Large-scale climate control on lake inflow in the Waitaki basin, New Zealand

DANIEL G. KINGSTON[1], CLARE S. WEBSTER[1] & PASCAL SIRGUEY[2]
1 Department of Geography, University of Otago, PO Box 56, Dunedin, New Zealand
daniel.kingston@otago.ac.nz
2 School of Surveying, University of Otago, PO Box 56, Dunedin, New Zealand

Abstract Improved understanding of causes of inflow to the main headwater lakes of the Waitaki basin (South Island, New Zealand) is an important challenge of direct practical relevance due to the role of this basin for hydroelectric power generation. This challenge is addressed here via investigation of large-scale climate drivers of monthly inflow to the three main Waitaki headwater lakes, Ohau, Pukaki and Tekapo. Analyses are undertaken using a novel combination of composite, correlation and wavelet analyses. Composite analysis indicates that variation in lake inflow is driven primarily by the strength of the NE–SW pressure gradient over the three lakes (i.e. parallel to the axis of the Southern Alps, from which the lakes originate). Correlation and wavelet analysis indicates that these conditions are described well by the MZ1 and MZ2 New Zealand-based circulation indices, but not larger-scale modes of atmospheric circulation.

Key words lake inflow; large-scale climate; atmospheric circulation; Trenberth indices; New Zealand

INTRODUCTION

In New Zealand, surface freshwater is a key national resource for the generation of electricity, and is important regionally for irrigation. The Waitaki basin in the South Island of New Zealand is the most important basin nationally for electricity generation, supplying about a third of the hydroelectricity or about 17% of total electricity generation (Electricity Authority, 2011).

Climate is generally acknowledged as the primary driver of river flow (e.g. Laize *et al*., 2010). Similarly, river flow and storage in lakes mitigate small-scale variation in climate inputs across the basin due to the integrative effects of hydrological buffering (e.g. Cayan, 1999). In the South Island of New Zealand, large-scale climate is particularly influential, owing to the orientation of the main axial mountain range (the Southern Alps) perpendicular to prevailing mid-latitude westerly winds, combined with the influence of two major modes of atmospheric variation: the Southern Oscillation (SO, and associated ocean mode, El Nino, together: ENSO) and Southern Annular Mode (SAM). In addition to indices of such large-scale patterns, atmospheric circulation over New Zealand has also been characterised by local-scale circulation indices – in particular, the so-called “Trenberth indices” (Trenberth, 1976; Salinger & Mullan, 1999), which quantify the strength of the meridional and zonal pressure gradient over New Zealand.

A number of studies have sought to characterise the relationship of ENSO and SAM to New Zealand river flow and lake inflow. However, relatively few have considered a process-based hydroclimatological approach to understanding the entire process cascade from atmospheric circulation to regional climate and subsequently river flow. Furthermore, previous studies have focused generally on prediction rather than concurrent relationships (e.g. McKerchar & Pearson, 1994; McGowan & Sturman, 1996; McKerchar *et al*., 1996, 1998; Moseley, 2000). Such studies have typically reported statistically significant but only weak-to-moderate relationships between ENSO/SAM and South Island lake inflow. Although the focus on prediction is understandable given the importance for electricity generation, a more robust understanding of concurrent relationships may provide an improved basis for the development of predictions.

Given the importance of large-scale climate for New Zealand and our understanding of the role of large-scale modes of variation such as ENSO and SAM, the relatively weak ENSO/SAM–river flow relationships are unexpected. The work described herein seeks to refine our understanding of the circulation–climate–inflow relationships for the three main headwater lakes in the Waitaki basin, namely lakes Ohau, Pukaki, and Tekapo. Two approaches are adopted to achieve this aim. Firstly, climate conditions associated with high and low lake inflow into the headwater Waitaki lakes are investigated through an environment-to-climate composite analysis

(Yarnal, 1993). This allows modes of atmospheric circulation variation that are most influential for Waitaki lake inflow to be identified. Secondly, a more direct characterisation of the statistical relationships between atmospheric patterns identified by approach 1 and lake inflow is undertaken (i.e. a climate-to-environment approach). Climate-to-environment relationships are investigated using both simple (correlation) and sophisticated (wavelet analysis) time series analysis techniques. This combination of approaches represents a novel means of quantifying the full cascade of processes from atmospheric circulation to regional climate and river flow.

