NOTES AND CORRESPONDENCE

Forecasting Annual Discharge of River Murray, Australia, from a Geophysical Model of ENSO*

H. J. SIMPSON, M. A. CANE, S. K. LIN, AND S. E. ZEBIAK

Lamont-Doherty Geological Observatory and Department of Geological Sciences, Columbia University, Palisades, New York

A. L. HERCZEG

Centre for Groundwater Studies and CSIRO Division of Water Resources, Glen Osmond, South Australia

14 October 1991 and 13 May 1992

ABSTRACT

Annual discharge (Q) in the largest river system in Australia, the River Murray (including the extensive tributary network of the Darling River), is often inversely related to sea surface temperature (SST) anomalies in the eastern equatorial Pacific Ocean. Conditional probability tables were constructed, with annual natural Q of the Murray for the period 1891–1985 divided into three amount categories; SST values were also divided into three groups. These tables permit probabilities of Q falling in each of three discharge categories to be estimated from either observed or forecast SST values. Using forecasts from a geophysical model, which indicated higher-than-average SST for most of calendar year 1991, natural Q of the River Murray from June 1991 to May 1992 is forecast to be in the lower half of annual discharges since 1891 (64% probability). Using similar assumptions, the probability of annual natural Q for the year beginning June 1991 falling in the highest one-third discharge category is only 21%.

1. Introduction

River discharge-amount variations in semiarid regions affect many management decisions concerning water allocations and agriculture. Interannual fluctuations in the hydrologic cycle of most of eastern Australia (Allan 1991) often occur in conjunction with a quasi-periodic cycle (2 to 7 years) of environmental parameters elsewhere (e.g., India, Indonesia, Peru, and the equatorial Pacific Ocean). These cyclic variations are components of the large-scale coupled ocean–atmosphere process termed El Niño–Southern Oscillation (ENSO) (Bjerknes 1969; Ropelewski and Halpert 1987). Annual amounts of rainfall and river runoff in eastern Australia frequently are inversely related to departures from mean monthly sea surface temperatures (SST) in the eastern equatorial Pacific (McBride and Nicholls 1983; Whetton and Baxter 1989; Whetton et al. 1990). Geophysical model calculations of the dynamics of this cycle in the central Pacific, using observed wind fields and sea surface temperatures, permit forecasting of ocean temperatures with significant skill up to at least one year (Cane et al. 1986; Cane 1991).

2. Discharge gauging of the River Murray, Australia

Estimates of natural discharge (Q) for the River Murray (Fig. 1), which is Australia's most extensive river system, refer to a location at the junction of the states of New South Wales, Victoria, and South Australia (SA). This site on the River Murray, which is approximately 680 km upstream of the river mouth as measured along the channel, has been the focus of surface water delivery obligations by the upstream states to SA since early in the century. It is downstream of the influx of all significant tributaries, including the Darling River, that drains almost two-thirds of the surface area of the Murray/Darling basin (1.06×10^6 km^2). The gauging site is more than 1800 km downstream of the headwaters of the River Murray in the Australian Alps. Actual Q of the River Murray to SA (Mu-SA) has been extensively modified during the twentieth century by diversions for irrigation and domestic supplies, plus evaporation from storage reservoirs. In addition, large interbasin transfers of surface waters into the Murray system now occur from the Snowy Mountain Scheme in the Great Dividing Range, especially during drought years. River Murray dis-

* Contribution No. 4934 from Lamont-Doherty Geological Observatory of Columbia University.

Corresponding author address: Dr. H. James Simpson, Geochemistry Department, Columbia University, Lamont-Doherty Geological Observatory, Palisades, NY 10964.

charges discussed below have been adjusted from gauged amounts by model calculations at several state agencies and the Murray Darling Basin Commission to remove the cumulative effects of human perturbations (Close 1990); they are thus referred to as "natural." Calculation of natural Q from actual Q data has been done by addition of a sequence of terms that approximate the effects of each contributing process (i.e., evaporation losses in storage reservoirs or diversions for irrigation). Annual natural River Murray Q's have been compiled here from monthly data, beginning in June and ending in May of the following year, and are referred to by the calendar year for which the period begins.

