Scatterometer estimates of the tropical sea breeze circulation near Darwin, with comparison to regional models

Andrew L. Brown 1 Claire L. Vincent 1* Todd P. Lane 1 Ewan Short 1 Hanh Nguyen 2

1 School of Earth Sciences and ARC Centre of Excellence for Climate System Science, The University of Melbourne
2 Bureau of Meteorology, Melbourne, Victoria, Australia

*Correspondence to: Claire Vincent, School of Earth Sciences, University of Melbourne, Parkville, Australia.
E-Mail: claire.vincent@unimelb.edu.au

In tropical coastal environments, simulating the diurnal cycle of wind and precipitation in numerical weather and climate models presents unique challenges due to the interaction of intraseasonal and mesoscale dynamics. This can lead not only to incorrect short term weather forecasts but also unphysical energy and momentum transport by convective processes. In particular, the sea/land breeze circulation and its role in initiating convection has been identified as a possible source of errors in the timing and offshore extent of coastal precipitation in the tropics.

In this study, the offshore land/sea breeze around Darwin, Australia, is examined using scatterometer wind observation and two regional atmospheric models. Although the comparison is limited by satellite swath times that cluster around two times of day, useful results are obtained by sub-sampling the simulated data to match the coverage of the scatterometer data.

We find that offshore surface sea breeze characteristics (intensity and horizontal spatial extent) from the models and satellite estimates are generally in good agreement, with intensity differences less than 2 m s\(^{-1}\), and offshore extents not varying by more than approximately 150 km. The variation in offshore extent and amplitude of the land/sea breeze wind perturbations with monsoon regime is well simulated. Furthermore, despite the simplifying assumptions of linear seabreeze theory, the model and scatterometer results are in broad agreement with theoretical values, particularly in the presence of the weak background winds during the monsoon break period.

Key Words: convection, mesoscale, ASCAT, land-breeze, offshore, WRF, ACCESS, monsoon

Received …
1. Introduction

The sea/land breeze circulation (SLBC) is a major forcing of convection and precipitation in the tropics on a diurnal scale (Peatman et al. 2014; Yang and Slingo 2001; Rauniyar and Walsh 2011; Vincent and Lane 2016). Therefore, realistic representation of the SLBC is an important building block for accurate simulation of the coastal diurnal precipitation cycle in the tropics. Errors in the timing and amplitude of the diurnal precipitation cycle have been found in mesoscale models including the Weather Research and Forecasting model (WRF) (Vincent and Lane 2016; Caine et al. 2013; Hassim et al. 2016) and the UK Met Office Unified Model (Birch et al. 2016), despite realistic representation of other key physical processes. Errors in the SLBC may partly explain these findings.

Over coastal land areas, the diurnal cycle and SLBC has been shown to be well simulated in numerical weather prediction models including the Weather Research and Forecasting model (Papanastasiou et al. 2010) and the Australian Community Climate and Earth System Simulator (ACCESS) model, which is a variant on the UK Met Office model (National Meteorological and Oceanographic Centre 2013). Offshore, WRF has been shown to accurately represent the wind at specific locations such as the Galician coast (Sousa et al. 2013) and in the north European seas (Karagali et al. 2013). However, the representation of offshore tropical SLBC characteristics, such as the intensity and horizontal spatial extent of the circulation, have not been evaluated, primarily due to a lack of observational datasets that capture the offshore wind field with adequate spatial-temporal resolution. Observations of near-surface wind from scatterometer instruments onboard polar orbiting satellites partly fills this gap by providing excellent spatial coverage over the sea, albeit at limited temporal resolution. Scatterometer satellite products have been used for global (Gille 2003) and regional (Aparna 2005; Karagali et al. 2014) studies of the offshore SLBC, which quantify intensity, as well as the horizontal spatial extent and timing. These characteristics will modulate the nature of offshore precipitation, which is either initiated over the land in the afternoon by the sea breeze before propagating offshore, forced by land breeze convergence in the late night/early morning, or associated with destabilisation due to offshore propagating, diurnal gravity waves (Yang and Slingo 2001; Houze et al. 1981; Mapes et al. 2003).

Scatterometer products have also been used to evaluate the mesoscale dynamics of regional atmospheric models such as WRF. Karagali et al. (2013) use the QuikSCAT scatterometer product to assess offshore variability of surface wind in the Northern European seas, and find that the difference in mean wind speed with WRF (which is run at 15 km horizontal grid spacing) ranges between -0.6 and 0.6 m s\(^{-1}\). They also show discrepancies between the temporal variability within WRF and QuikSCAT, with WRF failing to represent some seasonal features. Carvalho et al. (2014) compare the errors in simulated offshore wind from the WRF model with 5 km horizontal grid spacing to errors in ten different datasets, including QuikSCAT and several analyses/reanalyses. They find that along the Iberian Peninsula, WRF performs best, and is nominated as the most suitable alternative to in situ offshore wind data. When compared to in situ measurements, it had the highest temporal accuracy and best wind power estimations, and mean wind errors were lower than for QuikSCAT.

In this study, the Advanced Scatterometer (ASCAT) product (Verhoef et al. 2012) is used to examine the offshore SLBC at Darwin, Australia (Figure 1), relative to numerical simulations from the WRF and ACCESS models over a six-month wet season period (1 November 2014 - 30 April 2015). Both convection-permitting and parametrised versions of the ACCESS model are included in the study. It is demonstrated that the model representations of the SLBC are physically realistic, suggesting that errors in the intensity and offshore extent of the SLBC are not sufficient to fully explain errors in the diurnal precipitation cycle at this location.

