18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Assessing the impact of the 11-year solar cycle on drought in Australia

Wasko, C.D. [1] **and A. Sharma** [2]

[1] *Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales, Sydney, New South Wales, Australia.* [2] *School of Civil and Environmental Engineering, University of New South Wales, Sydney, New South Wales, Australia.*
Email: c.wasko@wrl.unsw.edu.au, a.sharma@unsw.edu.au

Abstract: Atmospheric moisture content serves as an important basis for the estimation of probable maximum precipitation (PMP) as well as a generic predictor for use in rainfall downscaling applications aimed at converting coarse-scale General Circulation Model (GCM) output to a fine catchment scale. As with other key atmospheric variables, the atmospheric moisture content depends on the extraterrestrial solar radiation, with the large scale transport of water vapour as latent heat one of the main redistribution mechanisms for the uneven radiative input from the sun. This extraterrestrial solar radiation, however, is not constant but changes in a predictable manner with time, varying cyclically with a period of 11 years.

To asses the impact of the 11-year solar cycle on drought, rationale was borrowed from the procedures used to estimate the storage capacity of a water supply reservoir. Regions of the Earth's atmosphere were conceptualized as storage reservoirs filling and depleting the atmospheric moisture with time. The amount of moisture in the atmosphere was conceptualised as the supply, and the demand for atmospheric moisture content was equated to 99% of the mean atmospheric moisture content for that region under a case where no cyclic solar radiation forcing exists. The required storage of our atmospheric reservoir is hence the largest volume of atmospheric water that will be needed to supply the demand during a drought period, so that the atmospheric reservoir is never empty. The critical period is the length of time from the reservoir being full to being empty. It is these measures of storage and critical period of atmospheric moisture content that are used to measure the severity of a drought. The larger the storage or critical period, the more severe the drought.

Four GCM simulations were subsequently performed with the results being analysed on the basis of atmospheric moisture content storage and critical period. The four scenarios include a "No Forcing" simulation which uses a perpetual mean solar irradiance, and three solar variability scenarios. The first is a scenario where the solar forcing is the result of an 'envelope' curve fitted to the available solar irradiance data. The other two represent amplified versions of the first solar variability case.

The results of the analysis of the above scenarios show that very large differences in drought severity exist between different climatic regions. The analysis also indicates that compared to a situation where no solar-variability exists, regions prone to severe drought exhibit a decrease in their drought severity, while regions of low drought severity tend to an increase in the severity of drought due to the 11-year solar cycle. It is noted that it may be plausible to suggest that this trend is exacerbated with higher amplitude solar cyclicity, though the nature of the results being inconclusive is a demonstration of the non-linearity of the Earth's climate.

It is hence concluded that it is plausible to suggest, in the absence of all other forcings, and other multi-decadal solar variability, the 11-year cycle acts to increase the severity of droughts in those climatic regions which are not susceptible to significant drought periods. However, for regions prone to large drought periods, the drought severity is decreased due to the presence of a solar cycle.

More pertinently, the observation is made that if GCM simulations use perpetual solar forcings, this can cause a misrepresentation of the complicated nature of short and long term behaviour of atmospheric moisture.

Keywords: *Drought, 11-year solar cycle, atmospheric moisture content, climate variability*

1. INTRODUCTION

Solar radiation and water vapour are intricately linked. Water vapour is one of the main agents in the overall energy budget of the atmosphere with condensation providing energy for circulation of the atmosphere. The large scale transport of water vapour as latent heat is thus one of the main redistribution mechanisms for the uneven radiative input from the sun (Brutsaert, 2005). More pertinently, atmospheric moisture content serves as an important basis for the estimate of probable maximum precipitation (PMP) (Hydrometeorological Advisory Service, 2003; Svensson and Rachecha, 1998) which is then used for probable maximum flood (PMF) prediction. Atmospheric moisture is also a crucial predictor for downscaling applications aiming to convert coarse-scale General Circulation Model (GCM) outputs to a fine catchment scale (Charles, 1999). An understanding of the interdependence of solar radiation and atmospheric water content is hence vital for accurate long-term rainfall forecasting.

2. ATMOSPHERIC MOISTURE STORAGE

Atmospheric moisture content is defined as the depth of water vapour in the atmosphere and is roughly equivalent to 25 mm on average. The amount of moisture in the atmosphere varies significantly spatially across the globe with average values near the equator closer to 50 mm and at the poles almost zero.

