

## Along-shore variations of offshore flow

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[1] Using eddy correlation data collected by the LongEZ research aircraft, the adjustment of atmospheric flow downstream from a coastline is examined. Along-shore variation of the turbulence over the water is generated by the varying width of the upstream land strip between the sea and inland water. Over the coastal zone, the turbulence is strongest downstream from the widest part of land. The along-shore variation of the turbulence decreases with increasing sea fetch due to horizontal mixing. In other terms, the footprint of the flux farther offshore includes a larger width of upstream land. Beyond 5 km sea fetch, the along-shore variation becomes small. *INDEX TERMS*: 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3379 Meteorology and Atmospheric Dynamics: Turbulence. **Citation**: Moore, E., and L. Mahrt, Along-shore variations of offshore flow, *Geophys. Res. Lett.*, 30(3), 1109, doi:10.1029/2002GL016240, 2003.

### 1. Introduction

[2] Boundary-layer adjustment in offshore flow may vary along the coast due to heterogeneity of the upstream land surface. *Winstead and Mourad* [2000] and *Winstead and Young* [2000] used synthetic aperture radar (SAR) imagery to show a connection between upstream variations of land surface and signatures over the water in offshore flow. In the present study, aircraft data are used to examine a similar connection between the width of land between inland water and the sea (Figure 1) and the turbulence measured downstream over the sea. Flow from the inland water over the land leads to development of a convective internal boundary layer due to heating over the warmer land surface and due to greater roughness over the land compared to the upstream water. The convective boundary-layer is expected to be deeper and more turbulent where the land is wider. The 1–5 km variation of land width is thought to influence the flow more strongly than the modest along-shore variations of the land roughness and surface heating although quantitative assessment from the data is not possible.

### 2. Data

[3] This study analyzes data taken on and off the coast of the Outer Banks, North Carolina, USA. The Outer Banks is a narrow strip of land between the Abermarle Sound and the Atlantic Ocean (Figure 1). The Outer Banks ranges from

about 1 to 5 km in width in the region of the aircraft flights. The Shoaling Wave Experiment (SHOWEX) took place during 26 October–12 November 1997, 2–18 March 1999, and 11 November–5 December 1999. The LongEZ (N3R) aircraft is equipped with a Best Aircraft Turbulence (BAT) probe, which measures the mean and turbulent wind fields. These data were collected at 50 samples per second, at approximately 55 ms<sup>-1</sup> airspeed, which corresponds to a sample interval of about 1 m.

[4] Further description of the flights and data can be found in *Crescenti et al.* [1999], *French et al.* [2000] and *Sun et al.* [2001]. This study focusses on repeated flight tracks parallel to the coast at varying heights above the surface and distances from shore. We emphasize 4 Dec. 1999, which included the most extensive spatial coverage near the surface in offshore flow over the coastal zone. On this day, parallel flight tracks were flown at 1, 2, 4, 8, and 16 km offshore.

[5] The lowest flight levels were approximately 10 m above the sea surface, the highest were about 300 m. Flights parallel to the shore are used in an attempt to ensure an approximately constant sea fetch. However, small variations in sea fetch can be important for flight tracks closest to the coast, which probably contributes to the scatter in relationships examined in the next section. Data are selected with wind directions of 190–310 degrees to ensure offshore flow.