The use of scatterometer data is limited by its temporal and spatial resolution, with observations clustered around two times of day in most locations. Near Darwin, the SLBC is sampled at 0900-1200 and 2100-0000 Local Time (LT). We use morning and evening perturbations about a 7-day running mean to represent the land and sea breeze respectively. Thus the offshore extent and intensity of the SLBC at these times can be determined, but not the phase. We also compare these characteristics to the theoretical, linear SLBC model of Rotunno (1983) (hereafter R83), providing an extra evaluation of the validity of each dataset, given this theory is assumed to
be a good approximation of key physical processes (Wood et al. 2009). However, the theory does not contain topography or surface inhomogeneities, which produce significant non-linear components in mountainous regions (Qian et al. 2012), or a background wind or other large scale variability.

The sensitivity of SLBC characteristics to phases of the Northern Australian monsoon is also assessed. The active, break and transition monsoon periods are each characterised by different convective regimes and large scale flow. The transition, or lead-up/dissipation of the wet season, has a convective signature which is very similar to the monsoon break, with a strong diurnal cycle, and localised convection concentrated over land. The active monsoon has much more widespread convection, with a suppressed diurnal cycle (May et al. 2012). Previous studies have shown that there are other modes of intra-seasonal variability in the Northern Australia wet season (Pope et al. 2009), however for our study only these regimes are considered. In addition to the different convective regimes of the three monsoon phases, it is expected that monsoonal variability in cross-shore prevailing winds and moisture will have a large effect on the SLBC (Arritt 1989; May et al. 2012; Kumar et al. 2013). In addition to monsoon variability, the diurnal cycle in land-sea temperature contrast will have a large affect on SLBC characteristics, given it is the fundamental driver of the SLBC. Therefore, in an attempt to diagnose any SLBC discrepancies between datasets, we investigate the diurnal cycle in modelled and observed land-sea contrast.

The sections within this paper will be presented in the following manner. Section 2 describes the two regional models used to simulate the SLBC, as well as ASCAT satellite estimates. Section 3 outlines the methods used to define monsoon periods and the SLBC, and how the regional models will be compared to ASCAT satellite swaths. The characteristics of the modelled and observed background wind and SLBC and their variation with monsoon regime is presented in section 4, together with an examination of the modelled and observed land/sea temperature difference. Discussion and concluding remarks are given in sections 5 and 6 respectively.

2. Data

This study makes use of scatterometer wind data and regional model simulations for the North Australian wet season 1 November 2014 - 30 April 2015. All datasets are available for the full study period.
2.1. Advanced Scatterometer

The Advanced Scatterometer (ASCAT) is produced by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), using measurements from instruments on-board their nearly sun-synchronous, polar orbiting Metop-A and Metop-B satellites. ASCAT produces 10 m equivalent neutral wind (ENW) in “wind vector cells”, which are spatially separated by 12.5 km, and have an effective resolution of around 30 km (EUMETSAT 2015). The ENW is the wind that would be observed if the atmospheric stability was neutral, given the same friction velocity. Here, the level 2 ASCAT product is used, meaning that wind vector cells are available within 550 km wide satellite swaths, both of which are approximately 336 km away from the ground track. For this study, a coastally optimised product is employed, which allows measurements to be taken closer to coastlines relative to the ASCAT standard level 2 product (KNMI 2010). That is, measurements as close as 15 km are allowed before being flagged for land contamination. The range of reliable wind output is specified as 0-50 m s\(^{-1}\), although for speeds over 25 m s\(^{-1}\), output is less reliable (Ocean and Sea Ice Satellite Application Facility 2013). The coastally optimised product has been shown to satisfy ASCAT standards relative to buoy data, with wind component RMS error less than 2.0 m s\(^{-1}\) (Verhoef et al. 2012). As discussed in section 3.1 and shown in the appendix, the mean difference between the ENW and the 10 m diagnostic wind reaches a maximum magnitude of 0.5 m s\(^{-1}\) in coastal areas.

ASCAT samples the Darwin domain (Figure 1) within two, three-hourly time blocks each day: 0900-1200 LT and 2100-0000 LT (LT = UTC + 9.5 hours). We expect these to sample the later stages of the land breeze and sea breeze respectively. ASCAT data coverage within the evening sea breeze time block is spatially uniform over the study period. However, during the morning there is less data on the eastern side of the domain (Figure 2). We assume that ASCAT coverage, passing over the domain twice-daily, is frequent enough to represent the Darwin SLBC in a mean sense within each time block. There are also more data points close to the coastline, which is most likely due to the spatial averaging used in ASCAT data processing, which varies between coastal and open ocean regions (Verhoef et al. 2012).

ASCAT data has been averaged over three-hourly time blocks corresponding to the sea/land breeze times mentioned above, and an 0.25° x 0.25° spatial grid. This spatial averaging was chosen as a smaller grid size led to patchy sampling, and a larger grid size resulted in loss of small scale wind structures (not shown). After the initial averaging of ASCAT measurements onto a regular spatial-temporal grid, the data is then composited over each monsoon period (see section 3.3).
2.2. Regional Models

We investigate SLBC representation within two regional atmospheric models. The first of these is the Weather Research and Forecasting model (WRF, Skamarock (2008)), with a setup similar to that described in Vincent and Lane (2016). The second is the Australian Community Climate and Earth-Systems Simulator (ACCESS), which is used operationally by the Australian Bureau of Meteorology (BoM), and is based on version 7.6 of the UK Met Office Unified Model (Bi et al. 2013).

Both the WRF and ACCESS models are run with nested domains around Darwin, with each inner domain (Figure 1) having 4 km horizontal grid spacing. WRF is run as a convection-permitting model, while ACCESS is run with a cumulus parametrisation for consistency with the operational version of the model. We also use a research version of ACCESS with the same spatial domain, but with 1.5 km grid spacing and cumulus parametrisation turned off. This version of ACCESS will hereafter be referred to as ACCESS-1.5, and the 4 km version will be referred to as ACCESS-4.

