Comments "On the Rotation Rate of the Direction of Sea and Land Breezes"

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10 May 1978 and 12 October 1978

Neumann (1977) has noted that, although the Coriolis parameter makes the most important contribution to turning of the sea and land breezes (SLB), and accounts for the usual clockwise turning, terms involving the pressure-gradient force make significant modifications that result in nonuniform turning of the wind.

Our purpose here is to call attention to the significant contribution of friction, which Neumann has formulated in such a way that it contributes nothing explicitly to his Eq. (13) for $\partial\alpha/\partial t$, where α is wind direction:

$$\frac{\partial\alpha}{\partial t}=-f+\frac{1}{V^2}\left[\frac{v}{\rho}\frac{\partial P_m}{\partial x}+f(uu_g+vv_g)\right]. \qquad (1)$$

Here f is the Coriolis parameter, $V^2=u^2+v^2$, $-\rho^{-1}\partial P_m/\partial x$ is the mesoscale pressure gradient force, and u_g and v_g are the geostrophic winds associated with the large-scale pressure gradients $\partial P_L/\partial x$, $\partial P_L/\partial y$. Through the equations of motion, friction, of course, may

0022-4928/79/020369-03$04.75

influence the values of u and v that appear in (1), but friction should also appear explicitly when this equation is accurately formulated.

To show the importance of friction, we show first that the form used by Neumann is a rather special, unlikely case and second, we examine the turning equation in more detail and call attention to model results that show the effect of stability variations on vertical eddy momentum transport and wind direction.

If the x axis is aligned with the geostrophic wind, then u will normally increase monotonically upward within the planetary boundary layer (PBL) and the stress $-\rho\overline{u'w'}$ decrease monotonically upward throughout the PBL. Thus,

$$F_x=\hat{\mathbf{i}}\cdot(\rho^{-1}\partial\boldsymbol{\tau}/\partial z)\approx-\hat{\mathbf{i}}\cdot\boldsymbol{\tau}_s/\rho h,$$

where $\boldsymbol{\tau}_s$ is the surface shear stress and h the PBL depth. Now if $\boldsymbol{\tau}_s$ can be expressed by bulk aerodynamic means as $\boldsymbol{\tau}_s=\rho C_D|\mathbf{V}_s|\mathbf{V}_s$, where $\mathbf{V}_s$ is the near-surface wind and C_D the drag coefficient, then $F_x=-C_D\mathbf{V}_s u_s/h$, where F_x is the friction force in the x direction.

If the wind has an Ekman-type turning with height, it is not so easy to justify the same form for F_y as for F_x. The stress $-\rho\overline{v'w'}$ will start out positive in the lower part of the PBL, decrease to zero at some height below h, reach a maximum negative value and then go to zero at h. [To understand this qualitative distribution, determine if upward eddies ($w'>0$) transport an excess or deficit of v momentum.] Hence, $F_y\neq-C_D|\mathbf{V}_s|v_s/h$, the form used by Neumann which causes friction not to appear explicitly in his (13). It would seem that Neumann's formulation of friction requires a well-mixed PBL so far as momentum is concerned, i.e., one in which wind does not turn with height. This is unlikely to be a useful formulation throughout the diurnal cycle of the PBL.

We now point out that Neumann's expression for turning rate which involves differentiation of $\tan^{-1} v/u$ [see Neumann's Eqs. (8), (9)] can be reformulated as

$$\frac{d\alpha}{dt}=\frac{1}{\mathbf{V}\cdot\mathbf{V}}\hat{\mathbf{k}}\cdot\mathbf{V}\times\frac{d\mathbf{V}}{dt}, \qquad (2)$$

where $\mathbf{V}$ is the horizontal wind vector. This expression shows simply that those forces having a component normal to the wind vector contribute to the turning of the wind.

