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Reconstructing annual inflows to the headwater catchments of the Murray River, Australia, using the Pacific Decadal Oscillation

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Abstract

The Pacific Decadal Oscillation (PDO) is a major forcing of inter-decadal to quasi-centennial variability of the hydroclimatology of the Pacific Basin. Its effects are most pronounced in the extra-tropical regions, while it modulates the El Nino Southern Oscillation (ENSO), the largest forcing of global inter-annual climate variability. PalaeoPDO indices are now available for at least the past 500 years. Here we show that the >500 year PDO index of Shen et al. (2006) is highly correlated with inflows to the headwaters of Australia's longest river system, the Murray-Darling. We then use the PDO to reconstruct annual inflows to the Murray River back to A.D. 1474. These show penta-decadal and quasi-centennial cycles of low inflows and a possible 500 year cycle of much greater inflow variability. Superimposed on this is the likely influence of recent anthropogenic global warming. We believe this may explain the exceptionally low inflows of the past decade, the lowest of the previous 529 years.

Keywords

catchments, murray, river, australia, inflows, headwater, annual, pacific, decadal, reconstructing, oscillation, GeoQUEST

Disciplines

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Reconstructing annual inflows to the headwater catchments of the Murray River, Australia, using the Pacific Decadal Oscillation

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1. Introduction

[2] Over the past 20 years it has become apparent that severe drought in Australia is not random, but is heavily influenced by cyclic climate patterns. The pattern that has attracted most attention has been the El Niño Southern Oscillation (ENSO) phenomenon. ENSO has been shown to explain up to 40% of seasonal rainfall variability, particularly in northeastern Australia [*Drosdowsky and Williams*, 1991], and to teleconnect globally to affect climates from Canada to Antarctica [*Gan et al.*, 2007; *Romolo et al.*, 2006; *Gregory and Noone*, 2008]. El Niño conditions typically occur every 3 to 7 years [*Cane*, 1986] with impacts often short lived, spanning several months to slightly more than 1 year. While the ENSO effects on local to regional climate and hydrological systems can be severe, they are typically transient, before a return to more "normal" conditions. Water supply infrastructure can therefore be designed to have sufficient capacity to meet demands at these timescales. However, low inflows during prolonged drought or drought sequences that span several years to more than a decade present a greater challenge to environmental and water resource managers.

[3] The Pacific Decadal Oscillation (PDO) is a long lived ENSO-like phenomenon that affects the Pacific Basin on multi-decadal time scales. During positive index warm phases of the PDO, the eastern Pacific experiences warm Sea Surface Temperature (SST) anomalies, while below average SSTs affect the central and western Pacific Ocean. Negative phases of the PDO index are associated with opposite conditions that result in a large horseshoe region of anomalously warm SSTs in the western Pacific. Changes between these states have occurred at bi-decadal (23–28 yr) and penta-decadal (50–70 yr) timescales over the past century [*MacDonald and Case*, 2005; *Shen et al.*, 2006]. *Allan et al.* [2003] and *Verdon and Franks* [2006] concluded that these changes in SST may modulate the higher frequency ENSO with El Niño events dominant during +PDO phases.

[4] Australia's weather and climate have been shown to respond to the PDO [e.g., *Mantua and Hare*, 2002; *Power et al.*, 2006; *Pezza et al.*, 2007] with positive phases linked to increased drought risk [*Kiem and Franks*, 2004]. This has been highlighted over the past two decades with a +PDO and El Niño events affecting climates over much of eastern Australia. At inter-annual timescales El Niño events modulate Australian rainfalls, with rainfalls affected most during winter and spring [*McBride and Nicholls*, 1983]. *Murphy and Timbal* [2008] showed that for the previous 12 El Niño's when the Southern Oscillation Index (SOI) was less than −8 (June–November), rainfall in the east of the continent including the Murray Basin was in the lowest tercile. The severity of these El Niño droughts is thought to be dependent on the location of equatorial Pacific positive SST anomalies and their effect on atmospheric subsidence over Australia [*Wang and Hendon*, 2007]. Less rainfall during El Niño is also believed to cause higher air temperatures due to reduced cloud cover, with lower soil moisture contributing to higher surface sensible heat flux [*Nicholls*, 2003; *Power et al.*, 1998; *Timbal et al.*, 2002].

