A dipole of tropical cyclone outgoing long-wave radiation

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Abstract

Large-scale (500 \( \leq r \leq 2,200 \) km) outgoing long-wave radiation (OLR) and water vapour (WV) fields are investigated in satellite observations over the Pacific, linked to ERA-5 reanalysis data and the ECMWF ensemble forecasts of tropical cyclones (TC) globally. A large-scale OLR dipole pattern of low and high fluxes are found in both the observations and model. As expected, a low OLR region is positioned within the TC circulation, but there is also a robust high OLR region poleward and west of the TC centre. A dry “black hole” on WV grey-scale imagery occupies the same region of high OLR. Relative to the central low OLR TC signal, the typical dipole magnitude, distance and orientation of the high OLR regions are 230 W m\(^{-2}\), 1,150 km, and 145° anticlockwise from east. From the reanalysis we find that the interaction between the vortex and the environmental flows produces upper-level convergence, low-level divergence and subsidence throughout the troposphere in the region of high OLR. Analysis of the ECMWF model shows that the position of the high OLR region rotates anticlockwise about the TC centre as the TC moves from westward to eastward. Through use of a sub-ensemble, we test if capturing the high OLR anomaly has a significant relationship with TC track. We apply a perfect model approach and find that sub-ensembles that are composed of models whose large-scale OLR fields closely match the target TC also have a better track. This improvement is mostly attributed to the high OLR component of the dipole.

KEYWORDS

outgoing long-wave radiation, subsidence, tropical cyclone

1 | INTRODUCTION

There have been numerous investigations of tropical cyclone (TC) composites to understand the large-scale (500 \( \leq r \leq 2,200 \) km) interaction with the environmental flow. However, no links have been made to systematic composite satellite observations. Both Frank (1977) and Holland and Merrill (1984) composite rawinsonde TC data to determine the TC structure and the environmental controls upon TC structure respectively. Both note inflow and outflow extend radially beyond 1,000 km. Reanalysis composites of environmental vertical motion and precipitation have demonstrated increased uplift and precipitation in eastern Pacific TCs compared to western Pacific.
TCs at large distances (Vincent and Fink, 2001). The large-scale upper-level model composite study by Hanley et al. (2001) found that interactions with upper tropospheric troughs can favourably increase TC intensity. Focused solely on outflow, a composite study of TCs in reanalysis by Ditchek et al. (2017) found that environmental eddy heat and momentum forcing enhances the TC secondary circulation. Whilst it is well understood that significant asymmetries occur at large radii, both Holland and Merrill (1984) and Ditchek et al. (2017) analyse azimuthal profiles so asymmetric patterns are not identified. An alternate method to understand the TC environmental interaction is to utilise idealised models (Shi et al., 1990; Corsaro and Toumi, 2017; Komaromi and Doyle, 2018; Ryglicki et al., 2019). A drawback of these model studies lies in their idealised environmental flow regime. Regardless, they find easterly upper-level outflow and subsidence at large distances. These behaviours should be detectable on satellite imagery.

The use of meteorological satellites began in the 1960s and over time has deepened our understanding of TC processes. Multi-spectral band satellite imagery is particularly useful as it shows cloud top temperatures, indicative of cloud height and water vapour features (Poc et al., 1980; Schmetz et al., 1995; Velden and Bedka, 2009). Successive images can be used to infer the large-scale and environmental dynamic processes associated with TCs such as atmospheric motion vectors via cloud and water vapour tracking (Merrill et al., 1991; Rodgers et al., 1991; Velden et al., 1997; 1998). Satellite imagery is sometimes used to describe large-scale TC environment conditions for case-studies (Rodgers et al., 1991; Zehr and Knaff, 2007). The expansive coverage, high temporal resolution, and the capacity for multi-spectral band satellite imagery to approximate the TC processes means that they are an extremely useful tool to understand the relationship between TCs and their environment as it develops. To date there has been no systematic investigation of large-scale (500 ≤ r ≤ 2,200 km) TC satellite outgoing long-wave radiation (OLR) and water vapour (WV) features to understand the common relationships found between TCs and their environment. Here we present for the first time a comprehensive statistical analysis of both observed and modelled remote (500 ≤ r ≤ 2,200 km) OLR and WV fields.

We assess the relationship between the TC OLR features and the cyclone track forecast error through sub-ensemble forecasting. Sub-ensemble forecasting is normally used as a way of optimising an ensemble prediction system (EPS). The standard practice of taking the arithmetic mean across the EPS yields higher skill than choosing any one ensemble member (Tracton and Kalnay, 1993; Molteni et al., 1996; Goerss, 2000; Richardson, 2001; Buizza et al., 2007; Yamaguchi et al., 2009). After any EPS is produced, identifying and excluding the most erroneous members from an ensemble yields a sub-ensemble. Taking an average across the sub-ensemble can improve upon the original EPS forecast (Elsberry and Carr, 2000). Here we use this technique in a different way. The sub-ensembles are selected to quantify the relationship between TC large-scale OLR features and TC track errors within the ECMWF EPS.

