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Annual River Discharge in Southeastern Australia Related to El Nino–Southern Oscillation Forecasts of Sea Surface Temperatures

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Annual natural discharge (Q) of the River Murray and its most extensive tributary, the Darling River system, is often inversely related to sea surface temperature (SST) anomalies in the eastern tropical Pacific Ocean. These SST variations are components of a planetary-scale phenomenon referred to as El Nino–Southern Oscillation (ENSO). Darling and Murray river historical values of Q indicate that annual surface runoff from regions dominated by subtropical summer monsoon precipitation and annual surface runoff primarily responding to temperate winter storms are both strongly influenced by ENSO cycles. Forecasting, approximately 1 year in advance, of ENSO-related SST from geophysical model calculations thus provides a mechanism for estimating probabilities of annual river discharge amount. Contingency tables relating annual Q to SST, based on combining observed data for 95 years and forecast SST over a period of 15 years, provide probabilities of expected annual Q as a function of forecast SST. The SST of the eastern tropical Pacific was successfully forecast to be appreciably warmer than long-term mean conditions for much of the year beginning in mid 1991. Precipitation data through 1991 indicated that annual natural Q for the Darling River was probably substantially below the mean. However, winter precipitation in higher-runoff portions of the Murray Basin was above average during this El Nino episode, contrary to the trend for most such events over the past century.

1. Introduction

1.1. *Major Issues in SE Australia Relevant to Management of Surface Waters*

Interannual river runoff in southeastern (SE) Australia is extremely variable, imposing appreciable difficulties on agricultural planning and other water management objectives in the region. Over the past century, large investments have been made to build physical infrastructure including storage reservoirs, river stage control weirs, diversion canals for irrigation, interbasin transfer tunnels, and domestic/industrial aqueduct networks. However, natural variability in runoff results in interannual differences in available surface water that are frequently either much less or much greater than desirable.

Water management in the region is further complicated by rising total dissolved solids concentrations in many rivers [*Cunningham and Morton*, 1983], caused primarily by enhanced discharge of saline groundwaters to streams. This trend has resulted partly from perturbation of basin-scale hydrologic balances by removal of native deep-rooted eucalyptus trees, which previously kept groundwater recharge at extremely low levels (<1 mm yr^{-1}) over large regions [*Allison et al.*, 1984]. Diversion of surface waters for irrigation has further raised groundwater recharge/discharge rates in some regions by orders of magnitude above natural conditions. Nuisance blooms of algae in main stem rivers during low-discharge years may also have become more frequent and extensive. If improved forecasting of natural river discharges were available of the order of 1 year in advance, decisions concerning irrigation supply allocations, river salinity management [*Simpson and Herczeg*, 1991*a*, *b*], dilution flow controls of algal blooms, and hydroelectric generation schedules could all potentially be influenced.

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1.2. *Influence of El Nino–Southern Oscillation on Variability in the Hydrologic Cycle in Eastern Australia*

Rainfall and river runoff in eastern Australia are clearly influenced by large-scale coupled ocean-atmosphere quasi-periodic variations centered in low latitudes of the Pacific Ocean [*Allan*, 1991], which have been termed El Nino–Southern Oscillation (ENSO). Years with higher than mean sea surface temperature (SST) in the eastern equatorial Pacific often have lower than average rainfall and river runoff in SE Australia (El Nino episodes). Conversely, wet years in the same area of Australia are usually associated with cooler ocean temperatures in the eastern equatorial Pacific.

Comparison of seasonal precipitation (P) variations

(1932–1974) with a Southern Oscillation Index (SOI, normalized monthly surface atmospheric pressure for Tahiti minus the same parameter for Darwin, Australia) indicated relatively strong correlation ($r^2 = 0.2$ to 0.4) with winter P in eastern Australia [*McBride and Nicholls*, 1983]. There was evidence of an appreciable shift in the geographical pattern of correlation between meteorological district average P and SOI from the first half of the series (1932–1953) to the second (1954–1974). Subsequent work indicated that more than 50% of the variance in correlation of winter P with SOI in the same region could be attributed to patterns of variation in SST in two distinct regions: (1) Indonesia and the central Indian Ocean and (2) eastern equatorial Pacific [*Nicholls*, 1989]. The second of these principal components was judged to be a response to the Southern Oscillation, but the first appeared to be influenced much less directly by ENSO.

Patterns of P variability in Australia have also been shown to be correlated with SST in several areas of the ocean immediately adjacent to Australia [*Streten*, 1981], in general agreement with trends expected from hemispheric-scale cycles associated with ENSO. However, forecasting potential for P based on these local variations in SST has been judged to be relatively weak [*Streten*, 1983]. Correlation of summer (December–February) P in eastern Australia with SOI has also been established to be relatively strong, although slightly less so than for winter P [*Drosdowsky and Williams*, 1991].

1.3. *Influence of Low-Latitude Indian Ocean Processes on Precipitation in Australia*

One of the most consistent features of large-scale meteorological coupling in the region of interest here involves formation of continuous cloud bands originating between 0° and 20°S latitude in the central Indian Ocean and extending southeastward across more than 25° in longitude. These features often extend across much or all of continental Australia and are sometimes referred to as tropical-extratropical cloud bands (TECB) [*Kuhnel*, 1990]. Episodes of formation of TECB appear to have appreciable influence on winter P in central and SE Australia [*Wright*, 1988]. The frequency of these poleward transports of low latitude moisture has some correlation with SOI, but the degree of coherence with SST variations in the eastern tropical Pacific and effect on precipitation amounts by region have not been well defined [*Kuhnel*, 1990].

1.4. *Representative Studies of River Discharge and ENSO*

River discharge in SE Australia has previously been shown to be strongly influenced by ENSO cycles. Annual discharge-gauging records covering about a century for each of five rivers in this region (Darling (log Q), Lachlan, Loddon, Upper Murray, and Murrumbidgee) have significant correlation ($r^2 = 0.14$ to 0.24) with SOI [*Whetton and Baxter*, 1989]. Correlation of river discharge variations in SE Australia with ENSO is considerably stronger than for the SE United States [*Kuhnel et al.*, 1990]. River discharge in other regions also correlates with SOI: $r^2 = 0.22$ (Krishna River, India); $r^2 = 0.12$ (Nile River, Egypt); $r^2 = 0.06$ (Senegal River, Senegal) [*Whetton et al.*, 1990].