[5] The PDO index is defined as the leading principal component of monthly SSTs in the Pacific Ocean north of 20°N [*Mantua and Hare*, 2002]. Many historical hydrometeorological records document regime changes in the PDO in the mid-1940s (warm to cool) and mid-1970s (cool to warm). Interpretation of recent satellite images suggests that another change is in progress (warm to cool). Instrument records therefore only record three regime changes. This is inadequate to capture longer term variability in the PDO such as change in amplitude and/or periodicity. This infor-

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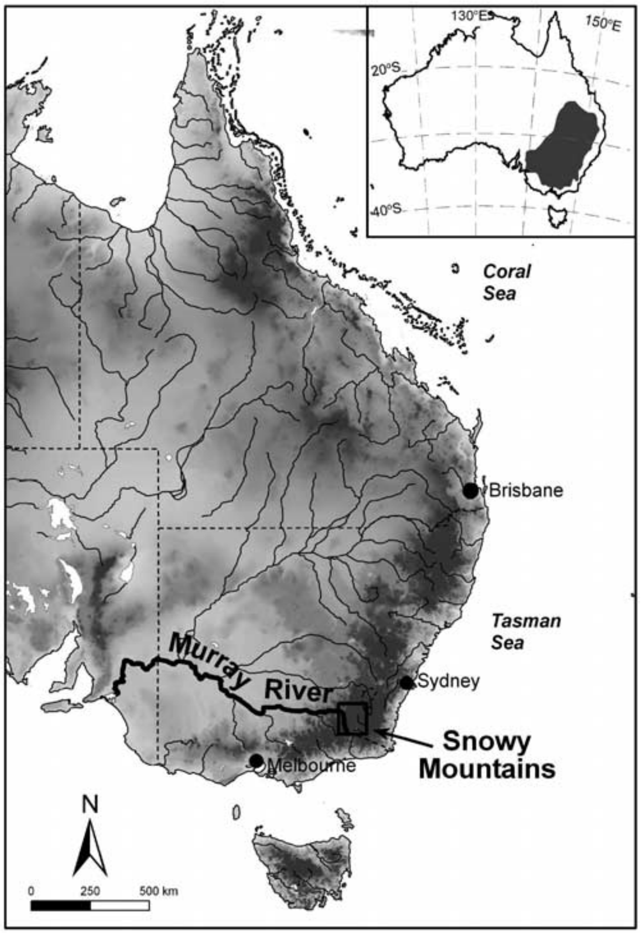

Figure 1. Location map showing the Murray River and the area of its headwater catchments in the Snowy Mountains. Insert shows the Murray-Darling Basin (shaded).

mation is required to improve understanding of the causes and magnitude of natural variability in regional hydro-climatology, particularly at inter-decadal time scales. In Australia, the most developed arid continent, this information is critical to the design of informed medium to long term water resource management policy.

2. Physical Setting and Method

[6] The Murray River runs for almost 2500 km from its headwaters in the Snowy Mountains to its mouth in South Australia. Its catchment forms a large proportion of the 1.07×10^6 km^2 Murray-Darling river system (Figure 1), the fourth largest in the world [*Barros and Bowden*, 2008]. Flows in the river are highly variable, reflecting climate variability in the systems large sub-catchments. An extensive network of dams and reservoirs have been constructed along the Murray River to mange its flow, to secure water supply to urban centers, and to generate hydro-electricity. Extensive irrigation systems that are reliant on water from the river support much of the Basin's agricultural product, which accounts for approximately 40% of Australia's total agricultural production [*Barros and Bowden*, 2008].

[7] Widespread severe drought in the catchments of the Murray River have seen inflows over the period 2001 to 2008 the lowest on record [*Murphy and Timbal*, 2008; *Cai and Cowan*, 2008] - a period dominated by El Niño and +PDO conditions. *Cai and Cowan* [2008] concluded that this most recent drought sequence could not be explained by a decline in rainfall alone, and that record high temperatures due to global warming were having a strong affect on water resources in the Murray-Darling Basin. They found an increase of 1°C in temperature led to approximately a 15% decrease in climatological annual inflows. This study followed that by *Nicholls* [2005] which concluded that recent decline in spring snow depth in the alpine headwaters of the Murray River was most likely associated, at least in-part, to the enhanced greenhouse effect.