The article is structured in the following way, Section 2 details the observations, model data, preprocessing, and the methods and algorithms employed. Results are presented in Section 3 with a discussion in Section 4; concluding remarks are presented in Section 5.

2 | DATA

The observed data used in this study constitute outgoing long-wave radiation (OLR) and water vapour (WV) observations of 191 TCs within the Pacific from all basins, from 2011 to 2019 (Figure S1). Observations from the GOES-15 (central wavelengths for OLR and WV are 10.7 and 6.5 μm respectively) and Himawari-8 (central wavelengths for OLR and WV are 11.2 and 6.9 μm respectively) satellites at 25 km resolution were analysed (Hillger and Schmit, 2011; Tabata et al., 2016). Given the different central wavelengths and frequency bands between the two satellites, brightness temperature (°C) observations were converted simply to black-body OLR (W·m⁻²). The dataset encompasses TC intensities between categories 1 and 5, and images were taken at the point of lifetime maximum intensity as reported in the international best-track archive (IBtracks: Knapp et al., 2010). Images are centred upon the TC minimum sea-level pressure (Pmin) (Knapp et al., 2010) and encompass a radius of 2,200 km.

The European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis (ERA-5) data for each of the observed cyclones were also examined at their lifetime maximum intensity (Copernicus Climate Change Service [C3S], 2017). These hourly reanalysis data have a spatial resolution ≈28 km and provides a dataset of the environmental dynamics at the time the satellite observation was taken. ERA-5 data were also centred upon the location of a central minimum sea-level pressure (Pmin) within the vicinity (220 km or 2°) of the IBtrack position. The average distance between model Pmin and IBtrack location was 44 km (0.4°). There were four TCs where no central low Pmin could be found in this range which, after inspection, presented no vortex-like structure in the ERA-5 dataset and were removed from composite analysis. A distance of 220 km was chosen as it represents an error in TC motion within the ERA-5 data equivalent to 10 m·s⁻¹ over 6 hr – the time between TC position updates within
IBtracks (Knapp et al., 2010). We use 10 m s\(^{-1}\) as the maximum possible TC translation speed. No significant relationship was found between the satellite OLR features and the ERA-5 TC position errors.

The ECMWF Ensemble Prediction System (EPS) contains 50 global ensemble members (Buizza et al., 2007). We select cyclones from the more recent, highest-resolution (15 km) model (March 2016–December 2018). A full EPS is available every 12 hr; model data fields within the EPS are available at 6 hr increments. This allows us to test an improved, sub-ensemble track forecast 6 hr after publication. The surface pressure (hPa); surface, 500 and 200 hPa wind fields (m s\(^{-1}\)); and OLR fields (W m\(^{-2}\)) are available from The International Grand Global Ensemble (TIGGE) database (Bougeault et al., 2010). The OLR fields are defined as the power output per square metre averaged over the 6 hr window. The full EPS was examined for 28 TCs from the North Atlantic, eastern Pacific, western Pacific and the Indian Ocean (red lines in Figure S1). Each TC attained at least observed category 4 strength within the mean of the remaining 49 members. We apply the sub-ensemble selection method to OLR fields 50 times by selecting one member as the target TC and taking the variation of the dipole distance (radius to centre), orientation and magnitude. The large region of anomalously high OLR is centred in the north (poleward) western quadrant for 500 < \(r\) < 1800 km at a mean distance of \(r = 1,148\) km (\(\sigma_r = 249\) km) and a mean angle of 128° (\(\sigma = 76°\)) (Figure 2a,b). This high OLR region typically emits about 229 W m\(^{-2}\) (\(\sigma = 47\) W m\(^{-2}\)) more than the inner 500 km of the TC where the region of lowest OLR is found. Investigations into the dipole geometry with vertical wind shear indicate no dependence on shear vector orientation or magnitude (not shown). Composites of the OLR anomaly between the TC OLR observation and the background OLR (observed 10 days prior when no TC is present) show that the high OLR region emits \(\approx 50\) W m\(^{-2}\) more than would be observed in the background environment (Figure S2a). Composite analysis of the geopotential height of the 1,000 hPa layer reveals a background meridional pressure gradient; however, no region of anomalously high pressure is visible in the northwest compared to the northeast regions (Figure S2b).