River stage level anomalies of the Parana River in Argentina (1884–1916) correlate appreciably ($r^2 = 0.31$) with another surface atmospheric pressure index of the Southern Oscillation [*Berlage*, 1966], opposite in ENSO phase to the pattern of river discharge in SE Australia [*Kousky et al.*, 1984]. The maximum amplitude of daily flood discharge for a number of rivers in Peru has been found to be high during El Nino episodes and low during La Nina years [*Waylen and Caviedes*, 1986], also opposite in sign with respect to ENSO phases of river discharge in SE Australia. Annual discharge of the Amazon experiences a much smaller proportional variation than Australian rivers, but also appears to be approximately in phase with interannual variations in SE Australia [*Richey et al.*, 1989].

1.5. *Outline of Strategy to Link Probabilities of Annual River Discharge to ENSO Forecasts of SST*

As understanding of the dynamics of ENSO has improved [*Bjerknes*, 1969; *Ropelewski and Halpert*, 1987; *Nicholls and Katz*, 1991], it has become possible to use geophysical model calculations to forecast eastern equatorial SST at least 1 year in advance [*Cane et al.*, 1986; *Zebiak and Cane*, 1987; *Cane*, 1991]. It appears feasible to use such forecasts of SST to estimate probabilities for hydrologic cycle parameters influenced by ENSO in Australia [*Simpson et al.*, 1991]. Total annual natural river discharge data for the combined Murray/Darling Drainage Basin have been previously compiled as a function of observed and forecast SST from the eastern equatorial Pacific [*Simpson et al.*, 1993]. Here variability in surface runoff is examined for each of the two major geographical regions of the Murray/Darling Drainage Basin in response to changes in ENSO-dominated SST variability.

The approach taken is based on two basic concepts: (1) An appreciable component of interannual variability of river discharge in SE Australia is statistically correlated with ENSO processes that result in interannual variability in SST in the eastern tropical Pacific; and (2) geophysical models of ENSO have been developed which permit forecasting of SST with significant skill in the eastern tropical Pacific. Together they provide a new tool for assessing probabilities for river discharge in SE Australia approximately 1 year in advance. The primary goal of the research outlined here is to link these two simple concepts. The resultant framework should be considered only as a beginning stage to estimate annual river discharge probabilities. No attempt has been made here to incorporate information about the following, any or all of which potentially could improve river discharge forecasting ability: (1) temporal variability of ENSO dynamics over the century of river discharge record; (2) explicit environmental parameters, other than SST in the eastern tropical Pacific, such as SST for the Indian Ocean which might modulate timing and intensity of TECB precipitation in SE Australia; or (3) potential influence of other periodic phenomena such as solar cycles or quasi-biennial oscillation in properties of the stratosphere and troposphere.

2. RIVER DISCHARGE IN THE MURRAY/DARLING BASIN

2.1. *Locations and General Characteristics of Discharge Records*

The River Murray, including the extensive tributary network of the Darling River, drains about 14% of Australia's

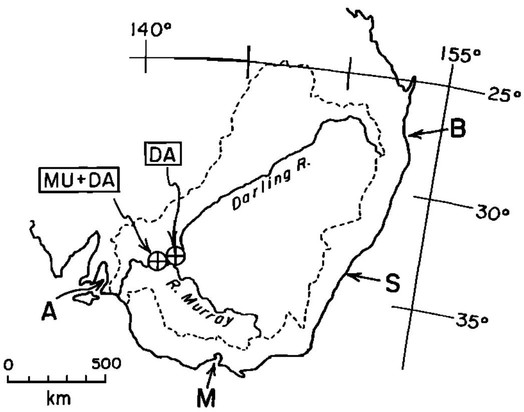

Fig. 1. Outline of combined Murray/Darling (M/D) Basin; state capital cities indicated by single letters: Brisbane (Queensland), Sydney (New South Wales), Melbourne (Victoria), and Adelaide (South Australia). Discharge gauging locations discussed are (1) Darling (DA) just upstream of confluence with the River Murray and (2) Murray to South Australia (MU+DA), which includes all significant tributaries from the entire M/D Basin.

land surface (Figure 1) and includes a major fraction of the largest and most economically important agricultural region in the country. Mean annual natural discharge of the Murray/Darling catchment is also one of the highest for any river system on the continent. The records for two gauging locations are discussed here: (1) the main stem of the Darling River plus a secondary channel (anabranch) with intermittent discharge, near its confluence with the River Murray and referred to as "DA" and (2) the main stem of the River Murray just upstream of the eastern border of the state of South Australia (SA). This latter gauge is located downstream of all significant tributaries including the Darling River and is referred to here as "MU+DA." Runoff characteristics of the Murray Basin, exclusive of the Darling, were assessed by subtracting DA from MU+DA. It is assumed that no significant natural gains or losses of water occur between influx of the Darling at kilometer point (KP) 825 and the gauging location on the main stem of the Murray at KP 696. This "synthetic" series, referred to as "MU," represents discharge by the main stem of the River Murray and all of its tributaries, except for the Darling River and its tributaries. Thus the two discharge series to be examined (DA and MU) represent integrated runoff from relatively distinct geographical regions and include essentially all surface runoff in the entire basin, which has been extensively modified by evapotranspiration upstream of the gauging points.

Precipitation in the higher runoff tributaries in the southeast of the MU catchment occurs predominantly in the 6-month period between late autumn and spring (May–October) as storm systems move inland from the southern ocean. In contrast, maximum seasonal precipitation in the DA catchment is associated with summer monsoons (November–March), deriving moisture largely from low-latitude marine sources. The decoupling of atmospheric moisture sources and seasonality of input for these two subbasins has significant implications for runoff processes and correlation of river discharge with ENSO parameters.

