

Inter-decadal Pacific Oscillation Modulation of the Impact of El Niño/Southern Oscillation on Australian Rainfall and Streamflow

F.H.S. Chiew and M.J. Leahy

Cooperative Research Centre for Catchment Hydrology, Australia
Department of Civil and Environmental Engineering, University of Melbourne, Australia
fchs@civenv.unimelb.edu.au

Abstract: The relationship between hydroclimate and El Niño/Southern Oscillation (ENSO) has been used in forecasting rainfall and streamflow. This paper presents a lag correlation analysis using rainfall and streamflow data from 284 Australian catchments that show that the ENSO-hydroclimate relationship is a lot stronger when the Inter-decadal Pacific Oscillation (IPO) phase is negative compared to when it is positive. The remarkable contrast in the hydroclimate-ENSO relationship between the two IPO phases suggests that the IPO should be considered in developing forecast models, particularly for long lead-times.

Keywords: *Rainfall; Streamflow; El Niño; Southern Oscillation; Inter-decadal Pacific Oscillation; Correlation; Australia*

1. INTRODUCTION

El Niño/Southern Oscillation (ENSO) has been linked to climate anomalies throughout the world. The ENSO-hydroclimate teleconnection is particularly strong in Australia and can be exploited to forecast rainfall and streamflow several months ahead. The forecasts can benefit the management of water resources systems considerably, particularly in Australia where the streamflow variability is higher than elsewhere in the world (see Ropelewski and Halpert, 1987; Chiew and McMahon, 2002; and Chiew et al., 2003).

Recent studies have shown that the strength of the ENSO-rainfall teleconnection varies on inter-decadal time scales. The ENSO-rainfall signal appears to be relatively strong from the mid 1940s to late 1970s when the Inter-decadal Pacific Oscillation (IPO) is negative (low sea surface temperatures in the tropical Pacific Ocean), while there is little to no ENSO-rainfall signal before the mid 1940s and after 1980 when the IPO is positive (see Power et al., 1999; and McCabe and Dettinger, 1999).

This paper investigates the inter-decadal modulation of the impact of ENSO on rainfall and streamflow in 284 catchments throughout Australia. The discussions in this paper are of a general nature and are based on a simple lag correlation analysis of the linear regression between rainfall and streamflow versus various explanatory variables (ENSO, IPO

and serial correlation). A more detailed discussion on the hydroclimate-ENSO teleconnection in Australia and the potential for forecasting can be found in Chiew and McMahon (2003) while Power et al. (1999) discuss the IPO modulation of the impact of ENSO on Australia in some detail using data from several sites.

2. DATA

2.1 Rainfall and streamflow

Monthly rainfall and unimpaired streamflow time series data from 1901 to 1998 at 284 catchments are used. The catchments are concentrated in the more populated and important agricultural regions of Australia (see Figure 1). Except for north-east Australia, they reflect the historical streamflow data availability across Australia. The catchment areas are between 50 and 2000 km².

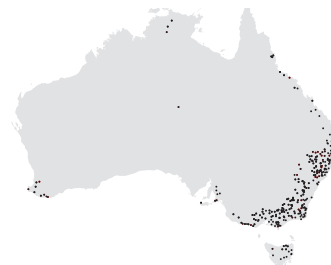


Figure 1. Locations of the 284 catchments analysed in this study.

The streamflow time series include data modelled using the daily conceptual rainfall-runoff model SIMHYD. The 284 catchments have between 25 to 70 years of streamflow data, with the streamflow data extended by running SIMHYD using the optimised parameter values obtained from the model calibration against historical streamflow data (see <http://audit.ea.gov.au/anra/water/docs/national/streamflow/streamflow.pdf>).

The source of the monthly rainfall data is the Queensland Natural Resources & Mines database of 0.05° by 0.05° interpolated gridded rainfall data based on over 6000 rainfall stations in Australia (see www.dnr.qld.gov.au/silo and Jeffrey et al., 2001). The lumped catchment-average rainfall for each of the 284 catchments is estimated by integrating the gridded rainfall falling within the catchment boundary.

2.2 SOI and IPO series

The Troup Southern Oscillation Index (SOI) is used as the ENSO indicator in this study (see www.bom.gov.au/climate/current/soihtml.shtml).

