ON THE USE OF CLIMATE MODELS TO ASSESS THE IMPACTS OF REGIONAL CLIMATE CHANGE ON WATER RESOURCES

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ABSTRACT

We critically analyse some of the major assumptions typically employed in climate model-based impacts studies of water resources. In particular, climate impacts studies have not considered whether current climate models are capable of simulating the factors important for determining regional hydrology. We set up a case study of the Sacramento Basin to test these assumptions. The Sacramento Basin has been the subject of a number of climate impacts studies. By comparing climate model simulations of the current climate with observational data, we show that there are critical shortcomings in the climate models' simulations of the synoptic-climatological processes important for Sacramento Basin precipitation. The stationary waves, jet streams, and storm tracks simulated in the climate models show significant differences from their observational counterparts in the climate mean, and respond differently in wet and dry winters and for individual storms than the observations.

On the scale of the Sacramento Basin, the climate model precipitation is too weak and too frequent relative to observations, and the models smear out the sharp spatial precipitation gradients observed along the west coast. The smearing effect is substantially reduced for a climate model run at high horizontal resolution. However, the model defiencies in the temporal distribution of precipitation, and in the simulation of large scale circulation features persist at high resolution. The use of time series of observed ocean boundary conditions also does little by itself to improve model deficiencies. Deficiencies in the model large scale circulation features are related to the model subgrid parameterizations.

Historical data indicates that streamflow amount in the Sacramento Basin is sensitive to precipitation, while the timing of streamflow is sensitive to temperature. During particularly wet years in the basin, streamflow increases proportionally more than precipitation. During particularly dry years the streamflow is more linearly related to precipitation. However, after runs of dry years the streamflow response to precipitation is diminished relative to other dry years. Since streamflow is nonlinearly related to precipitation, the amount of basin streamflow implied for a model's doubled CO_2 basin precipitation simulation depends on how much basin precipitation is simulated for the current climate.

For water resource planning, the GCM basin scenarios are probably no more uncertain than the use of historical data to plan for the future. For decisions involving long range investment in infrastructure to maintain existing water supplies in the basin, the choice of climate scenario is critical in determining the array of costs and benefits associated with any climate change. For decisions involving crop management policy in the basin, the time scales for implementation and operation are short relative to the likely rate of climate change, and the choice of climate scenario is less critical.

Thesis Supervisor: Peter H. Stone
        Professor of Meteorology

This thesis is dedicated to
the memory of my grandfather

Bert Johnson

who knew the value of water.

The fact is that water offends against nearly all the criteria of normality laid down by physicists and chemists. In the case of the biologist this is not quite so clear, since to the best of our knowledge life and water are so inseparable that any other standard of "normal" behavior does not exist ...

Let us look at some quite basic physical properties. There is for instance, a rule of thumb that the boiling point of a liquid is related to the size of its constituent molecules. In other words, the smaller the molecules the lower the boiling point. A comparison of H_2O with substances having the same molecular size suggests that water should boil at $-93°C$ and that it should freeze only a few degrees below that temperature. It is also well known that most substances are denser in the solid than in the liquid state, but it is equally well known that ice floats on water — that is, the freezing of water is accompanied by a bulk expansion. Again, every school child learns about the maximum density of water at $4°C$, but what is not known is the mechanism whereby a liquid can contract when it is heated. The ecological consequences of this density maximum are manifest: Freezing of rivers and lakes takes place from the surface downward, thus allowing life below the insulating ice layer to continue undisturbed by severe climatic fluctuations.

Much more significant even than the well-publicized density maximum is the abnormally high specific heat of water. Text-books state that the specific heat of a substance is the amount of energy required to raise the temperature of one gram of the substance by $1°C$. There is also the rule of thumb that, like the boiling point, the specific heat of a liquid is related to the size of its molecules, and yet another rule states that the specific heat of a solid is higher than that of the same substance in the liquid state. We shall see that for water all these rules, and many more, are overturned. The specific heat of liquid water is 1 calorie per gram for each degree rise in temperature. For alcohol the figure is 0.5 calorie, yet the alcohol molecule is three times larger than that of water. On the other hand, when water freezes, its specific heat drops to half the liquid value. All this means that when energy is supplied to liquid water, only half of it is used to raise the temperature; the remainder is stored away in the bulk of the liquid. The ecological implications are staggering ...

— Felix Franks, *Polywater*

I shall not introduce those who were present. It is not of them, nor their characters, nor their actions that I wish to speak. They were there like actors in a dream trying, sometimes genuinely, to wake up; all good comrades, each incorporating the others into his own fantasy world. All I wish to say at this point is that we were drunk and that we were thirsty. And we who were alone were many.

René Daumal
A Night of Serious Drinking

Acknowledgments

Many people have contributed to this work and to my well-being while carrying out the work, and my heartiest thanks go out to them all. This set of acknowledgments necessarily constitutes only a partial listing of those I would like to thank. There are bound to be egregious omissions here, for which I apologize.

My advisor, Peter Stone, has provided sound guidance and support throughout. He shared his interests and insights on the climate system and climate modelling with me, and encouraged me to pursue my own interests across the disciplines of climatology. It has been an enjoyable working relationship through some interesting times in the field, and he has my respect. My committee members were also crucial in helping to frame and carry out the thesis. Bill Clark and Ron Prinn identified those critical questions that helped focus the thesis and set its direction. Dara Entekhabi provided valuable direction and expertise on all aspects of the hydrological cycle in climate models and at basin scale.

There were many outside the committee who also helped in conception or completion of the work. Peter Eagleson at MIT and Peter Gleick at the Pacific Institute provided constructive feedback on early thesis proposals, and pointed my way toward others in the field. Mike Dettinger at USGS was tireless in answering my questions and educating me about the hydrology of the Sacramento Basin region. He also provided output from his model and some figures from his research. Dennis Lettenmaier at the University of Washington provided helpful comments on the problems inherent in basin climate impact studies. Dan Cayan at the Scripps Institution of Oceanography introduced me to the literature on climate variability and streamflow in the west. Gary Bates at NCAR kept me up to date on developments in nesting mesoscale models inside GCMs for climate impacts studies. Peter Whetton and Barrie Pittock and colleagues at CSIRO Division of Atmospheric Research provided valuable feedback on an early presentation of the thesis results that helped to focus the conclusions. Richard Rosen at AER cheerfully provided helpful answers to a range of questions. Bill Gutowski at Iowa State University described work on wave activity fluxes for me, and helped on earlier work on meridional energy transports. Mark Handel and David Keith provided helpful pointers and discussions along the way, and a friendly and collegial interest in my work that is so crucial, along with Peter Cebon, Peter Poole, Susan Wijffels, Tad Homer-Dixon, David Bennett, and Mark Engel. It was always encouraging to know that their advice and support was available when I needed it. Mark Handel also provided the LaTeX template for the thesis.

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List of Abbreviations

AMIP   = Atmospheric Model Intercomparison Project

BATS   = Biosphere Atmosphere Transfer Scheme

CCM2   = NCAR Community Climate Model version two

DOE   = Department of Energy

ECMWF = European Centre for Medium Range Weather Forecasting

ENSO   = El Niño / Southern Oscillation

ET   = evapotranspiration

GFDL   = Geophysical Fluid Dynamics Laboratory

GISS   = NASA Goddard Institute for Space Studies

GCM   = general circulation model

NASA   = National Aeronautics and Space Administration

NCAR   = National Center for Atmospheric Research

NMC   = National Meteorological Center

PBL   = Planetary Boundary Layer

PNA   = Pacific North America Index

SET   = sublimation and evapotranspiration

SLP   = sea level pressure

SOI   = Southern Oscillation Index

SST   = sea surface temperature

USGS   = United States Geoldicial Survey

WMO   = World Meteorological Organization

When you are thirsty, you watch out for any opportunity to drink and merely pretend to take an interest in other things, which is why it is so difficult afterwards to convey exactly what you experienced. It is very tempting, when you talk about the events of the past, to impose clarity and order upon what had neither one nor the other. It is very tempting and very dangerous. That is how you become a philosopher before your time . . .

René Daumal
A Night of Serious Drinking

Chapter 1

Introduction

This work is directed at the problem of projecting regional climate change, primarily in response to concerns about greenhouse climate change. Since much of the current work on projections of regional climate change, and probably much future work on this problem is carried out using three dimensional general circulation climate models (hereafter, simply 'climate models' or 'GCMs'), these tools will be the main focus of the work. In order to develop a concrete assessment of the problems of projecting regional climate change, we chose to study climate impacts on water resources, and have selected a particular case study region – the Sacramento Basin in California. The broad goal of the thesis then is to diagnose the capabilities of climate models for simulating regional climate change and its impacts on water resources. This will entail:

- A diagnosis of the water resource issues of importance in the Sacramento Basin.
- Selection of the synoptic climatological processes influencing the regional hydrology.
- Assessment of GCM simulation of these processes.
- Assessment of the sensitivity of the basin streamflow to climatological inputs.
- An exploration of the policy options facing water resource planners.

Our evaluation of GCM performance for simulating regional hydrology will encompass important features across a range of scales from basin scale to regional scale to planetary scale. We also consider the relevance of the results of this evaluation from a number of perspectives:

Future relevance: Will the results likely remain relevant given the rapid development of GCMs?

Relevance to streamflow: Is basin streamflow sensitive to GCM errors in simulation of the current climate, and to the typical GCM range of climate changes in precipitation?

Relevance to planning: Are long range planning decisions in the basin sensitive to choices of climate scenario from GCMs and other sources?

1.1   Motivation

Greenhouse climate change is perhaps the quintessential global energy and environmental problem. Climate change impacts will be felt at the regional level however, and it is at this level of detail that policymakers have requested information (The Economist, 1990). Climate change has the potential to exacerbate water resource shortages in many regions of the world.

In the past decade or so, concern has risen over the potential for adverse impacts associated with greenhouse climate change. In response to this, an increasing number of studies have been carried out using GCMs coupled to various regional impacts models. This has been done to assess potential impacts on water resources (Gleick, 1987; Lettenmaier and Gan, 1990), agriculture (Adams et al., 1990), forestry (Overpeck et al., 1990), and in other fields. The conclusions of these kinds of studies have been offered to policymakers as guidance. Yet without exception, these studies have not undertaken any kind of systematic analysis of the suitability of using GCMs to address the particular regional impacts in question. Most impacts studies now acknowledge the uncertainty of the GCM-produced regional climate changes. In response to this, they will often 'drive' their

impacts models with output from a range of GCMs. Yet this begs the question of whether any of the current GCMs are capable of adequately simulating the factors important for their studies.

The need for taking a closer look at GCM capability in regard to regional impacts assessment is implied by several studies. Grotch and MacCracken (1991) have shown that GCMs differ in their simulations of the present climate and greenhouse climates at regional scales. It is this kind of result that has led impacts modellers to select GCM results from several GCMs in an attempt to encompass the uncertainty. Yet a simple comparison of GCM fields and selection of multiple GCMs does not answer questions about why GCMs differ, nor about the relevance the GCM errors have for regional water resources or agriculture.

More fundamentally, Stone and Risbey (1990) undertook an analysis of atmospheric energy transports in GCMs on a global scale. This was in some sense a generous test for GCMs, which do better at larger scales. Further, the energy transport is nominally determined by dynamical processes, which are at the core of GCMs. They found that despite the fact that each of the GCMs tested successfully simulated the meridional temperature profile, the GCMs gave different atmospheric energy transports and did not match observations (see figure 1.1). This suggests the presence of compensating errors in the models, which would almost certainly prove to be important in the simulation of regional climates.

Recently, Hsu (1994) completed an analysis of meridional energy transports in the National Center for Atmospheric Research (NCAR) Community Climate Model Version Two (CCM2). This is one of the climate models examined in this work. While the total northward energy flux in CCM2 is in rough agreement with observations, the implied oceanic component of the northward energy flux appears to be grossly at odds with the available observations. In particular, figure 1.2 from Hsu's work shows that the implied oceanic transport in CCM2 is in the wrong direction in the southern hemisphere. This pathology in the models oceanic and atmospheric circulation is shared by a number of other so called 'state of the art' models as well. Almost all of the fifteen GCMs reported in the Atmospheric Model

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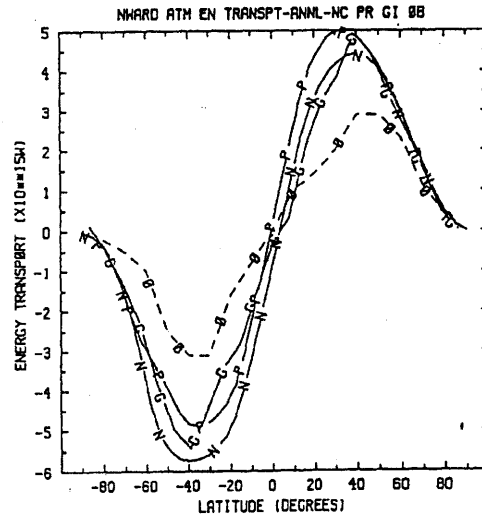
Figure 1.1: Annual mean zonal mean northward atmospheric energy transport for NCAR (N), GFDL (P), and GISS (G) models (control run), and for Carissimo et al. (1985) observations (O) [from Stone and Risbey (1990)].

Intercomparison Project (AMIP[1]) study of Gleckler et al. (1994) show northward ocean heat transports in the southern hemisphere. The models inability to portion the energy fluxes correctly and yet still yield a global energy balance in accord with observations implies the presence of compensating errors at sub-global (i.e. regional) scales.

1.2 Methodologies

This section provides a brief review of the various techniques that have been used to assess potential climate change impacts on regional water resources. The goal here is to place the method and emphasis of this work in context with work on climate impacts. It is important to bear in mind that this work is *about* climate impact studies on water resources, but is not an impact study per se. While we

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[1]The AMIP project is described by Gates (1992). AMIP current climate simulations use the observed monthly averaged distributions of sea surface temperature and sea ice as boundary conditions, rather than the climatological means as is usually done.
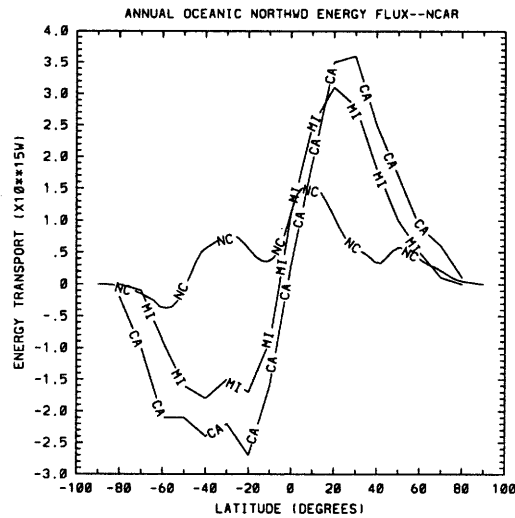
Figure 1.2: Annual mean zonal mean northward oceanic energy transport for CCM2 (NC), 1985-1986 ECMWF analyses from Michaud and Derome (1991) (MI), and for Carissimo et al. (1985) observations (CA) [from Hsu (1994)].

will not attempt to project changes in water supply in the Sacramento Basin in response to climate change, we *will* try to answer the following questions:

- How well suited are GCMs to the task of providing regional climate change scenarios for hydrological models of the Sacramento Basin?

- Where should efforts be placed to improve the performance of GCMs for this task?

- What are the options available for water resource planners in the Sacramento Basin?

While our interest is on the use of GCMs in assessing potential climate change impacts on water resources, we begin with a brief outline of non-GCM or empirical approaches before describing the various GCM-related methods.

1.2.1 Empirical Approaches

There are two main strains of empirical approach to the formulation of regional greenhouse climate change scenarios. One approach is to use data from recent

instrumental records. Typically in this approach, ensembles of data from warm or cold periods are compared with one another or with long term climate means for a region. Sometimes another region's climate is taken as an indicator of the type of climate that may predominate in the region of interest, usually after invoking some physical or dynamical reasoning to justify the comparison. This approach is embodied in the simple idea that climate regimes will shift latitudinally (north–south) in response to greenhouse warming for instance. In the instrumental record approach, climate analogues are sought in instrumental data from the recent past for the region of interest, or from contemporary climates in other regions.

The other main empirical approach is to seek analogues for the climate change in the paleoclimate record of the distant (pre-instrumental[2]) past. For greenhouse climate change analogues, warmer periods have been selected from the Holocene ($\sim 6000\,\mathrm{BP}$), the Eemian interglacial ($\sim 125,000\,\mathrm{BP}$), and beyond. The use of paleoanalogues for constructing regional greenhouse analogues has been criticized by Crowley (1990) and others on the basis that the forcing and boundary conditions were different from the present during those periods. Crowley notes that much of the variation in these climates can be explained in terms of seasonal rather than mean annual forcing. Boundary conditions such as the upper ocean circulation and temperature, sea ice distribution, and land vegetation were also different due to the protracted nature of the warming in the past interglacials.

Empirical approaches may be most useful when used in conjunction with other (GCM-based) approaches, such as by Pittock and Salinger (1981). Giorgi and Mearns (1991) note that empirical approaches "cannot be expected to provide accurate quantitative estimates of regional climate statistics", but can be "used to provide qualitative estimates of direction and ranges of possible regional climate variations". It is often assumed that GCM-based approaches can, by contrast, provide quantitative guidance. This assumption is scrutinized in this work.

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[2]The length of the instrumental climate record varies depending upon the region considered and the quantities of interest, but is generally said to extend back to the middle to latter part of the nineteenth century

1.2.2 Stand Alone GCM Studies

The earliest studies using GCMs to infer climate change impacts on water resources go back to the mid 1970's with work by Manabe and collaborators using the GFDL model. GCMs of the 1970's and 1980's used fairly crude land surface hydrology schemes — typically a bucket with a fixed field capacity. Stand-alone GCM studies (where the GCM alone is used to infer the surface hydrological response) have usually concentrated on larger scales or on typical regions such as midcontinental midlatitude. Manabe et al. (1981) and Manabe and Wetherald (1987) noted increased surface dryness during the summer in midcontinental regions in responsed to increased atmospheric CO_2 in the GFDL model. These findings were corroborated by other GCMs, though Kellogg and Zhao (1988) noted that there were also considerable differences between the five GCMs they included in their study of the sensitivity of soil moisture over North America to a doubling of CO_2.

Hansen et al. (1989) presented information on regional climate changes in the GISS model in aggregation, without corresponding to a particular region. They noted an enhancement of both ends of the hydrological cycle in their model in response to greenhouse gas forcing, with increased incidences in drought occurences and severe storms. Miller and Russell (1992) used the GISS model to compute changes in runoff between a control climate run and a doubled CO_2 run. They found increases in runoff in high latitudes with increases and decreases in low latitudes. They noted that the computed runoff depends on the models precipitation, evapotranspiration, and soil moisture storage, and called for improved representation of the land surface in GCMs. In most GCMs the land surface schemes are now more sophisticated and employ multiple soil layers and types, vegetative canopies and their effects, and subgrid scale precipitation effects.

The GCM stand alone studies paved the way for efforts to depict climate change in *particular* regions. When particular regions are considered it is desireable to translate the GCM output down from the coarse GCM grid scales (typically $100km - 300km$ per grid dimension) down to smaller basin scales for hydrologi-

cal modelling. In the long run with the advent of much faster computers it will be possible to increase the resolution of the GCMs by the order of magnitude or two necessary to generate output on basin hydrological scales. That time is still relatively distant on the time frame in which water resource planners need to make decisions for the coming years, and so alternative methods to generate basin scale information must be used. Scale translation efforts have been classified by Giorgi and Mearns (1992) according to those semiempirical approaches that use empirically derived relationships between large scale and local surface variables, and modelling approaches that embed a high resolution mesoscale model within the GCM over the region of interest.

1.2.3   Semiempirical Approaches

The basic strategy underlying semiempirical approaches is to "treat large-scale forcings explicitly through the use of GCMs, and account for mesoscale forcings in an empirical fashion" (Giorgi and Mearns, 1992). There are a number of variations on this theme. The most common is to append gridbox differences between perturbed climate GCM runs and control runs to observational data sets for the region. This is the approach that has been followed in many of the climate impact studies on the Sacramento Basin region (see section 2.3).

More sophisticated semiempirical approaches entail developing regression relationships between station data and regional average values of the same surface variables. The regression relationships are then applied to GCM grid box values to infer local station values over the grid box region. This is the 'climate inversion' technique developed by Kim et al. (1984). Further refinements on this approach consist of developing empirical relationships between observed surface variables and observed or model produced free atmosphere and surface predictors for application with model output. Karl et al. (1990) used this approach to obtain improved simulations of station precipitation at various sites in North America over direct interpolation from coarse scale GCM output.

The semiempirical approaches suffer from the limitation that there is no assurance that the predictive empirical relationships linking larger scale information with local values developed for the present climate will apply as well under different forcing conditions for a changed climate. Changes in forcing might be manifest at larger scales in say a change in the type of storm events experienced in a region in response to changes in planetary scale waves, or perhaps at local scales through a change in vegetative properties of the surface feeding back on evaporation and atmospheric stability.

1.2.4 Limited Area Model Approaches

The limited area model (LAM) approach nests a mesoscale model inside a GCM over the region of interest to transform from GCM scales to local scales using a more physically based method.[3] Ideally, the output from the LAM is fed back to the GCM (two-way nesting), but climate impact studies using this method to date have been one-way nested. Giorgi and collaborators at NCAR have used the LAM technique to generate high resolution (60km) time series of a few years duration over much of the United States (Giorgi et al. 1994). Their results show some improvement in representing the current climate at regional scales over direct use of the driving GCM fields. Since the LAM may be as computationally intensive as the driving GCM in order to represent the important mesoscale processes, this technique has been limited to date to short duration runs of less than a decade. For regional climate impacts on water resources, changes in climate variability may well be as important as changes in the mean (Rind, 1989). To capture any changes in variability in a greenhouse enhanced climate it will be useful to extend the nested LAM runs out to several decades or more.

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[3]All earth science models are at best only physically based and not purely physical as opposed to empirical, since they all still rely on some degree of parameterization of subgrid scale phenomena.

1.2.5   Working Backwards

Leaving aside the empirical approaches, each of the above techniques converts information about the climate from synoptic scales of clusters of GCM grid cells down to basin hydrological scales. While the method of scale conversion is different in each case, all of them depend on synoptic scale GCM climate input and assume it as a given. Effort is focused on the scale conversion from synoptic to local scales, but not on the synoptic scale inputs. In assessing climate impacts on water resources the unscrutinized GCM output is transformed to local scales and used as input to drive a hydrological model of a region. This approach takes little account of what is actually required of the climate models for policy purposes in working through the various stages of the analysis. Like the Congressionally mandated acid rain studies, it may produce some good science, but little information of real use to water resource planners.

Our approach in assessing GCM capability for regional hydrological studies works back from the policy requirements to the GCMs, rather than from GCMs to purported policy implications. If policy planners in the Sacramento Basin want to know how streamflow will change as climate changes, it is important to begin with a survey of the salient water resource issues in the basin. One must then ask what climatological processes impact on these water resource issues and are important for the region's hydrology. These topics are discussed in chapter 2. Chapter 3 describes the climate models selected for scrutiny. Chapter 4 presents a standard statistical evaluation of their regional performance, while chapter 5 analyses the climate model precipitation on local basin scales. We then analyse the ability of the GCMs to simulate the important synoptic-climatological processes for the region's hydrology in chapter 6. This step includes an analysis of the model simulation of major storm events over the basin. We diagnose reasons for shortcomings in the GCMs ability to reproduce the governing synoptic processes. This enables us to suggest areas where the climate models need to undergo further development to enhance their utility for water resource studies. The model diagnosis is extended in chapter 7 to examine the role of the oceans, resolution, and topography in setting the models regional climate.

In placing the errors in the GCM synoptic scale information in context with the hydrology of the region we undertake an analysis of the historical sensitivity of streamflow in the Sacramento Basin to the GCM input variables, precipition and temperature. GCM errors in simulation of precipitation for the current climate and for climate changes may be irrelevant if the basin streamflow is insensitive across the range of GCM precipitation changes. An examination of the physical characteristics of the basin's streamflow response is also useful in directing attention to processes that must be well simulated in the GCMs and in the hydrological models. This enables us to suggest some guidelines for further water resource planning studies in the region in chapter 8.

At the end of the day, water resource planners are still faced with decisions as to whether to plan for the future on the basis of the climate model scenarios or on some other basis, such as that the future will be like the recent past. We explore these sorts of choices for some typical water resource applications in the basin. Our examination of the consequences of planning on the basis of the different scenarios is directed particularly at discovering whether planning decisions and outcomes would be sensitive to the GCM basin climate scenarios. This work is presented in chapter 9, along with an outline of key diagnostics for assessing the suitability of using GCMs for water resource impacts studies, and a list of research priorities for improving information on basin climate impacts.

If I were to tell this story the way history is usually written or the way each of us recalls his own past, which means recording only the most glorious moments and inventing a new continuity for them, I should omit these little details and say that our eight stout hearts drummed from morning to night in time with a single all-encompassing desire — or some such lie. But the flame that kindles desire and illuminates thought never burned for more than a few seconds at a stretch. The rest of the time we tried to remember it.

René Daumal
Mount Analogue

Chapter 2

Water Resources and the Sacramento Basin

We chose the Sacramento Basin in California as our case study region for examining climate impacts studies on water resources. This chapter outlines the rationale for that choice, and describes the characteristics of the basin and its water resource issues. Further, we review existing climate impacts studies on the basin's water resources, and describe the synoptic-climatological factors influencing precipitation in the basin. This provides the grounding for later work to assess the ability of the climate models to simulate the critical synoptic-climatological features.

2.1 Selection Rationale

One of the biggest problems with interdisciplinary work like climate impacts studies is the extraordinary breadth of information that is relevant to the work. Some narrowing of scope is necessary to make useful progress. The major decisions that focused this project down to a tractable length are discussed in the following sections.

2.1.1   Water

We chose to focus on climate change impacts on water resources (rather than forestry, or agriculture for instance) since water resource issues underlie most climate impacts problems. For example, climate impacts on agriculture are often rooted in factors like the amount, timing, and quality of available water. Further, water resource issues are among the most persistent current environmental problems, and are likely to increase in importance in the coming century.

2.1.2   Case Study

We chose a *particular region* to study, the Sacramento Basin in California, deliberately. By doing this, we can structure our assessment of GCM capability in terms of this one region and its water resource problems. This ensures that our assessment of GCMs is carried out in concrete terms with direct policy relevance. We seek to bridge the efforts of those who carry out impacts studies using GCMs without assessing the appropriateness of GCMs for their task, and those of climate modellers who develop GCMs without considering the application of GCMs to particular policy problems.

2.1.3   Sacramento Basin

We chose the Sacramento Basin for several reasons. Precipitation in the Sacramento Basin is principally determined by large scale synoptic systems. This offers GCMs a better chance of succeeding here, since they do better at simulating larger scale features. In other regions of the world the task of simulating the local precipitation with fidelity is likely to be even more difficult[1]. This suggests that any

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[1]In midcontinental regions of the U.S. for instance, there is a substantial precipitation contribution from summertime mesoscale convective systems. Correct simulation of the precipitation in these regions is more explicitly dependent on parameterized sub grid scale convection in the climate models.

problems for GCMs encountered in our study region are quite likely to be salient in other regions too.

The Sacramento Basin has been the subject of a number of climate impact studies. This provides a suitable basis of past work to highlight potential issues of importance in the basin, and to assess the methodologies and assumptions used in climate impacts studies of the basin. Observations of hydrological quantities are scarce on much of the planet, and the Sacramento Basin region is one of the better observed regions. This is important for comparison of the model performance with the real world. Finally, the Sacramento Basin is important to the economy of California and the U.S.. We elaborate on specific water resource issues in the basin in section 2.4.

2.1.4 Current Climate

Most of the assessment of climate models in this work concentrates on their *current climate* or 'control run' simulations rather than on their simulations of greenhouse climate change. One of the main reasons for examining the current climate runs is to compare the model simulations of various features with their observational counterparts. There are no direct observations of enhanced greenhouse climates and it is therefore difficult to compare the model simulations with real world processes in that case.

In focusing on current climate simulations we are making the assumption that simulating the present climate well is a prerequisite for simulating the changed climate. There are some important caveats to this assumption however. It is possible that if the errors in climate model simulation of the current climate are small and systematic *and* if the climate change in question is small[2], that the

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[2]That is, if the climate change is small enough that a change may be considered to be a more or less linear perturbation from its mean state. The extent of linearity/nonlinearity of the climate response to enhancements in greenhouse gas concentrations is an open question. Palmer (1993) notes that the instability properties of the

model *may* still simulate the change correctly. For this reason it is important that the diagnosis of the models go beyond a simple finding of errors to try to relate their presence to physical or numerical processes where possible. If model errors can be related to the representation of physical processes, then one can begin to assess the importance of the errors by knowing something about the role of the processes. This provides further impetus to examine the model simulation of the important processes and features associated with precipitation in the Sacramento Basin region.

In examining current climate simulations, there is a second caveat that the presence of small or minor errors in the model simulation does not neccesarily mean that the model will contain only small errors for the quantity of interest in a climate change simulation. It may be for instance that the climate change is strongly nonlinear for the hydrological quantities of interest. It may also be that the climate model produces the right current climate for the wrong reasons. That is, there may be compensating errors in the model which become important when the model climate is forced to a new climate state. This problem is best addressed in the same manner as above: by relating the presence of errors to physical processes where possible.

Lorenz model for instance, are not uniform around the attractor. That is, the influence of forcing on the model is felt more keenly in some areas of the phase space. If the current climate in the GCMs is in error, then the model climate will effectively occupy a different part of the phase space than the real climate. The model climate attractor may then undergo the same translation as the real climate attractor in response to forcing, but the model climate will occupy different portions of the attractor with different frequencies than the real climate. One manifestation of this would likely be differences in regional climate between the climate model and the real climate — even when the climate change is inferred from the difference between the climates of the perturbed run and control run.

2.2 Basin Characteristics

The Sacramento Basin is located in northern California. Figure 2.1 shows the basin boundary and major rivers. Changes in water availability in this basin are already felt at many levels and any significant change in the timing or magnitude of streamflow due to changes in climate will have important societal implications. The Sacramento basin is a highly managed and monitored water resource system, partly because it supplies water for one of the most productive agricultural regions in the world (EPA, 1989). The following sections describe physical and societal characteristics of the basin in more detail.

Figure 2.1: The Sacramento Basin, California [from Gleick, (1987)]. Topographic representation of California [from McPhee, (1993)].

2.2.1   Physical Characteristics

There are four major rivers draining the Sacramento Basin: the Yuba, the Feather, the American, and the Sacramento. The Yuba drains the northern part of the Sierra Nevada mountain range before emptying into the Sacramento River. The Sacramento River drains the northern part of the basin and the Central Valley before leaving the basin near Sacramento. The low point in the basin is near sea level, and the high point is the crest of Mt. Shasta, at an elevation of over $4,300m$. The Sierra Nevada ridge line forms the eastern boundary of the basin, and the crest of the coast range bounds the western edge of the basin. The basin comprises two distinct regions: the long, low agricultural basin known as the Central Valley, and the northern end of the Sierra Nevada mountain range.

Precipitation has a highly seasonal distribution in the Sacramento Basin, following the wintertime maximum characteristic of the west coast of North America. The winter precipitation falls primarily in midlatitude storm systems moving across the coast from the Pacific Ocean. The wet season begins in late autumn (October and November) and extends through the spring. The wintertime precipitation generally falls as rain in the valley and snow in the Sierra Nevada. The dry season is characterized by very little or sometimes no precipitation, and extends from late spring through the summer months. Storm systems tend not to move across the California coast in summer because of the presence of a persistent ridge in the Pacific Ocean basin during this season. The extremes in mean annual precipitation in the basin range from $50cm$ to $75cm$ in the valley to $175cm$ in higher mountain elevations. The basin average precipitation is about $1m/year$. The interannual variability of basin precipitation is large, with amounts as low as $\frac{1}{2}m$ in extreme dry years and up to $2m$ in extreme wet years. Peak runoff in the basin currently occurs between February and May. The Sacramento Basin produces over 30% of the total runoff in California. The peak runoff lags the peak precipitation period principally because the Sierra Nevada snowpack stores precipitated water until the spring melt.

2.2.2   Societal Characteristics

The Sacramento Basin contains numerous reservoirs to regulate the flow of water from the basin and to provide storage, flood control, and hydroelectricity. Major water resource projects have been built in the Central Valley and surrounds – the Central Valley Project and State Water Project – whose function is "basically to capture runoff from the north and deliver it to uses in the south" (EPA, 1989). The bulk of California's water resources are in the northern section of the state, while most of the demand for water comes from the southern section. The Sacramento Basin supplies most of the the agricultural water that is transferred from northern California to southern California. Existing water usage in the basin is heavy, with over 90% of the total dependable water supplies used annually, either within the basin or after export out of the basin. Over 90% of the water consumed within the basin goes to agriculture. Peak water use occurs during the summer. California annually produces about 10% of the cash farm receipts for the U.S., and produces nearly $18 billion annually in farm income[3].

Table 2.1 summarizes some of the pertinent physical and societal characteristics of the Sacramento Basin.

2.3   Climate Impacts Studies

There have been several climate impact studies on water resources in the Sacramento Basin region over the last half dozen years. Gleick (1987) used a simple water balance hydrological model driven with observed precipitation and temperature time series to reproduce the observed hydrological variability in runoff and soil moisture conditions in the Sacramento Basin. To assess potential climate change effects on runoff, Gleick adjusted the observed time series of temperature and precipitation by the changes produced in temperature and precipitation in the

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[3]These are official figures, and may not include trade in illegal agricultural commodities.

Area	$41,000km^2$
Area of a 2° × 2° grid square for comparison	$\sim 50,000km^2$
Area of a 4° × 5° grid square for comparison	$\sim 250,000km^2$
Area of an 8° × 10° grid square for comparison	$\sim 1,000,000km^2$
Irrigated crop area	$8,500km^2$
Population	1,700,000
Reservoir capacity	$17 \times 10^9 m^3$
Average annual runoff	$22 \times 10^9 m^3$ ($\sim$ 50% of precipitation)
Peak runoff season	February – May
Average annual precipitation	$90cm$ ($40 \times 10^9 m^3$)
Peak precipitation season	winter
Average annual temperature	$13°C$
Net use of dependable water supply	$9 \times 10^9 m^3$ ($\sim$ 25% of pcp; $\sim$ 50% of runoff)
Total developed water supply	$10 \times 10^9 m^3$ ($\sim$ 25% of pcp; $\sim$ 50% of runoff)
Agricultural water use	$\sim$90% of net water use
Urban water use	$\sim$7% of net water use
Peak water use season	summer
Exports of water to other basins (1980 figure)	$6 \times 10^9 m^3$

Table 2.1: Summary physical and societal characteristics of the Sacramento Basin. Adapted and extended from Gleick (1987).

region from GCM doubled CO_2 and current climate runs[4]. This procedure was carried out using output from several GCMs to assess the response of streamflow to a range of climate change scenarios. Lettenmaier and Gan (1990) used a similar technique to assess potential climate impacts on the Sacramento – San Joaquin Basin[5]. They used a more physically based coupled snow-melt and soil moisture accounting hydrological model. These studies also tested a range of hypothetical precipitation and temperature change scenarios. The most consistent result that

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[4]In this procedure, usually the climate model $2 \times CO_2 - 1 \times CO_2$ temperature differences are added to the observed temperature data, and the observed precipitation data is multiplied by the ratio $2CO_2/1CO_2$ of the climate model precipitation.

[5]The San Joaquin Basin lies immediately to the south of the Sacramento Basin.

emerges from these studies is that runoff in the Sacramento Basin would be more concentrated in the winter wet season in response to the climate model greenhouse scenarios for the region. This is largely a temperature effect due to earlier melting of the snowpack and to an increase in the amount of precipitation that falls as rain rather than snow.

Dettinger and Jeton (1994) used a physically based precipitation-runoff hydrological model to study the sensitivity of the American River basin to climate change scenarios. The American River is one of the major rivers in the Sacramento Basin. They also adjusted the station precipitation and temperature data in their model for climate change runs by hypothetical amounts and according to changes from GCM doubled CO_2 and current climate runs. They found that the

> simulated changes in streamflow timing echoed changes in snowmelt, sublimation, and ET, and were in predictable directions; specifically, warmer scenarios caused earlier runoff as snowmelt was hastened, whereas cooler scenarios postponed snowmelt and peak runoff. Wetter and drier scenarios mostly affected volumes of streamflow and other hydrologic fluxes rather than their timing.

Duell (1994) used a regression model to simulate streamflow response in the American river to climate changes and found qualitatively similar results to Dettinger and Jeton. The regression models are not as well suited for providing quantitative guidance for climate change scenarios. This is because the changes in precipitation and temperature in the climate change scenarios require extrapolation of the regression models, which have no explicit physics, beyond the domain of their estimation.

There are a number of ways in which each of the above studies might be improved. We will defer suggestions along this line until section 8.4, after examining the hydrological sensitivity of the basin and its climate model inputs.

2.4   Climate Related Policy Issues

The climate impacts studies for the Sacramento Basin reviewed above collectively suggest that plausible changes in temperature and precipitation in the region induced by greenhouse climate change could have major impacts on the *amount*, and particularly the *timing*, of streamflow in the basin. In this section we outline some of the issues that would be posed for water resource planners in the Sacramento Basin if these streamflow changes come to fruition. While it is convenient to denote the changes in streamflow implied by the impacts studies according to changes in amount and changes in timing, water resources planners are more properly interested in the entire streamflow regime. The streamflow regime would refer to changes in mean (amount), extremes and duration of extremes (amount and variability), and seasonal distribution (timing). One of the shortcomings of the climate impact studies reviewed above is that the method of generating climate change scenarios by adjusting existing station data by GCM $2CO_2 - 1CO_2$ differences does not allow for changes in climate variability in the basin. This precludes a potential source of changed variability in the streamflow response.

The crux of the problem related to potential changes in the amount and timing of streamflow in the Sacramento Basin has been expressed by Gleick (1986):

> The most important unanswered question relating to changes in climate and the design and operation of storage systems is whether or not systems designed for today's basin-specific hydrological characteristics will be capable of adapting to new hydrological characteristics with changes in operation only. If changes in the operating system alone are insufficient to deal with new runoff characteristics, then expensive, long-term design changes may be required.

In order to assess whether the existing infrastructure can cope with climate induced changes in the streamflow regime and meet projected demands, water resource planners need to have quantitative as well as qualitative information on expected changes in the amount and timing of streamflow. The ability to provide useful quantitative information on streamflow changes will depend in part on

the utility of climate models in providing useful information to the hydrological models.

2.4.1   Streamflow Timing

Warmer basin temperatures and changes in the timing of streamflow toward a peak nearer winter than spring would cause problems. Some of the reasons for this are as follows:

Flooding: The risk of flooding would be increased. The precipitation maximum currently occurs in the winter. If more of the precipitation runs off then and is not stored in snowpack, then the capacity of the system, which has been designed for a gradual release of winter snow, may be exceeded. EPA (1989) notes that current reservoirs in the basin would not have the capacity to store the heavier winter runoff and at the same time retain flood control capabilities.

Water Supply: Available water supply would be diminished. This problem has been characterized by EPA (1989) who note that:

> Given current operating rules and storage capacity, much of the higher winter runoff would be spilled from the reservoirs to maintain enough storage capacity to capture heavy runoff later in the rainy season and thus prevent downstream flooding. When the threat of floods decrease at the end of the rainy season in the spring and the reservoirs could be filled, runoff into the system would be reduced because of the smaller snowpack. Thus, total storage would be lower at the end of spring and water deliveries would be lower during the dry summer months.

With system changes, the earlier winter runoff could be captured and stored for later use. Whether this would entail simple diversions and operational changes in the existing infrastructure or construction of new storage facilities would depend on the increase in magnitude of the winter runoff.

Water Quality: Water quality would be threatened. A reduction in streamflow in the basin in the late spring and summer could adversely affect aquatic

organisms and wildlife because of the reduced volume, which tends to concentrate pollutants more. The dimension of the water quality risk would depend on the amount of the spring and summer streamflow reductions. Nash (1993) provides a comprehensive review of the impacts of the recent California drought on aquatic organisms and wildlife.

2.4.2   Streamflow Amount

The climate impacts studies performed on the Sacramento Basin suggest that streamflow amount will respond proportionally to changes in precipitation amount in the basin. Climate model projections of greenhouse induced regional precipitation changes are, however, highly uncertain (Grotch and MacCracken, 1991). While a number of GCMs suggest small increases in overall precipitation amount in the region, changes in variability of precipitation and streamflow may be as important as changes in the mean. Greenhouse climate change may give rise to a change in variability of the streamflow in the Sacramento Basin, with perhaps longer and more intense drought episodes, such as the basin recently experienced (mid to late 1980's). Short and long term reductions in streamflow in the basin have a number of implications:

Supply and quality: Reductions in streamflow pose water supply and water quality risks, as for the change in seasonality of streamflow listed above. Sacramento Basin water is vitally important for California agriculture, and any long term drought in the basin would have significant impacts. Estimates of farm losses for 1991 during the recent California drought are of the order of a billion dollars (ACWA, 1991). The California Department of Water Resources estimated that about 800,000 acres of farmland were idle during 1991. Even with the reduced crop acreages, groundwater overdrafts were well beyond the basin's safe yield in many regions. Water supply for California agriculture may also be an issue because of greenhouse induced decreases in summer soil moisture. This would lead to an increased demand

for irrigation water to avert any increase in the moisture stress experienced by crops.

Hydroelectricity: Reductions in streamflow threaten hydroelectric production in the basin. Gleick (1986) notes that during two consecutive drought years in the basin — 1976 and 1977 — "reductions in runoff caused the loss of large portions of normal hydroelectricity production, which in turn forced the state to burn additional fossil fuels (an additional 33 million barrels of oil equivalent) at a cost of \$500 million". The California Energy Commission estimates that the recent drought (1987 – 1992) halved hydropower production in the state.

Saline intrusion: Reductions in streamflow would allow the incursion of saline tidal water into the upper part of the Sacramento – San Joaquin river delta above San Francisco Bay. The Sacramento – San Joaquin river delta is the source of all water exports to points further south (EPA, 1989). Freshwater outflow (carriage water) must be maintained at the required levels to prevent saltwater intrusion into the pumping plants in the upper delta which are the terminus for water exports to the south. The problem of salt intrusion in the upper delta is compounded by potential salinity changes in the basin brought about by possible greenhouse induced sea level rise. For a $1m$ sea level rise scenario, initial application of a salinity model to constant delta outflows indicates that the monthly carriage water requirements might have to be doubled to repel saline water from the upper part of the delta (EPA, 1989).

Industrial disruption: Much of the present high-tech industry and food processing firms in California depend on water supplies. ACWA (1991) reports an estimate that a single year shortage of 30% in water supplies could cost the state \$8 billion in lost production.

Given the potential for greenhouse climate induced streamflow changes in the Sacramento Basin to have the sort of impacts outlined above, it is all the more important to assess the fitness of the climate models in producing regional climate

change scenarios for the hydrological impacts studies. We begin this process in
the next section by outlining the factors influencing the regional climate and
streamflow of the Sacramento Basin.

2.5 Climate Variability and Streamflow

The processes influencing climate variability and streamflow in the Sacramento
Basin region occur across a broad range of spatial and temporal scales. We at-
tempt here to outline the most important processes, most of which are explicitly
or implicitly represented (albeit imperfectly) in state of the art climate mod-
els. We concentrate mostly on variability of precipitation and temperature in
the Sacramento Basin region, since these are the climate input variables used to
drive hydrological models of the basin. Precipitation is the single climate vari-
able that most directly relates to streamflow in the basin. We concentrate less on
temperature, which is in general easier to simulate in GCMs than precipitation
due to its higher spatial coherency. The region of interest occasionally includes
the whole west coast, since there are important synoptic scale processes that ag-
glomerate over that scale. Precipitation all along the west coast is part of a large
scale winter precipitation regime incorporating atmospheric and oceanic circula-
tion events in the northern hemisphere Pacific basin and surrounding continental
regions. In addition, factors that are currently not so important for Sacramento
Basin precipitation, but are important for precipitation along other parts of the
west coast may become important for the Sacramento Basin if there is a change
in the equator-to-pole temperature gradient in response to greenhouse climate
change for instance.

At the largest scales — Pacific basin scale and global scale — a weak source
of precipitation variability in California is provided by the El Niño - Southern
Oscillation (ENSO) phenomenon. ENSO derives from low latitude atmosphere-
ocean interactions, but is associated with precipitation anomalies covering much
of the globe. ENSO is associated with large negative pressure anomalies in the

central and eastern North Pacific. Anomalously deep central North Pacific lows occur in the northern hemisphere winter during the mature phase of ENSO. The central North Pacific teleconnection is one of the strongest extratropical responses to ENSO (Cayan and Peterson, 1989). One effect of the central North Pacific pattern is to generate wind patterns that pump warm moist subtropical air toward the west coast, resulting in generally warm and rainy conditions (Roden, 1989). The degree of warming and the intensity of rainfall depends upon the latitude of the storm tracks and the proximity of the low pressure pattern to the coast, so not all ENSO's have identical effects. Sacramento Basin region streamflow and precipitation is weakly correlated with the Southern Oscillation Index. Cayan and Peterson note that this is because California lies between the active centres of the strong central North Pacific pattern. ENSO correlations are better for precipitation in the south western U.S. Should the centres of the North Pacific pattern shift in a changed climate, the ENSO influence on California precipitation could be modified.

