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Observed wind and temperature profiles used as basic states in models often contain modification by the secondary flow. The correct basic state however, is the one existing prior to the onset of roll development. A low-order spectral model allows for efficient study of secondary instability and its effects on the initial basic state variables. Using an Ekman wind profile as an idealized case, we show that errors in the initial wind profile can lead to significant errors in the model results, particularly in values of the model however, is to observed boundary layers.

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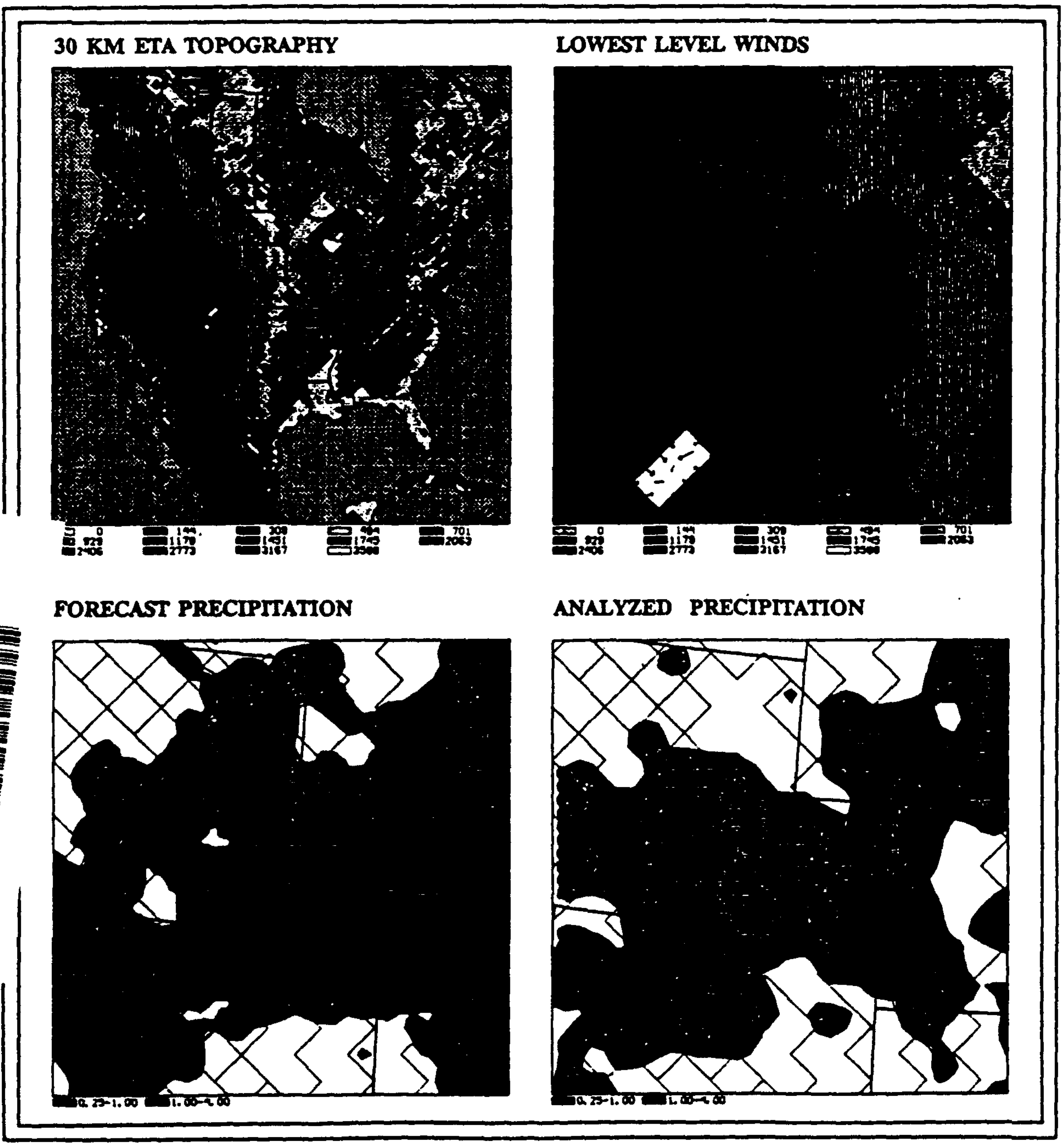






