecasts for the NINO3.4 region (170°W–120°W, 5°S–5°N) from four statistical models (Consolidation, CCA, Analogue, Neural Net) and three dynamical models (NCEP, Scripps/MPI). From Enfield (2001) based on Landsea and Knaff (2000).

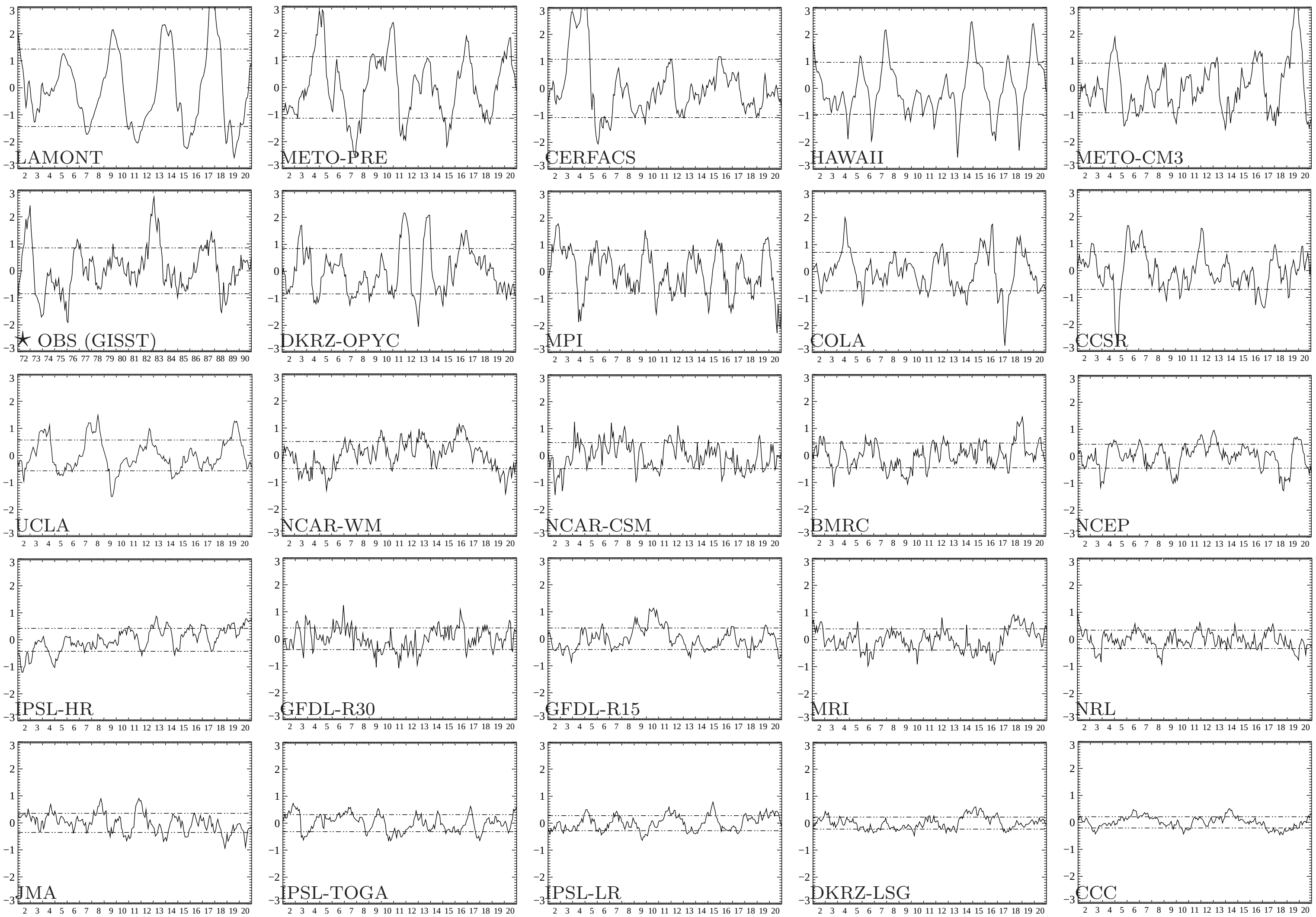

Figure 1.2: 19-year timeseries of NINO3 SST anomalies, sorted by standard deviation (dashed lines), from GISST observations (starred) and 24 coupled models. Adapted from Davey et al. (2000, 2002).