The atmospheric longwave pattern is crucial for the climatology of California and west coast precipitation. California is close to the node of the atmospheric long wave pattern emanating from the central North Pacific, so small variations in the position of remote central North pacific circulation anomalies (as regulated by the long wave pattern) can yield precipitation fluctuations in the region.

The Aleutian Low is the source of the largest monthly and seasonal scale variability in the northern hemisphere. The Aleutian Low is generally lower (pressurewise) during winters with frequent cyclone passages and higher during winters when these cyclone passages are less frequent, less intense, or diverted to another location. The Aleutian Low undergoes marked year to year changes in activity. The strength of the Aleutian Low in winter is often represented by the Pacific North America index (PNA), which is the average of the sea level pressure (SLP) anomaly south of the Aleutians and the western gulf of Alaska. Correlations between the PNA index and regional anomalies reflect alterations in the strength and position of the mean north Pacific storm track entering North America as well as shifts in the trade winds over the subtropical North Pacific. In winter, the

North Pacific storms are most active and the anomalous atmospheric variations are greatest. Precipitation along the broad west coast region is strongly affected by the orientation of the North Pacific storm track.

The locations of the storm tracks are closely associated with the jet stream and long wave pattern. Roden (1989) notes that:

> The dynamics of climate variability along the Pacific coast of North America are, to a large extent, controlled by the atmospheric jet-stream. Jets generate vorticity, and jets with large meanders can generate strong vorticity. Associated with jetstream vorticity are the high and low pressures at the sea surface, around which the large scale surface winds tend to blow. The jetstream variability is strongest in winter. Thus much of the climatic variability is generated during the cold season. The jetstream does not develop persistent large amplitude meanders and associated semistationary large surface pressure distubances every winter. When it does so, there are usually several intense pressure anomaly centers in the northern hemisphere with attendant large-scale anomalous patterns of air flow, ocean currents, precipitation, and temperature occuring nearly simultaneously in widely separated geographical regions.

Extreme winter flooding events in the Sacramento Basin region have been associated with jetstream meanders, the presence of a blocking high over the Pacific Northwest, and a southward displacement of the Pacific storm tracks, which pumps warm moist maritime air into California (Roden, 1989).

Near-coastal synoptic scale pressure anomalies are very important for west coast precipitation. The SLP pattern most reliably correlated with anomalous precipitation in California is located off the coast, west or northwest of California — the "coastal basin pattern" (Cayan and Peterson, 1989). An anomalous low pressure centre to the west or northwest in winter provides heavier precipitation, while an anomalous high pressure centre there results in reduced precipitation. The low pressure anomaly indicates increased storminess that is carried onshore from the northeast Pacific. Enhanced southerly to southwesterly flow is associated with the anomalous low, and represents an aggregate of weather systems that produce stronger advection of moisture and vorticity as well as increased upslope

vertical motion along the west coast mountain ranges. Atmospheric patterns producing heavy precipitation and streamflow in California generally apply locally to California only. Dryer anomalies are often shared over broader regions of the west and southwest (Cayan and Peterson, 1989). During the summer dry season (not to be confused with dryer winters as above), precipitation along the west coast is cutoff when the mid-Pacific ridge settles into position.

The precipitation amount, distribution, and variability in the Sacramento Basin is also influenced by mesoscale features and processes such as topography, vegetation, surface roughness and dryness, and snowdepth. The topography of the basin is effectively fixed on the time scales of climate change we are concerned with, though its representation varies with resolution in the climate models. We address this issue in chapter 7. The land surface may feed back on precipitation at local scales and at continental scales as during the 1988 U.S. drought for instance (Trenberth et al. 1988). This sort of coupling is probably weak in the Sacramento Basin due to its downwind proximity to the ocean during storm events.

Changes in ocean circulation are also sources of west coast precipitation variability. Fluctuations in the orientation and temperature of the California current (running south along the west coast) influence local atmospheric circulations and the moisture content of coastal storms. While the GCMs we examine do not allow for changes in ocean circulation, we will examine output from an AMIP run that includes observed SSTs in chapter 7 as a way to assess the potential importance of oceanic circulations for Sacramento Basin precipitation.

Table 2.2 lists some of the features associated with precipitation in the Sacramento Basin, together with a qualitative assessment of their relative importance. In assessing the models and observations we pay particular attention to these features and their association with one another in setting the precipitation regime in the Sacramento Basin region.

Process or Feature	Scales of Action	Importance
ENSO	$10,000km$; months to years	low now, potentially high
Longwave Pattern	$10,000km$; weeks	very high
Aleutian Low	$1,000km$; weeks to months	high
Jet Stream	1000's of km; week	high
N. Pacific Storm Track	$1,000km$; days to weeks	high
Blocking High	$1,000km$; weeks	moderate to high
California Coastal Low	100's of km; days	high
Mid Pacific Ridge	$1,000km$; weeks	high for no-precipitation
Topography	$100km$	high
Land Surface	$100km$; weeks to seasons	low
Snowpack	10's of km; season	low
Ocean Circulation	100's to 1000's km; months	moderate

Table 2.2: Features Associated with Precipitation in the Sacramento Basin Region.

2.5.1   Assumptions in Synoptic Climatology

The work described in this section and carried out in chapter 6 is the subject of 'synoptic climatology', which studies the relationships between the atmospheric circulation and the surface environment of a region. The work of synoptic climatology is fraught with some peril, for the reason that there is no general theory that links the atmospheric circulation with the surface environment. As Yarnal (1993) puts it:

> Perhaps the biggest problem in synoptic climatology is that there is no clearly articulated theory, methodology, or sense of purpose.

The links established between the atmospheric circulation and the surface environment are usually based on a combination of theoretical and empirical considerations, as they are in our case. Yarnal outlines a number of assumptions that are characteristically made in synoptic climatology studies. We review the quality of each of these assumptions for this work linking the large scale circulation with Sacramento Basin precipitation:

The atmospheric circulation is a critical determinant of the surface environment: This is a particularly good assumption for Sacramento Basin precipitation, which is deposited in synoptic storm systems following the North Pacific storm tracks across the west coast of North America. Interactions between the atmospheric circulation and the basin topography are also important in setting the precipitation regime.

The atmosphere can be partitioned into discrete, non-overlapping intervals: This assumption would apply to our classification of wet and dry modes, periods, or regimes in the Sacramento Basin. We sometimes plot ensemble circulation averages for wetter than normal and drier than normal Januaries or winters in the basin for instance. This obscures some intramonthly and intraseasonal variability during these periods, but we also examine circulation features during individual storms where there is little overlap between wet and dry. For precipitation this assumption is usually valid, as precipitation tends to be more discrete across a range of time scales than most atmospheric variables.

The classification identifies all important map patterns or synoptic types: It is hard to be completely certain that our review of the factors controlling Sacramento Basin precipitation has not overlooked some factors, though it is unlikely to exclude many important factors. The relationships between precipitation and the synoptic circulation in this basin have been extensively studied. Furthermore, the synoptic storm systems in the region are part of the northern hemisphere midlatitude general circulation, whose primary features — stationary waves, jet streams, storm tracks, persistent anomalies, etc. — have also been extensively studied on theoretical and empirical grounds. The basin's precipitation regime is almost classical in following traditional midlatitude storm mechanisms.

The temporal scales of the observations and the atmospheric circulation processes match: The large scale circulation features such as stationary waves, jet streams, and storm tracks are well resolved by the observational network. We study their characteristics from daily data over monthly and seasonal (winter) time scales. This is sufficient to describe the characteristics of these features that persist on these time scales. Because information about the response of these features in individual storms is lost on these time scales, we also analyse daily data in section 6.6.

The spatial scales of the gridded data and the circulation coincide: This assumption is also a good one in our case because the features we are interested in occur on synoptic scales and larger scales, which are resolved in both the gridded observations and climate models.

Within group variability is not a problem: The large scale circulation features we examine exhibit variability on a variety of time scales. We obtained observational data to describe them from a variety of sources, and covering a range of periods, to become familiar with the characteristic variations of the features. In classifying storms in the Sacramento Basin, we analyse circulation features for a reasonable number of storms and remain sensitive to variations from storm to storm.

The classification methods really do what the investigator thinks they are doing: The variables we use to classify the stationary waves, jet streams, storm tracks, persistent anomalies, and local circulations in the region have been used successfully by many investigators for the same classifications. We use these features to describe the large scale and regional circulation, which is also a well established practice.

Our study of the synoptic climatology of the Sacramento Basin is relatively uncontroversial as far as the assumptions above go. We feel confident that we have a reasonable foundation for the work in chapter 6 on the synoptic climatology of the large scale circulation features controlling Sacramento Basin precipitation. The more difficult aspect of this work is in assessing just how good the GCM

simulations of the large scale circulation features need to be in order to trust the model simulations for use by nested mesoscale models or basin hydrological models. This aspect of the problem is discussed in section 9.4.3.

"Now here, at least," he said, "is something relatively real, *if one can risk combining these two words without causing an explosion.*"

We sat down facing one another across one of those fine country stews in which every vegetable in season weaves its savour around a piece of boiled animal.

"My good Physics still has to use all her old Breton skill to put on this table a meal in which there is no barium sulphate, no gelatin, no boric acid, no sulphuric acid, no formaldehyde, and none of the other drugs now used by the food industry. A good stew is worth more than a false philosophy."

René Daumal
Mount Analogue

Chapter 3

Observational Data Sets and Model Output

The principal data sources used in this study are from climate models and from observations of the Earth's climate. The data cover spatial scales from global to that of point stations in the Sacramento Basin, and temporal scales from hourly to monthly over extended time series. This section describes the principal data sources, beginning with the observations. The main observational variables used are precipitation, surface air temperature, sea level pressure, 200hPa zonal wind, 500hPa geopotential height, and streamflow. These variables were the best available that help describe the climate and processes of interest in our study region. The particular reasons for choosing each of them are given in the initial instance of their application throughout the thesis.

3.1   Observations

The observational data employed here is used to describe the nature of the Sacramento Basin climate regime across a range of relevant scales, and for use as a measure to assess the performance of the climate models. Since the observations themselves do not represent actual 'truth', we have used multiple data sets where possible, either by taking data from different sources or by dividing the observations into separate time periods, or both. The observations used were among the

best or only available sources at the time. This work entailed use of long term gridded[1] observational data sets, which are rare for quantities like precipitation, or have been 'blended' with model output in the case of upper level quantities. These latter data sets might best be termed something like 'modservations' to convey their hybrid nature. The modservations are most heavily biased towards the model output in the data sparse regions where the blending schemes rely on model fields to fill data gaps. This becomes an issue in cases such as ours where modservations are used to assess model output. We have tried to be sensitive to this issue in interpreting results, and have limited our domain of interest to the more densely observed northern hemisphere.

3.1.1   DOE Gridded Precipitation

We use the Department of Energy (DOE) gridded precipitation data of Eischeid et al. (1991) to characterize precipitation over the western U.S. region containing the Sacramento Basin. This dataset contains monthly values of precipitation smoothed to a 4°latitude × 5°longitude grid for the period 1951 – 1989. This dataset provides good coverage over land areas, but almost no data over the oceans where sufficient coverage to provide time series of monthly values is not available from *in situ* sources[2].

We retained only the land grid boxes over North America in our analysis. The station data used to compile the gridded values were individually tested by Eischeid et al. (1991) for the presence of spurious trends, jumps, and other measurement biases. The density of stations used in the analysis over North America is relatively high. Furthermore, the gridded values over North America are fairly insensitive to the number of stations used in the gridding. Eischeid

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[1]The term 'gridded' data refers to data on a latitute – longitude grid.

[2]There are gridded precipitation data sets over the ocean regions, but these are for either a single climate average over a long time period, or provide only very short time series of a few selected years from satellite measurements.

(personal communication) recalculated grid values for different station densities — fixing the number of stations at their actual densities for each decade from the 1870's and redoing the gridding backwards and forwards in time to compare with the grids calculated with modern station densities. The results were similar in each case.

3.1.2 NMC Gridded Data

We obtained monthly values of gridded ($5°$latitude $\times$ $5°$longitude) surface air temperature and sea level pressure from the NCAR Data Support Group. These grids were derived from NMC analyses. Though there are some problems with the NMC temperatures in the polar region (Colony and Rigor, 1992), the temperature and sea level pressure fields are reasonably well determined. For instance, Trenberth and Olson (1988) evaluated global analyses from NMC and ECMWF and concluded that:

> There is fairly good agreement between the analyses over the extratropics of the NH so that some variables, including the rotational wind, geopotential height, and temperature, can be considered to be reasonably well know there.

This is also true of sea level pressure in the northern hemisphere extratropics. Our analyses are fortunately limited to the northern hemisphere extratropics. Trenberth and Olson find that problems with the NMC and ECMWF fields mostly arise in the southern hemisphere where data is sparse, and for particular variables such as the divergent wind, vertical motion, and humidity.

We also obtained daily values of 200hPa zonal wind, 500hPa geopotential height, and sea level pressure on the $5° \times 5°$ grid for the 1970's and 1980's. Daily time series data was necessary to examine individual storm events in the Sacramento Basin region and to calculate various time filtered quantities in describing the synoptic climatology of the North Pacific North America region.

We used monthly time series of 1000–500hPa thickness data from 1946–1993 for just the grid boxes located immediately near the Sacramento Basin to examine the average temperature of the lower troposphere over the region.

3.1.3 ECMWF Gridded Data

There are various archives of ECMWF global analyses on the 'Mass Store' at NCAR. These data sets and their characteristics are described in Trenberth (1992). We used the 'CCM Processor' (Buja, 1993) to extract monthly and daily gridded data from the ECMWF WMO archive. This archive spans the time period from December 1978 through December 1989. We extracted 200hPa zonal wind, 500hPa geopotential height, and sea level pressure to compare with the NMC data. The data were extracted on an R15 grid corresponding to 4.5°latitude × 7.5°longitude. As for the NMC data, the variables examined and region of analysis (NH extratropics) correspond to the higher quality fields in the dataset.

3.1.4 Sacramento Basin Data

The Sacramento Basin is one of the most intensively recorded watershed regions in the world, with instrumental observations of precipitation, streamflow, and temperature covering much of this century. We obtained monthly and daily time series of precipitation and monthly time series of streamflow from the California Department of Water Resources (DWR), along with monthly time series of temperature from the California State Climatologist.

The monthly precipitation data spans the period from water year 1920 to water year 1991. A water year runs from October to September and is denoted by the year in which January occurs. The water year period is convenient in California as precipitation in the region is highly seasonal with a winter maximum that is encompassed within the water year. The California DWR has a standard precipitation index for the Sacramento Basin — the "8 station index" — which we used. Precipitation data is averaged from the following eight stations to produce

the index: Mount Shasta City, Shasta Dam, Mineral, Quincy Ranger Station, Brush Creek Ranger Station, Sierraville Ranger Station, Blue Canyon, and Pacific House. This cluster of stations was picked because it provides continuous reliable records from representative sites spanning the basin.

The California DWR's standard measure of streamflow or unimpaired runoff[3] for the Sacramento Basin is defined as the sum of flows of the Sacramento River at Bend Bridge, the Feather River at Oroville, the Yuba River at Smartville, and the American River at Folsom. These are the major rivers in the basin. The four river index monthly streamflow record provided by the DWR spans the period from water year 1906 to water year 1992.

While the monthly time series of precipitation serves to define the seasonal characteristics of the basins precipitation regime, we are also interested in basin precipitation on shorter time scales such as during individual storms. Reliable continuous records of daily precipitation data are much harder to come by than monthly records. We were able to obtain good daily records for three stations in the basin: Blue Canyon, Mineral, and Shasta. The three station daily precipitation index defined from these stations spans the period from 1979 to 1988. As a check on the reliability of this index we calculated monthly means from the daily data and compared this time series with the 8 station monthly precipitation index over the period of common record from 1979 to 1988. The curves agree very well, and the magnitude of the 3 station index is marginally higher than the 8 station index as would be expected.

We use temperature records of the Sacramento Basin in analysing the sensitivity of streamflow in the basin to precipitation and temperature. We averaged temperatures from five representative stations in the basin to obtain a monthly temperature index. The stations used in this case are: Nevada City, Quincy, Sierraville, McCloud, and Canyon Dam. We compared this temperature index with others defined by different mixes of stations in the basin and obtained similar

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[3]Unimpaired runoff provides a measure of river flows upstream from artificial diversions of the flow. About half of the runoff is diverted for various uses.

results in each case. There is some variation in the magnitude of the average temperature depending on the elevations of the stations selected, but the variation is small, and the trends are very similar.

3.2   Models

This section provides brief descriptions of the various models used in this work. In each case we analysed output from the climate models or hydrological model which had been run at other institutions on prior occasions. In the case of the climate models it would not be practical to run a suite of models *in house* because of the enormous resources that would be required to do that. The main limitation of extracting output from prior models runs is that the user is limited to the set of variables that has been archived by the climate model group.

3.2.1   Climate Models

The climate models we analyse and compare with observations are various versions of the NCAR and GISS GCMs. We chose GCMs from these particular groups because the latest versions of their climate models are typical of the *state of the art*[4] in climate modelling, and output from their climate models has been widely used by the climate impacts community in driving regional models of water, crops, and so on for climate impact assessment. In addition, we had reasonable access to the output from climate runs at these groups.

We acquired output from ten year runs simulating the current climate with the NCAR CCM1 (Community Climate Model version 1) at resolution R15, the

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[4]We understand that this designation to describe any particular climate model is usually somewhat contentious. We have tried to use reasonable standards in denoting models as state of the art or not so. The difficulty can be seen in the observation that virtually *all* climate modelling groups reserve this label for their own model and are usually not so generous in so denoting other models.

	CCM1	CCM2	GISSII' (GISS 4°×5°; GISS 8°×10°)	GISSII'' (GISSAMIP)
model type	spectral	spectral	grid point	grid point
horizontal resolution	R15 (4.5° lat × 7.5° lon)	T42 (2.8° lat × 2.8° lon)	4° lat × 5° lon 8° lat × 10° lon	4° lat × 5° lon
vertical resolution	12 levels	18 levels	9 levels	9 levels
vertical coordinate	σ	hybrid (σ to 100mb) (pressure above)	σ	σ
time step	30 minutes	20 minutes	7.5 minutes	7.5 minutes
control length	15 years	20 years	10 years	10 years
sea surface temperature	specified from climatology	specified from climatology Shea et al. (1990)	specified from climatology	AMIP 1980's
diurnal cycle	no	yes, updated hourly	yes	yes
land surface	optional bucket scheme like Manabe, Budyko 15cm field capacity	4 soil layers specified soil moisture BATS available but not used	multiple soil layers vegetative resistance soil hydraulic properties subgrid spatial variability	as per II'
moist convection	convective adjustment Manabe	mass flux scheme Hack (1993)	penetrative convection as in GISS II	new mass flux scheme Del Genio and Yao (1988)
boundary layer	local diffusion	includes non-local vertical transport by convective turbulence	local diffusion	local diffusion with dependence on stability and depth of PBL
gravity wave drag	no	yes	yes	yes
ancestry	outgrowth of CCM0	new model successor to CCM1	GISS II plus: new ground hydrology	GISS II plus new: convection, PBL, clouds, ground hydrology, moisture and temperature advection.
references	NCAR TN-285 Randall and Williamson (1990)	NCAR TN-382 Hack et al. (1994)	Hansen et al. (1983) for GISS II	none yet

Table 3.1: Main features of the GCMs used in this work.

NCAR CCM2 at resolution T42, the GISS model II GCM modified to include a new hydrology scheme described by Abramopoulos et al. (1988) at resolution $8° \times 10°$, for a higher resolution version of this model run at $4° \times 5°$ (GISS II'), and for a substantially modified version of GISS model II used in an AMIP simulation (GISS II'' or GISSAMIP). We also obtained output from a CCM2 AMIP run, and from a higher horizontal resolution run of CCM2 at T106 ($\sim 1° \times 1°$). The output from this latter run was limited to a few selected months — all months were not saved in the original run. The main characteristics of these models are described in table 3.1.

CCM2 and GISSII'' are state of the art climate models in as much as they contain representations of most of the physical processes included in contemporary atmospheric GCMs, sophisticated numerical schemes, and reasonable resolution. Both of these models include improved ground hydrology schemes, mass-flux based moist convection schemes, improved treatment of boundary layer transfers, diag-

nosis of clouds and their interaction with the radiation field, incorporation of trace gases, gravity wave parameterization, and the diurnal cycle. The CCM series of models are spectral models and the GISS series of models are grid point models. CCM1 is probably no longer state of the art in that it has an older convective adjustment scheme for moist convection, a simplistic 'bucket' ground hydrology scheme, no diurnal cycle, and other excessively simplified physical parameterizations. In addition, the low horizontal resolution of CCM1 and GISSII' at $8° \times 10°$ now seems cruder than is necessary for near term climate studies.

3.2.2 Hydrological Model

Output from a hydrological model was provided by the U.S. Geological Survey (USGS) in order to assess the sensitivity of Sacramento Basin streamflow to climate variables, temperature and precipitation. We chose the USGS model because it is one of the better physically based models of the basin, and one of the few models of the basin for which working code of the model is still maintained and output archived.

The USGS model is described in Dettinger and Jeton (1994), and Jeton and Smith (1993). It is a distributed-parameter watershed model of the North Fork American River Basin, which is a sub-basin of the Sacramento Basin. The core of the model is the USGS Precipitation-Runoff Modeling System (PRMS) developed by Leavesley et al. (1983). The PRMS model includes a number of modular components designed to simulate snowpack accumulation and snowmelt runoff processes. Changes in moisture in the model are conceptualized as fluxes from a series of reservoirs. The basin is divided into a number of areas that each have a homogeneous hydrologic response to precipitation or snowmelt. These hydrologic response units (HRU's) are characterized according to physical properties such as altitude, slope, aspect, vegetation, soils, geology, and climate patterns. Water balance is computed daily for each HRU and summed on a weighted unit area basis to produce a basin response. The model outputs aggregate streamflow,

precipitation, and potential evapotranspiration (PET) for the basin. The latter quantity is computed based on the input temperature values.

"To claim to imitate nature is first vulgar and second sacrilegious; but most of all it is to attempt the impossible ..."

René Daumal
A Night of Serious Drinking

Chapter 4

Regional Climate

The climate of the Sacramento Basin is closely associated with synoptic eddy activity that spans almost the entire North Pacific Ocean and the western United States. In this chapter we show the major eddy features that define this synoptic region, and examine the ability of the climate models to simulate these features using statistical methods. In a couplet of papers, Santer and Wigley (1990) and Wigley and Santer (1990) present a set of "rigorous" statistical measures as a recommended foundation for examination of the regional performance of GCM control runs. We adopt these measures using ten year time series of monthly model and observational data to test the means, variances, and spatial patterns in the model and observational fields. This allows an initial determination of the fidelity of the model fields, points to systematic error regions in the models, and tests whether model and observational fields can be considered to be statistically drawn from the same or different populations. Following the statistical evaluation of the ten year long climates of the region, we use the monthly time series data to examine synoptic features associated with particularly wet and dry periods in the Sacramento Basin in models and observations. This provides an initial indication of the ability of the climate models to capture the processes responsible for the extremes in the hydrological cycle of the basin.

4.1 Ten Year Climate Statistics

Ten years is close to the lower end of the length of time series that is sufficient to characterize the climate of a region. It is however close to the upper end of the length of time that it is possible to obtain continuous time series of a range of climate variables in models and observations. We chose to examine three climate variables, precipitation, surface air temperature, and sea level pressure, using the statistical testing procedures outlined in Santer and Wigley (1990). Precipitation and temperature were chosen because they are good indicators of the climate and because they are the primary climate input variables to hydrological models of the Sacramento Basin. Sea level pressure provides a reasonable indication of the atmospheric circulation. It was also possible to obtain observational ten year monthly gridded time series of these variables. Chapter 2 provides descriptions of these observational data sets. Note that in the case of precipitation, the region of analysis is limited to western North America only, since there are no ten year gridded time series observations of precipitation over the North Pacific Ocean.

For each variable, precipitation, surface air temperature, and sea level pressure, we examined the *spatial* patterns of means, variances, and their significances for models, observations, and the differences between models and observations for the months of January and July. We present a selection of January results here. January is the more interesting month for the hydrology of the Sacramento Basin since that is the middle of the wet season. There is almost no precipitation in the basin in July. For each of the variables we also examined the *temporal* or seasonal nature of the means and variances of models and observations using the set of statistical measures recommended by Wigley and Santer (1990). The set of seasonal statistical indicators is defined in table 4.1. We adopt the notation of Wigley and Santer whereby the following variables are defined for a space-time field, d_{xt}, where x and t are the independent discrete variables representing space and time ($x = 1, n_x$ for each grid point; $t = 1, n_t$ for each month in the ten year time series):

$$\bar{d}_t = \sum_x d_{xt}/n_x \tag{4.1}$$

$$\bar{d}_x = \sum_t d_{xt}/n_t \tag{4.2}$$

$$s^2_{d,t} = \sum_x (d_{xt} - \bar{d}_t)^2/n_x \tag{4.3}$$

$$s^2_{d,x} = \sum_t (d_{xt} - \bar{d}_x)^2/n_t \tag{4.4}$$

$$\langle d \rangle = (\sum_x \sum_t d_{xt})/n_x n_t \tag{4.5}$$

d is used to refer to observed data, while m denotes model output.

statistic	description	defining equations
t	grid point test of difference in time means	$t = (\langle d \rangle - \langle m \rangle)/S$ where $S^2 = [(\sum_x \sum_t (d_{xt} - \langle d \rangle)^2) + (\sum_x \sum_t (m_{xt} - \langle m \rangle)^2)]/[n_x n_t (n_x n_t - 1)]$
F	grid point test of ratio of time variances	$F = s^2_{d,x}/s^2_{m,x}$
NT1 and NT5	fraction of grid points with significant differences in time means at the 1% and 5% level	$t = (\bar{d}_x - \bar{m}_x)/S_x$ where $S^2_x = (s^2_{d,x} + s^2_{m,x})/(n_t - 1)$
SITES	overall differences in means	$n_t \sum_x (\bar{d}_x - \bar{m}_x)^2/\sigma_D \sigma_M$ where $\sigma^2_D = n_x n_t s^2_{d,x}$
T1	differences between grand means	$(\langle d \rangle - \langle m \rangle)/S$ where S is as defined for t
NF1 and NF5	fraction of grid points with significant differences in temporal variances at 1% and 5%	$F = s^2_{d,x}/s^2_{m,x}$
SPRET1	overall ratio of temporal variances	$\overline{s^2_{d,x}}/\overline{s^2_{m,x}}$
SPREX1	overall ratio of spatial variances	$\overline{s^2_{d,t}}/\overline{s^2_{m,t}}$
r	differences in spatial patterns of time mean fields	$r = [\sum_x (\bar{d}_x - \langle d \rangle)(\bar{m}_x - \langle m \rangle)]/[n_x \sqrt{V(\bar{d}_x) V(\bar{m}_x)}]$ where $V(\bar{d}_x) = \sum_x (\bar{d}_x - \langle d \rangle)^2/n_x$

Table 4.1: Test statistics and their definitions

For the purposes of calculating both the spatial and temporal statistical measures, the data from the observations and models was interpolated to the same 5° latitude × 5° longitude grid. The results are presented for each variable in turn.

4.1.1   Sea Level Pressure

dec mn Jan obsn80 pressure   (hPa)   dec mn Jan obsn70 pressure   (hPa)

dec mn Jan giss81 pressure   (hPa)   dec mn Jan ccm1   pressure   (hPa)
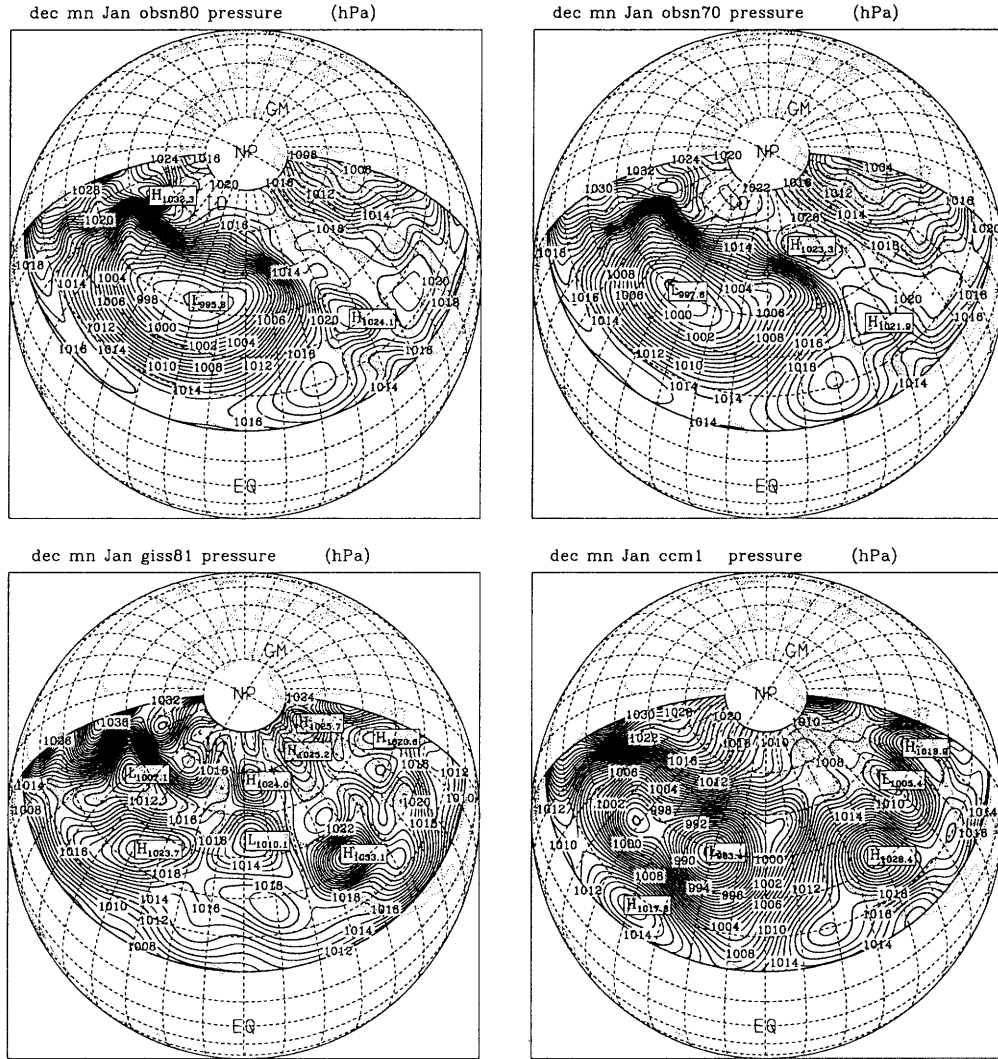
Figure 4.1: Decadal mean January mean sea level pressure for 1980's observations, 1970's observations, GISS 8°×10°, and CCM1 runs.

The decadal mean January mean sea level pressure is shown for each of the models and the observations in figure 4.1 and figure 4.2. The important and robust features in the observations (1970's and 1980's) are the broad scale Aleutian low, and the high couplet over the subtropical North Pacific and western U.S. Neither GISS 8°×10° or CCM1 produce a single coherent Aleutian low, but rather, have a series of highs and lows in this region. Santer and Wigley (1990) note that GCMs seem to have an unrealistically large fraction of their variance at high wave

dec mn Jan giss45 pressure   (hPa)   dec mn Jan ccm2   pressure   (hPa)

dec mn Jan gissam pressure   (hPa)   dec mn Jan ccm2am pressure   (hPa)
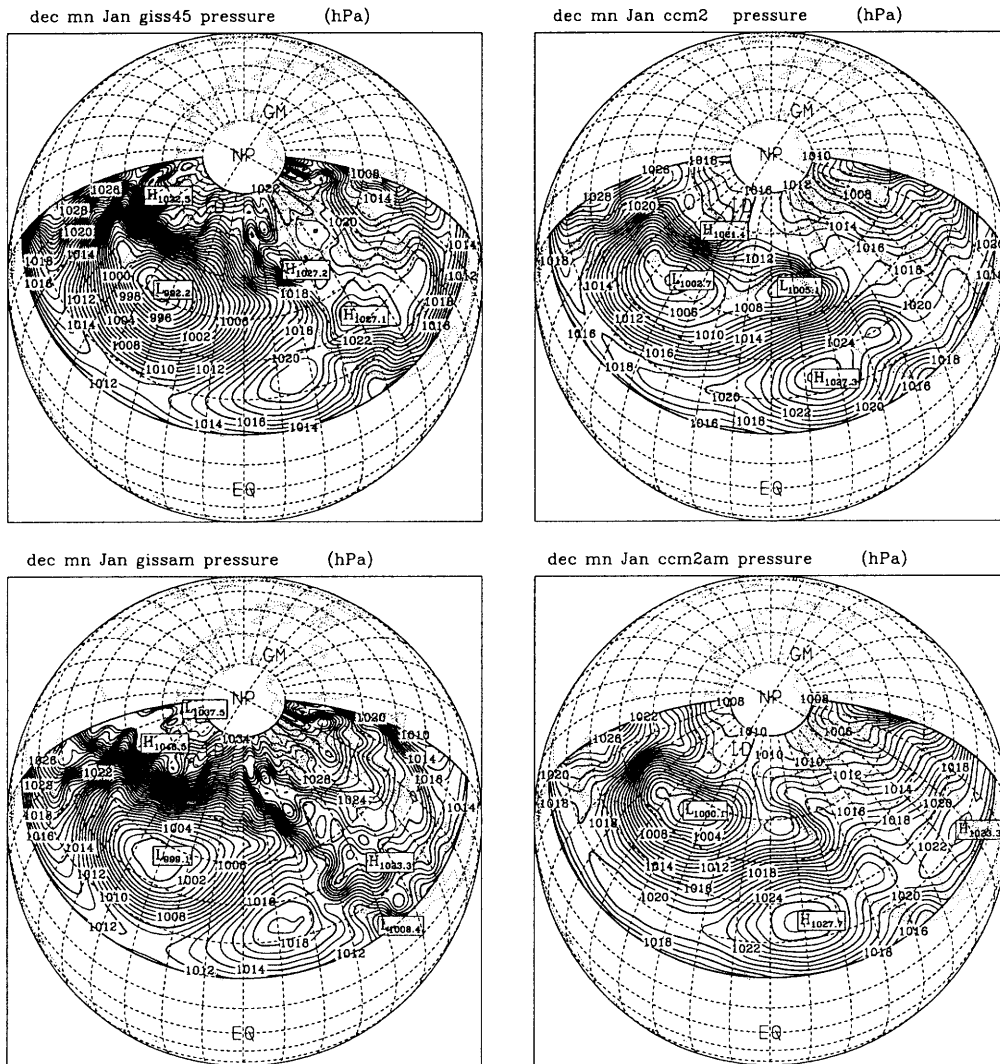
Figure 4.2: Decadal mean January mean sea level pressure for GISS 4°×5°, CCM2, GISSAMIP, and CCM2AMIP runs.

numbers, and speculate that this may be related to their coarse resolution. This speculation appears to be correct, since the higher resolution models are more successful in simulating the Aleutian low. For the GISS 4°×5° model, only the resolution has changed from the 8°×10° version, and the Aleutian low and western U.S. high are now coherently simulated. In CCM2 the Aleutian low is artificially split and too weak, though it is more coherent than for CCM1. The AMIP pressure patterns for GISS and CCM2 are not substantially different from the runs with climatological SSTs. Note that while the only difference between CCM2 and

CCM2AMIP is the specification of SSTs, the GISSAMIP run is for a different
version of the GISS model than GISS $4° \times 5°$ (see table 3.1). The intensity of the
Aleutian low is underestimated in all of the models except CCM1. Two-tailed
t-tests showed that the differences between models and observations are mostly
significant at the 1% level. By comparison, the differences in the observations for
the 1970's and the 1980's are not significant at the 1% level anywhere over the
domain examined.

Figure 4.3: Logarithm of the ratio of the variance of January mean sea level pressure
for 1980's observations to 1970's observations, GISS $8° \times 10°$, and CCM1.

The ratio of observed to model variance of January sea level pressure is shown

log var ratio obsn80/giss45 Jan pressure   log var ratio obsn80/ccm2   Jan pressure

log var ratio obsn80/gissam Jan pressure   log var ratio obsn80/ccm2am Jan pressure

Figure 4.4: Logarithm of the ratio of the variance of January mean sea level pressure for 1980's observations to GISS 4°×5°, CCM2, GISSAMIP, and CCM2AMIP runs.

in figure 4.3 and figure 4.4. The 1980's are used as the reference observational decade. The models underestimate the interannual variability of the sea level pressure in the eastern Pacific, and typically overestimate it elsewhere. CCM1 is the exception to this with an overestimate of interannual variability right across the domain. The observations for the 1970's show a similar pattern of variance ratio with 1980's observations to some of the models, except that the variance differences are nowhere significant in the domain for the observations comparisons. The models by contrast, do show significant differences with 1980's observations

across the domain. Model underestimates of the interannual variability in the eastern Pacific region are perhaps a symptom of the models inability to simulate the highly variable Aleutian low with sufficient fidelity. Model overestimates of variability elsewhere, and particularly over the continents may be associated with the spurious sub-synoptic scale highs and lows that the models (particularly the low resolution versions) tend to generate. In July (not shown) when the observations are less variable, the low resolution models (CCM1 and GISS $8° \times 10°$) overestimate the interannual variability over the entire study region, whereas the higher resolution models (CCM2, GISS $4° \times 5°$, CCM2AMIP, GISSAMIP) are both under-variable and over-variable across the domain with fewer significant differences with observations.

We calculated test statistic values and significance levels for each of the nine statistical measures defined in table 4.1. Plots of the test statistic value for each month and model are shown in figure 4.5. Significance testing was performed using the Poole Permutation Procedure (PPP) introduced by Preisendorfer and Barnett (1983), with 500 random time orderings of the observed and model data. Significance values close to 0 or close to 1 indicate significant differences from the reference observations (the 1980's). Significance values were calculated for each statistic for each month for each of the models and for the 1970's observations. The table of significance values is not shown here, since the results are quite uniform, and may be succintly summarized as follows. For each of the models for each statistic and for most months, the significance value is 0 or 1, indicating that the model fields can be considered to be drawn from statistically different populations from the reference observations. By contrast, the significance values for the 1970's observations are substantially different from 0 or 1, indicating that the 1970's observations may be considered to be drawn from the same population as the 1980's observations. This result is not only true for each test statistic for each of the models, it is also true for tests conducted on the surface air temperature and precipitation.

In figure 4.5, NT1 and NT5 are the percentages of grid points with significant differences in time means from the 1980's observations at the 1% and 5% level,
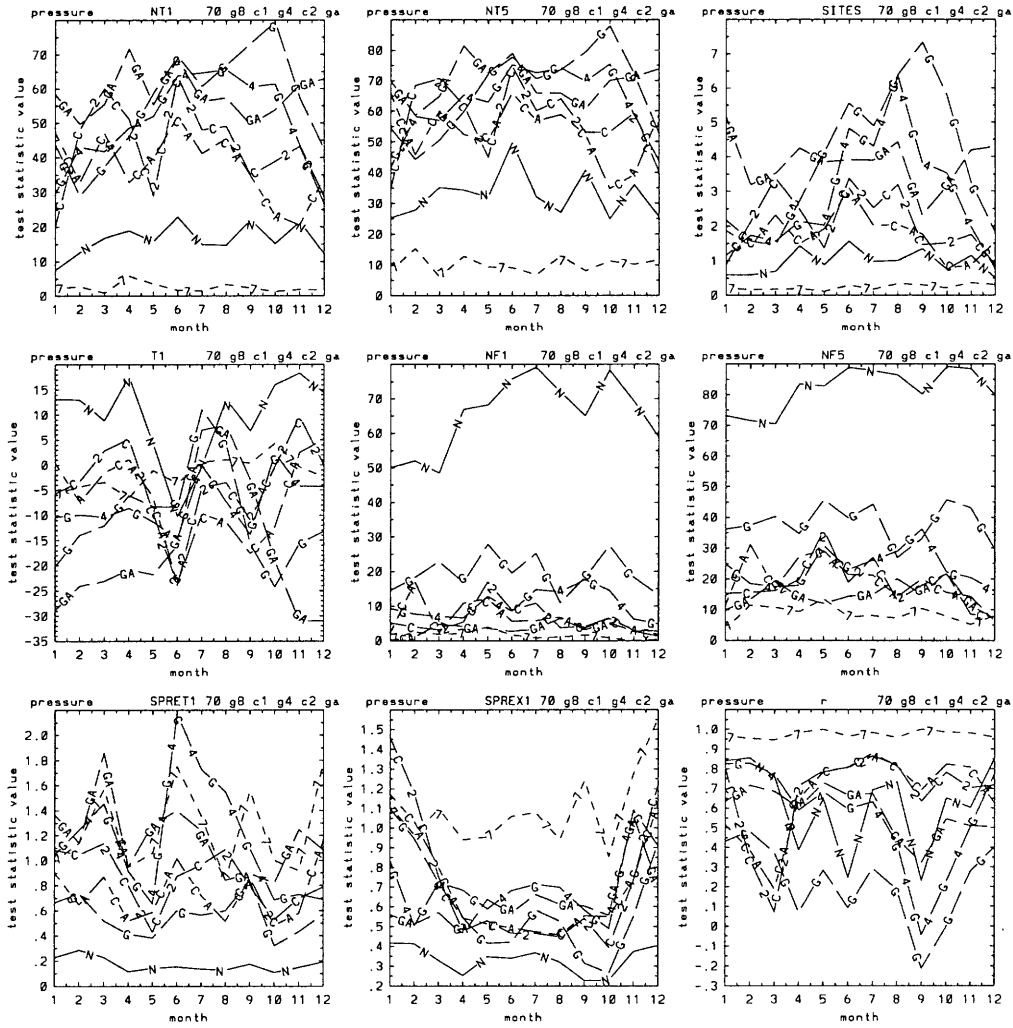
Figure 4.5: Monthly test statistic values for mean sea level pressure for 1970's observations (7), GISS 8°×10° (G), CCM1 (N), GISS 4°×5° (G-4), CCM2 (C-2), GISSAMIP (GA), and CCM2AMIP (C-A) runs.

respectively. The models are all appreciably worse than the 1970's observations, with CCM1 performing the best of the models by this measure alone. There is a slight tendency for the models to have fewer significant differences in the winter months. The SITES statistic provides a measure of the overall difference in the time mean fields, and shows similar results to NT1 and NT5. T1 provides a measure of the differences between grand means in the fields over space and time. In the winter months there is a bias in CCM1 toward lower pressure than in the observations (T1 > 0), whereas for the other models (particularly GISS) the bias

is towards higher pressure than observations (T1 < 0).

NF1 and NF5 are the percentages of grid points with significant differences in temporal variances from the 1980's observations at the 1% and 5% level, respectively. The GISSAMIP model is the best model performer by this measure, and CCM1 is by far the worst. Curiously, CCM1 is the best of the models on the first order statistics (means) in the set, and is the worst of the models on second order statistics (variances). This is also the case for the precipitation test statistics. This feature of CCM1 suggests that the model is heavily tuned to mean observational fields. It also highlights the need to go beyond first order statistics in assessing model performance.

SPRET1 is the ratio of the spatially averaged time variances. For most of the models in most months of the year, the model temporal variance is greater than for observations. This is especially true for the lower resolution models. This characteristic is even more pronounced for SPREX1, which is the ratio of the time averaged spatial variances. The overestimates of temporal and spatial variability in the models are probably further manifestations of the tendency for the models to simulate synoptic fields with relatively too much variance at higher wave numbers.

The final test statistic, r, is the correlation between observed and simulated time mean fields, or pattern correlation. The significance values for the pattern correlation show that the pressure fields for the observational decades are not significantly different from one another, while the model pressure patterns are all significantly different from observations. The models exhibit a seasonal cycle in their pattern correlations, with a tendency for improved correlations in the winter months. For most variables and statistical measures, the model performances are consistently worse in the summer and better in the winter.