The SOI is defined as ten times the standardised value of the Tahiti minus Darwin sea level pressure. The SOI is commonly used in Australia and is highly correlated with other ENSO indicators such as the Multivariate ENSO Index (MEI) and sea surface temperatures (SSTs) in the tropical Pacific Ocean.

The Inter-decadal Pacific Oscillation (IPO) series from the UK Meteorological Office is used here. It is derived from empirical orthogonal function (EOF) analyses of global SSTs. The IPO series is derived by filtering the dominant EOF SST series (mainly SST in the tropical Pacific Ocean) using a low pass spectral filter with a 13.5-year cut-off. Power et al. (1999) showed that there is little difference between the IPO series derived from different sources.

The annual SOI and IPO time series are shown in Figure 2. The plots show contrast between the long time scale variability in the IPO series and the inter-annual variability in the SOI series. As the IPO series is derived from the SST time series, the tropical Pacific Ocean SST tends to be warmer in the positive IPO phase and cooler in the negative IPO phase. The SOI is negatively correlated to the tropical Pacific Ocean SST, and therefore the SOI tends to be negative in the positive IPO phase and positive in the negative IPO phase. For the period 1946-1977 when the IPO phase is negative, there are four years with average annual SOI above +10

(strong La Niña) and no year with SOI below -10. For the periods 1922-1944 and 1978-1997 when the IPO phase is positive, there are no average annual SOI above +10 and two SOI values in 1922-1944 and four SOI values in 1978-1997 below -10 (strong El Niño).

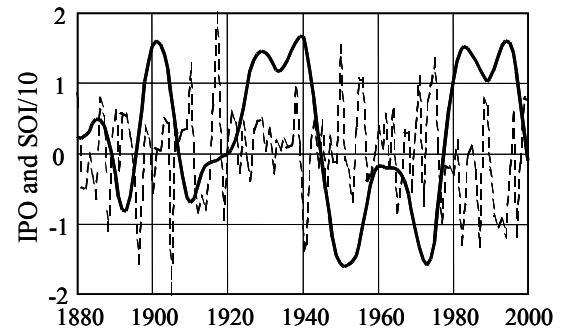


Figure 2. Annual IPO (thick line) and SOI (dotted line)

3. ANALYSIS AND DISCUSSION

3.1 Teleconnections during different IPO phases

The results presented and discussed in this paper are all based on the analyses of lag correlations of the linear regression between rainfall and streamflow versus explanatory variables in the previous season. Figure 3 summarises the lag correlations between Oct-Nov-Dec rainfall and streamflow versus Jul-Aug-Sep SOI in the 284 catchments for analyses over three periods: 1922-1944; 1946-1977; and 1978-1997. Figure 4 shows the lag correlations for Jan-Feb-Mar rainfall and streamflow versus Oct-Nov-Dec SOI. The results are presented for Oct-Nov-Dec and Jan-Feb-Mar rainfall and streamflow because the hydroclimate-ENSO teleconnection is stronger during this period than at other times of the year.

The plots show a remarkable contrast in the SOI influence on rainfall and streamflow between the positive and negative IPO phases. Figure 4 shows that the Jan-Feb-Mar rainfall-SOI and streamflow-SOI lag correlations are statistically significant at $\alpha = 0.05$ in 30% and 40% of the catchments respectively in 1946-1977 when the IPO phase is negative. In contrast, the correlations are statistically significant only in about 5% of the catchments in 1922-1944 and in 1978-1997 when the IPO phase is positive.

Figure 3 shows that in the negative IPO phase between 1946-1977, the Oct-Nov-Dec rainfall-SOI and streamflow-SOI lag correlations are statistically significant in about 40% of the catchments. The correlations are significant in less than 5% of the

catchments in the positive IPO phase between 1922-1944, although about 20% and 30% of the catchments show statistically significant rainfall-SOI and streamflow-SOI lag-correlations respectively during the 1978-1997 positive IPO phase.