DATA AND STUDY SITES

Lakes Ohau, Pukaki, and Tekapo form the three major headwater basins of the larger Waitaki River (11 900 km^2). The outlet rivers of the three lakes combine with the Ahuriri River to form the Waitaki River, New Zealand's fourth largest river. The Waitaki drains from the Southern Alps in an approximate southwesterly direction towards the east coast of the South Island (Fig. 1). Lakes Ohau, Pukaki and Tekapo have basin sizes of 1372, 1457, and 1148 km^2, respectively. The alpine nature of these sub-basins means that an important fraction of precipitation falls as snow. The highest inflows for all three lakes occur during summer, with annual low flows during winter. The majority of inflows are derived from seasonal snow and ice melt, together with northwesterly rainfall events (McGowan & Sturman, 1996, Sirguey *et al*., 2009).

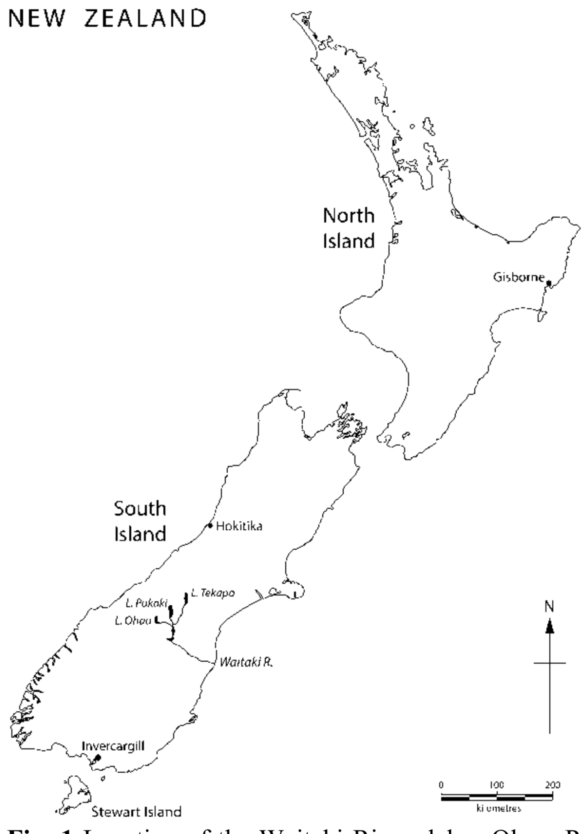


Fig. 1 Location of the Waitaki River, lakes Ohau, Pukaki and Tekapo, and the station centres for the MZ1 and MZ2 indices.

Climate within the upper Waitaki basin is varied and complex, ranging from high alpine (Aoraki/Mount Cook, 3764 m) through to the inter-montane Mackenzie valley (approx. 500 m) in which the three headwater lakes terminate. An extremely strong precipitation gradient is present in the upper Waitaki, with headwater annual totals estimated at 15 000 mm, falling to lower than 700 mm $year^{-1}$ at the termini of the three lakes (Kerr *et al*., 2011).

Daily lake inflow records for Pukaki, Ohau and Tekapo are available from the 1920s to the present day, and were obtained from Meridian Energy (Pukaki and Ohau) and Genesis (Tekapo), the current operators of the associated hydroelectricity generation schemes for these lakes. The NCEP/NCAR reanalysis (Kalnay *et al*., 1996) was the primary climate dataset used herein. Although this first generation reanalysis dataset is less sophisticated than later reanalysis products, it has the advantage of covering a long time period, from 1948 to the present. Results were also checked against the shorter but more recent ERA Interim reanalysis. Geopotential height at 800 and 500 hPa were used as descriptors of the general circulation. Additional weather station data were obtained for the upper Waitaki basin (namely the Mt Cook automatic weather station, located near the head of Lake Pukaki). Atmospheric circulation pattern index data were obtained from the following sources: the SAM index (Marshall, 2003); the SOI (Trenberth, 1984); and the New Zealand-based Trenberth indices (Trenberth, 1976; Salinger & Mullan, 1999).