4.1.2   Temperature

For the decadal mean January surface air temperature for observations and models, the models have a tendency to be too warm over the ocean and too cold over

the land, particularly over the western U.S. As for pressure, the model differences
with observations are highly significant across the region, while the observational
decades are not significantly different from one another anywhere in the region.

log var ratio obsn80/obsn70 Jan temperature

log var ratio obsn80/giss81 Jan temperature   log var ratio obsn80/ccm1   Jan temperature
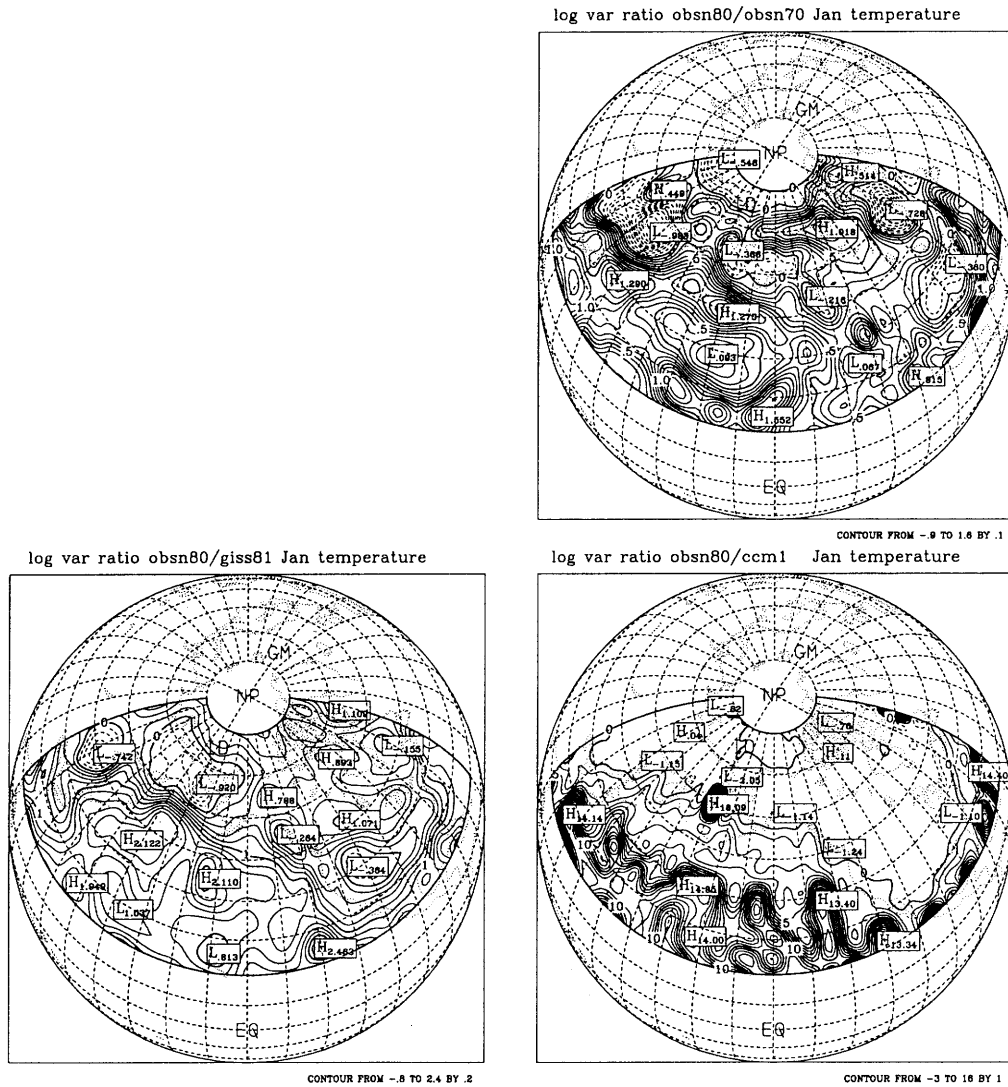
Figure 4.6: Logarithm of the ratio of the variance of January surface air temperature
for 1980's observations to 1970's observations, GISS 8°×10°, and CCM1.

The ratio of observed (1980's) to model variance of January surface air tem-
perature is shown in figure 4.6 and figure 4.7. The models underestimate the
interannual variability of temperature over the whole region. The underestima-
tion of variability is particularly acute for CCM1 and CCM2 over the ocean region.
The surface air temperature in the models is closely coupled to the sea surface

log var ratio obsn80/giss45 Jan temperature   log var ratio obsn80/ccm2   Jan temperature

log var ratio obsn80/gissam Jan temperature   log var ratio obsn80/ccm2am Jan temperature
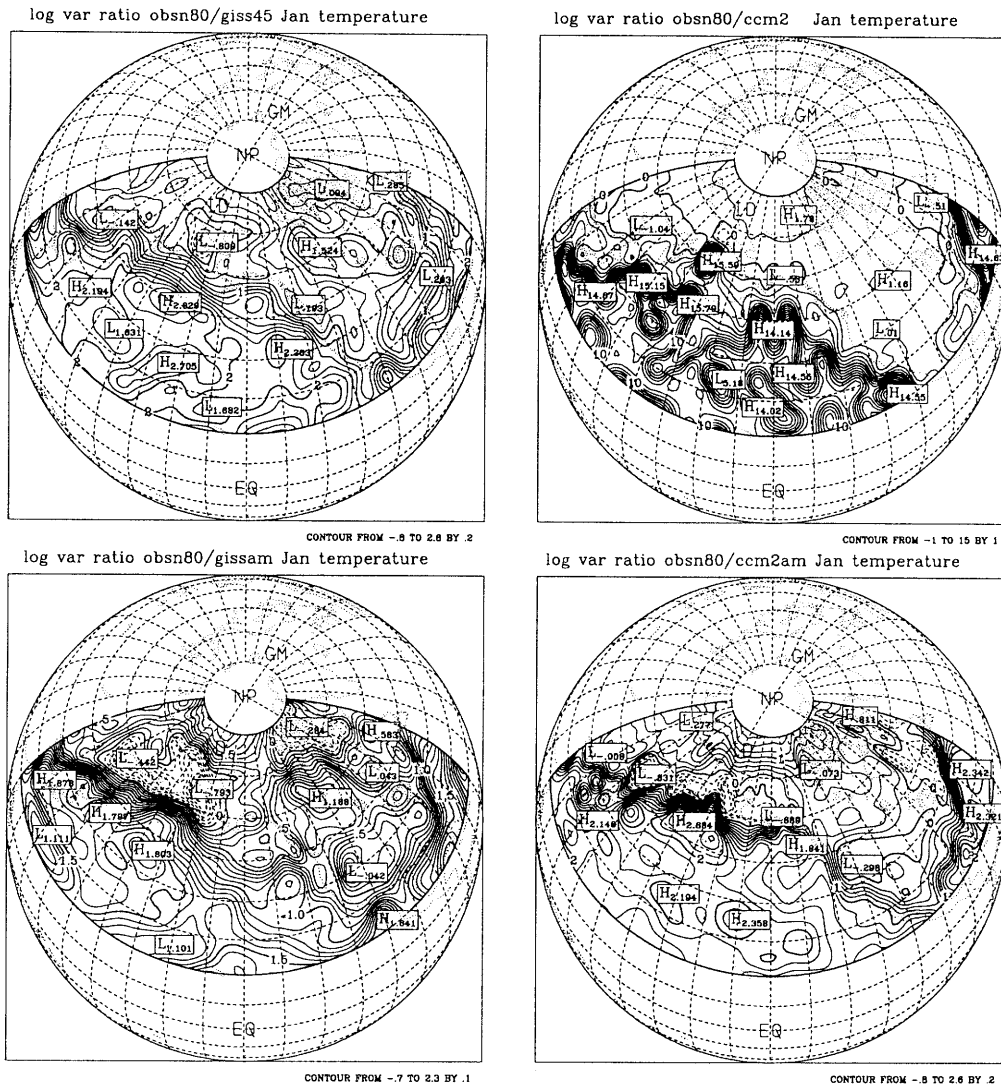
Figure 4.7: Logarithm of the ratio of the variance of January surface air temperature for 1980's observations to GISS 4°×5°, CCM2, GISSAMIP, and CCM2AMIP runs.

temperature over the oceans, and the sea surface temperature is specified from observed climatology to be the same every year. This accounts for the underestimate of variability over the oceans, and indeed the underestimate is greatly reduced for the CCM2AMIP run where the sea surface temperatures change every month according to the actual values observed during the 1980's. For climate impact applications near ocean regions that are sensitive to temperature variability, such as streamflow timing in the Sacramento Basin, the use of AMIP-style boundary conditions represents an advance over the use of climatology year after year. Both

the CCM2AMIP and GISSAMIP simulations are still significantly undervariable over the oceans however, so the specification of sea surface temperatures is not the sole factor that must be represented realistically.
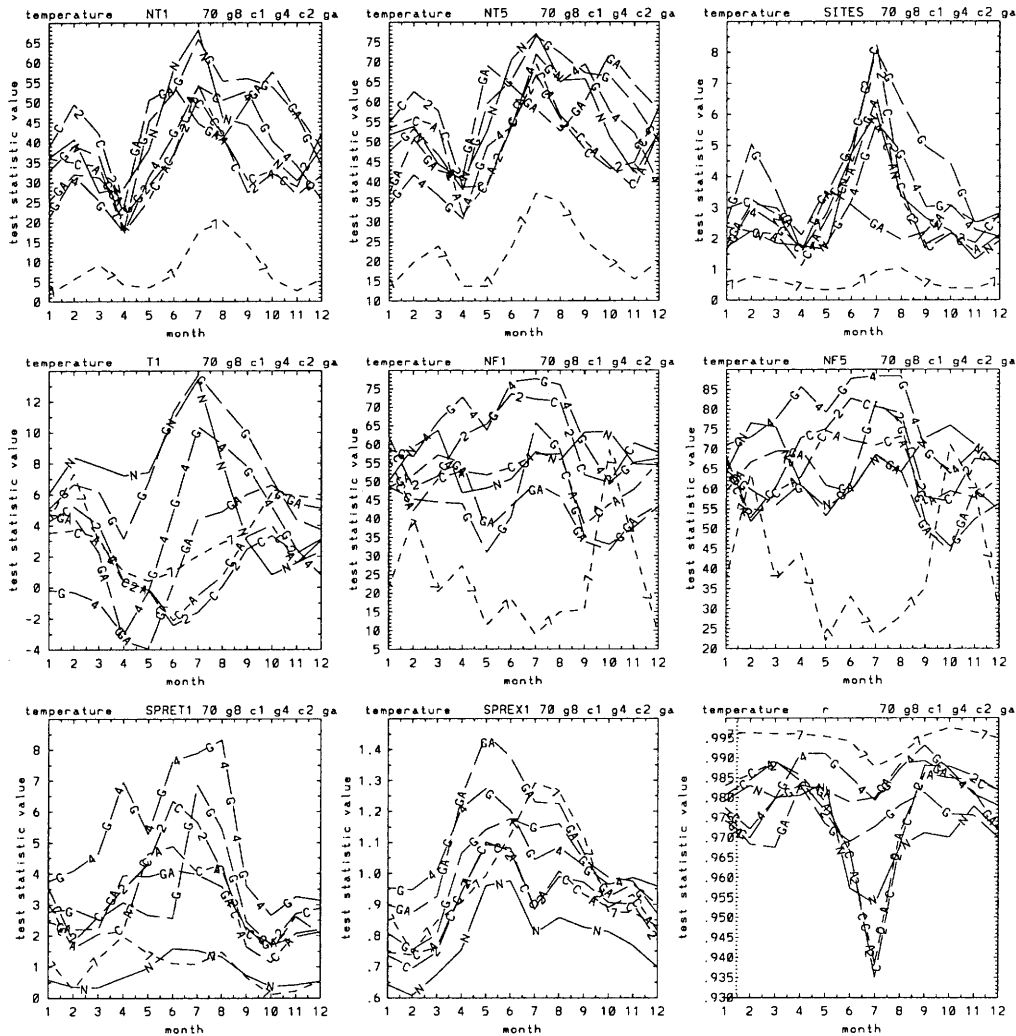
Figure 4.8: Monthly test statistic values for surface air temperature for 1970's observations (7), GISS 8°×10° (G), CCM1 (N), GISS 4°×5° (G-4), CCM2 (C-2), GISSAMIP (GA), and CCM2AMIP (C-A) runs.

The test statistic values for each month and model are shown in figure 4.8. As for pressure, the model differences with observations are almost all significant, while differences between the observational decades are rarely significant. The tendency for the models to be too cold and undervariable is evident from T1 (T1 > 0) and SPRET1 (SPRET1 > 1) respectively, and holds over most months

of the year. The models perform best for the ratio of observed to model spatial variance, SPREX1, though the spatial scales of temperature variability are constrained to a considerable degree by the land/ocean geography. This factor and the use of climatological sea surface temperatures contributes to the high model pattern correlations, r, though the model r values are still significantly different from observations.

4.1.3 Precipitation

The domain covered in the precipitation plots and statistical tests covers the much smaller region shown in figure 4.9. Though we would like to have used the same domain as for the pressure and temperature, there was not sufficient observational precipitation data to cover the larger domain adequately[1].

The January mean precipitation is shown in figure 4.9 and figure 4.10. The major features are robust across both observational decades, and are a sharp gradient down the west coast and a weaker high inland. The model gradients down the west coast are all too weak, and their interior precipitation is too strong. Model differences with 1980's observations are significant over most of the region, with the exception of CCM1. The models are generally not variable enough at the coast and too variable in the interior, consistent with the errors in the mean fields — precipitation variability is often proportional to intensity.

Figure 4.11 shows the test statistic values for the models and observations. As for pressure, CCM1 performs best of the models on mean statistics, and worst of the models on variance statistics. T1, the difference between grand means, shows that the models are all too wet in the region through the whole year (negative T1 values). SPRET1, the ratio of the spatially averaged time variances, indicates that the interannual variability in the GISS models is too small (SPRET1 > 1), while it is too large for CCM1 (SPRET1 < 1). The pattern correlation, r, for the

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[1]See chapter 3 for an expanded discussion of data issues.

dec mn Jan obsn80 precipitation mm/day

dec mn Jan obsn70 precipitation mm/day

dec mn Jan giss81 precipitation mm/day

dec mn Jan ccm1   precipitation mm/day
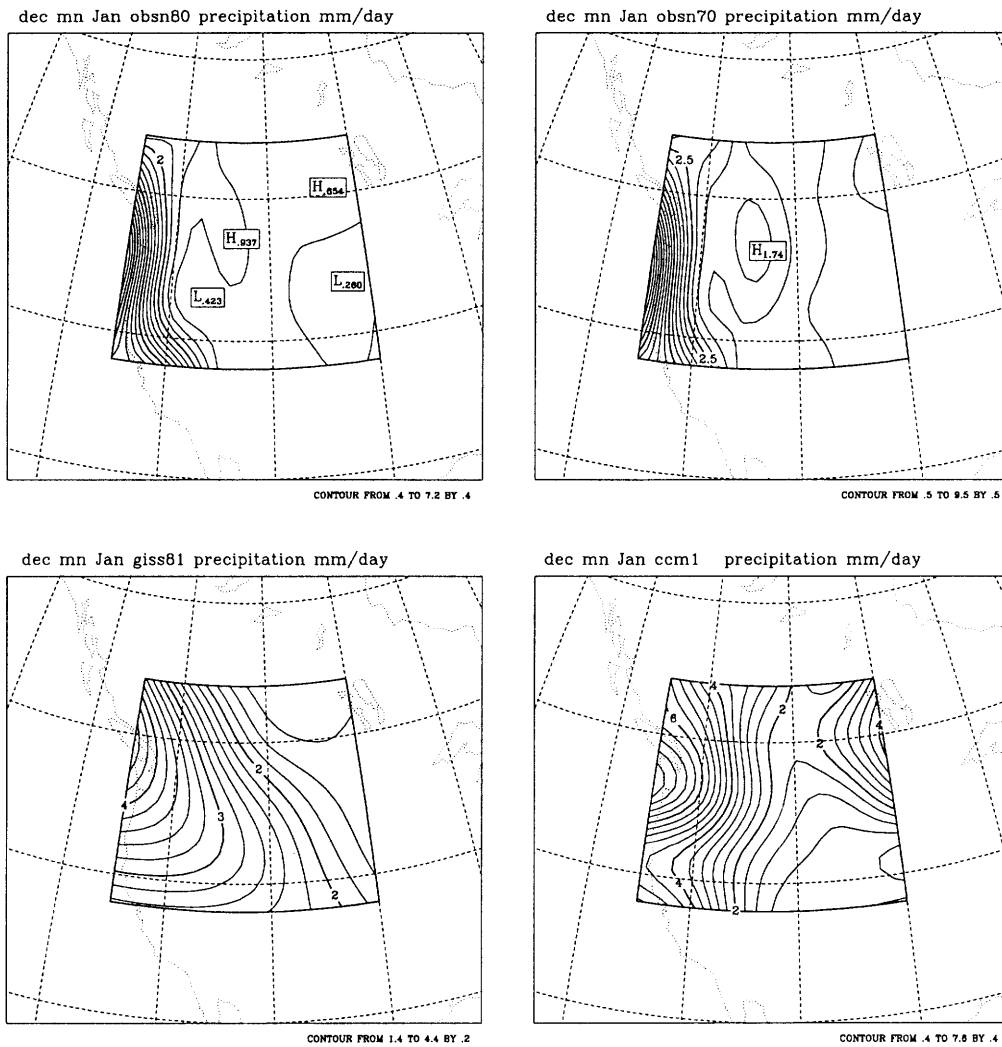
Figure 4.9: Decadal mean January precipitation for 1980's observations, 1970's observations, GISS 8°×10°, and CCM1 runs.

models is best in the summer months, but this is the period when there is very little precipitation in the region.

4.1.4   Summary

All of the tests above were repeated using the 1970's as the reference decade rather than the 1980's. The results were essentially the same in both cases, and so are at least robust according to the choice of observational decade. The major features of the results are as follows:

dec mn Jan giss45 precipitation mm/day

dec mn Jan ccm2   precipitation mm/day

dec mn Jan gissam precipitation mm/day

dec mn Jan ccm2am precipitation mm/day
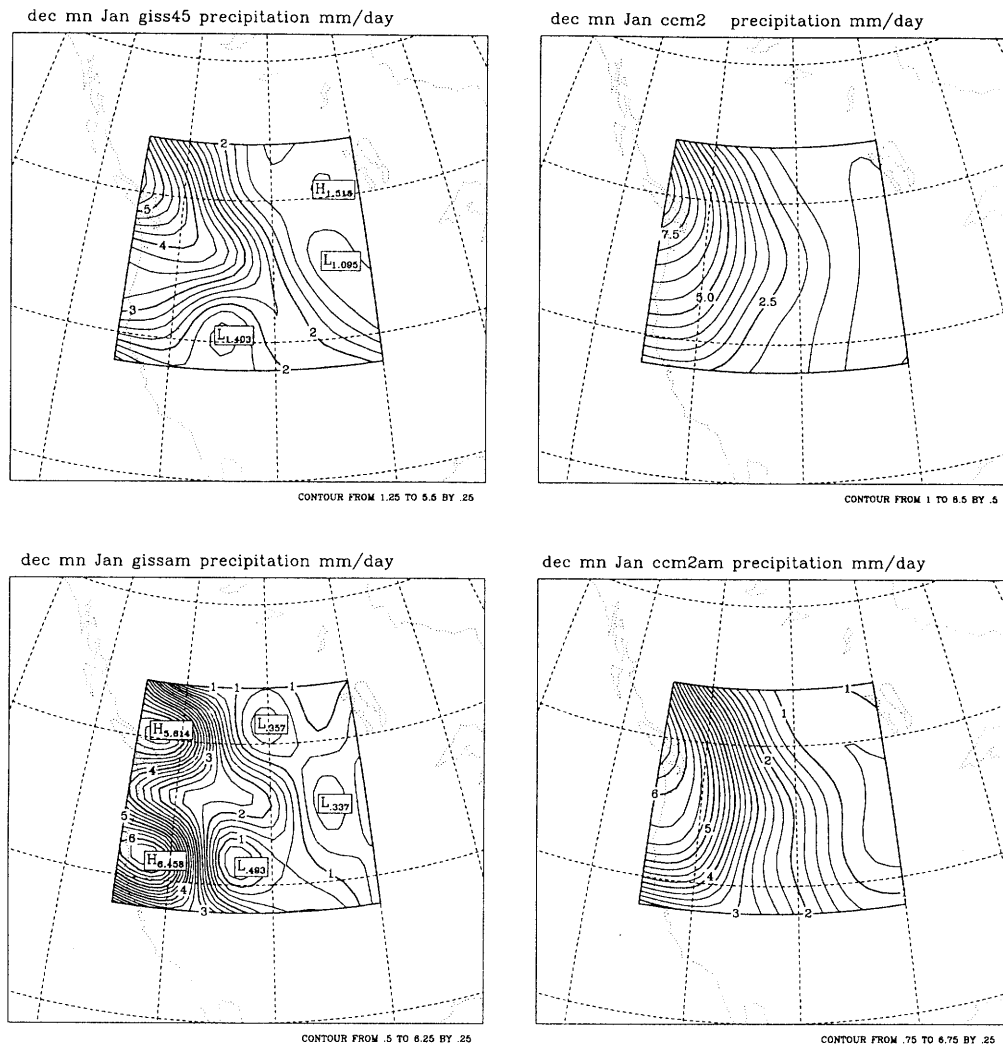
Figure 4.10: Decadal mean January precipitation for GISS 4°×5°, CCM2, GISSAMIP, and CCM2AMIP runs.

- All the models have difficulty simulating the magnitude, position, and variability of the prominent synoptic feature of the region, the Aleutian low, though this difficulty is particularly pronounced at low resolution.

- The use of AMIP sea surface temperatures rather than climatological sea surface temperatures greatly improves simulation of the interannual variability of surface air temperature in CCM2.

- CCM1 is the best of the models compared in the simulation of mean quantities and is the worst of the models in the simulation of variances.

- The model simulations are typically worse in July than they are in January.
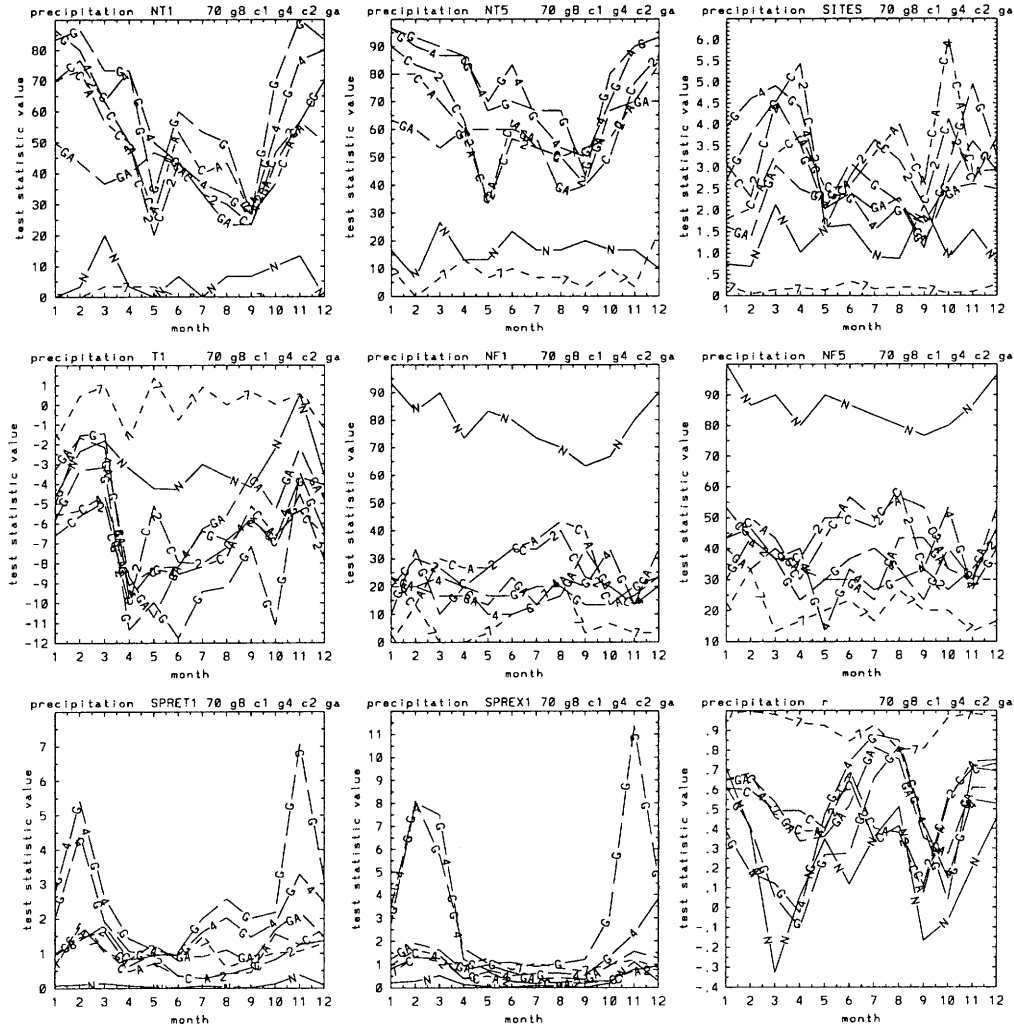
Figure 4.11: Monthly test statistic values for precipitation for 1970's observations (7), GISS 8°×10° (G), CCM1 (N), GISS 4°×5° (G-4), CCM2 (C-2), GISSAMIP (GA), and CCM2AMIP (C-A) runs.

- The model spatial and temporal means and variances are all significantly different from observations. In a statistical sense, the model fields are drawn from different populations to the observational fields.

The models are *statistically* not well suited to provide precipitation and temperature to hydrological models of the Sacramento Basin. It is possible however, that the models may be systematically in error in such a way that the differences in precipitation and temperature yielded in their climate change scenarios may still be useful. It is important therefore to go beyond the statistics considered

here to examine the physical processes and features controlling precipitation in
the models. To this end, we examine the precipitation characteristics of the Sacra-
mento Basin region in more detail in chapter 5, and the synoptic climatology of
the basin in chapter 6. We begin here with an analysis of the broadscale monthly
precipitation over the hemisphere to set the context for the local basin studies in
chapter 5.   .

4.2   Broadscale Precipitation

The observed January mean precipitation is shown in figure 4.12. Note that there
is almost no data over the oceans in this dataset. The main feature from our
point of view is the precipitation maximum running down the west coast of North
America. This maximum shows up clearly in individual January plots as well as
for the decadal January mean shown. In the models, the west coast maximum
shows up in the decadal January mean, but it is more sporadic from year to year.

Figure 4.12: Observed January mean precipitation.

Figure 4.13, and figure 4.14 show the January mean precipitation fields for
GISS 8°×10°, GISS 4°×5°, CCM1, and CCM2 respectively. The time-mean rate

GISS81 dec mn Jan precipitation (mm/day)

GISS45 dec mn Jan precipitation (mm/day)

CONTOUR FROM −1 TO 35 BY .5

CONTOUR FROM −1 TO 35 BY .5
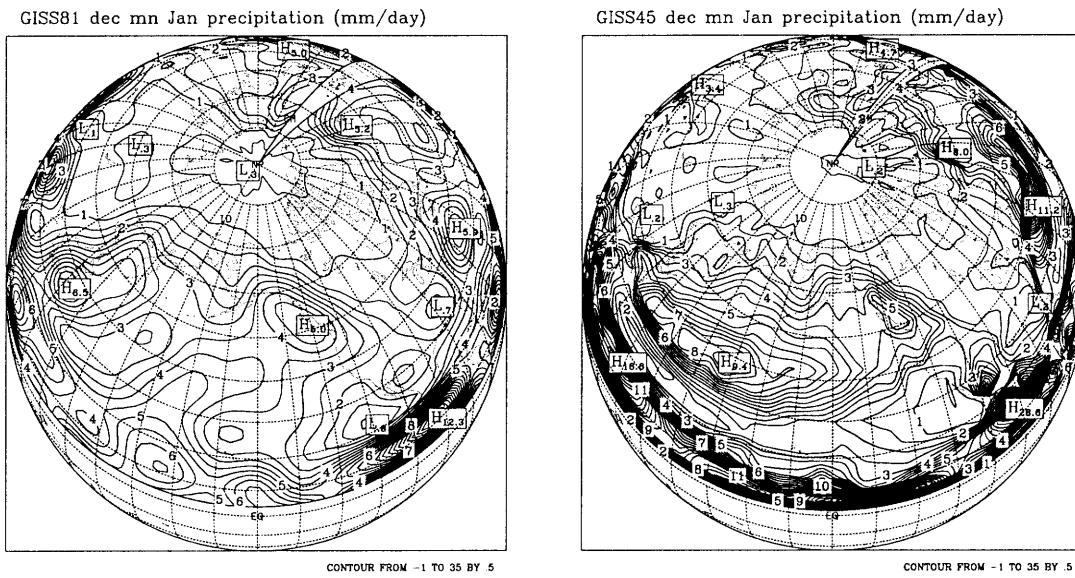
Figure 4.13: GISS 8°×10° and GISS 4°×5° January mean precipitation.

ccm1 dec mn Jan precipitation (mm/day)

ccm2 dec mn Jan precipitation (mm/day)

CONTOUR FROM 0 TO 120 BY .5

CONTOUR FROM 0 TO 120 BY .5
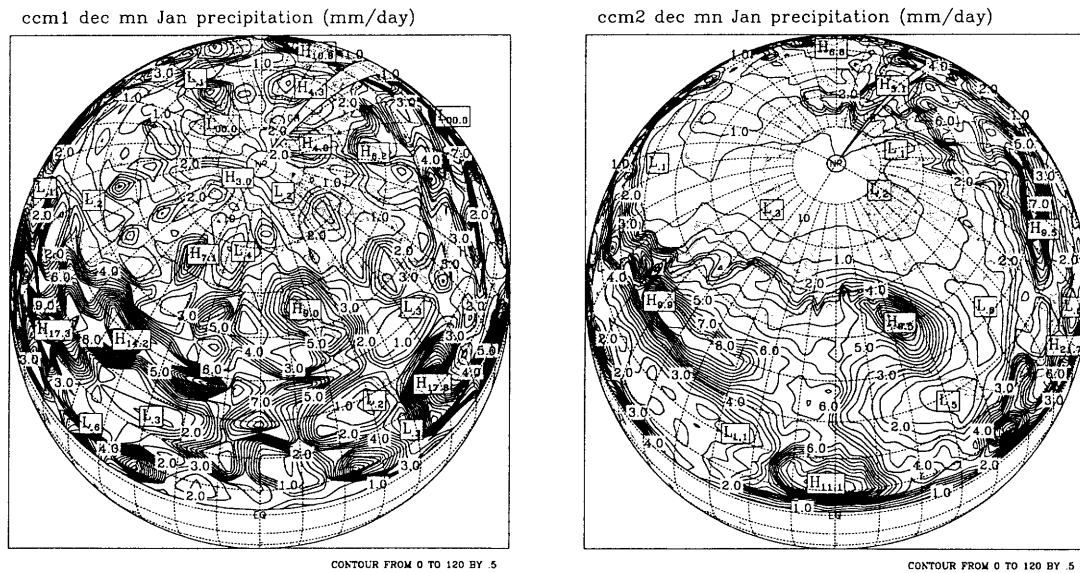
Figure 4.14: CCM1 and CCM2 January mean precipitation.

of the west coast precipitation maximum is reduced in the models relative to the observed maximum of 13.4mm/day. The maximum is 5.0mm/day for both GISS $8° \times 10°$ and GISS $4° \times 5°$, and about 9mm/day for both CCM1 and CCM2. The lack of increase in intensity with increasing resolution suggests that the precipitating systems are quite large in the models, which would not be realistic. It is possible however that there is some critical model resolution that needs to be achieved before the west coast precipitation maximum attains the appropriate strength. We analyse this issue further in chapter 7.

Note that for regions other than the Sacramento Basin, such as over the Pacific Ocean, the GISS $4° \times 5°$ precipitation maxima do tend to be larger than at $8° \times 10°$ resolution. This suggests that the response of the model precipitation simulation to resolution depends on the particular precipitation feature in question.

4.3   Composite January Wet and Dry Pressure Patterns

After examining mean flow patterns in the earlier part of this chapter, we now go on to explore the flow patterns associated with anomalous precipitation in the Sacramento Basin. Since winter is the important season for precipitation in the basin, we begin by showing composite pressure patterns for exceptionally wet Januaries in the basin and for exceptionally dry Januaries in the basin in figure 4.15. In wet Januaries, a low forms off the west coast and the high over the western U.S. retreats southwards, thereby directing a southwesterly flow off the ocean over the Sacramento Basin region. The splitting of the Aleutian low to form a low off the coast is common to most wet Januaries. In dry Januaries, the high over the west coast reasserts itself and the southwesterly flow from the Aleutian low does not extend into the California region. These wet and dry pressure patterns are very similar to the winter sea level pressure anomalies found by Cayan and Peterson (1989) for high and low streamflow in the Sacramento river. Precipitation

and streamflow amount are strongly coupled in the Sacramento Basin, as we show in chapter 8.

obs composite wet Jan pressure (hPa)   obs composite dry Jan pressure (hPa)
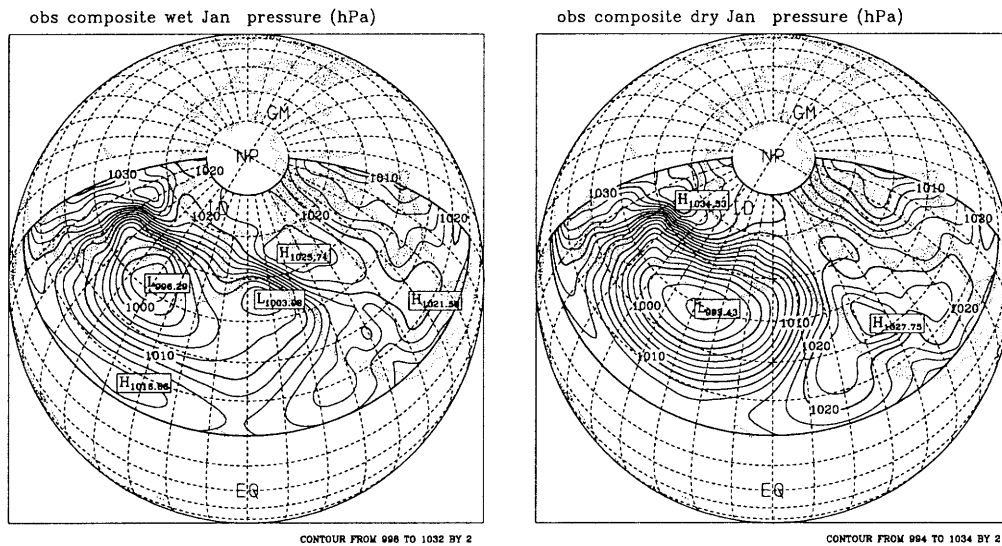
Figure 4.15: Composite mean sea level pressure for wet and dry Januaries in the Sacramento Basin.

We also examined pressure patterns in the models (GISS $8° \times 10°$, CCM1, GISS $4° \times 5°$, CCM2) for Januaries in which the grid boxes over the Sacramento Basin were wetter and drier than usual. In the case of the models however, we are limited to selection of wet and dry Januaries from a short sample of only ten Januaries, and we may not be capturing the extremes of the hydrological cycle in the model's Sacramento Basin region. With this important caveat in mind, the model wet Januaries do not feature the split Aleutian low pattern that shows up so often in the observations, with the exception of CCM2. In the case of CCM2 however, the low off the coast is a feature of the climatological mean sea level pressure pattern (see figure 4.2) as well, suggesting that CCM2 is fixed in some form of wet mode. We further diagnose this feature of CCM2's circulation in chapter 6. The wet and dry pressure patterns in the models bear so little resemblance to the observations that we begin to suspect that the models do not simulate wet and dry spells in the basin for the correct reasons. This provides further motivation to inspect the synoptic climatological features in the models in chapter 6.

"Most of you," he went on, "already know how I have been able to limit the area of investigation in a first approximation. But one or two of you are not yet informed. For you, and to refresh everyone's memory, I'll go over my calculations again."

At that point he gave me a roguish and forceful look demanding my complicity in this adroit falsehood. For naturally everyone was still in the dark. But by this simple ruse each person had the impression of belonging to a minority, of being among 'one or two not yet informed', felt himself surrounded by a convinced majority, and was eager to be quickly convinced himself. This simple method of Sogol's for 'getting the audience into the palm of his hand', as he phrased it, was a simple application of the mathematical method that consists in 'considering the problem as solved'. And he also used the chemical analogy of a 'chain reation'. But if this ruse was employed in the service of truth, could one still call it falsehood? In any case everyone pricked up his ears.

René Daumal
Mount Analogue

Chapter 5

Local Climate

By 'local climate', we mean the climate of the Sacramento Basin. Hydrological models require precipitation and temperature inputs at the scale of the basin and below. The Sacramento Basin occupies from one to a few grid points in the GCMs depending on their resolution, making it difficult to derive an unambiguous representation of the basin in the GCMs. To try to avoid this ambiguity or 'aliasing' problem, we use a variety of measures of the Sacramento Basin in the GCMs to examine the GCM precipitation over the basin. We select the nearest gridbox covering or in the basin, the average of the nearest two gridboxes, and we interpolate from surrounding gridboxes to the centre of the basin. By examining the precipitation characteristics on the basin scale in the observations and models, we hope to learn something about the precipitation processes in the models, and about the relative errors in the climate model precipitation values used to drive the hydrological models.

5.1   Sacramento Basin Precipitation Climatology

In this section we examine the precipitation characteristics of observations and models in the basin on monthly and daily time scales.

5.1.1   Monthly Precipitation

It is both convenient and important to analyse precipitation on *monthly* time scales, since that is the time scale on which long term observations are available, and it is also the time scale on which GCM precipitation values are usually used in creating climate change scenarios for hydrological models.
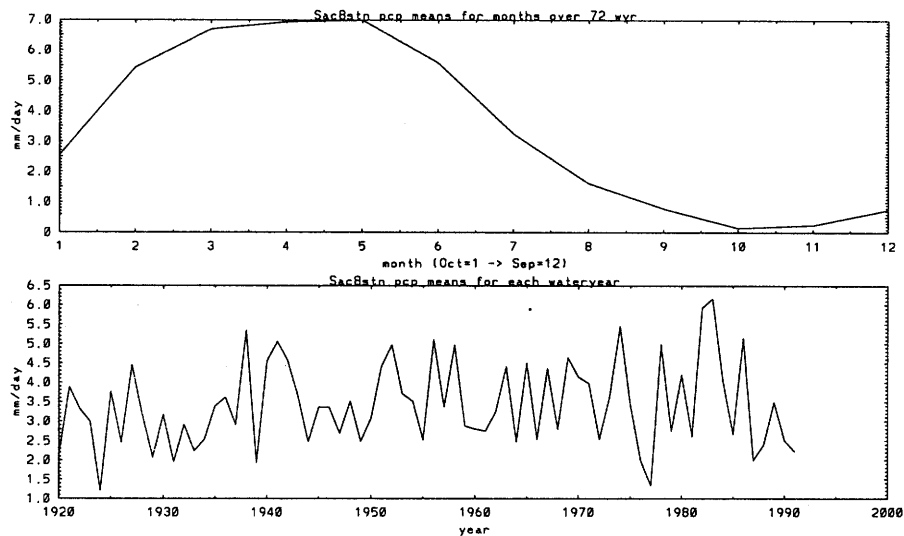
Figure 5.1: Seasonal cycle of Sacramento Basin 8 station precipitation index and time series of annual mean of 8 station precipitation index.

The pronounced seasonal cycle in Sacramento Basin precipitation is shown in figure 5.1. The monthly precipitation values in this figure are means over 72 years of the Sacramento Basin 8 station index. The second part of the figure shows the time series of precipitation over the last 72 years. The interannual variability of precipitation is quite large, with drought periods showing up in the early 1930's and late 1980's. The dominance of wintertime precipitation in determining the annual precipitation anomaly (departure from the mean) is evident in figure 5.2. This figure shows the percentage of the monthly precipitation anomaly over the annual precipitation anomaly for the 13 wettest and 10 driest years in the 72 year time series. In any given very wet or very dry year, the three winter months (December, January, February) invariably account for most of the annual anomaly. In very wet years there is exceptional precipitation in one or two of

the winter months that accounts for the annual anomaly, while in very dry years there is usually exceptionally low precipitation throughout the winter that sets the annual anomaly. This underscores the importance of simulating the wintertime precipitation regime correctly, and is the reason why we focus so heavily on winter circulation in our analyses.
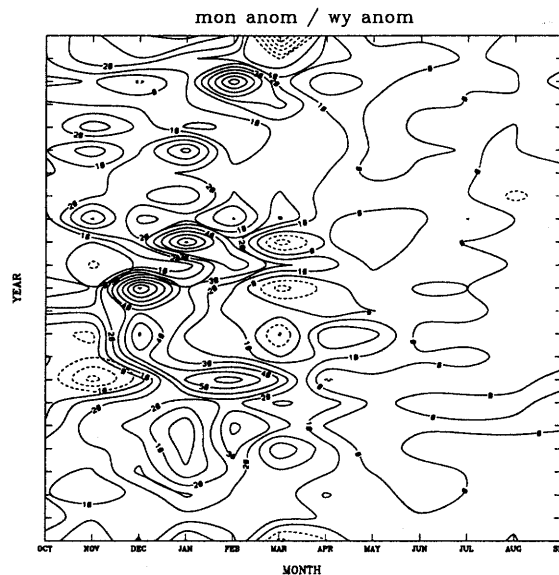
Figure 5.2: Percentage of monthly precipitation anomaly to annual precipitation anomaly for the 23 wettest and driest years in the Sacramento Basin 8 station data set.

The mean and variance of the ten year monthly Sacramento Basin precipitation values for observations and models is shown in table 5.1. Values are shown for the two grid box representation of the the Sacramento Basin in gridded observations and models, though the results are similar for the one grid box and interpolation representations of the basin. Note that the 8 station values are not gridded and represent a version of the 'truth' value for the basin. The observed precipitation has a mean of about $3\frac{3}{4}$ mm/day for both decades, regardless of whether it is given by the 8 station index or by the DOE gridded precipitation data. The climate model means over the decade are appreciably smaller on the scale of the Sacramento Basin despite the fact that they actually have larger mean precipitation than observations over the North Pacific North America region (see section 4.1.3). This is because the models tend to smear out the precipitation over

larger spatial scales than the observations, and do not capture the sharp precipitation gradients down the west coast. Note that the lower model precipitation means over the Sacramento Basin are apparently not simply an artifact of gridbox smoothing of precipitation over the grid box area, since the DOE gridded observational means are much larger than models, and that data has been smoothed over a $5° \times 5°$ grid which is comparable in resolution to the models. This is not to say that the weak model means are not a function of the coarse resolution of the models, but is just to say that they are not an artifact of the manner of comparing models and observations.

dataset/model	mean (mm/day)	variance
8stn70	3.41	16.8
8stn80	3.79	21.4
obs 70	3.78	14.6
obs 80	3.78	15.3
GISS $8° \times 10°$	1.94	1.3
GISS $4° \times 5°$	1.32	1.5
GISSAMIP	2.66	6.3
CCM1	1.68	13.6
CCM2	2.20	5.3
CCM2AMIP	2.21	5.2

Table 5.1: Mean and variance of the ten year monthly Sacramento Basin precipitation values for observations and models. '8stn' refers to the 8 station index. '70' and '80' refer to the 1970's and 1980's. 'obs' is the DOE gridded precipitation data. The Sacramento Basin is represented in gridded observations and models by the average of the two nearest gridboxes.

All the models bar CCM1 underestimate the variance of precipitation, as would follow at least partially from an underestimate of the mean. CCM1 is odd in having a mean in the basin well below observations, but a variance similar to observations. This is related to the unusual precipitation arrival process in CCM1. Figure 5.3 shows the time series of monthly precipitation in the models and observations. For CCM1, note that it rarely precipitates with any substantial intensity, but when it does precipitate heavily in a month, the amount of precipitation is

unusually large.

The first plot in figure 5.3 shows that the monthly 8 station precipitation values and the DOE gridded precipitation values match one another closely over the ten year periods for the 1970's and the 1980's. The differences between decades are much larger than the differences between data sets. The close agreement betweent the 8 station index and the 2 grid box representation of the DOE gridded data augers well for comparison of the gridded precipitation data with the models.

The gridded observations and models are shown in the remaining plots in figure 5.3. The three curves on each plot are for the three different representations of the Sacramento Basin from the gridded values. In most cases the three representations agree closely, with small differences only in magnitude (not phase), and usually for the one grid box representation, if at all. For the models in particular, there is little difference betweent the three representations. Note that the 'y' scale changes on the plots, and that the peaks in the precipitation plots are much smaller for the models with the exception of CCM1. There are some indications from these plots that the seasonal cycle is a little peculiar in GISS $8° \times 10°$ (too much spring rain) and CCM1 (too little spring rain).