3  RESULTS

3.1  Observed OLR

The first and simplest way to inspect the typical OLR pattern of TCs is by taking the average OLR across all 191 observed TCS. A clear OLR dipole structure is found, for both strong (categories 4 and 5) and weak (categories 1–3) cyclones (Simpson and Saffir, 1974) (Figure 1a–c). The mean latitude of the observed TCs is 18.6°. Figure 2 shows the variation of the dipole distance (radius to centre), orientation and magnitude. The large region of anomalously high OLR is centred in the north (poleward) western quadrant for 500 < \(r\) < 1800 km at a mean distance of \(r = 1,148\) km (\(\sigma_r = 249\) km) and a mean angle of 128° (\(\sigma = 76°\)) (Figure 2a,b). This high OLR region typically emits about 229 W m\(^{-2}\) (\(\sigma = 47\) W m\(^{-2}\)) more than the inner 500 km of the TC where the region of lowest OLR is found. Investigations into the dipole geometry with vertical wind shear indicate no dependence on shear vector orientation or magnitude (not shown). Composites of the OLR anomaly between the TC OLR observation and the background OLR (observed 10 days prior when no TC is present) show that the high OLR region emits \(\approx 50\) W m\(^{-2}\) more than would be observed in the background environment (Figure S2a). Composite analysis of the geopotential height of the 1,000 hPa layer reveals a background meridional pressure gradient; however, no region of anomalously high pressure is visible in the northwest compared to the northeast regions (Figure S2b). The area occupied by high OLR does not appear to vary with TC intensity; \(t\)-tests of the strong TC vs. weak TC distributions of radius and angle show no significant difference (\(p > .5\) and \(p > .4\) respectively). The distributions of the dipole magnitude for strong vs. weak TCs are significantly different (\(p < .01\); however, this can be attributed to a lower OLR flux within

Our models have a much coarser spatial resolution than those examined by Nguyen et al. (2014). We therefore utilise that paper’s first TC centre estimate defined by the minimum sea-level pressure, \(P_{\text{min}}\), within 450 km of the position reported by the IBtrack data (Knapp et al., 2010). This enables us to track each cyclone within the model environment. Subsequent centres are determined by the \(P_{\text{min}}\) location within 450 km of the previous location. This simplified method saves computational time for our \(\approx 200,000\) TC positions. The OLR fields, produced by ECMWF, are defined as the total power output per square metre averaged over the 6 hr window.
**Figure 1** OLR composite plots at lifetime maximum intensity for (a) all 191 observed TCs in the dataset, (b) 106 TCs reaching categories 1–3, and (c) 85 TCs reaching categories 4–5. Overlaid are the percentile contours for each composite after Gaussian smoothing is applied where $\sigma = 100$ km.

**Figure 2** Histograms of the dipole properties for all observations (blue), strong TCs (solid black line) and weak TCs (dashed black line). (a) Histogram of the radius (km) from the TC centre at which the centre of mass of the high OLR region resides for $500 \leq r \leq 2,200$ km. (b) Angle, measured clockwise in degrees, between the line connecting the TC and dipole centres and the line pointing due east (quadrants are also labelled). (c) Dipole magnitude calculated as the OLR difference between the average flux in the inner 500 km and the average flux for the identified high OLR region. The mean of all observations is plotted in red.

$r < 500$ km with increasing intensity ($p < .01$). There is no relationship between OLR flux in the high OLR region and intensity ($p > .5$). There appears to be some dependency upon TC intensity for the OLR anomalies extending from the southwest and southeast, where an arm of low OLR extends to the southwest with stronger cyclones (Figure 1). The composite across the water vapour channel grey-scale imagery reveals a striking dry air “black hole” in the same high OLR location (Figure 3).

The ERA-5 dataset has a 28 km ($0.25^\circ$) resolution and thus mostly fails to capture the complex dynamic processes operating within the eye and eyewall. Reanalysis thus poorly represents TC maximum wind speeds (Schenkel and Hart, 2012; Hodges et al., 2017). This study however is focused on composites of large-scale features ($500 \leq r \leq 2,200$ km), where reanalysis datasets have been used successfully (e.g. Vincent and Fink, 2001; Sobel and Camargo, 2005; Hart et al., 2007; Schenkel and Hart, 2012; Ditchek et al., 2017; Kim et al., 2020).

The important dynamical features associated with this OLR dipole are examined in the ERA-5 dataset. A significant match can be found between the observed composite OLR (Figure 1a) and the upper-level and low-level divergence field (Figure 4a,g). The spatial correlation coefficients between the low-level and upper-level divergence and the OLR are $R = -0.8$ and $R = 0.7$ (where $p < .01$ for...
The upper tropospheric flow at 200 hPa on the poleward side (Figure 4a) is largely anticyclonic for \( r > 250 \text{ km} \) and the cyclone outflows into an environment that is dominated by strong westerly flows in the north (poleward). The anticyclonic outflow on the poleward side of the TC converges with these westerlies in the north (poleward) west. In the boundary layer, on the poleward side, the flow is easterly (Figure 4g). As the easterly flow interacts with the cyclonic circulation (at \( r > 500 \text{ km} \)) it deflects anticlockwise. The flow becomes divergent after this deflection over a large region to the northwest of the cyclone centre. This combination of upper-level convergence and low-level divergence matches the location of the observed high OLR (Figure 1a) and low water vapour anomaly (Figure 3).