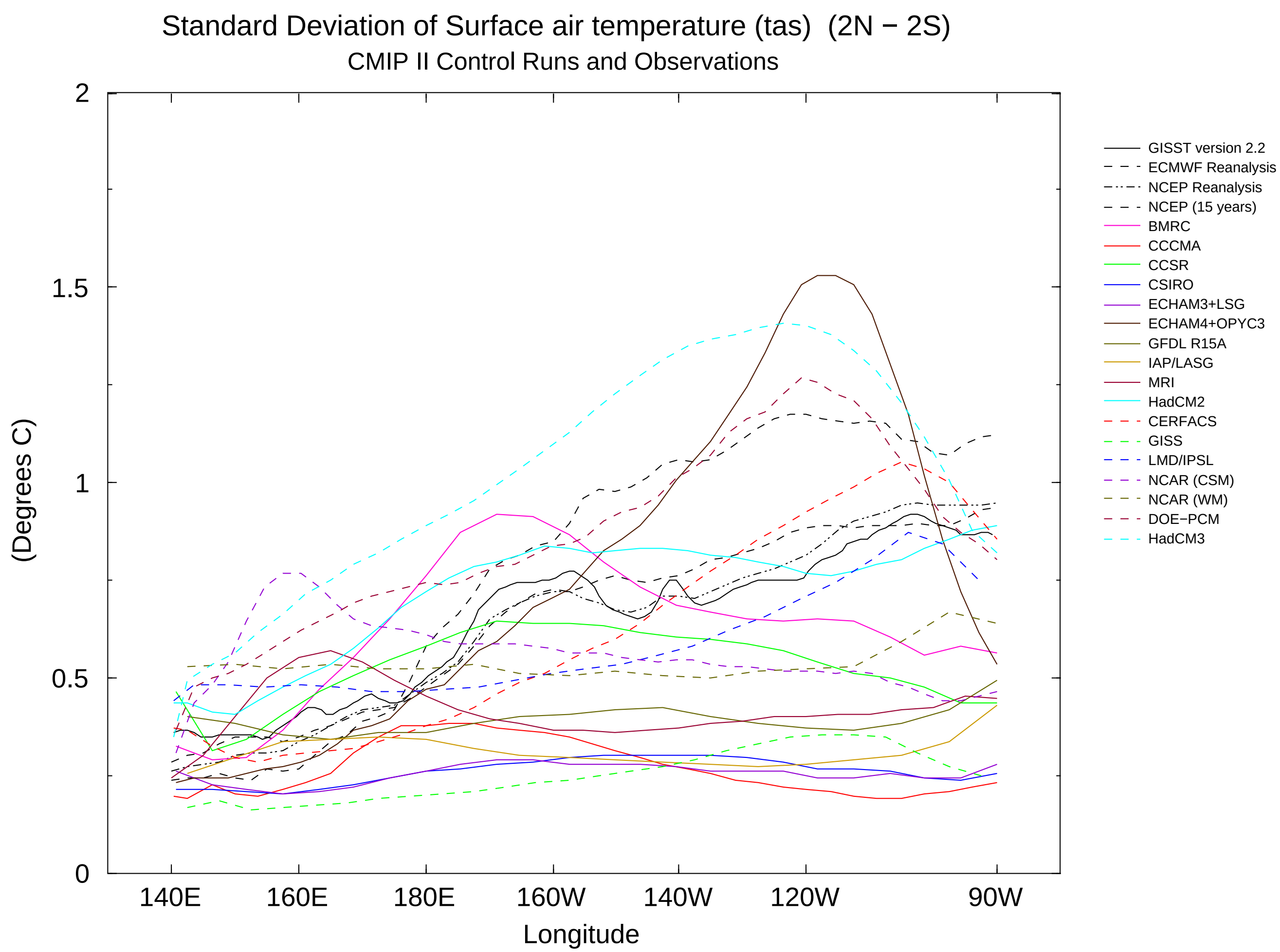

Figure 1.3: Standard deviation of tropical Pacific surface air temperature anomalies, averaged over 2°S–2°N, from the CMIP simulations. SSTs from the NCEP, ECMWF, and GISST reanalyses are shown for reference. From AchutaRao and Sperber (2002).

A role for the climatology?

That simulated ENSOs differ from each other and from reality may have partly to do with the climatological background, since there are clear differences among the climatologies of coupled models (Fig. 1.4; Mechoso et al., 1995; Latif et al., 2001; AchutaRao and Sperber, 2002; Davey et al., 2002). The majority of models tend to have a climatological cold bias in the equatorial central Pacific, a cold tongue that is too meridionally narrow, a warm bias along the western coast of South America, and an unrealistic "double ITCZ" straddling the equator. Although the climatological zonal gradient of SST is often as strong as observed, most models exhibit a mean tradewind stress that is too weak and shifted westward relative to the observations.

In addition to wind stress errors, many atmospheric GCMs also misrepresent the surface heat fluxes. This is largely due to errors in cloudiness (Kleeman et al., 2001), most notably off the coast of South America. Such errors tend to be amplified and redistributed in the coupled context, making them difficult to attribute specifically to the ocean model or the atmosphere model. Faced with two coupled models that give different simulations, sometimes the only recourse is to systematically eliminate differences between models until the sources of disparity are understood (Schneider, 2002).

Intercomparisons of coupled GCMs indicate suggestive, though not conclusive, evidence for climatological controls on ENSO. In an early study, Neelin et al. (1992) found that models with weak climatological cold tongues tended not to have strong interannual oscillations, although the evidence for climatological controls of ENSO was not very strong due to major differences in grid resolutions and physical parameterizations among the models. Meehl et al. (2001a) examined the behavior of 10 closely-related CGCMs of varying resolutions and vertical diffusivities. They found that the models with the weakest diffusivities had not only the sharpest mean thermoclines but also the strongest ENSO variability, especially in the east Pacific. Models with strong trades, furthermore, tended to have stronger zonal thermocline slopes, stronger zonal temperature contrasts, and stronger ENSO variability. Pontaud et al. (2000) compared the climatologies and ENSO simulations of four coupled GCMs in detail, and found large differences in the position and strength of equatorial mean upwelling in the models, as well as substantial differences in the spatial structure of interannual SSTAs. Models with the strongest cold tongues again appeared to support the strongest ENSO variability. The authors attempted to explain the ENSO amplitude differences with regard to the dominant terms in the mixed layer energy budget and their relation to the mean state; although their analysis was limited, it showed promise as a new way of understanding the ENSO differences among models.

Thus there appear to be some systematic links between the climatology and ENSO behavior among different GCMs. This suggests two competing hypotheses: (1) the climatology and ENSO do not interact, but instead are both controlled by a third factor such as the air-sea coupling strength; or (2) the coupling and other parameters affect the climatology, which then directly affects ENSO. It has proved difficult to falsify either hypothesis simply by intercomparing models, since the influence of climate is obscured by other major differences such as vertical and horizontal resolution, atmospheric convection, oceanic mixing, and the presence or absence of flux adjustments. To truly understand the influence of climate on ENSO, it seems that a targeted suite of sensitivity experiments in