The seasonal cycle of precipitation for observations and models is shown in figure 5.4. The first plot showing 8 station observations and gridded observations indicates that there is some interdecadal variability of the seasonal cycle in the winter months, with little interdecadal variability through the rest of the year. Again, the 8 station index and gridded observations agree well with one another. The second plot shows the seasonal cycle of all the observations and models together. The main feature to note here is that the models are all too weak in the winter months when most of the precipitation occurs. The GISS $8° \times 10°$ and GISS $4° \times 5°$ models are particularly flat in their seasonal cycles, with too much of their precipitation falling in the spring relative to winter (as noted above). The GISSAMIP run is much better in this regard, though we have no way of knowing whether this improvement is due to improvements in the model (the GISSAMIP model is more highly developed than the GISS $4° \times 5°$ model) or due to use of the
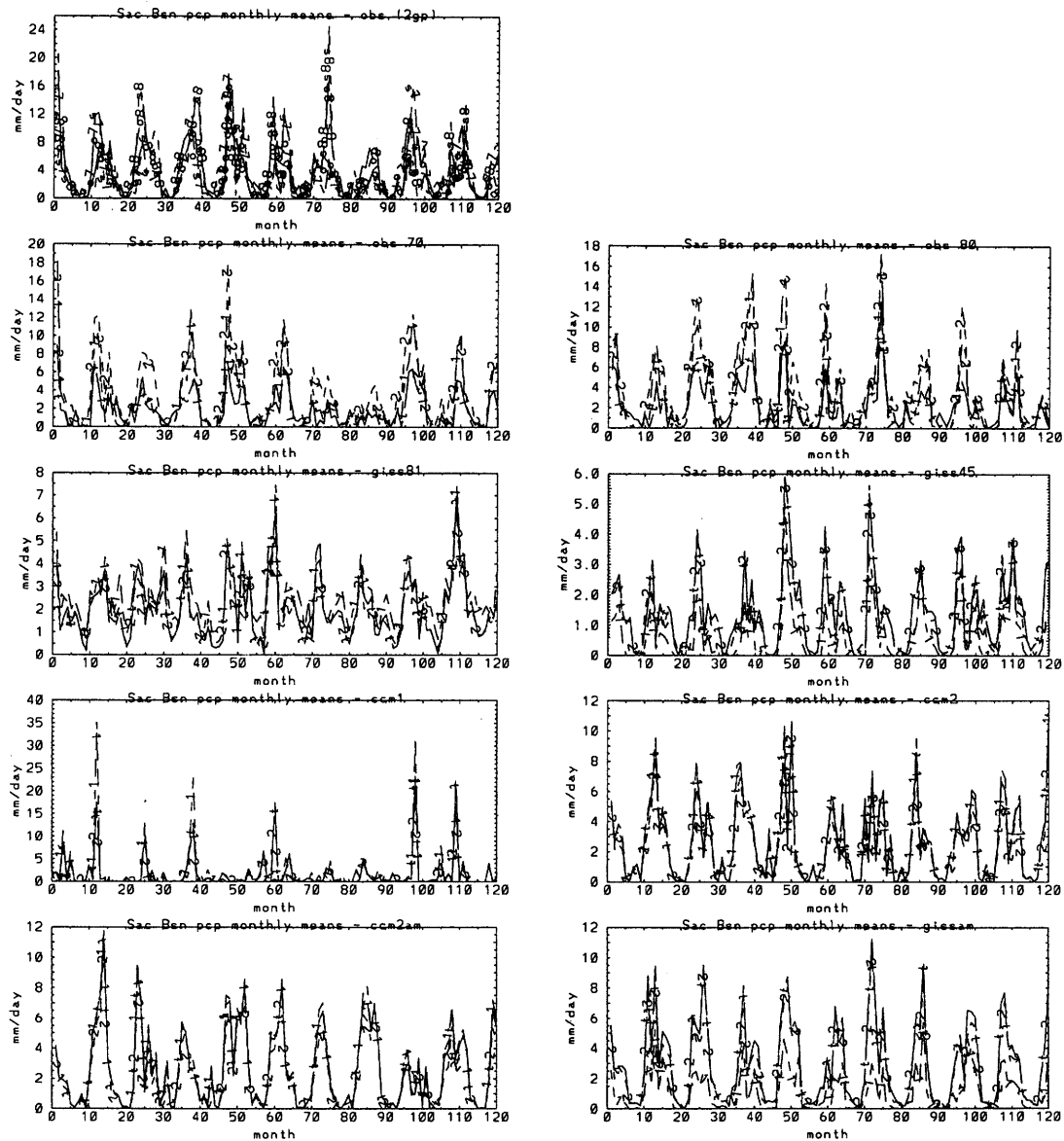
Figure 5.3: Monthly Sacramento Basin precipitation over ten years for observations (s7 = 8 station index for 1970's; s8 = 8 station index for 1980's; o7 = DOE precipitation for 1970's, o8 = DOE precipitation for 1980's), DOE precipitation for 1970's, DOE precipitation for 1980's, GISS 8°×10°, GISS 4°×5°, CCM1, CCM2, CCM2AMIP, and GISSAMIP. In the first plot the 2 grid point representation of the Sacramento Basin is used. In subsequent plots: 1 = 1 grid point representation; 2 = 2 grid point representation; t = interpolation representation of the Sacramento Basin.
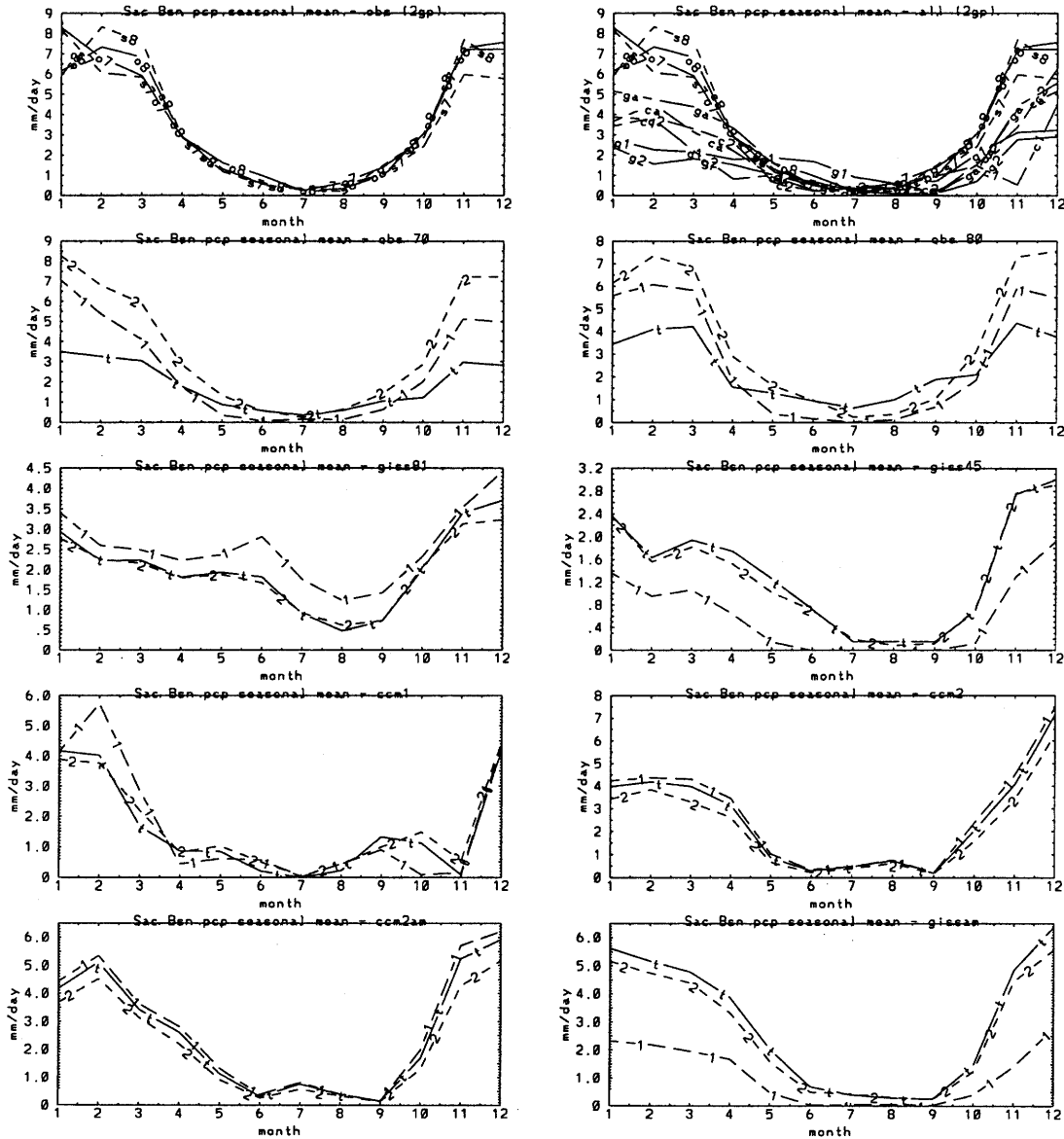
Figure 5.4: As in figure 5.3, but for the monthly mean seasonal cycle of Sacramento Basin precipitation. An additional plot is included here (top right) that includes two grid point representations of observations and models and the 8 station data on the same plot.

AMIP boundary conditions. It is probably due mostly to model improvements, given that there is only a small improvement in the seasonal cycle simulation for CCM2 when AMIP boundary conditions are used as in the CCM2AMIP run. The seasonal cycle in CCM1 is indeed too concentrated, with relatively too little precipitation in the spring and fall.

Figure 5.5 shows the frequency of monthly precipitation values as a function of precipitation intensity. This provides an indication at the monthly time scale of the spectrum of precipitation events of different magnitudes. The 8 station and gridded observations agree well, indicating a preponderance of months with lowest precipitation, decreasing towards wet months. Most of the models have this general profile, though CCM1 has too many months with little or no precipitation (as one would expect from the profile of the seasonal cycle in CCM1 above), and the GISS 8°×10° and GISS 4°×5° models are unusual. Both of these GISS models have relatively too many months with precipitation in the drizzly range between about $\frac{1}{2}$mm/day and 2mm/day. All the models have relatively too few months with precipitation at higher intensities. The models, GISS in particular and CCM1 excepted, tend to be too 'drizzly' in the sense of precipitating too much at low intensity and too little at the extremes of high intensity and zero intensity. This conclusion is confirmed by consideration of daily precipitation data in the next section. The GISS 8°×10° model is drizzling most of the time. This problem is partially corrected in the GISS 4°×5° run (picking up more of the zero precipitation months), indicating that the increase in resolution pays some dividends in simulating precipitation in the model. The GISSAMIP model is much better again in this regard. Given that differences between the CCM2 precipitation spectrum and CCM2AMIP precipitation spectrum are not very discernible, one is led again to speculate that improvements in the GISSAMIP precipitation simulation are most likely due to model improvements.
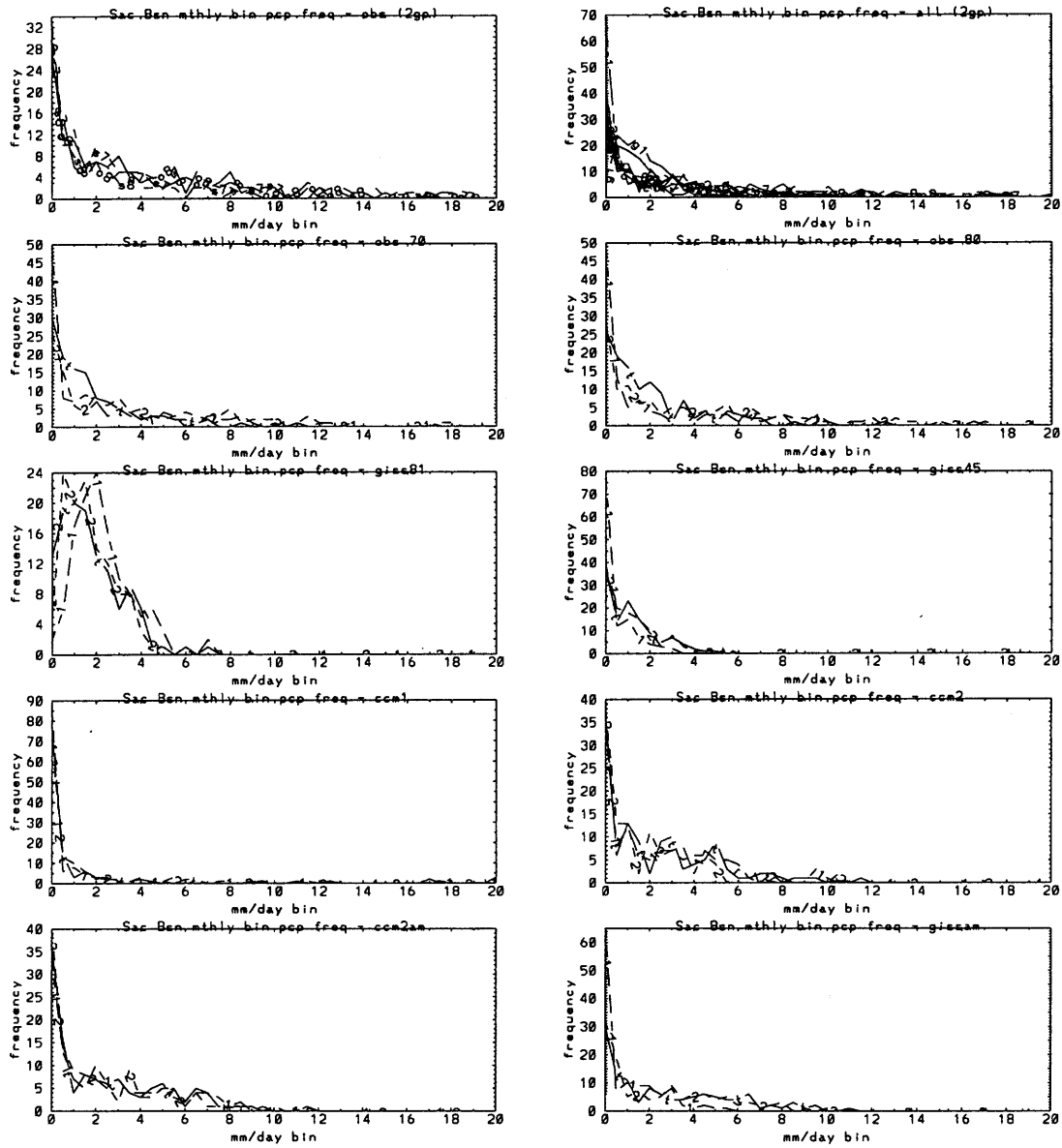
Figure 5.5: As in figure 5.4, but for the frequency of monthly precipitation values as a function of precipitation intensity. The frequency is calculated for discrete intensity bins every 0.5mm/day.

5.1.2   Daily Precipitation

To look in more detail at the precipitation characteristics of the Sacramento Basin
it is instructive to examine daily precipitation data, though the climate models
are not generally considered to be as reliable on such short time scales[1]. We
obtained daily precipitation data over the period 1979-1988 for three stations in
the Sacramento Basin, and compiled a 3 station index of precipitation over this
period. The 3 station index matches the 8 station index well over the period of
overlap as noted in chapter 2. We also obtained daily precipitation output for
each of the CCM series of models, but not for the GISS series of models.

We calculated the number of precipitation events per intensity bin as per fig-
ure 5.5 for models and observations from daily data in figure 5.6. The profiles are
similar to the monthly plots, and reveal the 'drizzly' nature of the models, which
have too few high intensity precipitation events (> 30mm/day), and too many
drizzle events around 1-2mm/day, but much too few days without precipitation
(see also table 5.2). The tendency to drizzle frequently rather than precipitating
harder or not at all also occurs in CCM1 in the daily data. That is, the realistic
looking CCM1 profile at monthly time scales in figure 5.5 is largely an accident. It
does not reflect a realistic precipitation arrival process. We repeated the analysis
shown in figure 5.6 over just the winter months (DJF), and for various represen-
tations of the Sacramento Basin from gridded output, with similar results.

The drizzly nature of the models is also elucidated by considering the dom-
inant precipitation events in the Sacramento Basin. That is, what size are the
precipitation events that contribute most to the precipitation totals for the basin.
Figure 5.7 shows the amount of precipitation (number of events per bin × size
of bin) per precipitation bin for observations and models. For observations, the
major contributions to precipitation totals in the basin are from events in the
range from 10 to 30mm/day, with substantial contributions from events out to
80mm/day. For CCM1 the dominant storm is the 1mm/day event, and for CCM2

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[1]CCM1 in particular, does not include the diurnal cycle.
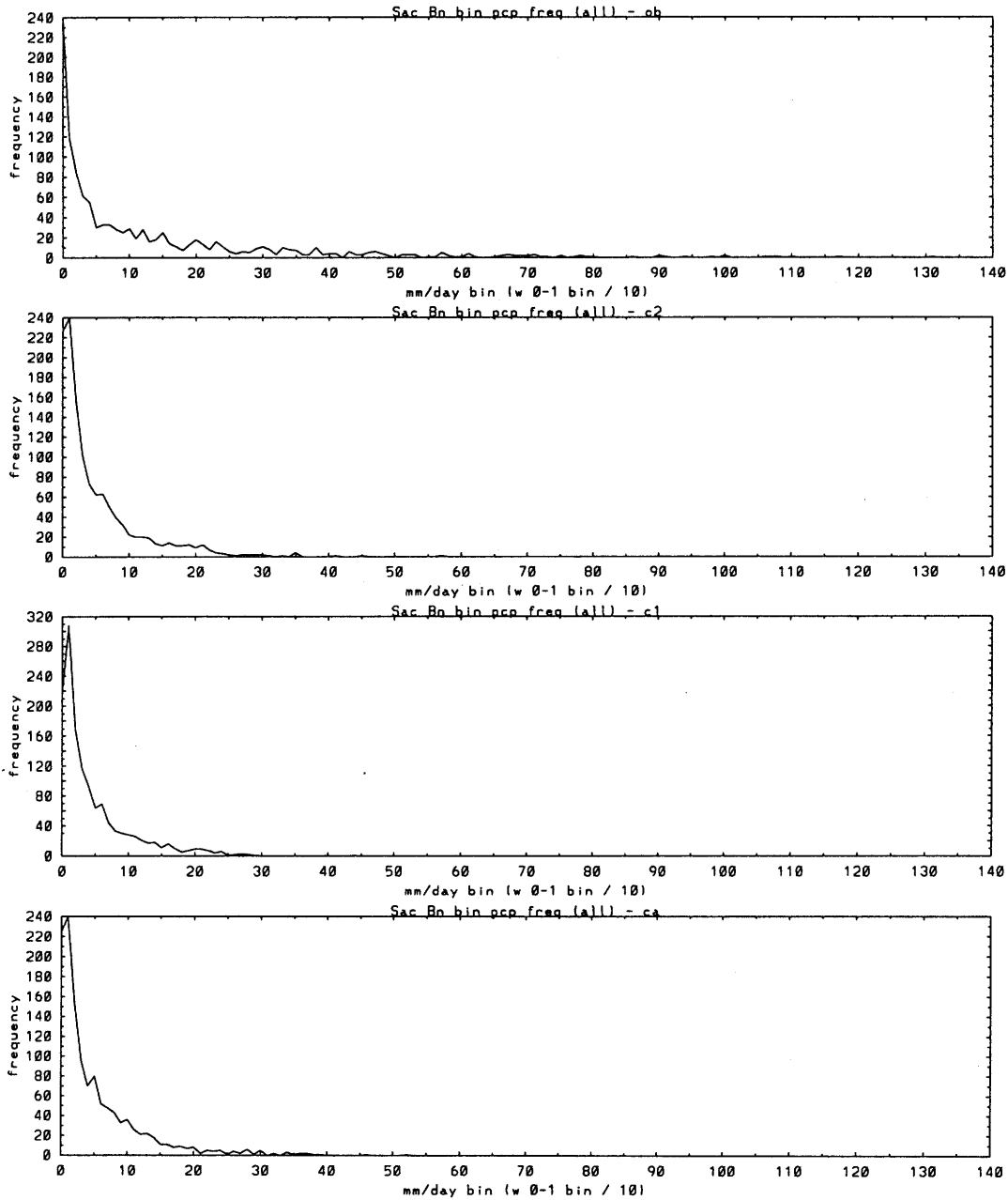
Figure 5.6: Frequency of daily precipitation values as a function of precipitation intensity. The frequency is calculated for discrete intensity bins every 1mm/day. 'ob' = 3 station index observations; 'c2' = CCM2; 'c1' = CCM1; 'ca' = CCM2AMIP. Note that the value for the 0-1 mm/day bin is shown at $\frac{1}{10}th$ of its actual value.
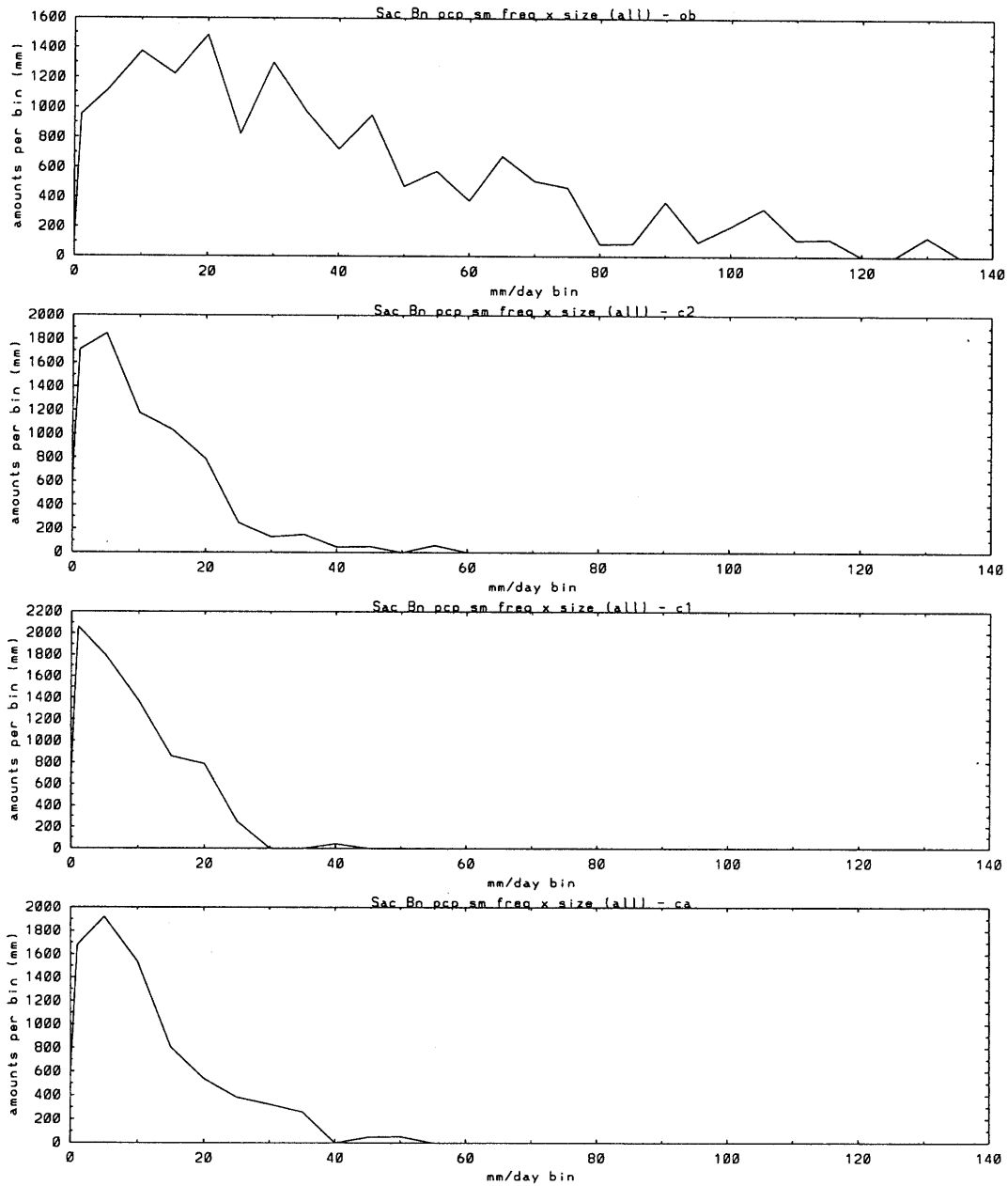
Figure 5.7: Total amount of precipitation per bin over a nine year period of daily data for Sacramento Basin 3 station index (ob), CCM2 (c2), CCM1 (c1), and CCM2AMIP (ca). The amount per bin is calculated as the number of events per bin times the mid range value of the bin.

it is the 5mm/day event. Contributions from events beyond 20mm/day are very small in the models. Most of the precipitation supplied to the basin from the models is from drizzle events, whereas for observations it is from storms of much higher intensities. This analysis was also repeated for winter months only, with similar results.

dataset/model	percent no precipitation days	percent precipitation days
3 station index	65	35
CCM2	31	69
CCM2AMIP	32	68
CCM1	24	76

Table 5.2: Percentage of days in a nine year period that are not precipitating and precipitating for observations and models in the Sacramento Basin. A 'no-precipitation' day is defined as a day in which the precipitation is less than 0.001mm/day.

The extent to which the models are precipitating most of the time is shown in table 5.2. We set a non-zero threshhold for no-precipitation days in the table, since the models frequently indicate grid box precipitation of 10^{-6}mm/day, which is effectively no-precipitation. The results are not very sensitive to the choice of threshhold for no-precipitation days. Over a nine year period in the Sacramento Basin, the 3 stations comprising the 3 station index are precipitating about 1/3 of the time. That is, the basin is mostly precipitation free. In the models the situation is reversed, and there is precipitation in the basin about 2/3 of the time. The tendency for the models to precipitate with weak intensities is compensated in part by their tendency to precipitate too often. The tendency to precipitate too weakly in the models may be related to the lack of explicit mesoscale dynamical processes in the models. Mesoscale dynamical processes are important in producing higher intensity, intermittent precipitation events, such as squall lines and thunderstorms that are often embedded in synoptic scale storm systems. It is possible that in order to produce about the right amount of precipitation in the global water budget, the GCM parameterizations of mesoscale processes are being tuned to precipitate too readily with weak intensity.

5.2   GCM Departures

The GCM grid point temperature and precipitation values for the Sacramento
Basin are traditionally not applied directly as inputs to hydrological models of
the basin in climate impacts studies. Rather, the difference between the $2\times CO_2$
and $1\times CO_2$ simulation values are used to adjust the observed time series of basin
temperature and precipitation as described in section 2.3. Use of this technique
assumes that any errors in the GCM current climate simulation of precipitation
and temperature at the Sacramento Basin are irrelevant (if not small) when dif-
ferences are taken. That is, the error remains constant in the $1\times CO_2$ and $2\times CO_2$
simulations. This assumption is likely to hold up best when the errors are small
and the GCM representations of physical processes are realistic. In this section
we attempt to deduce the size of the GCM errors at the basin, and take up the
question of GCM fidelity to physical processes in the following chapter.

Figure 5.8 shows the ratio of monthly Sacramento Basin precipitation in the
datasets and models to the gridded observations values for the 1970's and 1980's.
The largest departures from the reference dataset values are in the summer months
when very little precipitation occurs. The more important period is around the
winter months, where the models precipitation values are too weak, with ratios
between about 0.2 and 0.6. The different observational representations cluster
around the reference observations, with ratios between about 0.8 and 1.2. For
$2CO_2/1CO_2$ simulations, the climate model precipitation scaling ratios are usually
between about 0.8 and 1.2 (see Lettenmaier and Gan, 1990; figure 3 for instance).
This means that the basin precipitation changes simulated by the models for
greenhouse warming scenarios are actually smaller than their errors in simulation
of precipitation for the current climate.

The difference between Sacramento Basin surface air temperature in each of
the datasets and models and in the gridded observations is shown in figure 5.9.
With the exception of the CCM2AMIP run, the models are colder than observa-
tions throughout the cooler months of the year. The model temperature diffences
with observations range between about 1°C and 6°C, with some allowance for
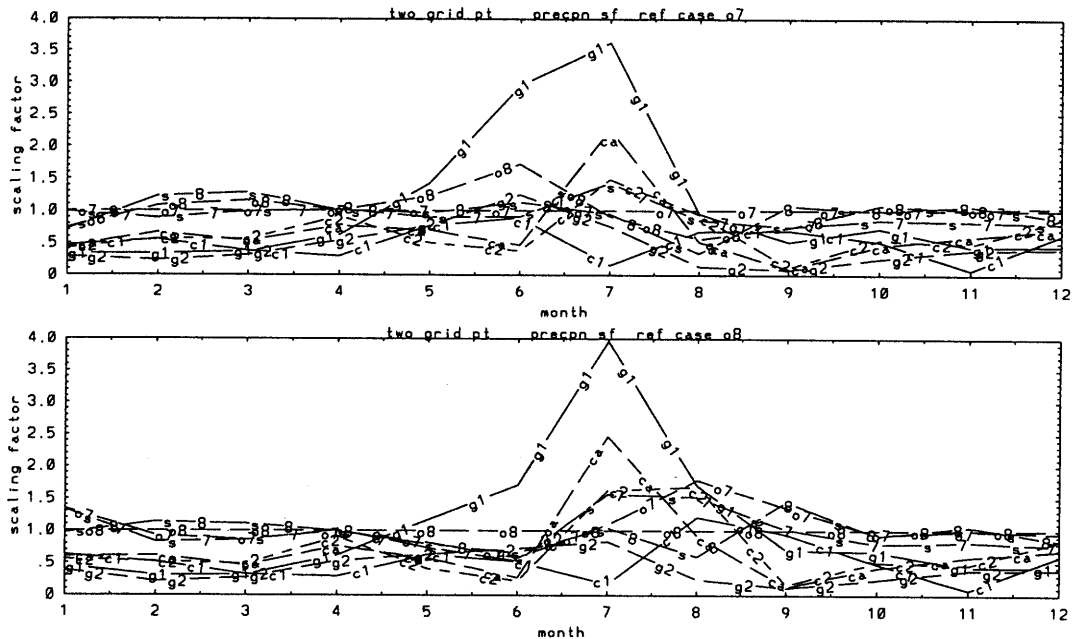
Figure 5.8: The ratio of monthly Sacramento Basin precipitation in each of the datasets/models to monthly Sacramento Basin precipitation for the gridded observations in the 1970's (top) and for the gridded observations in the 1980's (bottom). The monthly values are means over ten years in each case. s7 = 8 station index for 1970's; s8 = 8 station index for 1980's; o7 = gridded precipitation for 1970's; o8 = gridded precipitation for 1980's; g1 = GISS $8° \times 10°$; g2 = GISS $4° \times 5°$; c1 = CCM1; c2 = CCM2; ca = CCM2AMIP.

interdecadal variability in the observations. For comparison, the climate model warming for $2 \times CO_2$ scenarios in the basin varies between about $2°C$ and $6°C$, depending on the model and month (see Lettenmaier and Gan, 1990; figure 3). As for precipitation, the uncertainty in the climate model simulation of Sacramento Basin temperature for the current climate is as large as the temperature changes simulated by the models for doubled CO_2.

5.3   Summary

Precipitation in the Sacramento Basin is dominated by the winter months. While no one would have expected the climate model precipitation to be perfect on the spatial scale of the Sacramento Basin, we now have some understanding of the ways
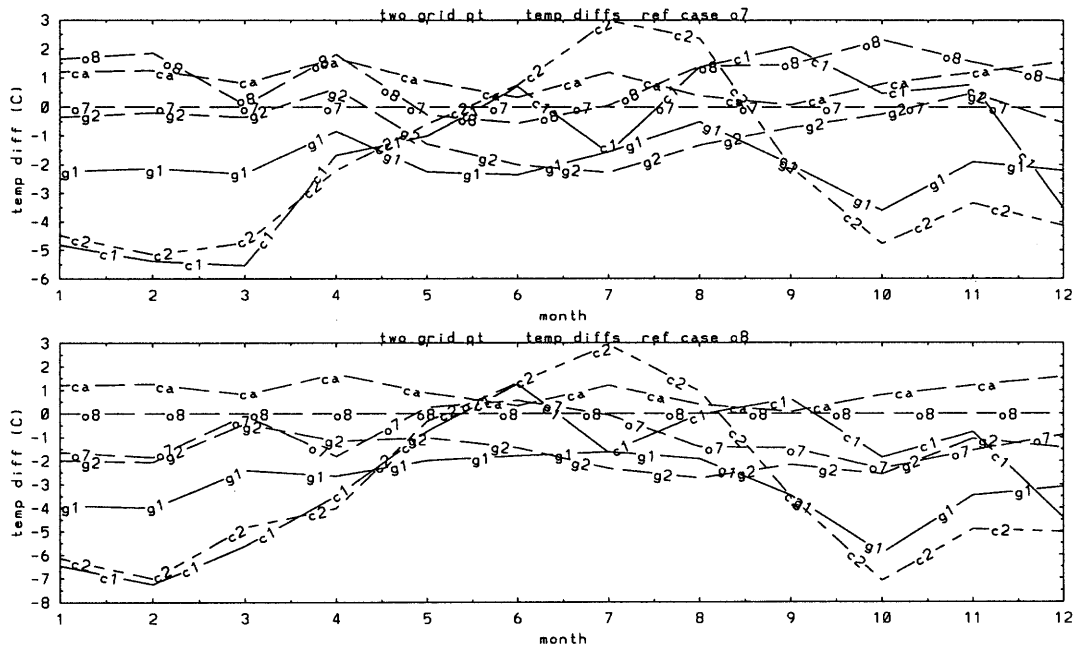
Figure 5.9: The difference between monthly Sacramento Basin surface air temperature in each of the datasets/models and the monthly Sacramento Basin surface air temperature in the gridded observations in the 1970's (top) and for the gridded observations in the 1980's (bottom). The monthly values are means over ten years in each case. s7 = 8 station index for 1970's; s8 = 8 station index for 1980's; o7 = gridded precipitation for 1970's; o8 = gridded precipitation for 1980's; g1 = GISS 8°×10°; g2 = GISS 4°×5°; c1 = CCM1; c2 = CCM2; ca = CCM2AMIP.

in which it is imperfect on this scale. The climate models smear out precipitation in the basin region in space and time. The spatial precipitation gradients are too weak along the west coast and the precipitation is too weak over the Sacramento Basin, despite the fact that the model precipitation is too strong over the larger western North America region. The spatial smearing of precipitation may be a consequence of resolution, topography, coastal effects, the convection scheme, or some combination of these factors. We will return to consideration of this question in chapter 7.

The models precipitate too often in the basin, and too many of their precipitation events are in the drizzle range of a few millimetres per day. Indeed, the models deliver most of their precipitation to the basin in the form of drizzle, whereas in observations the dominant precipitation events are storms yielding an order of magnitude more precipitation per event.

The climate model precipitation and temperature values for the Sacramento Basin are generally well outside the observational values as measured from station data and gridded observational data. Furthermore, the uncertainty in the climate model values for the Sacramento Basin is of the same order as their projected changes in these values for doubled CO_2.

The conclusions reached in this chapter are based on examination of model performances in a single location on the planet. It remains an open question at this point as to just how representative and generalizable they are. It is possible for instance, that the climate models have simulated the Sacramento Basin climate correctly, but in a propinquitous region just removed from the Sacramento Basin. To test this possibility we repeated many of the analyses here for nearby regions up and down the coast and inland from the Sacramento Basin. This resulted in no detectable improvement for the models, and so this possibility is discounted. It is also possible that the shortcomings in climate model simulation of Sacramento Basin precipitation do not occur in regions remote from the basin. We will be better placed to answer this sort of question after examining the large scale features and circulation in the observations and models that set the climate of the Sacramento Basin region.

"*And then you grew up, went to school, and began to 'philosophize', didn't you? We all go through the same thing. It seems that during adolescence a person's inner life is suddenly weakened, stripped of its natural courage. In his thinking he no longer dares stand face to face with reality or mystery; he begins to see them through the opinions of 'grown-ups', through books and courses and professors. Still, a voice remains which is not completely muffled and which cries out every so often — every time its gag is loosened by an unexpected jolt in the routine. The voice cries out its great questioning of everything, but we stifle it again right away. Well, we already understand each other a little. I can admit to you that I fear death. Not what we imagine about death, for such fear is itself imaginary. And not my death as it will be set down with a date in the public records. But that death I suffer every moment, the death of that voice which, out of the depths of my childhood, keeps questioning me as it does you: 'Who am I?' Everything in and around us seems to conspire to strangle it once and for all. Whenever that voice is silent — and it doesn't speak often — I'm an empty body, a perambulating carcass. I'm afraid that one day it will fall silent forever, or that it will speak too late — as in your story about the flies: When you wake up, you're dead.*"

"*Well, there it is!*" *he said, almost violently.* "*I've told you the essential thing. Everything else is mere detail. I've been waiting years to say all this to someone.*"

He had sat down, and I saw that this man must have a mind of steel to be able to hold on to his sanity. Now he seemed a little relaxed, almost relieved.

René Daumal
Mount Analogue

Chapter 6

Synoptic Climatology

The major circulation features associated with precipitation and streamflow in the Sacramento Basin were reviewed in chapter 2. In this chapter we examine the synoptic and planetary scale features reviewed there that are determining factors of, or closely associated with, the regional climate of northern California.

The atmosphere's stationary waves are probably the single most important factor in setting the climate of a region in the extratropics. The stationary waves are primarily forced by the flow of air past stationary orographic and thermal features, and by transient eddies. In particular, Plumb (1985) finds that the major forcing of the stationary wave field derives from the orographic effects of the Tibetan plateau, and from diabatic heating and/or interaction with transient eddies in the western North Atlantic and North Pacific Oceans and Siberia. Stationary waves propagate as Rossby waves. Their propagation depends on the potential vorticity gradients in the atmosphere, particularly at the tropopause level. The potential vorticity gradients are intimately related to the jet streams. The stationary waves and subtropical jets are associated with preferred regions of strong baroclinicity and cyclogenesis. Cyclonic eddies move downstream from these regions, thereby defining the storm tracks. The eddies feed back to the time mean flow by means of convergence of upper tropospheric potential vorticity fluxes, which also give rise to the growth and decay of low-frequency circulation anomalies. The low frequency anomalies, when sufficiently persistent, also influence the stationary wave pattern.

The above simplified picture serves to illustrate some of the complexity of the interactions among the large scale features that set regional climates. This picture is particularly applicable to the Sacramento Basin, where most of the precipitation arrives in winter storms that define/follow the North Pacific storm track. We examine the jet streams, stationary waves, persistent anomalies, and storm tracks in observations and climate models. These features are not only fundamental to the simulation of regional climate and regional climate change. They are also fundamental measures of the dynamics of the climate model circulation regimes on a large scale that is resolved by even the coarsest models we consider. While we did not expect the climate models to perform perfectly on the local scale considered in chapter 5, the above features are the 'bread and butter' of climate dynamics and climate models, and ought to be simulated well.

6.1   Jet Streams

The jet streams in the atmosphere are often represented by the zonal wind field at an upper level around about 200hPa. We are interested in the winter jet stream, and show the 200hPa zonal wind for an average of the winter months (December, January, February) over ten years of observations in figure 6.1. There are three major jet stream centres over the Pacific Ocean, North America and the Atlantic, and over the Middle East. These jet centres are fairly robust from period to period, and across different observational data sets. The most important jet from our perspective is the Pacific jet, which helps set the storm tracks over the west coast of North America.

For a small sample of wetter than normal and drier than normal winters in the Sacrameto Basin we plotted the 200hPa zonal wind field in figure 6.2. In wet winters the Pacific jet pushes further into the eastern Pacific toward the California coast, and further south as well. In dry winters the Pacific jet retreats well back into the central Pacific. These changes are consistent for samples of wet winter plots and dry winter plots from the 1970's as well. The changes are in the expected

obs winter mean 200mb zonal wind − 1980s (m/s)

Figure 6.1: Winter mean zonal wind at 200hPa for NMC observations. The winter mean is an average for December, January, and February over the 1980's.

obs wet win mean 200mb zonal wind − 83,86 (m/s)   obs dry win mean 200mb zonal wind − 85,89 (m/s)

Figure 6.2: Zonal wind at 200hPa for NMC observations for an average over two wet winters (left plot) and for an average over two dry winters (right plot) in the Sacramento Basin.

sense to provide greater and lesser amounts of precipitation from storm systems in the Sacramento Basin.

ccm1 winter mean 200mb zonal wind − 1980s (m/s)
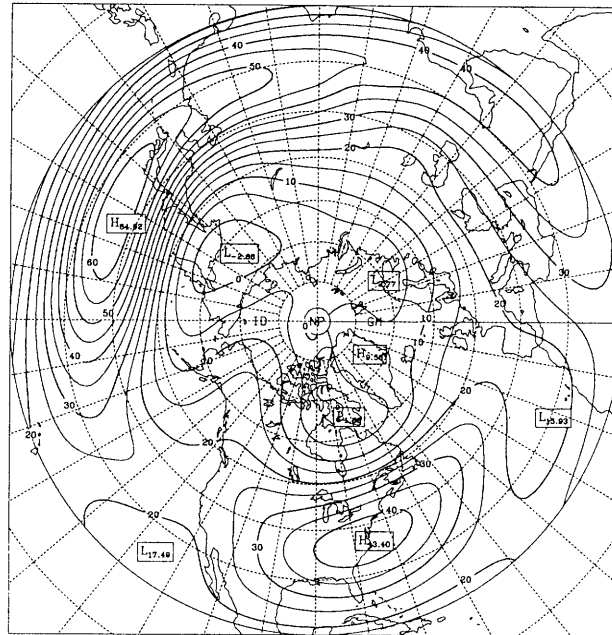
Figure 6.3: Winter mean zonal wind at 200hPa for CCM1. The winter mean is an average over December, January, and February for the ten years of model simulation.

The winter mean jet streams for the models are shown in figure 6.3 through figure 6.6[1]. Most of the models reproduce the three jet structure, with inaccuracies mostly in intensity and position. The CCM2AMIP jet streams are similar to the CCM2 jet streams. In fact, the CCM2AMIP plots are similar to the CCM2 plots for all the upper atmospheric quantities shown in this chapter, indicating that the use of real SSTs makes little difference to the large scale circulation in the middle and upper troposphere in the model. The Pacific jet in CCM1 and CCM2 is too weak by about 10m/s, and does not extend far enough into the eastern Pacific, especially for CCM2. A small spurious local jet shows up over the northeast Pacific in CCM2. The Pacific and Atlantic jets are well positioned in GISSAMIP, though the Middle Eastern jet is incoherent in the model. The zonal wind breaks

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[1]The GISS 4°×5° and 8°×10° runs are not included in these analyses, since appropriate upper air output was not available from the models.

ccm2 winter mean 200mb zonal wind − 1980s (m/s)
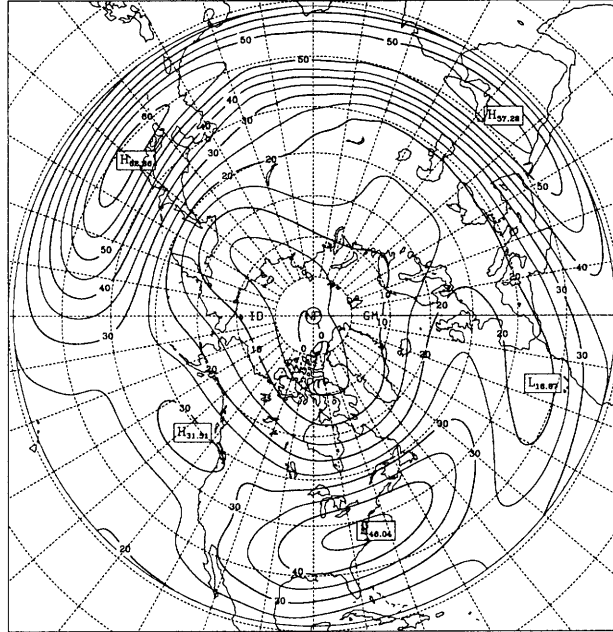
Figure 6.4: As in figure 6.3, but for CCM2.

ccm2amip winter mean 200mb zonal wind − 1980s (m
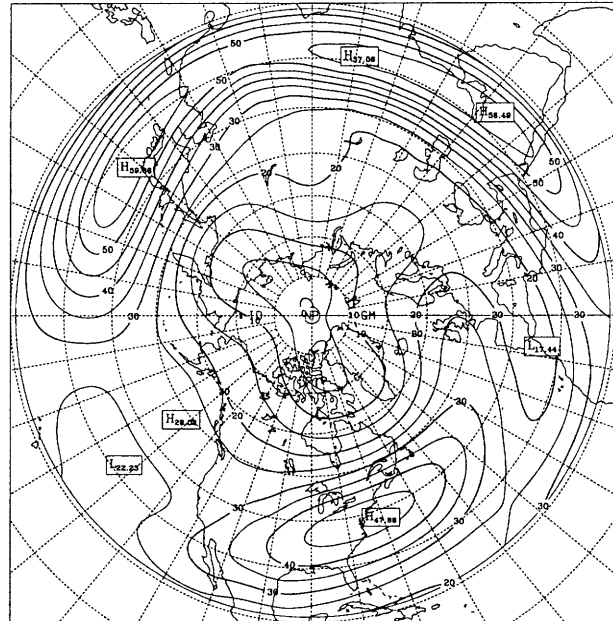
Figure 6.5: As in figure 6.3, but for CCM2AMIP.

gissamip winter mean u200 – 1980s (m/s)
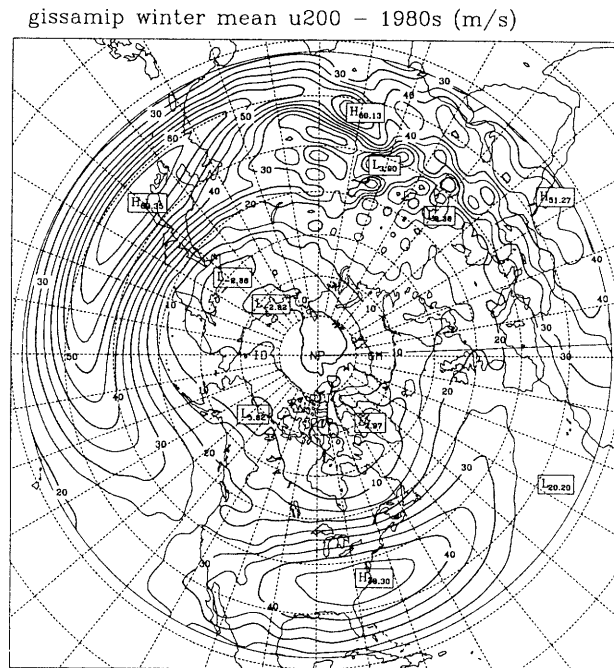
Figure 6.6: As in figure 6.3, but for GISSAMIP.

up into spurious small scales through the central Asian region of GISSAMIP. This behaviour also shows up in the stationary wave field for GISSAMIP over the same region. Lo (personal communication) suspects that the excessive fine scale structure in this region is related to interactions between the model's new numerical scheme for advection of temperature and moisture and the Tibetan plateau.

As for the observations, we examined the jet streams in the models for averages over winters that were wetter than normal and drier than normal in the Sacramento Basin in the models. They are not shown here, since in general these plots are very similar to the ten year mean winter model plots. That is, there is little change in the models, especially CCM2, from the ten year mean jets to means over the wettest and driest winters in the basin. The main exceptions to this are for the dry winters in the GISSAMIP simulation, where the Pacific jet does retreat marginally back into the central Pacific as per observations, and for wet winters in CCM1 where the Atlantic jet backs up slightly into the west coast region unlike observations.

