A Decision Support Tool for Managing the Impact of Climate Variability on Water Resources

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Abstract: Australia is largely dominated by high climate variability and limited water supplies. The uncertainty of water supply is one of the key issues that influences the efficient allocation and use of water resources amongst competing users, and an irrigator's choice of crop and area to plant. Availability of this information in a form that provides a rapid assessment of risk with a sufficient lead-time will improve a decision maker's chances of success, water use efficiency, and management of water resources. In Australia and some regions of the world short and medium term (2-12 months) variability in rainfall and streamflow is affected by phenomena such as the *El Niño* Southern Oscillation (ENSO). Longer-term variability (2 years or more) may be influenced by phenomena such as the Pacific Decadal Oscillation (PDO), luni-solar tidal forces or sunspots. FLOWCAST, a Decision Support Software system, was developed to examine the relationship between climate indices (e.g. Southern Oscillation Index, phases of SOI, sea surface temperatures, Inter-decadal Pacific Oscillation) and time series of rainfall, streamflow, water diversion or cropping history. FLOWCAST was primarily developed to link climate information with the output of hydrologic models such as the Integrated Quantity Quality Model (IQQM). The package, however, is generic and can be used for assessing the relationship between any indices and time series data. An important feature of FLOWCAST is the ability to examine the synergistic effect of several indices using Boolean operators. This feature may be helpful in explaining large variability in events perceived to be "similar" (e.g. *El Niño* events) where the dominant cause of such variability may be due to other factors. This paper will outline the framework used to develop FLOWCAST and cite examples of the use of the package from a case study in the northern Murray Darling Basin.

Keywords: Climate indices; Hydrologic model; Decision Support Software; Forecasting.

1 INTRODUCTION AND BACKGROUND

Australia is dominated by high climate variability and limited water supplies. In the most productive basin in Australia, the Murray Darling Basin, there is a high concentration of irrigated farming which is the nation's largest user of water, accounting for 70% of all water used. An audit of water use in the basin [MDBMC, 1995] concluded that the level of diversions in 1994 were deemed to have had adverse impacts on the river system and hence emphasis is being placed on efficient use of water.

Over the past two decades research has shown that the El-Niño Southern Oscillation (ENSO) has a major influence on climate variability in many parts of the world [Kuhnel et al., 1990; Hammer et al., 1996, Piechota et al., 1998, Mantua, 2001a].

The Southern Oscillation (SO) is conveniently measured by the monthly Southern Oscillation Index (SOI), which incorporates the sea level pressure difference between Papeete (Tahiti) and Darwin. Although the SO phenomenon is localised to within a few degrees of the equator, it is a predictor of rainfall [Stone et al., 1996] and has considerable utility in managing crop production in Australia and in other countries [Hammer et al., 1996].

Abawi et al. [2001] found that in northeast Australia, forecasting of streamflows and water supply for irrigation is possible several months ahead of the irrigation season based on the phases of the SOI.

Although ENSO is the best-known "natural pattern" of the earth's climate, there are other climate patterns, such as the Pacific Decadal oscillation (PDO) that appear to modulate ENSO variability and influence regional climate around the world [Mantua, 2001a].

The PDO has significant mid-latitude character and is derived as an empirical orthogonal function of Pacific sea surface temperatures [Mantua et al., 1997]. The PDO is defined for the north Pacific, its southern signature is referred to as the IPO (Interdecadal Pacific Oscillation). The correlation between PDO and IPO is 0.83 [Folland 2001, personal communication].

The North American climate anomalies associated with PDO warm and cold extremes are broadly similar to those connected with *El Niño* and *La Niña* [Zhang et al., 1997; Mantua et al., 1997]. In the absence of ENSO events, the PDO provides much of the skill in seasonal climate forecasting for North America [Mantua, 2001a]. Combining ENSO and PDO information offers improved statistical climate predictions over those based solely upon one of these two important climate patterns [Gershunov and Barnett 1998; Dettinger and McCabe, 2001].

Despite the significant progress in understanding the nature and impact of different climate predictors, its use as a management tool remains low. Critical reasons for this are the lack of information flow and the highly complex nature with which this information is presented.