AMERICAN METEOROLOGICAL SOCIETY

# MODIFICATION OF THE EKMAN WIND PROFILE BY ROLL CIRCULATIONS

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## 1. INTRODUCTION

Observed wind and temperature profiles used as basic states in models often contain modifications by the secondary flow. The correct basic state however, is the one existing prior to the onset of roll development. A low-order spectral model allows for efficient study of secondary instability and its effects on the initial basic state variables. Using an Ekman wind profile as an idealized case, we show that errors in the initial wind profile can lead to significant errors in the model results, particularly in values of the preferred roll orientation angle. The ultimate application of the model however, is to observed boundary layers.

## 2. MODEL SUMMARY

A nonlinear 14-coefficient spectral model of thermally and dynamically forced shallow Boussinesq convection is derived using truncated Fourier expansions for the stream function $\psi$ and perturbation temperature T (Haack and Shirer 1991). These expansions are composed of two parts: roll circulation patterns given by $T_r$ and $\psi_r$, and background modification profiles given by $T_b$ and $u_b'=-\partial\psi_b/\partial z$.

The roll patterns are specified by four components in the Fourier expansions that involve a horizontal wavenumber of one and vertical wavenumbers q=1 and n=2 (Haack and Shirer 1991). We also specify four components in the perturbation temperature expansion that represent the background temperature modification:

$$T_b=T_1\sin(q\pi z/z_T)+T_2\sin(n\pi z/z_T) +T_3\sin[(q-n)\pi z/z_T]+T_4\sin[(q+n)\pi z/z_T] \quad (1)$$

and two in the stream function expansion for the background wind modification:

$$u_b'(z)=U_1\cos[(q-n)\pi z/z_T] +U_2\cos[(q+n)\pi z/z_T] \quad (2)$$

The model accepts as input an observed or idealized wind profile, $U_s$ and $V_s$, in standard east/north coordinates that is rotated into a cross-roll wind U(z) by introducing a roll orientation angle $\beta$:

$$U(z)=U_s\sin\beta - V_s\cos\beta \quad (3)$$

Because the circulations are assumed to be two-dimensional in structure and the Coriolis terms are neglected, the along-roll wind V(z) is eliminated from the system. Thus, the basic state wind profile is represented in the model by the following expression:

$$U(z)=U_0+U_1\sin(q\pi z/z_T)+U_2\cos(q\pi z/z_T) +U_3\sin(n\pi z/z_T)+U_4\cos(n\pi z/z_T) \quad (4)$$

involving five Fourier coefficients, two vertical wavenumbers q and n, and the domain height $z_T$. In general, we find that (4) gives an excellent representation of most atmospheric wind profiles when q=1 and n=2. In addition to the Fourier coefficients, the dynamic forcing is also given in the dimensionless system by the Reynolds number

$$Re=\frac{|\underset{\sim}{V}(z_T)|z_T}{\pi\nu} \quad (5)$$

where $|V(z_T)|$ is the wind speed at the domain top and $\nu$ is the constant eddy viscosity.

The basic state temperature is more simply specified by a linear profile obtained from the vertical gradient $\Delta_z T$. This quantity includes the combined effect of the environmental lapse rate and a vertically distributed surface buoyancy contribution. The corresponding thermodynamic forcing in the dimensionless system is defined by the Rayleigh number

$$Ra=\frac{gz_T^3\Delta_z T}{\pi^4\nu\kappa T_{00}} \quad (6)$$

where $\kappa$ is the constant thermometric conductivity and $T_{00}$ is the surface air temperature.