Some indication of the magnitude of differences between annual natural Q and actual Q values is provided by a scatter plot of all the data between 1902 and 1985 (Fig. 2). Dispersion from the general trend in this figure partly results from construction of additional storage reservoirs and more extensive irrigation diversions during the period included and, hence, greater departures from natural Q for later years. During an early part of the record (1902–1926), mean annual actual Q was 11.7 ± 7.1 km^3 yr^{-1}, which is about 90% of natural Q for the same years (13.0 ± 7.4 km^3 yr^{-1}). Mean annual actual Q for the period 1961–1985 was 7.8 ± 6.8 km^3 yr^{-1}, only about 60% of natural Q for the same period (13.1 ± 6.6 km^3 yr^{-1}).

3. River Murray discharge during previous ENSO events

Annual natural Q of Mu-SA (1891–1985) ranged from 2.3 km^3 yr^{-1} (1982) to 45 km^3 yr^{-1} (1956), with a median value of 11.9 km^3 yr^{-1}. Important features of annual variability in natural Q (Fig. 3) are clearly related to occurrences of the El Niño phase (Australian drought) of the ENSO cycle. Choices of El Niño episode years, to illustrate this coherence, were based primarily on indices of eastern equatorial Pacific sea surface temperature anomalies (SST$_w$) (Wright 1989) and to a lesser extent on anomalies in the difference in surface atmospheric pressure between Tahiti and Darwin (SOI) (Ropelewski and Jones 1987). All but two of the years selected here as having widespread El Niño episodes

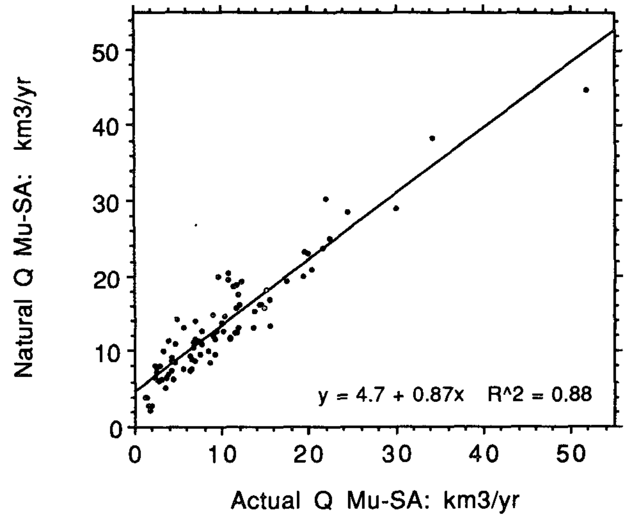

FIG. 2. Annual (June–May) natural Q vs actual Q of River Murray to SA (Mu-SA) for the period 1902–1985.

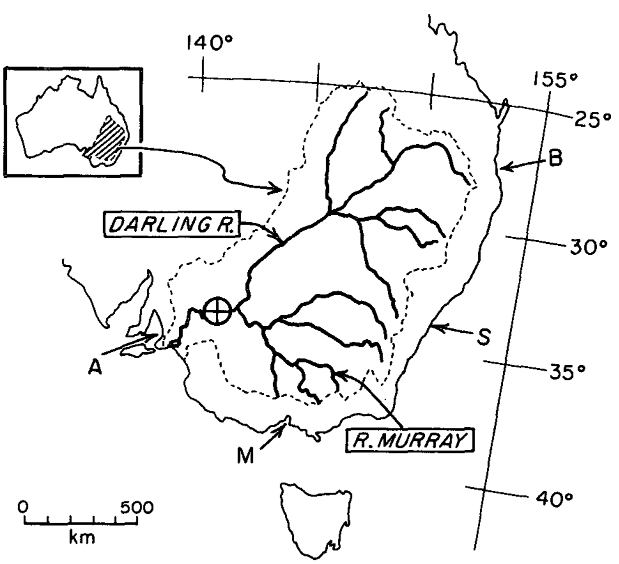

FIG. 1. Location map of Murray/Darling drainage basin in SE Australia. The discharge gauging site for data discussed here is indicated by a circled cross. Locations of capital cities of four states are indicated by single letters: *B*risbane (Queensland), *S*ydney (New South Wales), *M*elbourne (Victoria), and *A*delaide (South Australia).

