Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resources Management (Proceedings of Symposium HS2004 at IUGG2007, Perugia, July 2007). IAHS Publ. 313, 2007.

A multi-index approach to inflow prediction for water resources management

STEWART W. FRANKS & ADAM M. WYATT
School of Engineering, University of Newcastle, Callaghan 2308, New South Wales, Australia
stewart.franks@newcastle.edu.au

Abstract Significant variability in reservoir inflows is experienced across eastern Australia as a result of a number of known, identified climate modes. In particular, the El Nino Southern Oscillation (ENSO) is known to affect primarily summer (October–March) inflows. In this paper, a software suite is presented that enables: (i) the routine prediction of ENSO events, (ii) the assessment of likely inflow on monthly and seasonal timescales, and (iii) the updating of both climate and inflow prediction as new data are received. The scheme is demonstrated by application to a Sydney Catchment Authority (SCA) reservoir that supplies potable water for metropolitan Sydney. The tool is generalized and can be applied anywhere that significant correlations between ENSO and inflows are found.

Key words eastern Australia; ENSO prediction; monthly inflow; multi-index approach; reservoir; seasonal inflow

INTRODUCTION

Despite being identified some eighty years ago (Walker, 1923), hydrological research has only recently begun implementing the predictability of seasonal rainfall and runoff as a function of the El Nino-Southern Oscillation (ENSO). The development of the extreme phases of ENSO (the "warm" El Nino and "cold" La Nina) can be predicted with some accuracy from three to nine months in advance. Once an extreme phase is initiated, the predicted impacts on rainfall across Australia are well known and largely reliable (in terms of the seasons affected and the degree of rainfall enhancement/depletion) (Chiew *et al*., 1998; Kiem & Franks, 2001).

Additionally, recent research has elucidated the role of the Interdecadal Pacific Oscillation-Pacific Decadal Oscillation (IPO-PDO) in apparently modulating the strength of ENSO event impacts (Power *et al*., 1999) and ENSO event frequency (Kiem *et al*., 2003; Kiem & Franks, 2004). This research has demonstrated that the impact of individual El Nino and La Nina events is modulated through independent control of the location of the Inter-Tropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ), which variably delivers tropical rainfall to Eastern Australia (Salinger *et al*., 2001; Franks, 2004). This provides additional insight into expected seasonal and inter-annual rainfall and runoff as a function of ENSO and IPO that may be of benefit to water managers.

This paper documents the development of a software suite for use by water managers for providing future forecasts of ENSO-affected rainfall and reservoir inflows. The first section of this paper documents the rationale behind the adopted approach, whilst the subsequent sections detail the performance of the predictive suite using historical data and ENSO events.

RATIONALE FOR THE ADOPTED APPROACH

Whilst the El Nino-Southern Oscillation (ENSO) is an established and well-known climate phenomenon, significant uncertainty exists with respect to the range of different indices and methods for assessing ENSO events (see, for example, Kiem & Franks, 2001). Multiple indices have been proposed as key monitors of ENSO phenomena. ENSO events are caused by the interaction between the ocean and atmosphere, primarily in the eastern equatorial region of the Pacific Ocean. The original index, the Southern Oscillation Index (SOI) is taken as the difference in atmospheric pressure between Tahiti and Darwin and, as such, represents an indirect measure of ENSO itself. Nonetheless, as a measure of atmospheric pressure differences it does, however, provide a direct measure of the atmospheric circulation over Australia. In other words, the SOI is a noisy index of ENSO phenomena, but does represent a good index of the month by month variations of weather systems over Australia. It is consequently likely that the SOI may not provide as good a measure of ENSO events themselves but can be used to assess the impacts in the Australian region.

More direct measures of ENSO have been developed based on sea-surface temperature (SST) anomalies in the eastern equatorial Pacific Ocean, termed NINO-x where x represents a number specific to the area of the eastern equatorial Pacific where the anomalies are measured (for instance NINO3, see Fig. 1). The NINO SST indices represent a far more direct measure of ENSO behaviour although this is limited to the response of the oceans and, unlike the SOI, does not measure atmospheric anomalies.