In addition to cumulus parametrisation, WRF and ACCESS differ in style of initialisation. The WRF model used here is initialised on October 29, 2014, with boundary conditions supplied by ERA-Interim Reanalysis (Dee et al. 2011). It is then run continuously for the study period, with spectral nudging above the planetary boundary layer for wavelengths greater than 1000 km, to ensure the large scale atmospheric state remains consistent with observations. The first three days of the simulation are discarded as model spin-up. In contrast, ACCESS is initialised daily, with boundary conditions from a global version of the model, reflecting its operational nature. Output is then in the form of 36-hour forecasts, the first 12 hours of which are disregarded as model spin-up. Both WRF and ACCESS have sea surface temperatures (SSTs) updated daily from satellite derived products. The Regional Australian Multi-Sensor Sea Surface Temperature Analysis (Beggs et al. 2011) is used in ACCESS, and the Real Time Global Sea Surface Temperature product (Gemmill et al. 2007) is used in WRF. Both products are at 1/12° resolution.

For comparison with ASCAT, we linearly average output from each model onto a 0.25° x 0.25° spatial grid, and group instantaneous, hourly model data into diurnal ASCAT time blocks (see section 2.1). We limit model data to being collocated with ASCAT satellite swaths within those time blocks, except for in section 4.3 where the full diurnal cycle in the models is considered. 10 m model wind fields are used for comparison with ASCAT 10 m ENW output, as discussed in section 3.1.

3. Methods

3.1. Model Comparisons

In comparing the SLBC from ASCAT, WRF and ACCESS, various compromising factors must be considered. The first of these is creating a common spatial domain between all datasets, which may eliminate the presence of a SLBC produced by Timor and the Cape York Peninsula (Figure 1). Secondly, the limited temporal sampling of ASCAT severely restricts resolution of the SLBC, which is on a diurnal timescale. This is reconciled in model comparisons by only considering output during satellite passes. ASCAT sampling bias was tested by repeating the analyses using all model data. It was found that in a mean sense, the sampling bias did not have a large effect on SLBC composites (not shown). It must be kept in mind that due to the limited satellite data coverage, precise timing of the offshore SLBC cannot be resolved by the ASCAT dataset, and hence the SLBC timing within WRF and ACCESS is unable to be evaluated.

In addition, ASCAT outputs 10 m ENW, and is compared to 10 m model wind, which may be a source of wind speed bias. Unlike model surface winds, ENW is calculated without a stability correction function. We therefore expect that for stable conditions, ENW speed will be lower than the actual wind, with the opposite being true for unstable conditions. ENW has been found to be 10-30% faster than the actual wind in the tropical warm pool, owing to permanent moisture induced instability at the surface (Liu and Tang 1996), although this may vary in coastal regions. Kara et al. (2008) compare hourly QuikSCAT ENW estimates gridded at 0.25° to...
individual buoy measurements of actual 10 m wind. They show that differences can be as large as ±0.5 ms$^{-1}$ over the global ocean. We find similar amplitude ENW bias for the WRF model around Darwin (see Appendix). In addition, it appears that stability is important in determining ENW bias close to the coastline, due to the SLBC advecting warm/cold air. We will assume that mean comparisons between ASCAT and modelled 10 m winds are still valid, with some small, wind speed bias present.

3.2. Sea/Land Breeze Perturbations and the Offshore Extent

Given the temporal sparsity of the ASCAT data, we define the SLBC using perturbations from a 7-day mean wind at each spatial point. Although not a true background value of the wind, the model and scatterometer data are treated in the same way, thus making the comparison reasonable. Unless otherwise stated, all analysis herein is not of the actual wind, but a temporal perturbation which is assumed to be forced primarily by the SLBC. Other diurnal, orographically forced flows will be implicitly included (Li and Carbone 2015), but should be small for northern Australia due to a lack of steep topography (Figure 1).

The intensity of the circulation is defined by the magnitude of the perturbation wind component ($v'$) which is perpendicular to the quasi-straight coastlines shown in Figure 1 (A and B). We average $v'$ over a series of parallel transects, such that intensity becomes a function of distance from each coastline. The offshore spatial extent is then defined as when the magnitude of $v'$ becomes smaller than 5% of the maximum along each transect. This is based on the fact that the SLBC decays with distance, and that the circulation is largely perpendicular to the coastline (Aparna 2005; Bergemann et al. 2015). Positive $v'$ is defined as towards the sea (land breeze), whereas negative $v'$ is flow towards the land.

For further examination of the SLBC in each dataset and of our perturbation method, we compare the offshore extent of the SLBC from WRF, ACCESS and ASCAT to the frictionless, linearised model of R83. This model is assumed to be a good approximation of the SLBC in absence of a background wind (Wood et al. 2009), and has been shown to agree with idealised WRF simulations (Du and Rotunno 2015). The expression used to describe the horizontal spatial extent in R83 is given by

$$NH(\omega^2 - f^2)^{(-1/2)}$$

where $N$ is the Brunt-Väisälä frequency, $\omega$ is the frequency of heating which forces the SLBC (i.e. 2π/24 hrs), $H$ is the vertical extent of diurnal heating and $f$ is the Coriolis frequency. We calculate Eq. (1) for each monsoon regime by temporally averaging daily values of $N$ and $H$. These parameters are only able to be calculated from WRF output, since the required fields were not available to calculate them for the ACCESS model. This may slightly bias the results towards the WRF model. The vertical gradient in potential temperature below 5000 m is used for $N$, while $H$ is defined by daily maximum planetary boundary layer height (PBLH) diagnosed from the MYJ boundary layer scheme in the WRF model. The use of daily maximum PBLH is justified given that it represents the turbulent mixing of heat from the surface. The PBLH is averaged over an inland area where it shows a spatial gradient. $N$ is spatially averaged over the oceanic transects shown in Figure 1.