6.2 Stationary Waves

obs win (dly) mean 500mb geopotential–1980s (m)

Figure 6.7: Winter mean geopotential height at 500hPa for NMC observations. The winter mean is an average over December, January, and February for the 1980's.

The stationary waves are represented by the 500hPa geopotential height in figure 6.7. This figure shows NMC observations averaged over the 1980's, but the general features of the stationary wave field are common to other decades and data sets. We also plotted 1970's NMC observations, which are similar, as are observations for 1963–1972 (Blackmon, 1976), and for ECMWF IIIb observational analyses for the 1980's (Ponater et al. 1990). There are two major troughs in the winter stationary wave field over the east coasts of North America and Asia. The Asian trough extends well into the Pacific and is an important feature for Sacramento Basin climate. There are two major ridges over the eastern Atlantic and over the eastern Pacific along the west coast of North America. Note that the ridge along the west coast is a winter mean feature, and would not show up in the 500hPa height field for an individual storm in northern California. We examine the structure of the atmosphere on the time scale of individual Sacramento Basin storms in section 6.6.

In wet Sacramento Basin winters, the east Asian trough extends further into the Pacific, and the 500hPa flow field shifts further around to the southwest across northern California. In dry Sacramento Basin winters, the 500hPa flow field shifts around to the northwest across northern California. These features are common to wet and dry ensembles in the 1970's and 1980's.

ccm1 win (dly) mean 500mb geopotential–1980s (m)

Figure 6.8: Winter mean geopotential height at 500hPa for CCM1. The winter mean is an average over December, January, and February for ten years of model simulation.

The winter mean stationary wave fields for models are shown in figure 6.8 through figure 6.10. In CCM1 the amplitudes of the troughs are too weak, but the positions are reasonable. CCM1 is the only model to capture the winter mean ridge along the west coast of North America. In CCM2 the amplitudes of the troughs are better, but the positions of the troughs are off. The trough on the east coast of Asia is too narrow and does not extend far enough into the Pacific. Note that the Pacific jet stream in CCM2 does not extend far enough into the Pacific either. The ridge in the stationary wave field on the west coast of North America is absent in CCM2, as it is for GISSAMIP. In GISSAMIP the troughs are too weak and too broad, and there is unrealistic fine scale structure in the stationary wave field over Asia. For all of the models, there is very little change

ccm2 win (dly) mean 500mb geopotential–1980s (m)
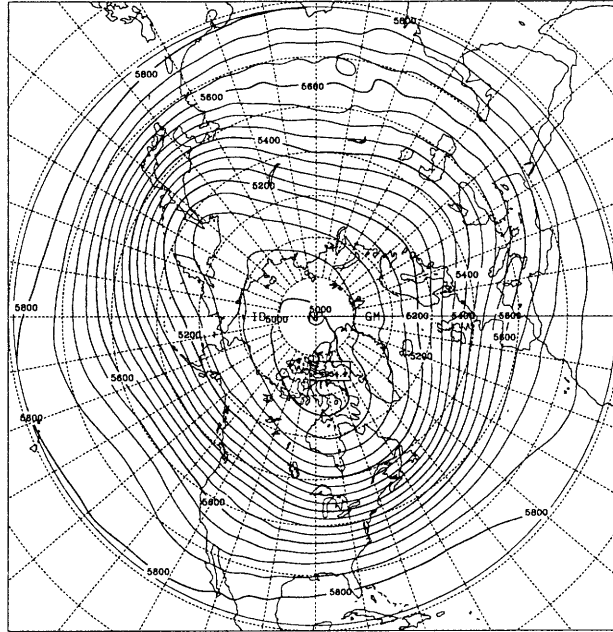
Figure 6.9: As in figure 6.8, but for CCM2.

gissamip winter mean h500 – 1980s (m)
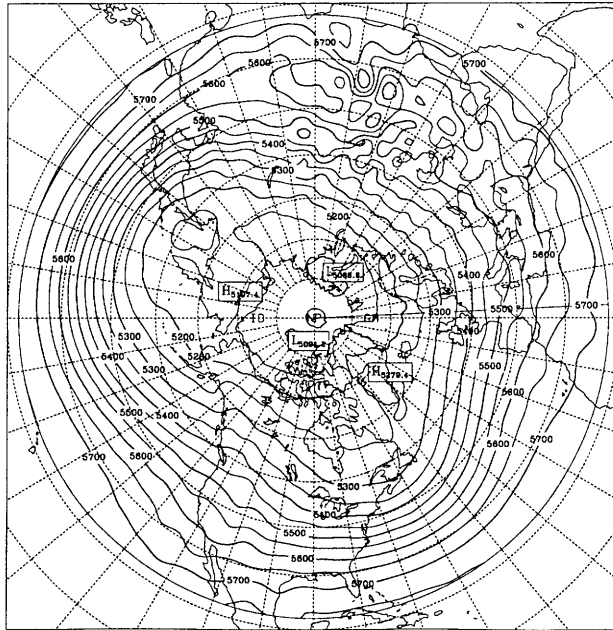
Figure 6.10: As in figure 6.8, but for GISSAMIP.

in the stationary wave fields for ensemble plots of wet and dry Sacramento Basin winters.

6.3   Persistent Anomalies

Persistent anomalies, like storm tracks, are a class of synoptic feature that are often best defined by their characteristic periods. Persistent anomalies are usually defined as those features of the circulation that persist from a little more than a week up to a season or so. They include "slowly changing systems such as large storms which have entered the dissipating stage and become quasi-stationary, slowly moving upper air lows with closed height contours around their centers, blocking ridges, etc." (Blackmon et al., 1977). We follow Blackmon (1976) in using a low pass filter to select out periods in the 500hPa geopotential height field in the range between approximately 10–90 days to denote persistent anomalies. The regions of maximum low frequency variability in the atmosphere have been found to coincide with regions where large scale persistent circulation anomalies are often observed (Blackmon et al., 1986).

Blackmon (1976) designed the low pass filter coefficients to have a sharp cutoff at 10 days. We removed the first four harmonics of the annual cycle from the height field before filtering to remove periods greater than 90 days from the data. The gridded daily geopotential height data for observations and models was filtered according to:

$$\bar{Z}_{\theta,\phi}(t_i) = a_0 Z_{\theta,\phi}(t_i) + \sum_{p=1}^{15} a_p [Z_{\theta,\phi}(t_{i+p}) + Z_{\theta,\phi}(t_{i-p})] \tag{6.1}$$

where the overbar denotes filtered data, Z is geopotential height, θ is latitude, ϕ is longitude, t is time, and the a_p are the filter coefficients, which are given in table 6.1. Note that the filter coefficients are not the same as those listed in Blackmon (1976) since those are for twice-daily data, and we use once-daily data.

coefficient	lowpass	bandpass
a_0	0.2000000030	0.4666666687
a_1	0.1859211624	-0.0880096257
a_2	0.1475836039	-0.2819721997
a_3	0.0953023061	0.0953023210
a_4	0.0422268249	0.0199889168
a_5	0.0000000047	0.0469283573
a_6	0.0246668588	0.0246668346
a_7	0.0313070007	-0.0598149188
a_8	0.0246548895	0.0022043285
a_9	0.0119688567	-0.0119688492
a_{10}	0.0000000028	0.0137386890
a_{11}	0.0071657342	0.0177234802
a_{12}	0.0087339515	-0.0087339515
a_{13}	0.0063974611	0.0005719781
a_{14}	0.0027830664	-0.0068835695
a_{15}	0.0000000000	0.0000000024

Table 6.1: Values of the coefficients for the lowpass and bandpass filters.
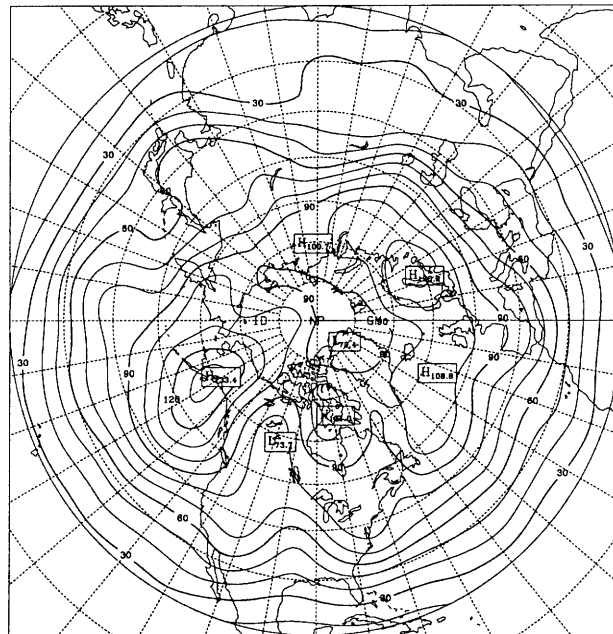
Figure 6.11: Winter mean lowpass filtered rms geopotential height at 500hPa for NMC observations. The winter mean is an average over December, January, and February for the 1980's. The filtering retains periods in the range between 10 and 90 days.

The winter mean lowpass filtered rms[2] geopotential height field at 500hPa
for observations is shown in figure 6.11. Though we do not show the unfiltered
rms geopotential height field at 500hPa, it is very similar to this picture, since the
total field is dominated by its low frequency components. This is true for models
as well as observations, indicating that the models are successful in simulating the
majority of the variability of the middle atmospheric flow field at low frequencies.
The most important feature of the persistent anomaly field from the perspective of
Sacramento Basin climate is the maximum region centred on the Aleutian island
chain in the northeast Pacific. This maximum is due to the presence of blocking
ridges or highs, which often persist near the west coasts of continents and eastern
ocean regions. The Aleutian ridge has a steering effect on storms that transit the
west coast region.

ccm1 win (sr) lowpass rms 500mb geoptl−1980s (m)
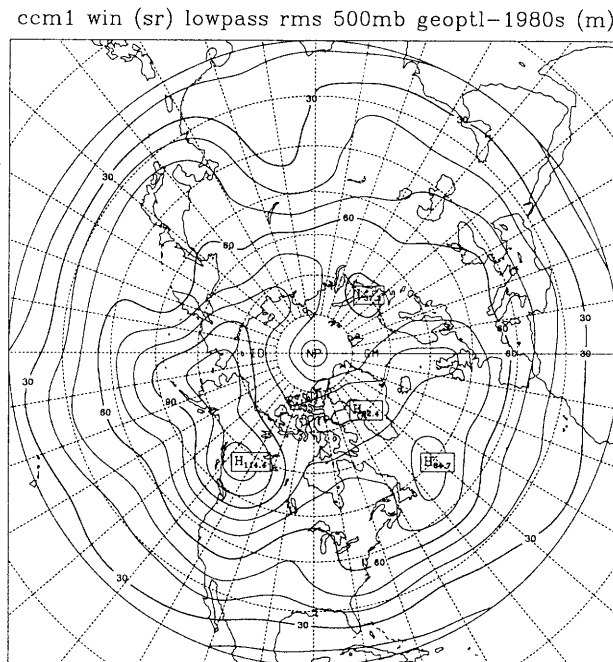
Figure 6.12: Winter mean lowpass filtered rms geopotential height at 500hPa for CCM1.
The winter mean is an average over December, January, and February for ten years of
model simulation.

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[2]We show the rms of the filtered geopotential height, since we are interested in the
fluctuations or variability of this quantity.

ccm2 win (sr) lowpass rms 500mb geoptl–1980s (m)
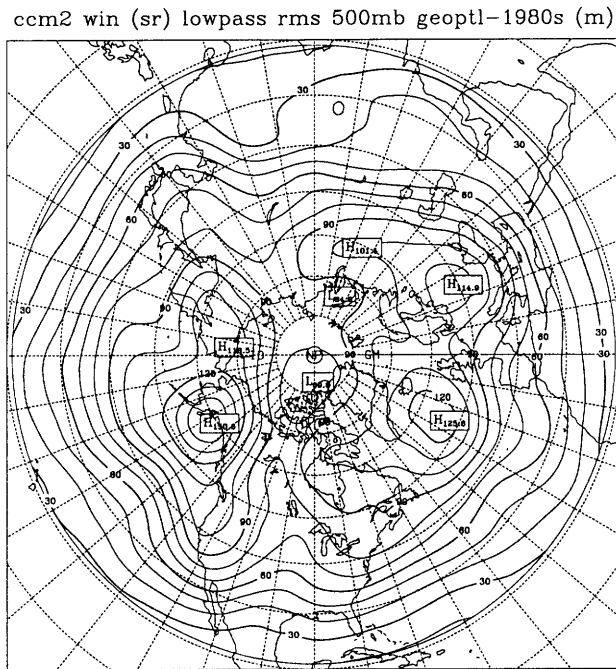
Figure 6.13: As in figure 6.12, but for CCM2.

The winter mean persistent anomaly fields for the models are shown in figure 6.12 and figure 6.13. Note that we could not calculate persistent anomaly and stormtrack fields for the GISSAMIP model, since daily data was not readily available for this model. In CCM1, the maximum region is located too far to the east, and the low frequency variability is undersimulated all over the northern hemisphere extratropics. In CCM2, the maximum is centred in about the right place, but the amplitude is too high, and the maximum region is over-elongated into the west coast region.

6.4 Storm Tracks

Following Blackmon (1976), we denote the storm tracks using the bandpass variance of the geopotential height at the 500hPa level. The bandpass geopotential height is calculated as for the lowpass geopotential height using equation 6.1 and the coefficients listed in table 6.1. The bandpass filter retains periods between about 2.5 and 6 days. Blackmon et al. (1977) note that there is a close correspon-

dence between regions of large bandpass variance at the 500hPa level and regions noted for having a high frequency of cyclonic activity. Developing cyclonic disturbances move quite rapidly during their development stage, and hence tend to fall within the bandpass portion of the frequency spectrum.

obs win bandpass rms 500mb geoptl–1980s (m)
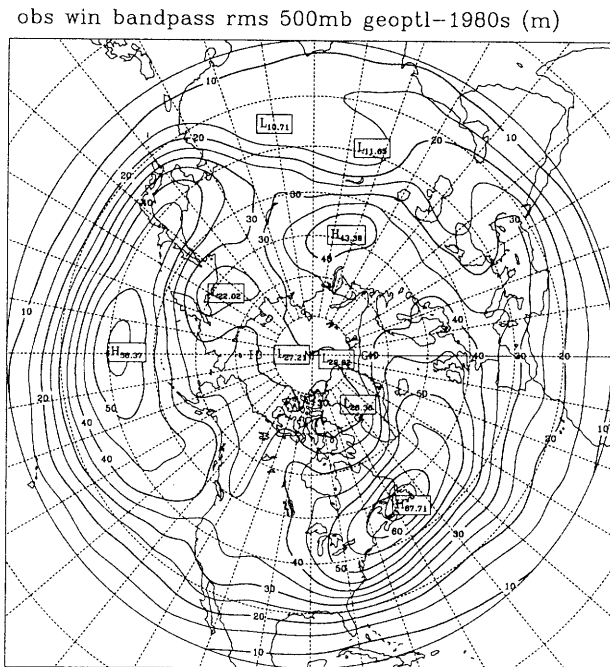
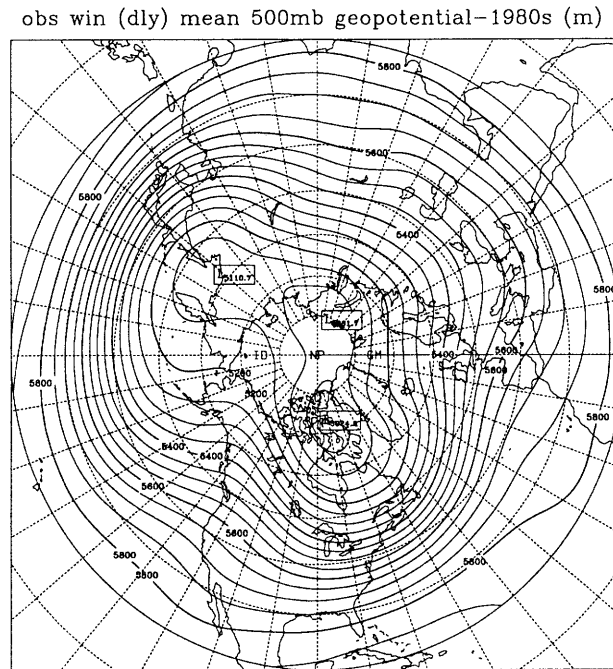Figure 6.14: Winter mean bandpass filtered rms geopotential height at 500hPa for NMC observations. The winter mean is an average for December, January, and February over the 1980's. The filtering retains periods in the range between 2.5 and 6 days.

Figure 6.14 shows the storm track field in NMC observations for the 1980's. As for the other fields, the storm track pattern and intensity is fairly similar across different observational data sets and periods. There are two major regions of storm track activity, from the east coast of Asia across the North Pacific Ocean to the west coast of North America, and from the east coast of North America across the North Atlantic Ocean into Northern Europe. The east coasts of continents are known as areas of cyclogenesis. The storm tracks are located slightly poleward and downstream of the principal wintertime jet streams (compare figure 6.14 with figure 6.1).

In wet and dry winters (figure 6.15) the storm track changes are consistent with the changes in the jet stream in wet and dry winters. In dry winters the

obs wet win bandpass rms 500mb geoptl−83,86 (m)   obs dry win bandpass rms 500mb geoptl−85,89 (m)
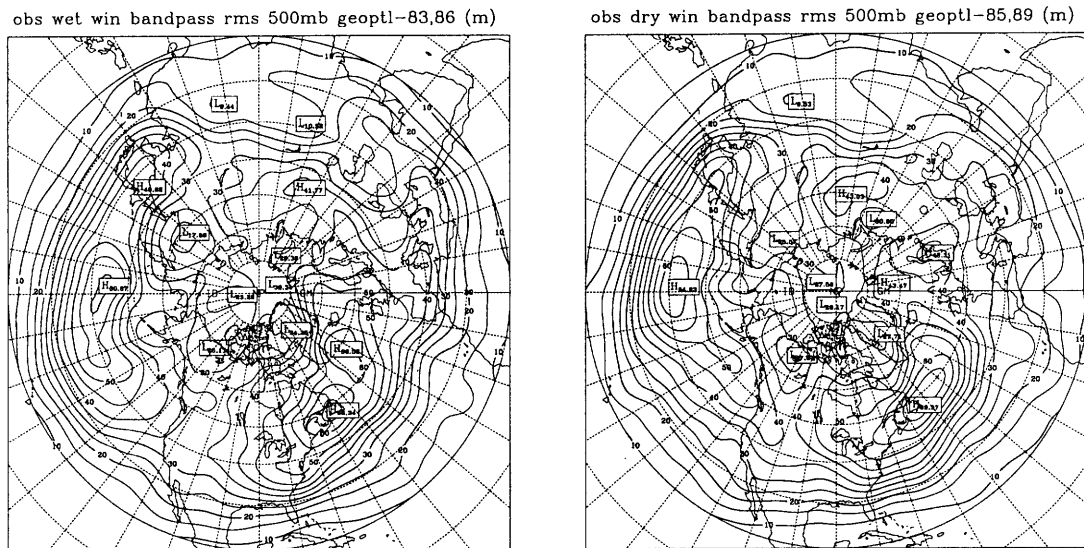
Figure 6.15: Winter mean bandpass filtered rms geopotential height at 500hPa for NMC observations for an average over two wet winters (left plot) and for an average over two dry winters (right plot) in the Sacramento Basin.

storm track narrows and moves further north of the Sacramento Basin in crossing the west coast. In wet winters the storm track retains a broader swath and moves a little further eastwards and south.

The storm track fields in the models are shown in figure 6.16 through figure 6.18. In CCM1, the Pacific storm track is located poleward and downstream of its Pacific jet stream (figure 6.3), but like the jet stream, the storm track does not extend far enough into the eastern Pacific. In other words, the Pacific storms in CCM1 tend to weaken and dissipate before they reach the west coast of North America. The activity along the Pacific and Atlantic storm tracks in CCM1 is weaker than for observations, even when allowing for interannual variability in the observations. The weak storm track activity in CCM1 is consistent with the weak stationary wave amplitudes in the model (figure 6.8). It is also consistent with the abnormally low frequency of Sacramento Basin storm events noted in the CCM1 precipitation output in chapter 5. For wetter than normal Sacramento Basin winters, there is a backward extension of the Atlantic storm track into the Sacramento Basin region evident in figure 6.17 for CCM1. In the observations,

ccm1 win bandpass rms 500mb geoptl–1980s (m)

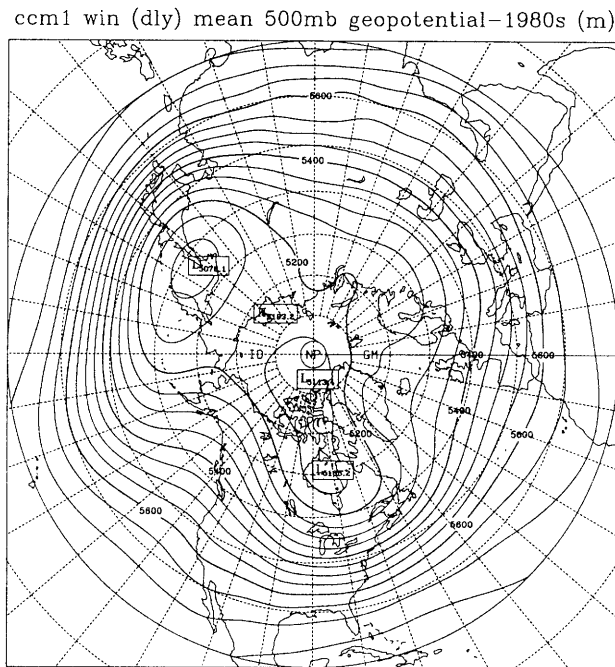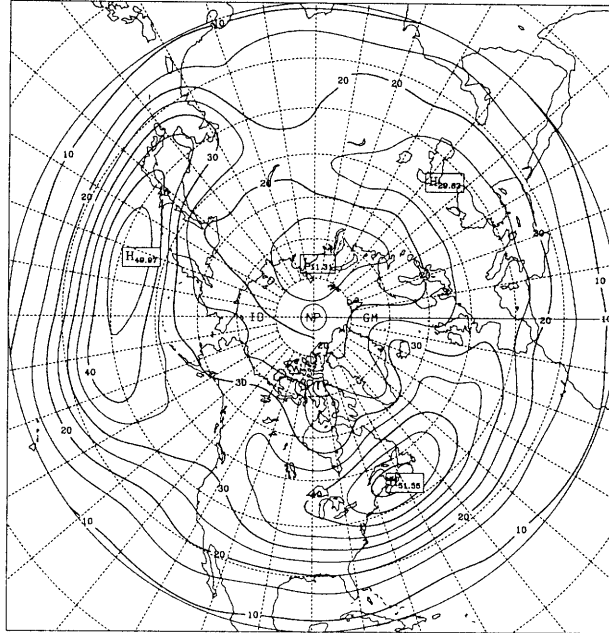Figure 6.16: Winter mean bandpass filtered rms geopotential height at 500hPa for CCM1. The winter mean is an average over December, January, and February for ten years of model simulation.

ccm1 wet win bandpass rms 500mb geoptl–1980s (m)
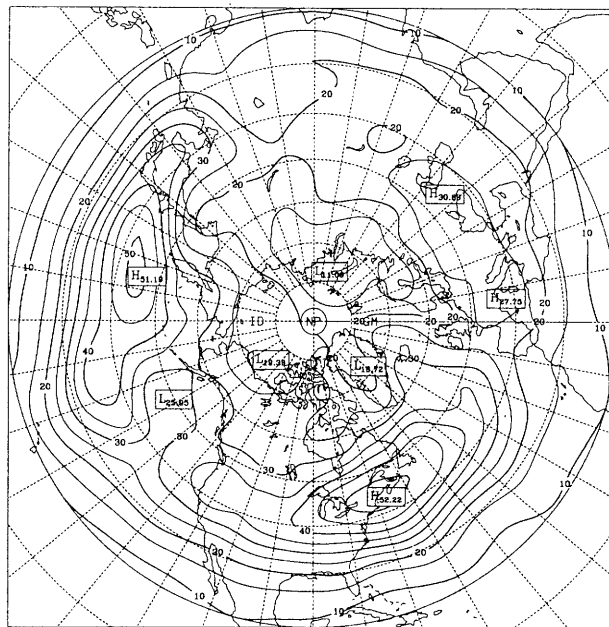
Figure 6.17: As in figure 6.16, but for an average over two wet winters in the Sacramento Basin.

storm events in the Sacramento Basin are associated with the Pacific storm track, not the Atlantic storm track. The backing of the Atlantic storm track in CCM1 is consistent with the unrealistic backing of the CCM1 Atlantic jet towards the west coast in wet winters.

ccm2 win bandpass rms 500mb geoptl–1980s (m)
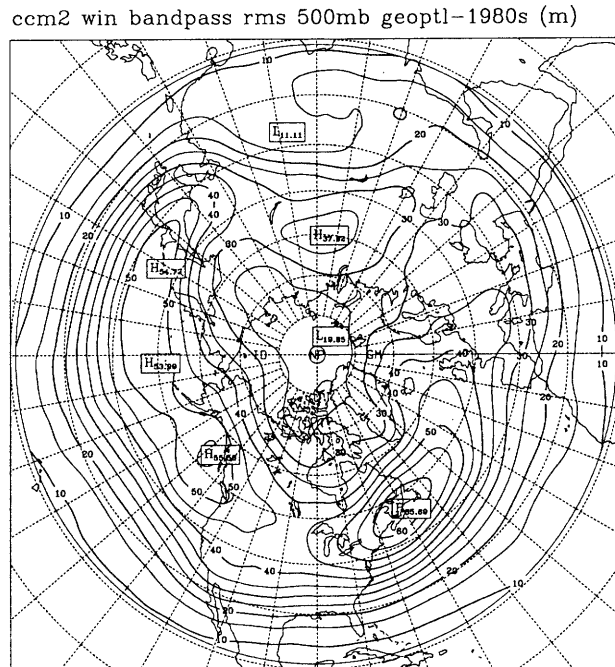
Figure 6.18: As in figure 6.16, but for CCM2.

The CCM2 storm track field is shown in figure 6.18. The CCM2 Atlantic storm track is reasonably well placed with the right intensity, but the Pacific storm track is less realistic. The CCM2 Pacific storm track extends all the way across the Pacific at near maximum amplitude, unlike observations, where the storm track tails off toward the west coast. The overextensive CCM2 Pacific storm track seems inconsistent with its underextensive jet stream, which peters out in the mid-Pacific region. The CCM2 stationary wave pattern has no ridge in the vicinity of the west coast region, unlike observations. This ridge would tend to block the progress of cyclonic systems across the west coast, so its absence may be a factor in the overextensive CCM2 storm tracks.

As for the other fields considered in this section, there are no noticeable changes for the CCM2 wet winter and dry winter ensemble storm track plots.

The lack of change from climatological mean to wet and dry cases for CCM2 is consistent with the observation made in section 4.3 that the model appears to be more or less continually in a kind of 'wet' mode with a low off the west coast in its climate mean producing precipitation in the west coast region, and a spurious overextensive Pacific storm track.

6.5   Model Discrepancies

The analysis of large scale circulation features such as the jet streams and stationary waves in the models reveals major discrepancies between the models and observations. Important questions in light of this are whether the discrepancies are real, and if so, what causes the deficiencies in the model simulations.

We are convinced that the discrepancies between models and observations are real, and can not be accounted for by errors in the observations or by undersampling of the observational variability for instance. We repeated all the observational analyses using the 1970's instead of the 1980's, with similar results. Some decadal variability is evident, but it is much smaller than the differences between observations and models. We also redid many of the analyses using data from the ECMWF WMO observational archive for the 1980's. These plots are almost identical to the NMC observational plots for the 1980's, indicating that the errors in the observations are also small compared to differences between observations and models. The model differences with observations are even large compared to the typical range of interannual variability in the observational fields we considered.

A thorough analysis of the causes of the model discrepancies in simulation of the jet streams and stationary wave fields would push the limits of understanding of what sets these fields, and would require a substantial investment in computer simulation time as well — tasks beyond the present scope of this work. The positions of the jet streams and stationary waves are intimately related to one another, as well as to various other forcings. Da Silva and Lindzen (1993) note that shifts

in the subtropical jet of only a few degrees can produce changes in the topographically forced stationary waves. The changes are concentrated downstream of the Tibetan plateau, extending across North America and into Europe. They find that shifting the jet equatorward increases the stationary wave response in mid and high latitudes, and conversely, shifting the jet poleward decreases the stationary wave response. In the observations (figure 6.1), the jet is displaced slightly equatorward in the Tibet region in Sacramento Basin wet years and slightly poleward in Sacramento Basin dry years. There is perhaps some increase in stationary wave amplitude at midlatitudes in the wet years, though this is not pronounced. In CCM1 the jet is a little too far poleward in the Tibet region, and consistent with this, the stationary wave amplitudes are too weak. In CCM2, the jet is too far equatorward in the Tibet region, and the stationary wave amplitudes are marginally strong, as would be consistent with this.

The locations of the subtropical jet stream and stationary waves are influenced by the distribution of tropical heating, among other factors. Hack et al. (1994) note that the errors in the simulation of the stationary wave field in CCM2 are related to an unrealistic simulation of precipitation over the maritime continent region in the model. They argue that an anomalous positioning of deep convection in the western Pacific region in CCM2 affects wave propagation and longwave positioning in the January simulation. "This results in excessive ridging over the North Pacific and an anomalous reduction in the height field over Western North America" (the missing ridge in figure 6.9). Plumb (1985)'s wave activity flux would be a useful diagnostic to confirm whether Hack et al. (1994) are correct in attributing errors in the stationary wave field to errors in diabatic heating in the maritime continent region, though this diagnostic has not yet been computed for CCM2.

Hack et al. (1994) believe that the errors in the CCM2 simulation of west Pacific deep convection are related to the representation of cloud optical properties, and to nonlinear interactions between moist convection and the atmospheric boundary layer scheme in the model. These schemes apparently transport too much water vapour in deep convective regions in the model. The moist convection

and boundary layer schemes are part of the model's subgrid scale parameterizations. This means that errors in the large scale synoptic climatology of the GCM are related, at least in part, to the subgrid scale parameterizations in the model. This point is underscored by Stone and Risbey (1990), who reached similar conclusions in examining the large scale vertical heat fluxes in several climate models. They found that not only did the GCM simulation of small scale heat fluxes depend on the parameterization of moist convection as would be expected, but the explicitly resolved large scale vertical heat flux also depended on the subgrid scale parameterization of moist convection in the model. The parallel point here is that the explicitly resolved stationary wave field also depends on the subgrid scale parameterization of moist convection. This result is not unexpected, since the convection schemes in the models will influence the diabatic heating fields in regions of convection, and the diabatic heating field is one of the forcing factors for the large scale stationary wave field. Furthermore, the heating field also influences the development and evolution of transient eddies in the models, which also force the stationary wave field.

The sensitivity of the large scale circulation to moist-convective parameterization has also been demonstrated by Yao and Stone (1987) using a 2-D zonally averaged statistical-dynamical model. They found that the greater the parameterized amount of deep convection in the subsident branch of the Hadley cell, the weaker the Hadley cell circulations and westerly jets.

6.6   Storm Events

In this section we examine the large scale flow patterns associated with individual storm events in the Sacramento Basin. Analysis of the large scale circulation features in the above sections was based on winter mean patterns, which can underrepresent the flow pattern of the phenomena primarily responsible for producing significant precipitation. For example, there is no upper level trough in the region off the west coast in the winter mean height field shown in figure 6.7.

Yet we know that a trough in this region is one of the important features usually associated with precipitation in the Sacramento Basin.

From the daily precipitation data for the Sacramento Basin in observations and models (see chapter 5), we selected the ten largest storm events occuring in each dataset during the decade of observations or model simulation. We then examined the sea level pressure field, 500hPa geopotential height field (stationary waves), and 200hPa zonal wind (jet streams) on the day defining the middle of each severe storm, and for the days immediately preceding and following that day. We examined the ten largest precipitation events in each dataset, since we are interested in severe events in the Sacramento Basin (they are important in generating streamflow in the basin), and because the largest storms are both easy to define, and contribute significant amounts of precipitation to the basin (see figure 5.7 for instance). For observations, the largest storms in the Sacramento Basin are typically about 100mm/day. They may last from 1 to 3 days, dumping around 200mm of precipitation, which is about 1/10th of the annual precipitation in the basin. The largest storms in the models in the basin are around 30mm/day.

In figure 6.19 through figure 6.22 we show the composite sea level pressure, 500hPa geopotential height, and 200hPa zonal wind fields for NMC observations and models. The composite plots are averages over the ten individual large storm fields in the observations and models. The individual storms in the observations are fairly similar from storm to storm, and are well represented by the composite storm plot (figure 6.19). The Sacramento Basin observations storm features a low off the coast to the west and northwest of California, with a trough at 500mb in this region, and an extension of the Pacific jet across the California coast. The ridge along the west coast that shows up in the winter mean plots is displaced inland in the storm pattern. We performed several checks on the observations to test the robustness of the above features. We produced two other sets of composite storm plots over five storms each, yielding similar results. We also obtained ECMWF WMO observations of 500hPa geopotential height and 200hPa zonal wind, and plotted these fields for each of the individual storms, and for a composite of the ten storms. The ECMWF observational fields are virtually identical to the NMC

ob slp (hPa) Sac Stm composite day -1   ob 500z (m) Sac Stm composite day -1   ob 200u (m/s) Sac Stm composite day -1

ob slp (hPa) Sac Stm composite day 0   ob 500z (m) Sac Stm composite day 0   ob 200u (m/s) Sac Stm composite day 0

ob slp (hPa) Sac Stm composite day +1   ob 500z (m) Sac Stm composite day +1   ob 200u (m/s) Sac Stm composite day +1
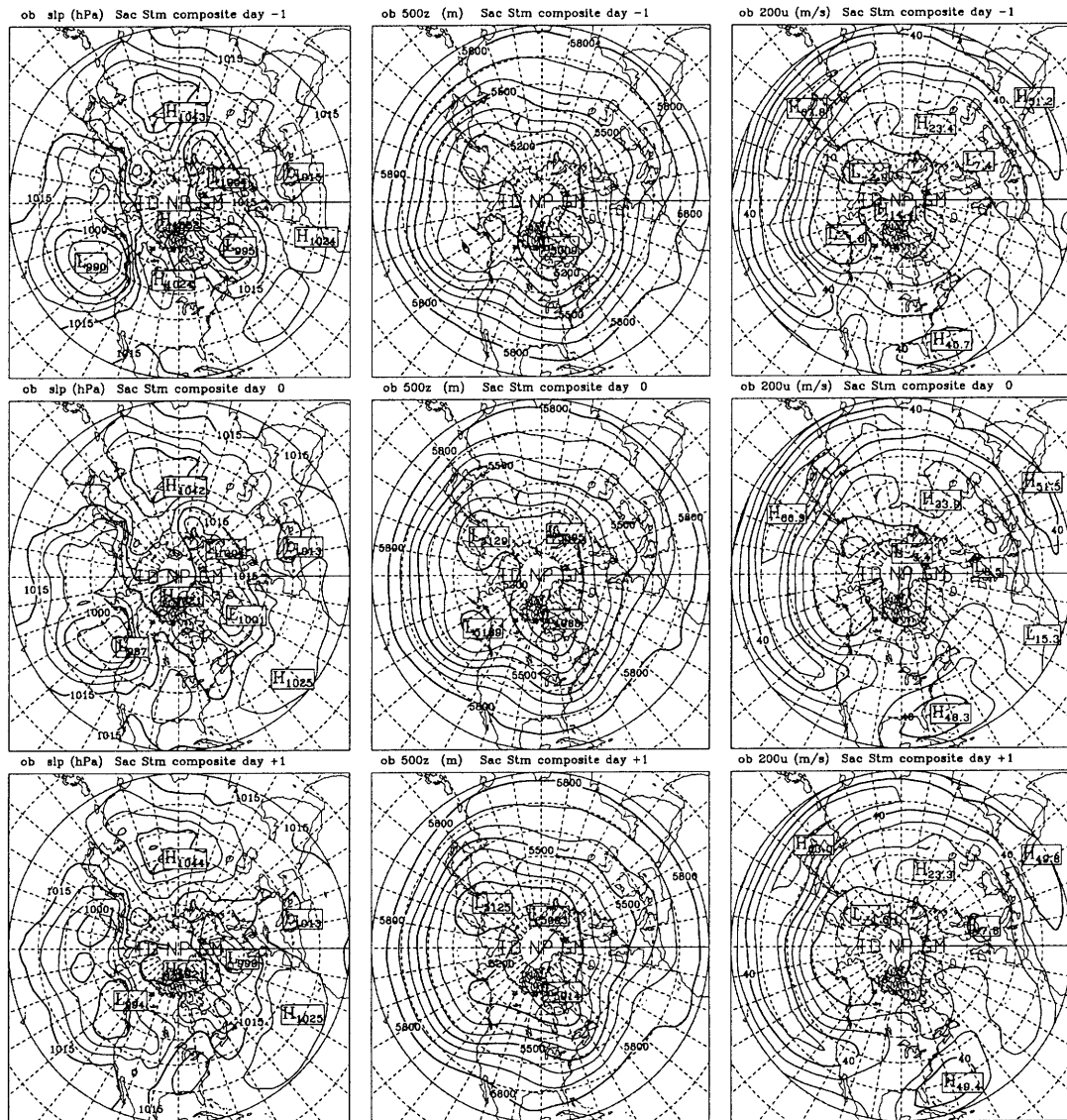
Figure 6.19: Composite Sacramento Basin storm patterns for NMC observations. The left column is sea level pressure, the middle column is 500hPa geopotential height, and the right column is 200hPa zonal wind. The top row is for the day before the precipitation maximum, the middle row is for the day of the precipitation maximum, and the bottom row is for the day after the precipitation maximum.

observational fields, giving us high confidence in the reality of the major features described above.
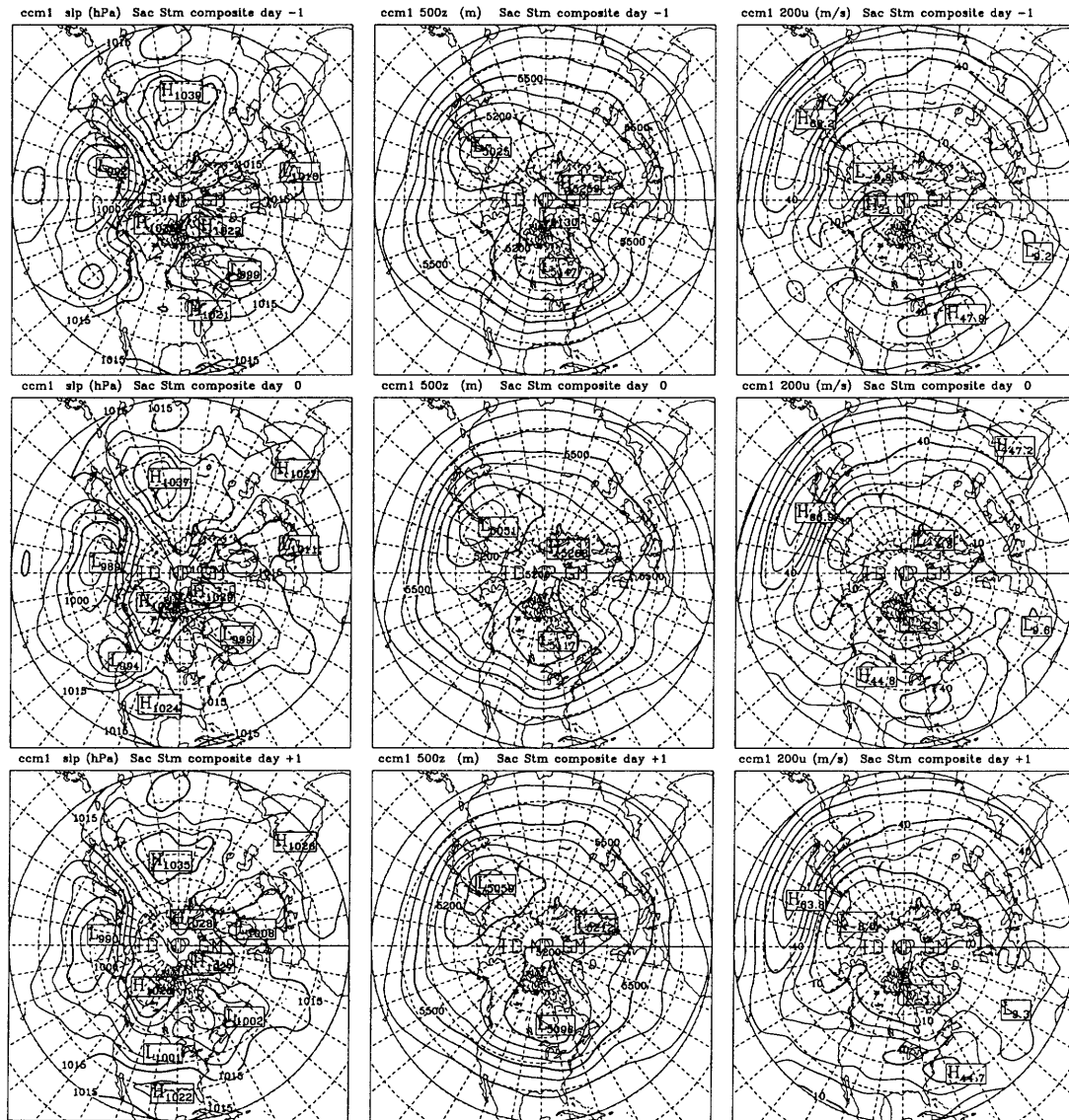
Figure 6.20: As in figure 6.19, but for CCM1.

The composite storm patterns for CCM1 are shown in figure 6.20. In the composite plot, CCM1 has a low off the coast as per observations, though in the individual storm plots the low is sometimes too far inland. There is sometimes no trough at 500hPa in the individual storms, and a very weak trough is present there in the composite storm. The jet stream position in CCM1 is hard to characterize, though it rarely looks like observations, even when the surface low off the coast is

in the correct position. More often than not, any jet maximum near the California coast seems to be more coherently related to the Atlantic jet than the Pacific jet. This backing of the Atlantic jet during storms was also evident in the CCM1 plots of the winter mean jet stream during wet Sacramento Basin winters. The surface low near the coast is not apparent in the CCM1 plots for the day after the precipitation maximum in the storm. This is unlike observations, where the surface low weakens at day+1, but remains coherent. This indicates that the storms are too short-lived in CCM1.
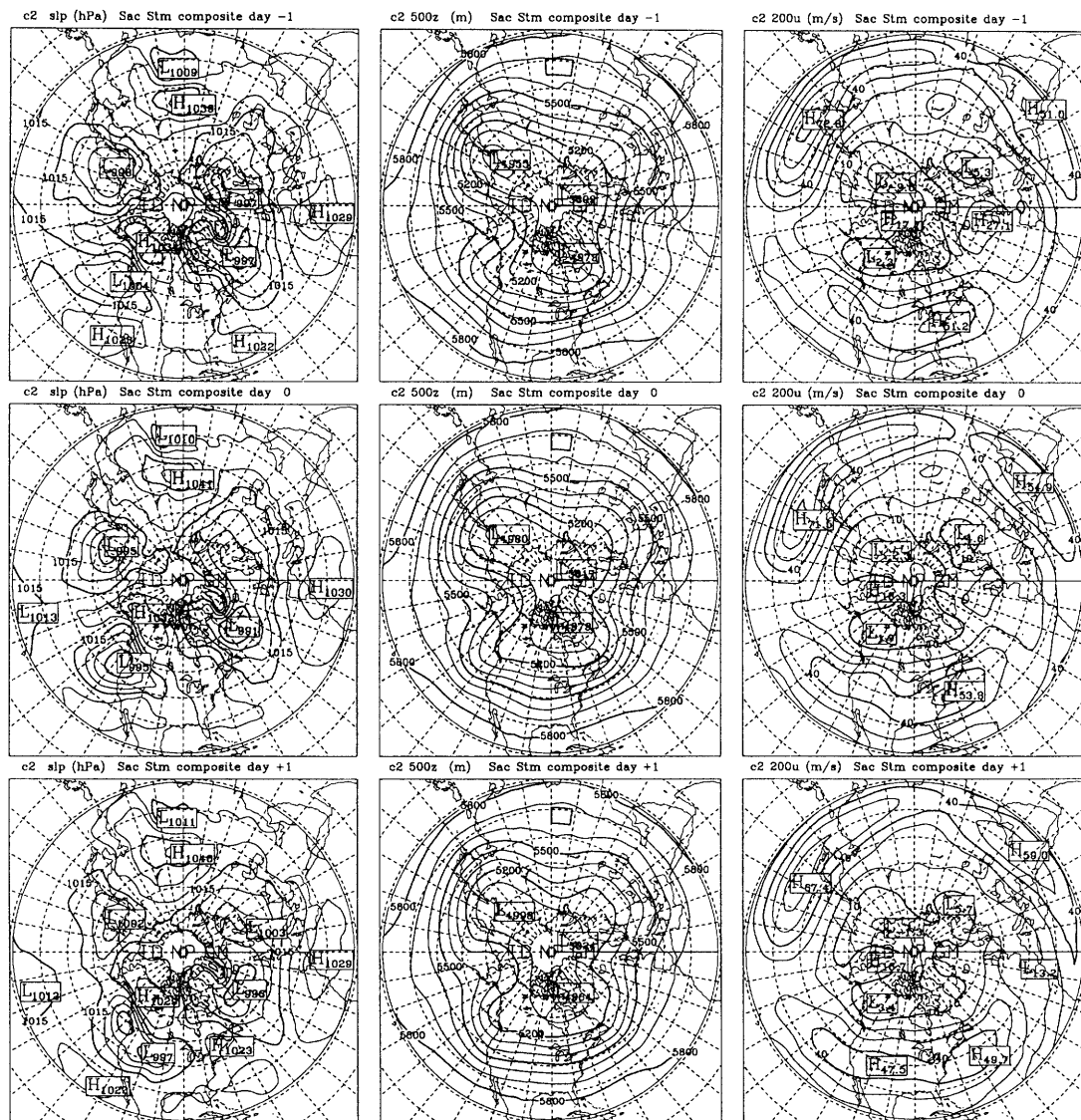
Figure 6.21: As in figure 6.19, but for CCM2.

