The Quasi-Quintennial Timescale—Synthesis

Raymond C. Smith
Xiaojun Yuan
Jiping Liu
Douglas G. Martinson
Sharon E. Stammerjohn

Introduction

The El Nino–Southern Oscillation (ENSO) is one of the most important contributors to interannual variability on Earth (Diaz and Markgraf 2000). It is an aperiodic phenomenon that tends to reoccur within the range of 2 to 7 years, and it is manifest by the alternation of extreme warm (El Niño) and cold (La Niña) events. There is also evidence (Allen 2000) that the aperiodic ENSO phenomenon must be considered in conjunction with climate fluctuations at decadal to multidecadal time frames that may modulate ENSO's lower frequency variability. Numerous studies show global climatic impacts associated with the ENSO phenomenon. Further, there is considerable evidence to indicate that ENSO impacts the climate of both middle and high latitudes, and a recent analysis (figure S.1, discussed below) provides a global picture of warm versus cold ENSO conditions. Consequently, it is not surprising that many LTER sites, from the Arctic to Antarctic, show evidence of ENSO-related fluctuations in environmental variables.

The quasi-quintennial timescale of variability is second only to seasonal variability in driving worldwide weather patterns. Consequently, an important theme in part II is the worldwide influence of ENSO-related climate variability and the teleconnected spatial patterns of this variability. Also, a common theme for several ecosystems discussed in this section is their high sensitivity to small climatic changes that are subsequently amplified and cascaded through the system. For example, the narrow temperature threshold for an ice-to-water phase change may create a pronounced nonlinear ecosystem response to what is a relatively small temperature shift (as demonstrated for the McMurdo Dry Valleys). Or alternatively, this narrow temperature threshold may shift a sea ice–dominated ecosystem (Palmer

LTER) to a more oceanic marine ecosystem by reducing the seasonality and magnitude of the sea ice habitat. Such nonlinear amplifications of small climatic changes can increase the ecological response and make it more detectable within the natural background of variability. We explore these themes here.

Global Teleconnections

To illustrate the global footprint of ENSO variability, composites of yearly averaged El Niño and La Niña conditions for surface air temperature (SAT) and sea surface temperature (SST, Reynolds and Smith 1994) were generated. The SAT data were derived from the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al. 1996) for the period 1980 to 2000 to avoid the lack of data in earlier years and analysis problems in the Southern Ocean (Kistler et al. 2001). In addition, using data from the last 20 years also avoids the climate regime shift of the late 1970s. Consequently, these results reflect the more recent ENSO teleconnections.

Our analysis involves two averaging steps in generating the composite maps. First, the ENSO yearly average includes data from June of the ENSO onset year to May of the following year. Then, data from all identified El Niño (La Niña) years are averaged together to produce an El Niño (La Niña) composite (see Liu et al. 2002 for details). Finally, the difference between the El Niño and La Niña composites reveals a global ENSO teleconnection pattern in these two temperature fields (figure S.1a,b). The characteristic El Niño pattern with warm anomalies in the central and eastern tropical Pacific and tropical South Indian Ocean and cold anomalies in the western tropical Pacific and subtropical Pacific in both hemispheres stands out strikingly. Associated with the 1–2.5°C warm SAT anomaly (solid contours in figure S.1a) in the tropical Pacific is a warming of the same magnitude in the eastern Ross Sea sector of the Antarctic and a cooling (dashed contours) of about 1.5°C in the Bellingshausen and Weddell Seas. As part of the ENSO footprint, this out-of-phase relationship in the Pacific and Atlantic sectors of the Antarctic represents a high-latitude climate mode named the Antarctic Dipole (Yuan and Martinson 2000, 2001). A Northern Hemisphere counterpart of the Antarctic Dipole appears in the SAT of the western Canada and northeast Canada/Greenland regions as well.