Table 1. Correlation of NCEP Reanalysis (Kalnay *et al.*, 1996) atmospheric moisture content and gridded rainfall across Australia (Australian Bureau of Meteorology, www.bom.gov.au, 2008) from 1948 to 2007.

		Longitude								
		115	120	125	130	135	140	145	150	155
Latitude	-15	0.50	0.48	0.39	0.33	0.36	0.36	0.42	0.40	0.35
	-20	0.47	0.33	0.25	0.20	0.17	0.15	0.23	0.30	0.31
	-25	-0.01	-0.08	-0.13	-0.18	-0.19	-0.20	0.08	0.00	0.05
	-30	-0.35	-0.45	-0.49	-0.50	-0.48	-0.46	-0.48	-0.58	-0.58
	-35	-0.48	-0.55	-0.54	-0.51	-0.52	-0.56	-0.60	-0.69	-0.69
	-40	-0.54	-0.52	-0.50	-0.49	-0.50	-0.54	-0.65	-0.69	-0.69

It would be expected that the amount of moisture in the atmosphere at any given time would be related to the rainfall experienced. Table 1 presents correlation coefficients for atmospheric moisture and rainfall for Australia. As we can see, a strong relationships exists in the northern and southern regions of Australia where rainfall is seasonal.

To assess long-term trends in the climate we use storage as a cumulative measure of the atmospheric moisture content in the atmosphere. The rationale is borrowed from well established procedures for estimating the storage capacity of a water supply reservoir (Ripple, 1883). To do this the atmosphere is conceptualised as a storage reservoir filling and depleting with atmospheric moisture over time. The required storage of the reservoir is hence the largest volume of water what will be needed to supply the demand during a drought period, so that the reservoir is never empty. The critical period is the length of time from the reservoir being full to being empty. This is shown in Figure 1 using NCEP Reanalysis data (Kalnay et al., 1996) for the Eastern seaboard of New South Wales. A larger storage or critical period for a climatic region implies the droughts for that region are more severe.

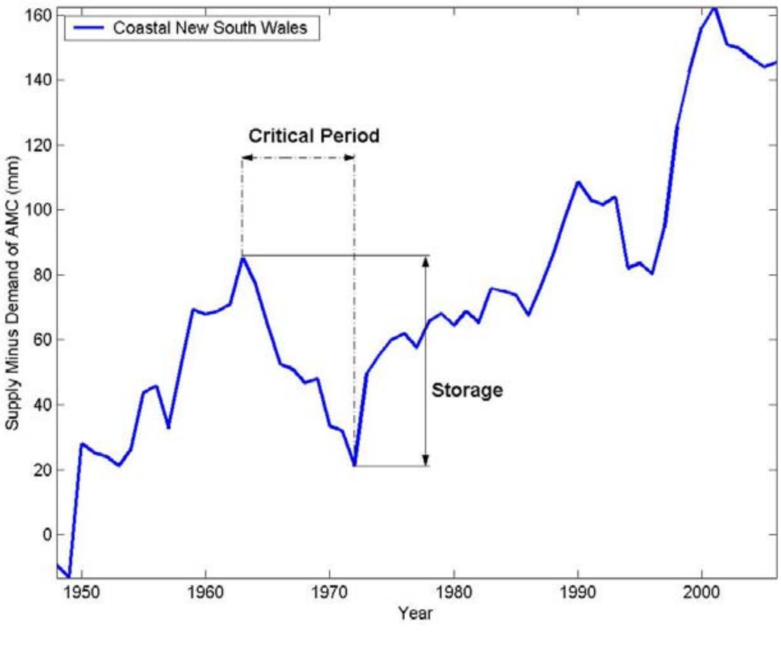


Figure 1. Storage of atmospheric moisture content for the Eastern seaboard of New South Wales, Australia.