Forecasting of rainfall and streamflow still requires careful selection and examination of different climatic indices (SST, SOI, PDO, IPO, and luni-solar tidal index) in order to establish a link between these global phenomena and its regional impact. FLOWCAST was developed as part of a Murray Darling Basin Commission funded project as a Decision Support Tool to enable rapid analysis of the relationship between climate variables (streamflow, rainfall) and climate indicators (SOI, SST, IPO, PDO, etc)

2 STRUCTURE OF FLOWCAST

In forecasting a water variable it is convenient first to identify similar historical events or "analogue" years with similar characteristics and the forecast is then made as a probability distribution of all events in the analogue group. FLOWCAST uses this approach and derives probability distributions that match sample definitions designed by the user. Several samples definitions can be constructed. By comparing the distributions of each sample using non-parametric tests (such as the Kruskal-Wallis or Kolmogorov-Smirnov [Howel, 1992]) inferences can be made about the utility of different predictors. It should be pointed out that significant differences between the distributions of various samples do not necessarily imply skill in a particular predictor, and other statistical approaches such as independent sampling or cross validation may be necessary to ensure the differences are not due to artificial skill.

FLOWCAST is written in C++ using Borland C++ Builder5 and runs under Windows 95, 98, 2000 and NT operating systems. The Windows platform allows users who have used other Windows programs to easily run FLOWCAST.

FLOWCAST was primarily developed as a post processor to analyse output from hydrological models such as the Integrated Quantity Quality Model (IQQM). However, the package is generic and will accept as input any time series data such as rainfall, crop production and streamflow. A schematic of FLOWCAST with some of its key features and analysis tools is shown in Figure 1.

The package is structured from a map interface to allow users to select the geographical area of interest (irrigation node, rainfall station, or river reach). The user is presented with a list of all available data for that location. One or more locations may be selected for subsequent analysis. The user selects an index or indices using the INDEXSAMPLER component. Several indices are incorporated including SOI values, SOI Phases, IPO, PDO, and SST. Users can import other indices such as the luni-solar phases (discussed later in this paper).

The period to be used for analysis is user defined. For example, to examine the relationship between the flow during October to January and the SOI phases in the preceding month of May, the user selects these periods by dragging the appropriate bars in the sample window to the required period.

The user may change the default settings and can choose up to 20 different samples of climate indices. Each sample can be logically constructed using a Boolean operator. For example, to select a sample of streamflow data (Oct-Jan) for all years that satisfies the following conditions (values in **BOLD** are user defined):

A. SOI phase in **May** is **Consistently Positive**
B. **Average** SST in the preceding three months **(July to September)** is **>1.5** °C
C. **Average** SOI values in the preceding three months (**July** to **September)** is **>5.0**

the following definitions may be constructed using (.AND., .OR.) operators. For example;

