Orography Drives the Semistationary West Australian Summer Trough

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Abstract During the summer months, there is a semipermanent trough in the low-level easterlies over the west coast of Australia. This "West Coast Trough" plays an important role in summer severe weather in western Australia including thunderstorms and severe heat waves. The land-sea contrast is believed to be the driver of the location of this trough. As land masses are warming more quickly than their surrounding oceans, it is timely to readdress the drivers of the location and intensity of this important climatological feature. Using a 20-year regional climate modeling simulation, we show that Australian orography is critical to the accurate representation of the trough in climate models, in contrast to earlier low-resolution studies.

Plain language summary During the summer, the average weather pattern in Western Australia includes a trough near the west coast. For this trough to exist in climate models, they need to include Australian elevation including the plateau in Western Australia. Otherwise, the trough does not exist and summer rainfall is lower.

1. Introduction

The summertime "West Coast Trough" (WCT) is a persistent feature of the climate of Western Australia (WA). This is a semipermanent trough in the low-level easterly flow that extends along the western coastline of Australia during the summer months and is a major influence on the mean circulation patterns in WA. On a seasonal basis the WCT is evident in maps of climatological mean sea level pressure (MSLP) and winds (Fandry & Leslie, 1984) and is frequently identified as an area of enhanced low pressure system development using extratropical cyclone tracking schemes (Jones & Simmonds, 1993; Lavender, 2017). On a day-to-day basis it exhibits larger variability in intensity and location, with shifts between an on- versus off-shore trough playing a critical role in sea breeze development and thus extreme temperatures and fire weather in coastal WA (Kepert & Smith, 1992). The WCT can also play a role in the location and severity of thunderstorm development when other factors are favorable.

The primary factor for the development of the WCT is the strong temperature contrast between very warm air that develops over the arid continental interior and is advected westward by the prevailing easterly winds and the cooler sea surface temperatures in the Indian Ocean (Fandry & Leslie, 1984). Although coastal orography is important for other similar troughs, such as on the east coast of Australia (De Lisle & Harper, 1961; Reason, 1996), the relatively low elevation of WA orography as well as the strong seasonality of the trough suggest that this plays only a minor role in formation of the WCT. This was supported by early modeling studies, which found that, although WA orography contributed to the development of the WCT, it was not required for simulating the WCT in simplified models (Fandry & Leslie, 1984; Kepert & Smith, 1992).

The apparently low importance of orography for the formation of the WCT suggests that as land masses warm more quickly as the globe warms (Joshi et al., 2008), the land-sea contrast will change and the location or intensity of the WCT might be altered. More complex models, such as 3D general circulation models, have not been used to analyze the influence of orography on the WCT, although the most recent generation of global climate models simulate the mean summer circulation over Australia well, including the WCT (Moise et al., 2015). However, a recent study assessing the influence of removing Australian orography on east Australian rainfall also identified a substantial change in the mean circulation over WA (Pepler et al., 2017). The 21-year regional climate model simulations performed in that study offer a useful data set to reassess the role of Australian orography in the generation of the WCT. It is thus timely to readdress the question of whether the land-sea contrast is the only driver of the location or intensity of the WCT, or if orography does in fact play a role.
2. Data and Methods

The model simulations used for this paper were described in detail in Pepler et al. (2017). In brief, version 3.6 of the Weather Research and Forecasting model (WRF; Skamarock et al., 2008) was used to downscale the ERA-Interim reanalysis (Dee et al., 2011) over the CORDEX-Australasia region (Figure 1). This is an equatorial rotated coordinate system with a resolution of 0.44° × 0.44° (a quasi-regular horizontal resolution of ~50 km) and 30 vertical sigma levels to a model top of 50 hPa, with lateral and surface boundary conditions from ERA-Interim. The physics parameters used include WDM5 microphysics, BMJ cumulus physics, Eta surface physics, the MYJ planetary boundary layer scheme, Dudhia shortwave physics, and RRTM longwave physics (Acronym definitions are available at http://www.ametsoc.org/PubsAcronymList). This combination has previously been comprehensively assessed for their skill at representing important features of southeast Australian climate (Evans et al., 2012) but has not been evaluated for northern and western Australia.