At upper levels, the equatorward side of the cyclone is dominated by anticyclonic wind emanating from the outflow (Figure 4a). The upper-level equatorward divergence co-locates with the lower-level equatorward convergence. On the equatorward side at low levels, air converges from the south towards the vortex and meets the easterly flows through an expansive lateral region \( \approx 750 \text{ km} \) south of the cyclone (Figure 4g). The divergence signals on the equatorward side of the TC are co-located with the low OLR anomalies (Figure 1a).

At the steering mid-levels, 500 hPa, the environmental flow impacting the cyclone is easterly with westerly flows on the poleward side and easterly flows on the equatorward side. Little or no wind enters the TC circulation from the poleward and equatorward boundaries. The cyclone, embedded in this east–west flow, sets up alternating cyclonic–anticyclonic circulations, 1,500 km to the east and west. Little air flow penetrates the cyclone compared to the boundary layer. Divergence here is very noisy with no substantial regions of convergence or divergence in the outer cyclone environment. There is no obvious association between 500 hPa divergence and the OLR or water vapour channel signal.

Both the mid- and upper-level vertical velocities (Figure 4b,e) show similar patterns with strong descent in the northwest quadrant. Vertical ascent is found across the broad band of low-level convergence on the equatorward side of the cyclone. There is a strong association between high OLR (Figure 1a), low water vapour (Figure 3), the low-level divergence, upper-level convergence fields and induced subsidence (Figure 4). This association is simply produced by mass continuity. The vertical descent at 500 hPa is co-located with those divergence fields.

The relative humidity fields (Figure 4c,f,i) are closely related to cloud structure and subsequently the OLR and water vapour channel fields (Poc et al., 1980; Schmetz et al., 1995). The patterns shown here closely map to the patterns of vertical velocity for each layer. As expected, a strong association can be made between the mid-level relative humidity and the water vapour channel composite. Contours of the tropical mean soundings of relative humidity (Dunion, 2011) are plotted and show that the descending air in the northwest is anomalously dry, where the OLR is also high. Conversely, on the equatorward side the ascending air is anomalously moist where the OLR is low.

Vertical cross-sections of the radial composite wind for each quadrant reveal strong asymmetries (Figure 5). The flow field in the northwest quadrant (Figure 5a) is dominated by subsidence throughout the troposphere for \( r > 500 \text{ km} \). At low levels in this quadrant the flow is heavily divergent, and whilst the wind is cyclonic (not shown), its radial component is away from the TC centre for \( r > 500 \text{ km} \). Flow is away from the vortex; however, the northwestward average vortex motion (not shown) implies the outward radial flow is orientated with the steering flow throughout the lower troposphere. The radial expansion is constrained by the opposing westerlies above 700 hPa. These winds are stronger than the TC outflow/steering and extend closer to the TC centre with height. The westerlies subside at all heights in the northwest cross-section. The boundary between the westerlies and the cyclonic outflow forms a saddle or “neutral point” (Figure 4d). Convergence is present in both the outflow and the westerlies in the upper levels to the north. This convergence, unique to this quadrant (Figure 5a), matches the region of convergence and subsidence shown in Figure 4a,b,e.

The flows in the northeast quadrant (Figure 5b) resemble those expected for a typical axisymmetric vortex (Emanuel, 1986) where classic regions of inflow, ascent and outflow are present. Generally the inflow and outflow
FIGURE 4 The composite of all observed TCs for three vertical layers. Columns from left to right show the divergence (s⁻¹) overlain with streamlines; the vertical velocity (Pa.s⁻¹) where positive (negative) values represent descending (ascending) air; and the relative humidity where a black contour of the tropical mean relative humidity for each layer is plotted (Dunion, 2011). The 200 hPa, 500 hPa and 1,000 hPa pressure levels are plotted on the top, middle and bottom row respectively. Divergence and vertical velocity values exceeding the limits of the colour bars are coloured with the value of the limit. All x-y units are in km from cyclone centre.

are confined to the 1,000–850 hPa and the 300–100 hPa layers respectively and vertical uplift is restricted to the inner TC (r < 500 km). All inflow in the 1,000–850 hPa layers reach the inner 500 km of the TC. This quadrant shows very little vertical motion at large radii.

The two southern (equatorward) quadrants display some similarities in their divergence signals (Figure 5c,d). At low levels intense convergence occurs at all radii which facilitates ascent. In the southwest (Figure 5c) a strong convergence signal between 1,000 and 800 hPa is present whereas the southeast exhibits a broader convergence signal between 1,000 and 700 hPa (Figure 5d). No coherent signal is present between 700 and 300 hPa and divergence is restricted to the 300–100 hPa layers, for both quadrants.
FIGURE 5  Cross-sections for each quadrant of the composite ERA-5 data. Divergence (s$^{-1}$), radial (m·s$^{-1}$) and vertical Pa·s$^{-1}$ components of wind are averaged over radial bins 30 km wide encompassing 90° of the flow field for each quadrant. The boundaries for each bin follow the major compass lines. Streamlines of the resulting averages are plotted on top of divergence fields. Divergence values exceeding the limits of the colour bars are coloured with the value of the limit; x units are in km, y units are in hPa. Panels are oriented such that the TC centre lies in the middle, therefore western quadrants radiate to the left, eastern quadrants radiate to the right.