3. AN APPROACH TO ASSESSING THE IMPACT OF THE 11-YEAR SOLAR CYCLE ON DROUGHT

The extraterrestrial solar radiation which is received by the Earth is measured as total solar irradiance (TSI), and has a well-established cyclic trend of approximately 11 years (Frölich and Lean, 2004). It is estimated that each radiometer used to produce the daily time series of TSI presented in grey in Figure 2 has an uncertainty of 0.4 % (Frölich and Lean, 1998), and the null underlying variation in the output of the Sun has uncertainty of not less than 0.3 % (Quinn and Frölich, 1999). Note that a variation of the order of 0.1 % is approximately 1.35 W/m^2.

The 11-year solar cycle is used as a basis for assessing the long-term impact of solar variability on drought. In order to simulate long-term trends the TSI needs to be represented as a regularly oscillating time series. Hence a Fourier series composed of the five most significant frequencies was fitted to the 95th percentile of the TSI daily time series maintained by PMOD/WRC, Davos, Switzerland. This curve, shown in black in Figure 2, forms the basis of the solar forcing, and can be thought as an approximate envelope of the observed data as it encompasses the majority of the data while excluding outliers. To account for any errors present in the data and to capture any extreme variations, the basis curve is magnified by a factor of 1.5 and 2 with the resulting curves shown in blue and green respectively. These three curves provide a set of simulated TSI forcing for not only testing the impact of the solar cycle, but also the impact of the amplitude of the solar cycle. Additionally it is possible to assess the potential non-linear response of atmospheric processes (Franks, 2002). Note that our amplitude modified curves are well within the bounds of the data set (the axes of Figure 2 are set on the maximum and minimum TSI data points). The pink dotted line Figure 2 is the mean of cyclic solar irradiance curves presented and forms the control (or No Forcing case) in the simulations so that the impact of the solar cycle being present can be compared with the case where there is no solar variability present.

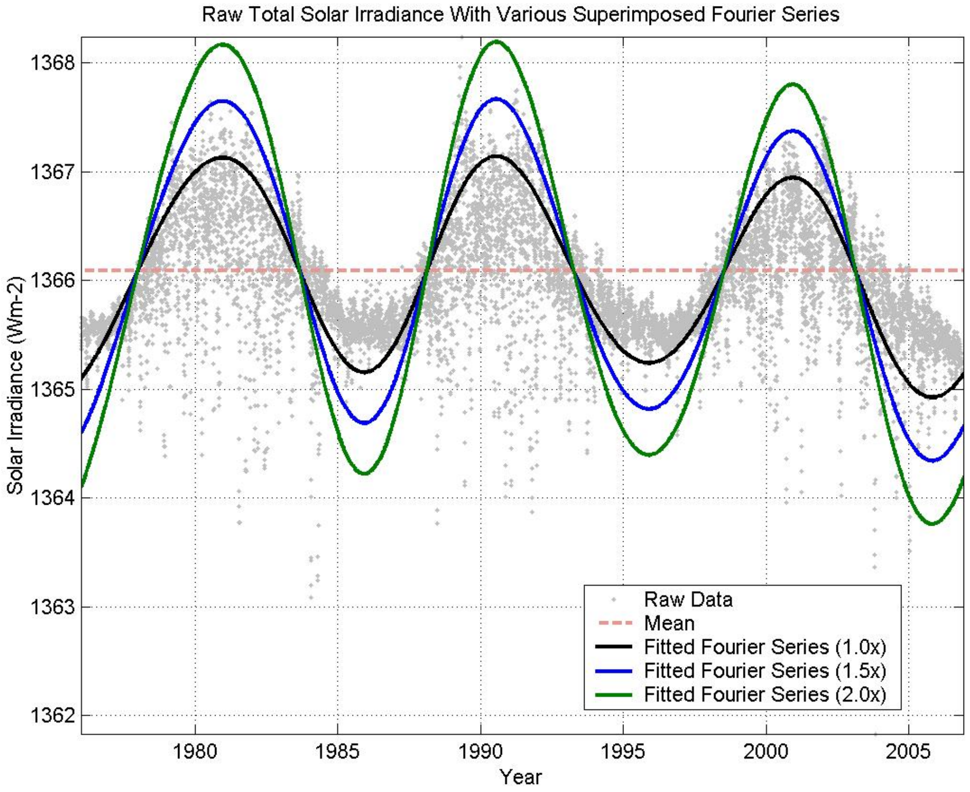


Figure 2. TSI daily time series with various superimposed solar forcings.