The model geometry is illustrated in Fig. 1 for a standard Ekman wind profile having a westerly geostrophic wind $\underset{\sim}{V}_g$ (Haack and Shirer 1991). The y-axis is aligned parallel to the rolls that are propagating slowly northward in the -x direction. A positive roll orientation angle $\beta$ is measured counterclockwise from the standard direction $x_s$ (east) to the roll axis y. The critical values $Re_c$ and $Ra_c$ of the forcing rates, which are found by a stability analysis of the conductive solution, depend on both the orientation angle $\beta$ and the aspect ratio $a=2z_T/L$, where L is the horizontal wavelength. The values of $Re_c$ and $Ra_c$, when minimized with respect to both $\beta$ and a (or L), give the preferred or

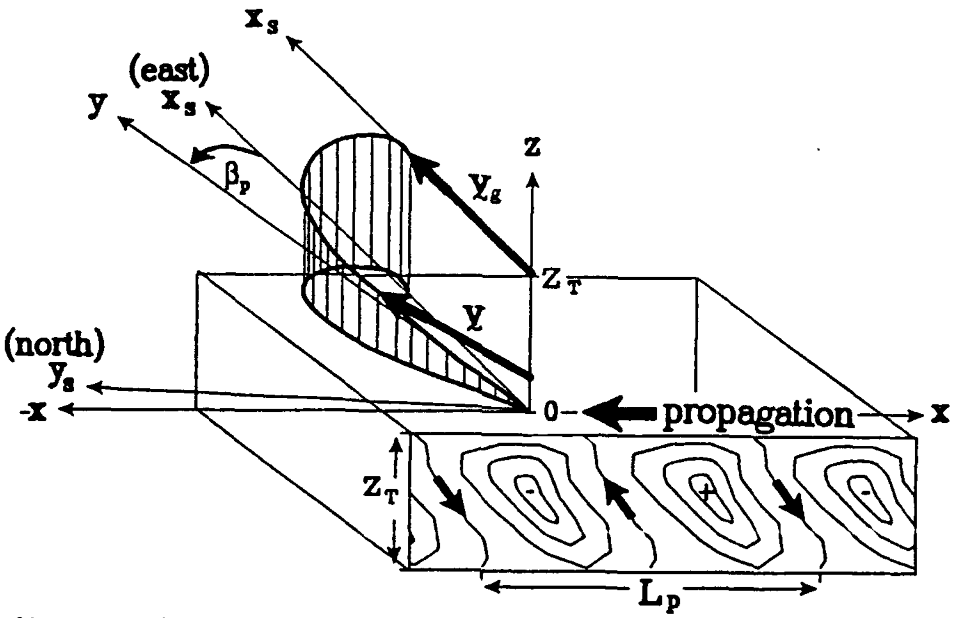



*Figure 1. Schematic depiction of a propagating roll stream function pattern given by the 14-coefficient model of Haack and Shirer (1991). Here a small positive orientation angle $\beta_p$ is shown for a case with a standard Ekman profile that has a westerly geostrophic wind vector $V_g$.*

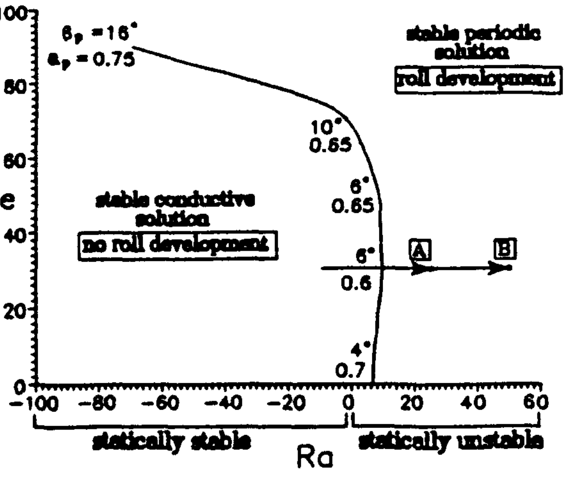
*The axes $(x_s, y_s)$ represent the standard (east/north) coordinate system, and the axes $(x, y)$ represent the roll coordinate system. The boundary layer depth is denoted by $z_T$ and the roll spacing by $L_p$.*

