The atmospheric water balance over the Murray-Darling Basin, based on numerical weather prediction output

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ABSTRACT

The hydroclimate of the Murray-Darling Basin in southeast Australia has been investigated by estimating the Basin's atmospheric water balance, based on numerical weather prediction (NWP) output. The water balance has been calculated for the period from 2000 to 2004, using archived output from the Australian Bureau of Meteorology's mesoscale model, the Limited Area Prediction System (LAPS). The central goal of this work was to characterise the Basin's atmospheric water balance, based on LAPS output. A parallel goal was to assess the ability of LAPS to generate viable and accurate water balances. This was necessary due the scarcity of previous work in this field in Australia (or other similarly arid regions), and due also to previous international studies having concluded that balance equations based on NWP model output contain systematic errors. The climate of the Murray-Darling Basin is arid, and was unusually dry for most of the study period, which included the severe drought of 2002, followed by an extended period of below average rainfall. The results of this study are therefore more relevant to dry conditions.

The area averaged atmospheric water balance for the Murray-Darling Basin was estimated using LAPS output, and was reported as annual and monthly accumulations. Precipitation and evaporation were found to be the leading terms at these time scales. The moisture flux divergence was smaller than is observed in other catchments, where it is often a leading term. This is consistent with the arid Murray-Darling Basin also generating a lesser discharge than the other regions that have been studied. Forecast evaporation exceeded precipitation during each year of the study, implying that the surface provided a net source of atmospheric moisture. A net negative surface water budget cannot be sustained over a long time frame (as Basin discharge is observed). Given that the region was experiencing drought conditions, some surface drying is expected during the study period, however, it is likely that model drift is responsible for a portion of the predicted drying.

Prior to calculating the atmospheric water balance, the LAPS model forecast precipitation was verified against observations to ensure that the model's treatment of moisture processes was sufficient to justify proceeding with the study. The Bureau of Meteorology's real-time analysis of rain-gauge observations was used in this comparison. A sufficient level of agreement was found to justify proceeding, although LAPS showed significantly less skill during extremely hot and dry conditions. The water balance results then have greater uncertainty during these conditions.

Current numerical weather prediction models do not offer perfect representations of the atmosphere, and balance studies based on model products are known to contain residual terms. The residual provides a measure of the model systematic error, as it is generated by the adjustments that are made to model humidity fields to correct for model drift during data assimilation. This process was illustrated by observing that a step change occurs in the forecast precipitable water at the introduction of each data assimilation cycle. A significant water balance residual was observed in this study, as it has been in other similar studies. The characteristics of the water balance residual provides valuable insight into the model's treatment of moisture processes, and it has been used to help assess the quality of the LAPS forecast water balance. The largest residual terms occur during the same hot and dry conditions that are associated with the greatest precipitation errors, confirming the previous conclusion that the results have greater uncertainty then. During these times the residual is strongly negative, indicating a model tendency to accumulate excess atmospheric moisture. The model has predicted suspiciously high evaporation excesses over precipitation during these times, and it has been reasoned that the over-prediction of evaporation may be partly responsible for the large residual terms.

1 INTRODUCTION

Over the last decade there has been an extensive amount of work published on regional and continental scale atmospheric water balances. To date there has been little such work focused on Australia. To address this gap, the Murray-Darling Basin in southeast Australia has been established as a Continental Scale Experiment (CSE) of the Global Energy and Water Cycle Experiment (GEWEX). This paper presents the results of the initial phase of the Murray-Darling Basin CSE Water Balance Project. This work has been based on archived output from the Australian Bureau of Meteorology's numerical weather prediction model, the Limited Area Prediction System (LAPS), and covers the five years from 2000 to 2004. The results of this study are expected to provide an interesting contrast to those from the other GEWEX CSEs, as the climate of the Murray-Darling Basin is much more arid than in the other basins.

