Journal of Hydrology (NZ) Vol. 32 No. 2, 1994

FORECASTS OF SEASONAL RIVER FLOWS USING SOUTHERN OSCILLATION INDEX

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ABSTRACT

The seasonal Southern Oscillation Index (SOI) and seasonal discharge of three New Zealand river basins are examined to determine what proportion of seasonal variance can be attributed to SOI. SOI and discharge are positively but weakly correlated for a large North Island river in three of four seasons. The results are less significant for two South Island flow records and support previous findings on the correlation between SOI and regional rainfall which show a tendency for more significant correlations in the lower latitude North Island. For Clutha Lake inflows for the austral summer, the correlation with the precursor September/October/November SOI is - 0.34, suggesting some scope for forecasting the lake inflows. Enhanced austral spring snow accumulation during negative phases of the SOI is a possible reason for enhanced summer inflows.

INTRODUCTION

The variability of the flows in New Zealand rivers is of vital interest to many sections of the community. Whether seasonal discharge in a river will be above or below its norm for the season has impacts for regional resource management, river control, irrigation, freshwater fisheries and energy generation.

Droughts are sustained periods when rainfall or discharge is less than the seasonal normal or when soil moisture is deficient. In the last decade droughts in New Zealand have caused substantial economic losses:

Date	Areas affected	Major impacts	Reference
Oct 1982-Mar 1983	Hawkes Bay	Loss of agricultural production. Fish strandings. Curtailment of forestry operations.	Harrison (1988)
1988-1989	South Island East Coast	Loss of agricultural production. (Farm gate cost $365m). Depletion of groundwater.	-
Nov 1991-Jul 1992	South Island Southern Alps	Inadequate inflow to Lakes Pukaki and Tekapo resulting in energy deficits throughout New Zealand, and 0.5% drop in Gross Domestic Product.	Electricity Shortage Review Committee (1992)

The severity of drought traditionally has been analysed using rainfall records. Analyses using discharge records are less common, as few discharge records commence before the mid 1960s. However, analyses of discharge are attractive because discharge is the integration over an area (the river basin) of precipitation minus evaporation, whereas precipitation is a point measurement. In the Southern Alps rainfall depths vary dramatically depending on distance across the mountains (Henderson, 1993) and long-term rainfall records are sparse, but lake levels and outflows, and hence inflows, are available since the late 1920s. In other parts of the country, discharge records commencing in the mid 1960s now offer more than 25 years of data for analysis.

Increased understanding of the links between climatic fluctuations and oceanographic features has developed in recent years. The influence of the Southern Oscillation is manifest in records of climate, sea surface temperature and ocean currents (Philander, 1990). An index of this oscillation is the standardised difference in sea level atmospheric pressures between Tahiti and Darwin. In this study, we examine the use of the Southern Oscillation Index (SOI) to predict seasonal fluctuations in river discharge. Weak correlations are expected to follow from known correlations between rainfalls and SOI (Gordon, 1986). Records for three basins affected by different weather conditions (Fig. 1) are used.