Between the polar and tropical regions, there is also a large cooling anomaly (about 1°C) in the subtropical region of the southwestern United States (in addition to the cooling anomalies in the subtropical North and South Pacific mentioned previously). This analysis clearly reveals a global ENSO footprint. Similar teleconnection patterns exist in the SST field (figure S.1b), except the warm anomaly in the tropics is twice as large as the warm anomaly in the polar regions. Moreover, the ENSO signal not only appears in sea surface temperatures but also is found below the surface. A study of vertical structure in polar oceans reveals that in the Weddell Gyre (Antarctic subpolar Atlantic and westernmost Indian Oceans) upper ocean heat content, salt budget, and water column stability are well correlated with ENSO indices (Martinson and Iannuzzi, 2003).

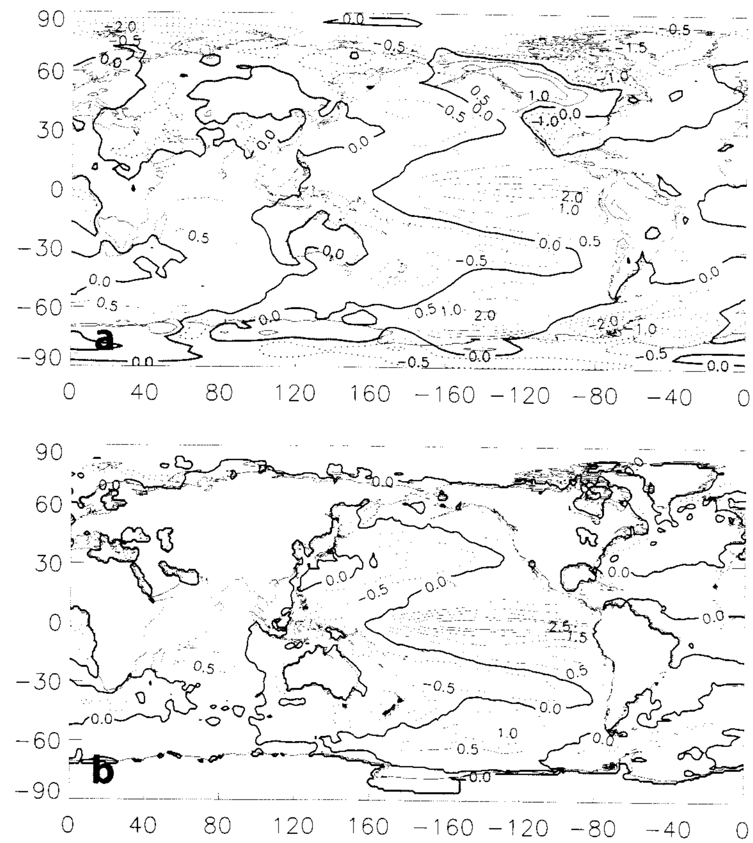

Figure S.1 (a) The composite differences of surface air temperature (SAT, °C) between El Niño (1982–1983, 1986–1987, 1987–1988, 1991–1992, 1997–1998) and La Niña (1984–1985, 1985–1986, 1988–1989, 1995–1996, 1998–1999, 1999–2000) years spanning 1979–2000 from NCEP/NCAR reanalysis. (b) Similar to (a), except for the Reynolds and Smith sea surface temperature (SST, °C) spanning 1981–2000 (Liu et al. 2002). Positive temperatures shown as solid contours, negative temperature shown as dashed contours.

This global ENSO footprint in temperature is similar to spatial patterns revealed in other climate variables. For example, Antarctic sea ice concentrations observed by satellite microwave imagery (Stammerjohn and Smith 1996; Comiso et al. 1997) also show the ENSO teleconnection pattern. Singular value decomposition (SVD), a powerful analysis tool often employed to isolate spatial patterns in two climate fields that tend to covary in time with one another (Bretherton et al. 1992; Wallace et al. 1992), was applied to global SATs and Antarctic sea ice concentrations. Figure S.2 shows the spatial patterns of the leading SVD mode in both variables. The leading spatial pattern in SAT shows a striking similarity to the ENSO footprint revealed in the composite analysis of figure S.1a. Coupled with this pattern is decreased sea ice concentration associated with the warming anomaly in the central and eastern Pacific sector of the Antarctic, and increased sea ice concentration as-