A.AND.B.AND.C
A.OR.(B.AND.C)
(A.AND.B).OR.C
A.AND.C

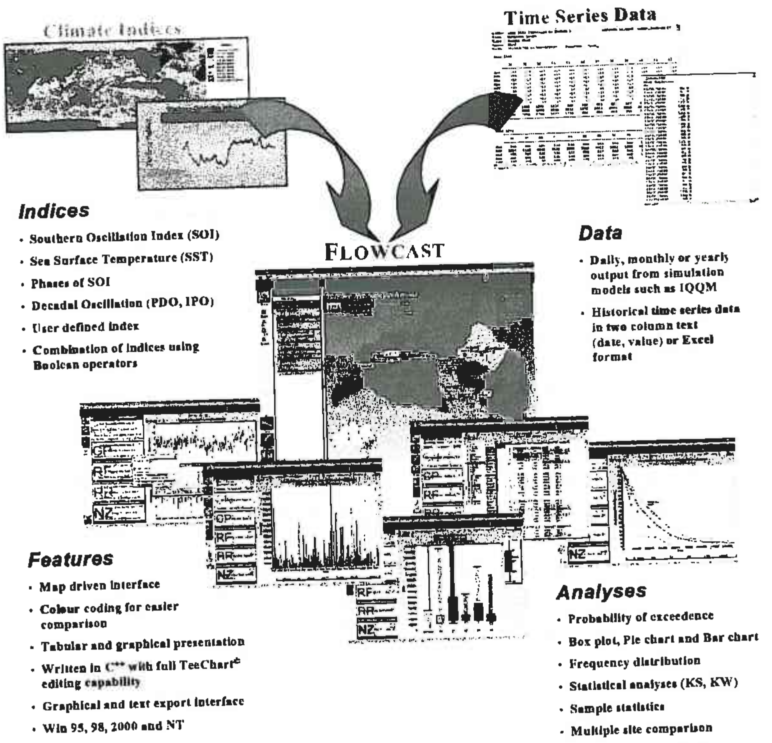

Figure 1. Schematic outline of the FLOWCAST Decision Support Tool

In the above construction .OR. may be substituted for .AND. and vice versa. The program graphically displays the selected logic through a series of connecting lines. The program also displays the number of years of data (sample size) for each option. If sample size is zero, no data is displayed and if the sample size is less than that required for valid statistical analysis, these tests cannot be preformed. The sample definition may be saved for future reference. Once samples are selected, various operations and analyses such as frequency and probability distribution, descriptive statistics, box plot, bar and pie charts, and non-parametric tests can be performed.

The probability distribution for each sample can be displayed; if the variables are highly skewed several transformation ($\log_e$, $\log_{10}$, $\sin^{-1}$) options are available for display in the package. Data can also be presented in box plot format with defaults of minimum, maximum, 25 and 75 percentile, mean and median. The percentile values can be changed to suit the user.

The sample data can be expressed relative to the long-term median (or user set percentile) using pie or bar charts. The data can be expressed as a frequency distribution for each of the samples selected. This allows an examination of extreme events and the climate type under which these events occurred.

FLOWCAST offers two non-parametric tests (Kruskal-Wallis and Kolmogorov-Smirnov). These tests are systematically carried out between all pairs of data (distributions) and the results are presented in tabular or graphical form. In this way the user can quickly identify those distributions that are statistically different and hence the predictors that offer the best potential for forecasting the variable of interest.

3 USING FLOWCAST

To illustrate various feature of the FLOWCAST package we have selected several examples from a case study in the Border Rivers catchment in the northern Murray Darling Basin. The catchment situated between 27°29.6′ and 30°2.3′ S, and 148°39.1′ and 152°9.5′ E, covers an area of 48,650 square kilometres and is the centre of extensive irrigated agricultural industries (mainly cotton) relying heavily on river flows.

For various nodes within the catchment, daily-synthesised natural streamflows (1890-1997) were derived using the IQQM model. Details of the IQQM model and its application in the Border Rivers catchment are described elsewhere [Abawi et al., 2001]. Natural streamflow data is useful for indicating the impact of climate variability and ENSO on the hydrologic response of the catchment as it excludes the effect of land use change, catchment development and irrigation diversion.

Monthly values of the Southern Oscillation Index [BOM, 2001], sea surface temperature anomalies [NOAA, 2001], Pacific Decadal Oscillation [Mantua, 2001b] and SOI phases [Stone et al, 1996] were obtained from the respective sources.

Interdecadal Pacific Oscillation data (1890-1996) averaged quarterly were obtained from [Power, et. al., 1999]. For a complete explanation of the various indices the reader is referred to several publications cited above.

3.1 Relation Between Summer Streamflow and SOI Phases.

In the Border Rivers Catchment, cotton is planted in October and harvested between February and May of the following year. Forecasting of water supplies several months prior to planting would be useful for the water users to make decisions on cropping area during the cotton irrigation season. FLOWCAST can be used to provide a rapid assessment of the relationship between the predictor (e.g. SOI phases) and the predictand (e.g. streamflow).

Probability distribution for **C**onsistently **P**ositive (CP) and **C**onsistently **N**egative (CN) in Figure 2 shows that the streamflow distributions are significantly different (P<0.05) as early as May, but not before May. The user may explore the relationship between the phases and streamflow in other months or periods by dragging the appropriate bars in the INDEXSAMPLER and data file windows. This is consistent with the ENSO cycle running from late autumn-to-autumn breaking up in late summer and early autumn.