All four of these scenarios were then simulated for 300 years using EdGCM (EdGCM Cooperative Project of Columbia University, http://edgcm.columbia.edu, 2007) which was developed at NASA’s Goddard Institute for Space Studies (GISS). EdGCM is an updated version of the GISS Model II described in Hansen *et al.*, (1983) which is a coarse gridded, research level GCM, requiring minimal computing power to be used for long-range climatic experiments. No other forcings other than those presented in Figure 2 were used. Each cyclic forcing was centered on the same mean to ensure the overall energy budget due to solar irradiance was not changed between simulations.

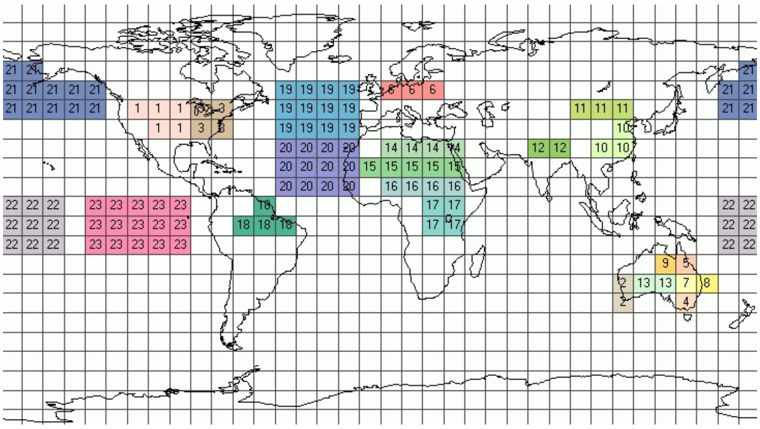


Figure 3. Regions simulated in the general circulation model

In the analysis the first 50 years of results were omitted as the model was deemed to be stabalising during this period. The regions subsequently analysed for their atmospheric moisture storage are presented in Figure 3. Each region was anaylsed for its atmospheric moisture content storage using the amount of atmospheric moisture in the atmosphere as the supply, and demand corresponding to 99% of the mean atmospheric moisture content for the No Forcing simulation in that region. The choice of this demand was to create critical periods in the order of 20 years to ensure statistical significance of the results obtained over the time-scale of the simulations. Note that this does not change the conclusions of our results as the results are presented as relative to the No Forcing simulation.

The four model simulations are summarized as follows:

- *No Forcing* – Solar irradiance corresponding to the mean of the fitted variability curves representing a situation where no solar variability is present.
- *Solar Forced (1.0x)* – A forcing which is the result from a fitted Fourier series to the 95th percentile of the TSI time series and represents an envelope of the 11-year solar cycle.
- *Solar Forced (1.5x)* – A forcing with 1.5 times the amplitude of the original envelope curve.
- *Solar Forced (2.0x)* – A forcing with 2 time the amplitude of the original envelope curve.

4. IMPACT OF THE 11-YEAR SOLAR CYCLE

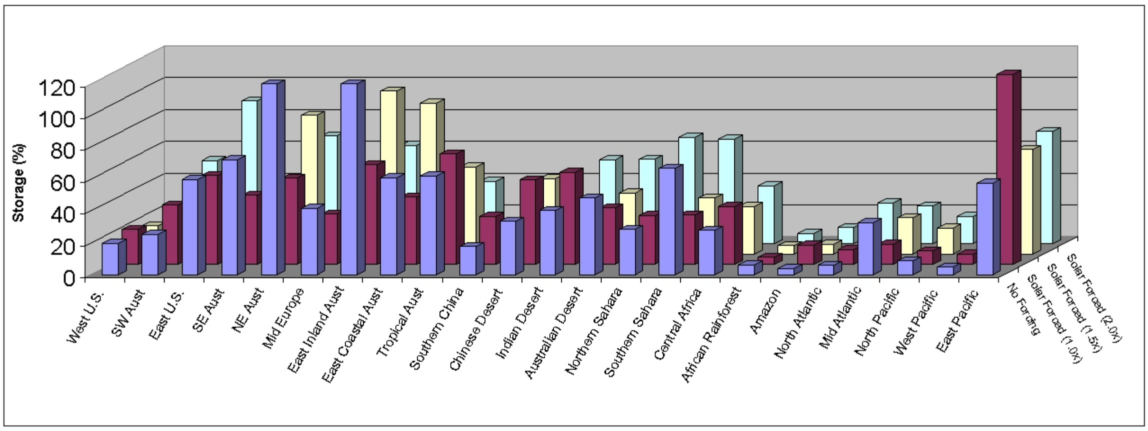
In order to validate the results from the GCM simulations a comparison of our methods on the GCM results and Reanalysis Data is presented in Table 2. We calculate the Atmospheric Moisture Storage and Critical Period for both Reanalysis Data and that from our Solar Forcing (1.0x) simulation for regions across the Eastern seaboard of Australia. The fact that the values are of the same order of magnitude suggests that the method and GCM results are justified. What is most significant is that that the regional trends in the GCM simulations appear to be well represented with those observed in the Reanalysis Data. Regions that experience a large storage in the reanalysis data also have a corresponding large storage in the GCM simulation. In fact if we rank each simulation in magnitude we find that for both storage and critical period the results for the two data sets correspond in rank. However, in all cases, the GCM results are larger in magnitude than those extracted from