*Roll propagation is downwind from right to left.*

expected values of the roll geometry. These expected values are labeled $\beta_p$ and $L_p$ in Fig. 1 and are the ones compared with observations.

3. RESULTS

Shown in Fig. 2 is the curve of critical forcing values for the transition from a conductive solution to a periodic roll solution as given by the linear stability analysis. Here we use an Ekman depth of D=190 m, which gives model results for Re≤60 that agree with those produced by a higher resolution numerical analysis of the linear model (Haack and Shirer 1991). Labeled along the curve are the preferred values of $\beta$ and a. The path arrows specify a possible transition to the supercritical forcing rates indicated at points (A) and (B). At these values of the forcing rates, we integrate the model and examine the roll patterns and modifications to the basic state.




The integrations are carried out until stable, energetically steady roll solutions are obtained. This generally requires less than four hours so that the neglect of the Coriolis terms is a valid assumption. For integration point (B), the roll structure in dimensionless quantities $T_r^*$ and $\psi_r^*$ are shown in Figs. 3a and 3b. For points (A) and (B), profiles of the background modification in dimensional quantities $T_b$ and $U_b$, given by (1) and (2), are shown in Figs. 4a and 4b. These profiles suggest that the roll modifications act to reduce the thermal and dynamic instabilities that initially produced the secondary flow. The basic temperature is altered by cooling the lower layer, and warming the upper layer which produces a near-neutral stratification. However, the magnitude of this modification is not likely to be measurable in the atmosphere nor great enough to significantly affect the stability results shown in Fig. 2.

However, as shown in Fig. 4b, the roll modifications to the basic wind profile can be significant. Here, the rolls alter the background wind shear by as much as 1.2 $ms^{-1}$/200 m in the center of the domain. Using observed winds as

*Figure 2. Transition curve representing the minimum values of critical forcing needed for roll development when using a standard Ekman wind profile having Ekman depth D=190m. Preferred values of roll orientation angle $\beta_p$ and aspect ratio $a_p$ are labeled along the curve. The path arrows indicate an atmospheric transition to the supercritical forcing rates at points A and B.*

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input to the model, we have found modifications of up to a few meters per second (Shirer and Haack 1990). Fig. 5 shows the original and the altered cross-roll Ekman profiles. The rolls create a dynamically more stable environment by reducing the cross-roll shear.

In Fig. 6, a comparison of the original Ekman spiral and the modified one for integration point (A) illustrates the characteristics of the altered flow. We note that the turning angle in the modified Ekman spiral is reduced, and the altered flow has maximum velocities and is more closely aligned with the direction of the geostrophic wind at low levels. These results are consistent with those found by Brown (1970) whose model of secondary circulations forced by Ekman flow had Coriolis forcing terms.

To examine the consequences of using roll-modified winds in boundary layer models, we use the point (B) modified cross-roll wind profile shown in Fig. 5 in the stability analysis. The resulting transition curves and preferred roll characteristics a and $\beta$ for the modified wind are shown in Fig. 7. Upon comparing these results with those in Fig. 2, we find that the transition to a roll solution occurs only in the statically unstable regime (Ra>0) because of the reduced wind shear in the modified profile. Moreover, values of preferred roll characteristics in Fig. 2 differ markedly from those in Fig 7. Significantly, values of $\beta_p$ are altered by a maximum of 14° at low values of Re. This error in $\beta_p$ is of the order reported by Shirer and Brümmer (1986) in which the contributions by the rolls were not considered.