The composite storm patterns for CCM2 are shown in figure 6.21. The surface low that shows up in the composite storm plot is present in most of the individual storm plots, but not all of them. The trough at 500hPa is sometimes present in individual storms, but is usually too far south, indicating that the system is more vertical than in the observations. In the composite storm plot the 500hPa trough is too weak. The ridge over western North America is also missing in the 500hPa field. The jet stream behaviour for individual storms in CCM2 is quite erratic. Sometimes there is no jet over the west coast region, sometimes there is a small local jet over this region, and for some storms there is a backward extension of the Atlantic jet over the west coast region. The latter jet feature shows up in the composite storm plot.

Figure 6.22 shows the composite storm patterns for the CCM2AMIP run. The CCM2AMIP storm patterns are much like the CCM2 patterns, indicating that the use of real SST's does little to improve the simulation of large scale features for storm events. The trough at 500hPa is a little deeper, but the jet stream simulation is still erratic. The composite storm jet stream is also consistent with an unrealistic backing of the Atlantic jet during storm events.

6.7 Summary

Having completed the analysis of the synoptic climatology of the Sacramento Basin for observations and models, it is now appropriate to summarize some of the main findings. The winter mean Pacific jet stream, stationary wave trough in the Pacific and west coast ridge, and Pacific storm track are robust in the observational fields, as is the Aleutian low at the surface. The surface low off the coast, upper trough at 500hPa, and extension of the Pacific jet stream across the west coast are also robust features for individual storms in the Sacramento Basin region.

In CCM1 the winter mean Aleutian low is incoherently simulated. The CCM1 Pacific jet stream is too weak and underextensive across the Pacific. The station-

ca slp (hPa) Sac Stm composite day −1   ca 500z (m) Sac Stm composite day −1   ca 200u (m/s) Sac Stm composite day −1

ca slp (hPa) Sac Stm composite day 0   ca 500z (m) Sac Stm composite day 0   ca 200u (m/s) Sac Stm composite day 0

ca slp (hPa) Sac Stm composite day +1   ca 500z (m) Sac Stm composite day +1   ca 200u (m/s) Sac Stm composite day +1
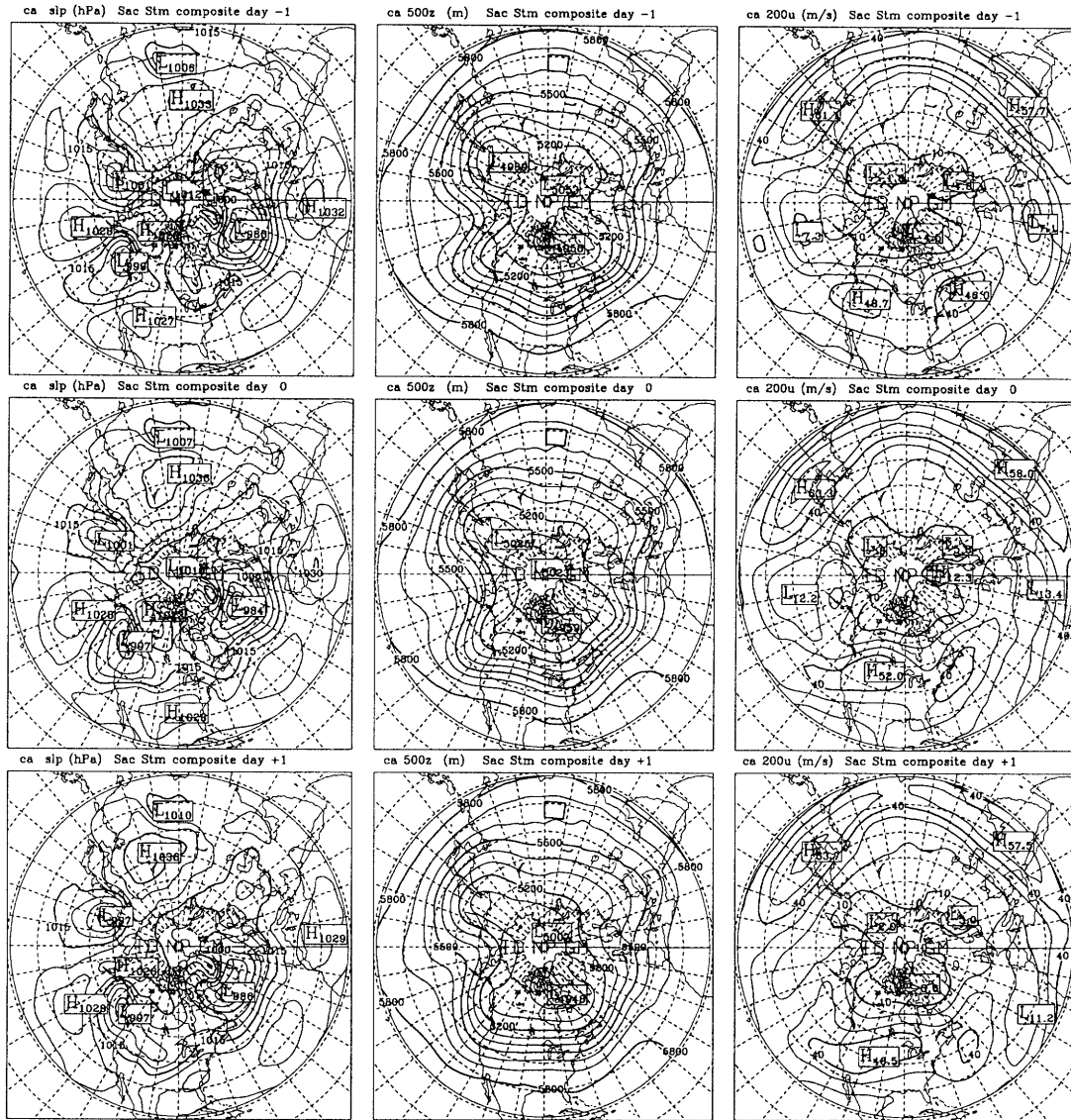
Figure 6.22: As in figure 6.19, but for CCM2AMIP.

ary wave trough amplitude is too weak in the Pacific and the stationary waves are generally too weak in the northern hemisphere extratropics. The CCM1 Pacific storm track has too little activity, and does not extend far enough into the east Pacific. In wet Sacramento Basin winters, there is an unrealistic backward extension of the CCM1 Atlantic jet and storm track toward the Sacramento Basin region. This response is confirmed for individual storms, where the backing of the Atlantic jet is readily apparent. During the winter precipitation season, most of the time there is no jet and storm track over the west coast in CCM1 and the model produces only very weak precipitation — it's storms are too few and far between. When CCM1 does produce a storm in the Sacramento Basin, it does so in an unrealistic manner via a backward extension of the Atlantic jet stream.

In CCM2 the climatological winter mean sea level pressure field shows a spurious low off the west coast of North America. There is no ridge at the 500hPa level down the west coast in CCM2 as there is in observations. The spurious low may be compensating for the underextensive stationary wave trough and jet stream in the Pacific, and is also probably responsible for the spurious overextension of the Pacific storm track through the west coast region. For winter mean plots, the large scale circulation features in CCM2 change little for ensembles over wetter than normal and drier than normal winters in the Sacramento Basin. In the climate mean, CCM2 appears to be stuck in a mode resembling the observations 'wet' mode with the low off the California coast. Even here though, the large scale synoptic structure supporting that mode is different from the observations wet mode. For instance the CCM2 jet stream field for individual storms is erratic, and CCM2 Sacramento Basin storms are most often associated with a backing of the Atlantic jet (like CCM1), rather than with an extension of the Pacific jet stream as in observations. The defiencies in the Pacific Ocean and North America region in CCM2's stationary wave field have been linked to a deficient precipitation simulation in the western Pacific region. This is turn was linked to deficiencies in the models moist convection and boundary layer schemes, and their interactions.

Analysis of the GISSAMIP model was hampered by lack of appropriate daily model output. Like CCM2, the GISSAMIP model shows a spurious low off the west coast of North America in the winter mean sea level pressure field. This low may also be a mechanism for the model to produce more precipitation along the west coast to overcome the unrealistically small storm precipitation amounts in the model. The winter mean Pacific jet stream and stationary wave field are reasonably well simulated in the model, which is encouraging from the point of view of the Sacramento Basin. The jet stream and stationary wave field are peculiar over the Asian continent, with too many small scale features. The model trends in these fields for wet and dry winters are smaller than for observations, though they are in the right direction for wet Sacramento Basin winters. It is difficult to make an informed judgement on the synoptic climatology of this model because of the lack of available data to calculate persistent anomalies, stationary waves, and individual storm fields. It seems however, that the model is prone to similar forms of compensation in its atmospheric circulation for the weak simulation of precipitation intensity as the CCM models.

For at least those models where we can make a reasonable judgement (CCM1, CCM2, CCM2AMIP), we conclude that the large scale processes producing precipitation in the Sacramento Basin region in the models are unlike those that operate in the real world. The model synoptic climatologies for the Sacramento Basin have such egregious differences with the observed synoptic climatology, that they might best be thought of as describing the climate of a region on another planet. We may conclude thus far then that the errors in climate model supplied precipitation to the Sacramento Basin region are not due to easily remediable systematic shifts of some kind in the models climate. The errors are due to unrealistic representations of the large scale circulation, and of the smaller subgrid scale processes producing precipitation and the heating fields that interact with the larger scale circulations. The assumption that one can take the difference between $2CO_2$ and $1CO_2$ climate model runs as being relatively error free on the basis that the model simulates the change correctly, even if the original climate is in error, is probably a bad one. If the physical processes producing the precipitation are unrealistic in the models,

then the model response to a climate perturbation such as increasing greenhouse gases may bear no relationship with the actual response in the Sacramento Basin region.

If the linearity assumption above for GCM climate change scenarios for the Sacramento Basin is currently a bad one, it is important to consider how the models might be improved to the point that this assumption isn't so bad. We take this issue up in chapter 7 to follow. From the point of view of water resource planning in the Sacramento Basin, it is also important to ask whether the basin streamflow is even sensitive to errors and climate changes of the size simulated by the climate models. If not, then the model analysis undertaken above is interesting, but largely academic. In the end too, it doesn't necessarily matter from the water resource planners perspective that the linearity assumption for climate model simulations is a bad one. The policy planners must make decisions about expected climate futures in the basin, and what really matters is how reliable the climate model scenarios are compared to information from other sources. We pursue these questions in chapter 9.

*Among numerous insect species there is the aeronaut grub, something
like a silk worm, which in good weather generates light gases in its intestines
and in a few hours blows up a huge bubble that carries it off into the atmos-
phere; it never reaches full maturity and reproduces itself ingloriously by larval
parthenogenesis.*

*Had these curious species been brought in long ago by settlers from other
parts of the earth, or were they forms of life truly indigenous to the continent
of Mount Analogue? Beaver could not resolve the question. An old Breton,
established in Port o' Monkeys as a carpenter, had related and sung to him
some old myths that touched on the subject. They were a kind of blend, it
seems, of foreign legends and the guides' teachings. Any guides we later asked
about the value of these myths always gave us what appeared to be evasive
answers.*

*"They are as true," one of them told us, "as your own fairy stories and
scientific theories."*

*"A knife," said another, "is neither true nor false. But someone who grasps
it by the blade is truly in error."*

René Daumal
Mount Analogue

Chapter 7

Prospects For Regional Climate Simulations

While the state of the art climate models we considered do not *currently* simulate the synoptic climatology of the Sacramento Basin region with much fidelity, it is important to remember that the models are more or less constantly evolving, and will be better able to do so in the future. In this regard, it is useful to know:

- what the major limitations are to improving the models for regional climate simulations
- where efforts ought to be directed to improve the models
- what time scales are involved in satisfactorily completing the work.

These questions are relevant to concerns about whether planning decisions for the Sacramento Basin ought to be delayed in the likelihood that more reliable regional scenarios are imminent from the models, as Sununu (1992) and others claim, or made sooner in the case that reliable model scenarios are not likely for some time, as Risbey and Stone (1992) suspect.

Among the major areas of ongoing research and development in climate models are dynamical ocean models, higher resolution grids, improved parameterizations of convection, the land surface, and boundary layer processes. In this chapter we examine the role of these factors in improving the simulation of regional climate. While we continue to focus specifically on the regional climate of

the Sacramento Basin, we will also take up the question of whether the climate models may do better in other regions.

7.1   Oceans

The climate models that we examined are atmospheric GCMs that use climatological sea surface temperatures. The sea surface temperatures are prescribed from the monthly climatological average in each location. We did not include a coupled dynamical ocean and atmosphere climate model, partly because of the rudimentary state of development of these models, which require large artificial fluxes of heat and moisture across the ocean atmosphere interface in order to maintain a stable climate anything like the present one. The use of simple ocean models with climatologically prescribed SSTs does not allow for dynamic responses of ocean circulation in response to the coupling with the atmosphere. Yet, changes in ocean and atmosphere circulation in response to ocean-atmosphere coupling may be crucial in setting the climate of a region, especially for near-coastal regions such as the Sacramento Basin.

One way to elicit the importance of ocean circulation to the Sacramento Basin climate is by use of the AMIP model runs (Gates, 1992) that use observed time series of monthly sea surface temperature and sea ice distributions. For these runs the atmospheric GCM in effect 'sees' a surface temperature of a near-perfect dynamical ocean model. It is 'perfect' in the sense that it is produced by the real ocean, and only 'near' perfect in the sense that observations have some error associated with them. It is also imperfect in as much as the real sea surface temperatures correspond to some forcing by the real atmosphere, which will not be perfectly represented in the atmospheric model, thereby creating a mismatch between the models. For instance, the AMIP sea surface temperatures will be influenced to some small extent by the radiative perturbation in the atmosphere due to the El Chichón eruption in Mexico during the AMIP decade. Yet the El Chichón radiative perturbation is not present in the atmospheric GCMs, so

the atmospheric GCM will 'see' a sea surface temperature signature that was produced by a forcing different to the forcing that it represents. The atmospheric model may compensate for this effect to some degree because of its relatively fast response time in adjusting to the ocean state. Another piece of missing physics is that the ocean is not free to respond to forcing by the atmosphere, since the sea surface temperatures are still specified.

The use of AMIP boundary conditions does not guarantee that the fluxes of heat and moisture into the atmospheric model are nearly perfect either. The fluxes are still only as good as their parameterizations permit them to be — the parameterized fluxes are empirical bulk functions of the surface temperature and surface wind speed. However, this would also be true for a perfect numerical ocean model, could one be developed. The AMIP runs provide a test of the potential benefit of developing better ocean models, if not a near-perfect ocean model.

Though we analysed both the CCM2AMIP and GISSAMIP model runs, only the CCM2AMIP runs serve as a meaningful comparison to the model runs with climatological sea surface temperatures. This is because the model used for the GISSAMIP runs is a more highly developed model than the version of the GISS model run with climatological sea surface temperatures, and most of the improvements in performance appear to be a stronger function of the model improvements, than due to the use of AMIP boundary conditions. Though the lack of a run of the GISSAMIP model with non-AMIP boundary conditions does not allow this conclusion to be drawn with any certainty (it is based on cases where performance gains were noted for the GISSAMIP model over the GISS $4° \times 5°$ model and where there was no corresponding performance gain for the CCM2AMIP model over the CCM2), it does suggest that the gain from incorporating better ocean models is smaller than the gain from improving the models physical and numerical schemes. These remarks apply to gains in the simulation of Sacramento Basin region climate only, since their are other applications for which development of a realistic ocean model is presumably of considerable value.

Comparison of CCM2AMIP performance with CCM2 performance throughout the prior chapters has shown few obvious differences. The sea level pressure

fields, jet streams, stationary waves, storm tracks, and structure of individual Sacramento Basin storms is similar for the two models. The major deficiencies in the synoptic climatology of CCM2 also show up in CCM2AMIP. This indicates that the deficiencies in the large scale atmospheric circulation across the North Pacific and North America in the model are not a strong function of the boundary conditions for sea surface temperature and sea ice distributions. Development of a near perfect ocean model *per se* would not be of major use in improving the Sacramento Basin synoptic climatology in CCM2. This does not mean that development of ocean models would not be important in conjunction with development of atmospheric models, it simply means that development of ocean models alone is insufficient.

Since the large scale circulation is similar in CCM2 and CCM2AMIP, it is not surprising that the precipitation characteristics in the west coast region and Sacramento Basin are similar in the two models also. All of the deficiencies in CCM2 precipitation in the region are shared by CCM2AMIP. The one area of significant improvent we detected is in the variability of surface air temperature across the North Pacific North America region in the models. The CCM models greatly underestimate the temperature variability in this region, and this underestimate is substantially reduced for CCM2AMIP. The underestimate of temperature variability is to be expected in models that use climatological sea surface temperatures.

7.2   Resolution and Topography

The resolution of state of the art climate models has been increasing slowly[1] over the past decade, and continues to increase as the cost of computer power decreases. The increase in resolution brings with it the ability to resolve increasingly smaller scale processes, and sharpens the representation of topography in

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[1]The increase in resolution has been slow, since for every factor of two increase in resolution, a factor of at least eight increase is required in computer power.

the models. There are some reasons to expect improvements in the models precipitation simulation over the Sacramento Basin with an increase in resolution. Precipitation in the Sacramento Basin depends to some degree on the interaction of the Sierra Nevada mountains with the storm systems passing over them. Increasing resolution will improve the representations of the Sierra Nevada and of the storm systems that pass over them. Increased resolution may also permit a better simulation of the large scale precipitation field by better representing the heterogeneous features in the field and their interactions with the broader field. Increased resolution may even improve simulation of the subgrid scale convective fields in the model by providing a more suitable environment for parameterization. However, the explicit resolution of moist convective processes in the model would require an increase in computer power that lies beyond current technological horizons.

Among the models we examined, a pure test of resolution is afforded by comparison between GISS 8°×10°and GISS 4°×5° models. CCM1 (R15) and CCM2 (T42) do not afford a pure test of resolution, since these models have different physics. The most notable gain in going from 8°×10° to 4°×5° in the GISS model is in the simulation of the Aleutian low in the winter sea level pressure field over the North Pacific (see figure 4.1 and figure 4.2). The Aleutian low is discernible at 4°×5°, but not at 8°×10°. Given the importance of the Aleutian low to Sacramento Basin climate, one would want to avoid use of 8°×10° resolution for climate impact studies there. Despite this gain in going to 4°×5° in the GISS model, the simulation of Sacramento Basin precipitation is only marginally better at 4°×5°. From section 4.2 we saw for instance that the precipitation maximum on the west coast of North America is 13.4mm/day in observations, but does not increase with resolution in either the GISS models (5mm/day for both 8°×10° and 4°×5°) or the CCM models (9mm/day for CCM1 and CCM2). If there is a threshhold for radically improving the simulation of Sacramento Basin precipitation, it must be at some higher resolution than 4°×5° and T42.

We had some opportunity to investigate the effects of going to significantly higher resolution in the case of CCM2. The CCM group have archived four years

CCM2 T42 topography (m)   CCM2 T106 topography (m)
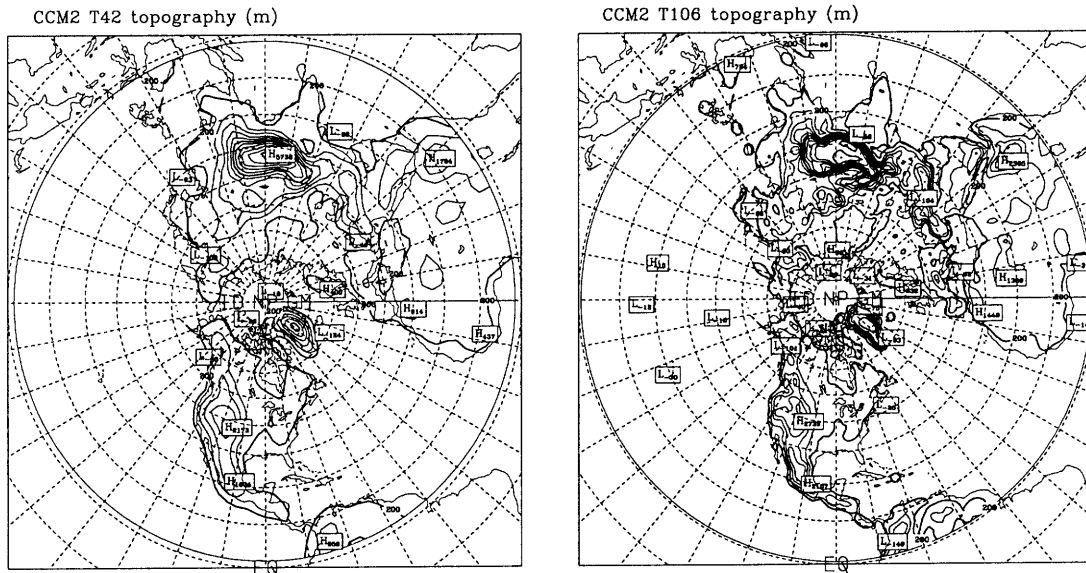
Figure 7.1: CCM2 topography at T42 and T106 resolutions.

of daily January output for a run of the model at T106 resolution. The CCM2T106 run is identical to the CCM2 run with the exception of the horizontal resolution, so this run allows a pure test of horizontal resolution[2]. T106 corresponds to a grid box resolution of about 1° latitude × 1° longitude. The CCM2 topography at T42 and T106 is shown in figure 7.1. At T106, CCM2 begins to resolve the Sierra Nevada mountains of the Sacramento Basin as separate features. This is an improvement over T42, where the Sierra Nevadas are completely lost as part of a smooth rise to a peak over the Rocky Mountains.

The January mean precipitation field for CCM2T106 is shown in figure 7.2. The January mean precipitation over the Sacramento Basin is still too weak as for T42 resolution, though the maximum to the north on the west coast has moved up to 12.3mm/day from 9mm/day at T42. This is much closer to the observed maximum on the west coast of 13.4mm/day. The increase in resolution to T106 has concentrated the precipitation maximum along the west coast, reducing the spatial smearing of precipitation that was evident in the lower resolution models.

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[2]Note that the vertical resolution remains the same for the CCM2T106 run. For optimizing the model performance, it is more usual to increase the vertical resolution when the horizontal resolution is greatly increased.

CCM2 T106 January mean precipitation (mm/day)
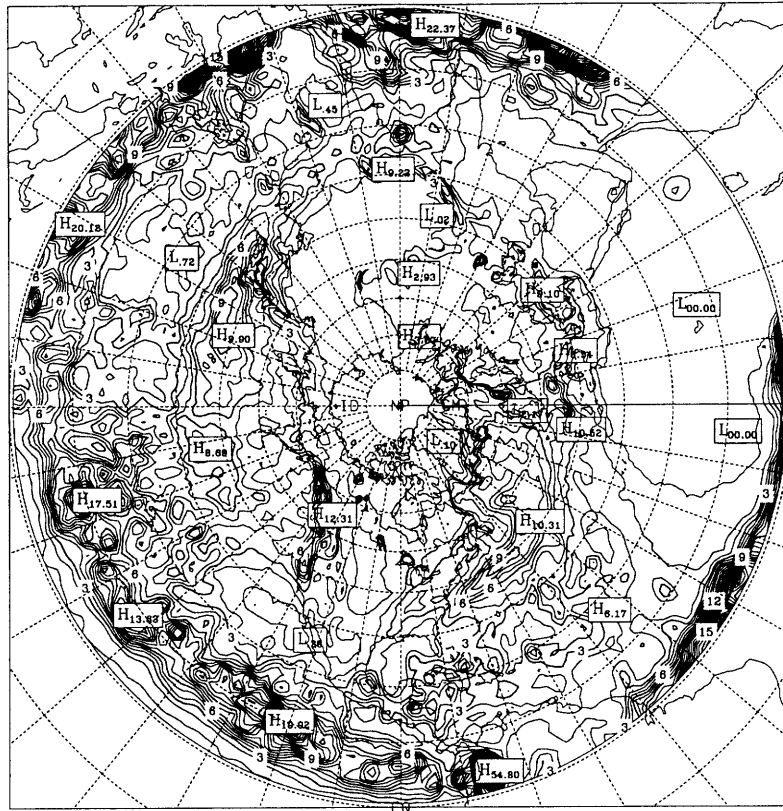
Figure 7.2: CCM2T106 January mean precipitation.
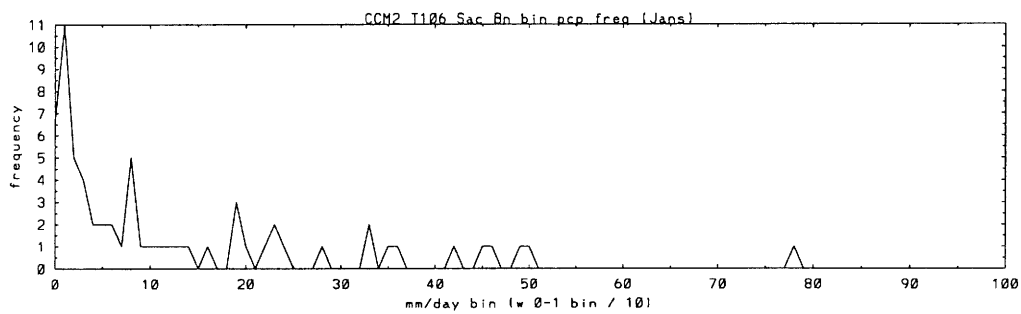
Figure 7.3: Frequency of daily January precipitation values as a function of precipitation intensity for CCM2T106. Note that the value for the 0-1 mm/day bin is shown at $\frac{1}{10}th$ of its actual value.
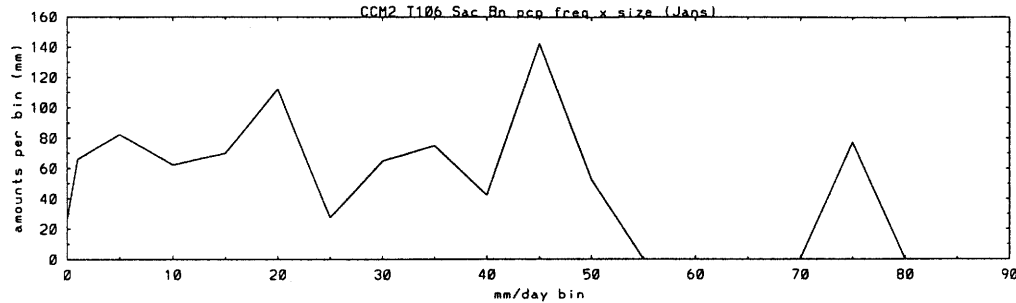
Figure 7.4: Total amount of precipitation per bin over four Januaries of daily data for CCM2T106.

The representation of the Sacramento Basin is no longer ambiguous at T106 resolution as there are nine grid boxes inside the basin at this resolution. We used the average of the nine interior grid boxes to represent the Sacramento Basin in CCM2T106. This yielded virtually identical results to a representation using interpolation to the centroid of the basin. Four Januaries of daily data is a very short sample to identify precipitation characteristics in the Sacramento Basin in the model. The undersampling is clear in figure 7.3 and figure 7.4 which show the frequency of daily precipitation values as a function of intensity, and the total amount of precipitation per intensity bin, respectively. Based on the short sample, the model still has too many drizzle events relative to 'no-precipitation' events as shown in figure 7.3. In figure 7.4 the model appears to yield more of its Sacramento Basin precipitation from larger events than at T42, though in comparing with figure 5.7, bear in mind that that figure is for all days of the year and this figure is for January days only. The T106 model still has too much of its precipitation coming from weak events, and this would only worsen for a plot of total amount of precipitation per intensity bin calculated using all days of the year.

Table 7.1 shows the number of precipitating January days in observations (3 station index) and CCM models for the Sacramento Basin. The CCM2T106 model is just as prone to precipitating too often as CCM2 (T42).

Based on the small sample of available data, it appears that CCM2 is still simulating precipitation arrival unrealistically in the Sacramento Basin at T106

dataset/model	percent no precipitation days	percent precipitation days
3 station index	52	48
CCM2	13	87
CCM2T106	10	90
CCM1	5	95

Table 7.1: Percentage of January days that are not precipitating and precipitating for observations and models in the Sacramento Basin. A 'no precipitation' day is defined as a day in which the precipitation is less than 0.001mm/day.

resolution, despite resolving the basin with nine interior grid boxes. The most apparent advantage we detected in going to T106 resolution is in the spatial representation of precipitation along the west coast, which is no longer so smeared into the interior. This may well be due to the enhancement of topography along the west coast at higher resolution, though the CCM2T106 model would need to be run again without topography to test this. The only 'no topography' runs we are aware of with recent CCM models are those carried out by Kutzback et al. (1993) with CCM1 (R15). In their work, the precipitation maximum along the west coast drops from about 5mm/day to 4mm/day when the topography is removed. This suggests that the topography is a relatively minor factor in setting the precipitation maximum along the west coast. However, the west coast mountain ranges are not resolved at R15 in CCM1, so this tells us little about the enhancement and concentration of precipitation observed along the west coast at T106 where the west coast ranges begin to be resolved.

The large scale jet streams and stationary waves in CCM2T106 are shown in figure 7.5. These figures are for averages over the four model Januaries. The improvements in these fields at higher resolution are marginal at best (compare with figures 6.4 and 6.9, which are for winter means for CCM2). The Pacific jet stream is still underextensive, and the spurious local jet is still present over the northeast Pacific. The stationary wave trough over the Pacific is too narrow, and the ridge present in the observations along the west coast of North America is absent, as in CCM2. Based on these features, it appears that the major deficiencies noted in the large scale circulation for CCM2 are still present at the higher resolution of T106.

CCM2 T106 January mean 200hPa zonal wind (m/s)   CCM2 T106 January mean 500hPa geoptl height (m)
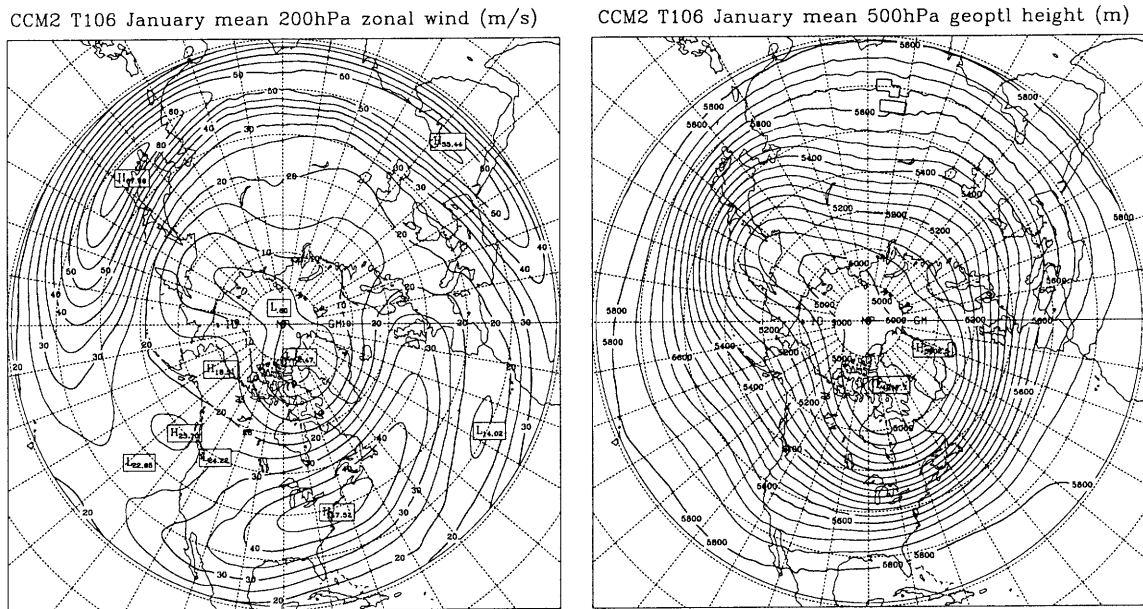
Figure 7.5: CCM2 T106 January mean 200hPa zonal wind and 500hPa geopotential height. The mean is over four model Januaries.

7.3   Other Factors

There is a potentially long list of other factors that may be important in limiting the ability of the climate models to realiably simulate the synoptic climatology of the Sacramento Basin. Without extensive data from sensitivity studies isolating changes in the physics and numerics in the models, it is not possible to make a rigorous determination of the relative importance of the many limiting factors. We mention here some of the more likely factors that emerge from our model studies.

Comparison of the GISSAMIP model run with the GISS 4°×5° model run generally reflected favourably on the GISSAMIP run. The GISSAMIP model incorporated new schemes for moist convection, the boundary layer, clouds, and improved advection of temperature and moisture. It also included a new ground hydrology scheme, as did the GISS 4°×5° model. Much of this development entails new parameterizations of subgrid scale physics. The CCM2 modelling

group (Hack et al., 1994) have pointed in particular to the importance of the moist convective parametization in influencing the stationary wave distribution in the model. They also highlighted interactions between moist convection and the boundary layer scheme as another contributor to the poor stationary wave simulation in the model. The boundary layer scheme has been improved in both CCM2 and the GISSAMIP model. The increase in realism of the schemes also entails an increase in complexity of interaction between the different parameterizations in the models, and the interactions themselves seem to be critical factors in the models performance.

Another type of interaction that is important in simulating the appropriate climate dynamics in the model is between the ocean and atmosphere. Experience with coupled ocean-atmosphere models suggests that this interface is important, as does work on the partitioning of meridional transports of heat and moisture in the observations and models. The parameterizations of the vertical fluxes of heat and moisture across the ocean-atmosphere interace are important in setting the coupled response of a model.

Both CCM2 and the GISSAMIP models incorporate more sophisticated treatments of the numerics associated with advection and/or diffusion in the model. While this has led to substantial improvements in the climate simulations by both models, these models still produce questionable synoptic climatologies of the Sacramento Basin, and it is unlikely that further improvements in numerics alone will be sufficient to overcome the existing deficiencies in the model synoptic climatologies.

Improvements in the land surface scheme in the GISSAMIP model have been less critical in improving that models performance than the other enhancements of the model. The land surface scheme may be a more critical factor in some regions where there is more local recycling of moisture, but Sacramento Basin precipitation is more heavily dependent on imports of moisture in large scale synoptic systems transiting the Pacific Ocean. For instance, Brubaker et al. (1993) find that for a large region in the midcontinental U.S., the winter ratio of locally

evaporated to total precipitation is less than $\frac{1}{5}th$. For the smaller Sacramento
Basin region on the west coast, the ratio would be much smaller again. The
land surface schemes in the models may still have an impact on the large scale
circulation systems in the models through local interactions with the boundary
layer and convection schemes in the models, though it is not yet known how
important these kinds of interaction are.

7.4   Other Regions

While the climate models we studied did not produce very good synoptic clima-
tologies for the Sacramento Basin, it is possible that they may be more suited
to simulating the regional climate of other regions. For other regions in northern
midlatitudes whose precipitation regime is heavily determined by the large scale
circulation in the atmosphere (jet streams, stationary waves, etc.) the prospects
are not very good. This is because these features are large scale, and the errors
in model simulation are not limited to a single jet stream or part of the station-
ary wave field. We did not study model performance in the southern hemisphere
extratropics. There are some reasons to expect that the model simulations of the
large scale circulation in the southern hemisphere might be better. The atmos-
pheric flow is more zonal in the southern hemisphere, and there are fewer extensive
mountainous regions to interact with the flow.

There are some midcontinental regions in the northern extratropics whose
precipitation is more closely associated with small scale summertime convective
activity than it is with synoptic scale cyclonic systems. For these sorts of regions,
and for the tropics as a whole, it is hard to expect the models to do better, as they
are being called on to simulate a class on phenomenon where all the important
physics occurs on sub grid scales. Yet one can sketch an argument, whereby a
GCM might be expected to do better in the tropics:

The argument: The large scale environment in the tropics is fairly uniform,
   so the GCMs have some chance of simulating that correctly, even though

tropical precipitation is dependent on sub grid scale convection. If the large scale environment and any changes in it due to greenhouse gas perturbations can be simulated correctly, then the sub grid scale convection can be tuned appropriately to the large scale environment to produce reasonable results.

There are unfortunately, a number of weaknesses in this argument. First, it is hard to trust a highly tuned moist convection scheme when the underlying physics are complex and not yet properly captured in current state of the art schemes (Renno et al., 1994). Furthermore, it is not at all clear that GCMs simulate well the large scale environment and its changes in the tropics.

There is some question about GCM simulations of greenhouse climate changes in the tropics, which are as large as $\sim$2–3°C for doubled CO_2. Yet, CLIMAP and other proxy data sources for the tropics suggest that sea surface temperature changes in the tropics have been very small for past climate changes. The extent of tropical sea surface temperature changes remains an open question however, since recent studies of coral reef proxies for Atlantic tropical sea surface temperature show larger changes locally than the earlier studies.

The large scale tropical environment is partially determined by ENSO, easterly waves, tropical cyclones, and Hadley circulations. GCMs have had some success simulating ENSO-like cycles, but are not yet regarded as reliable for determining how ENSO might change as climate changes. ENSO plays a big role in setting the large scale tropical environment, so this is a major limitation. The ocean circulation and ocean-atmosphere interactions are important for ENSO, yet coupled ocean-atmosphere models have major deficiencies in the coupling process as we have already mentioned.

Boer et al. (1992) find that GCMs (they tested fourteen) are generally too cold in the tropical lower troposphere, and note that in this region "near surface values are very important for the calculation of fluxes of sensible heat and moisture between the atmosphere and the underlying surface". Further, Boer et al. note that GCM temperature simulations are more sensitive to physics parameterizations than to resolution. In other words this problem will not be solved

simply by increasing the resolution of the models. The Hadley cell intensities in the model examined by Boer et al. vary considerably from model to model, with some stronger, and some weaker, than observations. Tropical precipitation rates in the models also span a large range from the "notably deficient to the notably excessive".

In conclusion, it seems that the models do not simulate the large scale environment in the tropics with sufficient reliability at present to provide much expectation that the argument above will hold up. Our findings about the shortcomings in the GCM simulations for the Sacramento Basin region are probably not exceptional, and can be expected to apply across a broad range of regions in the extratropics for similar reasons to why they apply to the Sacramento Basin, and in the tropics for the reasons outlined above.

7.5   Other Techniques

There are a number of techniques that have been used to transfer information from GCM grid scales down to local basin scales for climate impacts studies. These include climate inversion techniques, development of free atmosphere and surface predictors, and limited area model approaches discussed in sections 1.2.3 and 1.2.4. The climate inversion techniques depend on questionable grid box scale output, and are now generally less preferred than the other techniques that incorporate output from larger scales in the GCMs. It has generally been assumed that GCM output is more reliable from an agglomeration of grid boxes over a large area where the larger scale circulations in the model can be resolved. But from the point of view of the Sacramento Basin, even the large scale output from the models is unreliable, since the large scale circulation and its excursions in wet and dry winters and in storm events in the models differs radically from observations. Thus even limited area model approaches are not yet able to produce reliable climates for the Sacramento Basin, since the nested mesoscale model is still dependent on the large scale circulation in the driving GCM, which is in error.

In conclusion, the available techniques for transferring information from GCMs to local basins do not afford a way around the limitations we have identified in the synoptic climatologies of the GCMs. Furthermore, it is difficult to conceive of any new model related techniques that would not rely on the GCMs producing reliable large scale circulations.

7.6 Other GCMs

We examined here only a small number of the thirty or so atmospheric GCMs currently used as climate models. Furthermore, even the GCMs we did analyse have already evolved beyond the formulations they used when we extracted output from them[3]. However, all GCMs are subject to the kinds of limitations we have outlined above, and so the real question of interest is how long will it be before we can expect reliable GCM regional climate simulations.

In every GCM the large scale circulation governing precipitation in the Sacramento Basin depends on sub grid scale parameterizations of physical processes such as moist convection, and boundary layer transports of heat and moisture. This is an inescapable consequence of the interaction of the sub grid scale physics with the large scale atmospheric circulation. Our work so far suggests that the dependence of the large scale circulation on sub grid scale physics is probably the overriding limitation on simulation of the large scale circulation.

Subgrid scale processes such as moist convection and the turbulent transfers of heat and moisture in the boundary layer and across the ocean-atmosphere interface occur on scales orders of magnitude smaller than current GCM grid scales. These processes will thus have to be parameterized well into the foreseeable future. Work on the improvement of these parameterizations may well require concerted effort

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[3]For instance, CCM2 has now incorporated a new scheme for diagnosis of cloud optical properties, that substantially reduces a large warm bias in simulated summer surface temperatures in the northern hemisphere (Hack et al., 1994).

over perhaps several decades just to provide the necessary observations to enable the physical parameterizations to advance to the point that the model regional climate simulations are reliable.

The scenario that we have sketched for improving GCM simulations of regional climate is highly speculative[4], since one cannot rigorously determine exactly how long it will take to improve the subgrid scale parameterizatons to the point that the GCMs simulate reasonable large scale circulations. Our speculative scenario stands in considerable contrast to that produced by IPCC (1990) who do not appear to be very concerned about the limitations of subgrid scale parameterizations for simulating regional climate. The IPCC group state that

> a major advance in the ability to predict the regional differences in climate change is expected to take place in the late 1990s, with the implementation of higher resolution models of the atmosphere.

The IPCC timeline for narrowing the uncertainties for "predictions of regional differences in climate including water resources" ends in the year 2005 as "a result of higher resolution models and a better understanding of the water cycle". The IPCC reliance on resolution as a panacea for regional climate simulations is not justified by most of the available work on the sensitivity of regional climate simulations to resolution[5]. From our discussion in section 7.2, there are certainly grounds for expecting improvement with resolution, but there remain significant problems with the model simulations that relate more directly to subgrid scale physics than to resolution. This conclusion is supported by the work of Boer et al. (1992) cited in section 7.4 on the relative importance of resolution and physics

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[4]We have also been deliberately provocative in sketching the scenario, to make the point that from our present vantage point, limitations on knowledge are such that the future may span a wide range of possibility.

[5]One potentially brighter note for the IPCC conclusion is the study of Boville (1991), where the sensitivity of the winds and eddy fluxes in CCM1 is tested across a range of spectral resolutions from T21 to T63, with significant improvements with increasing resolution.

parameterizations in the tropical lower troposphere. It is also supported by Stone and Risbey (1990), who show dependence of the large scale heat transports in GCMs on subgrid parameterizations, and by Yang and Gutowski (1994) whose studies of the propagation of stationary waves in GCMs and observations lead them to conclude that:

> Improving the simulation of stationary wave activity forcing requires a much better understanding of the physics governing storm tracks and latent heat release in the atmosphere, so that improvements in stationary wave simulation in these models will not occur by simply increasing model resolution.

Yang and Gutowski's conclusion is confirmed by our analysis of the stationary wave field at high resolution in CCM2.

Deficiencies in the jet stream and stationary wave simulation in CCM2 persist at T106 resolution. To be sure, the model parameterizations were presumably not retuned for the higher resolution run, and so some further improvement might have been gained with tuning. However, if the sensitivity to tuning were strong, this would only further highlight the model's dependance on the subgrid parameterizations. At about $1° \times 1°$, T106 resolution is too expensive to allow long climate integrations at present. This resolution will no doubt be achieved and surpassed during the next ten years for long climate integrations, though it is hard to see the resolution going vastly beyond $1° \times 1°$ over this time frame.

The implications of citing resolution as the outstanding problem for simulation of regional climate are different than for the diagnosis that representations of subgrid scale parameterizations are more critical. If resolution is the problem, then the solution is only as far away as the next generation or two of faster computers. Furthermore, the diagnosis of resolution as the limiting factor implies that there is nothing fundamentally uncertain about three dimensional climate models. If physical parameterizations are the limiting factor, then solutions are harder to come by, and attention is drawn to fundamental limitations in the representation of the physics of the climate system.

In our considerations on the limits to simulating regional climate change we have assumed that the climate forcing due to greenhouse gases would be known, and ignored uncertainties due to this aspect of the problem. In reality, the climate forcing due to greenhouse gases, anthropogenic and natural aerosols, land use changes, and solar variability is regionally heterogeneous and not well known (Schneider, 1994). If regional climate proves to be sensitive to the precise nature of the heterogenous forcing, as is implied by Schneider's work, then the problem of simulating regional climate is further compounded. Schneider notes that "regionally heterogeneous forcing of any kind could be responsible for significant regional climatic anomalies".

If it does take several decades before uncertainties in regional climate simulations are substantially reduced, then water resource planners in the Sacramento Basin will need to come to terms with the uncertainty. Several decades is a significant amount of time in terms of both water resource planning in the basin, and in terms of the time scales of greenhouse climate change. Uncertain regional climate model scenarios will have to be stacked up against other uncertain forms of information about climate change in the basin. We will explore this issue further in chapter 9. In developing regional climate scenarios, it is clear that GCMs are not yet sufficiently reliable that fully empirical (non-GCM) scenario generation techniques such as those outlined in section 1.2.1 should be discarded. Use of GCM regional climate scenarios should incorporate a wide range of uncertainty in the GCM output.

