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Large-scale wind energy potential of the Caribbean region using near-surface reanalysis data

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ABSTRACT

The lack of dense, high quality, long-term in-situ wind data sets and wind resource maps for the Caribbean region is a major impediment to the development of wind energy projects. Thus, there is limited understanding of the large-scale near-surface wind climate and the regional wind resources. Through statistical analyses on 10 m level NCEP/DOE reanalysis wind data for the period 1979–2010, this work found that although the prevailing winds are from the east-north-east over the eastern Caribbean islands, their wind direction distributions are bimodal. The regional area-averaged wind speed attains a maximum in January and a secondary maximum in July which coincides with the Caribbean Mid-Summer Drought. The derived regional annual wind resource map shows that the Caribbean low-level jet (CLLJ) region is an area of superb wind power density (WPD), 400–600 W/m^2, the eastern Caribbean and the Netherland Antilles are locations of excellent resource, 300–400 W/m^2, and the Greater Antilles and the Bahamas are areas of good-very good resource, 200–300 W/m^2. In general, WPDs are greater in the dry season than the wet season. The regional mean annual area-averaged WPD is 308 W/m^2 with mean WPDs of 350 W/m^2 for the dry season, 290 W/m^2 for the early rainy season, and 247 W/m^2 for the late rainy season. Annual WPDs vary within $\pm$ 18% of their mean. The area-averaged WPD ranges from 124 to 592 W/m^2 ($\pm$ 92% of mean annual WPD) depending on the year, season, or month. Therefore, the reanalysis data are shown to be suitable for general assessments of the wind resources in the Caribbean and thus, may be used as initial and boundary conditions in numerical models for the development of high resolution wind maps through dynamical downscaling.

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Abbreviations: AGL, above ground level; CLLJ, Caribbean low-level jet; CREDP, Caribbean Renewable Energy Development Project; DOE, US Department of Energy; ECMWF, European Centre for Medium-Range Weather Forecasts; ENSO, El Niño – Southern Oscillation; ERS, early rainy season; ITCZ, Intertropical Convergence Zone; LRS, late rainy season; ML, maximum likelihood; NAH, North Atlantic High; NCEP, National Center for Environmental Prediction; PV, photovoltaic; SST, sea surface temperature; pdf, probability density function; WPD, wind power density

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1. Introduction

Caribbean small islands, because of their close equatorial location and alignment with the regional north-east trade wind system, are prime candidates for the use of a mixture of renewable energy technologies such as photovoltaic arrays and wind turbines. Trinidad and Tobago is the only Caribbean small island state with sufficient reserves of oil and gas for local consumption and for export. The remaining islands depend heavily on fossil fuel imports; for example, Barbados imports fossil fuels for 86% of their energy needs [1], while Jamaica imports 91% of its energy demand [2] and the Dominican Republic has a 78% dependency on imported oil [1]. Caribbean islands have pursued the use of renewable energy technologies because of this high dependence on energy imports. Over 23,000 solar water heaters have been in operation in Barbados since the 1970s due to fiscal incentives offered by the government [3,4]. However, the current cost of photovoltaic (PV) technologies makes it difficult to implement large-scale solar farms. Electricity generated from a wind turbine is cheaper than the PV counterpart [5,6]. For this reason, some of the Caribbean islands including Curaçao, Jamaica, Martinique and Guadeloupe have implemented wind energy technologies [7].

The Caribbean Renewable Energy Development Project (CREDP) has identified the lack of knowledge of wind resources as a barrier in development of wind energy projects in the Caribbean region [8]. The regional quantification of the wind resources could provide a reasonable estimate of the available wind power in regions such as the Caribbean where there is a lack of dense, high-quality in-situ data sets of long time periods and wind resource maps [9,10]. Previous studies by Elliott [11] and Elliott et al. [12] addressed the quantification of the wind resource in the Caribbean using ship data and interpolation-extrapolation based techniques in conjunction with land-based upper air data and surface data to derive land-based wind resources. Ship data have several limitations. Firstly, over 80% of the wind speeds from ships were estimated rather than directly measured [12]. Thus, large errors in the wind speed will be tripled in the wind power potential estimates. Secondly, the ship wind data were of monthly temporal resolution and do not account for the influence of daily and sub-daily wind speed variations on wind power density. Thirdly, the number of ship observations is dependent on ship travel paths and the frequency, and may not be spatially and temporally homogeneous. Homogeneity in wind data is a requirement for establishing the wind climate. In addition, the ship data used in [12] were for the time frame 1940s to 1970 and there is no in-depth study on the current wind climate that is relevant to the promotion and use of wind energy technologies in the Caribbean especially during this period of rapid increase in the use of wind energy technologies globally.

Therefore, alternative data sources must be explored. Since Elliott et al. [12] study, other data sets have become available, e.g. satellite data and reanalysis data. Satellite data have been used for investigating the large-scale wind energy potential for the world [13–15]. Satellite data are a good alternative and have the distinct advantage of higher resolutions over other types of data such as reanalysis data. However, one should note that satellite winds are inferred from the ocean roughness state [13,16]. The derived surface wind speeds may not be accurate since the signal may be quenched by thick clouds or heavy precipitation [17] which is prevalent in tropical regions such as the Caribbean, especially during the rainy season. Prior to analysis, observations contaminated by precipitation are removed, and may result in overestimating mean wind speeds. In addition, the atmosphere is assumed to be neutrally stable, introducing a bias during unstable and stable conditions. Furthermore, satellite data may not contain sufficient number of passes over a region for the computation of the wind resources [17].

Reanalysis data, which represent an assimilated form of land based meteorological station, buoy, ship and satellite data [18–20] into a general circulation model, may provide a more accurate representation of the large-scale wind resources of the Caribbean region. They are gridded and quality controlled allowing for a mapping of the wind resource on the large-scale and for the identification of potential areas of high wind resource. Reanalysis data span longer time periods than satellite datasets over higher resolution time periods. For example, the National Center for Environmental Prediction (NCEP)/Department of Energy (DOE) Reanalysis [20] provides wind components four times daily from 1979 which allow for a better representation of the wind speed probability distributions. In addition, the temporal and spatial homogeneity of the reanalysis data makes it more reliable for determining the wind climate and for assessing the influence of inter-annual variability on the wind resources. Reanalysis data have been used to study wind resources in Europe [21] and over the United States [22,23], investigate the stationarity in the wind statistics over the Baltic region [24] and climatic trends in wind speeds over the United States [25], assess high altitude wind energy globally [26] and over south east Europe [27], establish the current wind climate in climate change projection studies as in [28], and determine how spatial distribution of wind power plants reduces electrical grid variability [29].

Thus far, there has been no in-depth study for the Caribbean region using the reanalysis data sets to establish the wind climatology and the regional wind resource. Furthermore, no previous work on the Caribbean wind resources has quantified the wind potential