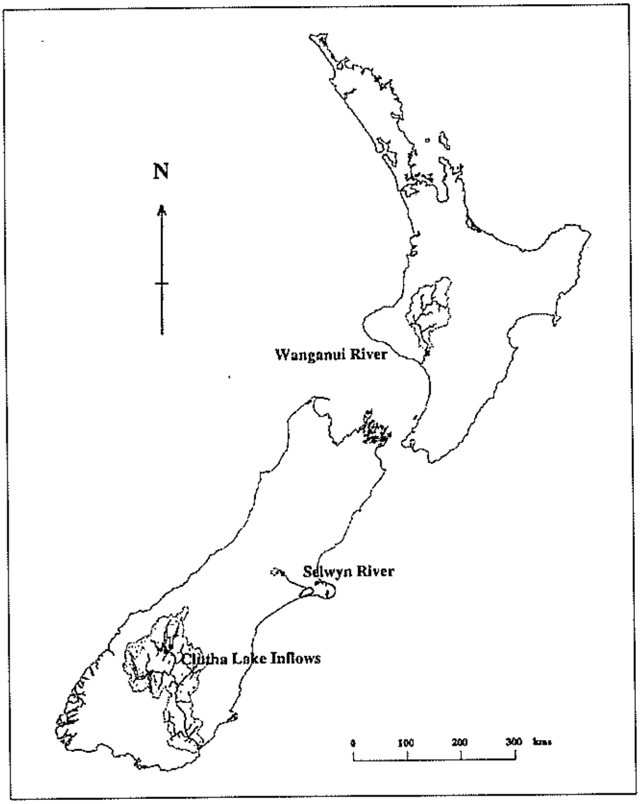


FIG. 1—Location of three river basins used in this study.

REVIEW

The Southern Oscillation is an irregular interannual fluctuation in global climate and the tropical Pacific ocean and atmosphere circulation. One of its best known features is a warm water current which sometimes appears off the Peruvian coast after Christmas, early in the calendar year, known as "El Niño" (the Christ Child). This warm surface water displaces nutrient-rich cold upwelling water. Fish catches in these years are poor, but as there is widespread intense rain in barren parts of Peru, such years are known as "years of abundance". Years when the cold upwelling is unusually intense are described as "La Niña" (the girl), although other terms such as "anti-El Niño" are also used (Philander 1990). The term "El Niño Southern Oscillation" (ENSO) is used to describe the phenomenon in its wider sense.

El Niño years correspond to unusual climate conditions in many parts of the world including drought in Australia, enhanced snowfall in western North America, and failure of monsoon rain in India, but abundant monsoon rain in Sri Lanka. World maps are available that show regions experiencing enhanced or reduced temperature and rainfall during El Nino events e.g. Philander (1990); Glantz (1991). Philander (1990) reviews the links between oceanographic and meteorological circulation to explain many of the features of the Southern Oscillation.

From the sparse network of climatological records in the Asia-Pacific tropical region, the best long-term index of the Southern Oscillation is the difference in barometric pressure between Darwin and Tahiti. This index is the mean Tahiti minus Darwin pressure for the month (from pressure readings every six hours), normalised by dividing by the standard deviation of the monthly mean pressure differences. That is Southern Oscillation Index

$$\mathrm{SOI} = (x_{ij} - \bar{x}_i)/s_i, \tag{1}$$

where x_{ij} is actual monthly (Tahiti-Darwin) pressure difference in month i ($i = 1 \ldots 12$) and year j; and

$\bar{x}_i$, s_i, are respectively mean and standard deviation of pressure difference in month i across the base period 1941-1980. It is multiplied by 10 to avoid decimal points.

Monthly values for this index are available from 1935 to the present. The index is a measure of the departure from average conditions of the low pressure Western Pacific conditions centred over Papua New Guinea, and high pressure Eastern Pacific conditions as indicated by Tahiti.

The SOI becomes negative when the charactistically low pressure centred over Papua New Guinea (as measured by the Darwin sea level pressure) rises and the characteristically high pressure around Tahiti reduces. In these conditions persistent easterly tradewinds break down, enabling warm surface water in the western Pacific to spread across the equatorial Pacific to the Central and South American coasts. This is the origin of the El Niño phenomenon, and it is associated with negative values of the SOI.

New Zealand meteorologists have studied the effects of the Southern Oscillation on New Zealand weather patterns. Gordon (1986) examined the autocorrelation characteristics of the SOI. He used three month running mean

TABLE 1—Discharge records for the study basins.

Record Number	Name	Period	Drainage area (km^2)	Broad region	Notes
33301	Wanganui at Paetawa	Dec 1951-Nov 1991	6643	Central/west, North Island	1 , 2
68001	Selwyn at Whitecliffs	Dec 1964-Nov 1991	163	East Coast, South Island	
	Clutha Lake inflows	Dec 1945-Nov 1991	7146	Southern Alps, South Island	3

Notes:

1) Records prior to 1 August 1957 are from a report "Wanganui River Hydrology" Power Design Office, Ministry of Works, 1967.

