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Assessment of direct normal irradiance and cloud connections using satellite data over Australia

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HIGHLIGHTS

- Strong anti-correlations exist in DNI and cloud amount variability over Australia.
- Significant DNI trends observed in the west, southeast and northeast regions.
- ENSO strongly modulates cloud coverage affecting DNI over northern Australia.
- Regions over Perth and northern Victoria show great potential for CSP development.

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ABSTRACT

Australia has some of the best solar energy resources on the planet. With a Renewable Energy Target (RET) scheme designed to ensure that 20% of Australia's electricity comes from renewable sources by 2020, these resources are rapidly being developed. Although not yet widespread, Concentrating Solar Power (CSP) plants are expected to play a significant role in Australia's future solar-derived electricity. The variability of Direct Normal Irradiance (DNI) is largely responsible for the fluctuations in solar energy outputs from CSP plants. The temporal and spatial variability of DNI over Australia provides an assessment of the solar resource for future deployment of CSP plants. As such, this study analyses recent trends in the hourly solar DNI resource using data from 1990 to 2012 obtained from the Bureau of Meteorology (BOM). The deseasonalized DNI anomaly trends were significant over the west, southeast and northeast of Australia for all seasons. Knowledge of these trends is extremely important for siting and the prediction of CSP plant outputs. DNI increased by 50 W m^{-2} over west and southeast of Australia, whereas it decreased by 100 W m^{-2} over northeast of Australia – representing approximately +5% and −12% deviations from the long-term averages, respectively. Seasonal analysis also showed significant DNI trends, especially during the summer and winter. Most of the changes seen in DNI over Australia were modulated by changes in cloud amount over the region. The cloud amount obtained from the International Satellite Cloud Climatology Product (ISCCP) showed high negative correlations associated with DNI anomalies over Australia. The anomaly in cloud amount is highly correlated with the Southern Oscillation Index (SOI) obtained from BOM. The strengthening convective activity over Indonesia associated with strong La Niña events modulates cloud coverage teleconnecting towards northern Australia. This increases cloud cover and lowers the DNI significantly over these regions during the summer and autumn season. Although the change in DNI associated with cloud amount is clear, the effect of change in aerosols over these years still needs to be investigated.

1. Introduction

Solar energy generation has immense potential in Australia due to high insolation and dry climate experienced over large areas of the country [1,2]. With the possible exception of a few island nations, Australia has the highest per capita annual solar resource (~3.2 TW h capita^{-1} year^{-1}) of any country [3,4]. The amount of annual solar radiation falling in Australia is approximately 10,000 times its annual average energy consumption, yet solar energy in Australia accounts for only about 0.2% of its total primary energy consumption [5,6]. Electricity can be produced from these resources with Photovoltaic (PV) collectors and Concentrated Solar Power (CSP) technologies [7–10]. CSP technology (with few excep-

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tions) can only utilise the direct beam component of the solar resource. Thus, the beam radiation, termed the Direct Normal Irradiance (DNI), is crucial for concentrating direct sunlight to drive CSP plants. Indirect or diffuse radiation is created when sunlight is scattered by clouds, aerosols and other atmospheric constituents.

The variability in solar radiation is associated with attenuation in the atmosphere, mostly from clouds [11,12]. Clouds reduce the amount of irradiance reaching the ground-level due to their varying optical depth. For instance, opaque clouds over photovoltaic arrays reduce output solar power production by as much as 50–80% [13]. Similarly, it has been shown that intermittent cloud cover over a CSP plant causes dramatic fluctuations in the power output [14]. This causes short-term voltage fluctuations and wears down line equipment on distribution feeders leading to high maintenance costs [15]. The management of solar energy due to these fluctuations may require a secondary power source, which adds to the cost of operations. Therefore, solar irradiance forecasts are needed to manage the grid effectively. Short-term (<5 h) irradiance prediction is critical in grid integration by anticipating and compensating for the power fluctuations [16]. Longer-term (>10 years) irradiance prediction is equally important in plant siting and determining the feasibility of a solar project and to account for seasonal variability in energy demand and production [17,18]. Taken together, solar resource assessments are crucial for those seeking to invest and/or operate in the solar energy sector.