The research presented here has two main goals. The first goal is to characterise the atmospheric water balance over the Murray-Darling Basin during the study period (2000- 2004), based on LAPS output. The second and parallel goal is to assess the ability of the LAPS model to forecast a viable and accurate water balance. This is necessary due the scarcity of previous work in this field in Australia (or other similarly arid regions) and due also to the fact that balance studies based on NWP output are known to contain significant residual terms. The ability of LAPS to forecast water balance terms is assessed by comparing LAPS forecast precipitation against the observed values. This is based on the assumption that the performance of a model in predicting precipitation is closely related to its performance predicting other atmospheric moisture processes, given the high level of interaction between these processes. Additionally, the behaviour of the water balance residual is investigated, and likely errors in the water balance forecasts are identified.

2 BACKGROUND

2.1 Climate of the Murray-Darling Basin

The majority of the Murray-Darling Basin is classified as arid or semi-arid, and it is estimated that 86% of the basin generates no runoff, except during flood events (Maheshwari 1995). For much of the study period, conditions in the basin were unusually dry. A severe drought occurred in 2002, with rainfall in the Basin in the lowest 5% on record during the last nine months of that year, while temperatures were the highest on record. Extensive agricultural losses were incurred, and the 2002-03 summer bush-fire season was one of the Basin's worst. Since then, there has been no prolonged period of widespread above average rainfall in the Basin to fully remove rainfall deficiencies. In November 2000, previous to the droughts discussed above, flooding occurred in extensive areas of the Basin, demonstrating the high variability of the its climate. These floods resulted from heavy rains, which were in the upper-most decile for November in the majority of the Basin.

2.2 NWP derived balance studies and the systematic tendency error

Balance studies based on output from numerical weather prediction (NWP) models are known to suffer from model contamination (Kanamitsu and Saha 1996, Roads et al 1998), and previous such studies have been observed to contain significant residual terms (eg. Roads et al 2002). This is true of balances based on either NWP forecasts or their associated analyses. The residual term is generated during the assimilation cycle, when model fields are constrained to stay close to observations. This is achieved by adding artificial increments to selected model fields to adjust them toward observations. The addition of these artificial increments violates the mass conservation laws and so introduces a residual into any balance equations derived from the assimilation products. The size of the residual measures the amount of adjustment required to constrain the model close to observations. For this reason the residual is often referred to as a systematic tendency error, following Kanamitsu and Saha (1996).

Despite the aforementioned problems, NWP model outputs, and their associated analyses, are favoured as the basis for modern atmospheric balance studies (eg. Berberry and Rasmusson 1999; Roads et al 2002). Forecast output from the LAPS model has been used in this study, rather than the associated analysed fields or observations, because it is available at a finer temporal resolution and includes all relevant moisture fields.

3 METHODOLOGY

3.1 The water balance equation

The vertically and time integrated atmospheric water balance equation is:

$$\overline{dW/dt} = \overline{E} - \overline{P} - \overline{divQ} + \overline{R} \qquad (1)$$

W is the vertically integrated water content of the atmosphere, or precipitable water, and dW/dt is the rate of change of precipitable water over time. The volume of water in the atmosphere is assumed to remain constant over time, so that dW/dt is expected to be close to zero over periods longer than approximately one month. Q is the vertically integrated moisture flux vector, and $divQ$ is the vertically integrated moisture flux divergence. Over long timeframes the moisture flux convergence should be equal to the basin discharge. P and E are precipitation and evapotranspiration. All vertical integrations are from the top of the atmosphere (estimated here at 250 hPa), to the surface. Overbars indicate the time integral. The water balance residual has been explicitly included through the R term, and is calculated as equal and opposite to the remaining terms.

3.2 The Limited Area Prediction System

The moisture balance calculations for this study have been based on output from the Australian Bureau of Meteorology's mesoscale model, the Limited Area Prediction System (LAPS). LAPS runs operationally on a latitude - longitude grid of $0.375°$, and has 29 vertical levels in sigma coordinates. The data assimilation scheme used is a three-dimensional multivariate statistical interpolation objective analysis system; and all fields are analysed on the same latitude - longitude - sigma grid as that used by the forecast model. For full details of LAPS refer to Puri et al (1998).