In the southwest quadrant the transitions between inflow, ascent and outflow are less discrete (Figure 5c). The aforementioned interaction between wind that is drawn from the Equator and the deflected easterlies (Figure 4g) creates intense low-level convergence between 500 and 1,500 km which dominates the inflow. Air from larger radii does not reach the inner ($r < 500$ km) TC circulation and is uplifted and ejected at large radii.
The southeast quadrant shows a limited inflow–ascent–outflow pattern. For \( r > 500 \text{ km} \) there is no outflow between 1,000 and 150 hPa and ascent occurs at all radii and heights. At these large radii the wind is directed towards the cyclone, consistent with the background steering flow. Any outflow is restricted to the 150–100 hPa layers and exits the circulation upwards towards the tropopause in the region \( r < 1,000 \text{ km} \).

Figure 6 shows the mean vertical extent of divergence and subsidence in the northwest quadrant (\( 500 \leq r \leq 2,200 \text{ km} \)). It is clearly visible that subsidence, within this composite, is present throughout the entire vertical column. The descent is maximum in the layers directly beneath 200 hPa and remains almost constant at \( \approx 1.5 \times 10^{-2} \text{ Pa} \cdot \text{s}^{-1} \) between 200 and 900 hPa. This subsidence is three times larger than the subsidence in the background environment (determined from a monthly averaged ERA-5 dataset – not shown). The descending air is co-located with the region of strong divergence extending from 1,000 hPa to 850 hPa and corresponding region of convergence between 250 and 150 hPa. Calculating the pressure-weighted total divergence through the column reveals a divergence surplus of \( 2.2 \times 10^{-6} \text{ s}^{-1} \).

### 3.2 ECMWF model OLR

We next explore if the same OLR and flow features are present in the ECMWF model. The EPS model provides an opportunity to explore many more TCs than observed, including TCs within a westerly flow. The composite OLR field of the 25,350 cyclones in the model database at \( t_1 \) shows the same dipole pattern as seen in the observations (Figure 7a). Unlike observations at lifetime maximum intensity (Figure 1a), the composite OLR field in Figure 7a is taken from models across the entire TC life span. The study region in this dataset is slightly smaller, encompassing \( r \leq 1,850 \text{ km} \). The modelled OLR is averaged over the 6 hr window whereas the observed OLR is a snapshot. A region of high OLR, located north (poleward) west of the TC centre, occurs in more than 50% of the modelled TCs (Figure 7b). The mean dipole position is at 1,046 km radius at an angle of 12° anticlockwise from due east (Figure S3). The mean dipole magnitude is 105 W·m\(^{-2}\). The model average positions are similar to those inferred from the OLR observations (Figure 2). The model average dipole magnitude is lower compared to observations (124 W·m\(^{-2}\)). This could be due to different calculations of OLR. The satellite observations are instantaneous and black-body total fluxes inferred from a relatively narrow band, whereas the ECMWF model OLR is a broadband calculation and averaged over 6 hr.

The model composite wind (Figure 8) is very similar to that found in the ERA-5 dataset (Figure 4) for all levels. The only difference of note is a small region of divergence in the model 500 hPa flow to the northwest of the cyclone at \( 500 < r < 1,000 \text{ km} \).

The large number of model cyclones within the EPS gives us an opportunity to investigate the role of cyclone translation direction. This is interesting as the boundary-layer vortex–environment interaction may dictate the dipole geometry, and the dynamics governing cyclone motion predominantly occur within the mid- and lower troposphere (for steering flow: Brand et al., 1981; Chan, 2005, for the beta gyres: Fiorino and Elsberry, 1989; Li and Wang, 1994; Carr et al., 1997; Wang et al., 1997).

There is a relationship between the dipole position and the cyclone motion. Figure 9 shows the average OLR when eastward propagating TCs are extracted from the model (4,500 TCs, where translation angle \(|\theta| < 60^\circ\) anticlockwise from due east). The extraction of westward propagating TCs is not shown as the patterns in flow, divergence and OLR at all levels do not significantly deviate from those found in the composite of all TCs (Figures 7, 8 and S3).
Eastward propagating TCs are embedded in westerly steering winds at mid-levels (Chan, 2005). The mean latitudes for the westward and eastward propagating composites are 17° and 25° respectively. As the cyclones move from westward to eastward propagation the location of the OLR dipole moves from poleward to westward (Figure 9). The mean angle to the dipole centre rotates from 113° to 171° from due east. According to t-tests of the distributions of dipole angle for westward vs. eastward propagation the relationship is significant (p < .001). Average dipole magnitude and radius remain unchanged between the two groups (Figure S3). The location of boundary-layer divergence and upper-level convergence aligns with this rotation. The spatial correlation coefficients between divergence and OLR fields for westward propagation are $R = 0.8$ (boundary layer) and $R = -0.9$ (upper level), p < .01 for both. For eastward propagation $R = 0.6$ (boundary layer) and $R = -0.74$ (upper level), p < .01 for both.