2) Diverted headwater flows to Tongariro Power Scheme via the Wairehu Canal (Stn no. 33359) are included from 1 February 1971.

3) Clutha Lake inflows are the sum of inflows to Lakes Hawea, Wanaka and Wakatipu. Inflows for each lake are calculated from records of lake levels and outflows.

of the SOI and the standard New Zealand (Southern Hemisphere) definition of seasons: summer - December, January, February (abbreviated DJF), autumn - MAM, winter JJA, spring SON. (These abbreviations avoid confusion with Northern Hemisphere seasons.) His analysis shows that the SOI for JJA correlates only weakly with preceding seasons but strongly with values through to about the following April. This lack of persistence in the SOI across the southern autumn is the reason why the 12 month period May-April, rather than the calendar year, is used to compute annual averaged relationships with the SOI.

The autumn decline in persistence occurs when the tradewinds and currents in the southeastern Pacific are weakest and most disturbed, and random disturbances most affect the SOI. Gordon (1986) notes that April is the one time of the year that the correlation between Darwin and Tahiti pressures is negligible, and when Darwin pressures show a break in persistence. This break in persistence may relate to air-sea feedbacks in the Indonesian area. Because of the seasonality, Gordon analysed data by season.

Seasonal SOI values were correlated with seasonal mean sea level (MSL) pressures. Typically, the correlations with New Zealand pressures as a whole are near zero, except for DJF when correlations are positive for the South Island. Although there are marked differences between seasons, the correlation for Australia is uniformly negative, and to the east and south of New Zealand it is generally positive. Gordon notes that: "For a negative SOI, the correlation fields imply anomalous southwesterly flow over New Zealand in SON and MAM, anomalous westerly flow to the north in DJF and anomalous southerly flow over the country in JJA."

The anomalous wind flow for a negative SOI influences land temperatures and rainfall. Gordon gives a set of maps (his Fig.15) which show significant positive correlation between SOI and temperature of western regions of the country in all seasons, and for most of the North Island except in MAM, and much of the South Island in DJF. Thus an El Niño event generally implies lowered temperatures for New Zealand.

Gordon's maps also show seasonal correlations between SOI and rainfall. For MAM there is significant negative correlation in the south and west of the North Island and the south of the South Island. There is positive correlation for JJA and SON over much of the North Island. For DJF there is negative correlation in the south of the South Island, and positive correlation on the East Coast of the North Island. None of the correlations exceeded 0.61, so that at most 37% of the seasonal variance can be explained by SOI.

In this study, we examine correlations between SOI and river discharge series. Such correlations would be of obvious benefit in forecasting river flows, if physical models (Cane, 1991) or time series methods (e.g., Keppenne and Ghil, 1992) have any prospect of forecasting El Niño occurrences one and more seasons ahead.

METHOD

Discharge series for three river basins (Table 1) are used in this study. These basins have the longest reliable discharge records available in separate climatic regions. The third record, Clutha Lake inflows, is the sum of inflows of three

