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Evidence for roll vortices associated with a land breeze

by Wayne V. Burt, Henry Crew and Stephen L. Poole

ABSTRACT

Time series measurements from an array of meteorological buoys off the Oregon coast displayed periodicities that suggest the presence of atmospheric roll vortices. The roll vortices were associated with nocturnal land breezes, cool air masses moving slowly seaward through the buoy array under the prevailing longshore wind of marine air. It appears that buoyancy and shear are the mechanisms responsible for the observed rolls.

1. Introduction

Horizontal roll vortices are helical movements of air that occur in the planetary boundary layer (PBL) of the atmosphere during neutral or slightly unstable conditions with moderately strong winds. The presence of roll vortices may be indicated by cloud streets above the surface convergence zones between adjacent counter-rotating rolls. Satellite photographs and other observations reveal that cloud streets typically have a spacing of 2 to 8 km, which is two to four times their height (roughly the height of the PBL), a length of 20 to 500 km, and are aligned approximately with the mean surface wind (Kuettner, 1971). Over the ocean these cloud streets are generally associated with air significantly colder than the underlying water (Malkus, 1958; Malkus and Riehl, 1964; Asai, 1964, 1966; Matsumoto and Ninomiya, 1965, 1966; Tsuchiya and Fujita, 1967).

Roll vortices are not necessarily accompanied by cloud streets, however; Woodcock (1941) deduced the presence of horizontal rolls over a warm sea from the soaring of seagulls. From balloon trajectory studies over land (Angell, et al., 1968) and aircraft and meteorological tower data (LeMone, 1973) it has been found that rolls migrate transverse to the mean surface wind at about 1 m/sec.

Theoretical studies indicate rolls may arise from Ekman layer instability in a homogeneous fluid (Gregory, et al., 1955; Faller and Kaylor, 1966; Lilly, 1966; Brown, 1970) and gravitational instability in unstable stratified shear flow (Kuo, 1963; Ingersoll, 1966; Asai, 1970).

Undoubtedly rolls play an important part in distributing heat and moisture in the PBL.

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2. Measurements and synoptic conditions

Time series records on magnetic tape were obtained with Aanderaa instruments\(^2\) from the array of stations off the central Oregon coast shown in Figure 1. The station records consist of measurements at 1.25 minute intervals of wind speed and direction, air temperature and, except at the land-based station, sea temperature. The offshore stations were moored toroid buoys with meteorological sensors on a mast at a height of 5 m and the sea temperature sensor at a depth of 0.5 m. The station array was situated off a relatively straight north-south coastline over a continental shelf sloping gently to the west. The coastline consists of bluffs about 30 m high which are cut by streams which form shallow valleys. Inland, the coastal range mountains extend a distance of approximately 60 km to the Willamette Valley.

During the measurement period, 1330 PST April 19 to 1120 PST April 21, 1973, generally clear skies prevailed and the predominant wind recorded was from the north at about 10 m/sec. This synoptic situation, dominated by an intense North Pacific High off the coast, is typical of summer conditions in this area. Preceding the measurement period conditions were typical of winter with flow around the Aleutian Low reaching the Oregon coast from the southwest. As winter conditions generally continue during April, May and June (Bouike et. al., 1971), the land breezes and accompanying roll vortices occurring during the measurement period may be unseasonable, arising from a typical summer type weather being imposed on winter land and sea temperatures. It is unlikely that roll vortices would occur regularly off the west coast of continents in mid latitudes in summer because of the presence of cold upwelled water near shore. On the other hand, it is more likely that they would occur off the east coasts of continents whenever the proper air and water temperatures occurred.

Time series records at the stations of wind speed, eastward \((u)\) and northward \((v)\) velocity components, and air temperature are shown in Figure 2. As seen from

\(^2\) These instruments are made by Ivar Aanderaa of Bergen, Norway.

\[\text{Figure 1. Station Array.}\]
Figure 2. Time Series Records at the Stations of:

(A) Wind speed;
(B) u-component of wind velocity;
(C) v-component of wind velocity;
(D) Air temperature at 5 m height.
these records there are two intervals, from about 2200 to 0800 PST on the 19th - 20th and 20th - 21st, during which a land breeze was present. That is, during these intervals some of the stations recorded an offshore (negative $u$-component) breeze. The land breeze arrived as a front of cold air around 2200 PST at the shore station (S1) and progressed seaward arriving at the furthest offshore station (S5) between 0500 and 0600 PST the following day. As well as lower temperature, the land breeze is associated with a decrease in the prevailing southward wind. The decrease is probably a consequence of the relatively calm land air mass underriding the sea air mass which is flowing south under geostrophic influence. The sea temperatures are almost identical at the buoy stations and with only a couple of exceptions (believed to be instrument malfunctions) the water temperature at 0.5 m depth is at least a degree warmer than the air at 5 m.

A detailed analysis of the land breeze during the measurement period has been given by Poole (1974). In this paper we focus on periodic variations which occurred on the records during the early morning hours of April 20th and 21st.