Table 2. Storage and Critical Period of Atmospheric Moisture Content for reanalysis and GCM data. (The index of each region corresponds to the regions presented in Figure 3.)

Region	Storage (mm)		Critical Period (Years)	
	Reanalysis	GCM (1.0x)	Reanalysis	GCM (1.0x)
(8) Coastal New South Wales	64.0	123.4	9	24
(7) Inland New South Wales	78.6	128.7	9	23
(5) Queensland	226.2	177.3	22	34
(4) Victoria	32.4	87.2	4	16

the Reanalysis data. It is possible that this is a result of the fact that the GCM results use a much longer time series than the Reanalysis Data, increasing the chance of a more severe drought.

It is not surprising that the when the Earth’s climate is forced with an 11-year solar cycle, the amount of moisture in the atmosphere tends to oscillate with the same frequency (Wasko and Sharma, 2009). What is more interesting however is the impact of the 11-year solar cycle on atmospheric moisture storage and critical period. Figure 4 presents storage and critical periods from various climatic regions around the world. The storages are expressed as a percentage of that annual mean atmospheric moisture content for that region, this is important as it is possible that a region can have a high measured storage, but as its mean atmospheric moisture content is high, the severity of the drought is not as significant in a region where that high storage is recorded in a region of low average moisture content. Thus the relative storages presented indicate the severity of drought in a particular region.



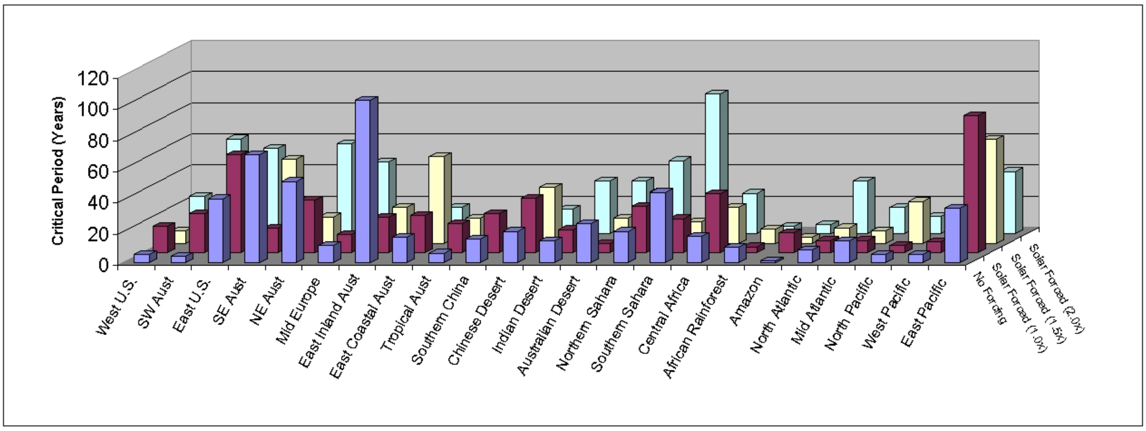


Figure 4. Atmospheric moisture storage and critical period for various climatic regions.