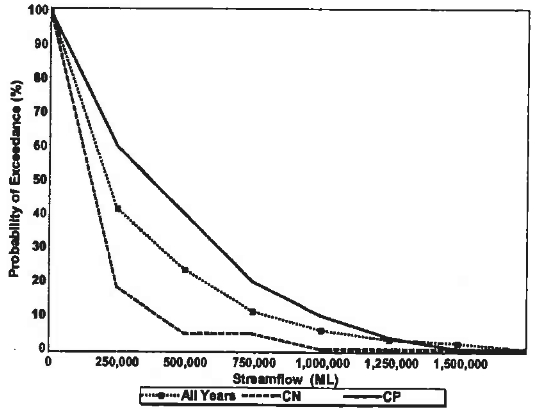

Figure 2. Probability distribution of streamflow (Oct-Jan) in McIntyre River based on the **C**onsistently **N**egative and **C**onsistently **P**ositive phase of the SOI in May.

3.2 Synergy Between ENSO and IPO?

Changes in climate trends in the Pacific have been reported about 1890, 1925, 1947, 1977 and 1989. Indices of the northern Hemisphere climate changed in approximately 1996, possibly indicating a new shift in climate/ocean ecosystems [Beamish, et al., 2001].

While the year-to-year variation in the climate of eastern Australia is predominantly influenced by ENSO, the interdecadal changes may be influenced by the Interdecadal Pacific Oscillation (IPO). An analysis of median annual streamflow for the McIntyre River at Goondiwindi (1890-1924, 1925-1946, 1947-1976, 1977-1996) shows that flows in these periods were significantly below or above the long term median, corresponding to the warm (positive IPO) and cold (negative) phases of the IPO respectively (Figure 3.).

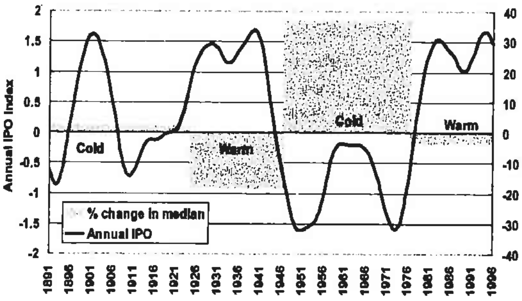

Figure 3. Annual IPO Index (Power et al., 1999) and percentage change (relative to long term medium) in the median annual flow for the warm and cold phases of IPO.

Power et al. [1999] noted that Australian rainfall is significantly correlated with the SOI when the IPO index is negative. When tropical Pacific SSTs are warm the interannual correlation between ENSO events and Australian rainfall decreases, with the converse being true during periods of anomalously cold tropical Pacific decadal SST's. However, they found no significant relationship between un-impacted streamflow (Murray River at Albury, NSW) and the SOI under different IPO phases.

We have repeated a similar analysis with "natural" modelled streamflow data for the McIntyre River using FLOWCAST. The analysis consisted of examining the distribution of streamflows over the summer period (Oct-Jan) using the ENSO signal (Average SOI from Jul-Sep >5.0) and (Average SOI from Jul-Sep <-5.0). The values of 5 and -5 were chosen to reflect the extreme influence of ENSO on our climate, but any other value (e.g. 3 and –3) or the phases of the SOI could be used. The data were then partitioned using positive and negative phases of the IPO. The IPO data used in the analysis were annual average values [Power et al. 1999]. Figures 4 and 5 show that negative values of IPO tend to enhance the impact of a high SOI and low SOI, resulting in increased flows. A positive phase of IPO tends to reduce the impact of a high SOI resulting in reduced flows, but had no impact on low SOI. While these results partly confirm observations made by other researchers [Power et al., 1999] using rainfall and cropping data, a more comprehensive analysis covering a wide geographical region is needed to establish a better understanding of the impact of IPO on our regional climate and water supplies.

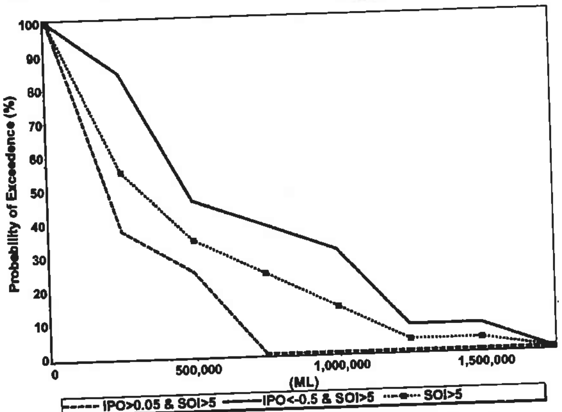

Figure 4. Distribution of streamflow (Oct-Jan) based on annual (positive and negative) values of IPO and average SOI (Jul-Sep) >5.