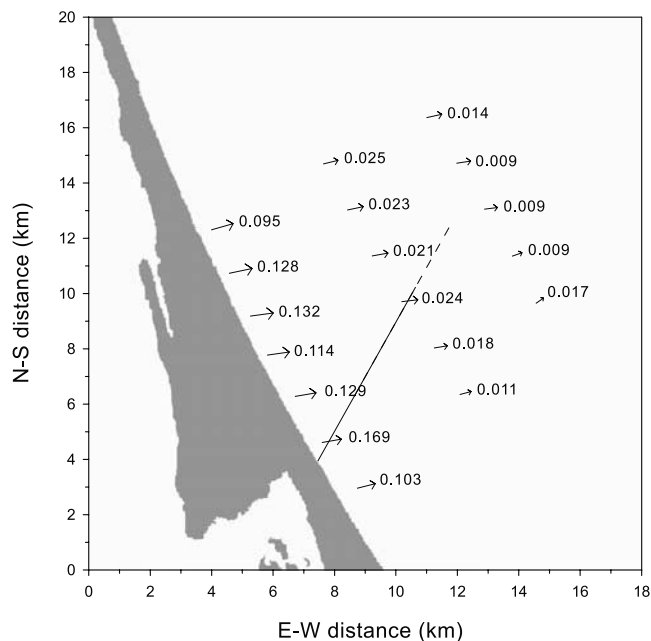
[6] To examine the influence of advection of turbulence from land on the structure of the offshore flow, the data are separated into classes of near shore (less than 2 km sea fetch), mid-distance (2–5 km sea fetch) and far shore (5–16 km sea fetch). To estimate the vertical structure of the flow, the data are also separated into low-level (<30 m), mid-level (30 m < z < 250 m) and high-level (>250 m) classes. To examine the along-shore variation, the flight tracks parallel to the shore are segmented into 2 km sections. These procedures partition the atmospheric boundary layer in the coastal zone into cubes. All of the turbulence quantities amongst the different aircraft passes, which fall into a given cube for a given flight, are aggregated into one value in order to reduce flux sampling errors. Even with such averaging, random sampling errors for turbulence quantities are estimated to remain significant. For 4 Dec. 1999, this aggregation includes 4 passes for each of the low-level cubes.

[7] The friction velocity at any level is computed as

$$u_* = \left( (\overline{w'u'})^2 + (\overline{w'v'})^2 \right)^{0.25} \quad (1)$$

and the drag coefficient is defined as

$$c_D = \frac{u_*^2}{U^2} \quad (2)$$



**Figure 1.** The spatial distribution of the vertical velocity variance,  $w'w'$ , and wind vectors over the coastal zone for flight levels below 30 m. The sketched line depicts the northward shift of the maximum vertical velocity variance with increasing offshore distance.

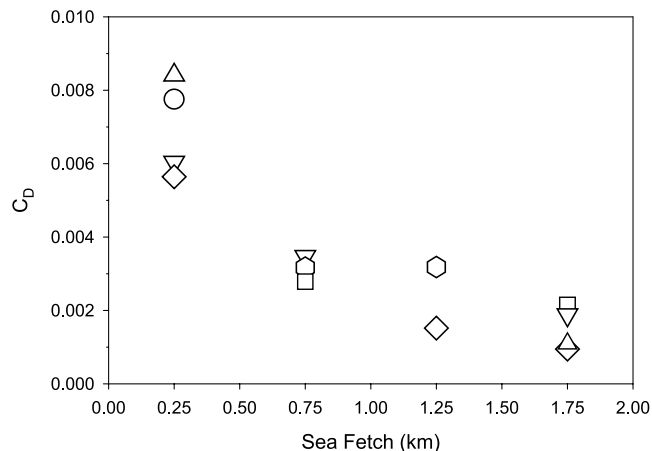
where primes denote fluctuations from an unweighted 1-km mean, overbars symbolize 2-km averages, and  $U$  is the wind speed computed from averaged wind components. The 1-km average is chosen to reduce contamination of the perturbation flow by mesoscale motions while the 2-km average of the flux is chosen to reduce flux sampling errors. For aircraft levels above the surface layer, the drag coefficient,  $c_D$ , would not satisfy Monin-Obukhov similarity theory.

### 3. Along-Shore Spatial Variations of Offshore Flow

[8] The drag coefficient and other turbulence quantities decrease rapidly with offshore distance (sea fetch) due to the decreasing roughness and formation of stable stratification (Figure 2), as examined in *Vickers et al.* [2001] and *Sun et al.* [2001]. The scatter is partly due to different atmospheric stability and different upstream land fetch. The turbulence decreases faster downstream from the coast in stable conditions (warm air over cold water) due to buoyancy destruction of the turbulence.