At low levels, in the eastward case, (Figure 10c) inflow originates from both the south and north. It is the inflow from the north that diverges strongly to the west of the cyclone. Convergence extends to the northeast of the cyclone from the interaction between southerly and easterly winds. At 500 hPa (Figure 10b) the cyclone is embedded in strong westerly flows. The westerlies deflect past the cyclone on the equatorward side where they interact with easterly winds. This interaction forms an anticyclone southwest of the cyclone centre. The convergence in the northeast, seen at low levels, persists to 500 hPa. The eastward propagating flow field at 200 hPa is dominated by strong westerlies (Figure 10a). Intense convergence occurs at large radii to the west and north of the TC centre. Outflow from the cyclone is oriented northeast where a strong, focused region of divergence is present ($r < 1,000$ km). The southern side of the TC at 200 hPa is primarily divergent where originally westerly winds recurve anticyclonically over a large region and move away towards the Equator. These patterns of flow, particularly those found in the mid- and upper levels, and the subsequent rotation of the dipole location, are to be expected of cyclones post-recurvature.

### 3.3 Relationship between the OLR anomaly and track

In this section we explore if those models that capture the OLR feature also have a lower forecast track error. This would confirm the vortex–environmental flow interactions diagnosed above. With the rationale detailed by Leslie et al. (1998) and Emanuel and Zhang (2016) we employ the “perfect model” approach to test the importance of the interaction seen. Under this “perfect model” regime our target TC is a perfect realisation of a tropical cyclone and the baseline ensemble mean is a perfectly constructed EPS forecast. A reduction in track forecast error represents a measure of the importance of the OLR fields.

An easy and effective way to test the ECMWF EPS forecast is to simply apply sub-ensemble selection algorithms to the entire $3,750 \times 3,750$ km square OLR fields centred upon the TC $P_{\text{min}}$. Extracting a 12 member k-nn sub-ensemble yields a significant reduction in track forecast error for all lead times (p < .01), where a 7 km
reduction in error is found at 24 hr (Figure 11). We decompose this whole OLR field into different regions to construct sub-ensembles. This has no operational benefit but allows us to understand the relative importance of the high OLR region, the inner \((r \leq 500 \text{ km})\) OLR field and the outer \((r \geq 500 \text{ km})\) OLR field. We use the error reduction found at 24 hr lead time as a simple metric for comparison between these regions.

In one algorithm, designed to extract the high OLR region, the upper 40 percentile of OLR values in the target TC are identified and clustered into contiguous groups (density-based spatial clustering of applications with noise (DBSCAN)). The most expansive group defines the high OLR region. Once the high OLR region is identified in the target TC OLR field, the \(k\)-nn algorithm extracts the sub-ensemble from the EPS based upon the OLR signal occupying the same region within each EPS member. This technique makes a 6.2 km reduction in track forecast error at 24 hr lead time (not shown). When testing the skill dependency upon \(a\) (where \(a\) = the upper percentile of the OLR field data) we found that \(a\) values within \(20 \leq a \leq 40\%\) reduce errors by 5.8–6.2 km at 24 hr lead time. These results demonstrate that this high OLR region provides much of the signal of the vortex–environmental flow interaction that is found in the whole OLR field.

To compare the skill found for the outer high OLR to the inner low OLR signal we cluster based upon circular OLR fields encompassing a radius \(r \leq 500 \text{ km} \) centred upon the TC \(P_{\text{min}}\). OLR fields here are then exclusively within the TC circulation. In this case, error reductions under-perform those found for the outer high OLR region where track forecast error is 4 km at 24 hr lead time \((p < .01)\). This inner region of the OLR flux therefore serves as a weaker proxy for the TC dynamics governing track than the high outer OLR region.

We tested an algorithm clustering an outer OLR field annulus for a range of annulus central radii \(r_c\) (where \(500 < r_c < 1,500 \text{ km}\)) and widths \(w\) (where \(300 < w < 900 \text{ km}\)). This tests the hypothesis that all regions of the outer OLR field are strongly associated with the vortex–environmental interaction. The vast majority of annulus configurations and sub-ensemble sizes under-performed, producing smaller error reductions in track forecasts, compared to those found by clustering based upon the high OLR signal. The reduction in track error was highly dependent on annulus size and radius.

**Figure 8** The composite outer flow fields at (a) 200 hPa, (b) 500 hPa, and (c) surface, across all TCs in the ECMWF dataset. Streamlines of the velocity field are overlain on divergence plots. Line thickness is directly proportional to velocity. All \(x\)-\(y\) units are in km from cyclone centre.