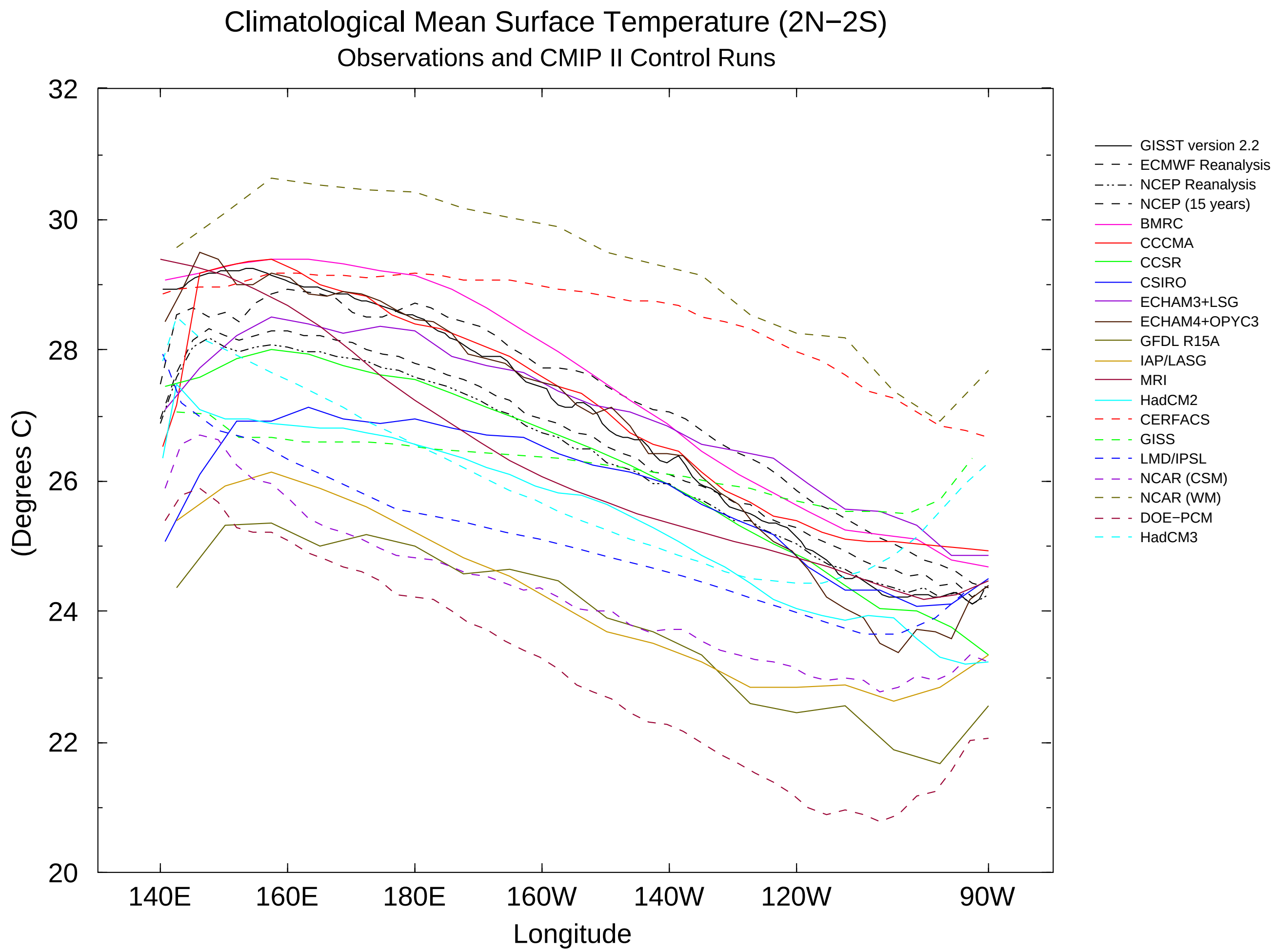

Figure 1.4: Annual-mean tropical Pacific surface air temperature, averaged over 2°S–2°N, from the CMIP simulations. SSTs from the NCEP, ECMWF, and GISST reanalyses are shown for reference. From AchutaRao and Sperber (2002); see also Fig. 1 of Latif et al. (2001).

a single model is required. This is the first key motivation for the present study.

1.1.4 Nature of the historical record

A natural place to look for climatological controls of ENSO is in historical data. Fig. 1.5a shows a timeseries of SST anomalies in the eastern equatorial Pacific from 1860–2001. Clearly the behavior of ENSO has varied substantially over the past 140 years. Interannual oscillations are strong from 1875–1930, weaker from 1930–60, and then grow stronger after 1960. The return period between events appears to be relatively long from 1875–95, shorter from 1895–1907, sporadic between 1907-60, short from 1960–77, and longer after 1980. Although most of the strongest warm and cold events peak around the end of the calendar year, the 1941 and 1987 warm events are notable exceptions. It also appears that SST in the equatorial eastern Pacific varies on decadal and longer time scales: it was relatively warm from the 1890s to the 1940s, then cooler through the 1950s and 1960s, warmed abruptly around 1976, and has since remained fairly warm.

The interdecadal changes and ENSO changes noted above have been documented in numerous datasets (see Wallace et al. (1998) for a review). The lack of data prior to 1960 and especially before 1920 (Fig. 1.5b) is problematic for detecting these changes, since it is often hard to tell whether an apparent change is real or simply an artifact of sampling error. Independent evidence from corals, however, appears to corroborate the strong decadal variability prior to 1920, and the weak and irregular ENSO behavior of the 1930s and 1940s (Urban et al., 2000). Taking Fig. 1.5a at face value, it seems that decadal connections between the slowly-evolving background state and ENSO irregularity may be subtle, and that chaos or random forcing probably play a role as well.

1.1.5 Recent changes in the background state

The interdecadal climate variability evident in Fig. 1.5a has received much attention in recent years, including two books (National Research Council, 1995; Navarra, 1999) and a workshop (Mehta et al., 2000). These studies are strongly motivated by the need to understand natural variations as a backdrop for possible human-caused climate changes. This section reviews what is known about tropical Pacific decadal variability, since (1) it provides a context for understanding and interpreting the observed changes in ENSO, and (2) it suggests how the climate-perturbation experiments in later chapters should proceed.