A more recent index, the Multivariate ENSO Index (MEI) has been developed in an attempt to provide a more direct, integrated measure of ENSO phenomena. The MEI is comprised of six variables known to be important in the development of ENSO events. These include sea-level pressure, zonal and meridional surface winds, sea surface temperature, surface air temperature and cloudiness fraction. Consequently, the MEI offers the promise of improved ENSO forecasts based on a range of key indicators that are direct measures of the very interactions between ocean and atmosphere that lead to ENSO events.

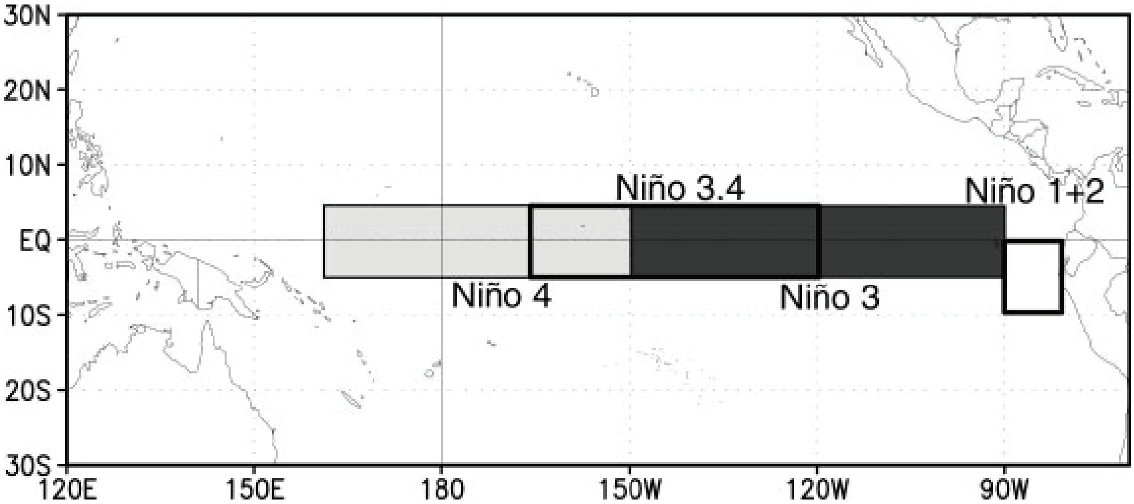

Fig. 1 Locations of sea-surface temperature (SST) anomalies that comprise the different NINO indices of ENSO.

Analogue and statistical models

Aside from the use of complex coupled ocean–atmosphere models for predicting ENSO events, there are two different approaches to using ENSO monitors to predict forthcoming ENSO events. These can be classified as analogue models, whereby the evolution of an ENSO event compared to historic event development is utilized to provide some assessment of the likelihood of upcoming events, and statistical models, whereby simple rules based on the average or trend of an index is utilized to assess the probability of a forthcoming event.

The analogue method is highly intuitive in that historic events are compared with the current evolution of a given index and the resultant analysis provides a list of years that appear most similar to the current conditions. This provides water managers with simple to understand comparisons. For instance, if 10 historic years are classified as similar to the current conditions, the user can readily assess how many of those 10 went on to develop into full-blown ENSO events, providing a coarse idea of the percentage likelihood of similar consequent ENSO event development. An additional benefit is that the particular years may be known as particularly deficient or excessive in rainfall/inflows.

The statistical method provides a more robust calculation of the probabilities of event development. Following Kiem & Franks (2001), when individual indices are significantly anomalous for a period of six months, or where a significant trend exists in the indices towards a particular ENSO state, then the upcoming impact period can be classified as an ENSO event. However, these criteria or rules are only met or not met – in other words, the criteria lead to a positive or negative prediction to be issued. To provide a rigorous basis for probabilistic assessment, a simple first-order auto-regressive model is utilized to provide a probabilistic forecast of the next months index value (equation (1)). The autoregressive model is simply parameterized according to the historic autocorrelation within the indices.

$$SST_{t+1} = \alpha_1 SST_t + \varepsilon \qquad (1)$$

As the residual term in equation (1) provides a distribution of likely values, the ENSO prediction criteria can be met for a range of possible values of ε, thus providing a robust estimate of the probabilities that each of the ENSO states (El Nino, Neutral and La Nina) will be met in the next months index given the previous and current values of the ENSO index.