Two simulations were performed. A control simulation was initialized in January 1979 and available for the period 1979–2009 that used the default WRF orography with four-point interpolation and one pass of smoothing. This is compared to a “Flat” simulation in which all orography was set to 0 m as part of the transformation of input data to the WRF model domain, which was initialized in January 1989 and run over the period 1989–2009. This approach allowed the changed orography to be accounted for in the process of generating the terrain-following vertical coordinates and other fields such as the slope of orography, while no changes were made to the land-sea mask or other parameters. Neither simulation employed nudging, with the large model domain allowing the regional model to develop freely over the Australian region, forced only by observed sea surface temperatures and the ERA-Interim reanalysis at the lateral boundaries.

The advantage of employing a regional climate model for these simulations is the capacity to run long model simulations at a higher spatial resolution than for global climate models. Higher resolution is necessary to accurately represent the relatively low-altitude Australian orography. However, as the atmosphere and ocean boundary conditions are from the real-world with observed orography, the model simulations are unable to fully integrate any indirect global impacts of the imposed changes in orography. This study thus focuses on the local and regional-scale effects in Australia of the imposed changes to orography.

Model circulation is evaluated in comparison to the ERA-Interim reanalysis, while rainfall over the Australian continent is evaluated in comparison to a 5-km resolution gridded rainfall dataset produced by the Australian Bureau of Meteorology (AWAP; Jones et al., 2009). While ERA-Interim is not a truly independent dataset, as it is also the source of the atmospheric and ocean boundary conditions used for the regional model simulation, it allows us to identify any major systemic biases in the downscaled climate.
3. Results

Both ERA-interim and the control WRF simulation exhibit similar climatological mean patterns of temperature and MSLP (Figure 2). There is a clear subtropical ridge situated over Australia, with easterly winds to the north and westerlies to the south. This circulation moves poleward during the winter and equatorward during the summer. The trough visible in the MSLP pattern over the WA coastline is relatively weak during the austral winter months (June–August) but pronounced during the austral summer (December–February). In winter there is also a trough in the westerlies off the southwest coast of Australia.

Figure 2. Average mean sea level pressure (contours, every 2 hPa), 2-m air temperature (color), and 850-hPa vector winds (vectors) in (top) ERA-Interim and the (middle) control and (bottom) Flat Weather Research and Forecasting simulations during (left) summer (December–February) and (right) winter (June–August), 1990–2009.
While the broad patterns are consistent, the control WRF simulation develops independently from ERA-Interim away from the model boundaries, with a slightly different mean climate. Surface temperatures are cooler in the model simulations, by 0.5–1.5 °C during the summer months, particularly in WA, and by more than 1.5 °C during the winter months. This was previously observed for the (nudged) NARCliM simulations by Olson et al. (2014). In addition, MSLP is higher across the whole model domain in the WRF simulations, by 0.5–1 hPa over WA but up to 3 hPa in parts of the Tasman Sea east of Australia. There are also differences between ERAI and WRF near the boundaries of the simulation, notably cross-isobaric flow in the Indian Ocean north of 25°S and in the Southern Ocean west of 105°E. This is suspected to be a result of the relaxation to boundary conditions, which should only affect the first ~5 grid cells (~2.5°) but may be extending further into the region. While this is sufficiently offshore from Australia that we believe it is unlikely to influence the WCT, it demonstrates the need for a more comprehensive study using a larger (or global) domain.