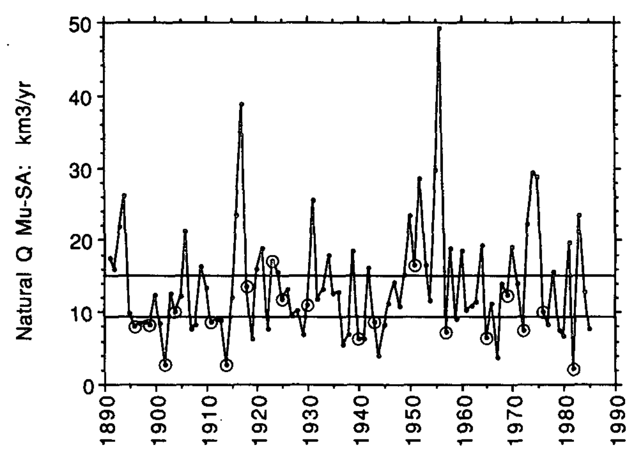

FIG. 3. Annual (June–May) natural Q of Mu-SA (1891–1985): circled values indicate that moderate-to-strong El Niño episodes occurred over much of the low-latitude Pacific region. Two horizontal lines divide the natural Q population into thirds: Low Q = <9.3 km^3 yr^{-1}, medium Q = 9.3 to 15.0 km^3 yr^{-1}, high Q = >15.0 km^3 yr^{-1}. El Niño episode years (June–May) included here (19): 1896, 1899, 1902, 1904, 1911, 1914, 1918, 1923, 1925, 1930, 1940, 1943, 1951, 1957, 1965, 1969, 1972, 1976, 1982.

had mean annual SST_w departures of greater than +0.5°C. One year (1943) judged elsewhere (Quinn and Neal 1987) to have had moderate expression of El Niño characteristics in the coastal region of western South America was included here, although SST and SOI annual anomaly values would not have justified inclusion. The three lowest annual values of natural Q of Mu-SA since 1891 occurred during El Niño years (1982, 1914, 1902). Of the 19 El Niño episodes illustrated (Fig. 3), 11 had River Murray Q in the lowest one-third of the series population and only 2 fell in the highest one-third category.

4. River Murray discharge vs observed SST indices

Two distinct sets of SST indices are discussed below in relation to Q of Mu-SA variations. The first (SST_w), which is expressed in departures from mean temperatures (°C × 100) for a relatively large area of the eastern equatorial Pacific, has been reported (Wright 1989) as monthly values for more than a century (1872–1986). The second (SST_3) also represents departures from mean SST (°C), but for only a portion of the geographical area included in the SST_w index, and is available for a much shorter period of time. However, this latter index provides direct linkage to most of the current SST forecasting efforts.

The general distribution of annual natural Q of Mu-SA versus SST_w for the period 1891–1985 (Fig. 4) indicates that the inverse relationship is somewhat stronger during the El Niño phase (warmer SST) of the ENSO cycle. During the opposite cool phase (La Niña), the total range of Q was much greater, and included years of quite low Q, as well as more than half of the years in the highest one-third Q category.

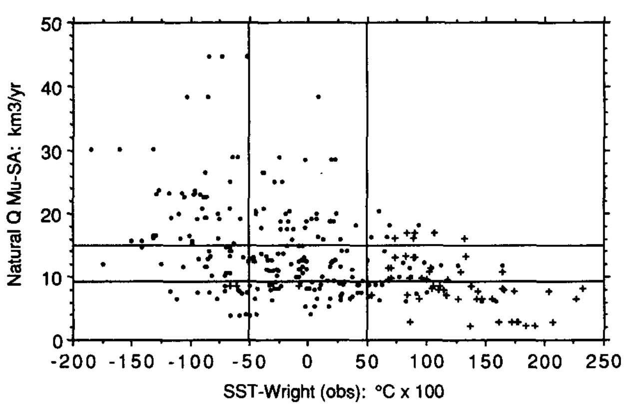

FIG. 4. Annual (June–May) natural Q of Mu-SA (1891–1985) vs SST_w during September, October, and November (S, O, N). Three SST_w values (S, O, N) are plotted for each year. El Niño episode years (see Fig. 3 caption) are indicated by +. Two horizontal lines divide annual, natural Q into thirds, as in Fig. 3. Correlation coefficients for linear and exponential regression relationships between Q and SST_w were $r = -0.40$, $r = -0.44$, respectively.