2.2. *Natural Discharge Versus Actual Discharge*

The current mean seasonal pattern of discharge at the downstream end of both river systems has been extensively

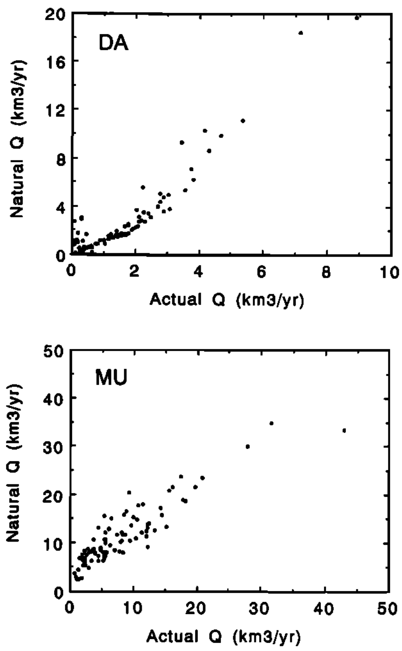

Fig. 2. Annual (June through May) natural discharge versus actual river discharge (1902–1985): (top) Darling (DA) and (bottom) Murray (MU).

modified by water storage and release practices to maximize supplies for delivery during the period of highest irrigation demand (late spring–early autumn). In addition there is considerable transfer of water into the MU portion of the basin during drought years, from the Snowy Mountain scheme located outside the southeastern margin of the Murray/Darling (M/D) Basin in the Australian Alps. Finally, storage reservoirs experience considerable evaporation losses and are managed to supplement low runoff during drought years. Attempts have been made by several state agencies and the Murray/Darling Basin Commission (MDBC) to estimate monthly discharge in the absence of human influence by scaling discharges from smaller tributaries that have not been subject to significant storage or diversion modifications. These synthetic (rather than directly gauged) values are usually referred to as "natural" discharges [*Close*, 1990] and are currently approximately double actual discharges. Since the primary interest here is to describe runoff characteristics in response to large-scale climate variations, nearly all of the following discussion will refer to natural discharges, rather than to the "actual" discharge series derived directly from the river stage gauging records. The most recent series (July 1992) of natural runoff estimates available from the MDBC for monthly DA and MU+DA were used.

Some indications of relationships between annual natural and actual Q for the Darling and Murray are provided by scatterplots of the data for the period 1902–1985 (Figure 2). Dispersion from general trends results partly from introduction of additional physical infrastructure and greater average annual irrigation diversions in recent decades. During the first 25 years of the series, mean annual actual Q for DA was 1.51 ± 1.21 km^3 yr^{-1}, about 70% of natural Q (2.20 ± 2.43 km^3 yr^{-1}). For MU, mean annual actual Q was 10.2 ± 6.4 km^3 yr^{-1}, about 90% of natural Q (11.2 ± 6.5 km^3 yr^{-1}). For the last 25 years of the series (1961–1985) actual Q

TABLE 1. Annual (June Through May) Natural Discharge Series Statistical Properties in the Murray/Darling Basin (1891–1985)

Parameter	MU + DA	DA	MU
Minimum Q	2.53	0.05[a]	2.37
10% Q	6.73	0.31	6.06
25% Q	8.54	0.85	7.50
50% Q (median)	12.0	1.67	10.3
75% Q	17.6	3.50	13.8
90% Q	27.7	8.61	20.3
Maximum Q	53.1	19.7	35.0
Mean Q	14.5	3.06	11.4
Standard deviation	8.6	3.73	6.2
Statistical Analysis			
Coefficient of variation, %	60	122	54
Skewness	1.60	2.41	1.52

Q values are in cubic kilometers per year.
[a]Natural annual Q of the Darling for the minimum year (June 1919 to May 1920) has been reported to be 0.00, but was included here with an arbitrary value of 0.05, approximately one half of the next lowest annual value (1918) of 0.09.

compared to natural Q amounted to 49% for DA (actual $Q = 1.53 \pm 1.47$ km^3 yr^{-1}, natural $Q = 3.14 \pm 2.87$ km^3 yr^{-1}) and 53% for MU (actual $Q = 6.2 \pm 6.0$ km^3 yr^{-1}, natural $Q = 11.7 \pm 6.5$ km^3 yr^{-1}). Thus during the last three decades about half of natural runoff from both subbasins was diverted to additional evapotranspiration, primarily due to irrigation diversions prior to reaching these downstream gauging sites.

2.3. *Monthly Discharge Aggregation and Series Statistical Properties*

The natural discharge series developed for DA and MU+DA by others (MDBC) have been compiled as monthly values. Those monthly data have been aggregated here into annual (beginning on June 1) amounts, referred to by the calendar year for which the discharge sum begins. This choice for compiling annual Q values was a compromise between the minimum in mean monthly discharge for MU (March–April) and one of two distinct minima in mean monthly discharge for DA (January, July). Thus it divides annual discharge amounts near minimum seasonal discharge in both geographical regions of the M/D Basin.

Median natural Q (1891–1985) for DA was only 16% of median natural Q for MU (Table 1), although the Darling River drains almost two thirds of the total catchment area. Annual natural Q of DA has a much higher coefficient of variation (122%) than MU (54%), as well as a more highly skewed distribution (Table 1). Mean annual natural Q of the entire M/D Drainage Basin (MU+DA, 1.06×10^6 km^2) of approximately 15 km^3 is about 70% of that for the Colorado River (United States, basin area of 0.64×10^6 km^2), and only 2 to 3% of the Mississippi River (basin area of 3.3×10^6 km^2), the highest discharge river in North America.

2.4. *Interannual Variations of Natural Q in the M/D Basin*

Annual natural Q values for the DA and MU series since 1896 are illustrated in Figure 3. The years indicated as moderate to strong El Nino episodes [*Quinn and Neal*, 1987], based on eastern equatorial Pacific SST anomalies, clearly tend to have lower than average river discharge, with only a few such episodes having Q values that fall in the highest third discharge category for either river system. From a total of 19 El Nino episodes illustrated, natural annual Q of either DA, MU or both of these series fell in the lowest third Q category in 14 of those years (Table 2). The statistical significance of association of low-Q years with El Nino episodes can be evaluated with the chi-square test [*Hoel*, 1971], comparing observed distributions of Q category with expected distributions for random occurrence. The probability that the observed frequency of low-Q years is due to chance is less than 1% (Table 2). Note that there were a number of low-discharge years in both basins in addition to those associated with El Nino episodes. Thus occurrence of moderate to strong El Nino episodes is an important, but not the only, environmental factor associated with low river flows in eastern Australia.

