Chapter 8

Conclusion

I hate quotations. Tell me what you know.

Ralph Waldo Emerson, *Journal*, 1822

8.1 Summary

8.1.1 The questions

The central question of this dissertation has been: *How do changes in the tropical Pacific climatology affect ENSO?* This question was motivated by the need to understand the wide range of ENSO simulations among general circulation models, the need to understand historical and paleo changes in ENSO, and the desire to predict what may happen to ENSO in the future.

The path to the answer has spawned a number of secondary questions: How have the tropical Pacific climatology and ENSO variability changed over the observed record, and what are the uncertainties in these changes? How should one model the climatology and ENSO, and how sensitive is the model to its uncertain parameters? How do different types of plausible changes affect the climatology, and what is the role of air-sea coupling in the response? How do these climate changes affect the mechanism and behavior of ENSO? What is the role of transients and nonlinearity, and how detectable are the ENSO changes in the stochastic context?

8.1.2 The answers

We have proposed answers to all of these questions, based on a detailed analysis of the observations, exploration of the ENSO sensitivity to climate in a hierarchy of theoretical and numerical models, and interpretation of the model results in terms of the mixed layer energy budget and coupled mode theory.

An analysis of observations (Chapter 2) indicated large differences among the available wind stress analyses. We conclude that the true stresses, their decadal changes, and their dependence on tropical SSTs remain very uncertain. These differences should be kept in mind when arguing for effects of climate changes based on recent ENSO behavior, when forcing ocean models for tuning and analysis, or when building statistical atmosphere models from the available stress products. Better understanding of what *really* happened to the stresses over the past four decades must come from improved analyses, including consistency checks with stress-interactive variables like the oceanic thermal structure.

In Chapter 3 a statistical atmosphere model was constructed using what appear to be the most reliable stress data (FSU 1980–99). This model includes a deterministic component, which depends linearly on large-scale SST anomalies, and a stochastic component that reproduces the observed spatial correlations and variance of intraseasonal stress anomalies not linearly related to large-scale SSTs. A key result from this chapter was that the stochastic component appears to be a very important contributor to the overall stress in the real world.

In Chapter 4 an intermediate-complexity ocean model was developed and calibrated, to enable realistic simulation of the tropical Pacific climatology and ENSO using a consistent set of parameters. The statistical atmosphere was then coupled to the ocean model to yield a stochastic/dynamic hybrid that gives a reasonable simulation of observed and GCM-simulated ENSO behavior, including its spatial structure, temporal spectrum, and mechanism. To provide a context for the climate sensitivity study, the linear stability, asymptotic properties, sensitivity to noise forcing, and predictability characteristics of the coupled model were mapped over a range of important (and uncertain) model parameters. The results were then interpreted physically, to build intuition regarding ENSO behavior. A new paradigm for ENSO forecasts is suggested, which downplays the uncertainty in the initial conditions and instead focuses on the influence of future random events.

Chapter 5 presented results from idealized experiments with the intermediate model, designed to test the sensitivity of the tropical Pacific climatology to imposed long-term perturbations. These perturbations were well-motivated by observed and hypothetical future changes in the real world; they included the strength of the equatorial and off-equatorial zonal wind stress, the longitude of the equatorial zonal stress, the meridional stress in the eastern equatorial Pacific, and radiative forcing of the surface ocean. The results suggest that because coupled feedbacks tend to dominate the time-mean response, a perturbed tropical Pacific climatology generally comes to resemble either an ENSO warm state (with weakened trades and flattened thermocline) or an ENSO cold state (with enhanced trades and steeper-sloping thermocline), with different perturbations more or less efficient at forcing these changes. Similar experiments in a hybrid coupled GCM yielded qualitatively different responses than in the intermediate model, particularly for changes in radiative forcing. Both models have limitations and it is not clear which model is more representative of the real world. If the climate manifold is indeed as simple as the intermediate model suggests, then the ENSO climate-sensitivity problem is largely reduced to one of understanding the ENSO response to El Niño-like and La Niña-like backgrounds.

The warm and cold climate extremes are found to support very different modes of interannual variability, due to thermodynamic changes which control the structure of the oscillations. Changes in the climatology operate through nonlinearities to modify the coupling between components of the ENSO system, thereby altering the mechanisms that produce SST anomalies. In Chapter 6 the effects of climate on the dominant coupled modes are illustrated by appealing to the phasing of the SST tendency terms relative to local SST. Phasor diagrams are proposed to simplify and unify the discussion of interannual coupled modes. Processes in phase with local SST produce pure growth, while those that lead SST by a quarter cycle contribute purely to the oscillation frequency. The climatology can be seen as modifying not only the relative *amplitudes* of the growth and transition mechanisms ("which tendency terms are important"), but also their *phase* relative to SST ("the role of a given tendency term").