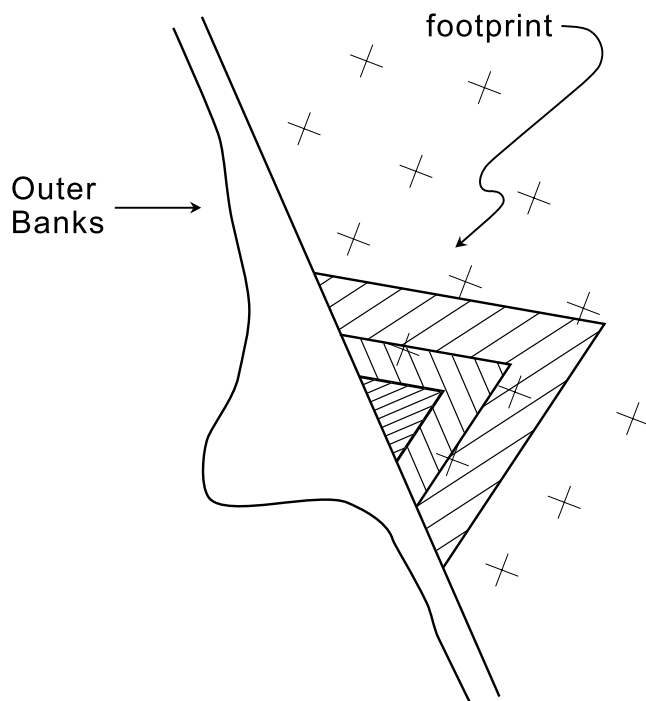
[9] Close to shore, the vertical velocity variance for the low-level flights is substantially larger downstream from wider land width (Figure 1). A secondary maximum of vertical velocity variance occurs farther north perhaps due to a small forest over the upstream land.

[10] Farther offshore from the widest part of the land, the footprint of the flux begins to include more of the narrower southerly land region. This causes the location of maximum vertical velocity variance to shift farther north, as shown by the sketched line in Figure 1. This process is schematically depicted in Figure 3, where the upstream footprint of the flux incorporates a larger north-south segment of the coast with increasing offshore distance. The footprint spatially



**Figure 2.**  $c_D$  as a function of sea fetch,  $z < 30$  m, sea fetch  $< 2$  km, for 6 study days. Flight dates with  $(z/L)$  values in parentheses are: square = 4 March 1999 ( $-0.077$ ); upside down triangle = 16 March 1999 ( $0.107$ ); triangle = 18 March 1999 ( $0.289$ );  $\circ$  = 2 Nov. 1997 ( $0.001$ ); pentagons = 9 Nov. 1997 ( $-0.151$ );  $\diamond$  = 4 Dec. 1999 ( $0.053$ ).

integrates the land influence so as to not show a sharp maximum farther offshore. Numerical application of footprint theory (e.g., *Horst and Weil*, 1994) is not attempted since the flow is in a state of rapid adjustment induced by the discontinuity in surface conditions. The along-shore variation fades with further increase of sea fetch and the north-south maximum of the vertical velocity variance for flight tracks greater than 5 km offshore becomes ambiguous (Figure 2). At higher flight levels, along-shore variation of the turbulence offshore is also evident, but the data sample is smaller than that for the low-level data. A similar pattern



**Figure 3.** Schematic of the land footprint captured in the flux measurements for different distances offshore.

occurred on other flight days but was noisier, probably due to the smaller sample of turbulence data at a given point.

#### 4. Conclusions

[11] The variable width of the upstream land, separating the open ocean from inland water, induces along-shore variation of the sea-surface stress with offshore flow, particularly in the first few kilometers offshore. The influence of spatial variations of heat flux and surface roughness over the land could not be quantitatively assessed. Future examination of offshore flow structure should include more days to examine different boundary-layer situations and a larger number of passes over a given point in order to accumulate a larger sample size for resolving the spatial variation of the turbulence quantities.

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