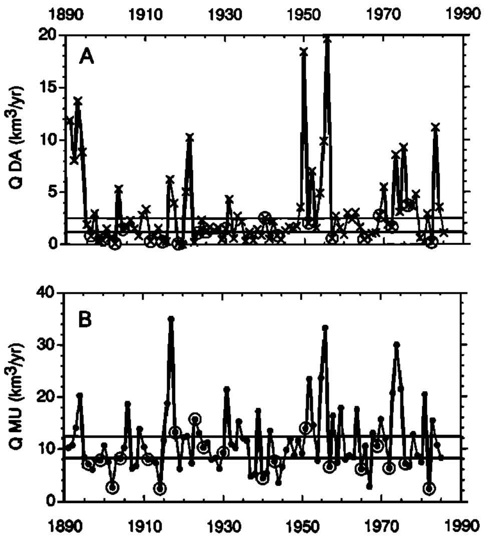

Fig. 3. Annual (June through May) natural Q (1891–1985) of (*a*) DA, where the two horizontal lines indicate 33.3 and 66.7 percentile Q (1.2 and 2.8 km^3 yr^{-1}, respectively); and (*b*) MU, where the two horizontal lines indicate 33.3 and 66.7 percentile discharges (8.12 and 12.2 km^3 yr^{-1}, respectively). El Nino episode years classified as "moderate to strong" [*Quinn and Neal*, 1987] are indicated by circles: 1896, 1899, 1902, 1904, 1911, 1914, 1918, 1923, 1925, 1930, 1940, 1943, 1951, 1957, 1965, 1969, 1972, 1976, and 1982.

TABLE 2. Distribution of Annual Natural Discharge (1891–1985) for the M/D Basin During 19 El Nino Episodes [*Quinn and Neal*, 1987], Grouped by Q Percentile Categories of Low, Medium, and High: < 1/3, 1/3 to 2/3, > 2/3

River Q Series	Low Q[a]	Medium Q	High Q[b]
MU + DA	11	6	2
DA	11	7	1
MU	12	4	3
MU or DA	14		
Statistical Analysis			
Chi-square	12.0	0.9	9.2
Probability of random occurrence	0.003	0.62	0.01

[a]$Q < 1.2$ (DA), 8.12 (MU), 9.7 (MU + DA) km^3 yr^{-1}.
[b]$Q > 2.8$ (DA), 12.2 (MU), 15.8 (MU + DA) km^3 yr^{-1}.

TABLE 3. Annual (June Through May) Natural River Discharge Categories for Two Series DA and MU, as Percentages of Occurrence (1891–1985)

	MU Low Q	MU Medium Q	MU High Q
DA high Q	16%	25%	58%
DA medium Q	22%	53%	26%
DA low Q	63%	22%	16%
	Statistical Analysis		
Chi-square	12.0	5.5	9.5
Probability of random occurrence	0.002	0.06	0.01

The number of events assigned to low, medium, and high Q categories for each river series were 32, 32, and 31, respectively.

Occurrence frequencies (1891–1985) for Q, grouped in thirds, are similar for the two geographical regions (Table 3). Coherence between the two subbasins appears to be strongest for the lowest one-third Q category, where 63% of low-Q years for DA were also in the same category for MU. Based on the chi-square test, the probability that this proportion of low Q values would occur by chance in both drainage basins during the same years is less than 1% (Table 3).

3. INDICES OF ENSO CYCLES

3.1. *General Considerations of ENSO–Surface Runoff Relationships*

The relationship between annual natural Q in SE Australia and SST variability in the eastern tropical Pacific was chosen as a focus for several reasons. First, this region of the low-latitude Pacific Ocean plays a central role in the large-scale dynamics of ENSO and thus contains a major component of the primary "memory" of environmental conditions which would be likely to permit successful interannual forecasting based on model calculations of geophysical processes. Second, annual natural Q experiences a much larger range of variability than does annual P in SE Australia and hence could be considered as an "amplified" signal of variability in P and other critical hydrological cycle parameters. For example, annual P in higher-runoff watershed areas between 1913 and 1985 for both DA and MU varied by a factor of about 3. In contrast, annual natural Q over the period 1891–1985 of the River Murray (exclusive of the Darling) and for the Darling River varied by fifteenfold and >200-fold, respectively. Clearly, there are many other factors besides variations in annual P that contribute to the large range of annual Q, such as interannual variations in effective evapotranspiration rates, intensity and frequency of P events, and seasonal distribution of P. The approach taken here ignores all processes which transform P to Q within the drainage basin and depends upon annual runoff amount as an integrator of variations of P and Q in time and space. The percentage of mean annual precipitation volume delivered to each of these two catchments [*Simpson and Herczeg*, 1991*a*] represented by mean annual natural river Q (Table 1) is very low: DA, 1%; MU, 6%.

3.2. *Sea Surface Temperature Indices*

The longest available time series of SST anomaly indices for the eastern tropical Pacific is for the period 1872–1986

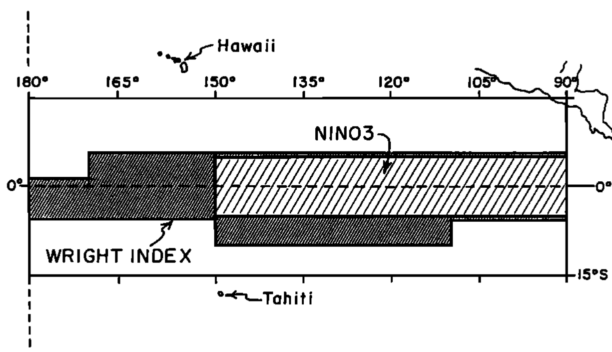

Fig. 4. Boundaries of eastern equatorial Pacific Ocean zones for which SST anomaly index time series are available: area of Wright index (1872–1986) includes entire area incorporated in the NINO-3 index (1970 to present).

[*Wright*, 1989]. The geographical area used for this compilation (designated here as SST_w) is substantially larger than the reference area (NINO-3, designated here as SST_3) for which ENSO forecasting has become most frequent (Figure 4). The time series of SST_3 anomaly observations (1970 to present) is much shorter than for SST_w. Forecast and observed SST_3 values have been converted here to equivalent SST_w, using a regression expression between the two series for all months during the period of February 1970 through December 1986 (total of 203 individual monthly values for each index). The expression derived was SST_w (°C × 100) = 86.8 SST_3 (°C) − 16.5 (r^2 = +0.93). The primary advantage of using the SST_w series is that its period of record covers the entire annual natural Q record for SE Australia through calendar year 1986.