[8] Understanding the natural climatic drivers of variability in the hydrology of the Murray River, particularly at decadal timescales when existing water infrastructure and water management policy can not meet all demands is of critical importance. At these timescales the PDO is important as a forcing of hydroclimatic variability [*Kiem and Franks*, 2004] on which anthropogenic forcing of climate as suggested by *Cai and Cowan* [2008] will be superimposed.

[9] The longest observational record of the PDO is available from the University of Washington from 1900 to present (http://jisao.washington.edu/pdo/PDO.latest) and was used by this study for calibration and verification. Two reconstructed PDO indexes where also obtained from the World Data Center for Paleoclimatology, NOAA (http://www.ncdc.noaa.gov/paleo/paleo.html). These were the record of *MacDonald and Case* [2005] constructed from tree-ring chronologies from Alberta, Canada and San Gorgonio in Southern California from A.D. 993–1996, and the *Shen et al.* [2006] record constructed from 530 years of historical flood-drought records from eastern China from A.D. 1470–2000. Mean annual total inflows into the headwater catchments of the Murray River were obtained from Snowy Hydro Limited from 1900 to 2007.

[10] Correlation analysis of total annual inflows with the constructed PDO indexes identified the strongest association with the *Shen et al.* [2006] PDO index. As a result, this index was selected and ten year running mean values where computed for the constructed PDO and total annual inflows from 1904 to 1994. This filtered the influence of temporally shorter climate variability such as associated with ENSO. Piecewise polynomial interpolation was then applied to generate a smoothing spline model to compute inflows using the *Shen et al.* [2006] PDO. Modeled inflows were compared to recorded inflows (Figure 2) for the 90 year training period. This returned a root mean square error of 184.8 Gl ($\approx$5%). Mean total inflows were then computed using the ten year running mean values of the *Shen et al.* [2006] PDO index back to A.D. 1474. A weighted moving average filter was then applied to remove extreme variability in computed values.

3. Results

[11] Modeled inflows into the headwater catchments of the Murray River for 520 years from A.D. 1474 to 1994 are presented in Figure 3. These show periods of increased variability of inflows from the mid-1930s to the mid-1990s,

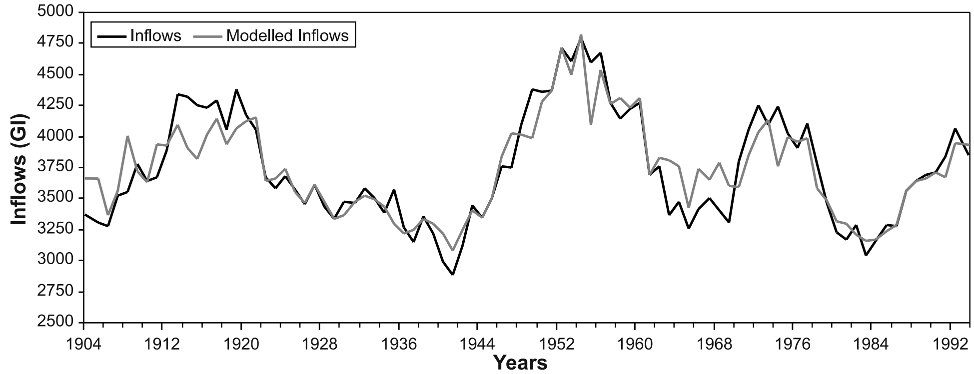

Figure 2. Ten year running mean inflows to the headwater catchments of the Murray River and modelled inflows using the *Shen et al.* [2006] PDO from A.D. 1904–1994.

and from A.D. 1474 to 1600. This early period experienced three very wet cycles centered on A.D. 1594, 1554 and just before 1474, with computed ten year mean annual inflows exceeding 4400 Gl. From A.D. 1640 to the early 1920s inflows fluctuated over a lower range of values with no extreme wet or dry sequences. The lowest inflows of the 520 year record occurred in the late 1930s, early 1940s and 1980s—periods of severe drought across southeastern Australia.