Chapter 7 applies these ideas to altered-climate simulations of ENSO in the intermediate model and hybrid GCM. For weakened trades, the transitioning effect of zonal advection in the intermediate model is inhibited by weak zonal SST gradients, and so the oscillation has a longer period than in the control run. The oscillation pattern also shifts eastward and weakens due to the increased depth of the mean thermocline, which desensitizes the entrainment temperature to vertical motions of the thermocline. For strong trades, the opposite happens: transitions are accelerated by zonal advection on enhanced zonal SST gradients, increasing the oscillation frequency, and the outcropping of the thermocline in the east causes SST variability to shift westward. Altering the strength of the equatorial trades in the hybrid GCM also results in large changes in the ENSO behavior, but in this case nonlinearities and mixing play key roles. The GCM results appear to be related to the intermediate model behavior at high coupling, suggesting that a broad view of ENSO variability (including sensitivities to both model parameters and climate parameters) can help link together different results from disparate models.

The effects of altered climates on the ENSO period, amplitude, and zonal structure largely persist in the nonlinear, transient, and stochastic ENSO regimes, though a few important differences are noted. In the stochastic case, detectability is hindered by random ("natural") modulations that affect ENSO behavior even in the absence of climate changes. In this case, long timeseries are required for unambiguous attribution of ENSO changes to climate changes, suggesting that paleo data may be essential for solidifying our understanding of climatology/ENSO interactions in the near future.

8.1.3 Contributions

Contributions of this dissertation to the climate community include:

1. A tropical Pacific wind stress comparison, which documents the essential features, changes, and uncertainties of a critical climate field in two widely-used operational analyses.

2. A new coupled model of ENSO, which improves upon an existing widely-used class of models. The model is capable of simulating the ocean climatology as well as coupled anomalies, and is carefully calibrated using newly available climate data to yield more realistic ENSO variability in forced, coupled, and stochastic modes. The model sensitivity analysis will be a valuable guide to potential users of the model.

3. A new way of thinking about ENSO forecasts, which downplays the uncertainty of the initial conditions and instead focuses on the influence of future random events.

4. Maps of the tropical Pacific coupled equilibrium response to relevant time-mean forcings, and a physical interpretation of these maps. The similarity of the responses to different forcings suggests that the strength of the equatorial trade winds is an essential metric for the climatology.

5. Mapping and understanding of the ENSO response to altered climates, with a demonstration of the similarity of ENSO responses to different time-mean forcings. Sensitivity maps are presented for linear, nonlinear, transient, and stochastic regimes.

6. A wavelet phasor diagram that compactly summarizes the roles of time-varying tendency terms in the growth rate and frequency of an oscillation. These diagrams are powerful tools for comparing the thermodynamics of different models as a function of location, frequency, and time.

7. Quantitative evaluation of the detectability of climate-induced changes in the ENSO probability distribution, spectrum, zonal structure, and predictability, in the context of short stochastic timeseries and small forecast ensembles.

8.2 Outlook

Much work remains before the links between ENSO and the climatology of the tropical Pacific are fully understood. Several more interesting studies could be done in the intermediate model:

- A study of the climate/ENSO response to *localized* changes in surface heat fluxes, relevant to the uncertain changes in cloud radiative forcings in a greenhouse world.
- A study of the climate/ENSO response to changes in thermocline depth and dispersion, relevant to the thermocline stratification errors in GCMs and to interdecadal temperature anomalies that reach the equator from midlatitudes.
- Inclusion of a seasonally-varying background state, a more realistic model for surface heat fluxes, and seasonally-to-interannually varying wind stress noise to see how these affect the ENSO sensitivity to climate changes.

Other essential items and avenues for further research on this topic include:

- Continued expansion of the historical and paleo data archives, with improved analyses of ocean-atmosphere fields for the past century (especially for the surface wind stress and subsurface ocean).
- Consolidation of existing paleodata into a reference dataset for use by climate modelers.
- More detailed model ENSO intercomparisons, with increased emphasis on subsurface oceanic fields and the thermodynamics of the mixed layer.
- Analysis of a very long control run of a coupled GCM that simulates reasonably realistic interannual and interdecadal variability.

- Systematic climate-sensitivity studies with ENSO-resolving CGCMs, including idealized climates, paleoclimates for which proxy data exist, and climates with increased atmospheric greenhouse gas concentrations.

Studies like these should help us better understand, predict, and coexist with our ever-changing climate system. Considering the tremendous progress of the last two decades, the outlook is bright indeed.