5. River Murray discharge vs forecast SST indices

Retrospective forecasts of mean monthly eastern equatorial Pacific SST anomalies (SST_3) in the NINO3 region (5°N–5°S, 90°W–150°W) have been made with a geophysical model (Zebiak and Cane 1987) for the period beginning in 1971. (We use the term "retrospective" forecast, rather than "hindcast" since no information subsequent to the initiation of each forecast influences the forecast procedure.) The model forecasts of SST_3 have been transformed here to a new set of forecast SST_w values using a linear regression ($r = +0.97$) between mean monthly observed SST_3 and observed SST_w (including all months from 1971–1985). The relationship used was SST_w (°C × 100) = 86.8 × SST_3 (°C) − 16.5. Forecast SST_w for each of three months—September, October, and November (S, O, N)—made nine months previously, can be compared to annual natural Q of MU-SA (Fig. 5). All but one of the years with River Murray Q in the highest one-third category (1973, '74, '75, '81) had forecast SST_w values cooler than the mean. Forecast SST for 1983 were much warmer than observed SST due to the failure of geophysical model forecasts of SST_3 to eliminate the outsized 1982 warming on schedule, a common error encountered in forecasts initialized from mature El Niño conditions (Cane 1991). The average of monthly forecasts (9 months) of SST_3 differed from observed SST_3 for S, O, N (1971–1985) by only +0.04° ± 0.89°C, indicating no systematic positive or negative bias in forecast SST_3 for this 15-year period.

Occurrence frequency tables of natural Q of Mu-SA (1971–1985) for observed SST_w (Table 1b) indicate that this recent period was underrepresented in intermediate Q years and included only three (out of a total of 15) years in the Medium Q category for the longer time series (1891–1985). Another difference in observed SST_w for the shorter time series (1971–1985) was a stronger inverse relationship between Q and SST_w than for the longer time series (compare Table 1a to 1b).

The years 1971–1985 were used to define relationships between forecast SST and natural Q because this was the entire period of overlap of the two series available to us. Calculations of natural Q by the Murray Darling Basin Commission for Mu-SA have not been completed for years subsequent to 1985.

6. Probability forecasts of River Murray Q for 1991

Forecast (nine-month) SST_3 anomalies for 1991 (S, O, N) were +0.8°, +1.0°, and 1.1°C, respectively, consistent with development of a weak-to-moderate El Niño episode in 1991 (Zebiak and Cane 1991). Transforming these forecast SST_3 to SST_w using the regression relationship discussed above, forecast SST_w indices for S, O, and N are +53, +70, and +79, respectively. These forecast SST_w can be compared with frequencies

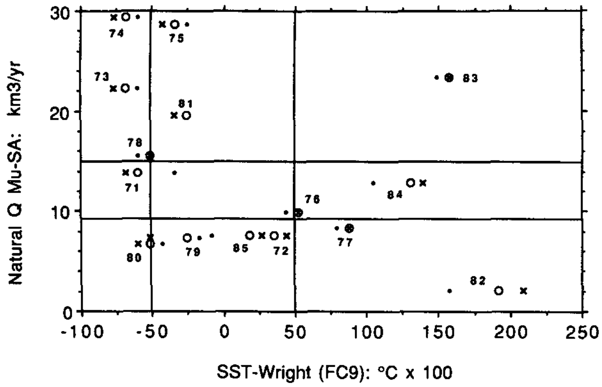

FIG. 5. Annual (June–May) natural Q of Mu-SA (1971–1985) vs SST_w forecast nine months prior to September (small, filled circles), October (open circles), and November (X's) of each year, using geophysical model calculations. Two horizontal lines divide annual natural Q at the same numerical values as in Figs. 3 and 4.

of occurrence for River Murray natural Q and observed monthly (S, O, N) SST_w from 1891 to 1985 (Table 1a). For *observed* SST_w with the above values, the probabilities of annual natural River Murray Q falling in the lowest and highest one-third of the series population for 1991 would be 50% and 14%, respectively. However, these probabilities must be adjusted to incorporate uncertainties associated with *forecast* SST_w versus observed SST_w.