3.3. Monsoon Sensitivity

Australian monsoon phases are defined here using a wind based index, similar to Drosdowsky (1996). An active monsoon burst is identified using upper (300 hPa - 100 hPa) and lower (850 hPa - 700 hPa) level zonal wind at Darwin, with ESRL radiosonde data (Govett 2016). Specifically, upper level zonal wind must be easterly, and low level zonal wind must be westerly while exceeding a threshold of

$$U(n + 1)/n \text{ ms}^{-1}$$

© 0000 Royal Meteorological Society

Prepared using QJRM4.cls
where $n$ is the duration of the low level westerly wind burst (days), and $U$ is 3 m s$^{-1}$. This value of $U$ eliminates bursts shorter than a day or two in duration. The monsoon break is then identified as when the upper level zonal wind is persistently easterly and an active monsoon is not already present. The monsoon transition is defined as when zonal wind showed neither a break nor an active phase.

According to this definition, there are two active bursts within the study period: 1 January – 24 January and 21 February – 24 February. The two active periods are separated by a month of break conditions (25 January – February 20), with two break periods occurring before and after the active bursts (29 November - 31 December, 25 February - 1 April). The two transitional phases are identified as occurring from 1 November - 28 November and 2 April - 30 April. The definition of these periods, as well as upper and low level zonal wind time series, is shown in Figure 3. For the composite SLBC analysis, all days falling within each respective monsoon phase will be included. The background wind conditions for each monsoon regime are found in section 4.1

4. Results

4.1. Mean Wind

Upon partitioning the 2014/15 Northern Australian wet season into monsoon regimes, we find that each period has a distinct mean wind field. This is as expected, given each regime is defined based on the vertical wind structure at Darwin. The monsoon active period (Figure 4a-c) has a wind field which is persistently westerly. The winds are equatorial and transport moisture into the domain, which when coupled with large scale tropical convergence, leads to widespread convection over the land and ocean during this period (May et al. 2012; Keenan and Carbone 1992). Consequently, large regions of cloud cover leads to a reduction in the diurnal cycle of precipitation and coastal winds (Kumar et al. 2013).

During the monsoon break (Figure 4d-f), the wind field remains mostly westerly, but with reduced speed relative to the active monsoon. Easterly winds are also introduced in the eastern sector of the domain. In this period, we expect convection to be less widespread, and more localised/diurnal due to mesoscale circulations such as the sea breeze (May et al. 2012). The monsoon transition sees a return to an easterly wind field (Figure 4g-i), with a near zero mean wind off the western coastal sector, likely due to the Pilbara heat low which will oppose the prevailing flow (Suppiah 1992). The convective signature is similar to the monsoon break (Kumar et al. 2013), however less available moisture results in reduced precipitation.
Figure 4. Mean 10 m wind vector composites for all models (red arrows): WRF (a, d, g), ACCESS-1.5 (b, e, h) and ACCESS-4 (c, f, i), shown together with ASCAT (blue arrows) for satellite swath times. Results are for the active monsoon (A, a–c), the monsoon break (B, d–f) and the monsoon transition (T, g–i). Contours represent composite speed difference (model - ASCAT). Note the change in scaling for the monsoon break, shown by a reference vector.

We also find that the mean wind field is generally similar between all datasets for each of the separate monsoon regimes. For the monsoon break and transition, WRF, ACCESS-1.5 and ACCESS-4 do not exceed a 2 m s\(^{-1}\) composite speed difference with respect to ASCAT and the models are similar to ASCAT in terms of flow direction (Figure 4). The monsoon active regime is also in fairly good agreement between datasets in terms of flow direction, but the composite speed difference can exceed 2.5 m s\(^{-1}\) in some regions of the WRF and ACCESS model simulations. The largest differences occur in the southeast corner of the domain (WRF) and on the southwest corner (ACCESS-1.5 and ACCESS-4). This will primarily affect transect B (Figure 1) for the WRF model, particularly since the wind has a significant cross-shore component. During the transition period, Figures 4g–i indicate a cross-shore easterly wind direction, which will influence the offshore extent of the SLBC along transect B.

4.2. Sea/Land Breeze Perturbations

Perturbation wind composites are shown for sea breeze times (Figure 5) and land breeze times (Figure 6), for the active and break monsoon. The monsoon transition is not shown as it appears similar to the break period. We note that on average, all datasets indicate an offshore SLBC along most coastlines and monsoon regimes (including the monsoon transition, not shown), with a relatively strong signal in the eastern part of the domain. The spatial variability in perturbation wind speed differences between the models and ASCAT is large, and some areas of the domain approach 2 m s\(^{-1}\). Because of large spatial variability in speed differences, the relative perturbation intensity between datasets may be more easily discerned by averaging along the transects.

The intensity of the SLBC as a function of distance from the coast is shown in Figure 7, for transects A and B (Figure 1). Also shown is the theoretical value for offshore extent given by Rotunno (1983), defined in section 3.2. The intensity of the SLBC is defined as the perturbation wind component which is perpendicular to the coastline, as described in section 3.2. Note that the 7-day running mean background wind against which the perturbations are calculated is biased by the sampling times of Metop-A and Metop-B satellites that cluster around two times of day. This precludes the possibility of deducing the relative strength of the land- and sea-
breeze perturbations, which, as defined here, will be symmetric about the background mean. The differences in the magnitude of the land- and sea-breeze perturbations therefore gives an indication of the uncertainty in the method. Despite the uncertainty in defining the background wind, the model data is sub-sampled and averaged to be analogous to the scatterometer data, making the comparisons presented here valid.

Figure 7 suggests that the offshore extent of the SLBC is between 150 km and 400 km for all datasets, however this quantity can be undefined in the monsoon active period, due to a suppression of the circulation. The intensity of the perturbation winds perpendicular to the coastline ($v'$) is confined to being below 3 m s$^{-1}$ in amplitude, for all datasets and monsoon regimes. On average, the SLBC signal is more intense close to the coastline along transect B relative to transect A, by around 1 m s$^{-1}$. This is likely due to the SSTs in
that region, which are amongst the highest on the globe during the Australian Summer (Berry et al. 2012). There is a large amount of variability in offshore SLBC extent and intensity due to monsoon regime, which is generally replicated by all datasets.