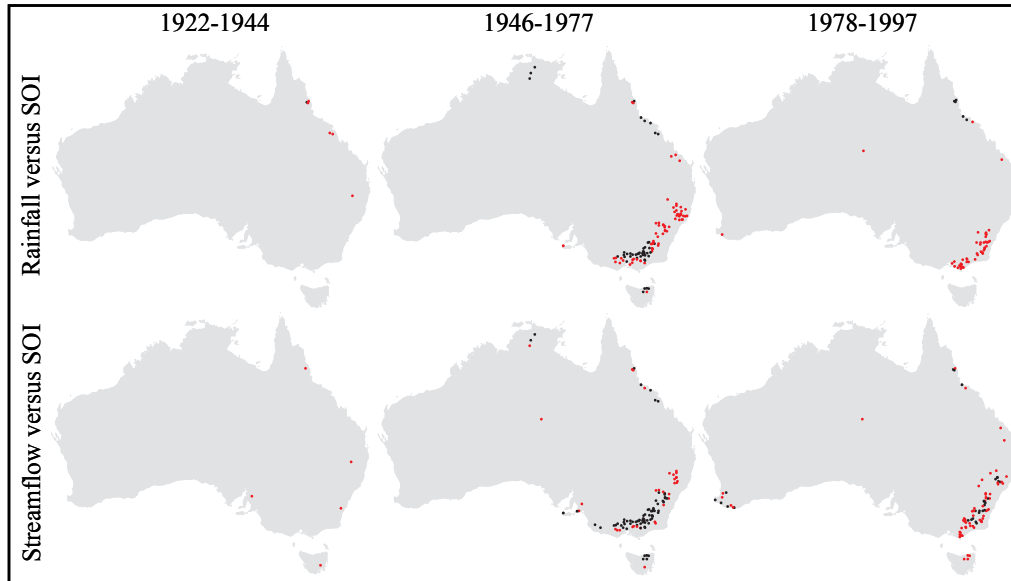


Figure 3. Lag correlations between Oct-Nov-Dec rainfall and streamflow versus Jul-Aug-Sep SOI for two positive IPO phase periods (1922-1944 and 1978-1997) and one negative IPO phase period (1946-1977). Dots show catchments with correlations that are statistically significant at $\alpha = 0.05$ – refer to Figure 1 for locations of the 284 catchments analysed in this study (when plotted in colour, red dots show correlations significant at $\alpha = 0.05$ and black dots show correlations significant at $\alpha = 0.01$)

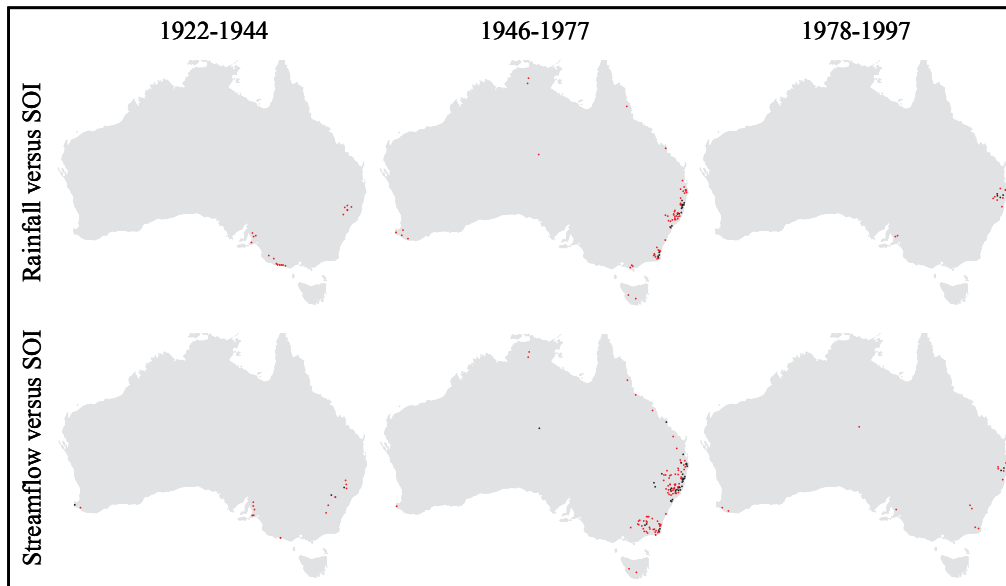


Figure 4. Lag correlations between Jan-Feb-Mar rainfall and streamflow versus Oct-Nov-Dec SOI for two positive IPO phase periods (1922-1944 and 1978-1997) and one negative IPO phase period (1946-1977) (Dots show catchments with correlations that are statistically significant at $\alpha = 0.05$)

It should be noted that for a given significance level, a higher correlation is required from a small sample than from a larger sample to indicate statistical significance of the derived association. Nevertheless, although there are 32 years of data for the negative IPO phase period compared to 23 and 20 years for the two positive IPO phase periods, the actual correlations for the negative IPO phase are a lot higher than the correlations for the positive IPO phase (except for Oct-Nov-Dec streamflow-SOI during 1978-1997).