Statistical correlations between quarterly SST_w anomalies and annual natural Q for the DA and MU are highest for the months September, October, and November (Figure 5). Thus SST_w values have been used from each of those three months for relating to variations in annual Q. The trend of SST_w over the past century illustrates the magnitude of temperature variations associated with El Nino episodes, most of which had departures of +0.5°C to +2°C from the long-term mean for the months September–November (Figure 6).

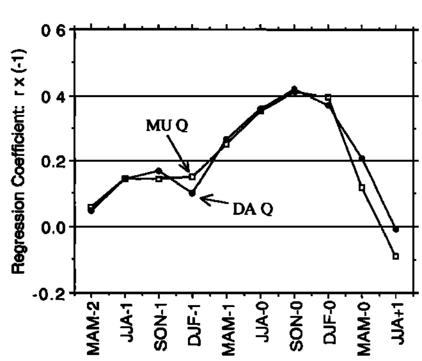

Fig. 5. Statistical correlations of annual (June through May) natural Q as a function of SST_w (quarterly means): −1 indicates year preceding period of Q record.

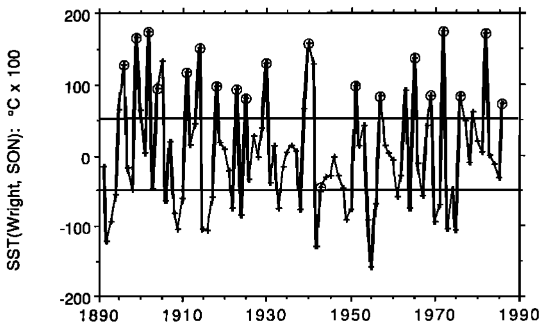

Fig. 6. Sea surface temperature (SST) anomaly time series, using mean Wright index values for September, October, and November [*Wright*, 1989]: El Nino years indicated by circles.

3.3. *Natural River Discharge in SE Australia Versus* SST_w

Both DA and MU have annual natural Q that are, in general, inversely related to SST_w (Figure 7). The inverse relationship appears to be stronger for warm SST conditions, as evidenced by the low incidence of higher Q years for SST_w values $>+50$. In contrast, the range of Q for $SST_w < -50$ was much greater, and included a number of low Q as well as most of the high Q values. General distributions of Q as a function of SST_w were similar for the two geographic regions of the M/D Basin. However, a larger fraction of DA Q values were very low.

Values of SST_w and natural Q for each river system have been divided into three categories, expressed in terms of percentage frequencies of occurrence (Table 4). The Q

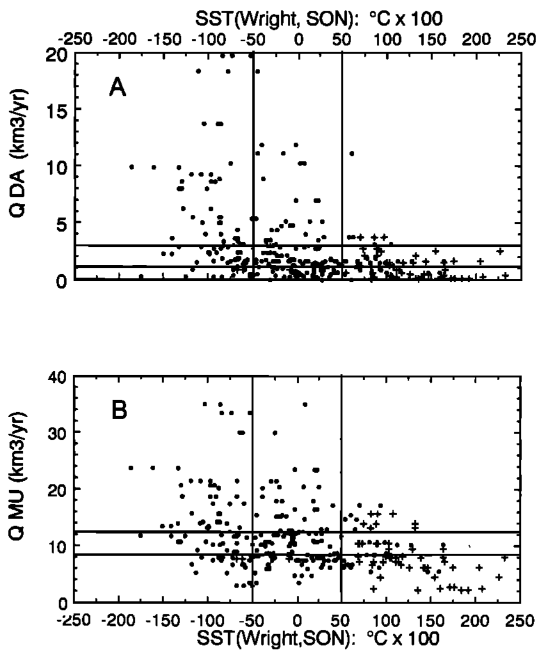

Fig. 7. (*a*) Annual (June through May) natural Q (1891–1985) of DA versus SST_w (degrees Celsius × 100) during September, October, and November (S, O, N). El Nino episode years are indicated by pluses. Three SST_w values (S, O, N) are plotted for each year. The two horizontal lines divide annual natural Q population into thirds, as in Figure 3. (*b*) Annual (June through May) natural Q (1891–1985) of MU versus SST_w, with the same conventions as in Figures 3*b* and 7*a*.

TABLE 4. Murray/Darling Basin Q Divided Into Three Categories: Occurrence Frequencies of Annual Natural Q of (1) DA and (2) MU Versus SST_W Observed for September, October, November With Each Monthly SST_W Observation Included as a Separate Event

	Cool SST	Moderate SST	Warm SST
DA Q Versus SST_W(obs) (1891–1985)[a]			
High Q	56%	31%	11%
Medium Q	27%	33%	41%
Low Q	17%	36%	48%
Statistical analysis			
Total number of events	[84]	[120]	[81]
Chi-square	22.2	0.3	17.7
Random probability	0.0001	0.87	0.0001
MU Q Versus SST_W(obs) (1891–1985)[b]			
High Q	50%	30%	19%
Medium Q	25%	43%	30%
Low Q	25%	28%	52%
Statistical analysis			
Total number of events	[84]	[120]	[81]
Chi-square	11.5	4.4	13.3
Random probability	0.003	0.11	0.001

SST denotes sea surface temperature; obs denotes observed.

[a]DA Q categories (cubic kilometers per year): high (>2.8), medium (1.2 to 2.8), low (<1.2). SST_Wcategories (°C × 100): cool (< −50), moderate (−50 to +50), warm (> +50).

[b]MU Q categories (cubic kilometers per year): high (>12.2), medium (8.12 to 12.2), low (<8.12).

values were placed into groups that each represented one third of the total population of natural Q (1891–1985). The SST_w parameters were divided at anomaly departures of −50 and +50 from mean monthly temperatures. Thus when SST_w values were in the warmest category (>+50), the occurrence frequencies for Q in the lowest one third group were 48% for DA and 52% for MU (Table 4). Probabilities of random occurrence of the observed Q distributions for warm and cool SST categories for both river systems are less than 1%.