It is apparent that there is a large difference between climatic regions in their relative storage requirements, with areas such as those in Australia requiring a larger storage of atmospheric moisture, suggesting Australia is more prone to drought than the other continents. As a result of the different amplitude solar forcings the required storages also change, however there is no discernable trend in Figure 4 as some regions experience an increase in their storage requirements, and some a decrease.

In Figure 5 on the x-axis we plot the storage and critical periods for the No Forcing simulation as presented in blue in Figure 4. On the y-axis, we have the change in storage and critical period as compared to the No Forcing case. It is clear that regions of low storage experience a large increase in storage and regions of high storage tend to a small decrease in their storage values. The same is observed for the critical periods, with regions that tend to have long critical periods experiencing a shorter duration critical period, and regions with short critical periods exhibiting an increase in the drought duration. Table 3 shows the rank based correlations for the changes in storage and critical period as compared to the base case.

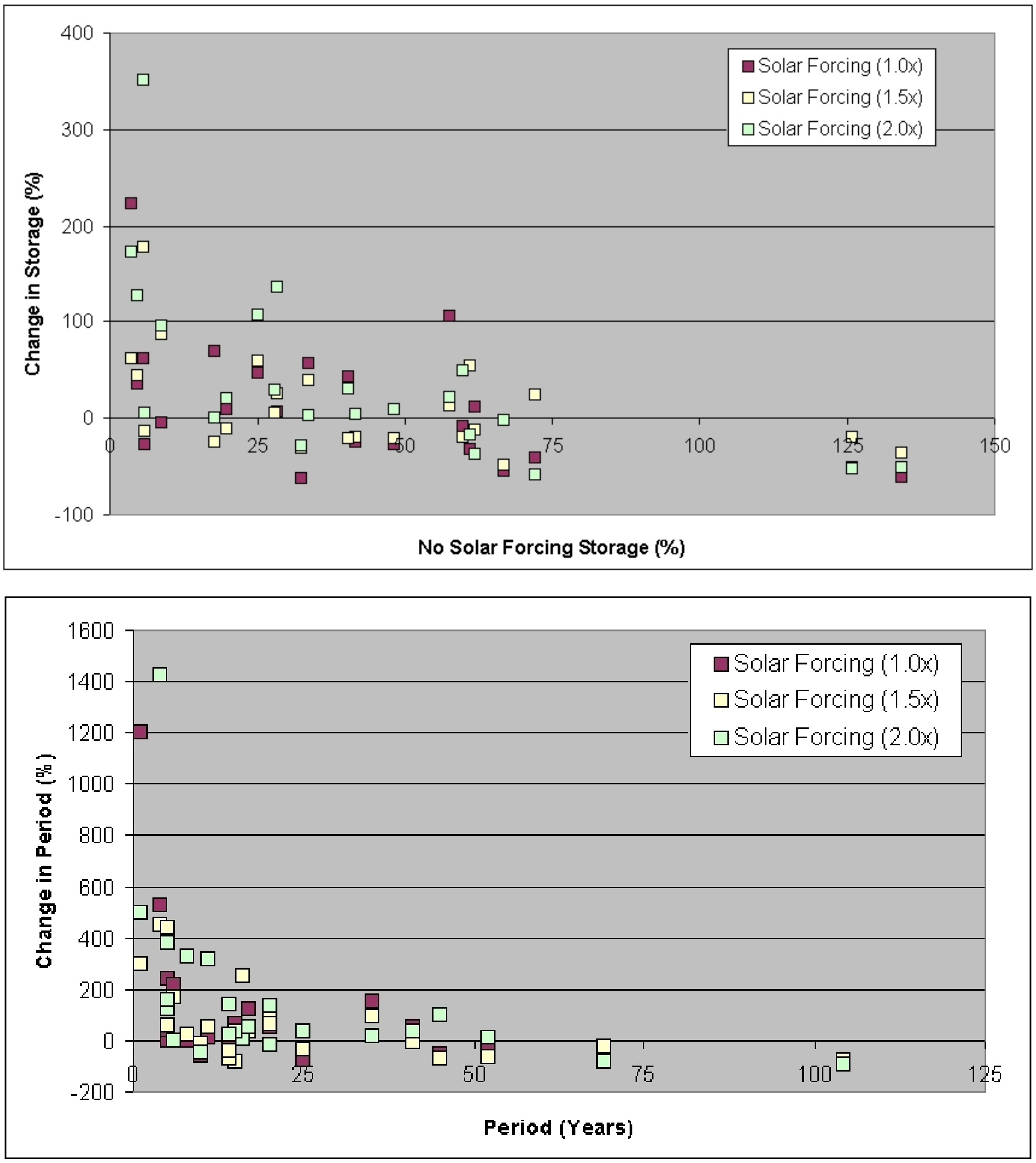


Figure 5. Changes in storage and critical period due to solar variability plotted against the base case.