In a corner, one chap who was a painter was explaining to another who was a photographer his plans to paint some beautiful apples, pulp them, distill them, and "that'll make a marvelous calvados, old man," he said. The photographer grumbled that "it sounded a bit idealistic," but that did not stop him from draining his glass. The young Amédée Gocourt complained that there wasn't enough to drink because, he said, the chocolate cakes he was stuffing himself with "made his down pipe like velvet and clogged up his stomach." Marcellin the anarchist moaned that "if we were to be left as scandalously as this to die of thirst, then really things were not much better than in the time of the popes," but no one grasped the sense of his words.

René Daumal
A Night of Serious Drinking

Chapter 8

Climate and Streamflow

The fact that there are shortcomings in the large scale circulations critical to California climate simulated by the climate models does not necessarily render the model basin scenarios useless. For one, the climate model scenarios may be no more unreliable than other methods of generating scenarios to plan future water resource policy. We take up this issue in chapter 9. In addition, it may well be that the streamflow regime in the Sacramento Basin is largely insensitive across the whole range of uncertain precipitation and temperature changes bounded by the various climate model scenarios. In this event, water resource planners could plan on maintainence of historical flows during periods of climate changes of roughly the magnitude (or smaller) simulated by the climate models. Much of this chapter is devoted to exploring the sensitivity of Sacramento Basin streamflow to climate inputs, precipitation and temperature.

8.1 Streamflow Sensitivity to Precipitation and Temperature

The hydrological model studies of Dettinger and Jeton (1994) and collaborators at the USGS have suggested that streamflow *amounts* in the American River Basin, which is a representative sub-basin of the Sacramento Basin, are highly sensitive to precipitation. Their model results suggest that streamflow *timing* through the

water year is quite sensitive to temperature. The simpler regression hydrological model employed in the USGS study (Duell, 1994) suggests that streamflow amount is sensitive to temperature also, though this is at odds with the more physically based hydrological model results that do not show a temperature dependence.
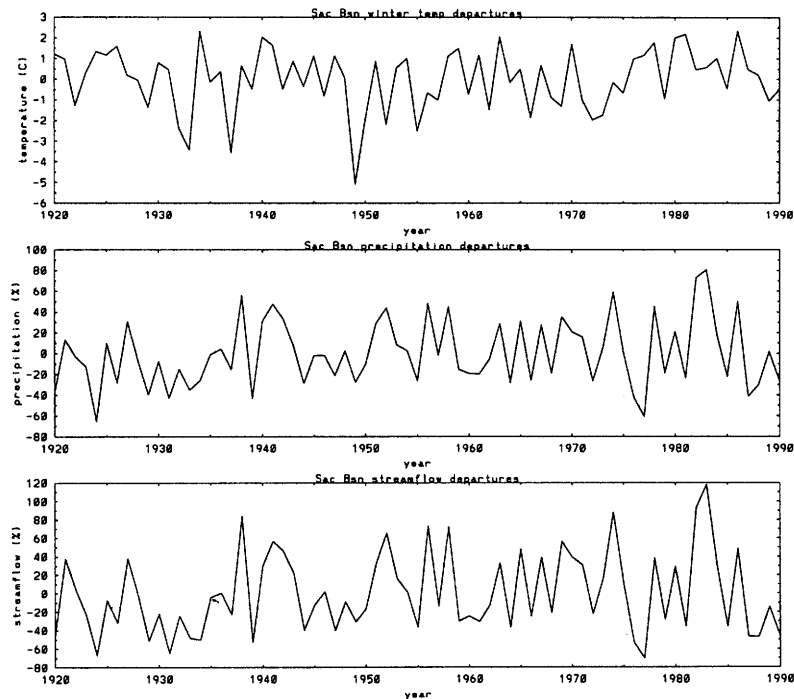
Figure 8.1: Time series of winter mean surface air temperature, precipitation, and streamflow for the Sacramento Basin. Values are shown as departures from the long period mean (1920–1990), and are expressed as percentages for precipitation and stream-flow.

We use observational data to determine the historical sensitivity of the basin streamflow to precipitation and temperature. The Sacramento Basin is somewhat unique in that it has been monitored consistently for a long period of time, and we were able to assemble streamflow, precipitation, and temperature records for the basin over the period between 1920 and 1990 — a much longer period than that available to calibrate the USGS regression models of the American River Basin within the Sacramento Basin. Streamflow is given by the four river index for the basin. Precipitation is given by the 8 station index, and we compiled a robust 5 station index of surface air temperature for the basin as well. The time series of these records are shown in figure 8.1. We use annual values of streamflow and

precipitation, and winter averages for temperature, since the winter temperature in the basin is more coherently associated with the annual precipitation than the annual temperature. This is because most of the precipitation falls in the winter, and precipitation totals are low at other times of year, whereas summer temperatures are high and have a disproportionate influence on the annual temperature. The relationship between annual precipitation and annual streamflow amount is already apparent from the time series plots.

The interannual precipitation departures from the long period mean can be quite large in the basin, and extend to $\sim \pm 80\%$ in extreme years. The interannual variability of precipitation is strong enough (i.e. beyond the climate change signal $2 \times CO_2 / 1 \times CO_2$ for precipitation) that we may use it to find the coefficient of proportional increase in streamflow and precipitation for various values of mean precipitation (i.e. climate).
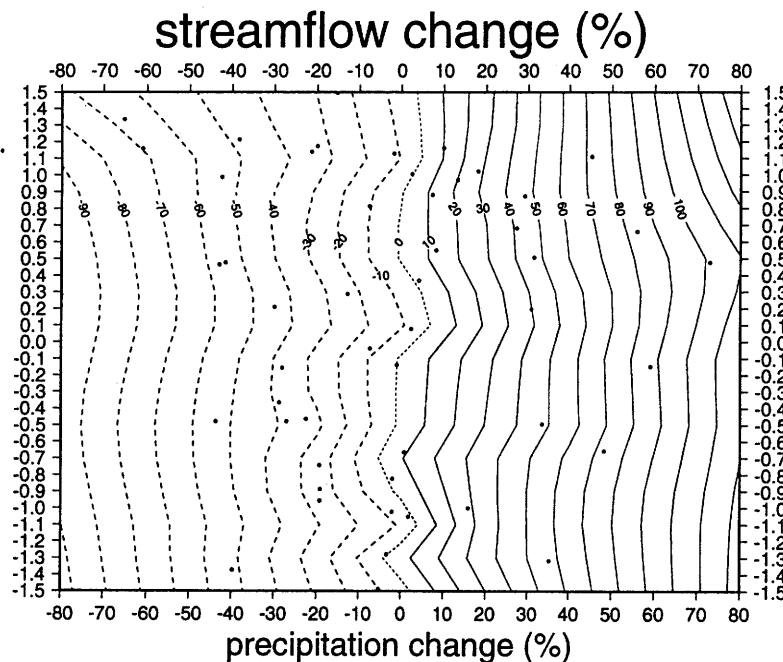
Figure 8.2: Contour plot of streamflow change as a function of precipitation and temperature change for the Sacramento Basin. Changes are with respect to the long period means, calculated from annual means for streamflow and precipitation, and from winter means for temperature. Temperature changes on the vertical ordinate are in °C. The circles mark the locations of precipitation and temperature data values that fall inside the contoured domain; each corresponding to a different year within the record.

For each of streamflow, precipitation, and temperature, we calculated the annual departures (winter departures for temperature) from the long term mean over the period, and then produced a contour plot of the surface of streamflow change as a function of precipitation and temperature changes. This contour surface is shown in figure 8.2. Though we use winter mean temperatures to calculate the temperature changes in this figure, the results are similar when annual mean temperatures are used instead. The most striking feature of the figure is that the basin streamflow *amount* displays a strong dependence on precipitation, but virtually no dependence on temperature. This appears to be true across the range of precipitation and temperature variation in the basin.
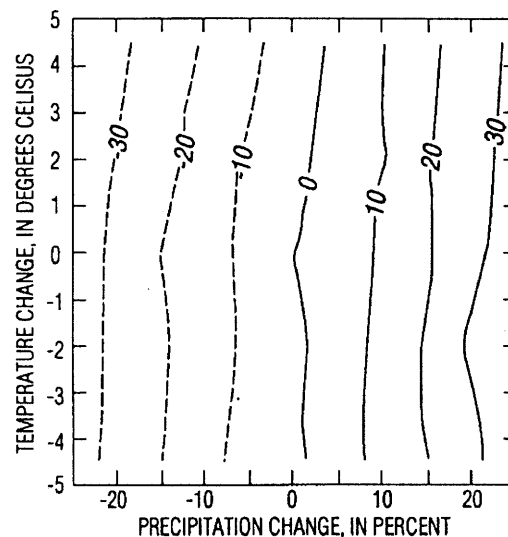
Figure 8.3: Simulated streamflow responses to uniform change scenarios in the North Fork American River Basin, showing percentage streamflow change as a function of changes in mean temperature (°C) and mean precipitation (percent). The simulations are for climate runs with the PRMS model. [From Dettinger and Jeton, 1994]

This result is in remarkably good agreement with the streamflow sensitivity determined by Dettinger and Jeton (1994) using a physically based precipitation-runoff hydrological model. Their results are shown in figure 8.3. There are a number of important differences between their model determined streamflow sensitivity, and ours determined from observations: First, they modelled just the North Fork American River basin, which is a sub-basin, albeit fairly representative, of the Sacramento Basin. In addition, our streamflow, precipitation, and

temperature values are for individual years, whereas they ran their model out for up to 100 years each for various precipitation and temperature change scenarios in order to produce their plot. In other words, their plot shows modelled climate mean streamflow sensitivity, whereas ours shows observed annual mean stream-flow sensitivity. In the region where the plots overlap out to ±25% precipitation change, the results agree well.

The simple regression model of Duell (1994) for the North Fork American River basin shows a strong dependence for streamflow sensitivity on temperature as well as precipitation. The lack of temperature dependence in the more physical hydrological model of Dettinger and Jeton and in the observations, suggests that the regression model results are not realistic. The temperature change scenarios in the regression model push it well beyond it's calibration range. Furthermore, the temperature variables in the regression relationships in the model enter the regressions barely above the levels of significance used to eliminate variables. The complex phase changes of water in the basin probably make it difficult to develop good regression models for the basin, and we discount the utility of current regression models for basin climate impact studies.

Dettinger and Jeton (1994) note several reasons for the lack of streamflow (amount) sensitivity to temperature. The main effect of temperature on stream-flow is through its action on SET (sublimation and evapotranspiration) to produce greater losses of water volume (snowpack and liquid water) to the atmosphere. However, losses to the atmosphere are only about half the streamflow in the total water budget for the basin, so the effect of changes in temperature is effectively diluted in this proportion. Furthermore, there is a buffering effect that reduces the streamflow sensitivity to atmospheric losses. When it is warmer there are greater SET losses at a given point in time than would occur with cooler temperatures, but the runoff occurs earlier during the winter months when the energetic potential for SET is near its annual minimum. Conversely, when it is cooler there is less SET at a given point in time, but the runoff occurs later in the spring when the SET potential is higher.

The *timing* of streamflow in the Sacramento Basin is sensitive to temperature changes (Dettinger and Jeton, 1994). In the PRMS model, warmer scenarios caused earlier runoff as snowmelt was hastened, and cooler scenarios postponed snowmelt and peak runoff.

From their studies with the higher altitude Carson River Basin as well, Dettinger and Jeton conclude that:

> Either streamflow timing or amount (but not usually both) would be sensitive to changing mean temperatures. So long as runoff timing changes in response to temperature changes, some buffering of annual streamflow sensitivity could occur. When such timing changes are precluded, the buffer is incapacitated and annual streamflow reflects temperature changes.

Basins with temperature independent streamflow timing would include those warm (low altitude) basins that yield mostly rainfall runoff, and those basins so cold (high) that temperature changes do not affect much the amount of snow falling or snowpack duration. The Sacramento Basin has contributions to runoff from both rain and snow. The Sacramento Basin would only be pushed into a temperature independent streamflow timing regime for quite large warm or cold climate changes. A uniform winter warming or cooling throughout the basin of about 5°C would be required to push the basin into rain only or snow only regimes. For small and modest climate changes in the basin, we can expect that streamflow *amount* will be sensitive to precipitation changes and relatively insensitive to temperature changes, and streamflow *timing* will be sensitive to temperature changes.

Some of the high end $2 \times CO_2$ climate model simulations show climate changes in middle latitudes of around 5°C at the surface. If such large climate changes came to pass in the basin, there would be a change toward a rain only rainfall regime, and therefore less sensitivity of streamflow timing to temperature. This would reduce the buffering of the effects of temperature changes on streamflow amount, and increase the sensitivity of streamflow amount to temperature. The effect of warming in this case would be to reduce streamflow amounts due to the increase in SET losses to the atmosphere. In other words, the actual sensitivity

of Sacramento Basin streamflow amounts to precipitation and temperature will depend on the size of the climate change in the basin, though will be mostly sensitive to precipitation only unless the climate change is quite large.

8.2 Nonlinear Streamflow Regimes

A curious feature of figure 8.2 is that the response of streamflow to precipitation increases appears to be non-linear. That is, for larger precipitation increases, the percentage increase in streamflow becomes larger than the percentage increase in precipitation. This would imply that the basin responds differently, depending on the magnitude of the precipitation change and mean climate state. In this event, just as the basin streamflow amount sensitivity to temperature may depend on the size of the temperature change, so the basin response to precipitation depends on the amount of precipitation change. The larger the precipitation change, the greater the nonlinear response of streamflow.

To elucidate the nonlinear nature of the streamflow response to precipitation, we show the difference between the percent change in streamflow and the percent change in precipitation in the basin in figure 8.4. Departures from the zero contour on the plot indicate nonlinear streamflow response to precipitation changes. The main feature of the plot is that there is a fairly linear relationship between precipitation and streamflow in dry years, and a more nonlinear response, increasing with increasing precipitation in wet years. In other words, a larger fraction of the precipitation becomes runoff in wet years when the ground is wetter and the snowpack volume is larger. As the saturated area of the basin increases in wet years, the amount of runoff relative to precipitation increases.

Note that the nonlinear response of streamflow to precipitation occurs for virtually all very wet years — it generally does not matter if a wet winter comes on the heels of a spell of dryer years in the basin. The implication is that the basin becomes saturated fairly quickly during an individual very wet season to produce expanded areas of saturation and runoff. The response surface based on individual
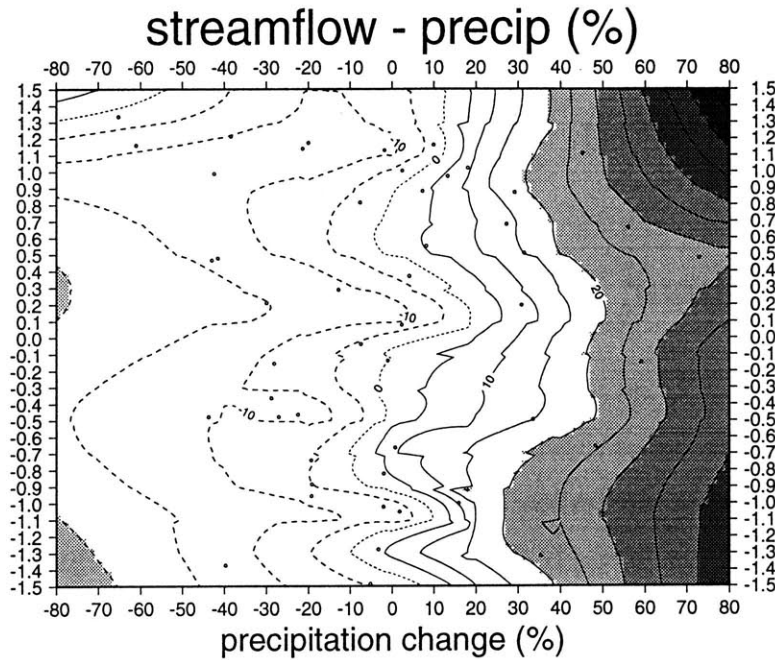
Figure 8.4: As in figure 8.2, but for the difference between percentage streamflow change and percentage precipitation change as a function of precipitation and temperature change for the Sacramento Basin. The temperature changes are in °C on the vertical axis.

years should therefore have much in common with a response surface based on climate runs for wetter basin climates. The dry summertime period flushes the basin of much of the water stored from the prior wet winter, and then the basin is quickly replenished from this base in very wet winters.

For dryer years the streamflow response seems to be linear or weakly non-linear. Non-linear effects do become apparent during runs of dry years (droughts) in the historical record however. This is not evident from figure 8.4, where the effects of individual nonlinear dry years are smoothed out when they are aggregated in with nearby years with similar precipitation and temperature changes before contouring. However, the nonlinearity is evident from an examination of the raw data. After runs of dry years during the early 1930s and late 1980s for instance, the amount of runoff relative to precipitation does show larger decreases. In these drought regimes a smaller fraction of the precipitation appears as stream-flow. This has important implications should the incidence of drought increase in the basin. The basin drought regime responds differently than for individual

extreme dry years.

Basin streamflow would become more nonlinear in its response if the climate mean became drier or if runs of dry years became more common. Precipitation shortages would be exacerbated, as relatively less of the precipitation would run off into the rivers. In the PRMS model of Dettinger and Jeton (1994), this experiment is performed by shifting the climate means. It is possible that the basin could adjust to a dry shift in climate means over the longer term by a shift in vegetative cover or other means. The basin would not normally have a chance to respond in this way for short drought periods. In any event, the PRMS model runs did not allow for changes in vegetative properties, so we might expect to see larger nonlinear responses for large dry shifts in the climate mean in the model than in the historical response surface based on individual years. To date however, the PRMS model has not been run with precipitation changes of greater than ±25%, which does not push the model basin into the very dry regimes where nonlinear responses showed up in observations for drought years in the basin.

ANNUAL RUNOFF - ANNUAL PPT, % (AR)
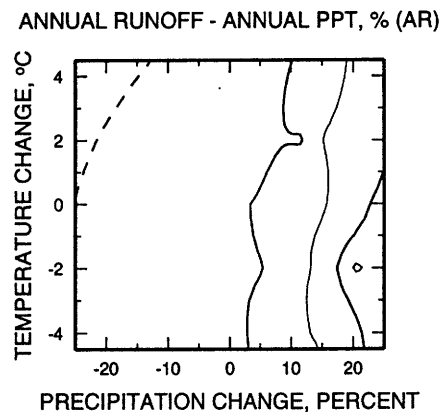
Figure 8.5: As in figure 8.4, but for climate simulations with the PRMS model for the American River Basin. The American River basin is a sub-basin of the Sacramento Basin. The dashed contour is -5%, and the solid contours represent 0%, 5%, and 10% respectively. [From Dettinger, personal communication.]

Figure 8.5 shows the nonlinear part of the streamflow response for the PRMS model of the North Fork American River (left plot) from climate simulations. Over the region of overlap with figure 8.4 for observations to ±25% precipitation change, the two figures agree well. The model also shows a nonlinear streamflow

response to increasing precipitation, and a more linear response for precipitation decreases.
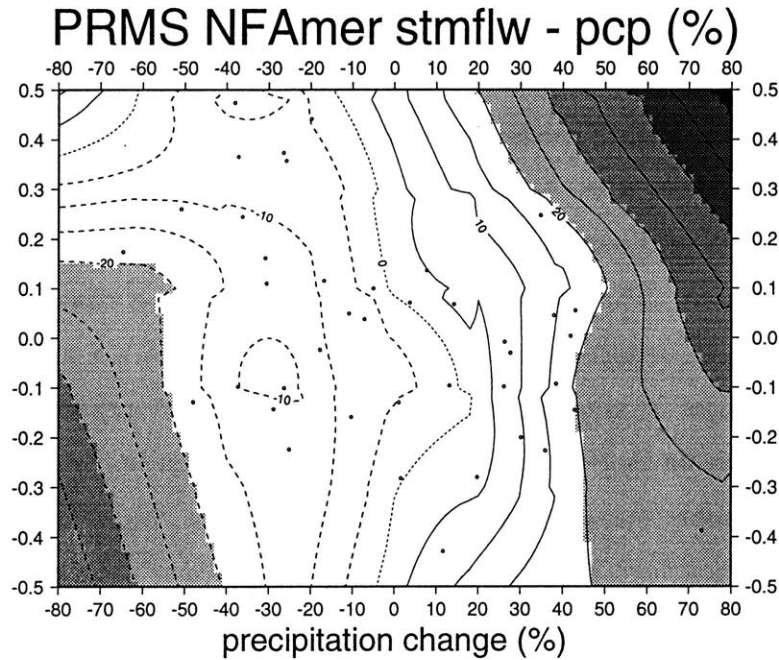
Figure 8.6: As in figure 8.2, but for streamflow simulated in the PRMS model of the North Fork American River Basin. The vertical axis shows changes in potential evapotranspiration (PET) as a proxy for temperature. The PET and precipitation changes are for departures in individual years from a 42 year (1949–1990) mean in a model simulation with observed PET and precipitation inputs in the basin.

To make a more direct comparison between the PRMS model results and the observations in figure 8.2, we obtained 42 years of simulated streamflow from a run of the PRMS model with observed precipitation and temperature. In this case the model is still simulating the North Fork American River Basin and not the full Sacramento Basin, but now the comparison is for the annual mean sensitivity (and not the climate mean sensitivity as in figure 8.5) in both cases. The model simulated nonlinear streamflow sensitivity agrees fairly well with the purely observational nonlinear streamflow sensitivity in figure 8.2, especially if the comparison is confined to the regions where there is a reasonable density of data points in both cases. This implies that the PRMS model does a reasonably good job in simulating the nonlinear response of streamflow to precipitation.

8.3 Seasonal Response

To determine more about the relationships between precipitation, temperature, and streamflow in the Sacramento Basin, we have plotted their seasonal cycles in figure 8.7. The wet and dry curves on each plot were optimised to include ensembles of years with a large nonlinear streamflow response to precipitation in the top row, a more linear response in the middle row, and just the extreme wet and dry years in the bottom row.

Comparison of the precipitation plots indicates that the extreme wet year seasonal cycle is very similar to the seasonal cycle for wet years where the streamflow response to precipitation is nonlinear. Conversely, the extreme dry year seasonal cycle is similar to the seasonal cycle for dry years whre the streamflow response to precipitation is linear. This confirms earlier observations that the nonlinear response is the norm for wet years and the linear response is the norm for dry years.

Years that are both exceptionally wet, and have a relatively linear response of streamflow to precipitation do not occur very often. When they do, there is a reduction in precipitation in the early part of the wet season that drops the totals below climatology. In this case, the basin stays drier longer, and when the additional precipitation does finally fall in February, it is short lived. Presumably, the basin does not saturate to the same degree that it does in wet nonlinear years, and the streamflow response is more linear. The presence of some wet linear years indicates that the seasonal distribution of the wet season precipitation is important in setting the response of streamflow to precipitation.

Years that are both exceptionally dry, and have a relatively nonlinear response of streamflow to precipitation do not occur very often, and usually fall on the tail of extended runs of dry years. While this suggests that basin memory from year to year is important for these types of events, the seasonal cycle plots show that there is also a tendency for these years to have more early season precipitation than regular dry years. This is not particularly robust across all the cases in this
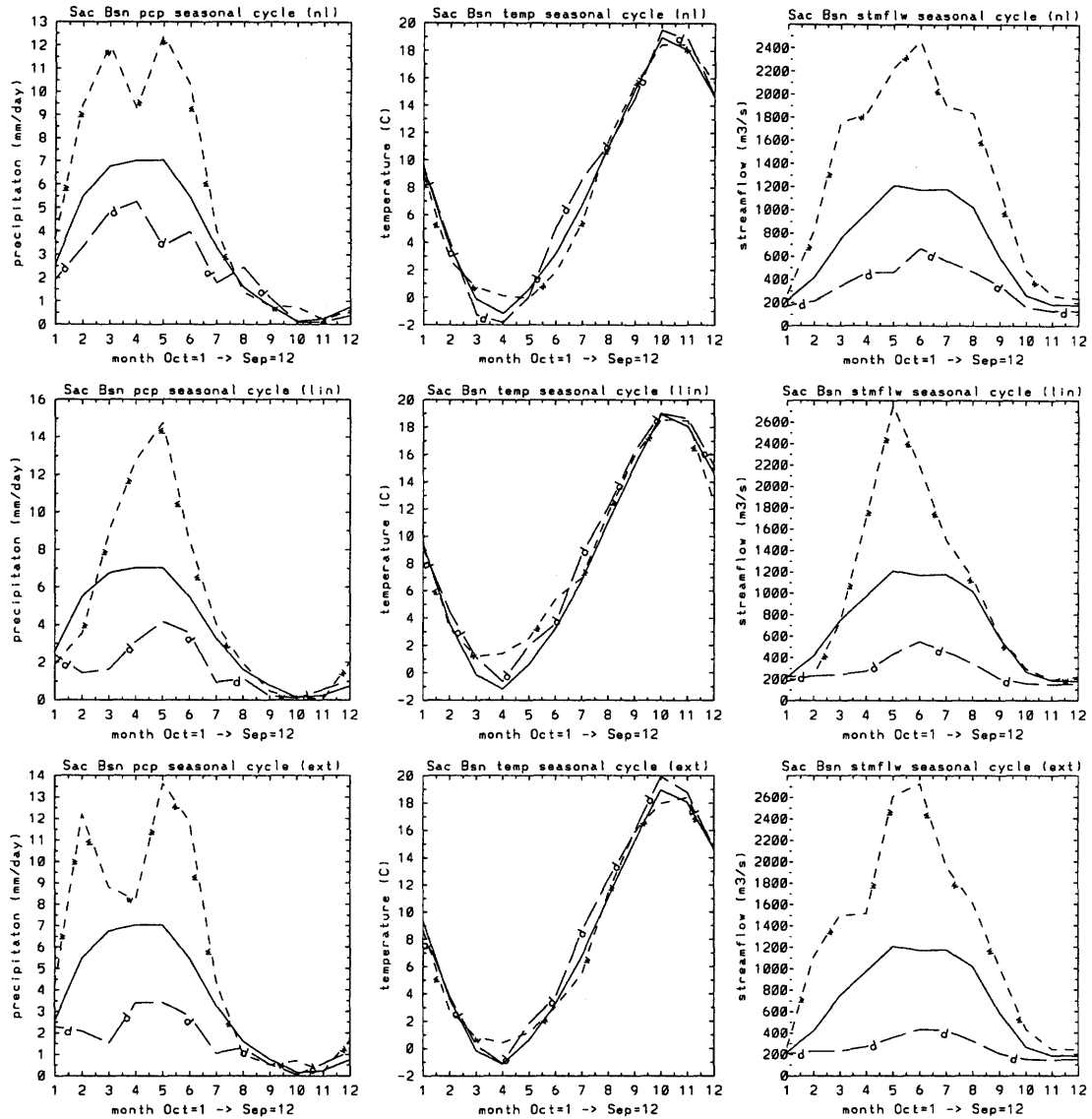
Figure 8.7: Seasonal cycles of precipitation, surface air temperature, and streamflow for the Sacramento Basin. In each case, the solid line is a mean over the years 1920–1990. The curve 'w' is a mean over five wet years, and the curve 'd' is a mean over five dry years. In the top row, the ensemble of wet and dry years was chosen to include those years where the streamflow response to precipitation was particularly nonlinear. In the middle row, the wet and dry years were chosen where the streamflow response to precipitation is particularly linear. In the bottom row, the 'w' and 'd' curves refer to the extreme wet and dry years, irrespective of streamflow response to precipitation.

category however, and we suspect that the interannual variation is more important than the intraseasonal variation in producing the dry nonlinear response.

The seasonal cycle plots for temperature run down the middle column of figure 8.7. The most interesting feature is that wet nonlinear years are warmer than climatology in the winter, colder than climatology in the spring, and right on climatology in the summer and autumn. Conversely, dry nonlinear years are colder than climatology in the winter, warmer than climatology in the spring, and right on climatology in the summer and autumn. The temperature differences with climatology occur during the hydrologically active time of the year when the basin is wet. If these temperature differences are real, they may be due to the effects of the large scale circulation, or local basin effects, or some combination of the two. We calculated t-tests of the significance of the temperature differences and found that for both wet and dry cases the differences are significant in the spring and marginally significant in the winter. We outline competing hypotheses to explain the observed temperature departures:

Large scale circulation: Wet winters tend to be warmer since there are more storms, more water vapour and clouds reradiating longwave radiation down to the surface, and warmer air masses off the ocean. Wet springs tend to be colder since in spring the ocean air masses are now cooler than the land, and storm clouds screen out the increasing shortwave heating of the surface. Dry springs tend to be warmer with clear skies and relatively more shortwave heating.

Local near surface physics: Wet winter snowpacks insulate the surface and moisten the ambient environment, raising surface temperatures. More cloud may even be generated locally from the moisture enhancement. Wet springs are colder as the long lasting snowpack cools the surface, and evaporative cooling serves to offset solar heating.

Though some combination of the large scale circulation and local physics is undoubtedly at play in setting the temperature response of the basin, it would

be useful to know which process, if either, is dominant. Then one could direct
attention to the appropriate aspect of the modelling programs. As one way to try
to resolve which effect is dominant, we show plots of the 1000–500mb thickness in
figure 8.8. Thickness data is readily available over much of the period covered by
the precipitation and temperature data, and it provides a rough measure of the
temperature of the lower half of the atmosphere. The temperature over the 1000–
500mb level in the vicinity of the Sacramento Basin is more heavily influenced by
the large scale circulation, than by local surface energy exchanges.
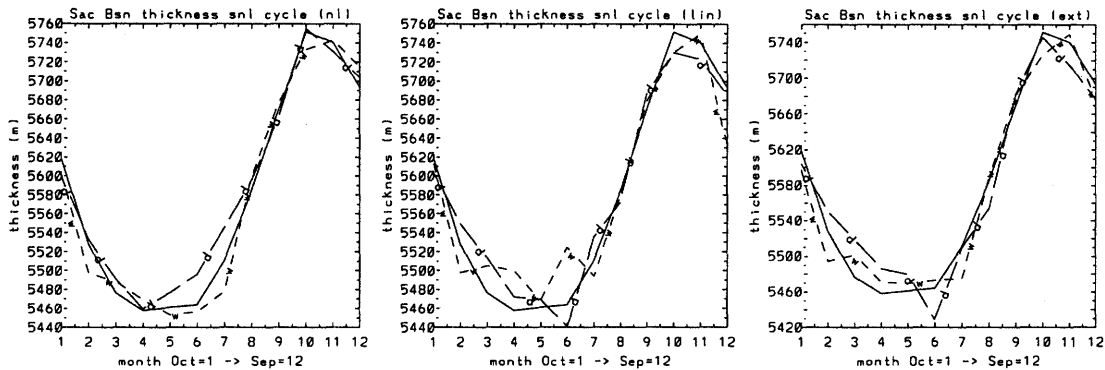
Figure 8.8: Seasonal cycle of 1000–500mb thickness for the Sacramento Basin region.
The labelled lines refer to the same cases outlined in figure 8.7.

Figure 8.8 shows the mean thickness over the period for a grid box over
the Sacramento Basin region, and the thickness for the ensembles of wet and
dry years used in the precipitation, temperature, and streamflow figures. The
thickness analysis was repeated for another nearby grid box with very similar
results, implying that the thickness field is fairly uniform in the vicinity of the
basin. Comparison of the thickness seasonal cycles with the temperature seasonal
cycles for wet and dry cases indicates a reasonably close association. For wet
nonlinear years, the thickness values are cooler in spring and marginally warmer in
winter, as per temperature. In wet linear years the thickness is warmer through the
winter and spring, as is the temperature. The winter and spring correspondence
between thickness and temperature also bears out for extreme wet years. In the
case of dry years, the thickness and temperature are in general agreement, except
for extreme dry years in the spring. In as much as the thickness values mirror the

temperature values, the large scale circulation hypothesis is supported over the local effects hypothesis. This conclusion should be viewed as somewhat tentative however, since the thickness is not a pure indicator of the large scale circulation, and the correspondence between thickness and temperature is not perfect.

A final note on figure 8.7 is that the wetter than average winter months are warmer than average precipitation winter months. This holds for nonlinear, linear, and extreme wet year cases. This is in contrast to the finding of Dettinger and Cayan (personal communication) that wet days in the region are 2–3°C cooler than dry (precipitation=0mm) days. We believe this can be resolved as follows: Precipitation totals in wetter years receive much of their contribution from medium to large size storms, as was shown in section 5.1.2. Wetter years will contain more storms than other years and so their winter months will contain more of the warm storm events than usual and be warmer than climatology. In daily data, most of the precipitation events are not actually storms. The majority of precipitation events in the basin are small events, as was also demonstrated in section 5.1.2. The most frequent precipitation event is a small event, but the most dominant event in terms of precipitation contribution is the middle size event. A straight comparison of wet days with dry days would be dominated by the most frequent precipitation event, which is the small event, not by storms. It must therefore be the case that the small precipitation events are colder than dry days, but that larger events (storms) are warmer than dry days.

8.4 Development of Basin Impact Studies

There are a number of ways in which hydrological model studies of climate impacts on water resources can be improved. We demonstrated that the streamflow response of the Sacramento Basin depends on the size of the climate changes in precipitation and temperature. In this regard, the model studies can be improved by providing better climate inputs; a topic that was taken up in the last chapter.

The method of driving the hydrological models by applying the difference between $2\times CO_2$ and $1\times CO_2$ climate model results to basin observations has various shortcomings. For one, the results produced by the climate models have been called into question in this work. Further, this technique does not allow for changes in climate variability. Results above suggest that the basin streamflow is sensitive to the seasonal distribution of precipitation, and so changes in precipitation variability on this time scale would be important.

To allow for changes in variability in the model experiments, it would be more desirable to drive the hydrological models with output from transient greenhouse change climate model simulations. If the difference between the transient run and the control run were continually updated and applied to the basin observations, then some longer term variability could be incorporated, though the basic precipitation arrival time scales would remain the same. Ideally, the dependence on the basin observations would be removed and the GCM transient output would be applied directly (at fine scale, or after climate inversion or LAM translation) to the hydrological model. For this to be possible, the hydrological models should be as physically based as possible, as we have already noted that the simpler regression models do not operate well outside their range of calibration for the Sacramento Basin.

The technique of adding GCM differences to basin observations of precipitation and temperature also has the shortcomings that the spatial pattern of precipitation in the basin remains the same, and so does the temporal sequence of precipitation arrival in the basin. The sensitivity of basin streamflow to the spatial and temporal patterns of precipitation has not been investigated in much detail, though these features of the basin precipitation regime may well change as climate changes. We have proposed a series of experiments to test these assumptions in driving the hydrological models. We describe them briefly here, though their actual implementation lies beyond the scope of the present work:

Drizzle extreme: Drizzle the observed monthly total precipitation down by dividing it equally among each day of the month. The problem with this, as

with all the cases, is that there is no thermodynamic and energetic consistency when precipitation is arbitrarily changed. If the original temperature time series is run along with the drizzled precipitation time series then the temperature and precipitation are decoupled. For instance, the soil will be wet with drizzle and evaporation will be quite high on the higher temperature days, whereas in reality the drizzle would correspond with overcast conditions and often diminished temperatures. In the drizzle case we would expect streamflow decreases due to greater SET losses to the atmosphere from longer exposure of drizzled precipitation relative to storm precipitation. The drizzle case also serves as a worse case test of the drizzle problem in GCMs, should their output be applied directly to a basin model.

Storm extreme: Lump all the precipitation for each month into a single storm spanning a few days in the middle of each month. This is a worst case test of the GCM result outlined by Gordon et al. (1992) for precipitation to increase in intensity and the number of rainy days to decrease in response to greenhouse climate change. In this case the hydrological model would be pushed into a wet mode on short time scales, and we might expect relative increases in streamflow if the nonlinear enhancement of streamflow found for wet years operates on this time scale.

Drought run: Increase the incidence of droughts in the input data by sporadically repeating the time series for past droughts. Compensate by adding the missing precipitation to the intervening years between droughts. In this case we would expect a reduction in streamflow in the basin, even though the total precipitation over a 100 year run was the same, since the model would spend more time in the nonlinear dry year regime where runoff is reduced proportionally more.

Spatial shifts: Redistribute precipitation from low altitude parts of the basin to high altitude regions, and/or from southern regions to northern regions. The latter test would probe a northward shift in storm tracks for instance.

At least in the case of the tests of the temporal arrival of precipitation in the basin, it would appear from our discussion of nonlinear wet and dry regimes that

the streamflow is indeed sensitive to assumptions about the nature of precipitation arrival. This is almost certainly the case on longer time scales (months to years), though it is still somewhat unclear for concentrated storms. The reliance on basin observations for use in climate change scenarios will eventually have to be abandoned for updated information on expected changes in precipitation arrival on long, and probably short, time scales. This task ultimately falls on the climate models.

8.5 Summary

The Sacramento Basin streamflow response to precipitation exhibits substantial nonlinearity. The nonlinearity is related to the hydrological memory of the basin on intraseasonal scales with surface saturation for wet years, and to hydrological memory from year to year for runs of dry years. During very wet years in the basin the streamflow increases substantially, even when the wet years come on the heels of dry years. Some wet years exhibit a more linear streamflow response to precipitation in association with a preference for additional precipitation in the beginning of the wet season, with a relative deficit later in the season. For most dry years in the basin the streamflow response to precipitation is fairly linear. However, on the tails of droughts the streamflow response to precipitation is diminished relative to other dry years, and the basin apparently retains memory from year to year.

For small climate changes in the basin the streamflow amount is insensitive to temperature. The streamflow timing is however sensitive to temperature. For substantial climate warming in the basin, there would be a shift to a rain regime from a snow regime, and the sensitivity of streamflow timing to temperature would be reduced. This in turn would likely increase the sensitivity of streamflow amount to temperature.

The functional dependence of streamflow, Q, on precipitation, P, and tem-

perature, T, depends on nonlinear factors R, and S, as follows:

$$Q(P,T) = R(P)P + S(T)T \qquad (8.1)$$

where $S(T) = 0$ unless ΔT is larger than about 5°C in the basin.

Temperatures in the basin are altered during winter and spring in extreme wet and dry years, apparently as a consequence of the relative presence or absence of warm, moist flows off the ocean during storm events. Climate changes in the basin are not well captured in simple regression models. The explicit representation of the physics of snow storage and infiltration is important in simulating climate changes beyond the immediate range of basin calibration.

Basin streamflow is sensitive to precipitation arrival characteristics on monthly and annual time scales due to the nonlinear relationship between precipitation and streamflow. Streamflow may also be sensitive to the timing of precipitation on sub-monthly time scales as well. As a consequence, it is desireable to incorporate information on likely changes in precipitation arrival characteristics in climate change experiments with hydrological models.

We have determined thus far that streamflow in the Sacramento Basin is sensitive to precipitation changes of the range simulated by climate models in greenhouse experiments. In the next chapter we assess whether planning strategies for the basin are sensitive to the climate change streamflow scenarios.

OUT BACK

The old year went, and the new returned, in the withering
weeks of drought,
The cheque was spent that the shearer earned, and the sheds
were all cut out:
The publican's words were short and few, and the publican's
looks were black —
And the time had come, as the shearer knew, to carry his swag
Out Back.

For time means tucker, and tramp you must, where the scrubs
and plains are wide,
With seldom a track that a man can trust, or a mountain peak
to guide;
All day long in the dust and heat — when summer is on the
track —
With stinted stomachs and blistered feet, they carry their
swags Out Back.

He tramped away from the shanty there, where the days were
long and hot,
With never a soul to know or care if he died on the track or
not.
The poor of the city have friends in woe, no matter how much
they lack,
But only God and the swagmen know how a poor man fares
Out Back.

He begged his way on the parched Paroo and the Warrego
tracks once more,
And lived like a dog, as the swagmen do, till the Western sta-
tions shore;
But men were many, and the sheds were full, for work in the
town was slack —
The traveller never got hands in wool, though he tramped for
a year Out Back.

In stifling noons when his back was wrung by its load, and the
air seemed dead,
And the water warmed in the bag that hung to his aching arm
like lead,
Or in times of flood, when plains were seas, and the scrubs
were cold and black,
He ploughed in mud to his trembling knees, and paid for his
sins Out Back ...
It chanced one day, when the north wind blew in his face like
a furnace-breath,
He left the track for a tank he knew — 'twas a short-cut to his
death;
For the bed of the tank was hard and dry, and crossed with
many a crack,
And, oh! it's a terrible thing to die of thirst in the scrub Out
Back.

Henry Lawson
from "Out Back"

Chapter 9

Water Resource Planning

Water resource planners in California must make decisions that involve some assumptions about future water resource availability, regardless of how uncertain future water resource availability may be. The information from climate impacts studies of streamflow in the basin provides one possible scenario for future water resource availability on which to base decisions. There are other possible assumptions on which to plan, such as the notion that future streamflow behaviour will be like past streamflow behaviour. This 'history scenario' was in fact the traditional assumption of water resource planners prior to the growing awareness in the 1980's that the climate may be changing due to increases of greenhouse gases.

Knowledge of climate and water resources is still so limited, that it is not yet possible to make a very rigorous determination of the likelihood of realizing the GCM scenarios or history scenario for instance. We will therefore set ourselves the more modest task in this chapter of outlining some of the possible scenarios for climate change in the basin, and probing the implications of planning on the basis of the different scenarios in the event that any one of the scenarios is realized. In other words, we outline a matrix of planning scenarios and outcomes, and begin to fill in the matrix as a way of describing the problem space faced by planners. We pick a couple of typical water resource applications as a way to focus this exercise.

In the last part of this chapter we attempt to provide some aids for water resource planners in light of the results of this work. We present a list of key diagnostics that could be used to assess whether a given GCM is suited to provide regional climate scenarios for water resource impacts studies. We also suggest research priorities for the development of better planning for responses to the impacts of regional climate change on water resources.

9.1 Climate Scenarios

As a way of placing the climate model precipitation and temperature scenarios in context with streamflow, precipitation, and temperature in the Sacramento Basin, we show a composite plot of the basin streamflow response to precipitation and temperature changes in figure 9.1. In this figure, we have superposed and idealized the streamflow response to precipitation and temperature changes from the PRMS model and observations.

It is an interesting exercise to place the GCM current climate precipitation and temperature values for the Sacramento Basin on this plot. For the climate models we analysed[1], precipitation in the basin is from about 0.2–0.6 of the observed intensity in the annual mean. This represents a precipitation change of between -80% to -40% from the observed value. The surface air temperature in the Sacramento Basin in the GCMs is from about 4°C warmer to 4°C cooler than the observed annual mean temperature, depending on the model. The range of GCM current climate precipitation and temperature is represented by the box labelled 'GCM $1 \times CO_2$' in figure 9.1. These GCM precipitation and temperature values correspond to streamflow reductions in the basin of between 40% and 85% from current basin streamflow amounts. This is clearly a bad starting place for the GCMs, which is why climate impact studies in the basin do not use raw GCM values to drive the hydrological models. Furthermore, since there is a nonlinear

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[1]Excepting the CCM2 T106 model, where appropriate results were not available.
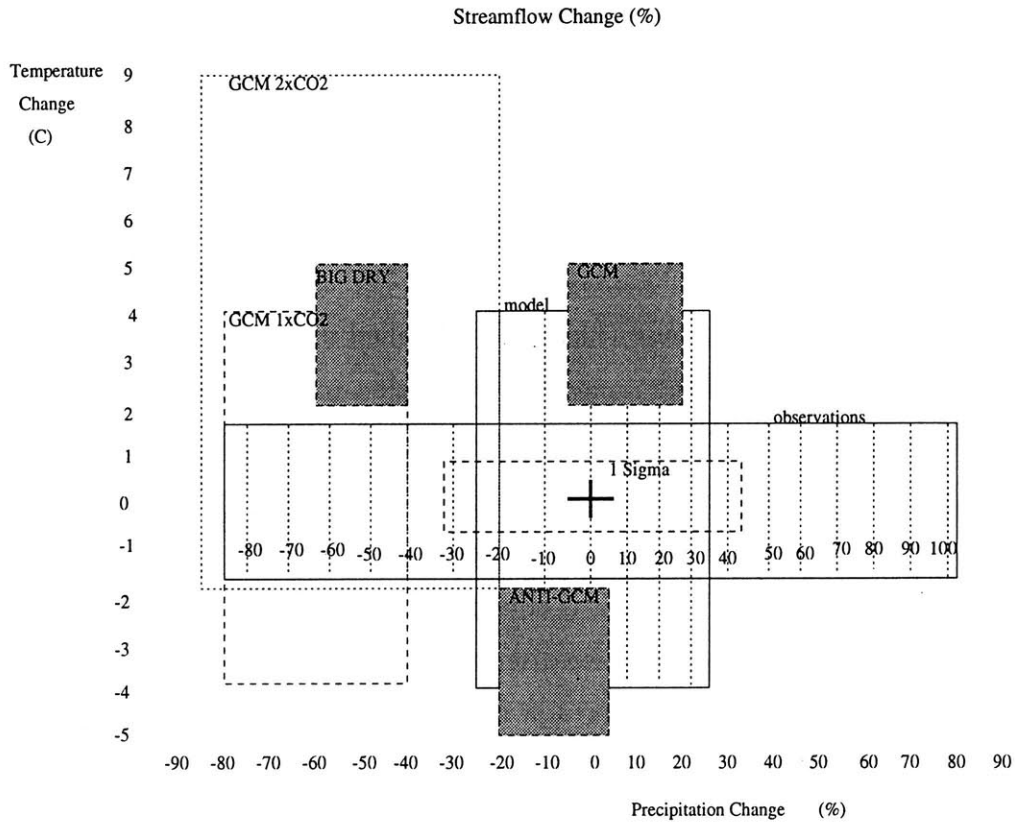
Figure 9.1: Contours of streamflow change as functions of precipitation and temperature change for the Sacramento Basin. The box labelled 'observations' shows contours for the annual mean streamflow sensitivity from observations. The box labelled 'model' shows contours of the climate mean streamflow sensitivity from the PRMS model. The streamflow change contours are idealized representations from figure 8.2 and figure 8.3. The cross indicates the current climate, and the box labelled '1 sigma' indicates one standard deviation of precipitation and temperature in the current climate. The shaded boxes encompass precipitation and temperature ranges for the climate change scenarios referred to in the text.

response of streamflow to precipitation, the response of streamflow for doubled CO_2 changes depends on what the current climate precipitation is. The basin streamflow is sensitive to the range of uncertainty of the GCM representations of basin precipitation. This is to say that the errors in GCM basin precipitation outlined in section 5.2 do matter for basin streamflow.