Retrospective forecasts of mean monthly eastern equatorial Pacific SST_3 anomalies have been made with a geophysical model [*Cane et al.*, 1986; *Zebiak and Cane*, 1987] for the period from 1971 to 1985, and forecasts from 1986 onward. (The term "retrospective forecast" is used for the earlier 15-year period rather than "hindcasts" because no information subsequent to initiation of each forecast influenced the forecast procedure.) Model forecasts of SST_3 have been transformed here to a new set of forecast SST_w values using the linear regression described in section 3.2. Occurrence frequency tables relating observed SST_w to forecast SST_w 9 months ahead (SST_w (FC9)) were then calculated (Table 5). Probabilities of random occurrence of these frequencies for warm and cool categories were less than 3%. Combining these two sets of occurrence frequencies (Tables 4, 5), contingency tables relating forecast SST_w values to annual natural river Q categories were then calculated for DA and MU (Table 6). Probabilities of random occurrence of the resultant percentages for warm and cool categories were 6% for DA and about 22% for MU.

Annual natural Q for both river systems can also be divided into two groups separated at the mean of the population (Table 7), instead of the three categories discussed above. For observed SST_w values in the warm group (>+50), occurrence frequencies (1891–1985) for river dis-

TABLE 5. Occurrence Frequencies of SST_W Observed (obs) and SST_W Forecast 9 Months Ahead (FC9) for September, October, and November for 1971–1985 With Each Monthly SST_W Observation and Forecast Included as a Separate Occurrence

	Cool SST (FC9)	Moderate SST (FC9)	Warm SST (FC9)
Cool SST (obs)	50%	24%	0%
Moderate SST (obs)	50%	47%	43%
Warm SST (obs)	0%	29%	57%
Statistical analysis			
Total number of events	[14]	[17]	[14]
Chi-square	7.8	1.0	7.3
Random probability	0.02	0.11	0.03

charge less than the mean for DA and MU were 75% and 67%, respectively. Combining these percentage occurrences with those relating forecast to observed SST_w, the probabilities that annual natural Q in the DA and MU systems would fall below the mean for warm SST_w category years are 66% and 61%, respectively (Table 8). Probabilities of random occurrence of the reported contingency table percentages for warm and cool categories would be 1% for DA and 10% for MU.

3.4. *Forecast Annual Natural Q in SE Australia in 1991*

Forecast (9 month) SST_3 values for 1991 were as follows: September, +0.8°; October, +1.0°; November, +1.1°C [*Zebiak and Cane*, 1991]. Transforming these forecast SST_3 values to SST_w, forecast SST_w indices (°C × 100) for September, October, November were +53, +70, +79, all three of which fall into the warm category for SST_w discussed above. Using contingency table frequencies relating forecast SST_w to observed Q (Table 6), probabilities of DA and MU discharges falling in the lowest one third Q category for the period June 1991 to May 1992 would be 43% and 41%, respectively. For the lower one half Q category for DA and MU during this same period, the probabilities would be 66% and 61%, respectively (Table 8).

TABLE 6. Murray/Darling Basin Q Divided Into Three Categories: Contingency Tables of Annual Natural Q of (1) DA and (2) MU Versus Forecast (FC9) SST_W for September, October, and November With Each Monthly SST_W Forecast Included as a Separate Event

	Cool SST	Moderate SST	Warm SST
DA Q Versus SST_W(FC9)[a]			
High Q	44%	32%	20%
Medium Q	30%	34%	38%
Low Q	27%	35%	43%
Statistical analysis			
Chi-square	5.6	0.001	5.6
Random probability	0.06	0.999	0.06
MU Q Versus SST_W(FC9)[b]			
High Q	40%	32%	24%
Medium Q	34%	35%	35%
Low Q	27%	34%	41%
Statistical analysis			
Chi-square	2.9	0.001	3.1
Random probability	0.23	0.999	0.21

Tabulated numerical values are occurrence frequency percentages calculated for each column. Q and SST categories as in Table 4.

[a]Value is from the upper part of Table 4 times Table 5.
[b]Value is from the lower part of Table 4 times Table 5.

TABLE 7. Murray/Darling Basin Q Divided Into Two Categories: Occurrence Frequencies of Annual Natural Q of (1) DA and (2) MU Versus SST_W Observed for September, October, and November With Each Monthly SST_W Observation Included as a Separate Event

	Cool SST	Moderate SST	Warm SST
DA Q Versus SST_W(obs) (1891–1985)[a]			
Upper Q	79%	46%	25%
Lower Q	21%	54%	75%
Statistical analysis			
Total number of events	[84]	[120]	[81]
Chi-square	28.4	0.6	19.9
Random probability	0.0001	0.42	0.0001
MU Q Versus SST_W(obs) (1891–1985)[b]			
Upper Q	67%	48%	33%
Lower Q	33%	52%	67%
Statistical analysis			
Total number of events	[84]	[120]	[81]
Chi-square	9.9	0.06	8.4
Random probability	0.002	0.80	0.004

[a]DA Q categories (cubic kilometers per year): upper (>1.68), lower (<1.68). SST_W categories (°C × 100): cool (< −50), moderate (−50 to +50), warm (> +50).
[b]MU Q categories (cubic kilometers per year): upper (>10.35), lower (<10.35).

4. PRECIPITATION TRENDS FOR SE AUSTRALIA IN 1991

4.1. *Monthly Precipitation in Higher Runoff Areas of the M/D Basin*

Although calculated natural Q values for DA and MU for the full year beginning June 1, 1991, are not yet available,

TABLE 8. Murray/Darling Basin Q Divided Into Two Categories: Contingency Tables of Annual Natural Q of (1) DA and (2) MU Versus Forecast (FC9) SST_W for September, October, and November With Each Monthly SST_W Forecast Included as a Separate Event

	Cool SST	Moderate SST	Warm SST
DA Q Versus SST_W(FC9)[a]			
Upper Q	62%	48%	34%
Lower Q	38%	52%	66%
Statistical analysis			
Chi-square	6.7	0.004	6.6
Random probability	0.01	0.95	0.01
MU Q Versus SST_W(FC9)[b]			
Upper Q	57%	48%	39%
Lower Q	43%	52%	61%
Statistical analysis			
Chi-square	2.9	0.003	2.8
Random probability	0.09	0.96	0.10

Tabulated numerical values are occurrence frequency percentages calculated for each column. Q and SST categories as in Table 7.