METHODS

An environment-to-climate approach using composite analysis (Yarnal, 1993) was used to determine the large-scale climate control on lake inflow in the upper Waitaki. For each month of the year, composites of climate conditions during high and low lake inflow years were generated. A monthly time-step was used to eliminate influence of the seasonal cycle on the identification of instances of high and low inflow. Composite analysis is a robust and conceptually simple technique that is well suited for hydroclimatological research (e.g. Kingston *et al*., 2007, 2009). Furthermore, the open-ended nature of an environment-to-climate approach means that the analysis is not limited to analysing only pre-specified circulation patterns (i.e. the SO and SAM).

Following analysis of the inflow time series for each lake, high and low inflow years were defined as the upper and lower quartiles for each lake inflow time series. For the period of the NCEP/NCAR reanalysis data set, this resulted in a composite size of 16 such years. Composite climate conditions were calculated for high and low inflow years for each month and for each lake. Similarly, high minus low inflow composite anomaly patterns were calculated. The two-sample t-test was used to determine whether composite anomalies were statistically significant.

Following the identification of large-scale controls and modes of variation important for Waitaki inflow, the analysis was "reversed" – i.e. a climate-to-environment analysis was undertaken. This was achieved firstly through correlation of lake inflow with circulation pattern indices, using Spearman's Rank. This non-parametric correlation technique is used to guard against possible skewed data and nonlinear relationships. Secondly, a wavelet analysis was employed to provide further detail on the link between lake inflow and circulation index time series. This non-stationary spectral analysis method involves a decomposition of the signals into time-frequency space, which reveals the partition of power in terms of timing and periodicity and so allows comparison to be made between different signals (Torrence & Compo, 1998). Here the Torrence & Compo (1998) implementation in MATLAB® of a Morlet wavelet was used. The inflow time series were first de-trended and filtered to remove the 1-year period associated with the natural hydrological cycle, to better reveal the distribution of power at other time-scales that could be associated with circulation pattern signals. A lag-1 autocorrelation coefficient was computed for each signal and used to model a red-noise spectrum to infer the significant components (95% confidence level) of the wavelet power spectrum (Torrence & Compo, 1998).

RESULTS

Environment-to-climate

High and low inflow years are largely similar for each month across the three lakes. As such, only results from Lake Pukaki are shown. The strongest and most consistent differences in geopotential height between high and low inflow years occur from spring to early summer (i.e. September–December). Similar patterns occur in both sea level pressure and geopotential height at the 800 and 500 hPa levels. The patterns consist primarily of a NE–SW pressure gradient formed by anomalously high pressure to the northeast and anomalously low pressure to the southwest of New Zealand (Fig. 2). This pressure gradient is strongest during high inflow months. Analysis of the surface and upper level wind fields indicates that a stronger NE–SW pressure gradient results in strong northwesterly winds over the South Island (relative to low flow conditions; Fig. 2). Differences in geopotential height and wind vector between high and low inflow composites follow similar patterns for the remainder of the year, but are weaker (and in some cases not statistically significantly different).

Analysis of rainfall records from the Mt. Cook rainfall station indicates that high inflow years for a given month correspond to high precipitation totals. For example, the mean October precipitation during Pukaki high flow years is 666 mm, and only 190 mm during low flow years, a difference which is statistically significant ($p < 0.01$, independent samples t-test). This difference indicates that concurrent climate is important for variation in monthly lake inflow.