Linking forecast ENSO events to flows

Whilst the prediction of ENSO events provides valuable early warning for water resource managers, it is also imperative to be able to provide some probabilistic forecast of the likely inflows for individual catchments and reservoirs. Again, the adopted approach provides both analogue and statistical forecast schemes for predicting future inflows on the basis of historic inflows under the different ENSO states.

Once the user has performed the analogue predictive routine, the years classified as similar to the current index evolution are then made available in the flow prediction screen. The historic analogue years are then taken from the historic inflow data set that is specified by the user. The inflow sequences from the analogue years are then summarized, again providing the user with a simple tool to analyse the historic response of catchments under similar developing ENSO conditions. This provides a readily accessible and intuitive method of assessing the likelihood of different inflow scenarios based on current data. An additional option for assessing the role of IPO-PDO in providing enhanced depleted or excess rainfalls, is an option to filter the candidate analogue flow years according to the IPO-PDO epoch. This enables the user to provide additional scenarios to assess future water management under alternative IPO scenarios.

Once the user has performed the statistic predictive method on their chosen index, the probabilities of each of the three ENSO climate states are passed to the inflow prediction screen. The user can then generate distributions of likely inflows from an automatic analysis of all historic inflow sequences under El Nino, Neutral and La Nina events. This provides a probability distribution for each future month's inflows weighted according to the probability of each of the three ENSO climate states. An additional feature is the ability to select a single ENSO climate state (for instance El Nino) to generate probabilisitic inflow forecasts. This may be particularly useful in the case that the probabilities of the future climate states are dominated by one particular state. For instance, if the probability of an El Nino event is listed as 70%, neutral as 14% and La Nina as 6%, then the user may decide that as an El Nino event is most likely, it would be conservative to base their probabilistic inflow forecasts on a 100% probability of an El Nino. Consequently, the developed predictive suite allows the user to make explicit conservative assumptions to provide worst-case scenarios based on current and anticipated ENSO climate states.

User flexibility

A key feature of the software is to provide as much user flexibility as possible. Climate science is not a precise science and there exists an array of alterative indices and assumptions associated with predicting future inflows. One important feature of the software is the ability to analyse any data within the software suite. For instance, where large headworks schemes may involve complex inter-basin transfer schemes and numerous reservoirs, the user may wish to analyse total system inflows, or, at the other end of the spectrum, individual components of the system. The suite has been developed to permit the uploading of any data including non-flow data such as water demand, estimated evaporative losses etc. In this way, the suite has been designed for maximum flexibility and should also be easily portable to alternative systems and even geographic regions.

ANALYSIS OF HISTORIC PERFORMANCE – CASE STUDIES

Analogue model

To assess the performance of the predictive software, this section provides a demonstration of the analogue model for the 2006 ENSO season. In the following