[a]Values from upper part of Table 7 times Table 5.
[b]Values from lower part of Table 7 times Table 5.

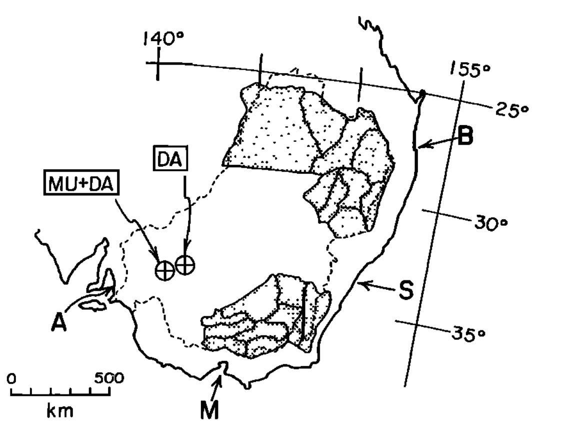

Fig. 8. Locations of rainfall districts representative of most surface runoff from DA and MU basins. Rainfall district numbers included for DA: 41, 42, 43, 44, 52, 53, 54, 55, 56. Rainfall district numbers included for MU: 70, 71, 72, 73, 74, 80, 81, 82, 83, 88. See Figure 1 caption for other notation.

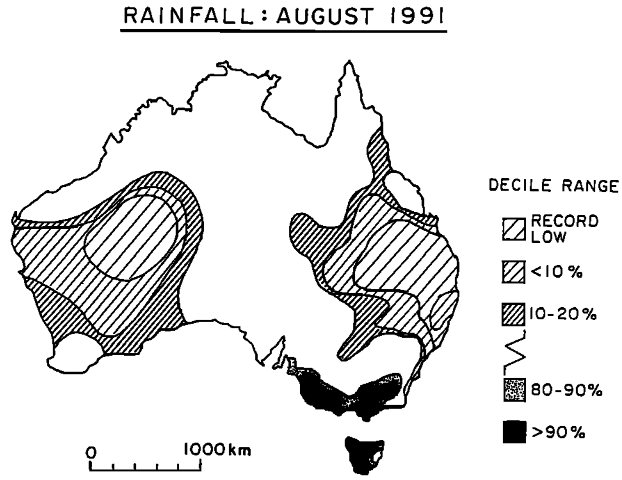

Fig. 10. Distribution of August 1991 P for Australia, expressed in terms of decile range for mean P (1913–1990), adapted from monthly summaries based on telegraphic reports [*Australian Bureau of Meteorology*, 1991].

some relevant P trends can be examined. Area-weighted mean monthly P during 1990 and 1991 from each of two geographical regions (Figure 8) can be compared with long-term monthly means. Darling P was generally well below normal beginning in March 1991 for most of the year (Figure 9). Gauged discharges of the Darling River approached historic low values by October 1991 and an enormous bloom of blue-green algae occurred throughout much of the river network. This bloom presented great difficulties for domestic and animal water supplies for much of the Darling Basin. There is little doubt that natural Q of DA for the year beginning June 1991 was well below the mean. Low annual natural Q from this large geographical area in 1991 is consistent with forecasts and subsequent observations of warm SST_w, documenting the occurrence of an El Nino episode in 1991 [*Kerr*, 1992].

Precipitation trends in the MU area of SE Australia during 1991 were quite different than for the DA region. Monthly P during June–September 1991 were well above the long-term mean (Figure 9). Thus the two major geographical components of the M/D Basin had P amounts that reflected quite different responses to this most recent El Nino episode.

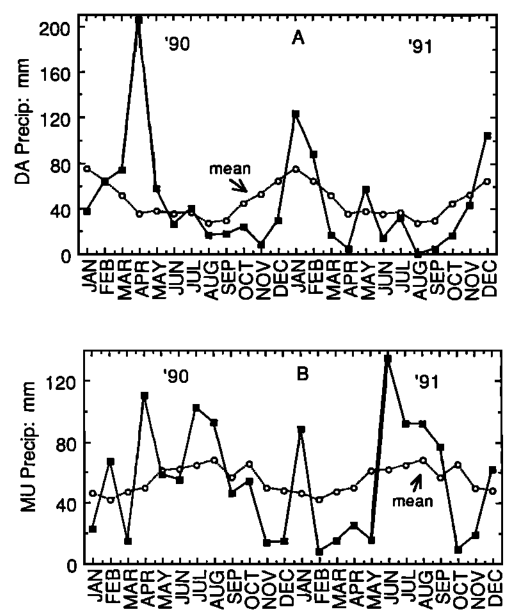

Fig. 9. Monthly P for 1990–1991 and mean monthly P (1913–1985) for rainfall districts providing most runoff to (*a*) DA and (*b*) MU.

4.2. *Precipitation Distribution During August 1991*

The difference between measured P [*Australian Bureau of Meteorology*, 1991] and long-term mean P was especially pronounced during August 1991 (Figure 9). DA P was far below the mean and MU P well above the mean. These extreme conditions in the M/D Basin were part of a dramatic spatial divergence of patterns of P from mean conditions for large areas of Australia (Figure 10). The DA seasonal P pattern, although typical in direction of departure for El Nino conditions, was associated with an unusually severe drought. In contrast, much of southern Victoria and the SE margin of the MU catchment had monthly P greater than 90% of the historical record since 1913. Clearly P amounts, and likely annual natural MU Q for 1991 did not behave in a manner consistent with most previous El Nino episodes, which have tended to display low Q for both DA and MU.