**Figure 9** The composite OLR field \(\text{W} \cdot \text{m}^{-2}\) for eastward propagating TCs in the dataset. Propagation direction is defined as the angle between the 24 hr average motion vector and due east. For eastward cyclones \(|\theta| \leq 60^\circ\). The average motion vector is plotted in red. All \(x\)-\(y\) units are in km from cyclone centre.
The best annulus configuration clustered the OLR field data within $650 < r < 1,450$ km with a $k$-nn algorithm where $k = 15$; however, this provides no additional benefit to clustering based upon the high OLR region alone.

### 4 DISCUSSION

We identify a dipole of outgoing long-wave radiation and water vapour associated with tropical cyclones. This robust OLR dipole has a typical magnitude of 230 W m$^{-2}$ and is located 1,200 km poleward and westward of the TC centre. The region of anomalous high OLR is robust and appears not to have been reported previously. Regions of high OLR are visible in the dataset used by Zehr and Knaff (2007) at the periphery of OLR fields; however, no composite of TCs was taken and the feature is not identified; instead only low OLR regions are analysed. The apparent dry “black hole” in water vapour channels and high OLR is visible in the work by Rodgers et al. (1991); however, the link between its location and low/upper level divergence/convergence is not established. Velden et al. (1997; 1998) present much larger satellite images of cyclones than those presented here; however, there is no mention of this dipole structure. Knaff et al. (2014) presented composite average OLR fields of TCs; however, their data encompasses a radius $r \leq 600$ km and therefore the dipole cannot be identified.

There is a strong spatial correlation between average OLR and low/upper-level divergence fields. The low/upper-level wind is divergent/convergent in the highest OLR and driest region. This correlation demonstrates that the wind field is closely linked to the OLR field such that low/upper-level divergent/convergent winds accommodate subsiding dry air and suppress convection. The mechanism relating the OLR signal to the outer wind field is illustrated in Figure 12. The cross-sections present a clear asymmetry in the outer circulation (Figure 5) and are similar to the radial dropsonde wind presented by Frank (1977). At large radii, inflow and ascent are only
FIGURE 12  A schematic of the mechanism responsible for the OLR dipole (hollow arrows). The surface and upper-level streamlines (solid arrows) are overlain on divergence (red) and convergence (blue). The radial and vertical wind components (azimuthally averaged across each quadrant, as in Figure 5) are in dashed arrows. Both upper and lower layers are split into quadrants defined by the major compass axes with an \( r = 500 \text{ km} \) ring (solid) around the TC centre where the eye is drawn (solid).

found to the southwest, southeast and northeastern quadrants. In the northwest quadrant at large radii (\( r > 500 \text{ km} \)) air moves away from the centre and joins the steering flow throughout the entire column. Outflow subsides at \( r > 700 \text{ km} \) and inhibits convection in all layers (Figures 5a and 6). Whilst the flow in the northwest is cyclonic, the secondary circulation in this quadrant at large scale is not directly connected to the core. Subsidence occurs as wind moves away from the cyclone. However, this subsiding air curves cyclonically in the boundary layer and can then rejoin the TC from the southwest. Prevailing easterlies are driven by the background large-scale meridional surface pressure gradient. However, downstream and closer to the vortex the cyclone radial pressure gradient competes with this meridional surface pressure gradient which creates divergence. Aloft, the sign of the background environmental pressure gradient and the radial pressure gradient are reversed compared to the surface. The upper-level anticyclonic outflow converges with prevailing westerlies in the northwest. Divergence and convergence facilitate subsidence throughout the column. The vertical column in the northwest is net divergent confirming the prominent role of the boundary-layer divergence in that quadrant and the OLR feature.

We know from both idealised models and observations that the secondary circulation includes an upper tropospheric outflow with one or two jets, extends past 1,000 km and is asymmetric at these distances (Black and Anthes, 1971; Willoughby, 1979; Holland and Merrill, 1984). Most of the research into secondary circulation is focused on the relationship between the TC outflow jet, the environment and intensity changes (Molinari and Vollaro, 1989; Rodgers et al., 1991; Hanley et al., 2001; Komaromi and Doyle, 2018; Ryglicki et al., 2019). Outflow jet orientation has been attributed to dynamic cyclone characteristics and interactions with environmental winds, particularly the midlatitude westerlies (Black and Anthes, 1971; Holland and Merrill, 1984; Merrill, 1988; Ditche et al., 2017). Holland and Merrill (1984) and Merrill (1984) present statistical analyses identifying a poleward preference for the TC outflow jet. The 200 hPa outflow jet streamlines (Figure 4a) are analogous to those found previously. Here we have shown how this creates a large-scale asymmetric circulation. Shi et al. (1990) presents subsidence of the secondary circulation in idealised model particle trajectories that descend \( \approx 1,000 \text{ km} \) west of the cyclone; however, this is not explained further and there is no reference to the corresponding boundary-layer role we have identified here. Critically, cyclones in their study are initialised with zero environmental flow, and therefore miss the vortex environmental interaction we identify. In another idealised study, also without environmental flow, Corsaro and Toumi (2017) demonstrated subsiding and dry air to the west of the TC. They proposed that some of the dry air from the outflow eventually penetrates the core as a self-weakening mechanism of the TC. Analysis of humidity data shows that the northwest dry anomaly is also stronger during rapid weakening in the North Atlantic, northeast Pacific (Wood and Ritchie, 2015) and northwest Pacific (Ma et al., 2019). The authors do not explain the location or origin of the dry anomaly. Frank (1977) shows asymmetries in dropsonde radial wind profiles; however, divergence and vertical velocity fields were not decomposed by quadrant to reveal the asymmetries presented here. The composites presented by Vincent and Fink (2001) show subsidence poleward and west of the TC centre; however, this region is not analysed and the work is focused on vertical ascent in the TC environment. Our results indicate that there is a strong north (poleward) west preference to the subsidence of the outer secondary circulation (Figures 5 and 12). Whether this region, created by the boundary-layer vortex–environment interaction, aligns with the subsidence of the outflow jet is determined by the outflow jet orientation. The cross-section (Figure 5a) indicates that this region aligns with subsidence in the secondary circulation at all levels.