The active monsoon is the period in which the models under focus perform most poorly in terms of replicating the ASCAT SLBC (Figure 7a, d). There is a large spread in $v'$ between datasets, especially along transect A where none of the models are able to replicate a SLBC signal (Figure 7a). It is likely that less insolation during this period due to cloud cover leads to a reduced SLBC signal along this transect. Therefore, it is reasonable to expect a greater spread in datasets during this regime, due to, for example, phase differences in the timing of convection and other mesoscale processes.

The SLBC is much more coherent in all datasets during the monsoon break period, with generally, a maximum intensity appearing close to the coastline which decays with distance offshore (Figure 7b, e). WRF, ACCESS-1.5 and ACCESS-4 each replicate the mean

Figure 6. Same as for Figure 5 but for land breeze perturbations (0900-1200)
SLBC with similar intensity, offshore decay and spatial extent, and are in good agreement with ASCAT, although the models tend to slightly over-estimate the intensity of the transect B sea breeze (Figure 7e). The offshore extent for all datasets is approximately 250-400 km for the transect A circulation, and 400 km for the transect B circulation. Each of these values agrees well with the theoretical value of R83, which is consistent with the near-zero cross-shore background wind with respect to both coastlines (Figure 4).

During the monsoon transition, our analysis again presents a coherent offshore SLBC, which is well replicated by each model with respect to ASCAT estimates (Figure 7c, f). The transect A offshore extent ranges from 150 - 300 km, with a slight overshoot from the models during the land breeze with respect to ASCAT. The transect B offshore extent is approximately 250 km in all datasets for the sea and land breeze, and here (similar to the monsoon break along the same transect), the intensity of the ASCAT sea breeze is slightly over-estimated by the models. In addition, the offshore extent of each dataset falls well short of the theoretical value defined by R83. This is likely due to the prevailing easterlies during the monsoon transition, which will introduce an onshore wind along transect B, and a slight onshore wind component along transect A (Figure 4). A prevailing onshore wind will tend to advect the SLBC signal towards the coastline, reducing the offshore extent (Arritt 1989). The differences between the offshore extent and R83, which does not contain a background wind, demonstrates the effect that the prevailing wind has on the SLBC. This effect seems to be replicated by each model.

The results for the monsoon transition are suggestive of a colliding SLBC from the Cape York Peninsula land-mass along transect B (Figure 7f). This is evident from the large amplitude $v'$ signal at the oceanic end of the transect, which is of opposite sign to $v'$ close to the coast for both the sea and land breeze. In contrast, transect A has perturbation winds which decrease in magnitude with distance from the coast (Figure 7c), although there is a slight jump in ASCAT sea breeze magnitude at the oceanic end of transect A, which may represent an opposing sea breeze signal from the New Guinea land-mass. The Cape York SLBC is only present in the domain during the monsoon transition because of the prevailing easterlies (Figure 4g-i), which push the circulation towards Darwin. It is no surprise that the mesoscale models under-represent the intensity of the Cape York sea breeze, given that the land-mass which produces it is outside their inner domain (Figure 1).

The differences between model and scatterometer data presented in this section may be partly limited by the fact that the analysis is constrained by the sampling times of ASCAT, which make it impossible to know the phase of the diurnal cycle that is actually being observed. Any phase difference between the models and ASCAT will map onto this analysis as an error in intensity. For some transects/monsoon regimes, the maximum in modelled sea/land breeze intensity is shifted slightly away from the coastline (for example, WRF in Figure 7b, c). This suggests that the modelled SLBC signal may have propagated offshore by the time ASCAT samples the domain. The difference in this behaviour between the models and observations may reflect differences in propagation speed, or alternatively uncertainties in ASCAT measurements very close to the coast. This propagation is investigated further in section 4.3.

### 4.3. Timing and Propagation

Although the full diurnal cycle cannot be deduced from ASCAT data due to its limited temporal sampling, this information is readily available from gridded model data. This section contains an analysis of the SLBC timing in the WRF model and ACCESS, and how the circulation propagates offshore. Although timing is unable to be investigated by ASCAT, we are still able to: compare the relative timing of the SLBC between WRF and ACCESS, assess what stage the simulated SLBC is in during ASCAT satellite passes, and gauge the modelled, offshore propagation of the circulation.

We use Hovmoller diagrams of $v'$ along transects A and B to elucidate timing of the SLBC, with results averaged over each monsoon regime. The Hovmöller diagrams for the WRF model (Figure 8), ACCESS-1.5 (Figure 9) and ACCESS-4 (Figure 10) all show clear propagation of landbreeze and seabreeze perturbations from the coast towards the sea. The greatest offshore extent of the SLBC is seen for the monsoon break period, consistent with results already presented in Figure 7. The three models have similar timing near the
coast, with sea and land breezes commencing at around 1400 and 0300 LT respectively. In general, strong perturbations of over 1 m s\(^{-1}\) persist near the coast for approximately 5-6 hours before dissipating, with some signals lasting for additional hours farther offshore.

There are, however, some important differences between models and between regimes. Changes in SLBC timing could be due to a number of factors including the prevailing wind, local SSTs, cloud cover or interaction with topography. For instance, during the active monsoon period in WRF along transect A, onshore flow commences at around 1100 LT, with a maximum around 1430 LT, while offshore flow commences around 2100 LT (Figure 8a). These surface flow regimes occur out of phase with the expected sea/land breeze ASCAT time blocks. In contrast, in ACCESS-1.5, onshore flow begins around 1200 LT and reaches a maximum around 1700 LT. The absence of a clear land/sea breeze perturbation along transect A (Fig. 7) is therefore partly due the sampling time being misaligned with the apparently diurnally varying winds. ASCAT time blocks are shown on the Hovmöller diagram (0900-1200 LT and 2100-0000 LT for the land and sea breeze respectively). It is also evident that the offshore extent of the SLBC in the active period along transect A is limited to around 100 km in the WRF model and 100–200 km in ACCESS-1.5. The greater offshore extent in ACCESS-1.5 could reflect greater radiative heating at the surface and might be suggestive of less cloud cover from reduced convective organisation.