Over the past 50 years, the trade winds, meridional overturning circulation, and east-west thermocline slope in the equatorial Pacific appear to have weakened, in tandem with a warming of the eastern equatorial Pacific despite decreased surface heat flux entering the ocean (Curtis and Hastenrath, 1999; Chao et al., 2000; Kerr, 2000a; Levitus et al., 2000; Liu and Huang, 2000; Casey and Cornillon, 2001; Huang and Liu, 2001; McPhaden and Zhang, 2002). There is also evidence for an eastward shift of the Pacific trade winds (Curtis and Hastenrath, 1999), although as will be shown in Chapter 2 this conclusion depends on the wind dataset used. One must always keep in mind that nonstationarities of the observing system and measurement techniques have been linked to spurious trends and shifts in the data (Wright, 1988; Posmentier et al., 1989; Clarke and Lebedev, 1996, 1997; Harrison and Larkin, 1997; Huang and Liu, 2001).

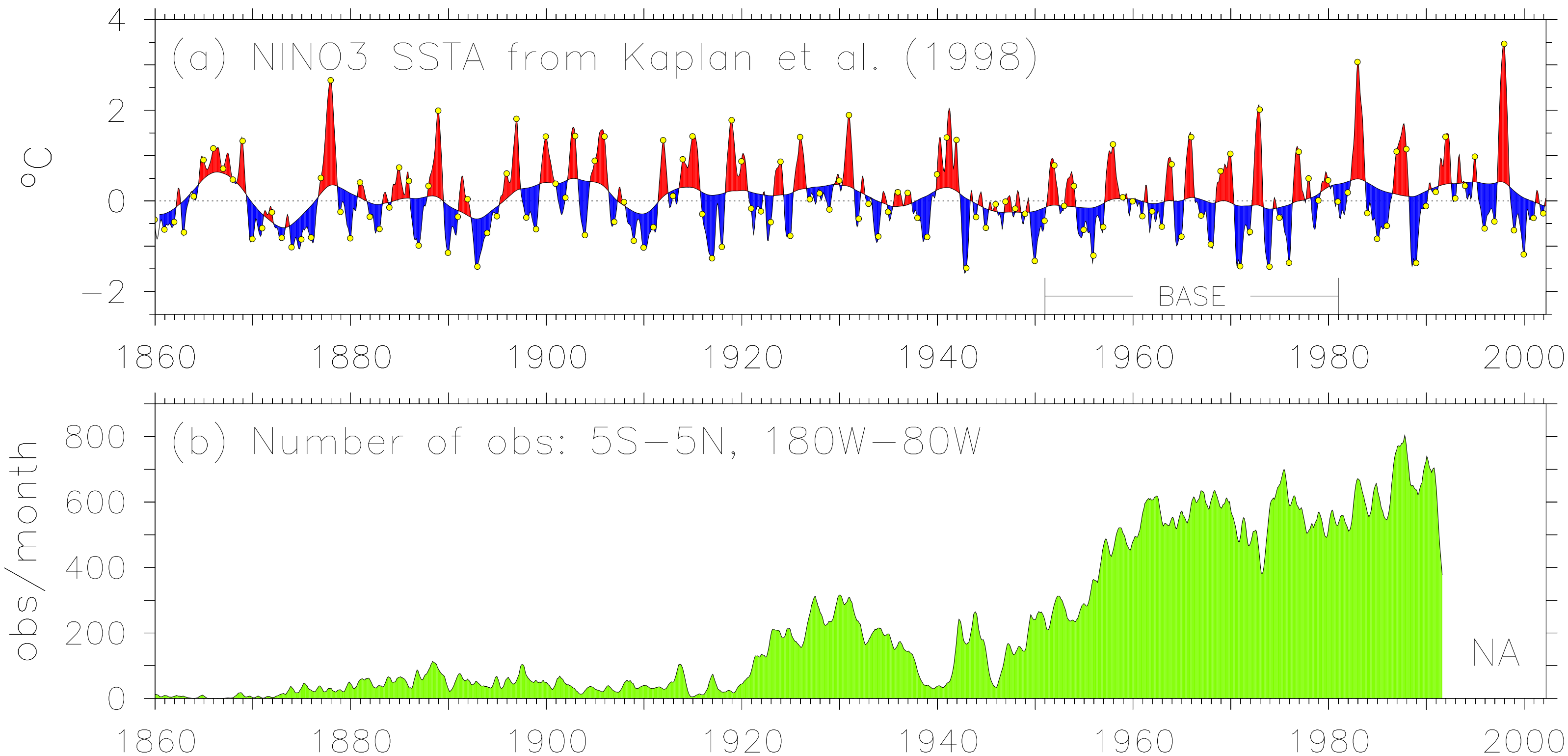

Figure 1.5: (a) SST anomalies with respect to 1951-1980. Data from 1856-1981 are reconstructed by reduced space optimal smoothing (Kaplan et al., 1998); data after 1981 are obtained by projection of the optimal interpolation analysis of Reynolds and Smith (1994) onto the reduced space of the earlier period. The data have then been low-pass filtered with half-power points at 0.5 and 10 yr. White dots are December values. (b) Number of observations per month used in the Kaplan et al. (1998) reconstruction, east of the dateline between 5°S–5°N (low-pass filtered with a cutoff at 1 yr).

Many patterns of recent decadal variability have been described which include signatures in the tropical Pacific (Kleeman et al., 1996; Kachi and Nitta, 1997; White and Cayan, 1998; Kerr, 1999a; Zhang et al., 1999; Giese and Carton, 1999; Goswami and Thomas, 2000; Tourre et al., 2001; Tomita et al., 2001; Mestas-Nuñez and Enfield, 2001). Spectral analyses indicate that interdecadal variations in Pacific climate are prevalent throughout the historical record (Mann and Park, 1994; Zhang et al., 1998; Moron et al., 1998; Lau and Weng, 1999; Tourre et al., 2001), and proxy data provide evidence of decadal variability as far back as the seventeenth century (Dunbar et al., 1994; Linsley et al., 2000; D'Arrigo et al., 2001). These decadal and interdecadal variations are stronger than the longer-term (centennial) trends over the observed record (Enfield and Mestas-Nuñez, 1999). The decadal changes often resemble abrupt shifts (Chao et al., 2000). One such shift evident in multiple atmospheric and oceanic fields, which some have argued is part of an ongoing "Pacific Decadal Oscillation" or PDO, occurred around 1976–77 and included a warming of the east Pacific that occurred nearly simultaneously with changes in the North Pacific (Graham, 1994; Trenberth and Hurrell, 1994; Talley, 1995; Zhang, 1998; Zhang and Liu, 1999; Liu and Zhang, 1999; Barnett et al., 1999; D'Arrigo et al., 2001; Stephens et al., 2001; Giese et al., 2002). The tropical radiative budget also appears to vary on decadal timescales: the 1990s saw a sharp increase in outgoing longwave radiation (OLR) and a smaller decrease in shortwave reflection, ostensibly due to altered cloudiness associated with a possible recent strengthening of the Hadley and Walker circulations (Hartmann, 2002; Chen et al., 2002; Wielicki et al., 2002). Interestingly, these very large changes in the tropical radiative balance appear to have occurred without correspondingly large changes in average tropical SST.