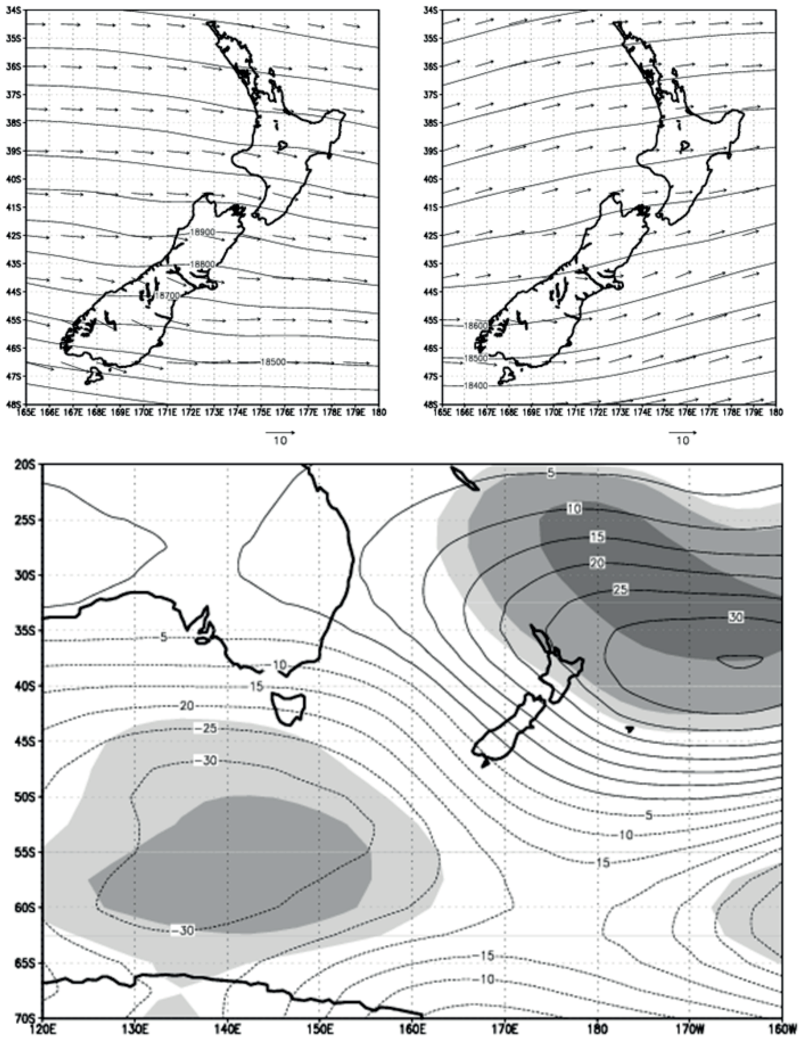
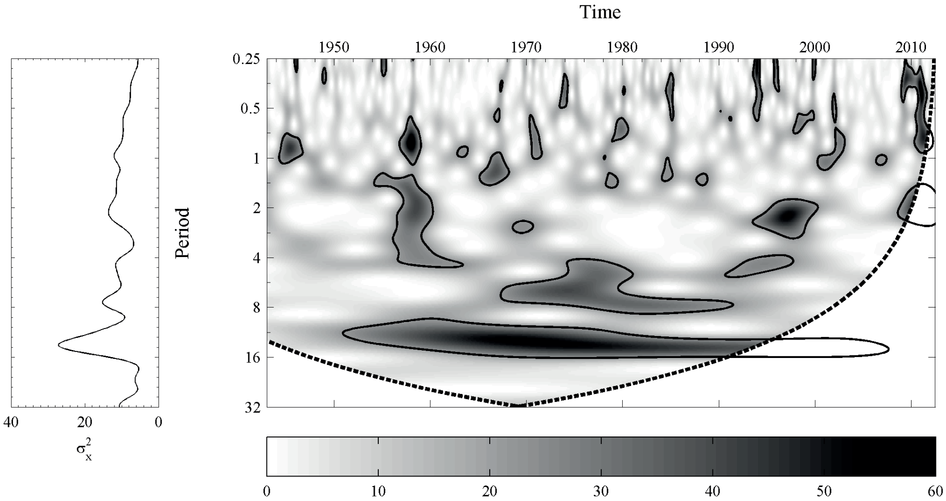


Fig. 2 Upper: composite October high (left) and low (right) inflow 800 hPa wind vector (m s^{-1}, arrow length indicates magnitude). Lower: October high minus low inflow 800 hPa geopotential height anomaly (m), shading indicates statistical significance at p = 0.1, 0.05, 0.01 from light–dark.

Climate-to-environment

The clear NE–SW pattern of circulation anomalies that is at its peak from September to December strongly resembles the characteristic anomalies described by the MZ1 and MZ2 circulation indices. This is to be expected, given the clear alignment of the composite anomalies along the axes of these indices (MZ1: Gisborne-Hokitika; MZ2: Gisborne-Invercargill; Figs 1 and 2). Rank correlation of these two circulation indices with monthly inflow for all three lakes supports the presence of a relationship, with statistically significant ($p \leq 0.05$) correlation coefficients of up to 0.74 between inflow and at least one of the MZ1 and MZ2 in every month of the year except May. Statistically significant coefficients are present for the other Trenberth indices in some months of the year, but in all months except February higher coefficients for all three lakes can be obtained using either the MZ1 or MZ2 indices. The correlation of monthly lake inflow with indices of the SAM and SOI was also investigated. Very few statistically significant coefficients were found, with relatively low correlation occurring in just one or two months of the year.