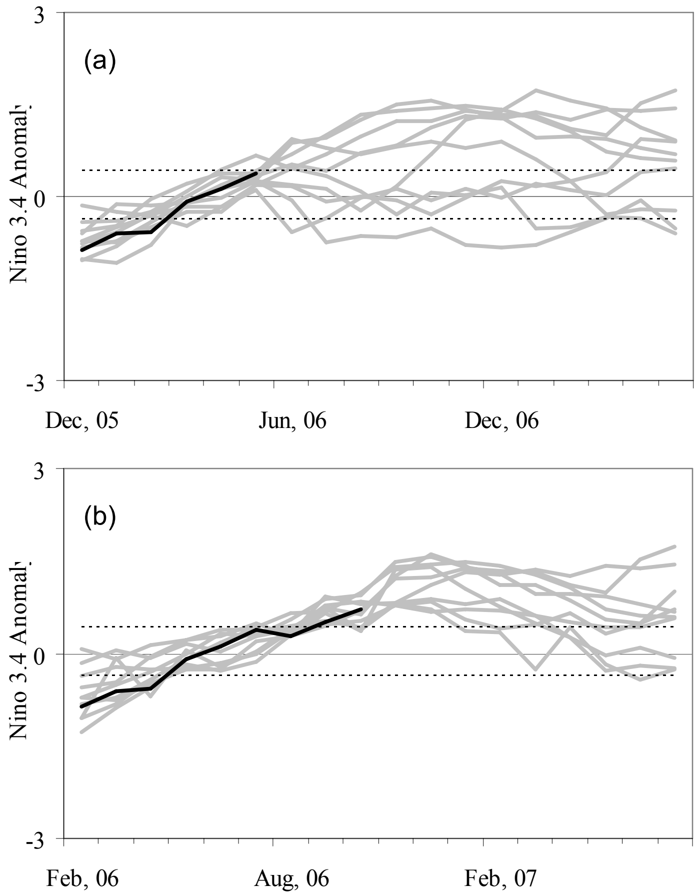

Fig. 2 Top 10 analogue years for the evolution of the NINO3.4 index as at (a) June and (b) October 2006, respectively. Note that 6 of the 10 analogues predict anomalously warm (El Nino) conditions in June over the impact period (Oct–March), rising to 8 of the 10 by October.

example, the NINO3.4 index was utilized. Figure 2(a) and (b) demonstrates the top 10 analogue years when compared to the evolution of the NINO3.4 index in June and October, respectively. As can be seen, by June, six of the 10 years (60%) deemed most similar eventually led to El Nino conditions (persistent El Nino anomalies for months 4–9 from present). However, by October, this has increased to eight of the 10 years (for months 0–5 from present). Figure 3 shows the resultant historic inflow series for Cataract Dam under the identified analogue years in October, where inflow data were available. As can be seen, all inflows for the identified and available analogous years show markedly suppressed recharge to the reservoir.

Statistical model

To assess the performance of the statistical model, the historic time series of ENSO events, as represented by the NINO3.4 index, is utilized within a calibration–validation exercise. The data prior to 1980 are utilized to calibrate the autogressive parameters of the statistical model. The predictive scheme is then run for each year from 1980 to the present time. In addition, to demonstrate the worth of updating the statistical model as

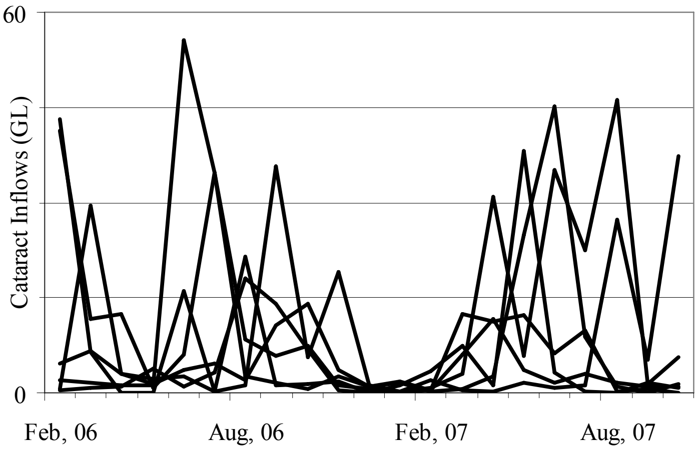

Fig. 3 Flow time series for the Cataract catchment inflows for six of the analogous years (data not available for the other four analogous years). Note, the suppressed inflows for November to February (months 1 to 4).

new NINO3.4 data become available, the analysis was performed for data available in March, June and September for each of the years since 1980.

Figure 4(a)–(c) shows the probability of each of the three ENSO states (El Nino, La Nina and Neutral) for March, June and September predictions, respectively. Also shown on the plot is the resultant ENSO state that eventuated. As can be seen from these figures, predictions made in March are rather uncertain, with typically lower probabilities, whereas by June, the probabilities of individual events tends to increase as does the correct prediction of the eventual ENSO state. By September, the predictive scheme can be seen to quite accurately predict the coming ENSO season with relatively high confidence. These figures demonstrate that the most likely state eventuated in 33% of the predictions made in March, 63% made in June and 73% made in September.