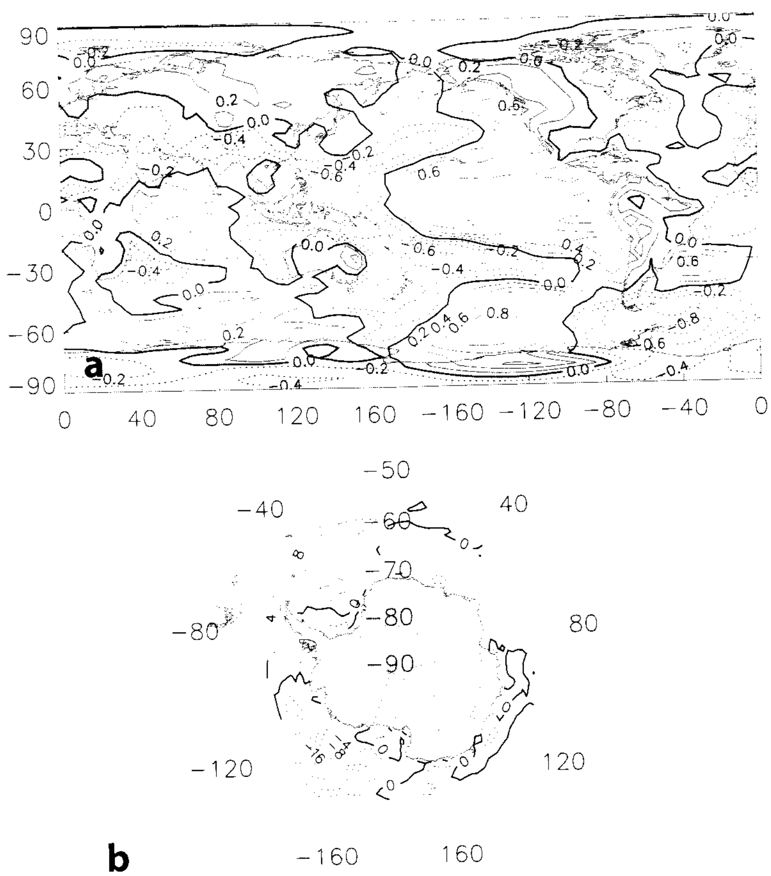

Figure S.2 The spatial patterns of the leading coupled mode in global SAT anomaly field (a) and Antarctic sea ice concentration anomaly field (b) derived by a Singular Value Decomposition (SVD) analysis. The total squared covariance explained by this mode is 15%. Sea ice concentration data were derived from satellite microwave observation from September 1978 to December 1999, whereas SAT data were taken from NCEP/NCAR reanalysis during the same period. Positive (negative) anomalies shown as solid (dashed) contours and are in arbitrary units.

sociated with the cooling anomaly in the Bellingshausen and Weddell Seas (i.e., the Antarctic Dipole in the sea ice field). This analysis indicates that the Antarctic Dipole in the sea ice field is regionally coupled with the dipole in the SAT field and remotely associated with the tropical ENSO pattern as part of the global ENSO teleconnection. The temporal correlation coefficient between the two spatial patterns in figure S.2 is 0.8, indicating that the spatial variability pattern observed in the sea ice field (as shown in figure S.2b) is most likely associated with the spatial variability pattern in the temperature field (as shown in figure S.2a). This is consistent with Yuan and Martinson (2000), who found statistically significant correlations between detrended sea ice edge anomalies in the dipole region and tropical ENSO indices.