A comparison of the wavelet spectra for each of the three lakes with those of the MZ1 and MZ2 add further support to the presence of a statistical relationship between these time series, and provide additional information with respect to the timing and periodicity of this connection. The Pukaki, MZ1 and MZ2 time series share variation at multiple timescales from 1948 to 2010 (Fig. 3; MZ2 not shown). In particular, shared variation is apparent at the 16-year period from *ca*. 1965–1990, 4-year period from 1970 to 2000, with smaller intervals of shared variation at the one and two year timescales throughout. Such coincident distribution of power components at various timescales further supports the hypothesis of a relationship between MZ1 and lake inflow.



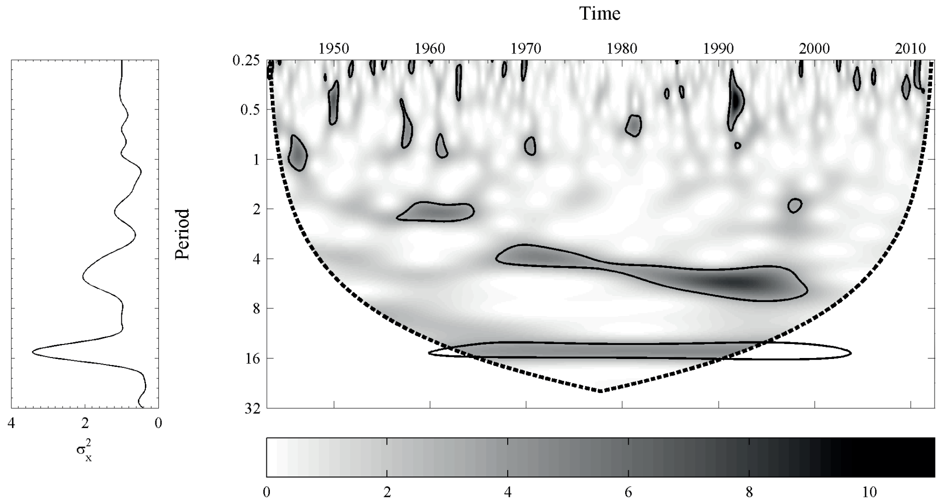


Fig. 3 Wavelet power spectra for Lake Pukaki (upper) and the MZ1 (lower) time series. The period axis is in years. The thick dotted line indicates the Cone of Influence; the solid line indicates the significant peaks of power based on a lag-1 autoregressive red-noise.

DISCUSSION AND CONCLUSION

The series of differences in large- and local-scale climate between high and low inflow months identified herein are physically consistent with the occurrence of high and low lake inflow. An enhanced northwesterly airflow is commonly associated with increased precipitation due to the adiabatic cooling of the moist air mass as it lifts against and spills over the topographic barrier of the Main Divide (McGowan & Sturman, 1996). Composites from a local station (Mt Cook) confirm that more precipitation occurs under such conditions. Although not examined here, increased temperatures are also common under northwesterly airflow, and are again physically consistent with increased inflow due to the resultant increase in snow and ice melt and a reduced proportion of precipitation falling as snow (McGowan & Sturman, 1996).

The MZ1 and MZ2 circulation indices perform well at capturing variations in the strength of the northwesterly circulation over the Southern Alps, due to the axes of these indices being approximately parallel to this mountain range. Few previous studies have focused on the role of these indices for New Zealand climate. However, a robust relationship has been identified herein from both correlation and wavelet analysis, with a physical mechanism also suggested via composite analysis. As such, this is likely to be a promising avenue for further research. Indeed, Purdie & Bardsley (2010) found that the MZ2 had some skill as a predictor of Pukaki and Tekapo inflow.