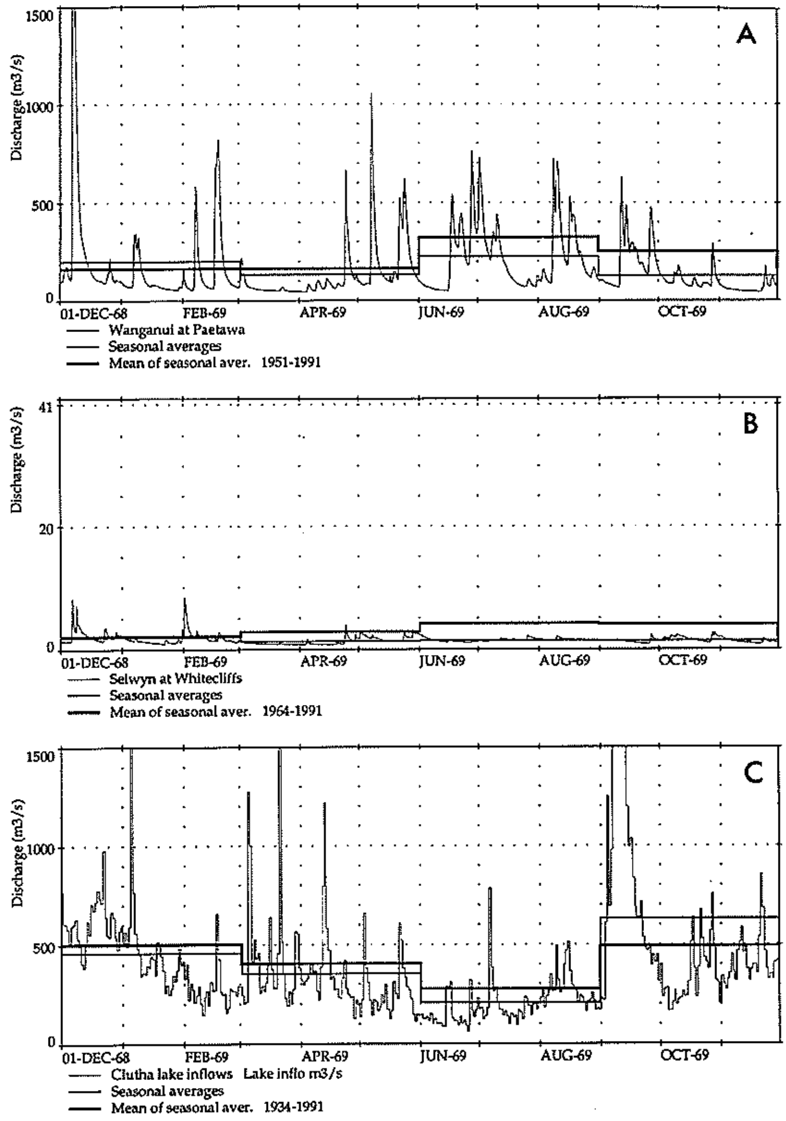


FIG. 2—Discharge, seasonal mean discharge and mean of seasonal mean discharge for December 1968 through November 1969 for

a) Wanganui River
b) Selwyn River
c) Clutha lake inflows.