## 4. CONCLUSIONS

A 14-coefficient spectral model of shallow Boussinesq flow was used to study modifications of initial background wind and temperature profiles by boundary layer roll circulations. Temporal integrations at supercritical values of the dynamic and thermal forcing rates Re and Ra produced stable periodic roll solutions and time-independent nonlinear wind and temperature modification profiles. Alterations by the rolls of the basic temperature were dimensionally small, while those of the basic wind created modified profiles with significantly reduced cross-roll shear. When a modified Ekman wind spiral was used in a linear stability analysis, roll orientation angles shifted by a maximum of 14° from those given by an analysis using the original winds. Consequently, roll perturbations can markedly change the structure of background wind profiles — even in the absence of Coriolis forcing. This secondary flow contribution should be removed from wind measurements before using the observed profiles as basic states in boundary layer models.

## 5. ACKNOWLEDGMENTS

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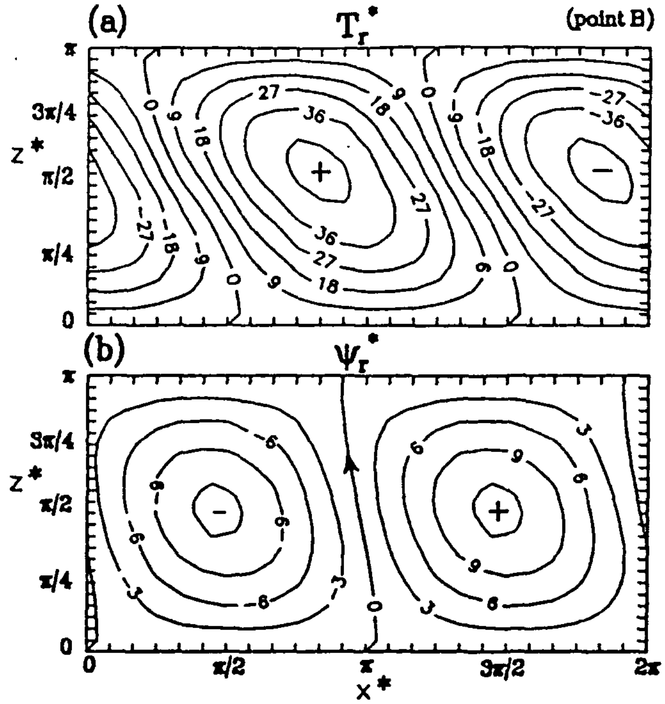


*Figure 3. Patterns of dimensionless roll temperature $T_r^*$ in (a) and stream function $\psi_r^*$ in (b) for point B in Fig. 2.*

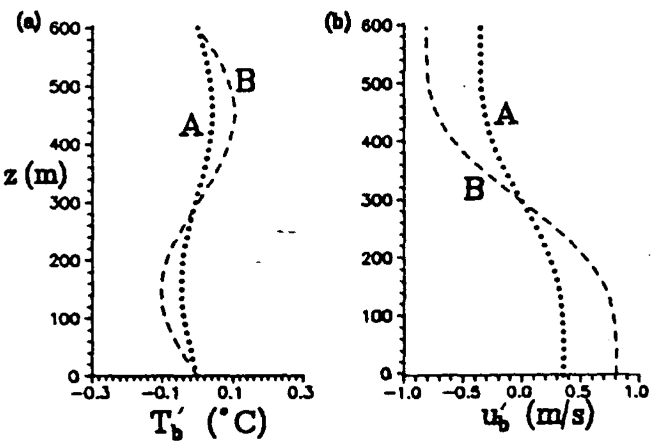


*Figure 4. Profiles of dimensional roll temperature modification $T_b'$ in (a) and roll wind modification $u_b'$ in (b) for points A and B in Fig. 2.*