Occurrence frequency tables for forecast SST_w versus Q (Table 2c) and forecast SST_w versus observed SST_w (Table 2d, $r = +0.51$) provide some indication of the

TABLE 1. Occurrence percentages of annual natural Q (Mu-SA) vs observed (obs) SST_w for September, October, November (S, O, N): Each monthly (S, O, N) SST_w observation was included as a separate event. All values are percentages calculated for each column, except for the total number of events given in brackets at the bottom of each column. Discharge categories ($km^3\ yr^{-1}$) were high Q (>15), medium Q (9.3 to 15), low Q (<9.3). SST_w categories in anomaly units of °C × 100 were cool (< −50°), moderate (−50° to +50°), warm (> +50°).

a. Q vs SST_w (obs) {1891–1985}

	Cool SST	Mod SST	Warm SST
High Q	54%	30	14
Medium Q	25	38	36
Low Q	21	32	50
Total number	[87]	[118]	[80]

b. Q vs SST_w (obs) {1971–1985}

	Cool SST	Mod SST	Warm SST
High Q	73%	43	8
Medium Q	27	14	23
Low Q	0	43	69
Total number	[11]	[21]	[13]

TABLE 2. (c) Occurrence percentages of annual natural Q (Mu-SA) vs forecast (FC9) SST_w made nine months in advance for September, October, and November (S, O, N), and (d) occurrence percentages of observed SST_w vs forecast SST_w. Each monthly (S, O, N) SST_w observation and forecast in (c) and (d) was included as a separate event. See Table 1 for Q and SST_w category definitions and unit conventions.

c. Q vs SST_w (FC9) {1971–1985}

	Cool SST	Mod SST	Warm SST
High Q	64%	35	21
Medium Q	14	12	36
Low Q	21	53	43
Total number	[14]	[17]	[14]

d. SST_w (obs) vs SST_w (FC9) {1971–1985}

	Forecast		
	Cool SST	Mod SST	Warm SST
Observed Warm SST	0%	29	57
Mod SST	50	47	43
Cool SST	50	24	0
Total number	[14]	[17]	[14]

distributions of these parameters for the period 1971–1985. Combining the occurrence frequencies from Tables 1a and 2d, conditional probability relationships between forecast SST_w and annual natural Q of the River Murray can be derived (Table 3e). This permits incorporation of the range of differences encountered between forecast SST_w and observed SST_w for 15 years to be explicitly included along with the Q record relative to observed SST_w, over a period of 95 years (Simpson et al. 1991). Thus, the probabilities of low, medium, and high Q from forecast $SST_w > +50$ are 42%, 37%, and 21%, respectively (Table 3e). Using the same approach for $SST_w > +50$ with the population of Q divided into two pools (greater than and less than median Q), rather than three pools, the probability of natural Q of Mu-SA being less than the median (1891–1985) of 11.9 $km^3\ yr^{-1}$ is 64% (Table 3f).

7. Final comments

Forecasts of annual natural Q of Mu-SA sketched here, based on conditional probability tables, rely on combining a relatively short period (15 years) of SST_3-forecasting experience with a much longer time series (95 years) of observed SST_w and natural Q. They do not include any explicit treatment of effects of conversion of forecast SST_3 to SST_w. Although this conversion is unlikely to introduce significant additional uncertainty, it would have been preferable to use occurrence frequencies for Q versus observed SST_3, combined with relationships between observed SST_3 and forecast SST_3. Unfortunately, we are not aware of

TABLE 3. Conditional probabilities of annual natural Q (Mu-SA) vs forecast (FC9) SST_w made nine months in advance for September, October, and November (S, O, N): each monthly (S, O, N) SST_w forecast was included as a separate event. Discharge categories for Table 3e were the same as in Table 1. Discharge categories ($km^3\ yr^{-1}$) for Table 3f were upper Q (>11.9), lower Q (<11.9). SST_w categories for both 3e and 3f were the same as in Table 1. All values are percentages calculated for each column.

e. Q vs SST_w (FC9) $\{A \times D\}$

	Cool SST	Mod SST	Warm SST
High Q	42%	31	21
Medium Q	32	34	37
Low Q	27	35	42

f. Q vs SST_w (FC9) $\{A' \times D\}$

	Cool SST	Mod SST	Warm SST
Upper Q	60%	48	36
Lower Q	40	52	64

a long time series of SST_3 (about 100 years) having been developed. Second, to preserve a relatively simple approach for construction of conditional probability relationships for Q versus SST, we have combined all data for the entire period of 95 years into a single set, despite indications that there have been significant changes in the power spectrum of SOI variations over the period 1935–1985 (Kuhnel et al. 1990).