For doubled CO_2 climate simulations, GCMs yield a range of changes in temperature and precipitation for the Sacramento Basin. Taking the GCMs used by Lettenmaier and Gan (1990)[2] for doubled CO_2 simulations in the Sacramento Basin, the range of precipitation changes is from -5% to +20% in the annual mean, and the range of temperature changes is from +2°C to +5°C in the annual mean, depending on the model. If these changes are applied directly to the raw GCM $1\times CO_2$ values, then the resulting range of precipitation and temperature spans the box labelled 'GCM $2\times CO_2$'. This exercise would produce meaningless streamflow results if the doubled CO_2 results were applied directly to the hydrological model. To get around this, the difference between the $2\times CO_2$ and the $1\times CO_2$ results is added to the basin observations. This is equivalent to mapping the 'GCM $1\times CO_2$' box into the cross on figure 9.1. As we discussed earlier, the assumption in doing this is that even if the current climate of the GCM is in error, the changes are meaningful. Unfortunately, our analysis of the GCM synoptic climatologies of the Sacramento Basin throws the changes in doubt as well. From the pragmatic water resource planner's point of view however, the GCM scenarios are only as good or as bad as the alternatives. In the following we outline a GCM scenario for the basin, and some alternative scenarios.

GCM scenario: Applying the GCM climate change differences outlined above to basin observations yields the set of precipitation and temperature changes contained in the box labelled 'GCM' in figure 9.1. This is our GCM scenario for climate change in the basin over the next 50 years or so[3]. The precipita-

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[2]Most of the GCMs we analysed have not been run in doubled CO_2 simulations.

[3]To be sure, the equilibrium response for doubled CO_2 may not be reached for some

tion change from -5% to +20% corresponds to streamflow changes of from -5% to +30%, and the warming of from 2°C to 5°C would result in earlier runoff than normal. If runoff occurs earlier, much of the early season runoff would need to be released through the basin dams for flood control purposes, and less water would be available later in the season. One proposed remedy to this scenario is to build more dams.

Anti-GCM scenario: It is possible that the GCM scenario will be in error in the Sacramento Basin, perhaps even as to sign. We have thus devised an 'ANTI-GCM' scenario, which is shown by the box with this label in figure 9.1. In this case the precipitation changes of +5% to -20% correspond to streamflow changes of roughly the same percentage. Cooling of between 2°C and 5°C in the basin would result in later runoff than normal. The major impact in this case would be the reduction in streamflow, which may necessitate development of alternative water sources to maintain supply at prior levels.

Big Dry Scenario: In order to include something like a worst case scenario, we have devised the 'BIG DRY' scenario, labelled as such in figure 9.1. The Big Dry scenario corresponds to a climate mean with about half the present amount of precipitation in the basin. This corresponds to a streamflow reduction by about half also. We have assumed a warming of between 2°C and 5°C, as for the GCM scenario, which would hasten the timing of runoff in the basin. The major impact in this case would again be the reduction in streamflow, which would necessitate major development of alternative sources to maintain supply at prior levels.

History scenario: The assumption that the future will be like the past is our History Scenario. This scenario is marked by the cross in figure 9.1. The cross marks the climate mean, which will have excursions about this point from year to year. The 1σ level of excursion of annual precipitation and temperature about the mean is indicated by the box around the cross. Note

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time beyond the next 50 years, so this scenario may be a little too extreme over this time period.

that the boxes for the other scenarios show potential locations of the climate mean, and there will be excursions about this mean, which we have not indicated. If the variability of climate were to remain unchanged, then each of the scenario boxes would include outer 1σ boxes of the same size as that indicated around the history cross.

Though we cannot assign rigorous probabilities to the various climate scenarios, we can say something about our prior expectation of their occurence. We know that the GCM scenarios are uncertain, but there is a general expectation that the large scale climate will become warmer and wetter in response to increases in greenhouse gases. Therefore we might expect the GCM scenario to be more likely than the Anti-GCM scenario. The GCM scenario entails a bigger excursion of the local climate than the history scenario, though there are plausible reasons to expect an excursion of the GCM type. This makes it hard to distinguish between these two scenarios. The Big Dry scenario is perhaps the least likely, as it involves the furtherest excursion of the climate system, and there are not compelling reasons to expect such an excursion. The Big Dry scenario would therefore be more of a surprise, though its impacts would be greatest.

9.2   Water Resource Problems

We selected two different water resource issues to trace though the different climate scenarios. We chose to examine water delivery policy and agricultural policy because of the characteristically different time scales associated with solutions in these areas.

Maintaining or increasing water deliveries in the basin can be achieved through management policy, construction of additional storage facilities, and by developing other water sources from outside the basin. We focus particularly on the problem of whether to build new storage facilities because of the long time scales entailed in the planning, implementation, and operation of this type of

work, which can vary from a decade for small facilities to several decades for larger dams. Options for development of other water sources include desalinization, which entails a commitment of several decades of operation, use of Colorado River allotment, which is politically difficult, and reuse of wastewater.

By way of contrast, we focus on issues of agricultural policy that entail much shorter time scales. This includes choices about what to grow (crop selection), how much to grow (acreage), when to grow it (crop planting and rotation), and how to grow it (types of irrigation, fertilizer, and pest management). Each of these decisions need to be adapted and optimized for available resources of land, water, and climate. The time scales to plan, implement, and operate crops on the basis of these sorts of decisions is typically from months to a few years.

The problems of maintainance of water delivery and agricultural policy are also related in as much as one component of agricultural policy involves planning on the available water supply. For each of the two problem areas, we explore what might happen when planning decisions are based on a particular scenario and the future turns out according to each of the different scenarios. This approach can elucidate what the potential costs of being right or wrong are for decisions based on particular scenarios.

9.2.1 Agricultural Policy

Table 9.1 lays out the possible consequences of planning agricultural policy on either the history or GCM scenario, and experiencing any one of the scenarios. From table 9.1 it appears that the cost of choosing the wrong scenario to plan on is generally relatively small so long as there is continuous monitoring of the climate regime and adjustments are made accordingly. Adjustments are possible more or less 'on the fly' as the climate changes, since the time scales for agricultural adjustment are short relative to the several decade and longer time scale characteristic of greenhouse climate change. The wildcard scenario is the Big Dry scenario, which would entail radical changes in agricultural policy, and greater costs. The costs associated with the Big Dry scenario are probably somewhat

asymmetrical however. That is, the costs incurred in lost agricultural production should the Big Dry occur by surprise would likely be substantially larger than the costs incurred in adapting agriculture to a drier climate regime should it not occur.

	Get History Scenario	Get GCM Scenario	Get Anti-GCM Scenario	Get Big Dry Scenario
Use History to plan	Successful planning. Expenses optimized.	With no feedback, would get climatically suboptimal crop selection and planting. Would lose some crops in hot years. The planning process can respond relatively quickly to climate changes though.	As with GCM scenario, can make adjustments on time scales shorter than the characteristic climate change time scales.	Larger costs entailed in making more radical adjustments to the new climate regime. Adaptation alone may fall short and require development of new water supplies.
Use GCM to plan	Some initial additional costs until adjustment is made back to the history regime.	Successful planning.	Losses greater than if get history, but correction still curtails losses.	As above.
Use Big Dry to plan	Radical adjusment of crops and development of additional supply unnecessary.	As per History.	As per History.	Maintain optimal agricultural output in the face of declining streamflow.

Table 9.1: Scenario matrix for agricultural policy decisions.

A potentially important factor for agricultural planning that was not explicitly included in our scenarios is the variability of climate. Some GCMs simulate an increase of the variability of climate in association with increases of greenhouse gases (e.g. Rind, 1989). It is probably therefore appropriate to associate an increase in variability with the GCM scenario. If the variability of precipitation and streamflow increased in the basin, but was not planned for, there would likely be additional crop losses in extreme years. Furthermore, it may take longer to convince planners that the variability of climate has changed than it would take to convince them that the mean had changed. If this were the case, then losses would accrue over a greater period before appropriate adaptive measures were taken. Factoring in a potential increase in climate variability would increase the costs associated with being wrong or right in the GCM scenario.

9.2.2 Water Delivery Policy

The various climate scenarios and the potential consequences of planning water delivery policy on them are laid out in a matrix in table 9.2.

	Get History Scenario	Get GCM Scenario	Get Anti-GCM Scenario	Get Big Dry Scenario
Use History to plan	Successful planning. No new dams required. Small cost. Conventional payback.	New dams needed to catch earlier runoff. May be several decades delay before dams built, so defer costs til then, but get some water shortages as extra precipitation runs out of the basin.	Get chronic water shortage due to precipitation decrease. New dams little help. Need to develop moderate amount of alternative supply.	New dams little help. Get large chronic water deficits. Need to find substantial alternative sources. Continued losses while implementing these.
Use GCM to plan	Incurred dam building costs that are largely unnecessary, since original system would have sufficed.	Cost in building new dams to cope with earlier runoff, but payback in capturing runoff to boost supply.	Incur very unnecessary dam building costs. And have water shortages to boot.	Again, unnecessary dam costs, and chronic water shortages.
Use Big Dry to plan	Unnecessarily spent large sums on alternative supply.	Need not have invested in costly new supplies, but can use them to offset streamflow losses now incurred from earlier runoff with no new dams in place.	Need not have invested in costly new supplies, but can use them to offset water shortages due to precipitation decreases.	Developed alternative supply at large cost, but maintaining supply in face of dry climate. Worst case ameliorated.
Use Anti GCM to plan	Moderate amount of alternative supply developed unnecessarily.	Alternative supply perhaps suboptimal to basin resources, but since no new storage built, can use this to make up for runoff losses.	Some investment in alternative supply needed and carried out. Supply successfully maintained in the face of moderate ongoing basin shortages.	Under investment in alternative supply, but better than no investment. Some amelioration of chronic shortages.

Table 9.2: Scenario matrix for water delivery policy decisions.

By contrast with the decision matrix for agricultural policy, the investments required to maintain basin water deliveries in the non-history scenarios are quite substantial in terms of time to implementation and cost. The investment time scales for contructing new facilities and developing alternative sources are beginning to approach the several decade time scales characteristic of greenhouse climate change. For these cases it is much more difficult to adapt decisions 'on the fly' without incurring substantial costs as a result of the delay in implementing solutions.

From table 9.2, the major water delivery policy tradeoffs are as follows:

History v/s GCM: There is a tradeoff between the cost of building unnecessary dams if planning on the GCM scenario and history prevails, versus the cost of

decadal length or more water shortages and subsequent dam costs if planning on history and the GCM scenario is realized. The costs of ignoring the GCM scenarios if they are roughly correct could significantly exceed the costs of investment in planning on the basis of the scenarios.

History v/s Anti-GCM: There is a tradeoff between the cost of developing unnecessary alternative supply if planning on the Anti-GCM scenario and history prevails, versus the cost of decadal length water shortages and subsequent investment in supply if planning on history and the Anti-GCM scenario is realized.

History v/s Big Dry: There is a tradeoff between the cost of developing unnecessary large investments in alternative supply if planning on the Big Dry scenario and history prevails, versus the cost of decade length or more severe water shortages and subsequent investment in alternative supply if planning on history and the Big Dry scenario is realized.

9.3   Abatement Strategies

As is characteristic of complex problems of uncertainty, not only do the costs associated with the different scenarios differ, but so do the probabilities of occurence of each of the scenarios. And neither the costs nor the probabilities are well known. A full accounting of the costs of investment in impact abatement versus the costs of impacts is beyond the scope of this work. In principle, one might attempt to find the optimal tradeoff point between abatement and impacts. The tradeoff curves may look something like those depicted in figure 9.2. In practice these curves would not be smooth, as different technologies (desalinization, reuse, diversion, small dams, large dams) would have different costs and water supply potential associated with them. It is often customary to do those things first that provide more water supply protection per dollar invested.

In the case of protection of basin water supply, the measures that are most cost effective (small storage facilities, artifical recharge of groundwater during wet
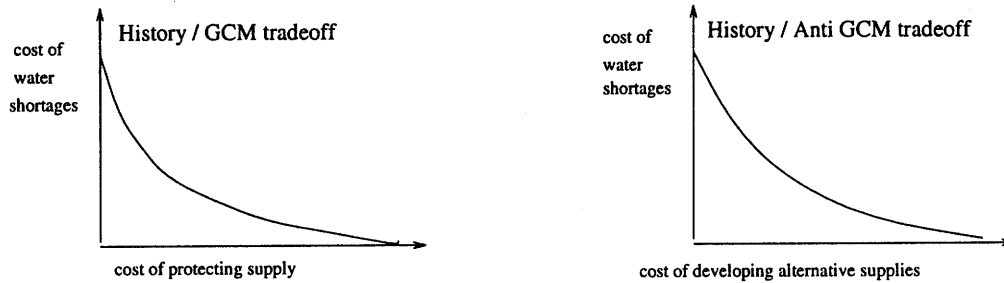
Figure 9.2: Idealized sketches of the cost of climate impacts due to water shortages versus the costs of protecting and developing water supply for the History / GCM and History / Anti-GCM tradeoffs respectively.

years, reuse of wastewater, etc.) also tend to be those with the fastest implementation time scales. This is good insofar as it is possible to ratchet-up the amount of investment in these options quickly in response to any changes of climate that threaten supply beyond the measures already taken. For continued large climate changes that disrupt supply and exceed the capacity of the more cost effective measures to ameliorate them, the remaining options (large dams, desalinization) have longer time scales for implementation. In this case, if the climate change were rapid enough, then sizeable water shortages are bound to ensue for a period. For large rapid climate changes, one might want to have the largest supply technologies in place first that take longer to implement, so that faster adjustments could be made later as necessary.

To summarize, for agricultural policy decisions of the short time scale type we have considered, the costs of being wrong in choosing a climate scenario, and the costs and benefits of being right are both moderate when planning decisions continually adapt to the evolving climate. In this case, it probably doesn't matter too much which scenario is picked, so long as the feedback between monitoring of the basin and planning decisions is maintained. This picture is complicated somewhat by the potential for a shift to a very dry climate regime, which entails more substantial costs if unchecked, and would also probably entail more longer term investment in developing alternative supply.

For water delivery policy decisions of the longer time scale type we have considered, the choice of climate scenario potentially makes quite a difference

to the ultimate array of costs and benefits associated with any climate change. The choice of climate planning scenario will likely influence the type of costs and benefits, their timing, and who the initial[4] recipients of burdens and benefits are. For instance, if history is chosen as the basis for planning and the GCMs are instead right, impacts will likely befall agriculture and industry through water shortages some decades in the future. If the GCM scenario were adopted, then the State of California and it's revenue base might meet the burden of the construction of new facilities over the next couple of decades.

For truly informed decisions to be made, we require better understanding of the probabilities of the different scenarios, and better accounting of the costs and benefits associated with different technological and social choices. It is necessary to draw out the decision matrix as we have attempted here, so that we may be better aware of the structure of the matrix when filling it in.

9.4   Key GCM Diagnostics

Since GCM-derived scenarios are one of the potentially useful sources of scenarios for water resource planning, it is important to describe appropriate standards for assessing the suitability of the current and next generation of GCMs for this task. In this section we attempt to describe some of the key diagnostics that a water resource planner or basin hydrological modeller might use to assess whether a particular GCM provides a reasonable simulation of regional climate for water resource impacts studies. On the one hand the list of diagnostics should not be too cumbersome if they are actually going to be calculated for GCMs and observations. On the other hand, the list should be comprehensive enough to ensure that the climate model is indeed a good model and simulates the key diagnostics well for the right reasons. We suggest use of a structured set of diagnostics in light of our analysis here.

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[4]We say 'initial' recipients of costs and benefits, since the ultimate burdens and benefits may be shared and/or passed on to others.

The diagnostics should test the large scale circulation in GCMs, since all techniques for deriving regional climate from GCMs rely on the GCM simulation of the large scale circulation. Sacramento Basin streamflow is highly sensitive to precipitation, and so it is also important to test the simulation of precipitation on basin scales. If GCM output were used directly in the basin, then one would test the GCM basin scale precipitation simulation. If a nested limited area model (LAM) were being driven by GCM large scale fields, then one would test the basin scale precipitation simulation in the limited area model. The reliance on basin scale precipitation simulations is partially circumvented in many current impacts studies by making use of the observed precipitation distribution for climate change studies, though this assumption will eventually have to be disgarded if greater realism is to be attained.

A basic limitation in assessing the performance of GCM simulations is that there are no exact analogues in the real world of the greenhouse gas and aerosol perturbed climate changes the models are simulating. Using current observational data, the models can be tested for their climate variability on seasonal, interannual, and decadal time scales. Variance statistics of the model fields on these time scales provide a necessary, but not sufficient test of the models ability to simulate climate changes over many-decade time scales. Tests using proxy data for past climate changes are also useful, but are hampered by lack of definition of the proxy data on key diagnostics. Lacking true tests of model performance for climate changes, we frequently recommend that the set of diagnostics used be expanded to cover those underlying processes or fields that can be used to diagnose errors in primary diagnostic fields.

9.4.1 Large Scale Circulation

A first set of useful diagnostics to calculate to test a model's ability to simulate the large scale circulation are the meridional energy transports in the atmosphere and oceans as per figures 1.1 and 1.2, and the meridional moisture transport in the

atmosphere[5]. Errors in the large scale circulation may be reflected in the profiles of meridional transports. Gross errors in the simulation of meridional transports, such as is evident in many current GCMs (Gleckler et al., 1994), would be associated with errors in regional climate simulations. A good simulation of meridional transports does not guarantee that the large scale circulation and regional climate will be well simulated however, so one must include further diagnostic tests.

A good indication of the large scale circulation is provided by the storm tracks, jet streams, and stationary waves. These diagnostics are not all independent in terms of their information content, since these features all depend on one another, but together they help to characterize the large scale flow field producing synoptic-scale storm systems in the Sacramento Basin. If these features are well simulated, then one gains confidence that the model storms are growing, propagating, and decaying in response to the right overall large scale steering patterns. Though the models we examined had identifiable deficiencies according to these diagnostics, there may be other models that do a better job. If the stationary wave field for instance is reasonably well simulated in terms of its mean characteristics, it is still important to consider whether the field is well simulated for the correct reasons, since one model may just happen to produce the right looking fields. One important check on the realism of the mean field is provided by an examination of the variability of the field within and between seasons.

Another way to tell whether the stationary wave field is realistic looking for realistic reasons, is to examine the processes that help set the stationary wave field in the atmosphere. As we discussed in chapter 6, the major forcing of the stationary wave field derives from orographic effects, and from diabatic heating and/or interaction with transient eddies. The propagation of stationary waves depends on the refractive index of the atmosphere, which is influenced by gradients of potential vorticity.

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[5]Rosen and Salstein (personal communication) for instance, have calculated the meridional fluxes of water vapour for a number of GCMs and observations.

The diabatic heating field is influenced by processes that release latent heat in the atmosphere, such as moist convection, which are part of the subgrid scale parameterization of climate models. The diabatic heating field is another key diagnostic that is desirable to examine because of its reflection of the quality of the moist convection parameterization, and because it forces the large scale stationary wave field. Unfortunately, diabatic heating rates in the atmosphere are not well known from observations, though estimates of the zonally averaged diabatic heating rate for each season have been made (Hantel and Baader, 1978).

For propagation of stationary waves, potential vorticity fields in the atmosphere are available from observations, and should be tested against the equivalent fields in models. The atmosphere's refractive index for propagation of stationary waves can be tested via Plumb (1985)'s wave activity flux, which diagnoses wave source and sink regions, as well as propagation. The wave activity flux can be calculated from conventional observational analysis fields and compared with models, as done by Yang and Gutowski (1994) for instance.

The above list of diagnostics could easily be extended, but it should provide a water resource planner with the ability to discern a good climate model for simulating large scale circulations, should they come across one. Stone (personal communication) notes that one way to satisfy this list of diagnostics with a climate model would be to 'linearize' a GCM about the current climate. That is, the full set of primitive equations and subgrid scale parameterizations in the GCM is linearized about observations for the current climate. In principle, this approach would be reasonable for simulating small perturbations about the present climate, such as due to transient increases in greenhouse gases. This may be problematic for aspects of the hydrological cycle such as we are interested in however, since the response of the hydrological cycle to climate perturbations is particularly nonlinear. In any event, to test a GCM that had been linearized in this manner, we would have to test it's simulations against other climates such as the last glacial maximum or climatic optimum in order to gain a feel for the validity of the linearization for various perturbations. This is difficult to do however, since

there is relatively little proxy data indicating features of the large scale flow for past climates.

9.4.2   Basin Precipitation

Streamflow in the Sacramento Basin responds to the spatial and temporal characteristics of the precipitation distribution. The spatial simulation of basin precipitation can be diagnosed by the kinds of simple statistical measures used in chapter 4 that test means, variances, and correlations with patterns in the observed precipitation fields. There are also a number of simple diagnostics that can be used to test the temporal characteristics of the precipitation simulation. A plot of the total amount of precipitation falling in a period versus precipitation event size, as per figure 5.7, indicates the relative importance of precipitation events of different sizes in observations and models. This diagnostic highlights the over-drizzly nature of current GCMs for instance, with too few large events and dry days, and too many small events. A plot of the cumulative basin precipitation over time would be useful in testing the arrival characteristics of precipitation, as would statistics on the number of wet and dry days, and on the return periods of major storms and drought periods.

Once the spatial and temporal characteristics of precipitation are properly simulated, it is still important to go further to test whether the features producing precipitation in the model are similar to those that operate in the real world. The sea level pressure field, stationary wave field, and jet stream field provide a useful indication of the synoptic features associated with basin storm events, as in section 6.6. In the case where limited area mesoscale models are used to translate GCM information to basin scales, it would also be useful to diagnose the simulation of mesoscale dynamical features in the limited area model and compare with relevant observations where they are available.

9.4.3   How Good is 'Good Enough'?

Developing a list of key diagnostics for assessing GCM suitability for generating regional climate change scenarios is a good starting point. For each of the key diagnostics we want to assess how good the GCM simulations are. However, we have not addressed the question of just how good is 'good enough' in GCM simulations of each diagnostic. For instance, what sort of error can be tolerated in GCM simulations of the position and intensity of the Pacific jet stream without compromising the model's ability to successfully simulate storms in the Sacramento Basin region? Or, how well does the model need to match the observed distribution of dominant precipitation events in the basin in order to produce roughly the right streamflow response in the basin?

When the models show gross errors in the diagnostics, such as in the GCM jet stream simulations we analysed, one can at least make plausible arguments based on synoptic-dynamical reasoning as to why the simulation of storms in the model basin would be compromised. But how does one make this judgement in the case where a model has qualitatively the correct jet stream and stationary wave field for instance? One approach is to then examine an associated diagnostic that helps set the feature in question to see if that is well simulated. In the case of a questionable simulation of stationary waves, one would then examine the diabitic heating fields and wave activity flux as suggested above. This may also prove inconclusive, since the same question can be asked of the simulation of the underlying feature in the case where this is qualitatively well simulated. At this point, the best approach would probably depend on the diagnostic in question on a case by case basis.

To illustrate, consider the example of a qualitatively correct simulation of the Pacific jet stream and stationary wave trough, which are only slighly in error as to position and intensity. There are perhaps a couple of different approaches that could be used to assess the potential importance of this kind of error. If a sufficiently large observational data base were available, one could try to determine the sensitivity of basin precipitation to changes in jet stream and stationary wave

position from observations. Observational patterns could be selected that match those simulated in the GCM. This procedure would only be useful in the case where close observational analogues of the model simulation exist. Alternatively, a modelling approach could be used, though this would also have shortcomings. One approach might be to force a linearized GCM such as discussed above with the slightly erronous fields from the full nonlinear GCM in order to examine what effect this has on basin storms and precipitation in the linearized model.

In the case of uncertainty in the quality of simulations of basin precipitation diagnostics, one could use a physically based hydrological model of the basin to examine the sensitivity of basin streamflow to the errors in question. We have already made some suggestions along this line in section 8.4.

9.5   Research Priorities

Our work here has shown, perhaps unsurprisingly, that current GCMs can not yet produce reliable regional climate scenarios for the Sacramento Basin. The obvious questions arise as to whether GCMs will ever be able to produce reliable scenarios, and if so, what research needs to be undertaken to accelerate the approach to the time when they can. There is yet no good answer to the first question. All we can reasonably say for now is that there is room for improvement of GCMs and every reason to expect that they will become better tools for climate simulations. With this background in mind, we suggest research priorities from the point of view of providing water resource planners with better information about the impacts of regional climate change on water resources.

We can identify at least four areas that are relevant to the task of providing better information about climate change impacts on water resources:

Generation of climate scenarios: This stage refers to the use of GCMs and other techniques to construct future climate scenarios for the basin.

Streamflow response: This stage entails a diagnosis of the response of basin streamflow to the climate evolution identified in the first stage.

Water resource planning: This refers to management of water resources in the basin in light of future streamflow expectations for the basin. This would include an analysis of the costs and benefits associated with various assumptions about streamflow changes and management options.

Interactions between areas: Breaking the problem down into separate parts is convenient, but artificial. There also needs to be research on the interactions between planning decisions and future climate, and between atmospheric and surface coupling and feedback for instance.

Our work here has concentrated mainly on the first aspect of the problem; that of generating better climate scenarios. This problem can be further broken down into GCM and non-GCM approaches (bearing in mind that some approaches — perhaps the best ones — combine both sources of information). While we did not study non-GCM approaches, we do feel confident in recommending that these empirical approaches for generating climate scenarios continue to be researched. The reason for this is that GCM-based regional scenarios are currently so unreliable that they do not offer a clear advantage over the empirical approaches. GCMs are potentially better tools for this purpose, but they have not realised this potential to date.

For the development of better GCM regional climate scenarios, research efforts should be directed towards improving the subgrid scale parameterizations in the models. This particularly applies to moist convection and the other subgrid scale schemes that help set the moisture and diabatic heating fields in the atmosphere. Successful simulation of these fields is critical for successful simulation of large scale circulations in the models. The large scale circulation is critical for regional climate. Part of the research effort in improving subgrid scale parameterizations is theoretical, and part of it entails collecting better observations of the distribution of key quantities like water vapour. Better observations will also serve to assist in assessing model simulations of the key diagnostics outlined

in the previous section. Improvements in resolution of GCMs are also desireable, but not as important as improvements in subgrid scale parameterizations from the point of view of improving simulation of large scale circulations (see section 7.6). Observational and numerical studies of the sensitivity of basin storms and precipitaton to large scale flow features, as outlined in the previous section, will improve diagnosis of the ability of GCMs to provide adequate regional climate simulations for water resource applications.

The task of improving the simulation of basin streamflow responses to climate changes entails development of better hydrological models and better techniques for coupling those models to climate models. The surface model and atmospheric model should exchange heat and moisture in an energetically consistent manner, rather than simply having the GCM pass precipitation and temperature values on to the surface model. This entails work on the physics of boundary layer processes and their incorporation into coupled climate-hydrological models. While important strides have been made in incorporating the physics of snow into hydrological models, research now needs to develop better schemes for incorporation of vegetative changes into the models, which would become important in a basin if climate changes. It is also important that research continue on incorporating sophisticated soil moisture and runoff schemes into the models, since these are sensitive to precipitation arrival characteristics, which may also change. We have proposed some studies testing the sensitivity of hydrological models to precipitation scenarios in section 8.4, which may suggest further research priorities in this area when complete.

Research on water resource planning in the basin should include studies on changes in water demand in the basin, as well as on any potential climate induced changes in water supply, since the former could easily swamp the latter. Research needs to be directed towards assessing potential management and technology options for maintaining future supply in the face of a variety of plausible scenarios for streamflow changes, and in assessing the potential costs and benefits associated with the various options and scenarios outlined in table 9.2 for instance. Research should also be carried out on strategies for adaptation in the event that there

are acute and/or chronic disruptions to supply. There is also a need for research on questions of equity and fairness that arise in investing public and private resources in the management of future water supply in the basin. Last, but not least, research that addresses the societal factors contributing to anthropogenic perturbations of the climate system could help slow rates of climate change in the basin.

"Fine weather we're having, eh?"

"Just a minute," he said, looking up. And after a moment's thought he went on "This is how it ought to be expressed: All fine weather is pleasant. Now, today's weather is fine. Therefore, today's weather is pleasant. A syllogism in Barbara: *irrefutable. So indeed, my good man, you were right. Fine weather!"*

We were friends from that moment. He went on: "But if we are to raise your proposition to the status of universal law, I must make a few calculations. So come back in a quarter of an hour."

He turned to one of his machines; I went off to have a rest under a bandstand and then came back. He 'proffered a folder of type-written sheets, and the first of them follows.

weather: W today's weather: tW
fine: f pleasant: p
Me: M (negative): $'$

Proposition:
$$(W = f > p/M)\ (tW = f) > tW = p/M + p/M'$$
Postulate:

Courtesy (c) calls for confirmation of a natural affinity between those concerned within the relationship we are dealing with; otherwise:
$$c(M + M') > (p/M = p/M').$$
Proof
$$W > (W \times M)\ (W \times M')$$
and
$$(f = p)/M + (f = p)/M' < c(M + M')$$
Therefore:
$$(tW = f) > tW(M = c) \times tW(M' + M) \times p \times c$$
$$p \times M' = (c \times M)\ (p/M)$$
and, by virtue of the absurd nature of:
$$(f = f') > (M = M') \times c'$$
and of:
$$c' \geq 1 \times pM,$$
we have:
$$(tW = f) = p \times M' = 1 \times (c \times c') \times (tW.p. + M.c) \ldots$$
There were five pages like this. I pretended to read them and the Logologist said to me: "And so anybody who had spoken as you did would have been right, and I rejoice with you, with a logically unassailable joy, that it's fine."

René Daumal
A Night of Serious Drinking

Chapter 10

Conclusions

10.1 In Short

We have attempted to scrutinize some of the major assumptions typically employed in climate impacts studies on water resources. We focused in particular on the assumption that the large scale climate simulated by GCMs provides a suitable starting basis on which to infer changes in streamflow in regional basins. We set up a case study of the Sacramento Basin in order to test this assumption directly for a particular region. The best way to test the GCM adequacy assumption is to work in the reverse sense from typical impacts studies, which take the GCM output as given and work towards divining streamflow response to the GCM output. By contrast, we outlined the synoptic climatological processes thought to be responsible for controlling the hydrological response of the basin streamflow, and then sought to determine how well GCMs simulate the important synoptic climatological processes. In short, we noted major shortcomings in the GCM synoptic climatologies of the Sacramento Basin, and question the assumption that the large scale climate simulated by GCMs provides a suitable starting basis on which to infer changes in basin streamflow.

10.2 Longer

To gain a full understanding of the climate and hydrology of the Sacramento Basin
it is necessary to examine basin hydrological features and their interaction with the
atmosphere across a range of spatial and temporal scales. We divided our analysis
up into regional synoptic scales spanning the Pacific Basin, local scales spanning
the Sacramento Basin, and planetary scales spanning the northern hemisphere
extratropics. It is important that the climate models simulate the climatology of
the basin across the range of scales, though basin impacts models rely particularly
on the large scale climate simulation.

Regional-scale analysis is particularly amenable to statistical methods. Sta-
tistical tests provide good objective tests of the model regional simulations, though
state of the art climate models do not withstand rigorous statistical scrutiny —
for what it is worth. The climate model spatial and temporal means and variances
for precipitation, temperature, and sea level pressure are all significantly different
from observations. In a statistical sense, the model fields are drawn from differ-
ent populations to the observational fields, and one can only conclude that the
models are *statistically* not well suited to provide precipitation and temperature
to hydrological models of the Sacramento Basin.

All the climate models we examined have difficulty simulating the magni-
tude, position, and variability of the prominent synoptic feature of the region, the
Aleutian low, though this difficulty is particularly pronounced at low resolution.
CCM1 is statistically the best of the models in the simulation of mean quantities
on regional scales, and is the worst of the models in the simulation of variances.
This highlights the importance of examining higher order statistics in evaluat-
ing model performance. The model simulations are typically worse in July than
they are in January. The sea level pressure patterns for relatively wet and dry
Januaries in the models bear little resemblance to the corresponding patterns in
observations, implying that the models do not simulate wet and dry spells in the
basin for the correct reasons.

On local basin scales, the climate models are generally not expected to provide accurate simulations of complex features like precipitation. While we found this to be true, we now also have a better understanding of the ways in which GCM output is imperfect on this scale. The climate models smear out precipitation in the basin region in space and time. The spatial precipitation gradients are too weak along the west coast and the precipitation is too weak over the Sacramento Basin, despite the fact that the model precipitation is too strong over the larger western North America region. The spatial smearing of precipitation along the west coast is reduced in the CCM2 model at T106 resolution, indicating that present state of the art models are resolution-limited in simulating sharp coastal precipitation gradients. The sensitivity of precipitation to horizontal resolution in the models is heterogeneous across the precipitation field, and depends on the precipitation feature in question.

The models precipitate too often in the basin, and too many of their precipitation events are in the drizzle range of a few millimetres per day. The models deliver most of their precipitation to the basin in the form of drizzle, whereas in observations the dominant precipitation events are storms yielding an order of magnitude more precipitation per event. The climate model precipitation and temperature values for the Sacramento Basin are generally well outside the observational values as measured from station data and gridded observational data. Furthermore, the uncertainty in the climate model values for the Sacramento Basin is of the same order as their projected changes in these values for doubled CO_2. And importantly, streamflow in the Sacramento Basin is sensitive to errors of the size of those for Sacramento Basin precipitation in the climate models.

The main features (jet streams, stationary waves, storm tracks, persistent anomalies) characterizing the synoptic climatology of the Sacramento Basin are fairly robust in different observational data sets and for different observational periods. The synoptic climatological features in the climate models exhibit a number of differences with observations that exceed even the interannual variability of the observational features.

In CCM1 the winter mean Aleutian low is incoherently simulated. The CCM1 Pacific jet stream is too weak and underextensive across the Pacific. The stationary wave trough amplitude is too weak in the Pacific and the stationary waves are generally too weak in the northern hemisphere extratropics. The CCM1 Pacific storm track has too little activity, and does not extend far enough into the eastern Pacific. In wet Sacramento Basin winters, there is an unrealistic backward extension of the CCM1 Atlantic jet and storm track toward the Sacramento Basin region. This response is confirmed for individual storms, where the backing of the Atlantic jet is readily apparent. During the winter precipitation season, most of the time there is no jet and storm track over the west coast in CCM1 and the model produces only very weak precipitation, with storms that are too few and far between. When CCM1 does produce a storm in the Sacramento Basin, it does so in an unrealistic manner via a backward extension of the Atlantic jet stream.

In CCM2 the climatological winter mean sea level pressure field shows a spurious low off the west coast of North America. There is no ridge at the 500hPa level down the west coast in CCM2 as there is in observations. The spurious low may be compensating for an underextensive stationary wave trough and jet stream in the Pacific, and is also probably responsible for the spurious overextension of the Pacific storm track through the west coast region in the model. For winter mean plots, the large scale circulation features in CCM2 change little for ensembles over wetter than normal and drier than normal winters in the Sacramento Basin. In the climate mean, CCM2 appears to be stuck in a mode resembling the observations 'wet' mode with the low off the California coast. Even here though, the large scale synoptic structure supporting that mode is different from the observations wet mode. For instance, the CCM2 jet stream field for individual storms is erratic, and CCM2 Sacramento Basin storms are most often associated with a backing of the Atlantic jet (like CCM1), rather than with an extension of the Pacific jet stream as in observations.

On the basis of the comparison between the model synoptic climatologies and those for the observations, we conclude that the large scale processes producing precipitation in the Sacramento Basin region in the models are unlike those that

operate in the real world. The errors in the model large scale fields are related to limitations of the subgrid scale parameterization schemes producing precipitation and the heating fields that interact with the larger scale circulations. Lack of physical veracity in the models implies that the assumption that one can take the difference between $2CO_2$ and $1CO_2$ climate model runs as being relatively error free on the basis that the model simulates the change in climate correctly, even if the original climate is in error, is probably a bad one.

We discussed some of the potential benefits for regional climate simulations of developing various aspects of climate models. The AMIP model runs using time series of observed sea surface temperatures and sea ice distributions provide a test of the potential benefit of developing better ocean models. The comparison between CCM2 and the CCM2AMIP run provided a pure test of the use of AMIP boundary conditions. The major deficiencies in the synoptic climatology of CCM2 are also present in the CCM2AMIP simulation. This indicates that the deficiencies in the large scale atmospheric circulation across the North Pacific and North America in the model are not a strong function of the boundary conditions for sea surface temperature and sea ice distributions. On smaller scales, the precipitation characteristics in the Sacramento Basin region are also similar in the CCM2 and CCM2AMIP runs, with common pathologies. This suggests that development of a better ocean model *per se*, would not be of major use in simulating regional climate for the Sacramento Basin, though it may still be an important factor in conjunction with improvements in the atmospheric model, and in their coupling.

An increase in the resolution of the GCMs provides a number of salient improvements in the model simulations. Increasing the resolution from $8° \times 10°$ to $4° \times 5°$ in the GISS model allows the model to develop a coherent simulation of the Aleutian Low in the North Pacific basin. Increasing the resolution of CCM2 from T42 to the very high resolution of T106 results in a successful sharpening of the precipitation gradient along the west coast of North America. While increases in resolution are highly desireable from the point of view of simulating Sacramento Basin climate, it is almost certainly not the panacea that IPCC (1990) claim it will be. For instance, the major deficiencies noted in the CCM2 T42 large scale

circulation simulation are still present at T106. Despite resolving the Sacramento Basin with nine interior grid boxes, the simulation of precipitation arrival still appears unrealistic at T106, and the model is still too drizzly. This underscores the fact that even with substantial improvements in resolution, the model simulations are still dependent on the parameterizations of subgrid scale processes.

While we have been concerned mainly with simulating the regional climate of the Sacramento Basin, it is hard to imagine that the GCMs will have considerably more success in other regions. This is partly because the deficiencies we noted in the model simulations extend to the largest planetary scales that influence the climate of much of the extratropical regions. In the tropics, there are also persistent shortcomings in the model simulations of the large scale tropical environment.

The apparent dependence of the GCM large scale circulations and basin scale precipitation simulation on the subgrid scale parameterization of moist convection provides further support for the contention of Stone and Risbey (1990) that "in effect, the subgrid scale parameterizations are the achilles heel of general circulation models". Improvement of the subgrid scale physics parameterizations in the models will take more than a few years, to be sure, which means that the uncertainties in regional climate simulations will likely persist for some time.

We used historical data from the well monitored Sacramento Basin to elicit the basin streamflow response to precipitation and temperature. The streamflow response exhibits substantial nonlinearity. During particularly wet years in the basin, the streamflow increases proportionally more than the precipitation. During particularly dry years the streamflow is more linearly related to precipitation. However, on the tails of droughts the streamflow response to precipitation is diminished relative to other dry years, and the basin apparently retains some memory from year to year. The relative diminishment of streamflow from precipitation in drought periods would be of particular concern if the incidence of droughts in the basin increases due to greenhouse climate change. Since streamflow is nonlinearly related to precipitation, the amount of basin streamflow implied for a models doubled CO_2 basin precipitation simulation depends on how much basin precipitation is simulated for the current climate.

For small climate changes in the basin, streamflow amount is insensitive to temperature. Streamflow timing is however sensitive to temperature. For substantial climate warming in the basin, there would be a shift to a rain regime from a snow regime, and the sensitivity of streamflow timing to temperature would be reduced. This in turn would likely increase the sensitivity of streamflow amount to temperature, yielding a diminishment of streamflow relative to precipitation.

Climate changes in the basin are not well captured in simple regression models, which simulate a streamflow dependence on temperature for small climate changes that is not present in the more physical PRMS model. Nor is it indicated from historical data. The PRMS model simulates nonlinear streamflow responses to precipitation consistent with the observations.

Water resource planning decisions for California are made all the time, increasingly with attention to the potential for climate changes to occur in the Sacramento Basin in the long term planning period spanning the next fifty years or so. A recent dilemma for planners has been whether to assume that the next fifty years will be like the past fifty years, or whether climate model scenarios or some other scenarios for the basin might come to pass. Given the limitations in knowledge about future climate in regions, it is not yet possible to make rigorous determinations of the likelihood of the various scenarios coming to pass. We chose planning issues with characteristically short (agricultural policy) and long (water delivery policy) implementation and operational time scales to probe the sensitivity of planning decisions to the choice of climate scenario. By filling in the likely consequences of planning on the basis on each particular scenario, when any one of the scenarios are actually realized, we can at least gain some appreciation for the relative magnitude of the decisions, and some awareness of the stakes.

For agricultural policy decisions of the type we considered, the planning, implementation, and operational time scale for investment in alternative crop practices is short relative to greenhouse climate change time scales. In this case, the costs of being wrong in choosing a climate scenario, and the costs and benefits of being right are both moderate when planning decisions continually adapt to the

evolving climate. As such, it probably doesn't matter too much which scenario is picked, so long as the feedback between monitoring of the basin and planning decisions is maintained. This picture is complicated by the potential for a surprise shift to a very dry climate regime, which would entail more substantial costs if unchecked, and would also probably entail more longer term investment in developing alternative water supplies. Further, the costs incurred in lost agricultural production should a shift to a much dryer climate regime occur by surprise would likely be substantially larger than the costs incurred in adapting agriculture to a drier climate regime should it not occur.

For water delivery policy decisions about whether to invest in new dam construction or develop alternative water sources to ameliorate the impacts of climate change, the time scales for implementation and operation approach those characteristic of the greenhouse climate change process. The investment costs involved are also quite substantial. In this case, the choice of climate scenario potentially makes quite a difference to the ultimate array of costs and benefits associated with any climate change. Long term planning decisions in the basin are sensitive to the choice of future climate scenario.

10.3 Further Work

The results of this work imply that the subgrid scale parameterizations are the most critical determinants for improving the simulation of large scale circulation features in the climate models. For instance, the stationary wave simulation in CCM2 is apparently sensitive to the representations of moist convection and boundary layer processes over the maritime continent region. Further insight into what sets the all-important stationary wave field in the climate models can be gained through use of diagnostics like the wave activity flux that probe the three dimensional propagation of wave activity in the atmosphere. Through a determination of source regions for wave activity in the models, it should be possible to

make better deductions about which aspects of the subgrid scale physics and their interaction with the large scale flow are most in need of attention.

The reliance in contemporary climate impact studies on basin observations of precipitation as a basis for climate change experiments has the shortcoming that the spatial pattern and temporal sequence of precipitation is unchanged. Basin streamflow is sensitive to precipitation arrival characteristics due to the nonlinear relationship between precipitation and streamflow. As a consequence, it is desireable to incorporate information on likely changes in precipitation arrival characteristics in climate change experiments with hydrological models. Meanwhile, the nature of the dependence of basin streamflow on the spatial and temporal distribution of precipitation should be tested in physical hydrological models such as the PRMS model.

Finally, there is much to be done in developing an account of the costs and benefits associated with the different technological and social choices for different climate scenarios facing planners in the Sacramento Basin.

"... And at the other extreme, when we wish to express the opposite of love, which we call hatred, we can find no stronger or more intelligent a symbol than 'water and fire'; for us, this is the idea of two irreconcilable enemies. But the one exists only through the other. Without fire, all the water in the world would be an inert lump of ice, stone amongst rock; robbed of all the characteristics of a liquid, it would make neither sea nor rain nor dew nor blood. Without water, fire would die for all eternity, since for all eternity it has consumed and scorched all things around it; it would give neither flame nor star nor lightning flash nor sight. But we continually see water putting out fire and fire turning water into steam, yet never have any overall perception of the perfect balance by which the one exists through the other. When we see a plant grow or a cloud rise over a mountain, when we cook our food or are conveyed by steam engines, we have no idea that we are looking at and using the fruits of their infinitely fertile love ... "

Totochabo *in*
René Daumal
A Night of Serious Drinking

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"Sorry, old man, I'm looking for the exit."

That's just what he should not have said. Three big blokes appear from the shadows and grab him by the collar:

"The what? You're looking for the what?"

"The exit, like I said."

"This place has only three exits, sir," one of the big blokes snarled! "Madness and death."

I tot them up on my fingers, feel very intelligent and ask:

"What's the third?"

Thereupon, they hurl themselves upon me, cover my mouth with their great mitts, pick me up like one of those floppy stretchers, run smartly up a small, steep, dirty stairway with me so arranged that my buttocks and head in turn bang against the steps; then we are at the top, staggering somewhat, in a garret where there is a low doorway and over it a sign:

SICK BAY

"Go and have a look in there," the largest of them said.

I go in and while the big blokes observed me through the keyhole and various other chinks deliberately made in the door (for this was one of the few amusements that they were allowed) and with the walls shaking with the laughter they found difficult to control, I walk between two rows of iron bedsteads which held patients who were sick, wounded, had gone mad, or been dried out, in a word, anybody who had insisted on leaving.

René Daumal
A Night of Serious Drinking