LAPS is run operationally twice a day, at 00:00 and 12:00 UTC, and the model output is archived every three hours. Each of the terms in Equation 1 have been calculated as the time integral over the three-hour period between the archived outputs, for the 3 to 24 hour forecasts, for both the 12:00 and 00:00 UTC model runs. There is no systematic difference between the water balance estimated from the 12:00 and 00:00 UTC model run, so an average of the two has been taken at each time.

3.3 Rain-gauge observations

In order to check that moisture processes are adequately handled by LAPS, precipitation has been verified against the observed rain-gauge measurements, using the Australian Bureau of Meteorology's daily real-time objective rainfall analysis. Approximately 200 rain-gauges within the Murray-Darling Basin are included in the real-time analysis each day, and there are no known uncertainties in the analysis for this region. The rain-gauge data are analysed onto a $0.25°$ grid. For full details see Weymouth et al 1998.

During the automated verification of LAPS rainfall forecasts, the observed Murray-Darling Basin area averaged rainfall is calculated from the real-time analysis, providing readily available data for this study (supplied by E. Ebert). The observed and forecast rainfall have been compared for a truncated period, from October 2000 to December 2004, as the archived verification is very incomplete prior to then. In each year, between 5 and 30 non-consecutive days are missing from the archive. These days have also been excluded from the forecast monthly values used in the comparison.

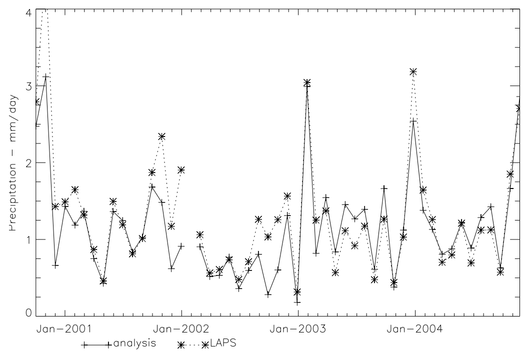

Figure 1. Monthly forecast and observed precipitation.

4 VERIFICATION OF FORECAST PRECIPITATION

Visually, the forecast precipitation compares well to observations (see Figure 1), with some noticeable exceptions: rainfall during the period of severe rainfall deficiency in the summer of 2002-03 was persistently over-predicted by 50%- 100%; the low rainfall the previous summer was also persistently over-predicted, although to a lesser extent. The flood inducing rains in November 2000 were again over-predicted, by roughly 50%, although this is of lesser consequence as it was a single event of relatively short duration. The net bias across the study period was 0.16 mm/day, and the mean error in the monthly observations was 0.27 mm/day. A scatter-plot (not shown) of the forecast and analysed rainfall confirms the above statistics. While there is not a large net bias in the forecast monthly rainfall (a 0.16mm/day bias is equivalent to 10% of the average forecast value), the forecasts are spread widely on either side of the observations.

From the above analysis it has been concluded that LAPS is sufficiently accurate to proceed with the water balance, although it has less skill during extremely dry conditions, and the results during these times will have a greater uncertainty. During the verification period LAPS has predicted the general pattern of the monthly observed precipitation reasonably well, although with some deviation, both positive and negative. The deviations are not randomly distributed, and occur more during extreme dry events.