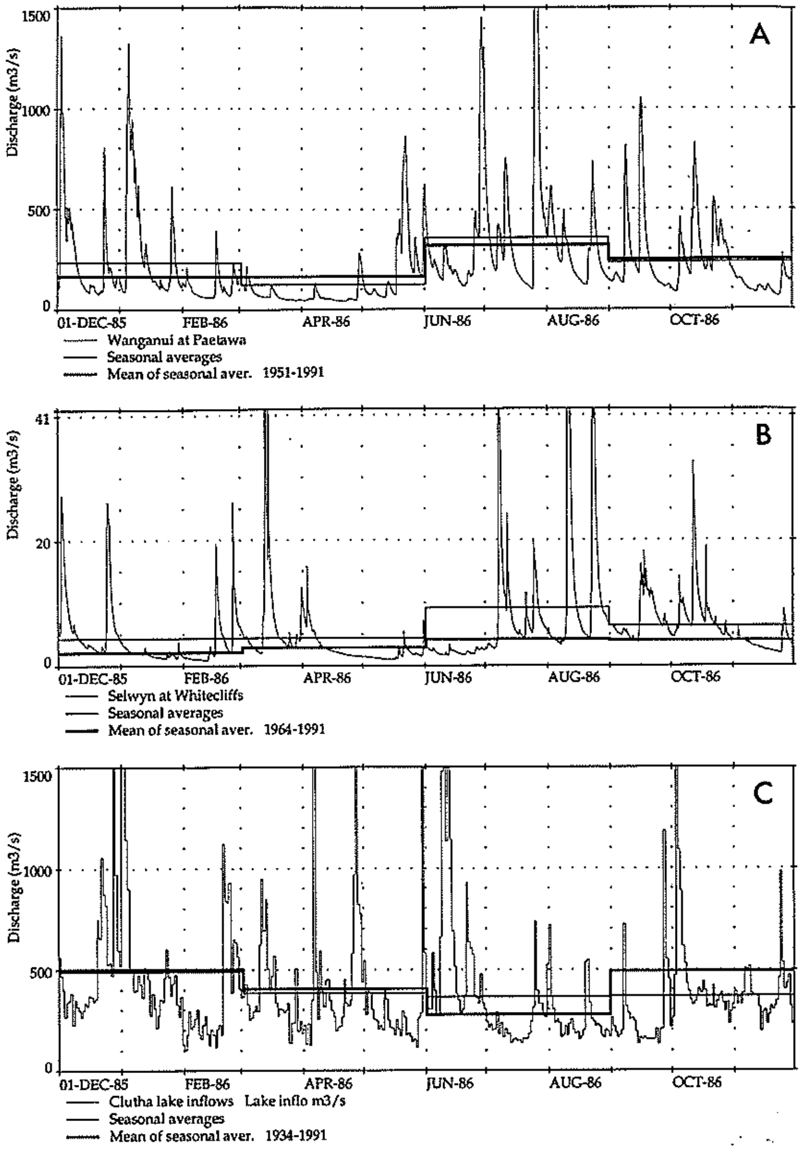


FIG. 3—Discharge, seasonal discharge and mean of seasonal mean discharge for December 1985 through November 1986 for

a) Wanganui River
b) Selwyn River
c) Clutha lake inflows.

lakes which are the main source of flow for the Clutha River. Locations of the drainage basins are given in Figure 1.

The series are expressed as seasonal means commencing from 1 December of the first year of record. The duration of seasons is taken as 365.25/4 = 91.31 days, which differs only slightly from the calendar definition. Plots of samples of the data are used to demonstrate independence between the three records.

Linear correlation analysis between seasonal discharges and the seasonal SOI values is used to investigate the extent of their linkage.

RESULTS

Independence of records

Samples of discharge records for two years (1968-1969 and 1985-1986) are plotted (Figs. 2, 3) to illustrate the extent of coincidence of storms over the three basins. These two years have respectively the lowest and highest discharge for the Selwyn river. Some hydrograph peaks for the Wanganui and the Selwyn coincide, but the magnitudes of the peaks appear unrelated. No correlation between the Clutha Lake inflows and the other records is evident.

Seasonal means (Figs. 2 and 3) used in subsequent analysis typically are averaged over several floods. The presence or absence of several events will determine how far discharge in a particular season departs from the mean of seasonal values. However, in the Clutha catchment (Fig. 2C) one large event dominates the whole 1968 SON season. Seasonal patterns in the discharge differ: mean seasonal discharge for Wanganui and Selwyn is highest in winter (JJA) and least in summer and autumn (DJF and MAM), whereas the Clutha Lake inflows are highest in spring and summer (SON and DJF) and least in winter (JJA). The lesser winter discharge reflects the reduced temperatures, and the accumulation of precipitation in snowpacks, which melt in spring (SON) and summer (DJF). All three seasonal series and seasonal SOI values (1935-1991) are plotted in Figure 4. The 1982-1983 and 1988-1989 droughts noted earlier correspond respectively to the overall minimum and the decadal maximum in the quarterly SOI record.

Seasonal correlation analysis

River discharge and SOI indices (Fig.4) are sorted according to season, and correlations between seasonal discharges and SOI for the current and the two preceding seasons are listed in Table 2. Correlations between discharge and current SOI are significant only for the Wanganui for JJA and SON: even then, the variance of discharge attributable to SOI is low, the maximum value being $R^2 = 15\%$. Table 3 lists the simple linear regression equations whose fit to the Wanganui flow is illustrated in Figure 5.

Neglecting seasonal changes in storage in the basins, so that discharge is equated to rainfall-evapotranspiration, and assuming little year-to-year variation in seasonal evapotranspiration, Gordon's maps suggest a pattern for correlations between discharge and SOI for the same time period that are largely confirmed by the results (Table 2). Although most of the Clutha lake basin areas lie within a "Central Otago" region on Gordon's maps, much of the precipitation falls on their mountainous northwestern edge, and is best represented by West Coast raingauges, such as that at Milford Sound (Trenberth, 1977). The rainfall correlation for the "West Coast" region (Gordon's Fig. 15) shows no correlation with SOI for any season and this is confirmed by the results in Table 2.