3.2 Lag correlations and implications for forecasting

Figure 5 shows the lag correlations of the linear regression between Oct-Nov-Dec rainfall and streamflow versus Jul-Aug-Sep SOI, versus rainfall or streamflow (serial correlation), and versus SOI & IPO (multiple linear regression) for the analyses using 98 years of data from 1901-1998. Figure 6 shows the lag correlations for Jan-Feb-Mar rainfall and streamflow versus the explanatory variables in Oct-Nov-Dec. Table 1 shows the percentage of catchments with statistically significant correlations. The results in Figures 5 and 6 should not be compared directly with the results in Figures 3 and 4 because they involve analyses of data of different lengths. There is more likelihood of detecting a statistically significant teleconnection (if there is one) from a longer data series.

Table 1. Percentage of catchments with statistically significant lag correlations

Level of significance	Oct-Nov-Dec rain versus Jul-Aug-Sep variables			Oct-Nov-Dec flow versus Jul-Aug-Sep variables		
	SOI	rain	IPO	SOI	flow	IPO
$\alpha = 0.05$	75	58	30	68	76	37
$\alpha = 0.01$	48	40	12	55	64	13

Level of significance	Jan-Feb-Mar rain versus Oct-Nov-Dec variables			Jan-Feb-Mar flow versus Oct-Nov-Dec variables		
	SOI	rain	IPO	SOI	flow	IPO
$\alpha = 0.05$	42	17	57	66	37	61
$\alpha = 0.01$	27	3	45	47	24	42

The Oct-Nov-Dec rainfall-SOI and streamflow-SOI lag correlations are statistically significant at $\alpha = 0.05$ in about 70% of the catchments and at $\alpha = 0.01$ in about 50% of the catchments (see Figure 5 and Table 1). The notable spatial differences include: the streamflow-SOI correlations in south-west Australia are significant but the rainfall-SOI correlations are

not; the rainfall-SOI correlations in the north-east coast are slightly stronger than the streamflow-SOI correlations; and the streamflow-SOI correlations east of the Great Dividing Range in south-east Australia are lower than the correlations inland. The serial correlations in streamflow (Oct-Nov-Dec streamflow versus Jul-Aug-Sep streamflow) are generally similar or higher than the lag streamflow-SOI correlations (about 75% of the catchments show statistically significant serial correlation at $\alpha = 0.05$) while the rainfall serial correlations are lower than the lag rainfall-SOI correlations. The high streamflow serial correlation results from the delayed response in the rainfall-runoff process due to soil and groundwater storage, giving streamflow a memory of conditions over several months.

The rainfall-SOI lag correlations are lower in Jan-Feb-Mar than in Oct-Nov-Dec (compare Figures 6 and 5), with only 40% of the catchments showing Jan-Feb-Mar lag correlations that are statistically significant at $\alpha = 0.05$ (all along the coast of eastern and south-west Australia) compared to about 70% in Oct-Nov-Dec. The streamflow-SOI lag correlations in Oct-Nov-Dec and Jan-Feb-Mar are similar, most likely because the delayed response in the rainfall-runoff process extends the streamflow-SOI teleconnection further into the year. The notable differences between the Jan-Feb-Mar and Oct-Nov-Dec streamflow correlations include: the streamflow-SOI correlations east of the Great Dividing Range is statistically significant in Jan-Feb-Mar, but generally not in Oct-Nov-Dec; fewer catchments in Victoria show significant correlations in Jan-Feb-Mar compared to Oct-Nov-Dec; and unlike Oct-Nov-Dec, the Jan-Feb-Mar streamflow-SOI lag correlations are higher than the streamflow serial correlations (except in Victoria and south-west Australia).