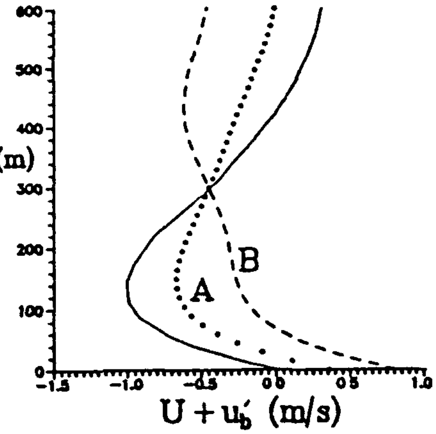


*Figure 5. The original cross-roll Ekman wind profile (solid) when $\beta=6°$, and the roll-modified Ekman profiles for points A (dotted) and B (dashed) in Fig. 2.*

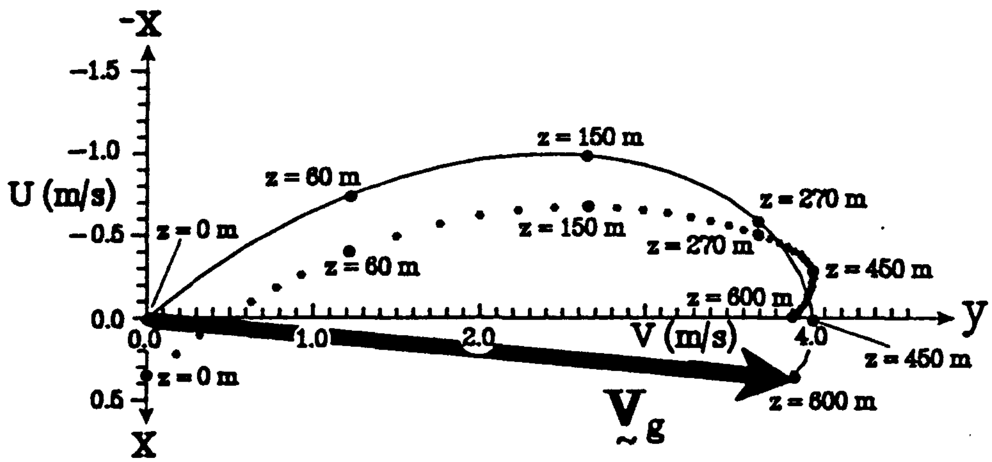


*Figure 6. Roll coordinate depiction of the original Ekman spiral (solid) and the geostrophic wind vector $\underset{\sim}{V}_g$ when $\beta=6°$, and the roll-modified Ekman spiral (dotted) for point A in Fig. 2.*

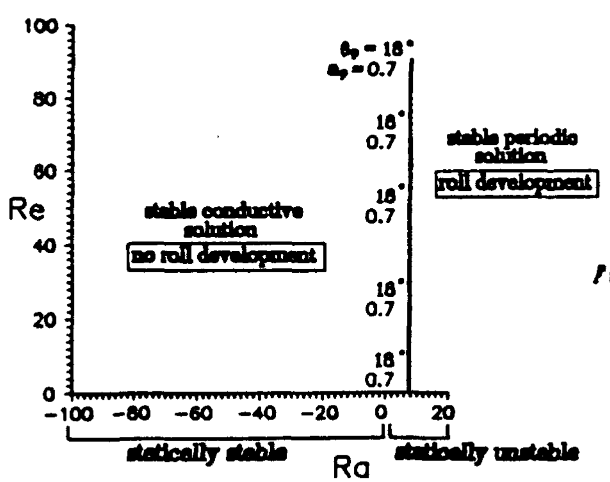


*Figure 7. Transition curve representing the minimum values of critical forcing needed for roll development when using the roll-modified Ekman wind profile given in Fig. 5 for point B. Preferred values of roll orientation angle $\beta_p$ and aspect ratio $a_p$ differ substantially from those shown in Fig. 2 for the original Ekman profile.*

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