The absence of a link between Waitaki lake inflow and larger regional-scale modes of circulation variation (i.e. ENSO and SAM) was unexpected. For example, McGowan & Sturman (1996) found that the SOI was a statistically significant predictor of Tekapo inflow. Similarly, a series of linked studies (McKerchar & Pearson, 1994; McKerchar *et al*., 1996, 1998) described a link between the SOI and South Island lake inflow, via a link to seasonal snow accumulation. However, it should be noted firstly that none of these studies explored the physical link from the SOI to flow generating climate variation, relying on statistical analysis instead. Secondly, these studies are all concerned with prediction, rather than concurrent relationships. It may be that stronger links can be obtained when lagged ocean–atmosphere relationships are considered, for example due to ENSO/SAM-related climate anomalies influencing the storage of frozen water rather than more immediate flow generating climate variation (i.e. rainfall). A matter for further study is the extent to which the concurrent MZ–lake inflow relationships are influenced (at concurrent and lagged timescales) by larger regional-scale modes such as SAM and ENSO.

Acknowledgements This work was supported by a University of Otago Research Grant. Les O'Neill (University of Otago) produced Fig. 1.

REFERENCES

Cayan, D. R., Redmond, K. T. & Riddle, L. G. (1999) ENSO and hydrologic extremes in the western United States. *J. Climate* 12, 2881–2893.

Electricity Authority (2011) *Electricity in New Zealand.* Electricity Authority/Te Mana Hiko.

Kalnay, E. *et al.* (1996) The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Met. Soc*. 77, 437–471.

Kerr, T., Owens, I. F. & Henderson, R. D. (2011) The precipitation distribution of the Lake Pukaki Catchment. *J. Hydrol., NZ* 50, 361–382.

Kingston, D. G., McGgregor, G. R., Hannah, D. M. & Lawler, D. M. (2007) Climatic controls on New England streamflow. *J. Hydrometeor*. 8, 367–379.

Kingston, D. G., Hannah, D. M., Lawler, D. M. & McGregor, G. R. (2009) Climate–river flow relationships across montane and lowland environments in northern Europe. *Hydrol. Processes* 23, 985–996.

Laize, C. L. R. & Hannah D. M. (2010) Modification of climate-river flow associations by basin properties. *J. Hydrol*. 389, 186–204.

Marshall, G. J. (2003) Trends in the Southern Annular Mode from observations and reanalyses. *J. Climate* 16, 4134–4143.

McGowan, H. A. & Sturman, A. P. (1996) On the application of hydrometeorological techniques to the forecasting of inflows into alpine hydro-lakes. *Physical Geography* 17, 513-533.

McKerchar, A. I. & Pearson, C.P. (1994) Forecasts of seasonal river flows using southern oscillation index. *J. Hydrol*. 32, 16–29.

McKerchar, A. I., Pearson, C. P. & Moss, M. E. (1996) Prediction of summer inflows to lakes in the Southern Alps, NZ, using the spring southern oscillation index. *J. Hydrol*. 184, 175–187.

McKerchar, A. I., Pearson, C. P. & Fitzharris, B. B. (1998) Dependency of summer lake inflows and precipitation on spring SOI. *J. Hydrol.* 205, 66–80.

Mosley, M. P. (2000) Regional differences in the effects of El Niño and La Niña on low flows and floods. *Hydrol. Sci. J.* 45, 249–267.

Purdie, J. M. & Bardsley, W. E. (2010) Seasonal prediction of lake inflows and rainfall in a hydro-electricity catchment, Waitaki River, New Zealand. *Int. J. Climatol.* 30, 372–389.

Salinger, J. M. & Mullan, A. B. (1999) New Zealand climate: temperature and precipitation variations and their links with atmospheric circulation. *Int. J. Climatol.* 19, 1049–1071.

Sirguey, P., Mathieu, R., Arnaud, Y. & Fitzharris, B. B. (2009) Seven years of snow cover monitoring with MODIS to model catchment discharge in New Zealand. In: *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium*, II, 863–866.

Torrence, C. & Compo, G. P. (1998) A practical guide to wavelet analysis. *Bull. Am. Met. Soc.* 79, 61–78.

Trenberth, K. E. (1976) Fluctuations and trends in indices of the southern hemispheric circulation. *Quart. J. R. Met. Soc.* 102, 65–75.

Trenberth, K. E. (1984) Signal versus noise in the Southern Oscillation. *Monthly Weather Rev.* 112, 326–332.

Yarnal, B. (1993) *Synoptic Climatology in Environmental Analysis*. Belhaven Press, 195 pp.