Whether these decadal changes interact with or can be attributed to ENSO is unknown. Some studies argue that the tropical signatures of the decadal patterns arise from mechanisms distinct from ENSO (Graham, 1994), while others suggest they may derive from random fluctuations in ENSO itself or mechanisms similar to ENSO (Zhang et al., 1997). Tropical decadal modes with differing mechanisms have been simulated in coupled climate models (Latif, 1998). In some models (Knutson and Manabe, 1998; Jin, 2000; Yukimoto et al., 2000) the decadal variability resembles ENSO, both in its spatial pattern and in its evolution by delayed-oscillator/recharge mechanisms that depend on slow oceanic adjustment via off-equatorial Rossby waves. In others (Vimont et al., 2002), the spatial patterns of variability resemble ENSO but events decay by surface heat fluxes rather than equatorial recharge.

Others have argued that interactions between the tropics and extratropics may give rise to interdecadal variability. One hypothesis (Gu and Philander, 1997) is that temperature anomalies subducted into the midlatitude pycnocline propagate slowly toward the equator, affecting the structure of the equatorial thermocline roughly a decade later. Although many observational and modeling studies support this "oceanic bridge" (Zhang et al., 1998, 1999, 2001b; Johnson and McPhaden, 1999; Weaver, 1999; Huang and Pedlosky, 2000), other studies have suggested that the effects of these subducted anomalies on Pacific surface temperatures may be relatively weak on decadal time scales, at least compared to more rapid and direct forcing by off-equatorial wave propagation/reflection and changes in shallow overturning near the equator (Zhang et al., 1997; Kleeman et al., 1999; Schneider et al., 1999a,b; Wu et al., 2000; Hazeleger et al., 2001; McPhaden and Zhang, 2002). An "atmospheric bridge," in which decadal changes in extratropical SSTs affect the tropical trade winds, thus seems viable for explaining observed concurrent climate shifts throughout the Pacific (Barnett et al., 1999; Pierce et al., 2000a,b; Wang and An, 2001, 2002). The extratropical signals conveyed along either bridge could in turn be influenced by changes in the tropics, since it is known that ENSO affects the intensity of the Aleutian Low and associated winds and evaporation over the North Pacific (Weaver, 1999). There is little evidence in observations or models, however, to support a closed tropical/extratropical loop, and the current thinking is that extratropical decadal variability arises from oceanic integration of random atmospheric forcing (Mehta et al., 2000).

That Pacific climate is continually changing is a strong motivation for understanding the ENSO sensitivity to the background state. The apparent importance of wave dynamics and the tropical trade winds in the decadal variations of the tropical Pacific further suggests that a tropical Pacific-only model, perturbed by slowly-changing tradewind and heat fluxes, may be quite relevant to the way ENSO is modulated in the real world. This motivates the model development in Chapter 4 and the perturbation experiments of Chapters 5 and 7.

1.1.6 Recent changes in ENSO

Observed and inferred changes in ENSO behavior over the past few centuries have been extensively documented (Quinn et al., 1987; Enfield and Cid, 1991; Mann and Park, 1994; Rasmusson et al., 1995; Wang, 1995; Gu and Philander, 1995; Wang and Wang, 1996; Kestin et al., 1998; Torrence and Compo, 1999; Torrence and Webster, 1998; Setoh et al., 1999). These studies have concluded that although ENSO is reasonably stationary on centennial timescales, it shows large decadal variations in its amplitude, period, spatial structure, and propagation characteristics.

Much attention has focused on ENSO changes associated with the 1976 climate shift (An and Wang, 2000; An and Jin, 2000; Trenberth and Stepaniak, 2001; Wang and An, 2001, 2002). In the decades leading up to the shift, the climatology was apparently more La Niña-like and ENSO exhibited a short period of only 2–3 years with westward-propagating SST anomalies. After the shift to warmer temperatures, the ENSO period lengthened to 4–6 years and SST anomalies propagated eastward or remained stationary. An and Jin (2000) explain these changes in terms of increases in the mean equatorial upwelling, the entrainment temperature sensitivity to thermocline motions, and the decrease in the zonal SST contrast, all of which acted to enhance thermocline feedbacks over zonal advection feedbacks to favor eastward propagation of SST anomalies after 1976. Wang and An (2001, 2002) further suggest that an eastward shift of the mean wind convergence, equatorial upwelling, and shallow thermocline led to an eastward shift in the anomaly patterns as well. They argue that this reduced the speed of equatorial recharge of heat content, thus allowing more growth by local feedbacks in the eastern basin and permitting a longer ENSO period and larger amplitude.

Attention has also focused on the long and unpredictable series of warm events of the early 1990s, and the very strong warm events of 1982–83 and 1997–98 (Kerr, 1993; Trenberth and Hurrell, 1994; Kleeman et al., 1996; Latif et al., 1997). Whether these unusual events represent a fundamental change in ENSO behavior due to global warming, or are the result of natural stochastic fluctuations, internal chaos, or interactions with internal or external decadal modes is a source of much debate (Cane et al., 1995; Trenberth and Hoar, 1996, 1997; Latif et al., 1997; Harrison and Larkin, 1997; Rajagopalan et al., 1997; Kirtman and Schopf, 1998; Kestin et al., 1998; Kleeman et al., 1999; Timmermann, 1999; Wunsch, 1999; Trenberth and Hurrell, 1999; Timmermann and Jin, 2002). This debate is more than academic: it bears directly on our ability to detect and forecast what will happen to ENSO in the future. Unfortunately, there are so few realizations of ENSO in the observational record that the issue appears unlikely to be resolved anytime soon without further clues.