Table 3. Correlation of changes in storage and critical period due to solar variability

Solar Variability	Storage		Critical Period	
	Spearman's Correlation	p-value	Spearman's Correlation	p-value
Amplitude (1.0x)	-0.60	0.0024	-0.53	0.0061
Amplitude (1.5x)	-0.52	0.0074	-0.64	0.0013
Amplitude (2.0x)	-0.74	0.0003	-0.68	0.0007

Each solar forcing case is significantly negatively correlated confirming what is presented in Figure 5. Critical period correlations decrease in value and increase in significance as the amplitude of the solar forcing increases. This suggests that as we increase the amplitude of the solar forcing we amplify the trend of regions of short critical period increasing in critical period and regions of long critical period decreasing in duration. Note however this same trend is not present in the storage correlations. This presents the non-linearity of the problem and the dynamic nature of the Earth's climate. Figure 4 demonstrates that few climatic regions show signs of monotonic increases of decreases in their storage or critical period of atmospheric moisture.

5. DISCUSSIONS AND CONCLUSIONS

It is plausible to suggest, in the absence of all other forcings, and other multi-decadal solar variability, the 11-year cycle acts to increase the severity of droughts in those climatic regions which are not susceptible to significant drought periods. However, for regions prone to large drought periods, such as Australia, the drought severity is decreased due to the presence of a solar cycle.

More pertinently the observation is made that the GCM simulations often use perpetual solar forcings, and this can cause a misrepresentation of the complicated nature of short and long term behaviour of atmospheric moisture. This can result in an inadequate representation of long-term rainfall behaviour.

ACKNOWLEDGEMENTS

This work is based on the following publication by Wasko and Sharma in Geophysical Research Letters:

Wasko, C., and A. Sharma (2009), Effect of solar variability on atmospheric moisture storage, *Geophysical Research Letters*, *36*, L03703, doi:10.1029/2008GL036310.

REFERENCES

Brutsaert, W. (2005), *Hydrology: An Introduction*. Cambridge University Press, New York.

Charles, S. P. (1999), Stochastic downscaling for changed climate conditions: The importance of using moisture dependent predictors. *Spring Meeting American Geophysical Union (AGU) ACACIA Special Session.*

Franks, S. W. (2002), Assessing hydrological change: Deterministic general circulation models of spurious solar correlation?, *Hydrological Processes*, *16*, 559-564.

Fröhlich, C., and J. Lean (1998), The Sun’s total irradiance: Cycles, trends and related climate change uncertainties since 1976, *Geophysical Research Letters*, 25, 4377-4380.

Fröhlich, C., and J. Lean (2004), Solar radiative output and its variability: Evidence and mechanisms, *Astronomy and Astrophysics Review*, *12*, 273-320.

Hansen J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis (1983), Efficient three-dimensional global models for climate studies: Models I and II, *Monthly Weather Review*, *111*, 609-662.

Hydrometeorological Advisory Service (2003), *The Estimation of Probable Maximum Precipation in Australia: Generalized Short-Duration Method (GSDM)*, Commonwealth Bureau of Meteorology.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bulletin of the American Meteorological Society*, *77*, 437-470.

Quinn, T. J., and C. Fröhlich (1999), Accurate radiometers should measure the output of the sun, *Nature*, *401*, 841

Ripple, W. (1883), The capacity of storage reservoirs for water supply, *Proceedings of the Institution of Civil Engineers London*, *71*, 270-278.

Svensson, C., and P. R. Rachecha (1998), Estimation of probable maximum precipation for dams in the Hongru River catchment, China, *Journal of Climate*, *59*, 79-91.

Wasko, C., and A. Sharma (2009), Effect of solar variability on atmospheric moisture storage, *Geophysical Research Letters*, *36*, L03703, doi:10.1029/2008GL036310.