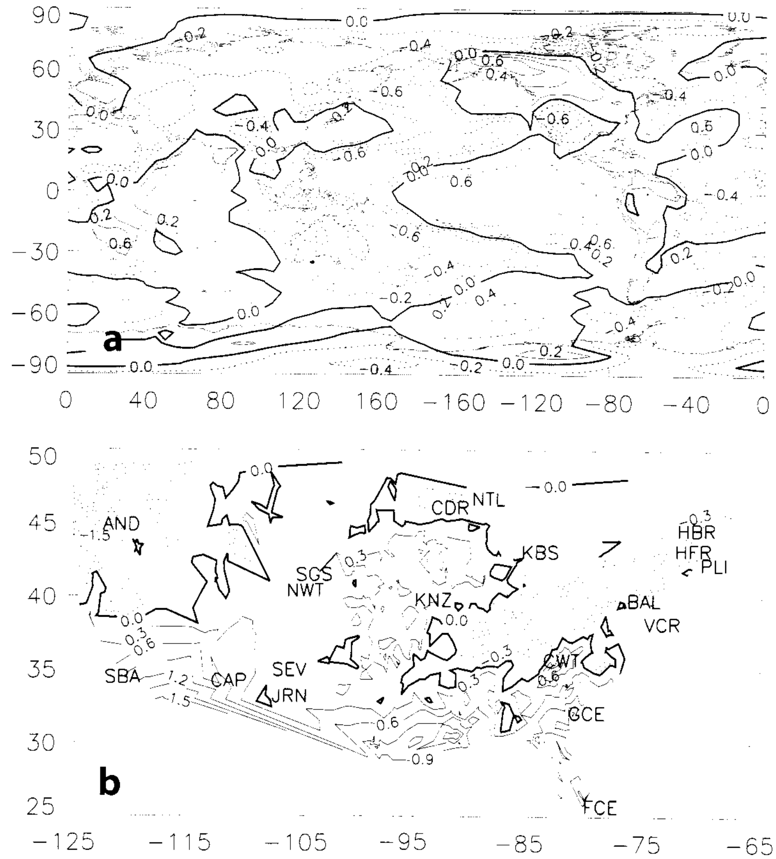

Figure S.3 The second coupled mode between monthly global SAT and U.S. precipitation derived by the SVD analysis. The total squared covariance explained by this mode is 3%. Both temperature and precipitation data span January 1975 to December 1996. The precipitation data were the weather station data provided by NCAR. Positive (negative) anomalies shown as solid (dashed) contours and are in arbitrary units. LTER site symbols as given in table 1.1.

Another example of the global ENSO teleconnection pattern is given by the SVD analysis between global SAT and precipitation in the United States (figure S.3). The monthly precipitation data are from U.S. Historical Climate Network weather stations available from the National Climate Data Center (NCDC). This data set provides high-quality and long-term meteorological data for climate studies (Easterling and Peterson 1995). The second coupled mode reveals nicely the global ENSO teleconnection pattern in the SAT field. Associated with the SAT pattern is a precipitation pattern reflecting above-normal precipitation in the southwestern, midwestern, and southeastern United States (Cayan 1996; Cayan and Peterson 1989), and below-normal precipitation in the northwest, Ohio Valley, and northeast of the United States during warm phases of ENSO (vice versa for cold phases). These precipitation patterns are consistent, for example, with the reported patterns from several LTER sites, as discussed next.

Two pathways can transport climate signals from low to high latitudes: the oceanic bridge and the atmospheric bridge. Although many researchers have studied the atmospheric pathway linking tropics and high latitudes, the underlying mechanisms remain poorly understood. In the Southern Hemisphere, earlier studies suggested that the variability of tropical convection generates Rossby waves that propagate anomalous atmospheric signals out of the tropical regions at intraseasonal timescales (Mo and Higgins 1998; Renwick and Revell 1999). These Rossby waves comprise a barotropic standing wave train of alternating anomalies in the pressure/height fields that extends southeastward from the subtropical Pacific near Australia, across the Antarctic Peninsula, and into the southwestern Atlantic, forming the Pacific–South America (PSA) pattern. The PSA is modulated at interannual timescales, with changes in the strength and phases of the Subtropical Jet, the Polar Front Jet, and the Amundsen Sea Low that comprise the PSA pattern (Mo and Ghil 1987; Karoly 1989; Mo and Higgins 1998).