1.1.7 Clues from the distant past

Paleoclimatology attempts to reconstruct climates of the distant past using proxy data (corals, tree rings, ice cores, ocean and lake sediments) and appropriate numerical models. Paleodata offer a potentially better signal-to-noise ratio for testing ENSO theories than the historical record, since the climate changes are larger and the records are longer. It is important to remember, however, that these data are only indirect measures of ENSO and can be affected by changes in local climate or ENSO teleconnections.

Several reconstructions of the past few centuries have been prepared. A reasonably direct thermometer is afforded by corals from the Galápagos Islands (Dunbar et al., 1994), which indicate the following long-term interdecadal and centennial-scale climate fluctuations in the eastern equatorial Pacific SSTs: cold (1640), warm (1670), moderate (1700), warm (1710-50), cold (1810), moderate (1830-1900), and cold (1950). The warm epochs appear to show a relatively weaker and shorter-period ENSO than do the moderate and cold epochs. Less direct reconstructions based on data from the periphery of the Pacific basin (Diaz and Pulwarty, 1994; Stahle et al., 1998; Mann et al., 2000; Jones et al., 2001), suggest that ENSO teleconnections were attenuated in the early 1800s, then grew more active into the 1900s in tandem with a possible strengthening of the climatological Walker circulation.

Moving farther back into the past, several authors have worked to reconstruct the tropical Pacific climate and variability of the Holocene period (10 ka–present). Cole (2001) and Enfield and Mestas-Nuñez (1999) provide reviews. Based on proxy data, ENSO appears to have been weaker prior to 5-6 ka, with a longer period between strong events (Sandweiss et al., 1996; Kerr, 1999b; Rodbell et al., 1999; Tudhope et al., 2001). Some model simulations of the early-to-mid Holocene concur with this picture of a weakened ENSO (Liu et al., 2000a), while others suggest that ENSO may have been similar to today but may have had different seasonal locking (DeWitt and Schneider, 1998), skewness (Codron, 2001), and teleconnection properties (Otto-Bliesner, 1999), the latter having important implications for distant proxy data.

There is some evidence that the climate of the early-to-mid Holocene (10–5 ka) may have been more La Niña-like than today; paleodata indicate a warmer west Pacific but are in conflict regarding temperature in the eastern Pacific (Colinvaux, 1972; Farrell et al., 1995; Ravelo and Shackleton, 1995; Sandweiss et al., 1996, 1997; DeVries et al., 1997; Wells and Noller, 1997; Gagan et al., 1998). With a few exceptions (Codron, 2001), coupled GCM simulations concur with a La Niña-like picture of the early-to-mid Holocene (Bush, 1999;

Otto-Bliesner, 1999), and at least one (Liu et al., 2000a) also produces a narrow warming along the South American coast despite cooler temperatures in the central Pacific. Liu et al. (2000a) argue that the enhanced Pacific tradewinds and lack of ENSO during the early-to-mid Holocene are due to the strengthening of the Asian summer monsoon and the deepening of the equatorial thermocline due to subduction of warm water in the South Pacific. Another hypothesis is related to the date of perihelion, which is affected by the precession of earth's orbit around the sun and has a period of roughly 22,000 years. Perihelion currently occurs in January, but in the mid-Holocene it occurred in September. Because the equatorial Pacific climatology is most zonally-asymmetric in September when the ITCZ is farthest north of the equator, Clement et al. (1999) argue that September perihelia should be most effective at enhancing convection in the western basin, strengthening the Walker Cell, and seeding coupled feedbacks that enhance the zonal contrast of SST. Model simulations by Clement et al. (1999) indicate that Holocene-like orbital parameters should have contributed to a more La Niña-like climatology and a less regular ENSO.

Still farther back in time, there is evidence for climate/ENSO connections spanning the ice ages. Ancient corals from Indonesia (Hughen et al., 1999) and New Guinea (Tudhope et al., 2001) indicate that ENSO has existed for at least 130,000 years. Tudhope et al. (2001) suggest that over this vast epoch, ENSO has never to been stronger than over the past 120 years or so. Although these records offer little evidence for prehistoric changes in the period or regularity of ENSO, they do suggest that ENSO tends to be weaker during September perihelia, and also during glacial periods, which appear to be associated with a more La Niña-like climatology in the tropical Pacific (based on studies of the very strong Last Glacial Maximum; Bush and Philander, 1998; Liu et al., 2000b; Lea et al., 2000; Nurnberg, 2000; Andreasen et al., 2001). The weaker ENSOs during glacials could result from weaker coupling due to colder SSTs, from outcropping of the climatological thermocline in the eastern equatorial Pacific that limits the ability of the system to oscillate, or perhaps to lower sea level which could expose more land area in the western Pacific and anchor convection over Indonesia (Cole, 2001). Orbitally-induced changes in ENSO/annual cycle interactions have also been shown to produce abrupt shutdowns of ENSO on glacial timescales in an intermediate model (Clement et al., 2001).

Clement et al. (1999) and Cane and Molnar (2001) have suggested that the closing of the Indonesian and/or Panama seaways around 3–4 million years ago may have heralded the establishment of the first strong zonal thermocline slope in the Pacific, and the onset of strong ocean-atmosphere interactions. This fundamental change could have had a major impact on global climate and ENSO, which Clement et al. (1999) argue might be connected to the onset of Milankovitch forcing oscillations in eastern equatorial Pacific plankton deposits around that time.

These intriguing links between ENSO and paleoclimates further motivate our study of climate/ENSO interactions. That paleodata suggest ENSO may be stronger at present than ever before brings up some fundamental questions: Is the modern climatology optimal for ENSO, such that any departure from this climatology will cause ENSO to weaken? Or are we headed toward a world with even stronger ENSO variability?