The statistical significance of the multiple regression correlations between Oct-Nov-Dec rainfall and streamflow versus Jul-Aug-Sep SOI & IPO are similar to the correlations of rainfall and streamflow versus SOI alone (see Figure 5). The lag correlations of Jan-Feb-Mar streamflow versus Oct-Nov-Dec SOI & IPO and versus SOI alone are also similar (see Figure 6). However, in Jan-Feb-Mar when the rainfall-SOI lag correlations are relatively low, the correlations of rainfall versus SOI & IPO are higher than the correlations of rainfall versus SOI alone. This suggests that the use of IPO as an additional explanatory variable can improve the predictability of Jan-Feb-Mar rainfall.

As the IPO describes the inter-decadal variability of SST (and therefore SOI), the hydroclimate-SOI teleconnection should also be reflected as a weak

relationship between hydroclimate and IPO. This is the case in the Oct-Nov-Dec lag correlations where about 30% of the catchments show statistically

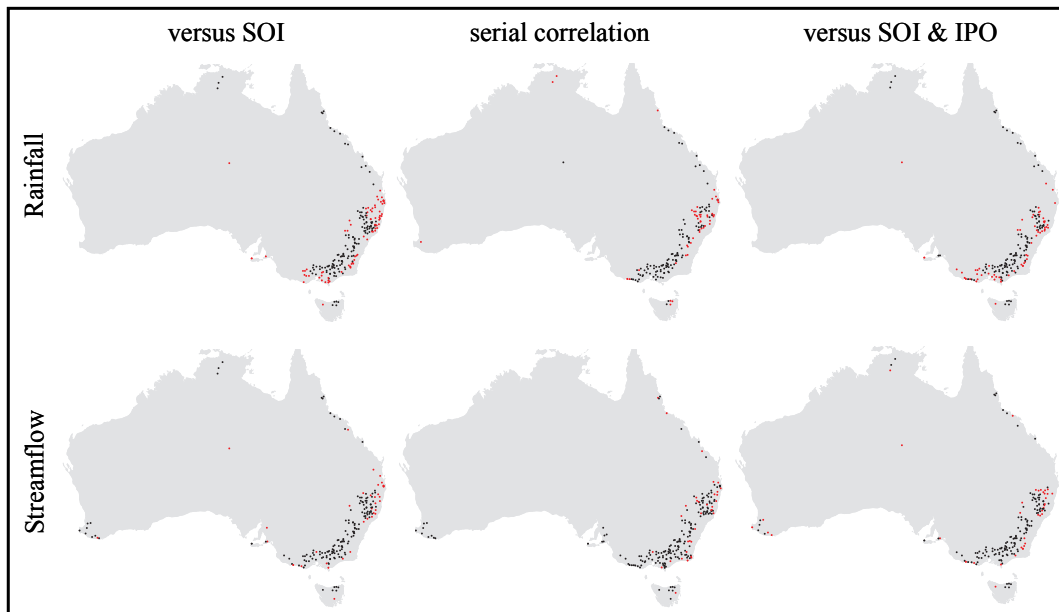


Figure 5. Lag correlations between Oct-Nov-Dec rainfall and streamflow versus Jul-Aug-Sep SOI, SOI & IPO and rainfall or streamflow for analyses using 98 years of data from 1901-1998 (Dots show catchments with correlations that are statistically significant at $\alpha = 0.05$)