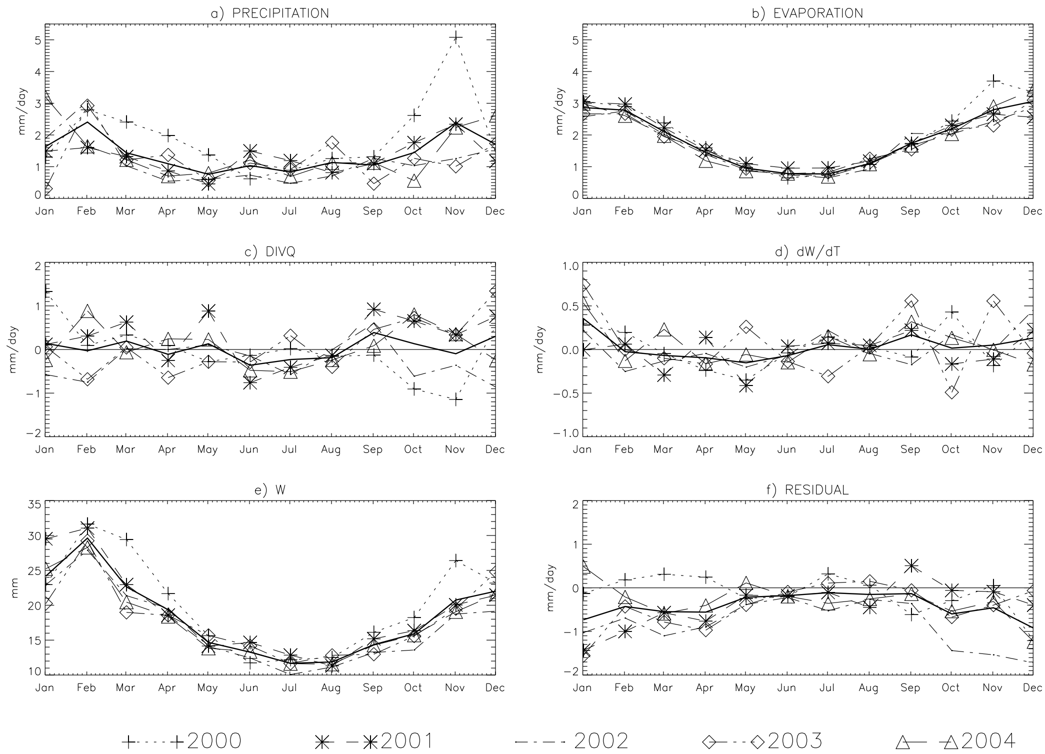

Figure 2. Monthly LAPS forecasts of (a) precipitation, (b) evaporation, (c) moisture flux divergence, (d) change in precipitable water over time, (e) precipitable water, and (f) the residual.

5 RESULTS

5.1 The estimated water balance

Precipitation and evaporation are the leading terms in the annual water balance over the Murray-Darling Basin (see Table 1). The residual term is significant, and is smaller than the leading terms, although of the same order of magnitude. The moisture flux divergence is an order of magnitude smaller than the leading terms, consistent with the Basin's low surface discharge. dW/dt is small, as expected.

Table 1. The MDB Annual Water Balance. All values are in mm/year.

Year	P	E	divQ	dW/dt	R
2000	697	746	−9	10	47
2001	473	703	93	−5	−142
2002	425	647	−96	6	−311
2003	440	659	35	28	−157
2004	520	675	24	20	−111

The monthly water balance terms are briefly described below, and are plotted in Figure 2. Note that the vertical scales vary.

The seasonal cycle in precipitation follows the same general trend in each year, with higher values in the warmer months. Superimposed on this are sporadic episodes of very high precipitation in these months, the largest of which occurred in November 2000.

Evaporation varies smoothly throughout the year with larger values in the warmer months, suggesting that the forecast evaporation is principally determined by incoming solar radiation. November 2000 stands out with a relatively high evaporation, which was likely a response to the greater surface water availability during that period. Otherwise there is very little inter-annual variation.

The surface water budget (plotted in Figure 3), defined as precipitation minus evaporation, is an important parameter in the water cycle, as it measures the flow of water between the atmosphere and the surface. The seasonal cycles of precipitation and evaporation produce an excess of precipitation over evaporation during the winter months of less than 0.5 mm/day, and an evaporation excess for the remainder of the year, of up to 1-2 mm/day in summer. There are two exceptions to this pattern: in 2000 high precipitation in autumn and spring generated a relatively large precipitation excess; and in 2002 monthly precipitation was less than evaporation during winter. The excess evaporation in the warmer months is generally greater than the precipitation excess in winter, so that the annual surface water budget for each year is negative.