It is also worthwhile to note that, even when two states may have similar probabilities, the third state tends to be essentially discounted due to very low probability of occurrence. Such insights may be of great benefit given that, even if the specific climate state to eventuate is unclear, the water manager may still be able to reject the opposite extreme and plan accordingly. These figures demonstrate marked utility for water managers. An additional benefit of the requirement to update predicted probabilities is that it forces water managers to be regularly and routinely aware of developments in key ENSO indices.

Finally, Fig. 5 represents the likely inflows to Cataract Dam based on the NINO3.4 index as at October. The figure shows median expected inflows as well as uncertainty quantiles based on historic inflow behaviour under El Nino conditions.

DISCUSSION

This paper has attempted to describe a software suite recently developed for use by water managers that enables: (i) the routine prediction of ENSO events, (ii) the assessment of likely inflow on monthly and seasonal timescales, and (iii) the updating of both climate

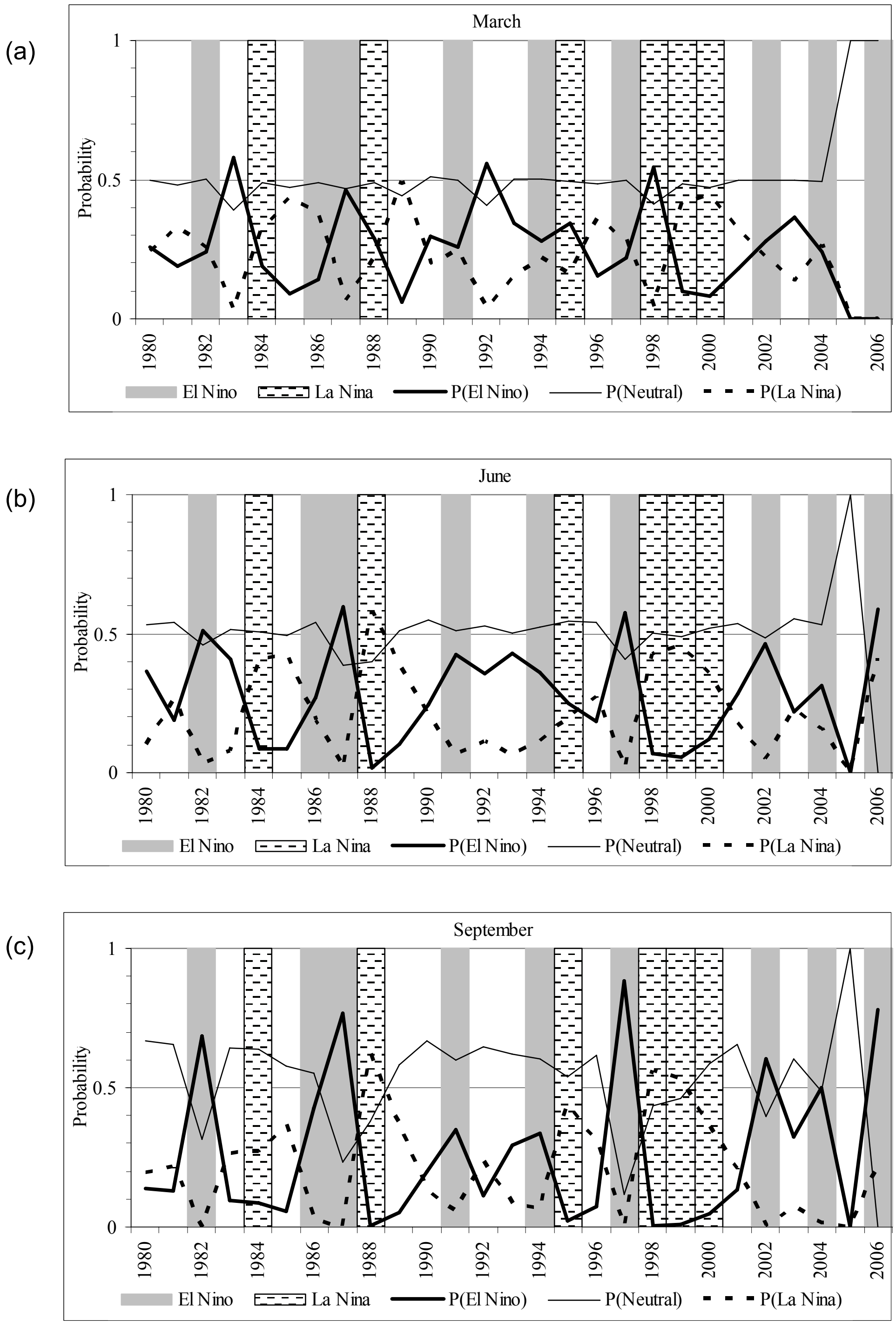

Fig. 4 Probabilistic predictions of each of the three ENSO climate states made in (a) March, (b) June and (c) September. Annual background represents the ENSO climate state that eventuated.