[12] The ten year running mean total inflow for 2003, the most recent year of the current drought sequence for which a running ten year mean could be calculated was 2951 Gl. This value is the lowest inflow of the past 529 years. It is 310 Gl. less than the next lowest value computed for 1939 of 3261 Gl. highlighting the severity of the most recent drought.

[13] The modeled inflows display penta-decadal dry sequences since 1800 occurring around A.D. 1820, 1880, 1939 and 1982. *Sturt* [1834], *Jevons* [1859], *Foley* [1957] and *Kimber* [1997] reported the effects of drought around A.D. 1820 and 1880 in southeastern Australia, while the droughts around A.D. 1939 and 1982 have been discussed widely [see *Stone and Partridge*, 2003]. Quasi-centennial dry sequences are evident before A.D.1800, most notably around A.D. 1510 and 1610 and are concurrent with +PDO phases of the *Shen et al.* [2006] index. There is also evidence of a lower frequency ≈500 year cycle of greater variability of inflows in the mid to late 1500s and again in the late 20th century. *MacDonald and Case* [2005] also presented evidence of a 500 year PDO cycle from their analysis of tree rings from the north-eastern Pacific.

4. Discussion

[14] The PDO is increasingly acknowledged as a robust feature of inter-decadal to centennial climate variability throughout the northern Pacific region [see *Shen et al.*, 2006; *MacDonald and Case*, 2005; *Gedalof and Smith*, 2001]. Evidence from corals and historical records including crop yields and river flows also indicate that the PDO has considerable influence over the climate of the southwest Pacific and Australia [see *Linsley et al.*, 2000; *Power et al.*, 1999; *Crimp and Day*, 2003]. In this region, variability of extra-tropical synoptic weather systems in relation to decadal variability of the Pacific Ocean and PDO, is believed to be less influenced by the Southern Oscillation (SO) than the closely related Interdecacal Pacific Oscillation (IPO) [see *Power et al.*, 1999; *Folland et al.*, 2002]. On this basis, we infer that the PDO is a robust indicator of interdecadal to centennial variability of the hydroclimatology of southeastern Australia including the Murray River.

[15] Climate variability at decadal time scales often determines the viability of agriculture in marginal settings where prolonged drought may exceed design capacities of

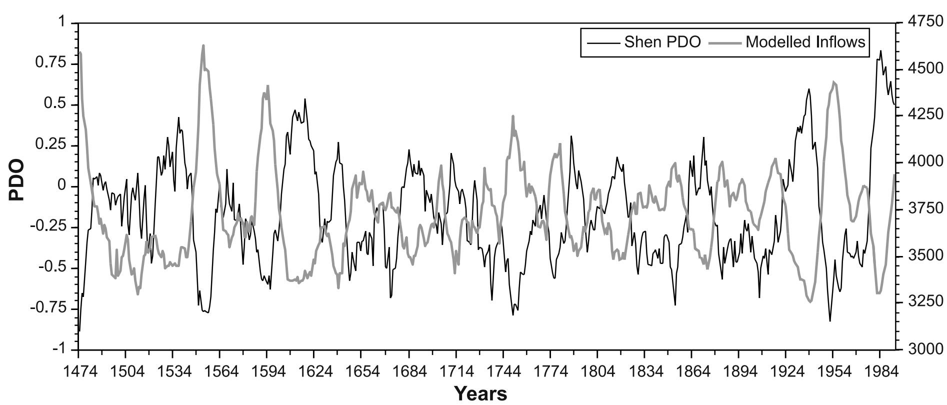

Figure 3. Inflows to the headwater catchments of the Murray River from A.D. 1474–1994 modelled using the *Shen et al.* [2006] PDO.

water supply infrastructure. Ongoing drought conditions and low inflows to the Murray River, arguably Australia's most important river system, have over the past decade highlighted the vulnerability of Australia's agriculture, towns and cities to water scarcity. Results presented here indicate that at decadal timescales, the PDO is a major influence on inflow variability, and that toward the end of +PDO phases, inflows to river systems such as the Murray River may reach historic lows. Of concern are the unusually low inflows of the current drought sequence. While exact cause(s) of these unmatched low inflows remains equivocal, their unusual character in the context of our reconstructed inflow record lends support to the results of *Cai and Cowan* [2008] of an enhanced greenhouse effect already reducing inflows to the Murray River.