In addition to the Rossby wave hypothesis, a recent study (Liu et al. 2002) suggests that changes in the regional mean meridional circulation (consisting of the Hadley, Ferrel, and Polar Cells) also drives tropical-polar teleconnections. This study shows that ENSO events change the strength of the regional Ferrel Cell. For example, poleward heat transport in the lower level of the Ferrel Cell in the South Pacific during El Niño years is larger than during La Niña years, with the opposite occurring in the Bellingshausen and Weddell Seas (i.e., the Antarctic Dipole in Ferrel Cell variability). Lui and colleagues (Lui et al. 2002) suggest that changes in the regional Ferrel Cell associated with ENSO variability influence the temperature and sea ice fields at high southern latitudes through the modulation of the mean meridional heat flux. These global teleconnections provide the climate variability linkages observed among the spatially disperse LTER sites.

LTER Site Responses

Many U.S. and international LTER sites are located within the global ENSO footprint. There is good, but not always detailed, congruence between Greenland's overview analysis (table 6.3), showing strength (as determined by correlation analysis) of the SOI for selected LTER site locations (figure 1.1), and the warm and cold locations shown here for the composite surface air temperatures (figure S.1a). There also is good congruence between the overview analysis (table 6.3) and ENSO-related precipitation (figure S.3b) across the United States. In particular, the Southwest United States (Central Arizona, CAP; Jornada Basin, JRN; Sevilleta, SEV) and the Northwest United States (Andrews, AND) show consistency between the earlier correlation analysis and the SVD derived patterns. Sites in the Northeast (HBR, HFR) and Midwest (KNZ, SGS, NWT) that showed weak correlation in Greendland's analysis are areas that show relatively low anomalies in figure S.3b. One reason for a lack of complete congruence is that the various indices (Southern Oscillation Index, SOI; El Niño–Southern Oscillation, ENSO; Multivariate ENSO

Index, MEI; etc.), although highly correlated, are not exactly the same. As Trenberth (1997) points out, both the definition of indexes, which are continually evolving, and the base period climatology of the index can make a difference in spatial coherency, temporal variability, and subsequent correlation analyses with various environmental variables. Beyond this, there are several requirements for an ENSO signal to be imprinted on an ecosystem. First, the given location (i.e., the LTER site locations shown in figure 1.1) must be within the ENSO teleconnection footprint. Figures S.1 and S.3b provide a visual indication of the possible spatial congruence of an LTER site with the ENSO-related temperature or precipitation variability, respectively. Second, the strength of an ecological response to climate variability is itself highly variable and, as noted in the overview by Greenland (chapter 6), dependent on many factors including preexisting conditions, possible cascades and threshold triggers, characteristic ecosystem time scales, and linearity or nonlinearity of the system response.

The arid and semiarid ecosystems of the southwestern United States (CAP, SEV, JRN) provide examples of systems that typically show a strong response to precipitation. These ecosystems are most strongly linked to the ENSO phenomenon during fall, winter, and spring. Some connections are strong enough that it may be possible to make seasonal forecasts on impending conditions based on key index precursors (e.g., chapters 7 and 15). Under El Niño conditions, precipitation and temperature tend to increase and decrease, respectively, whereas regional soil moisture deficit typically decreases. In these ecosystems periods of precipitation offset drought-driven impacts, which are linked to dust storms, wildfires, changes in vegetation, and reduced soil moisture, water quantity, and quality, as well as serious reductions in agriculture and livestock production. Also, as Brazel and Ellis discuss for the CAP urban site (chapter 7), human-modified urban and agricultural ecosystems may display unanticipated and amplified feedbacks with respect to climate-mediated ecosystem relationships. Consequently, efforts to understand underlying mechanisms and to improve predictive capabilities have significant economic and ecological incentives. An oscillation between wet and dry conditions would appear to be the norm for these arid and semiarid ecosystems. Processes whereby these ecosystems may be tuned to quasi-quintennial periods are less clear, particularly given the more than century-long anthropogenic impacts. Brazel and Ellis (chapter 7) provide several examples of how the CAP urban-rural ecosystem responds, typically via several complex cascades, to alternating periods of wet and dry conditions. Clearly, the ENSO signal is imprinted on many components of these arid and semiarid ecosystems that often show amplification because of strong nonlinear responses.