TABLE 2—Correlations between seasonal discharge and seasonal SOI. SOI(-1) refers to SOI for the preceeding season; CLI(-1) refers to Clutha Lake inflow for the preceeding season.

			Season			
River	N	Variable	DJF	MAM	JJA	SON
Wanganui	41	SOI	-0.132	-0.262	0.393*	0.378*
		SOI(-1)	-0.060	-0.192	0.230	0.207
		SOI(-2)	0.110	-0.033	0.261*	0.151
Selwyn	27	SOI	0.158	-0.092	0.320	0.089
		SOI(-1)	0.117	-0.015	0.123	0.145
		SOI(-2)	0.036	-0.061	-0.168	0.387*
Clutha	57	SOI	-0.203	-0.147	0.128	0.052
Lake		SOI(-1)	-0.342**	-0.222*	-0.078	-0.024
Inflows		SOI(-2)	-0.211	-0.229*	-0.051	-0.199
(CLI)		CLI(-1)	0.259*	0.329**	0.126	0.321*
		CLI(-2)	0.080	-0.011	0.082	0.053

* Significant at 5% level.
** Significant at 1% level.

TABLE 3—Regression Equations for Wanganui River.

Season	Equation	R^2	std error (m^3/s)
DJF	No useful result	-	-
MAM	No useful result	-	-
JJA	$Q_{JJA} = 323 + 3.62\ SOI_{JJA}$	0.15	75
SON	$Q_{SON} = 251 + 3.06\ SOI_{SON}$	0.14	74

Lagged correlations

Table 2 also gives correlations between seasonal discharge and SOI lagged by one and two seasons; this analysis is to identify correlations useful for forecasting discharge. Results are significant mainly in the Clutha Lake basins, in particular between spring (SON) SOI and summer (DJF) inflows. There the correlation is -0.342 and the proportion of summer seasonal flow variance that can be explained by spring SOI is 12%.

Correlations between lake inflows in successive seasons (Table 2) are also significant in three cases for the Clutha lakes. This suggests some persistence in seasonal inflow anomalies, but the proportions of variance explained (up to 11%) are again low. Correlations between successive seasons for the other rivers were not significant, and are not listed in Table 2.

The correlation between DJF inflow and the previous season SOI suggests some scope for forecasting lake inflows. When SOI for SON is strongly negative (less than -10) (Fig. 6) the data suggest that the probability that the DJF inflows exceed 400 m^3/s is high. On the other hand when the SOI for SON is strongly positive, (greater than 10), the probability that the lake inflows exceed 400 m^3/s is much lower. We examine these probabilities in a Bayesian context in a separate paper (Moss et al., 1993).

DISCUSSION

The influence of the Southern Oscillation on rainfalls in tropical regions is well established (e.g. Philander, 1990). In mid-latitude New Zealand, the influence of the SOI is not as dramatic as it is in lower latitude locations, but nonetheless it does yield some statistically significant correlations with river flows which confirm seasonal rainfall correlations reported by Gordon (1986).

More significant values occur at lower latitudes, in the North Island. (Gordon's highest correlation with seasonal rainfall ($R = 0.61$) occurs in Northland for SON in Northland (latitudes 34 to 37 degrees south).

The correlations vary substantially between seasons which justifies the seasonal partitioning of the data.

Prediction equations for the Wanganui account for up to 15% of within-season variance. The positive correlations between rainfall and SOI for much of the North Island for JJA and SON and negative correlations for the south western parts of the North Island for MAM (Gordon, 1986) suggest that linear correlations of order ±0.2 to 0.4 or 0.5 may be expected for other North Island rivers. Gordon explains that the JJA correlation patterns result from drier than average anomalous southerly airflow for a negative SOI, causing lower than average rainfall. The SON correlations are partly a result of sheltering by mountains giving lower rainfall in the east for negative SOI and anomalous southwest flow, but also reflect generally higher pressures and more settled weather in the north.