There was a net moisture flux divergence across the study period, although there was net annual convergence in 2000 and 2002. The monthly moisture flux divergence timeseries is noisy, and it is difficult to discern a clear seasonal cycle. The average for each month is close to zero, due to positive and negative values in different years. Nonetheless, the average is negative in each of the winter months, indicating convergence, in support of the precipitation excess over evaporation in these months. During the rest of the year divergence is slightly favoured. The monthly averages are obscuring the large convergence events that occur over several days, related to precipitation events. October and November 2002 experienced relatively large convergence, supporting the enhanced precipitation that occurred then.

The change in precipitable water over each year is small, as expected. The water content of the atmosphere is principally determined by temperature, which is well illustrated in Figure 2e, which shows that W follows the seasons closely. There is little spread between the years, with the exception of 2000, which had relatively high precipitable water in autumn and spring.

The water balance residual term was significant. It is not uncommon for it to be amongst the leading terms of water balance experiments (eg. Roads et al 1998; Yarosh et al 1999). The residual has a strong tendency to be negative, and the average value for each month is negative, with the largest negative values generally occurring in summer. The largest annual residual occurs in 2002, which is the only year with a negative value every month. Autumn 2000 is the only period to experience a sustained positive residual.

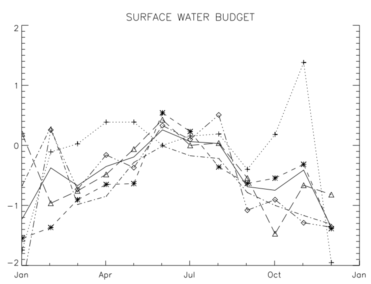

Figure 3. Monthly LAPS forecasts of precipitation minus evaporation, legend as for Figure 2.

5.2 The precipitable water diurnal cycle

To illustrate how artificial moisture increments are added to the model atmosphere during data assimilation to adjust for model drift, the diurnal cycle of the forecast precipitable water has been plotted for a period that incurred a large water balance residual. Figure 4 shows the diurnal cycle of the forecast

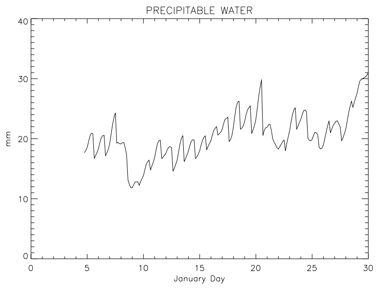

Figure 4. Forecast precipitable water for January 2003, from the 12:00 UTC model run.

precipitable water, from the 12:00 UTC LAPS model run for January 2003. There is an apparent unnatural diurnal cycle, with a discontinuity in the time series at 15:00 UTC each day, marking the introduction of each new assimilation cycle. There is a similar pattern in the 0:00 UTC model forecast precipitable water (not shown), with the discontinuity occurring at 3:00 UTC. The persistent downward adjustment of the atmospheric moisture at the introduction of each new assimilation cycle indicates that the model is systematically accumulating excess atmospheric moisture during each forecast, which must then be systematically removed during each assimilation. This is the systematic tendency error responsible for generating the water balance residual during this time period.

To check that the diurnal cycle observed above is artificial, the forecast precipitable water for January 2003 has been compared to a time series constructed from radiosonde observations (not shown). While the daily forecast values verify well, the observed precipitable water does not have the diurnal cycle shown in Figure 4. This confirms that the unnatural appearing diurnal cycle in the precipitable water is a model artifact.

6 DISCUSSION AND CONCLUSIONS

6.1 Characteristics of the water balance

Precipitation and evaporation are the leading terms in the atmospheric water balance over the Murray-Darling Basin. This contrasts with the water balances of most other regions, where the moisture flux divergence is usually a leading term (eg. Zangvil et al 2001; Smirnov and Moore 1999), and is consistent with the low discharge from the arid Murray-Darling Basin.