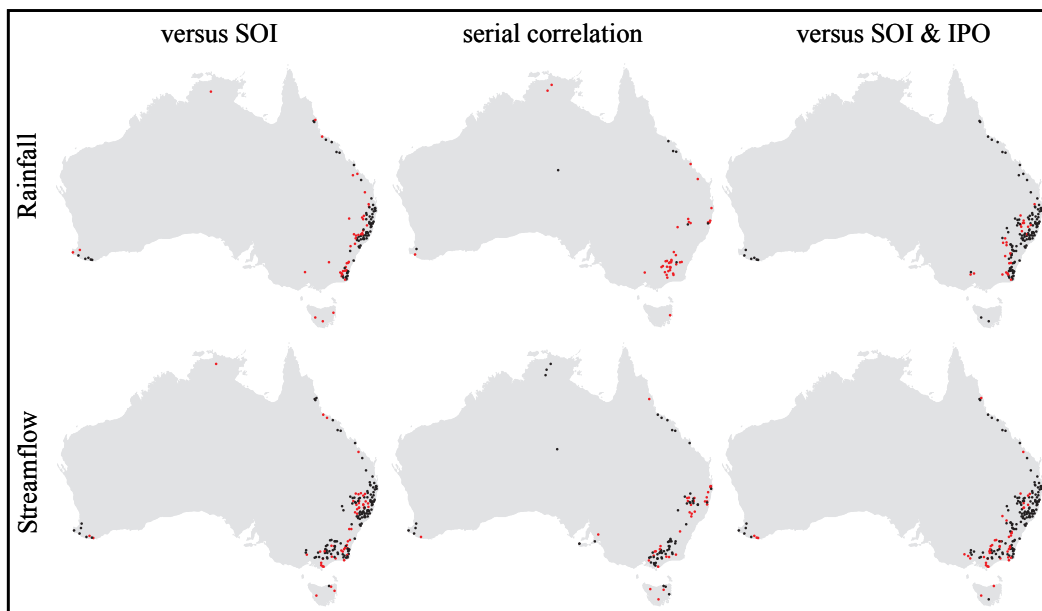


Figure 6. Lag correlations between Jan-Feb-Mar rainfall and streamflow versus Oct-Nov-Dec SOI, SOI & IPO and rainfall or streamflow for analyses using 98 years of data from 1901-1998 (Dots show catchments with correlations that are statistically significant at $\alpha = 0.05$)

significant hydroclimate-IPO correlations at $\alpha = 0.05$ compared to 70% of the catchments showing significant hydroclimate-SOI correlations (see Table 1). However, the lag hydroclimate-IPO relationship is considerably stronger in Jan-Feb-Mar than in Oct-Nov-Dec. The lag Jan-Feb-Mar streamflow-SOI and streamflow-IPO correlations are similar while about 60% of the catchments show statistically significant rainfall-IPO correlations at $\alpha = 0.05$ compared to about 40% of the catchments showing significant rainfall-SOI correlations.

The hydroclimate-ENSO relationship becomes weaker for longer lags. However, because the IPO value changes very slowly compared to the SOI value, the strength of the hydroclimate-IPO relationship is similar even for lags of more than one year. For example, the Jan-Feb-Mar streamflow versus Oct-Nov-Dec SOI correlation is statistically significant at $\alpha = 0.05$ in about 65% of the catchments (40% for rainfall) but the Jan-Feb-Mar streamflow versus Jul-Aug-Sep SOI is significant in only about 40% of the catchments (25% for rainfall). In contrast, the number of catchments showing statistically significant Jan-Feb-Mar hydroclimate versus Oct-Nov-Dec IPO and versus Jul-Aug-Sep IPO and longer lags are similar (about 60% for both streamflow and rainfall). Therefore, when the hydroclimate-IPO relationship is relatively strong, like in Jan-Feb-Mar, the relationship can be used to provide long lead-time forecasts.

4. CONCLUSIONS

The ENSO-hydroclimate relationship can be exploited to forecast rainfall and streamflow several months ahead in the latter part and very early in the year. The serial correlation in streamflow should also be used when forecasting streamflow because it is generally similar or stronger than the streamflow-ENSO correlation.

The hydroclimate-ENSO relationship is a lot stronger during the negative IPO phase (when there are more La Niñas and conditions in Australia are more often wetter than normal) than in the positive IPO phase. The current climate system appears to be moving into a negative IPO phase, which implies that rainfall and streamflow may be forecast more realistically in the coming decades. The results also indicate that the use of IPO as an additional explanatory variable may improve forecast, particularly for rainfall early in the year. The hydroclimate-IPO relationship is also relatively strong early in the year and it is possible that the IPO

can be used to forecast rainfall and streamflow then, particularly for longer lead-time forecasts.

The paper provides only a simplistic interpretation of the IPO impact of ENSO on Australian rainfall and streamflow. The discussions are of a general nature and are based on statistical significance of the linear relationships, rather than a detailed analysis of data in particular catchments or regions. In addition, because the IPO series is derived from the ENSO series itself, it is difficult to tell conclusively whether the varying strength in the hydroclimate-ENSO relationship over the 1900s is part of the natural system or whether it is influenced by the IPO. Nevertheless, the remarkable contrast between the hydroclimate-ENSO relationship during the positive and negative IPO phases suggests that the IPO should be considered in making ENSO-based hydroclimate forecasts.

5. ACKNOWLEDGEMENTS

We would like to thank Scott Power for the useful discussions and for providing the IPO data series and Steve Wealands for helping us prepare some of the figures in this paper.

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