To evaluate the relative importance of friction upon the turning of the wind, we examine a simpler situation than that of the SLB; *viz.*, one in which the mesoscale pressure gradient is zero. Inserting the equation of motion into (2) yields

$$\frac{\partial\alpha}{\partial t}=-f+f\frac{\mathbf{V}\cdot\mathbf{V}_g}{\mathbf{V}\cdot\mathbf{V}}+\frac{\hat{\mathbf{k}}\cdot\mathbf{V}\times\mathbf{F}}{\mathbf{V}\cdot\mathbf{V}}. \qquad (3)$$

Here $\mathbf{V}_g$ is the geostrophic wind vector and $\mathbf{F}$ the frictional force. Following Neumann, we have neglected the advection of α in (3). For purposes of discussion, we further assume that time changes in the geostrophic wind are small. The third term in (3) is the friction term which Neumann found to be zero since his selected form of $\mathbf{F}$ is proportional to $\mathbf{V}$. The ratio appearing in the second term of (3) may be written as

$$\frac{\mathbf{V}\cdot\mathbf{V}_g}{\mathbf{V}\cdot\mathbf{V}}=\frac{|\mathbf{V}_g|\cos\alpha}{|\mathbf{V}|}. \qquad (4)$$

This ratio typically is greater than unity near the surface. Thus, when the near-surface wind direction is steady, all three terms in (3) tend to be important, with the friction term being negative.

Wyngaard (1975) discusses the behavior of the near-surface wind as the boundary layer stabilizes. During this transition, which usually occurs near sunset, the turning angle α generally increases. As Wyngaard (1975) notes, friction tends to cause $|\mathbf{V}|$ to decrease during this period. Thus, the ratio in (4) increases, and the second term in (3) becomes increasingly more positive.[1] The friction term is negative. Therefore, it is an increased excess of the pressure gradient force over the Coriolis force when increased friction reduces the wind speed that accounts for the increase in α as the PBL stabilizes. However, as we now discuss, the term explicitly involving friction is not negligible.

We examined the pressure gradient and friction term in (3) with a second-moment turbulence closure model. The numerical experiment selected is that discussed by Burk (1977) in which the diurnal behavior of the PBL is simulated. Fig. 1 shows the behavior of the near-surface wind through several diurnal cycles. Apparent in these results is the increase in α between 1800 and 2200 LT which is under discussion. As expected, model results do indeed show that the pressure gradient term is dominant during this period. However, the friction term is of the same magnitude as the Coriolis parameter and cannot be neglected.

The decrease in α which appears during late morning and afternoon in Fig. 1 may be interpreted in a similar manner. High-momentum air aloft is mixed close to the surface during this convective period. As a result, the friction term decreases, the wind speeds up, and the excess of the pressure gradient force over the Coriolis force is reduced. The negative Coriolis and friction terms in (3) then dominate, producing the α decrease.

Thus, the fact that our model results indicate that the explicit friction term is important in the turning equation (2) means that taking $\mathbf{F}$ to be proportional to $\mathbf{V}$ is not a good assumption close to the surface. As Tennekes (1973) notes, the wind turns only a little near the surface, while the stress (and, hence $\mathbf{F}$) turns a lot.

Our comments dealing with (3) have been directed

[1] The authors are grateful to Dr. Wyngaard for pointing out this important behavior of the second term in (3) as the PBL stabilizes.

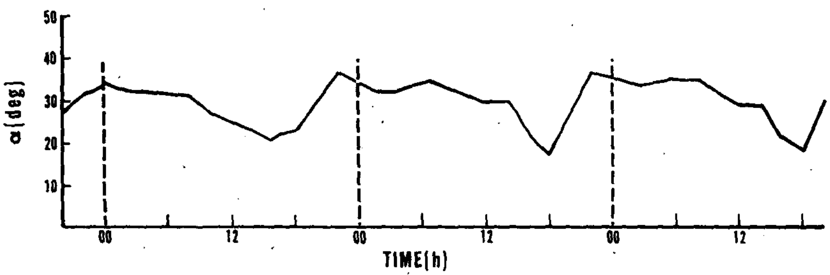

FIG. 1. Angle of surface wind to the geostrophic during first 72 h of integration in numerical experiment discussed by Burk (1977).

toward a simpler situation than the SLB. However, we see little reason to believe that friction will play a less important role in the SLB behavior.

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