NOTES AND CORRESPONDENCE

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

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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 1891-1983 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; Whetten and Baxter 1989; Whetten 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 × 10⁶ km²). 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-
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 perturba-
tions (Close 1990); they are thus referred to as "nat-
ural." Calculation of natural $Q$ from actual $Q$ data has
been done by addition of a sequence of terms that ap-
proximate 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 be-
tween 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 depar-
tures from natural $Q$ for later years. During an early
part of the record (1902–1926), mean annual actual
$Q$ was $11.7 \pm 7.1 \text{ km}^3 \text{ yr}^{-1}$, which is about 90% of
natural $Q$ for the same years ($13.0 \pm 7.4 \text{ km}^3 \text{ yr}^{-1}$).
Mean annual actual $Q$ for the period 1961–1985 was
$7.8 \pm 6.8 \text{ km}^2 \text{ yr}^{-1}$, only about 60% of natural $Q$ for
the same period ($13.1 \pm 6.6 \text{ km}^2 \text{ yr}^{-1}$).

3. River Murray discharge during previous ENSO
events

Annual natural $Q$ of Mu-SA (1891–1985) ranged
from $2.3 \text{ km}^3 \text{ yr}^{-1}$ (1982) to $45 \text{ km}^3 \text{ yr}^{-1}$ (1956), with

![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: Brisbane (Queensland),
Sydney (New South Wales), Melbourne (Victoria), and Adelaide
(South Australia).](image)

![Fig. 2. Annual (June–May) natural $Q$ vs actual $Q$ of River Murray
to SA (Mu-SA) for the period 1902–1985.](image)

![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 hori-
zontal lines divide the natural $Q$ population into thirds: Low $Q = <9.3$
$\text{ km}^3 \text{ yr}^{-1}$, medium $Q = 9.3$ to $15.0 \text{ km}^3 \text{ yr}^{-1}$, high $Q = >15.0$
$\text{ km}^3 \text{ yr}^{-1}$. El Niño episode years (June–May) included here (19):
1896, 1899, 1902, 1904, 1911, 1914, 1918, 1923, 1925, 1930, 1940,
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 \(\times 100\)) 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.

5. River Murray discharge vs forecast SST indices

Retrospective forecasts of mean monthly eastern equatorial Pacific SST anomalies (SST\(_3\)) in the Niño3 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 \(\times 100\)) = 86.8 \(\times\) SST\(_3\) (°C) – 16.5. Forecast SST\(_w\) for each of these 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
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 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).

### 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 $^\circ$C × 100 were cool (<−50$^\circ$C), moderate (−50$^\circ$C to +50$^\circ$C), warm (> +50$^\circ$C).

<table>
<thead>
<tr>
<th></th>
<th>Cool SST</th>
<th>Mod SST</th>
<th>Warm SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $Q$</td>
<td>54%</td>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>Medium $Q$</td>
<td>25</td>
<td>38</td>
<td>36</td>
</tr>
<tr>
<td>Low $Q$</td>
<td>21</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>Total number</td>
<td>[87]</td>
<td>[118]</td>
<td>[80]</td>
</tr>
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</table>

### Table 2c. 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 2 for $Q$ and SST$_w$ category definitions and unit conventions.

<table>
<thead>
<tr>
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<th>Cool SST</th>
<th>Mod SST</th>
<th>Warm SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $Q$</td>
<td>64%</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>Medium $Q$</td>
<td>14</td>
<td>12</td>
<td>36</td>
</tr>
<tr>
<td>Low $Q$</td>
<td>21</td>
<td>53</td>
<td>43</td>
</tr>
<tr>
<td>Total number</td>
<td>[14]</td>
<td>[17]</td>
<td>[14]</td>
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### Table 2d. SST$_w$ (obs) vs SST$_w$ (FC9) (1971–1985)

<table>
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<th>Cool SST</th>
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</thead>
<tbody>
<tr>
<td>Observed Warm SST</td>
<td>0%</td>
<td>29</td>
<td>57</td>
</tr>
<tr>
<td>Mod SST</td>
<td>50</td>
<td>47</td>
<td>43</td>
</tr>
<tr>
<td>Cool SST</td>
<td>50</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Total number</td>
<td>[14]</td>
<td>[17]</td>
<td>[14]</td>
</tr>
</tbody>
</table>

### Table 3. 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$_w$ 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$_w$ 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$_w$, combined with relationships between observed SST$_w$ and forecast SST$_w$. Unfortunately, we are not aware of...
TABLE 3. Conditional probabilities of annual natural $Q$ (Mu-SA) vs forecast (FC9) SST, made nine months in advance for September, October, and November (S, O, N); each monthly (S, O, N) SST, forecast was included as a separate event. Discharge categories for Table 3e were the same as in Table 1. Discharge categories ($\text{km}^3 \text{yr}^{-1}$) for Table 3f were upper $Q (>11.9)$, lower $Q (<11.9)$. SST, categories for both 3e and 3f were the same as in Table 1. All values are percentages calculated for each column.

<table>
<thead>
<tr>
<th></th>
<th>Cool SST</th>
<th>Mod SST</th>
<th>Warm SST</th>
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</thead>
<tbody>
<tr>
<td>High $Q$</td>
<td>42%</td>
<td>31</td>
<td>21</td>
</tr>
<tr>
<td>Medium $Q$</td>
<td>32</td>
<td>34</td>
<td>37</td>
</tr>
<tr>
<td>Low $Q$</td>
<td>27</td>
<td>35</td>
<td>42</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Cool SST</th>
<th>Mod SST</th>
<th>Warm SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper $Q$</td>
<td>60%</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>Lower $Q$</td>
<td>40</td>
<td>52</td>
<td>64</td>
</tr>
</tbody>
</table>

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.

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REFERENCES