There is similar offshore propagation of the SLBC within all models, but this is most clear for transect A (Figure 8a-c, Figure 9a-c and Figure 10a-c). The propagation along transect B is not as obvious, likely due to the concave coastline from which it extends (Figure 1). All models have similar propagation speeds, with an acceleration at around 100 km offshore. During the break and transition periods, approximate propagation tracks have been indicated by solid black lines. These tracks have speeds of \(4 \text{ m s}^{-1}\) close to the coast, and \(15 \text{ m s}^{-1}\) further offshore. These speeds are consistent with those identified previously from offshore propagating precipitation in the literature, where they have been shown to be due a density current near the coast and gravity wave mechanisms farther offshore (Vincent and Lane 2016; Yang and Slingo 2001; Hassim et al. 2016). In addition to Figure 7f, a collision with the Cape York Peninsula SLBC can be seen in Figures 8f, 9f and 10f, with the Cape York sea breeze (positive \(v'\)) colliding with the Darwin land breeze (positive \(v'\)), and vice versa. This is most visible in the monsoon transition, where it is indicated by a dashed black line, due to a prevailing easterly wind which pushes the Cape York perturbation towards Darwin.
If we assume that the timing in WRF and ACCESS is realistic, then the Hovmöller diagrams show that generally ASCAT will sample the Darwin domain as the sea/land breeze begins to dissipate near the coastline and/or moves offshore. Sampling times are mostly under either a sea or land breeze regime, although some may be in a transitional state with no clear SLBC (containing positive and negative $v'$. Comparing ASCAT sampling times with Hovmöller diagrams of $v'$ explains why some transect peaks are shifted away from the coastline, as the maximum intensity of the circulation may propagate offshore by the time ASCAT samples the region.

© 0000 Royal Meteorological Society

Prepared using \texttt{qjrms4.cls}
4.4. Diurnal Cycle in Land-Sea Temperature Contrast

Although for the most part, offshore intensity and spatial extent is in good agreement across all datasets, there are some differences which we attempt to diagnose here. This is achieved by investigating the driver of the SLBC, namely the diurnal cycle in land-sea temperature contrast, caused by differential surface heating. Automated Weather Station (AWS) observations are used for temperatures over the land, provided by the Australian Bureau of Meteorology. The locations of the AWS stations are shown in Figure 1, and are assumed to be representative of the area over which land surface heating is important in forcing the SLBC.

For temperatures over the sea, the real-time global sea surface temperature (high spatial resolution) dataset is used (Gemmill et al. 2007), which is also used as a lower boundary condition in the WRF model. However, this product is daily and neglects any diurnal variation in SSTs, which are large in the tropics (Zhang et al. 2016) and non-negligible for atmospheric processes such as the SLBC (Kawai et al. 2006). If diurnal SST variation is large due to increased insolation (decreased convection) and decreased wind speed (decreased ocean mixing), then daytime SST can be under-estimated, and land-sea temperature contrast can be over-estimated by using daily SST products. In addition, this may cause a simulation of the SLBC to be too intense. Note that the ACCESS models also use a daily SST product (section 2.2). For the purpose of calculating the diurnal land-sea temperature contrast, daily SST data is spatially averaged over the area of each transect (Figure 1). The more appropriate variable to use over the ocean rather than SSTs would be 2 m air temperature, but this is not available in a gridded product.

The diurnal cycle in land-sea temperature contrast, averaged over each monsoon regime, is shown in Figure 11, along with the differences between the models and observations. Figures 11a, c, e reveal an expected diurnal temperature contrast. There are two distinct forms of temperature change, the first of which is the solar heating profile during the day, which results in a maximum in land-sea contrast at around 1800 LT. The second form is due to nocturnal outgoing shortwave radiation, and is much slower than its daytime counterpart, leading to a minimum in temperature contrast at around 1000 LT.

Due to moisture availability and corresponding cloud cover (May et al. 2012), the land heats up less during the day and cools down less at night during the active monsoon, relative to the break and transition periods in the Northern Australian wet season. AWS observations show that on average, the land does not become warmer than the domain averaged SSTs, at any time during the day.
The Regional Sea Breeze Estimated from Scatterometer

In contrast, the land becomes approximately 1.5° and 2° warmer than the ocean in the monsoon break and transition respectively (Figure 11c, e). This is consistent with the suppressed SLBC in the active monsoon period.

When comparing the observed land-sea temperature contrast to that in ACCESS and WRF, it is clear that the diurnal cycle is in good agreement between all datasets in terms of timing. However, all models tend to heat up the land surface too much during the day compared to AWS observations, resulting in a warm model bias which persists throughout the night and early morning (Figure 11b, d, f). The maximum in temperature bias is around 1.0° in WRF and ACCESS-1.5 for all monsoon regimes, corresponding to around three to four hours after the maximum temperature contrast (around 2200 LT). The WRF and ACCESS-1.5 model bias occurs earlier in the day during the active monsoon than for the break and transition. During the active phase, bias is reduced in ACCESS-4, but for the monsoon break and transition, ACCESS-4 bias is similar to ACCESS-1.5 and WRF.

This warm bias, which stems from exaggerated daytime heating, is likely to be due to model representation of convective organization and stratiform cloud. Mesoscale models have been shown to have isolated, intense convective regions, rather than widespread convective organization (Done et al. 2004; Vincent and Lane 2017; Stein et al. 2015), which is unphysical, and will cause an underestimation of reflected insolation. This is consistent with the warm model bias being greatest during the active monsoon, and it is hypothesized that ACCESS-4 has a reduced bias during the day in this phase because it employs convective parametrisation. Although the warm model bias is small, it could be an important factor in explaining the apparent difference between the simulated and observed SLBC perturbations along transect B (see section 4.2).