In the model, the high OLR region depends on the direction of TC propagation. Westward propagating TCs,
embedded in low-level easterly flows, produce a large region of divergence as this wind interacts with the TC to the northwest of the TC centre (Figure 10e). Eastward propagating TCs produce divergence in low-level northerly winds to the west of the TC centre (Figure 10f). Both these divergent regions correspond to convergence aloft.

The differing environmental flow fields lead to changes in the outer cyclonic circulation and create different orientations of the OLR dipole. We therefore attribute the skill improvement in TC track forecasts to the ability of the OLR field to capture the vortex–environmental flow interaction. Tests that decompose the whole OLR field into different regions reveal that slightly larger error reductions (≈6.2 km) are found when the OLR fields solely encompass the large high OLR region versus the inner (r < 500 km) TC OLR signal (24 hr position error ≈4.5 km, significance between these two error distributions is p < .01). Clustering extracts models with similar background environmental flows. We found that the skill for large annulus geometries is similar to the skill for the high OLR region. Given the high OLR region always resides somewhere within a large annulus geometry, this result implies that there is no additional signal, beyond the region of high OLR, that is available in the outer OLR field that provides a strong proxy of the dynamics governing TC track.

Could the OLR field be used to produce a near real-time improved track forecast in between traditional assimilation windows? The error reductions demonstrate the maximum potential benefit available to a forecaster when utilising a sub-ensemble formed just by the OLR field. The ECMWF EPS models run at a 4 min temporal resolution, therefore sub-ensembles could be formed at the temporal resolution of satellite OLR observations, every 15 min. Whilst the target TC develops, erroneous ensemble members can be identified and excluded based on the discrepancy between the member’s forecasted TC position and the observed target TC position. Identifying members that are either: within a certain distance of the target TC (Qi et al., 2014); or the n most proximal members (Dong and Zhang, 2016), have yielded an improvement in track forecast skill of 30 and 18% at 24 hr lead time respectively. These methods, whilst skilful, require a TC position update (typically every 3 hr) whereas providing a sub-ensemble forecast based upon OLR fields could be accomplished every 15 min. When the method used by Dong and Zhang (2016) is applied in our “perfect model” EPS, a reduction in track forecast error of 8 km at 24 hr lead time is found. An analysis of track forecast errors, from 1990 to 2019, at 24 hr lead time showed an error reduction from 169 to 56 km over this time period (Cangialosi, 2020). The potential error reductions presented here (7 km), through a frequent sub-ensemble based upon OLR, would be equivalent to a 2-year advance in the error reduction of the 24 hr forecast.

5 CONCLUSIONS

The large-scale observed and model tropical cyclone OLR and water vapour fields have been examined. A clear dipole of high/low OLR and dry/moist water vapour has been identified and it has been shown that the dipole geometry is closely related to the divergence field. The high OLR and dry region occupies an area of low/upper level divergence/convergence to the west or north (poleward) west of the TC at large distances (500–1,500 km). This facilitates subsidence across the entire vertical column, suppressing convection, drying and thus enhancing OLR. This large, preferred region of subsidence and radially outward motion indicates that the TC outer circulation typically extends to 2,000 km, is asymmetric at these large distances and this asymmetry is governed by the vortex–environmental wind interaction in the boundary layer and aloft. Understanding and identifying this OLR dipole can provide a good proxy for the vortex–environment interaction. To demonstrate the significance of this structure we have shown that track forecasting can be improved when sub-ensembles are selected based upon the high OLR region.

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How to cite this article: Smith M, Toumi R. A dipole of tropical cyclone outgoing long-wave radiation. Q J R Meteorol Soc. 2021;147:166–180. https://doi.org/10.1002/qj.3912