1.1.8 Where are we headed?

Perhaps the most obvious and important motivation for this study is the need to understand how ENSO may change in the future, due to possibly human-induced changes in the tropical Pacific climatology.

Model projections of future climate

What will the future climate of the tropical Pacific look like? A number of studies have addressed this question, with contradictory results (Tett, 1995; Knutson and Manabe, 1995; Meehl and Washington, 1996; Knutson and Manabe, 1998; Noda et al., 1999; Timmermann et al., 1999; Barnett et al., 2000; Boer et al., 2000; Meehl et al., 2000a,b; Washington et al., 2000; Dai et al., 2001; Jin et al., 2001; Yu and Boer, 2002). Although most coupled GCMs give a uniform or slightly El Niño-like warming of the equatorial Pacific in response to increased concentrations of greenhouse gases, others give more of a La Niña-like response with an enhanced zonal SST gradient at the equator.

Because the structure of the tropical Pacific climate response is crucial to teleconnections around the globe, many theories have been put forward to explain the different SST responses in these various simulations. The first (Knutson and Manabe, 1995) is based on the Clausius-Clapeyron relation. For a uniform downward radiative heat flux, the cold eastern equatorial Pacific must warm more than the warm west Pacific to evaporate enough water from the surface to balance the radiative heating; this would act to *reduce* the east-west SST gradient. Such an idea does not account for changes in clouds that would render the radiative heat flux zonally-asymmetric, nor does it consider the ocean circulation.

A second mechanism (Ramanathan and Collins, 1991; Meehl and Washington, 1996) invokes changes in clouds. An SST increase in the warm and convergent west could produce more cirrus cloud shielding than in the cold and divergent east. This would limit the warming in the west and thus *reduce* the zonal SST gradient. Whether cirrus clouds would actually respond in this way to SST increases has been questioned (Fu et al., 1992; Hartmann and Michelson, 1993; Lau et al., 1994; Pierrehumbert, 1995).

A third mechanism (Clement et al., 1996; Sun and Liu, 1996; Cane et al., 1997) invokes an "ocean dynamical thermostat." Given a uniform radiative heating, warming in the east is limited by continual entrainment of cold water from below the mixed layer, which thus *enhances* the zonal SST gradient. Note that the dynamical thermostat can be defeated if the radiative heating is weighted toward the eastern Pacific, and this idea does not account for long-term changes in the structure and zonal-mean depth of the equatorial thermocline.

A fourth mechanism (Gu and Philander, 1997; Liu and Huang, 1997; Seager and Murtugudde, 1997; Liu, 1998) operates on a slower timescale. Enhanced warming in the extratropics can subduct, reach the equatorial thermocline, and then upwell to counteract the dynamical thermostat. Because the off-equator is relatively warm, fairly small SST anomalies can balance the radiative heating there and so the subducted temperature anomalies may be too weak to fully cancel the dynamical thermostat (Seager and Murtugudde, 1997). Even if the subducted anomalies are strong, they might take a decade or more to reach the equator through the ventilated thermocline; thus if the change in radiative forcing is rapid enough, the dynamical thermostat response may be evident for some time before the subduction has an effect.

As shown by Clement et al. (1996) any net zonal asymmetry generated by the combination of these mechanisms can be strongly enhanced by air-sea feedbacks like those involved in ENSO. The equatorial wind stress response is particularly important, since the equatorial temperature climatology appears to be mainly advection-driven, with surface heat fluxes acting primarily as a damping on ENSO and longer time scales (Huang and Liu, 2001; Jin et al., 2001; Yu and Boer, 2002).

The extent to which the mechanisms above are simulated in a given model may depend fundamentally on oceanic resolution (for the dynamical thermostat) or uncertain cloud parameterizations (for the cloud thermostat and other cloud feedbacks). The radiative forcing associated with cloud changes under enhanced CO_2 is highly model-dependent, and depends as much on changes in the atmospheric circulation (associated largely with SST gradients) as on local SST (Rind, 1987; Cess et al., 1989, 1990; Bony et al., 1997; Dutton et al., 2000). Cloud radiative forcing thus remains one of the largest uncertainties in future projections of tropical Pacific climate.

Given the large number of competing feedbacks, imperfect models, and conflicting model projections, the future of tropical Pacific climate is not at all clear. This provides another strong motivation for exploring the sensitivity of ENSO to a range of possible future climates.

Model projections of future ENSO behavior

Given that GCM projections vary so widely regarding the future of the tropical Pacific climatology, it is perhaps no surprise that they also disagree on what will happen to ENSO (Easterling et al., 2000; Hu et al., 2001; Collins, 2000a). Coupled models with low oceanic resolution near the equator (Meehl et al., 1993; Tett, 1995; Knutson et al., 1997) tend to show little change in ENSO for higher CO_2, while some higher resolution models are more sensitive. Knutson et al. (1997) and Boer et al. (2000) found slightly weaker interannual variability of the SST anomalies and surface stress, despite stronger precipitation anomalies in a greenhouse world. Greenhouse simulations by Timmermann (1999) and Timmermann et al. (1999) showed *increased* ENSO variability that was skewed more toward cold events, with little change in the ENSO period; these changes, which occurred in the context of an El Niño-like warming of the mean state and a sharpening of the equatorial thermocline, were linked by Timmermann (2001) to an increased effect of ENSO SST anomalies on the equatorial recharge of heat content. A $4xCO_2$ simulation by Collins (2000a) also showed a stronger and shorter-period ENSO, which was explained in terms of the increased climatological vertical temperature gradients at the equator and an increased efficiency of equatorial recharge due to stronger meridional temperature gradients off-equator. In contrast, a higher-resolution simulation by Collins (2000b) with an updated model showed less warming at the surface, a smaller increase in the vertical and meridional temperature gradients, and little change in the statistics of ENSO.