In the simulation without orography, the weak coastal trough over northern western WA is completely absent during winter and largely absent during the summer months. In summer, this amounts to an average 2-hPa increase in MSLP over the WA coast and the complete absence of the northeasterly winds observed over western WA in the control simulation. In winter the trough in the westerlies off the southern coast of WA is also weakened. The weakening of the WCT is also apparent when individual low pressure systems are identified using the Murray and Simmonds (1991) cyclone tracking scheme, incorporating additional modifications from Simmonds et al. (1999) (not shown). While a weak cyclone is identified over the region 110–120°E, 20–35°S more than 30% of the time during the summer months in the control simulation, consistent with the high frequency of cyclones in this region observed by Jones and Simmonds (1993), this is true only 13% of the time in the Flat simulation.

Compared to the control simulation, the mean surface temperature in the Flat simulation is 1–2 °C higher across western WA, with a slight increase in the air-sea temperature contrast (Figure 3). The largest increases in surface temperature are over areas of higher elevation in Australia, New Zealand, and the Maritime Continent, suggesting that the difference can be largely attributed to the decrease in elevation. In the free atmosphere at 850 hPa, circulation changes drive a greater than 2 °C decrease in the mean air temperature during the summer months (Figure 3b), due to the decrease in the northeasterly advection of warm air from the arid interior. In contrast to the summer months, during the winter, there is little difference in 850-hPa temperature in southwest WA between the control and Flat simulations, with the strongest declines on parts of the northwest coast (0.5–1.5 °C), although the decrease in surface temperature is similar to summer (not shown).

In the absence of orography, there are marked differences in summer rainfall in WA. The top panels of Figure 4 show the average summer rainfall across Australia in both the AWAP gridded observational data (Figure 4a) and the control simulation (Figure 4b). The patterns of rainfall are broadly similar, with the highest average totals in the tropics and lower totals in inland Australia, although the control simulation tends to underestimate tropical rainfall and overestimate rainfall in inland southeast Australia. In comparison,
Figure 4c shows the average summer rainfall in the simulations where orography has been removed, with a decline in rainfall across most of WA of more than 30% (Figure 4d). This decline can be attributed to a lack of moisture flux into this region in the absence of the WCT, with the moisture flux anomalies directing moisture away from WA and into the Indian Ocean. Differences in vertical stability might also contribute to the decreased rainfall in the Flat simulations; however, the anomalies of potential temperature (not shown) are of a similar magnitude to the actual temperature changes at 850 hPa, suggesting that changes in the profile were small relative to the large differences in the moisture flux.

Similar declines in moisture flux and rainfall are also observed in the other three seasons, resulting in a greater than 40% decline in total annual rainfall (Pepler et al., 2017). There is, however, a wet bias in the control WRF simulation in inland Australia during the rest of the year, associated with anomalous northeasterlies in inland Australia, which may exaggerate the role of orography in rainfall during these seasons.

4. Discussion and Conclusions

The WCT is a persistent feature of the Australian climate during the summer months. This is relatively well represented using the WRF regional climate model, although it is weaker in model simulations than in the reanalysis. In the absence of orography, this trough also largely vanishes, with zonal flow over Australia during the winter months and near-zonal flow during the summer months. This results in a greater than 30% decline in summer rainfall in inland WA.

This result is in contrast to earlier numerical studies, in which orography was identified as playing only a minor role in the development of the WCT when compared to the larger role of air-sea contrasts between warm air over inland Australia and cooler sea surface temperatures (Fandry & Leslie, 1984; Kepert & Smith, 1992). However, the removal of coastal orography itself has an influence on these very factors—while the
change in elevation to sea level necessarily involves an increase in air temperature, there is a large decrease in the average 850-hPa air temperature over coastal WA when orography is removed. This can be attributed to the decrease in the frequency of warm northeasterly winds associated with the absence of the coastal trough. Consequently, the role of orography and air temperature in the setup of the WCT cannot be easily disentangled.

This is a single model simulation, using settings that were optimized for other areas of Australia and for a case using spectral nudging, which is not employed in this analysis. The use of a regional atmosphere-only model also adds additional uncertainty, as the effect of orography on the global large-scale circulation and sea surface temperatures cannot be accounted for. However, the results demonstrate that the role of orography in the WCT may be more significant than previously anticipated and should motivate further research into this question.

References


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