5. STATISTICAL RELATIONSHIPS BETWEEN VARIABLES

5.1. *Linear Regression Coefficients for Variable Pairs*

Some indication of correlations between pairs of variables used to prepare contingency tables here can be derived from a compilation of linear regression coefficients (Table 9). In all cases, SST index values (September–November, SON) have been averaged to yield a single index number for each year. The r^2 values for annual Q for the entire data series (1891–1985) as a function of SST_w-SON were of the order of 0.2 for both subbasins of the M/D system and for the combined MU+DA discharge. During the period for which SST forecasting experience was available (1971–1985), r^2 values between Q MU (and Q MU+DA) and SST_w-SON

TABLE 9. Statistical Correlations of Pairs of Variables Included in Contingency Tables Plus Related Variables

Variables	Years	r^2	Regression Equation[a]
[Q MU + DA], [SST_W-SON][b]	1891–1985	0.23	$Q = 14.6 - 5.1E{-2}X$
[Q DA], [SST_W-SON]	1891–1985	0.18	$Q = 3.1 - 1.9E{-2}X$
[Q MU], [SST_W-SON]	1891–1985	0.17	$Q = 11.5 - 3.2E{-2}X$
[Q MU + DA], [SST_W-SON][b]	1971–1985	0.53	$Q = 17.5 - 8.3E{-2}X$
[Q DA], [SST_W-SON]	1971–1985	0.27	$Q = 4.0 - 2.1E{-2}X$
[Q MU], [SST_W-SON]	1971–1985	0.50	$Q = 13.5 - 6.2E{-2}X$
[SST_W-all], [SST_3-all][c]	1970–1986	0.93	$SST_W = -16.5 + 86.8X$
[SST_3-SON], [SST_3(FC9)-SON][b,d]	1971–1985	0.31	$SST_3 = 2.1 + 0.56X$
[SOI-SON], [SST_W-SON][b,e]	1891–1985	0.52	$SOI = -0.1 - 7.7E{-3}X$
[Q MU + DA], [SOI-SON][b,e]	1891–1985	0.26	$Q = 15.1 + 5.0X$
[Q DA], [SOI-SON]	1891–1985	0.16	$Q = 3.2 + 1.7X$
[Q MU], [SOI-SON]	1891–1985	0.22	$Q = 11.9 + 3.3X$

[a]Linear regressions of Y on X; units: Q is in cubic kilometers per year; SST_W values are departures from mean SST in degrees Celsius × 100 for Wright index region; SST_3 values are departures from mean SST in degrees Celsius for NINO-3 region. Read 5.1 E−2 as 5.1×10^{-2}.

[b]SON denotes mean of September, October, November values of SST_W, SST_3, or SOI.

[c]Here all denotes all months of period used in regression expression: January–December.

[d]FC9 denotes forecast of SST_3 made 9 months in advance.

[e]SOI is the Southern Oscillation index [*Ropelewski and Jones*, 1987]; SOI equals the difference in surface atmospheric pressure anomalies in millibars between Tahiti and Darwin, expressed in standard deviation units.

observed were considerably higher (about 0.5), but for Q DA the correlation was similar to that for the longer time series.

Correlation between the two series of observed SST values for the period 1970–1985 (SST_w, SST_3) was quite high ($r^2 = 0.93$), as would be expected. Thus conversion of observed and forecast SST_3 index values from geophysical model calculations to SST_w index values introduces little additional uncertainty to contingency tables relating Q to SST_w forecasts.

Correlation between the Southern Oscillation index (SOI), based on the difference in surface air pressure anomalies between Tahiti and Darwin [*Ropelewski and Jones*, 1987], and SST_w(obs) was also relatively high ($r^2 = 0.52$), as would be expected for the two index series which are most commonly used to describe the temporal variability of ENSO processes. Note that r^2 values relating annual Q in SE Australia to SST are only about half as great as those relating the two primary ENSO indices (SOI and SST) for the longer time series (1891–1985), again indicating that ENSO processes alone are not responsible for all of the interannual variability of annual Q in this region.

The correlation of annual river discharge (Q MU+DA, Q DA, Q MU) with SOI index values was comparable (r^2) to that for SST_w(obs), indicating no appreciable difference in variance associated with either of these ENSO index values and river discharge in SE Australia. Since the output of geophysical model calculations used as input parameters for the discussion above provides explicit forecasts of SST rather than SOI, sea surface temperature ENSO index values form the basis for the treatment outlined here of annual river discharge variability.

5.2. *Applicability of Contingency Tables to Annual Q Estimates*

For years in which SST_w(obs) values fell in the moderate temperature range (±0.5°C from mean values for SON), annual Q for DA were randomly distributed (Figure 7 and Table 4). When occurrence frequencies relating SST_w(FC9) to SST_w(obs) were incorporated in contingency tables (Table 6), annual Q for MU were also randomly distributed for this SST category. Thus for about 40% of years in the long time series, information about forecast SST_w would have provided no indication of expected annual Q. For the remaining 60% of years, however, forecast SST_w values would have indicated expected annual Q values significantly better than random probability (Tables 6 and 8).

6. CONCLUSIONS

Surface runoff in SE Australia (1891–1985) expressed in terms of annual natural river discharge (Q) for each of two geographical areas of the Murray/Darling Basin show an inverse relationship to sea surface temperature (SST) in the eastern tropical Pacific Ocean. This inverse relation has historically been more consistent for warm SST conditions, which often correlate with Australian drought. Occurrence frequencies of annual natural Q categories relative to SST index values [*Wright*, 1989] are similar for the Darling and Murray (exclusive of the Darling). About 60% of the years over the past century had SST that departed from mean values sufficiently to provide statistically significant indication of expected Q for both river basins.

Geophysical model calculations of SST forecast 9 months in advance for years since 1970 provide a new approach to estimating probabilities of annual river Q on the basis of contingency tables, approximately a year in advance. Forecast SST values for September, October, and November 1991 were appreciably above long-term means; hence contingency table percentages of natural Q in SE Australia for the year beginning June 1991 indicated relatively high probabilities that Q would be below the mean for the Darling River (66%) and the River Murray exclusive of the Darling (61%).

Observed precipitation (P) for high surface runoff rainfall districts of the Darling and Murray catchments in 1991/1992 indicated that the Darling probably did experience annual natural Q well below the mean for the year beginning June

1991, consistent with the general relationship to SST in the eastern equatorial Pacific Ocean over the past century. In contrast, very high P along the extreme southeastern margin of the Murray catchment indicated that the River Murray, exclusive of the Darling, probably did not have annual natural Q below the mean during 1991, as occurred during most historical El Nino episodes. Thus additional large-scale meteorological forcing, beyond ENSO, is likely to be important in generating variability of annual P and Q for the Murray/Darling Basin. Such processes need to be explicitly identified and incorporated into natural Q forecasting activities.

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