In sharp contrast to the ecosystems of the southwestern United States, the tropical rainforest in Puerto Rico (LUQ) has one of the highest annual rates of precipitation and shows only a weak, if any, quasi-quintennial variability with respect to precipitation. (However, it does show a strong response to temperature consistent with table 6.3 and figure S.1 for the LUQ site.) As Schaefer has noted (chapter 8), hurricanes impact Puerto Rico with an average annual interval of 9.5 years. However, most of the extreme rainfall events are not linked to hurricanes, tropical storms, or tropical depressions. Again, for this ecosystem the response to extreme rainfall events is very nonlinear, with 75% of sediment export from watersheds occurring during only 1% of the days with the greatest rainfall. Schaefer notes that surface flow of water is the minimum necessary precondition for sediment mobilization and that this occurs whenever rainfall rates exceed the hydraulic conductivity of the surface soil. Also, soil erosion and sediment deposition do not generally return to a previous state after an extreme event, and the biota may or may not persist in the remaining soil resource. Thus, an important characteristic of these tropical ecosystems is their nonlinear response to rainfall. Consequently, the variability of annual rainfall totals is of less significance than the variability of extreme events.

For the Antarctic sites (MCM, PAL), temperature is a key climatic factor influencing ecosystem structure and function, because it directly influences the phase state of water. In the McMurdo Dry Valleys (MCM), relatively small interannual variations in temperature, cloudiness, and solar radiation determine the number of days above freezing, thus the availability of liquid water. In turn, this availability of liquid water is an important driver for the function and biodiversity of the MCM ecosystem. For the Antarctic marine ecosystem (PAL), relatively small temperature changes give rise to glacier melt, ice shelf collapse, and sea ice reduction, with subsequent impacts at all trophic levels within this sea ice–dominated marine ecosystem.

For both Antarctic ecosystems the ice-to-water phase transition is, therefore, a critical temperature threshold that induces nonlinear ecological response. Consequently, both ecosystems are extremely sensitive to climate variability. The McMurdo Dry Valleys have cooled during the past several decades (Doran et al. 2002). However, the relatively short temperature and pressure records do not exhibit a significant correlation with ENSO (Welch et al. chapter 10). In contrast, temperature trends in the western Antarctic Peninsula region (Smith et al., chapter 9) show a statistically significant warming, and temperature and sea ice extent are strongly correlated with ENSO variability. Thompson and Solomon (2002) have recently interpreted climate change in the Southern Hemisphere (SH) in terms of the SH annular mode (SAM), a large-scale pattern of variability characterized by fluctuations in the strength of the circumpolar vortex. Also, Liu et al. (2002) have discussed mechanisms linking ENSO and southern high latitude climate teleconnections. These authors provide evidence that illuminates the connections between the seemingly disparate trends observed at MCM and PAL.

The western Antarctic Peninsula, the location of the Palmer LTER (PAL), is recognized as a "hot spot" in terms of global warming (IPCC 2001). Smith and colleagues (chapter 9) review and summarize statistically significant climate changes observed in this region of the Antarctic and discuss the response of the marine ecosystem to these changes. This sea ice–dominated marine ecosystem is located between relatively warm and moist maritime conditions to the north and cold and dry continental conditions to the south. Consequently, a small climate shift can be amplified directly by a latitudinal change in climate regimes and by subsequent shifts in the sensitive balance between the solid and liquid phase of water. Thus, climate variability becomes amplified, and this physical forcing appears to influence all trophic levels of the ecosystem. This influence is relatively direct, because physical forcing and ecological response are tightly coupled in marine systems (Steele