The LAPS model has predicted a negative surface water budget across the study period, inferring that the surface has supplied moisture to the atmosphere over this time period. Annual precipitation exceeds evaporation in every year of the study, and there is a net divergence of atmospheric moisture flux during the study period, although not in each year. The greatest surface drying occurs during summer, when evaporation is at a maximum, and can exceed precipitation by 1-2 mm/day. In most of the study years there is an excess precipitation of 0.5 mm/day during winter, providing some surface water replenishment. During the drought conditions of 2002 there was no winter precipitation excess, so that the surface continued to dry throughout the year. In contrast, during the much wetter 2000, the surface water budget was positive in autumn and spring, as well as in winter.

A net negative surface water budget for the Murray-Darling Basin cannot be supported in the long term, since basin discharge is observed. It is possible to have a negative budget in some years, as discharge could be maintained through supply from the terrestrial water store. In fact, this is known to have occurred in the past; previous to surface water management, the Murray River was observed to dry to a series of stagnant pools during drought conditions. The question is then raised as to whether the forecast negative surface moisture budget is artificial and due to model drift, or whether it is a real occurrence. Unfortunately there are no available observational data for terrestrial water storage across the entire Murray-Darling Basin to easily answer this question. Given that there is a systematic tendency error in the model, it would not be surprising if this error were partitioned in such a way to produce an artificial surface water budget drift. The small negative surface water budget in 2001 is likely a model error, as precipitation was above average this year, and extensive flooding occurred in areas of the Basin. However, the later part of the study period was unusually dry, particularly in 2002, so that surface drying would be expected during this period. Surface drying during 2002 is evidenced in the agricultural losses over the cool season, and the severity of the bushfire season the following summer.

6.2 Uncertainty in the atmospheric water balance

The behaviour of the systematic error, and any obvious discrepancies in the LAPS forecast water balance terms have been discussed below, in order to assess the confidence level of the forecast water balance, and to identify likely problems.

The water balance residual, or model systematic tendency error, provides a useful tool for assessing the LAPS model treatment of moisture processes in the model. The persistently negative systematic error indicates that during the study period the model has a tendency to accumulate excess atmospheric moisture, which must then be removed at the introduction of each new assimilation cycle (as illustrated in Figure 4). The negative systematic error appears to be correlated with hot and dry conditions and is largest in summer. During the 2002 winter the Murray-Darling Basin experienced severe rainfall deficiencies and record high temperatures, and this was the only winter during which the systematic tendency error was persistently negative. The following spring and summer included the four months with the highest systematic tendency errors in the study (Oct. 2002 - Jan. 2003).

It is extremely difficult to partition the systematic tendency error into its constituent term(s) due to the strong interactions between the dynamical and physical terms, and between the physical processes (Kanamitsu and Saha 1996). In other words, a correlation between a discrepancy in one of the water balance terms, and the systematic tendency error term does not imply causality, as the discrepancy may be a consequence of the same processes causing the tendency error. Nonetheless, suspected errors in the water balance terms are discussed below, focusing on the leading terms of precipitation and evaporation, which due both to their scale and the fact that they are derived terms are likely to be responsible for the greatest errors. The moisture flux divergence is less likely be a major cause of systematic error, due to its relatively small scale.

The LAPS model is able to predict the general characteristics of monthly precipitation, although it has over-estimated precipitation during the study period, and is less accurate during extremely hot and dry conditions. This was illustrated by the comparison between forecast and observed precipitation in Section 3. Interestingly, the periods of greatest precipitation forecast error shown in Figure 1 are well correlated with the periods of greatest systematic tendency error shown in Figure 2. Somewhat confounding is the fact that replacing the forecast precipitation with the smaller observed values increases the magnitude of the residual. This could suggest that the over-prediction of precipitation is offsetting an even larger systematic error than is currently observed. However, it is as likely that the over-prediction of precipitation is symptomatic of the model tendency to accumulate atmospheric moisture.

The water balance has not been reported below daily resolution, as inaccuracies were observed in the LAPS forecast diurnal cycle. A comparison of observed and forecast precipitable water revealed an artificial diurnal cycle in the forecast values (although they verified well on longer time scales). There are then likely to be inaccuracies in the diurnal variation of the other water balance terms, introducing significant uncertainty at the sub-daily time scale.