Thus the ENSO response appears to be very sensitive to the nature of the warming, and most GCMs have enough trouble simulating the present tropical Pacific climatology and ENSO, let alone future changes. The disparate GCM projections of future ENSO variability thus further motivate an investigation into the climate sensitivity of ENSO.

1.1.9 The role of this study

A number of previous studies have revealed links between the climatology and ENSO behavior (Hirst, 1986; Battisti and Hirst, 1989; Neelin, 1991; Wakata and Sarachik, 1991, 1992; Yang and O'Brien, 1993; Moore, 1995; Jin, 1996; Kirtman and Schopf, 1998; Dijkstra and Neelin, 1999; Codron et al., 2001; Wang and An, 2002). Some of these have explored the stability properties of ENSO over a wide range of parameter space, typically using simple models and an analytically efficient and convenient set of parameters (Neelin, 1991; Hao et al., 1993; Jin and Neelin, 1993a,b; Neelin and Jin, 1993; Neelin et al., 1998). Among the most important of these parameters are the *coupling strength*, namely the strength of the wind response to SST anomalies; the *wave adjustment time*, which is the time required for the equatorial ocean to come into balance with the wind stress by internal wave processes; and the *surface layer feedback*, i.e. the strength of the surface currents and upwelling induced by the winds. Application of these results to CGCMs, however, has been hampered by confusion over just what these parameters represent in nature.

Fedorov and Philander (2000, 2001) helped to bridge the gap between ENSO theories and observations by establishing a set of important climate parameters based on measurable quantities, like the strength of the equatorial trade winds, the zonal-mean depth of the equatorial thermocline, and the sharpness of the thermocline in the vertical. Using a simple model, the authors then constructed maps of the linear growth rate and period of ENSO as a function of tropical Pacific ocean climates forced by idealized winds. Fedorov (2002) extended these results to the time-dependent regime, by considering the impact of discrete westerly wind bursts that occur at different phases along a pre-existing ENSO cycle. Together, these studies provide a tentative road map for understanding ENSO behavior in different models and different climate regimes.

Many questions remain, however. How does coupling of the climatological ocean-atmosphere constrain the path through climate-parameter space? How relevant are the linear results to the more realistic nonlinear, stochastic, and meridionally-asymmetric regimes found in observations and models? How detectable are climate-induced ENSO changes in the stochastic context? What is the effect on the tropical climatology and ENSO of other climate parameters, like the longitude and meridional width of the trade winds, the strength of the cross-equatorial southerlies in the eastern Pacific, and the surface heat flux? To what extent do the sensitivity results from simple models apply to more comprehensive GCMs?

The purpose of this dissertation is to answer these questions and carry the simple linear road map into more realistic (but also more complex and challenging) regimes. Such a study is well-timed, because (1) a wealth of new paleodata are now coming online which should provide excellent tests for the results; (2) recent coupled-model intercomparisons are improving awareness of climate differences among models and how they affect seasonal-to-interannual forecasts; (3) the climate community may be on the verge of adequately detecting and simulating how human-induced changes in the climate system may affect ENSO; and (4) there is a growing appreciation of the strong influence of ENSO on global climate at multiple timescales, from intraseasonal to interglacial. A further investigation of the climate sensitivity of ENSO is thus strongly motivated.

1.2 Formulation of the problem

1.2.1 Central question

The central question of this study is: How do changes in the background state affect ENSO behavior? The *background state* refers to the climate of the tropical Pacific averaged over a decade or more. *ENSO* will refer to anomalous tropical Pacific variability with time scales ranging from a few months to one decade. The *behavior* of ENSO refers to its amplitude, period, structure, propagation characteristics, physical mechanism, and predictability.

Our central question is related to the question of why ENSO varies so much among coupled GCMs, since these GCMs show large differences in their climatologies. It may also be related to the question of why the behavior of the *observed* ENSO changes through time, since observed climate has low-frequency components spanning from decades to millennia.

1.2.2 Thesis

Our thesis is that *the climatology of the tropical Pacific exerts strong controls on ENSO behavior*. To test this thesis, we devise a model to represent climate/ENSO interactions, and then assess the extent to which the simulated ENSO responds to changes in the background state.

Two important points must be considered. First, there is much debate about just what constitutes an appropriate model for ENSO (Chang et al., 1996; Thompson and Battisti, 2001; Wang, 2001a,b). Is ENSO a damped linear oscillation sustained by atmospheric noise, an unstable oscillator whose irregularity arises from chaos, or some combination of the two? A complete understanding of ENSO sensitivity will necessarily involve different types of models at different levels of sophistication. The models in this study will range from a simple conceptual oscillator to a comprehensive coupled GCM, but for the most part we shall focus on a reasonable, intermediate-complexity model of ENSO. It is anticipated that a careful analysis of the intermediate model will yield insight into more sophisticated models, an approach which has proved successful in the past (McCreary and Anderson, 1991; Neelin et al., 1998).

Second, to the extent that stochastic events affect ENSO, we must pay careful attention to the statistical *significance* of changes in ENSO behavior to ensure that they are not simply chance events arising from a small number of cases. Robust determination of the stochastic climate sensitivity will therefore require long simulations containing many events. The computational burden is even higher to assess the *sensitivity* of predictability, as this requires ensembles of stochastic runs launched from a large number of initial conditions. Fortunately, the intermediate model we describe is very efficient and up to the task of generating so many runs in a reasonable time.

1.2.3 Overview of the dissertation

The structure of remaining chapters is as follows. Chapter 2 characterizes the observed climatology and interannual variability of the tropical Pacific, and Chapter 3 draws upon these results to develop a stochastic model of wind stress anomalies. Chapter 4 introduces an intermediate coupled model for climate/ENSO interactions, describes its essential characteristics, and investigates its sensitivity to dynamical parameters. Chapter 5 describes the sensitivity of the tropical Pacific climatology to key background variables, using the intermediate model and a hybrid coupled GCM. Chapter 6 constructs a theoretical framework for thinking about the influence of climate on ENSO, which is then applied to the intermediate and GCM simulations of Chapter 7. Chapter 8 concludes with a discussion of real-world applications of the results and suggests promising avenues for further research.