1978). Interestingly, the ecological response most clearly seen is in the population size and distribution of upper level predators. The life histories of three sympatric, congeneric penguin species are closely related but have different breeding cycles tied to their preferred habitats: ice-free or ice-covered waters. The abundance and distribution of these species have shifted in response to the timing and magnitude of seasonal sea ice extent. Although the mechanisms that control the ecological response to shifting climate conditions are not fully understood, the paleoecological record also suggests a tight coupling between climate variability and ecological response. As noted by the authors, this implies that climate-induced ecological effects cascade through the system rapidly.

The McMurdo Dry Valleys (MCM) are cold deserts composed of a mosaic of alpine glaciers, exposed bedrock, ephemeral streams, arid soils, and perennially ice-covered lakes. Welch and colleagues (chapter 10) emphasize the nonlinear and amplifying influence of the sensitive balance between solid and liquid water. The key climate parameters that influence this ecosystem are those that affect the conversion of solid to liquid water: temperature, solar radiation, and precipitation. Since liquid water remains the primary limiting condition to life in the MCM, any such climate-related change has a significant impact on the hydrologic budget with subsequent cascades through the system. In spite of this ecosystem's sensitivity to small-scale climate variability (relative to temperate latitudes), Welch and colleagues find that the temperature and pressure records do not exhibit a significant correlation with ENSO. As the authors suggest, this may be because the records are too short to reveal statistically significant trends. It may also be because the ENSO-related temperature influence is relatively less intense in this area, as suggested by figure S.1.

Summary

The global teleconnection patterns (figures S.1–S.3) discussed previously show a very broad spatiotemporal coherency. The analysis shown here is unique because it includes high-latitude areas. Thus, LTER sites from the Arctic to the Antarctic can be placed within these global patterns. Other studies (Allan 2000) and the chapters in part III of this volume present evidence to suggest that the "classical" ENSO-like patterns discussed here must be considered within a lower frequency envelope of concurrent decadal to multidecadal time periods. Also, at longer timescales, there is growing evidence that ENSO may not be spatially or temporally stable, so the patterns shown here are expected to vary in the longer term. This reinforces the idea that the various timescales used for organizing this book cannot be viewed in complete isolation and that climate forcing and ecological response will vary across a wide range of time and space scales.

Several ecosystems discussed in this section (CAP, LUQ, PAL, MCM) were distinguished by having processes whereby nonlinear ecosystem amplification of the ENSO climatic pattern gave rise to observable response. These sites were also distinguished by being on the outside edge of the cluster of sites distributed on a plot of mean annual temperature versus precipitation, as shown in figure 1.2. Ecosystems will vary in response and susceptibility to climate variability. We can speculate that possible ecosystem characteristics that make sites likely to show a more observable response to climate variability at timescales discussed in this section include a location within the ENSO teleconnection footprint of strong variability, a nonlinear ecosystem amplification, and with a climate "on the edge" with respect to mean values of temperature and/or precipitation.

References

Allan, R. J. 2000. ENSO and climatic variability in the past 150 years. Pages 3–55 in H. F. Diaz and V. Markgraf, editors, *El Niño and the Southern Oscillation*. Cambridge University Press, Cambridge.

Bretherton, C. S., C. Smith, and J. M. Wallace. 1992. An intercomparison of methods for finding coupled patterns in climate data. *Journal of Climate* 5:541–560.

Cayan, D. R. 1996. Interannual climate variability and snowpack in the western United States. *Journal of Climate* 9:928–948.

Cayan, D. R., and D. H. Peterson. 1989. The influence of the North Pacific atmospheric circulation and streamflow in the West. In *Aspects of Climate Variability in the Western Americas*, D. H. Peterson (ed.), Geophysical. Monographs. 55, American Geophysical Union, Washington, D.C., 375–397.