5. Discussion

Through composites and transects of $v'$, it has been shown that there is on average, an observed (ASCAT), offshore sea/land-breeze along every Northern Australian coastline in the Darwin domain, during each monsoon regime for the 2014/15 wet season. This is expected, as the SLBC occurs around most of the Earth’s coastlines (Gille 2003), and is strongest in the tropics due to strong forcing and limited Coriolis effect. Similar to Aparna (2005), both sea and land breezes are shown by a perturbation wind method to decay at a finite distance away from the coast. Our results agree with the global scatterometer survey of Gille (2003), which suggests that the land breeze will extend several hundred kilometres offshore in the tropics. However, that study defines the circulation using diurnal harmonics, rather than as explicit perturbations from a daily mean, and does not quantify the effect of adjacent landmasses with colliding sea/land breezes.

The WRF, ACCESS-1.5 and ACCESS-4 models and ASCAT all produce a similar SLBC in terms of offshore intensity and decay/extent, with the exception being for the active monsoon period. During this regime, there is only a small observed signal with consequent large spread between datasets, due to a reduction in solar heating of the surface caused by cloud cover (May et al. 2012). The model spread likely reveals varying degrees of convective organisation. The models under focus demonstrate realistic sea/land breeze dynamics without relying on parametrisation, suggesting promising applications to numerical weather prediction at a regional scale. In addition, the cumulus parametrisation in ACCESS-4 does not seem to significantly affect the SLBC forcing and characteristics, nor do the differing setups between WRF and ACCESS.

The results presented in this study do not demonstrate any clear evidence of large enough errors in the SLBC to adversely affect convective initiation. To the contrary, the intensity and offshore extent of the SLBC was generally modelled very well. However, this study did not address the issue of the timing of the SLBC, and only looked at the surface manifestation of the SLBC. Moreover, this study focused only on a single location, with relatively low topography. In parts of the Maritime Continent with more complex topography, such as New Guinea, Sulawesi or Sumatra, there may well be a close coupling between the SLBC and the diurnal precipitation cycle both on and off-shore - particularly because in these locations it may be impossible to separate the SLBC from anabatic and katabatic flows initiated by steep mountains near the coast.

© 0000 Royal Meteorological Society

Prepared using QJRM4.cls
The land-sea temperature difference was also examined, as the main driver of the SLBC. The limitation of this analysis was that a daily SST product was used, which is the same temporal resolution as the prescribed SSTs in ACCESS and WRF. Therefore, the effect of diurnal SST variation on land-sea temperature contrast was unable to be examined, which may be large in the tropics (Zhang et al. 2016). It was found that each model heats up the land surface too much during the day with respect to daily SSTs, with a consequent warm bias during the night. This effect is most prevalent during the convectively active monsoon period, suggesting that the problem may stem from model representation of convective organisation. This could lead to an over-estimation of the sea breeze and underestimation of the land breeze, but a properly resolved diurnal wind cycle would be required to assess this. It has been shown in previous studies that mesoscale models have isolated, intense convective regions, rather than widespread cloud cover (Done et al. 2004), which is unphysical and will cause an underestimation of reflected insolation. It appears that ACCESS-4 has a reduced warm bias, possibly related to the characteristics of the cloud population as a result of the convective parametrisation relative to that in the two convection-permitting simulations. Therefore, correct simulation of convective systems is not only crucial for precipitation and energy/momentum transport, but also for other thermally driven mesoscale systems such as the sea/land or mountain/valley breezes, especially during convectively active large scale regimes.

In addition to corresponding moisture availability and cloud cover, the Darwin SLBC is highly sensitive to changes in prevailing wind with monsoon regime. It has been suggested by previous work that the cross-shore component of the prevailing wind will strongly modulate the offshore extent of the SLBC (Arritt 1989), which will have important implications for diurnal, offshore precipitation.
The Regional Sea Breeze Estimated from Scatterometer

(Houze et al. 1981). This is consistent with the current study, which compares the offshore extent of each dataset to the linear theory of R83, which does not contain a background wind. For monsoon regimes/coastlines with significant onshore prevailing wind (easterlies in the monsoon transition cause onshore winds along both transects), the offshore extent of the SLBC in all datasets falls well short of the theoretical value. The opposite will be true for offshore prevailing wind, and the datasets are in alignment with R83 for near-zero cross-shore wind (the monsoon break). Clearly, these results indicate that the offshore spatial extent of the SLBC is governed largely by the prevailing wind, as well as the quantities within the expression produced by the linear theory, namely atmospheric stability, Coriolis frequency and the vertical heating scale. These will therefore have a large effect on offshore precipitation, as well as any non-linear processes which are not included in the theory.

The perturbation winds used within this study need to be treated with caution, given that mean winds used to define them are constructed using the limited sampling time of the ASCAT satellite product. This could be improved by combining multiple scatterometer datasets with overlapping operational windows, and which sample the SLBC at varying times of the day. This has been addressed in this study by limiting model data to ASCAT satellite passes.

However, results for the offshore intensity and spatial extent of the SLBC agree with theory and other regional studies (Aparna 2005). Therefore, we are confident that our perturbation method is suitable for the purpose of assessing regional models and satellite wind estimates. The method has the advantage of identifying a definite quantity for the horizontal spatial extent from a given landmass and detecting colliding sea/land breezes, which are crucial for convective initiation in the tropics (Wapler and Lane 2012).

6. Conclusion

The Darwin SLBC is estimated by the Advanced Scatterometer (ASCAT) over a six-month wet season period, and analysed using a perturbation method. We find, as expected, a mean offshore SLBC along all coastlines in the domain, which varies with monsoon regime due to moisture availability and the prevailing cross-shore wind component. Through the use of ASCAT data, we have demonstrated the potential to incorporate satellite-derived winds into mesoscale meteorological studies, assuming that offshore quantities are of interest.