[16] *Pezza et al.* [2007] using ERA40 and NCEP reanalysis data found evidence of the PDO being linked to storm tracks around Antarctica and the mid-latitudes. Over the Tasman Sea, a region were synoptic systems have significant impact on the weather of southeastern Australia their study identified more and stronger cyclones during −PDO phases. The opposite was found to occur during +PDO phases, when anticyclonic circulation was more common to the south of Australia [*Pezza et al.*, 2007]. PDO forced change in synoptic circulation affects precipitation and temperature regimes in the study area. Positive PDO phases produce drier and warmer conditions with less frequent precipitation bearing weather systems affecting the headwater catchments of the Murray River. As a result, winter and spring snowfalls and subsequent snowmelt are less resulting in smaller inflows. The opposite may occur during −PDO phases. This is supported at decadal timescales by our results which show the very strong link between the PDO and inflows to the headwaters of the Murray River, which are very reliant on winter snowfall followed by warm spring rains. Rain is required to effectively flush snowmelt into the rivers, thereby reducing the amount of snowpack that is lost to evaporation and sublimation.

[17] Warm cool season rains in southeastern Australia are associated with tropical-extra-tropical cloudbands, which if they interact with mid-latitude systems, may produce significant rainfall in the headwaters of the Murray River [*Wright*, 1997]. *Wright* [1997] found evidence that the occurrence of these conveyors of tropical moisture into the mid-latitudes appeared to be affected by ENSO which is modulated by the PDO. The reappearance of significant cloudband events over central and southeastern Australia may reflect the current change to −PDO conditions. Clearly this is an area that requires further study, particularly as snow cover in the headwaters of the Murray River shows signs of decline, possibly due to global warming [*Nicholls*, 2005]. As a result, there is urgent need to understand the role of the PDO and other teleconnections in regional atmospheric moisture budgets.

[18] Results presented here highlight the importance of understanding medium to longer term drivers of regional hydrometeorology. Our reconstructed inflow series indicates that we may have entered a period of greater natural inflow variability similar to that of the 1500s that is possibly associated with a ≈500 yr PDO cycle [*MacDonald and Case*, 2005; *Shen et al.*, 2006]. Implications are that both wet and dry periods may become more extreme, although the impact of the enhanced greenhouse effect on the PDO is unknown. Nonetheless, our results show the need to consider such variability in the design of water allocation policy and infrastructure, and the management of environmental systems along the Murray River including river red gum (*Eucalyptus camaldulensis*) forests, and wetlands. As the effects of the PDO are felt Pacific wide, the implications of our findings are truly regional, particularly in the extra-tropical regions including eastern China [*ZhuGuo*, 2007], where drought/flood cycles on which the *Shen et al.* [2006] PDO is based have been shown here to be highly correlated with the hydroclimatology of southeastern Australia.

5. Conclusion

[19] Results presented here show the PDO to be a robust indicator of the hydroclimatology of the headwaters of the Murray River. This supports previous findings by *Kiem et al.* [2003] and *Verdon et al.* [2004] of significant inter-decadal variability of river flows in southeastern Australia associated with the closely related IPO. Using the *Shen et al.* [2006] PDO record we have modeled inflows to the headwater catchments of the Murray River back to A.D. 1474. These show penta-decadal and quasi-centennial cycles with lowest inflows toward the end of +PDO phases. Lower frequency penta-centennial variability may also occur, although this remains equivocal highlighting the need for longer PDO/inflow records. Interestingly, inflows during the past decade are far less than the lowest of the modeled inflow record for the previous 529 years. Whether this reflects a global warming signal on the hydroclimatology of southeastern Australia is unknown. However, it highlights the urgent need for future studies to reconstruct inflows to rivers of critical national importance such as the Murray River, preferably using a locally derived PDO index which is likely to better reflect local conditions.

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