and inflow prediction as new data are received. The scheme has been demonstrated in application to the Cataract reservoir that supplies potable water for metropolitan Sydney.

Whilst multiple methods and monitors have been developed for assessing ENSO extremes and their consequent impacts on hydrological fluxes, the developed software

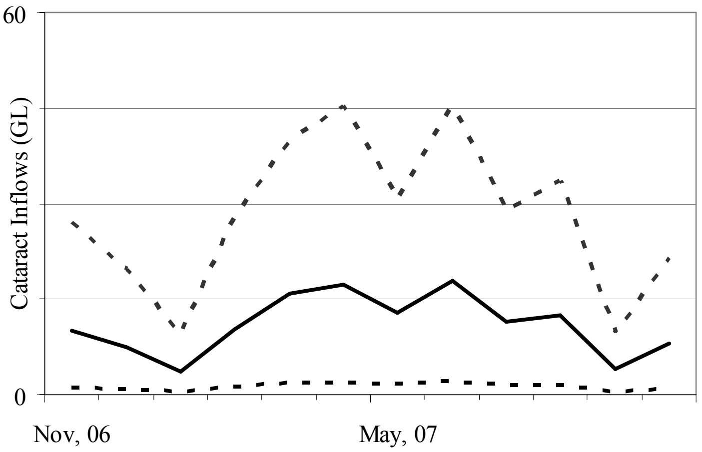

Fig. 5 Median (solid line) and 90% confidence limits (dotted lines) of the probabilistic inflows for the Cataract Reservoir based on NINO3.4 predictions of El Nino in October 2006.

suite permits ultimate flexibility for the user both in the indices and impact time series assessed as well as providing two key alternative methods of assessment. The analogue model provides a simple and intuitive approach to assessing future climate state and impacts, whereas the statistical model provides a robust method of assessing the evolution of the individual indices that represent ENSO processes. Importantly, the developed tool is generalized and can be applied anywhere that significant correlations between ENSO and inflows are found.

Acknowledgements This work has been funded by Sydney Catchment Authority (SCA) project "Assessing simple indices of climate variability for the prediction of reservoir inflows".

REFERENCES

Chiew, F. H. A., Piechota, T. C., *et al*. (1998) El Nino Southern Oscillation and Australian rainfall, streamflow and drought: links and potential for forecasting. *J. Hydrol*. **204**(1-4), 138–149.

Franks, S. W. (2004) Multi-decadal climate variability, New South Wales, Australia. *Water Sci. Technol*. **49**(7), 133–140.

Kiem, A. S. & Franks, S. W. (2001) On the identification of ENSO-induced rainfall and runoff variability: a comparison of methods and indices. *Hydrol. Sci. J.* 46(5), 715–727.

Kiem, A. S. & Franks, S. W. (2004) Multi-decadal variability of drought risk, eastern Australia. *Hydrol. Processes* **18**(11), 2039–2050.

Kiem, A. S., Franks, S. W. & Kuczera, G. (2003) Multi-decadal variability of flood risk. *Geophys. Res. Lett*. **30**(2), 1035–1035.

Power, S., Casey, T., Folland, C., Colman, A. & Mehta, V. (1999) Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics* **15**(5), 319–324.

Salinger, M. J., Renwick, J. A. & Mullan, A. B. (2001) Interdecadal Pacific Oscillation and South Pacific climate. *Int. J. Climatol*. **21**(14), 1705–1721.

Walker, G. T. (1923) Correlation in seasonal variations of weather. VIII. A preliminary study of world-weather. *Memoirs of the Indian Meteorological Department* **24**(Part 4), 75–131.