Comiso, J. C., D. J. Cavalieri, C. L. Parakinson, and P. Gloersen. 1997. Passive microwave algorithms for sea ice concentration: A comparison of two techniques. *Remote Sensing Environment* 60:357–387.

Diaz, H. F., and V. Markgraf. 2000. *El Niño and the Southern Oscillation*. Cambridge University Press, Cambridge.

Doran, P. T., J. C. Priscu, W. B. Lyons, J. E. Walsh, A. G. Fountain, D. M. McKnight, D. L. Moorhear, R. A. Virginia, D. H. Wall, G. D. Clow, C. H. Fritsen, C. P. McKay, and A. N. Parsons. 2002. Antarctic climate cooling and terrestrial ecosystem response. *Nature* 415:517–520.

Easterling, D. R., and T. C. Peterson. 1995. A new method of detecting undocumented discontinuities in climatological time series. *International Journal of Climatology* 15:369–377.

IPCC. 2001. *Climate Change 2001, Synthesis Report*. A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change [R. T. Watson and the Core Writing Team, editors]. Cambridge University Press, Cambridge.

Kalnay E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Lettma, R. Reynolds, R. Jenne, and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77:437–471.

Karoly, D. J. 1989. Southern hemisphere circulation features associated with El Niño–Southern Oscillation events. *Journal of Climate* 2:1239–1252.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Cheliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne, and M. Fiorino. 2001. The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society* 82:247–267.

Liu, J., X. Yuan, D. Rind, and D. G. Martinson. 2002. Mechanism study of the ENSO and southern high latitude climate teleconnections. *Geophysical Research Letters*, 29(14), 24-1:24-4.

Martinson, D. G. and R. A. Iannuzzi. 2003. Spatial/temporal patterns in Weddell Gyre characteristics and their relationship to global climate. *Journal of Geophysical Research Oceans*, in press.

Mo, K. C., and M. Ghil. 1987. Statistics and dynamics of persistent anomalies. *Journal of Atmospheric Science* 44:877–901.

Mo, K. C., and R. W. Higgins. 1998. The Pacific-South American modes and tropical convection during the Southern Hemisphere winter. *Monthly Weather Review* 126:1581–1596.

Renwick, J. A., and M. J. Revell. 1999. Blocking over the South Pacific and Rossby wave propagation. *Monthly Weather Review* 127:2233–2247.

Reynolds, R. W., and T. M. Smith. 1994. Improved global sea surface temperature analyses using optimum interpolation. *Journal of Climate* 7:929–948.

Stammerjohn, S. E., and R. C. Smith. 1996. Spatial and temporal variability of western Antarctic Peninsula sea ice coverage. Pages 81–104 in R. M. Ross, E. E. Hofmann, and L. B. Quetin, editors, *Foundations for Ecological Research West of the Antarctic Peninsula*. American Geophysical Union, Washington, D.C., Antarctic Research Series 70.

Steele, J. H., ed. 1978. *Spatial pattern in plankton communities*. Plenum, New York.

Trenberth, K. E. 1997. The definition of El Niño. *Bulletin of the American Meteorological Society* 78:2271–2777.

Thompson, D. W. J., and S. Solomon. 2002. Interpretation of recent southern hemisphere climate change. *Science* 296:895–899.

Wallace, J. M., and C. Smith, and C. S. Bretherton. 1992. Singular Value Decomposition of Wintertime Sea Surface Temperature and 500-mb Height Anomalies. *Journal of Climate* 5:561–576.

Yuan, X., and D. G., Martinson. 2000. Antarctic sea ice variability and its global connectivity. *Journal of Climate* 13:1697–1717.

Yuan, X., and D. G. Martinson. 2001. The Antarctic dipole and its predictability. *Geophysical Research Letters* 28:3609–3612.

CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE AT LONG-TERM ECOLOGICAL RESEARCH SITES

Edited by

David Greenland

Douglas G. Goodin

Raymond C. Smith

LTER

OXFORD
UNIVERSITY PRESS
2003