The significant negative correlation between the DJF Clutha lake inflows and the precursor SOI value is a new finding, and is probably connected with snow accumulation and melt: a seasonal water balance analysis for the Clutha lake suggests that on average 255 mm accumulates as snow by the end of September (Jowett and Thompson, 1978). We hypothesise that the lower temperatures caused by anomalous southwesterly flow over the country in SON during negative phases of the SOI enhance snow accumulation. The additional summer snowmelt in DJF accounts for the anomalously high inflows. We would expect similar findings for other South Island basins with seasonal snow accumulation. This suggests some scope for using the spring SOI to forecast summer inflows. Study of seasonal snow accumulation will help to confirm this hypothesis.

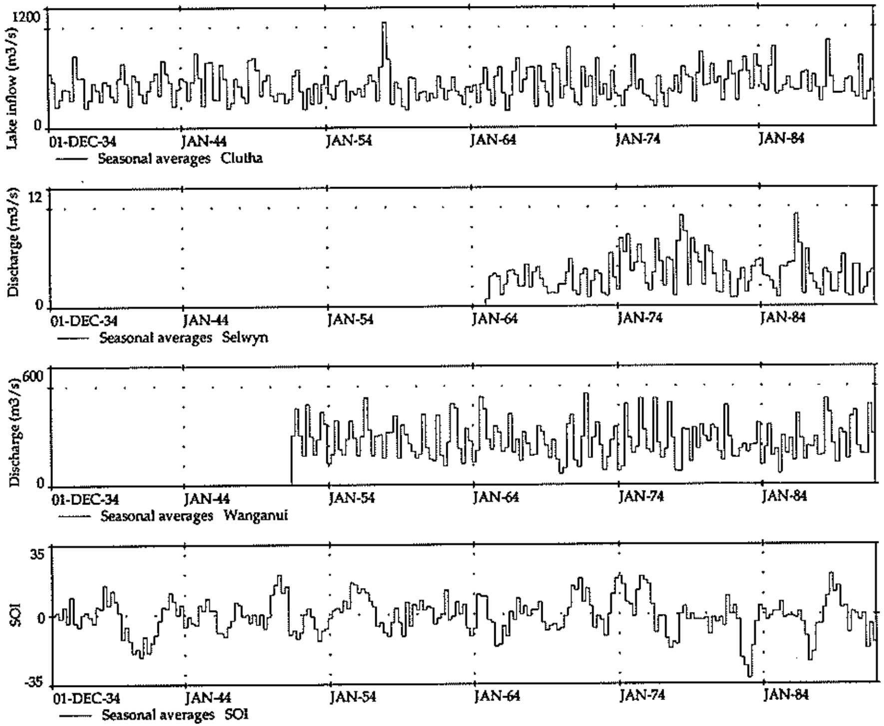


FIG. 4—Seasonal discharges for the three selected river basins, and the corresponding quarterly SOI series, from December 1934 to November 1991. (The SOI value for December/January/February 1934-1935 is the mean of the January/February values only.)

CONCLUSION

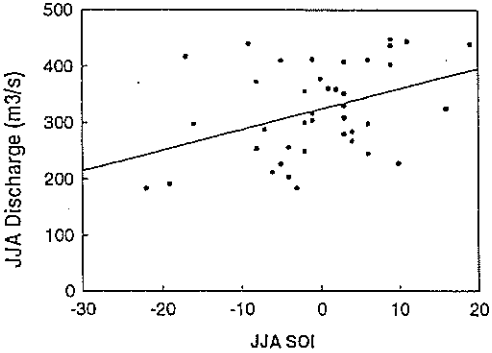
The correlations we observed between SOI and contemporaneous seasonal river flow confirm the results of Gordon (1986) who reported on the extent of correlations between SOI and seasonal rainfall, and seasonal temperature.

Significant correlation between SOI and seasonal Wanganui River flow of up to 0.393 indicate some potential for prediction of seasonal flow from contemporaneous SOI values. Similar results are likely for other North Island records.