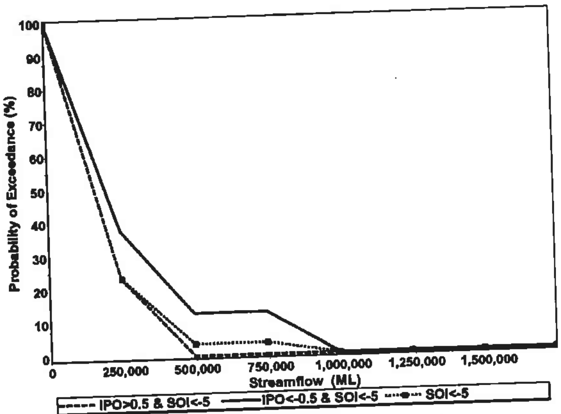

Figure 5. Distribution of streamflow (Oct-Jan) based on annual (positive and negative) values of IPO and average SOI (Jul-Sep) <-5.

3.3 Tidal Forces, a Driver of Our Climate ?

Tidal forces exerted by the Sun and Moon have recently been examined as an exogenous driver for terrestrial climate variability [Treloar, 2001]. The mechanism is unclear but the varying tidal force may slightly vary the rotation of the Earth, with subsequent impacts on atmospheric and ocean circulation patterns. The variability of tidal force is known centuries in advance, therefore, an established link with climate would have large implications.

The "luni-solar" tidal force has cycles with periodicities in the one to one hundred year range, which is an important time scale for climate variability. There are a small number of cycles in the 10 – 100 year range, but many in the 1 - 10 year range. If these cycles have been correctly characterized by the tidal approach, then it should be possible to improve climate forecasting over these time scales. The FLOWCAST software is a useful tool to probe the validity and skill of the tidal approach and its application to streamflow

A detailed explanation of the tidal indices is beyond the scope of this paper. In this analysis we have used 4 of the 9 indices (phases 1,3,7 and 9). The tidal indices used can be provisionally classified as being equivalent to:

Tidal phase 1: Negative IPO +Positive SOI
Tidal phase 3: Negative IPO +Negative SOI
Tidal phase 7: Positive IPO +Positive SOI
Tidal phase 9: Positive IPO +Negative SOI

Streamflow results from October to January are given in Figure 6 using values for tidal parameters averaged over November to January. We are able to use a concurrent period for the tidal because tidal forces are known in advance.

The hypothesis tests show greatest pair-wise differences ($p<0.05$) between phases 1&3, 1&7 and 3&7. No significant differences were found between phase 7&9. These results appear to be consistent with results using "real" IPO and SOI. If these results can be confirmed in further research underway, then the potential benefits of forecasting climate variables years in advance provides exciting opportunities in the management of water resources.

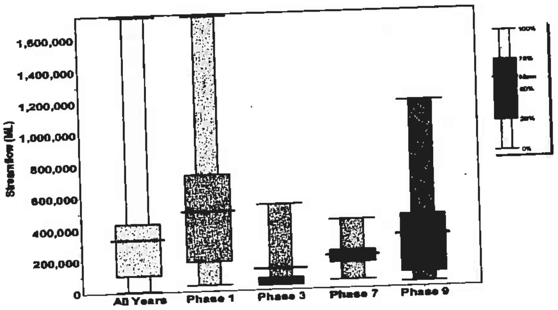

Figure 6. Distribution of streamflow (Oct-Jan) based on the luni-solar tidal indices.

4. CONCLUSIONS

Despite the significant progress in understanding the nature and impact of different climate predictors, its use as a management tool remains low. Critical reasons for this are the lack of information flow and the highly complex nature with which this information is presented.

FLOWCAST has been developed to facilitate a rapid assessment of the link between various predictors and climate variables.