The greatest challenge in improving solar irradiance forecasts lies in understanding solar irradiation intermittency, which is directly related to moving clouds [19]. However, cloud motion is governed by atmospheric circulations with complex land and ocean dynamics. The distribution of clouds is associated with heating and moistening of the atmosphere, and heating of the surface. The changing atmospheric conditions induce stochastic feedback in the climate system, limiting our understanding of future clouds and climate [20]. Recently, Crook et al. [21] examined the impact of projected changes for the 21st century in temperature and irradiance on the power output of PV and CSP using coupled ocean–atmosphere climate models. Interestingly, they found that the change in CSP output were more significant than PV output from 2010 to 2080 in Australia. Most of the change in CSP output was dominated by irradiance changes as compared to PV output which was mostly affected by changes in the temperature. Thus, with growing interests in CSP plant establishment in Australia [1,22,23], this paper assesses the variability of solar irradiation (DNI) across Australia relating to changes in cloud amounts. To understand cloud variability, the process of cloud formation relating to Australia's climate and weather has to be thoroughly investigated.

The weather includes diurnal fluctuations of clouds mostly due to land and ocean convection whereas cloud variability at seasonal and decadal scales relate to climate change. Jovanovic et al. [24] developed a long-term monthly cloud amount dataset using 165 stations in Australia, but the trend analysis with this dataset was not statistically significant. However, they found a strong positive correlation of cloud amount and rainfall over all stations. Recently, Elliston et al. [25] characterised the frequency and duration of rare events such as extended periods of heavy cloud cover and hence low solar insolation over regions of Australia driven by broadscale atmospheric circulation. Similarly, Cheung et al. [26] analysed solar irradiance data from multiple surface stations across Australia to determine patterns of solar absorption by clouds using factor analysis. They identified distinct geographical regions associated with synoptic features modulate the cloud coverage. Troccoli and Morcrette [12] also showed that the skill of direct solar radiation predicted by models over specific sites in Australia is influenced by cloud cover and background climatic conditions.

There are a number of patterns of variability known to affect seasonal climate globally, especially cloudiness and rainfall. The North Atlantic Oscillation (NAO) influences the Northern Hemisphere [27–29], whereas the Southern Hemisphere is mostly affected by El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM) [30]. Davy and Troccoli [31] investigated the effects of ENSO and IOD on solar radiation in Australia. They showed that the ENSO phenomenon accounts for solar energy changes of more than 10% in some locations seasonally. However, it is not clear if ENSO alone can explain a decline in direct normal irradiance of 1 W m^{-2} per year derived using satellite and reanalysis data over Australia [17]. More research is needed in this area to understand the variability in solar irradiance associated with cloud fluctuations at various temporal and spatial scales.

Due to gaps in literature associated with the relationship of cloud intermittency and DNI variability that are crucial for future CSP installations in Australia, this paper addresses the following questions:

i. What is the seasonal variability of DNI and cloud amounts over Australia?
ii. How strongly is DNI variability correlated with the variability in cloud amounts over Australia?
iii. What is the absolute change in DNI and cloud amounts over Australia from 1990 to 2012?
iv. What are the driving forces associated with these seasonal variations?

2. Data

2.1. Solar irradiance estimates from satellites

The Australian Bureau of Meteorology (BOM) provides hourly estimates of solar irradiance (DNI and GHI) at 0.05° (≈5 km) latitude and longitude resolution over Australia. Since this study focuses on recent phenomena, we use data from January, 1990 to June, 2012. The solar irradiance estimates are based on images from the Geostationary Meteorological Satellites GMS-4 and GMS-5, Geostationary Operational Environment Satellite (GOES-9) and Multi-functional Transport Satellites (MTSAT) which is a series of geostationary satellites operated by the Japan Meteorological Agency (JMA). GHI values are processed from raw satellite data based on the two-band physical model [32] and corrected for biases. The bias corrected GHI values are converted to DNI using a modified form of the Ridley et al. [33] model. Bureau of Meteorology [34] described the quality of the most recent dataset as follows: "*The accuracy of the satellite-based DNI values is estimated by comparison with 1-min averaged DNI measurements from Bureau of Meteorology surface-based instruments. The mean bias difference (average of the satellite – surface difference), calculated on an annual basis across all surface sites, is -20 to +18 W m^{-2} depending on the year. This is −4% to +4% of the mean irradiance of around 500 W m^{-2}*". The data quality has improved significantly from earlier comparisons conducted with older datasets [35]. For each day, the hourly measurements start at 18 UT on the proceeding day and end at 11 UT of that day. The satellite observations are made once every hour, and the time of observation varies smoothly with latitude and differs between satellites. Further information about this dataset can be found in the metadata files [34] and in Dehghan et al. [36].

2.2. Cloud amount estimates from ISCCP

The International Satellite Cloud Climatology Product (ISCCP) combines satellite measured radiances with atmospheric temperature–humidity and snow correlative datasets to obtain information about clouds. The analysis method first classifies clouds at each