The procedures discussed above represent only an initial outline of potential approaches to aid river-discharge forecasting for eastern Australia. Incorporation of SST_3 forecasts for the eastern equatorial Pacific from geophysical model calculations could become an important element in more mature hydrologic system-management schemes for Australia (Nicholls and Katz 1991), permitting explicit consideration of forecast probabilities of natural river-runoff amounts—available for the summer irrigation season (December–February)—to be estimated approximately one year ahead.

Acknowledgments. We thank Andrew Close and others at the Murray Darling Basin Commission for providing unpublished computer-file data of monthly natural River Murray discharges. Financial support was provided by the U.S. National Oceanic and Atmospheric Administration TOGA Project Office Grant NA87AA-D-AC081 and the Division of Water Resources of CSIRO, Australia.

REFERENCES

Allan, R. J., 1991: Australasia. *Teleconnections Linking Worldwide Climate Anomalies,* H. Glantz, R. W. Katz, and N. Nicholls, Eds., Cambridge University Press, 73–120.

Bjerknes, J. H., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.,* **97,** 163–172.

Cane, M. A., 1991: Forecasting El Niño with geophysical models. *Teleconnections Linking Worldwide Climate Anomalies,* H. Glantz, R. W. Katz, and N. Nicholls, Eds., Cambridge University Press, 345–369.

——, S. E. Zebiak, and S. C. Dolan, 1986: Experimental forecasts of El Niño. *Nature,* **321,** 827–832.

Close, A., 1990: The impact of man on the natural flow regime. *The Murray,* N. Mackay, and D. Eastburn, Eds., Murray Darling Basin Commission, Canberra, 61–74.

Kuhnel, I., T. A. McMahon, B. L. Finlayson, A. Haines, P. H. Whetton, and T. T. Gibson, 1990: Climatic influences on streamflow variability: A comparison between southeastern Australia and southeastern United States of America. *Water Resour. Res.,* **26,** 2483–2496.

McBride, J. L., and N. Nicholls, 1983: Seasonal relationships between Australian rainfall and the Southern Oscillation. *Mon. Wea. Rev.,* **111,** 1998–2004.

Nicholls, N., and R. W. Katz, 1991: Teleconnections and their implications for long-range forecasts. *Teleconnections Linking Worldwide Climate Anomalies,* H. Glantz, R. W. Katz, and N. Nicholls, Eds., Cambridge University Press, 511–525.

Quinn, W. H., and V. T. Neal, 1987: El Niño occurrences over the past four and a half centuries. *J. Geophys. Res.,* **92,** 14 449–14 461.

Ropelewski, C. F., and M. S. Halpert, 1987: Global and regional-scale precipitation patterns associated with the El Niño–Southern Oscillation. *Mon. Wea. Rev.,* **115,** 1606–1626.

——, and P. D. Jones, 1987: An extension of the Tahiti-Darwin Southern Oscillation index. *Mon. Wea. Rev.,* **115,** 2161–2165.

Simpson, H. J., M. A. Cane, S. E. Zebiak, S. K. Lin, and A. L. Herczeg, 1991: Forecast SST in the NINO3 region as an indicator of probabilities of Australian river annual discharge amounts. EOS, *Trans. Am. Geophys. Union,* **72,** 76.

Whetton, P. H., and J. T. Baxter, 1989: The Southern Oscillation and river behaviour in south-eastern Australia. *Climanz III* T. H. Donnelly and R. J. Wasson, Eds., CSIRO, Inst. Nat. Res. and Env., Div. Water Res., Melbourne, 62–69.

——, D. A. Adamson, and M. A. J. Williams, 1990: Rainfall and river flow variability in Africa, Australia, and East Asia linked to El Niño Southern Oscillation events. *Geol. Soc. Australia Sym. Proc.,* **1,** 71–82.

Wright, P. B., 1989: Homogenized long-period Southern Oscillation indices. *Int. J. Climatol.,* **9,** 33–54.

Zebiak, S. E., and M. A. Cane, 1987: A model El Niño-Southern Oscillation. *Mon. Wea. Rev.,* **115,** 2262–2278.

——, and M. A. Cane, 1991: Forecasts of NINO3 anomalies. *Climate Diagnostics Bulletin (NOAA),* **91/2,** 33.