In the case of the tropical SLBC, this work is important due to the potential interplay with offshore precipitation.

Mean offshore intensity as a function of distance from the coastline is investigated in ASCAT, along with offshore horizontal spatial extent. These characteristics are then compared with two regional atmospheric models, the WRF model and ACCESS. Both models agree well with the offshore intensity and extent of the Darwin SLBC from ASCAT, with associated monsoon sensitivity. These results suggest that errors in SLBC representation may not be sufficient to explain known errors in modelled timing and amplitude of offshore convection in tropical coastal areas.

Model representation of the SLBC appears to be independent of the varying configurations between the two versions of ACCESS and the WRF model. However, the diurnal cycle in simulated land-sea temperature is slightly improved in the 4km resolution version of ACCESS with convective parametrisation. This may also improve SLBC representation, given that some of the biases in intensity that were found in this study were attributed to the land-sea temperature contrast, with the models all containing a warm bias relative to observations.

We also find that all datasets are well predicted by the linear theory of R83, in absence of a background wind. This suggests that the characteristics that were investigated in this study may largely be governed by linear processes, with offshore extent given by atmospheric stability and the depth of the boundary layer in the tropics. The departure from the linear theory due to a cross-shore prevailing wind demonstrates the influence this variable has on the SLBC, especially on the offshore spatial extent.

This study presents important results about the offshore extent of the tropical seabreeze at the surface, which is relevant to other recent studies that have shown diurnal variations in precipitation associated with a squall line that closely mirrors the offshore extent of the land breeze in the tropics (Vincent and Lane 2016). Moreover, there has been a recent focus on the coupling between intraseasonal...
and diurnal variability in the tropics that is highly consistent with results presented in this study. For example, Peatman et al. (2014), Birch et al. (2016) and Vincent and Lane (2016) all showed a suppressed diurnal precipitation during the active phases of the Madden Julian Oscillation (MJO), which is likely to have a similar effect on surface radiative forcing and moisture availability as the active monsoon period around Darwin. The ability of mesoscale models to reproduce many aspects of the variation in SLBC with monsoon phase is also consistent with Vincent and Lane (2016) and Vincent and Lane (2017), who suggested that the main physical processes governing the diurnal cycle in the tropics could be reproduced in a mesoscale model, despite large precipitation biases over the land.

This work has also demonstrated that the use of scatterometer data is a powerful tool for validation of offshore structures in high resolution numerical weather models. The results suggest that generally, the offshore SLBC can be modelled very well. In parts of the Maritime Continent influenced by steep topography, errors in the diurnally varying winds may be more significant. Our ongoing work will extend to a more general study over the whole Maritime Continent region.

Acknowledgement

This work was funded by the ARC Centre of Excellence for Climate System Science (CE110001028). Thank you to the Australian Bureau of Meteorology for providing weather station data, as well as ACCESS forecasts. ASCAT data was obtained from the NASA JPL Physical Oceanography Distributed Active Archive Centre (https://podaac.jpl.nasa.gov/). Radiosonde data was obtained from the NOAA/ESRL radiosonde database server. Thanks to Adrian D’Alessandro for sharing his ideas. Thanks to two anonymous reviewers for insightful suggestions.

A. Appendix

The wind reported by ASCAT is the “Equivalent Neutral Wind” (ENW), which is the wind that would be observed if the atmospheric stability was neutral, given the same friction velocity ($u_*$). The ENW can be calculated from model data, provided $u_*$ and the roughness length, $z_0$ are known. $u_*$ is saved as standard output from the WRF model, and over the sea, the roughness length is calculated according to the Charnock relation (Stull 1988). Since $u_*$ was not available from the operational ACCESS forecasts, the analysis in this paper has been carried out using diagnostic 10 m winds from both the WRF and ACCESS models.

To help quantify the loss of accuracy due to the difference between the 10 m wind and ENW, the composite land and sea breeze perturbations for the whole study period for 10 m diagnostic wind and ENW from the WRF model are compared in figure A1. During the landbreeze ASCAT sampling time (Figure A.1a), $u_{10} - ENW$ is less than zero around most of the coastal areas, as would be expected for unstable conditions. This may be due to the advection of cool air from the land over the comparatively warm water. During the seabreeze ASCAT sampling time (Figure 1b), $u_{10} - ENW$ is greater than zero close to the coast, as would be expected for stable conditions.

The difference between the 10 m wind and the ENW has a maximum magnitude of 0.5 m s$^{-1}$, with the maximum differences concentrated in coastal areas. The differences between ASCAT and model data in this study exceed 0.5 m s$^{-1}$ (eg. Figures 5, 6 and 7), so cannot be explained by differences between 10 m wind and ENW.
Figure A.1. Land breeze (a, 0900-1200 LT) and sea breeze (b, 2100-0000 LT) perturbation composites for WRF 10 m model winds (red arrow) and ENW, constructed using WRF data fields (blue arrow). The difference in speed between the two composites (10 m model wind minus ENW) is contoured. Composites are for the whole study period.

References


The Regional Sea Breeze Estimated from Scatterometer


The Regional Sea Breeze Estimated from Scatterometer

The Regional Sea Breeze Estimated from Scatterometer


© 0000 Royal Meteorological Society

Prepared using Q3RMS4.cls
Author/s:
Brown, AL; Vincent, CL; Lane, TP; Short, E; Nguyen, H

Title:
Scatterometer estimates of the tropical sea-breeze circulation near Darwin, with comparison to regional models

Date:
2017-10-01

Citation:
Brown, AL; Vincent, CL; Lane, TP; Short, E; Nguyen, H, Scatterometer estimates of the tropical sea-breeze circulation near Darwin, with comparison to regional models, QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY, 2017, 143 (708), pp. 2818 - 2831

Persistent Link:
http://hdl.handle.net/11343/197700

File Description:
Accepted version