3. Analytical treatment

Time series of the $u$ and $v$ wind velocity components at 1.25 minute intervals were block-averaged to form 10 minute averaged series for each station. These averaged series were then employed to form time series of divergence in the triangles formed by the array of stations (see Figure 1). To compute divergence, wind velocities at a pair of stations forming two vertices of a triangle were vectorily averaged; this average velocity is considered the velocity at the midpoint of the side of the triangle between the two stations. Letting $V_{n_i}$ be the component of this midpoint velocity
normal to triangle side \( i \), where \( V_{ni} \) is positive for flow out from the triangle, the net divergence within the triangle is computed as

\[
\frac{1}{A} \sum_{i=1}^{3} V_{ni} L_i,
\]

where \( A \) is the area of the triangle and \( L_i \) are the lengths of the sides.

Time series plots of divergence for triangle \( A \) exhibit an interesting feature. During 0300 to 0500 PST on April 20, which we shall designate interval I, and 0015 to 0415 PST on April 21, designated interval II, there are a set of alternating relatively
uniform peaks of divergence and convergence. Inspection of velocity time series reveal what appears to be simultaneous oscillations in the wind velocity u-components at stations S5 and S3 having approximately the same period, between 30 and 40 minutes. Data on divergence-convergence for triangle A and the u-component (cross wind) for station 3 during interval II are shown on Figure 3. None of the other station velocities exhibited oscillations. Spectra of the divergence of triangle A and the velocity u-components of stations S3 and S5 during the oscillation intervals, as well as the cross correlation and coherency between the divergence and u-components, are shown in Figure 4.

4. Interpretation

During interval I the divergence spectrum of triangle A and the u-component spectrum of station S5 have major peaks around 1.6 cph, and the coherency of these two series also peaks at this frequency. Significant oscillations of 40 minute period (frequency 1.6 cph), therefore, exist in both series. Furthermore, since the cross correlation between the series is strongly negative at zero lag, when triangle A is experiencing negative divergence (convergence) the u-component at S5 tends to be more positive (eastward), and the reverse. While the u-component spectrum of station S3 does not exhibit a peak at 1.6 cph, there is high coherency at this frequency between this series and divergence in triangle A. And since the cross correlation between these two series has a positive peak at zero lag, the u-component winds at S3 and S5 tend to be out of phase. These results suggest that when the air in triangle A is convergent the wind at S5 tends to be more eastward and that at S3 more westward, while when there is divergence in triangle A one-half period (20 minutes) later the wind tendencies are reversed.

The results for interval II are similar and corroborate the interpretation given for interval I. In interval II the u-component spectrum of S3, as well as that of S5 and the divergence spectrum of triangle A, exhibit strong peaks around 1.6 cph. Again at zero lag the cross correlation with triangle A divergence is strongly negative for the u-component velocity of S5 and strongly positive for that of S3, and the coherencies between these u-component velocities and divergence are high at 1.6 cph.

The preceding findings can be interpreted in terms of simple horizontal roll models. In Figure 5A we consider horizontal roll vortices alligned parallel to the prevailing northerly wind and having a width, 7 km, equal to the separation between stations S5 and S3. When roll axes are situated above the two stations the convergence (or divergence) of triangle A is a maximum and the signs of the u-components of velocities at the stations is in agreement with the results of the previous time series analysis. In order to account for the observed 40-minute periodicity in divergence and velocity u-components, however, the rolls in this model must migrate normal to their axes at a speed of about 6 m/sec. This speed is considerably greater than the 1 m/sec migration speed found by Angell et. al. (1968) and LeMone (1973). Also, the width of the rolls in this model is somewhat large; Kuettner (1971) reported the
distance between adjacent convective zones (i.e., cloud street spacing) is typically 2 to 8 km, while in this model the distance is 14 km.

A model in agreement with previous investigations of atmospheric roll vortices and with time series analysis of the data presented here is shown in Fig. 5B. In this model there are three roll widths between stations S5 and S3; the distance between adjacent convective zones, 4.7 km, is therefore in agreement with the observations of Kuettner (1971). With the rolls situated as shown in Figure 5B there are two convergence zones and one divergent zone within the triangle. Thus there is net convergence within the triangle. The signs of the velocity $u$-components at stations S5 and S3 are in agreement with the results of the time series analysis. When the rolls shown in Figure 5B migrate normal to their axes a distance equal to a roll width, the signs of the velocity $u$-components at S5 and S3 reverse and air within the triangle becomes divergent; again the signs of the velocity $u$-components are in agreement with the time series results. To account for 40-minute periodicity, the rolls must migrate normal to their axes (and the prevailing wind) at a speed of 2 m/sec; this is higher than the 1 m/sec migration speed observed over land, but as the ocean surface may present less drag it is reasonable.

5. Discussion

The first direct quantitative measurements of the wind field over the ocean that indicates the possible presence of horizontal roll vortices as part of a land breeze regime are discussed.

The presence of relatively cool air flowing off the land over warmer water and underriding the long shore breeze suggest that buoyancy and shear may have played important parts in the formation of rolls during the land breeze intervals.

Acknowledgements. We wish to thank Dr. Clayton Paulson, Mr. Lyle Ochs and Mr. Asa Robinson for their suggestions and assistance during the course of this research.

This research was supported by the Global Atmospheric Research Program of the National Science Foundation under Grant GA-28004.
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Received: 29 October, 1974; revised: 3 January, 1975.