An assessment of the impact of ENSO, IPO and luni-solar indices on streamflows in north-eastern

Australia shows that the interannual variability in the streamflow is largely influenced by ENSO with possible interdecadal influence of IPO. A negative value of IPO tends to enhance the probability of higher streamflow for both high and low values of SOI (>5 and < -5). However, a positive value of the IPO tends to reduce the probability of higher streamflow with high SOI, but to have no impact if the SOI is low

The luni-solar tidal indices, which may effectively incorporate both the SOI and IPO signals, offer the potential for forecasting rainfall and streamflows with longer lead times. This could offer new opportunities for the management of water resources. However, considerable research is needed to assess this relationship in more detail.

5 ACKNOWLEDGMENT

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6 REFERENCES

Abawi, Y., S. Dutta, J. Ritchie, T Harris, D. McClymont, A. Crane, D. Keogh, and D. Rattray, A decision support system for improving water use efficiency in the Northern Murray-Darling Basin, Final report to the MDBC, Department of Natural Resources and Mines, 2001.

Beamish, R.J., J.R King, D. Noakes, G.A MaFarlane, and R. Sweeting, http://www.pac.dfo-mpo.gc.ca/sci/pbs/english/pages/Npafc/npafc321.pdf , 2001.

Bureau of Meteorology (BOM), http://www.bom.gov.au/climate/current/soihtml.shtml, 2001.

Dettinger, M. and G. Mccabe, El Niño, Pacific decadal oscillation, and historical drought/flood episodes in western north America and eastern Siberia. http://www.geology.er.usgs.gov/eespteam/workshop/abs.html. , 2001

Folland, C., Personal communication, Hadley Centre for Climate Prediction and Research, Berkshire, England, 2001.

Gershunov, A. and T. Barnett, Interdecadal modulation of ENSO teleconnections, *Bulletin of the American Meteorological Society*, 79, 2715-2726,1998.

Hammer, G.L., D.P. Holzworth, and R. Stone, The value of skill in seasonal climate forecasting to wheat crop management in a region with high climate variability, *Australian Agri. Res.*, 47: 717-737, 1996.

Howell, D. C., *Statistical Methods for Psychology*, Third Edition. Duxbury Press, California, USA: 611, 622, 657-661,1992.

Kuhnel, I., McMahon, T. A., Finlayson, B. L., Haines, A., Whetton, P. H., & Gibson, T. T., Climatic influences on streamflow variability: a comparison between south-eastern Australia and United States of America, Water Resources Research, Vol. 26: 2483-2496, 1990.

Mantua, N.J., S.R. Hare, J.M. Wallace, and R.C. Francis, A Pacific decadal climate oscillation with impacts on salmon production, *Bulletin of American meteorological society*, 78, 1069-1079, 1997.

Mantua, N., The pacific Decadal Oscillation and Climate Forecasting for North America, http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm, **2001a.**

Mantua, N.J, URL: ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest , **2001b.**

McCabe, G.J. and M.D. Dettinger, Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States, *International Journal of Climatology*, 19, 1399-1410, 1999

Murray-Darling Basin Ministerial Council, An audit of water use in the Murray-Darling Basin, water use and healthy rivers – working towards a balance, 761, 1995.

National Oceanic and Atmospheric Administration (NOAA), ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/sstoi.indices, 2001.

Piechota, T.C., F.H.S. Chiew, J. A. Dracup, T.A. McMahon, Seasonal streamflow forecasting in eastern Australia and the El Niño-Southern Oscillation, Water Resources Research, Vol. 34, No. 11, 3035-3044, 1998.

Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta, Inter-decadal modulation of the impact of ENSO on Australia, *Climate Dynamics*, 15, 319-324, 1999.

Stone, R.C., G.L. Hammer, and T. Marcussen, Prediction of global rainfall probabilities using phases of the Southern Oscillation Index, *Nature*, 364: 252-255, 1996.

Treloar, N. C., Luni-solar tidal influences on climate variability, International Journal of Climatology, [Submitted]. 2001.

Zhang, Y., J.M. Wallace, and D.S. Battisti, ENSO-like Interdecadal Variability: 1900-93, *Journal of Climate*, 10:1004-1020,1997.