It is likely that the LAPS model is over-predicting evaporation during warm, dry conditions. Unfortunately, there are no direct observations available that can be used to estimate evaporation across the Murray-Darling Basin, making it difficult to verify the forecast values. The forecast evaporation does not vary significantly between years, and has only a weak dependency on the occurrence of recent rains, which should provide additional available surface water for evaporation. Some months have suspiciously large evaporation excesses over precipitation, in particular during the 2002-03 summer. The evaporation could be expected to have been below average then, as the drought conditions would have limited available surface water. Despite this, the evaporation forecast for the 2002-03 summer was only slightly below average, suggesting that evaporation was overestimated during this summer. This is likely to be responsible for at least a part of the large systematic error during this period.

Some insight can be gained into the forecast evaporation errors by considering the LAPS soil moisture parameters, since these provide the source moisture for evaporation. The artificial diurnal cycle in the atmospheric moisture during January 2003 (see Figure 4) is matched by an opposite trend in the LAPS surface moisture parameters (not shown). During daylight hours the atmospheric moisture content systematically increases, while the surface moisture systematically decreases. At the introduction of each new assimilation cycle, the atmospheric moisture is adjusted down, and the surface moisture is adjusted up, by adding appropriately signed artificial increments to each of these field. This supports the suggestion that LAPS is predicting too much evaporation during these extremely warm and dry conditions.

7 SUMMARY OF MAIN FINDINGS

Precipitation and evaporation are the leading terms of the monthly atmospheric water balance during the period from 2000-2004, as predicted by the Bureau of Meteorology's LAPS model. This result contrasts most water balance studies of other regions, where the moisture flux divergence is usually a leading term; the lower moisture flux divergence in this study reflects the aridity of the Murray-Darling Basin. Evaporation exceeded precipitation during each year studied, suggesting that the surface was acting as a net source of atmospheric moisture. Much of the study period was unusually dry, including a period of severe drought. The above described behaviour may well differ during wetter conditions.

The LAPS model appears to be able to capture the main characteristics of the monthly Murray-Darling Basin water balance, although there are some discrepancies in the forecast water balance, particularly during extreme hot and dry conditions. The results during these conditions have a high degree of uncertainty. It is difficult to confidently identify the direct cause(s) of these discrepancies, however, the over-prediction of evaporation during these conditions is a likely candidate.

8 REFERENCES

Berberry, E.H., Rasmusson, E.M. 1999. Mississippi moisture budgets on regional scales, *Mon Wet Rev*,**127**,2654-2673.

Kanamitsu, M. and Saha, S. 1996. Systematic tendency errors in budget calculations, *Mon Wet Rev*,**124**, 1145-1160.

Maheshwari, B.L. 1995. Effects of regulation on the flow of the River Murray, Australia, *Regulated Rivers*,**10**, 15-38.

Puri, K., Dietachmayer, G.S., Mills, G.A., Davidson, N.E., Bowen, R.A., and Logan, L.W. 1998. The new BMRC Limited Area Prediction System, LAPS, *Aus Met Mag*, **47(3)**, 203-223.

Roads, J.O., Chen, S,-C., Kanamitsu, M. and Juang, H. 1998. Vertical structure of humidity and temperature budget residuals over the Mississippi basin, *JGR*, **D4(103)**,3741-3759.

Roads, J.O., Kanamitsu, M, and Stewart, R. 2002. CSE water and energy budgets in the NCEP-DOE Reanalysis II, *J Hydromet*,**3**, 227-248.

Smirnov, V.V, and Moore, G.W.K. 1999. Spatial and temporal structures of atmospheric water vapor transport in the Mackenzie River Basin, *J Climate*, **12(3)**,681-686.

Weymouth, G., Mills, G.A., Jones, D., Ebert, E.E., and Manton, M.J. 1998. A continental scale daily rainfall analysis system, *Aus Met Mag*,**48**,169-179.

Zangvil, A., Portis, D.H., and Lamb, P.J. 2001. Investigation of the large-scale atmospheric moisture field over the midwestern United States in relation to summer precipitation. Part 1., *J Climate*,**14(4)**,582-597.