For Clutha lakes there is significant correlation between the summer inflows and the precursor SOIs which suggests scope for prediction of inflows.

ACKNOWLEDGEMENT

Funding for this work has been provided by the Foundation for Research Science and Technology. The Clutha lake inflow data are provided by the Electricity Corporation of New Zealand. We acknowledge suggestions from reviewers, and Dr B B Fitzharris (University of Otago).



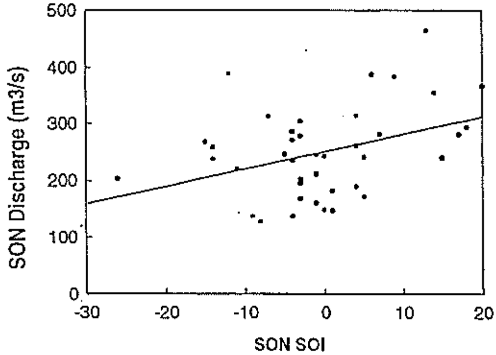


FIG. 5—Regression lines showing the linear correlation between seasonal Wanganui discharge and seasonal SOI. Details of the regressions are in Table 3.

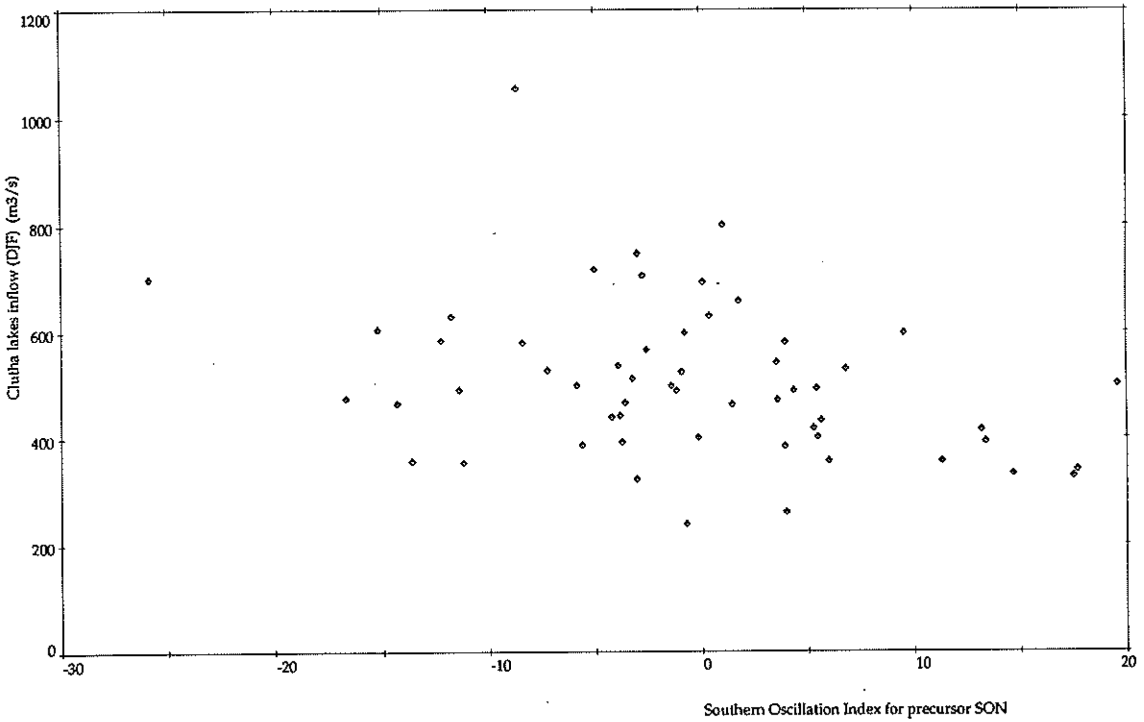


FIG. 6—Plot of Clutha lake inflows for DJF against the precursor SOI during SON.

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Manuscript received 2 July 1993, accepted for publication 5 November 1993