REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

D-A252 198

(2)

2. Report Date.
October 1990

3. Report Type and Dates Covered.
Proceedings

Modification of the Eckman Wind Profile by Roll Circulations

5. Funding Numbers.

Program Element No.	0601153N
Project No.	0310 & R0007
Task No.	380 & 001
Accession No.	DN251030
Work Unit No.	14321A

6. Author(s).
Tracy Haack and Hampton N. Shirer*

7. Performing Organization Name(s) and Address(es).
Naval Oceanographic and Atmospheric Research Laboratory
Atmospheric Directorate
Monterey, CA 93943-5006

8. Performing Organization Report Number.
PR 91:111:432

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Naval Oceanographic and Atmospheric Research Laboratory
Basic Research Management Office
Stennis Space Center, MS 39529-5004

10. Sponsoring/Monitoring Agency Report Number.
PR 91:111:432

11. Supplementary Notes.
*The Pennsylvania State University, University Park, PA 16802

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.
A

13. Abstract *(Maximum 200 words).*

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.

14. Subject Terms.
Arctic leads, boundary layer, mesoscale

15. Number of Pages.
4

16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
Unclassified	Unclassified	Unclassified	SAR

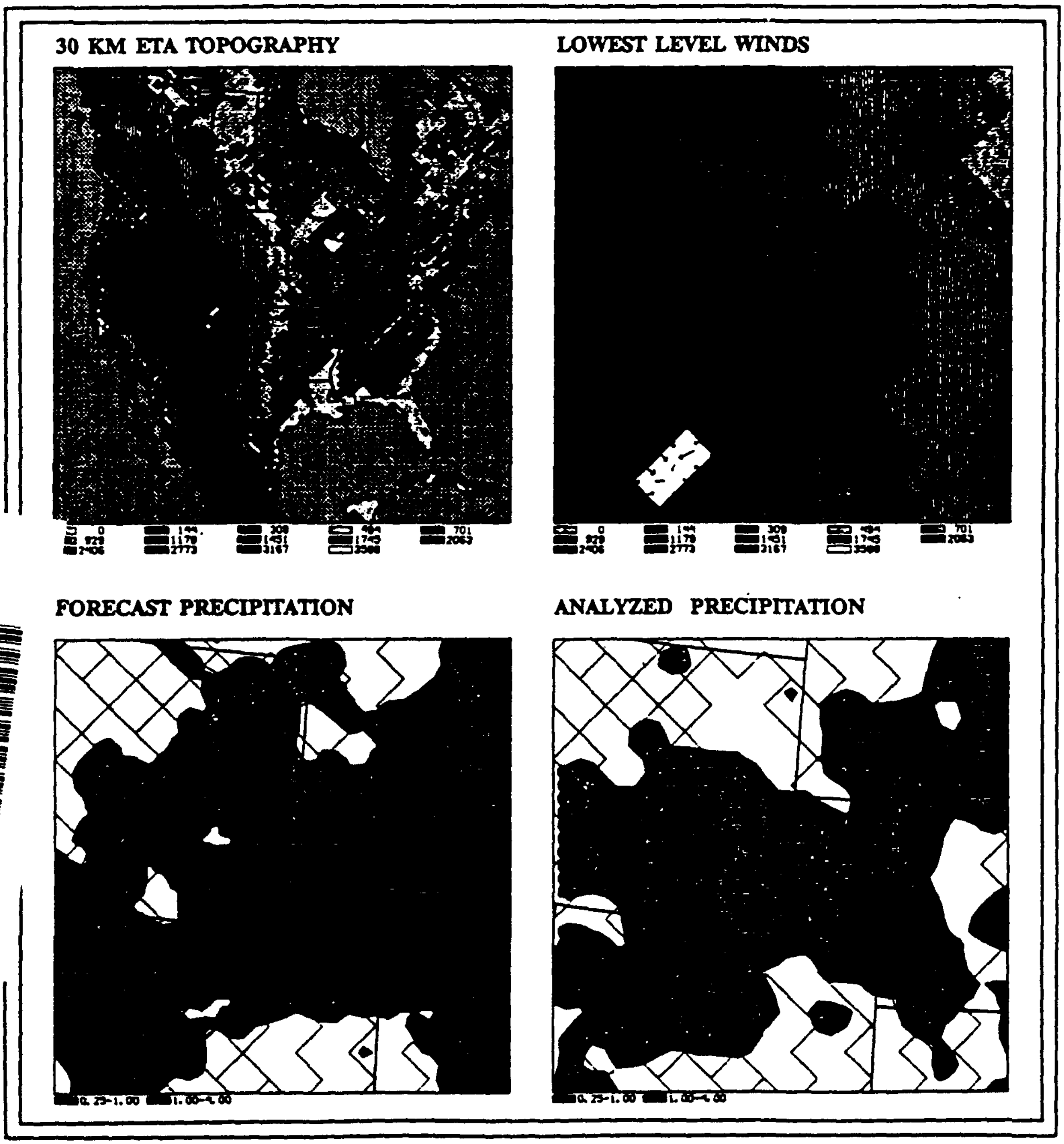
NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Preprints

NINTH CONFERENCE ON NUMERICAL WEATHER PREDICTION

October 14–18, 1991 Denver, Colorado



AMERICAN METEOROLOGICAL SOCIETY

MODIFICATION OF THE EKMAN WIND PROFILE BY ROLL CIRCULATIONS

Tracy Haack

Naval Oceanographic and Atmospheric Research Laboratory
Atmospheric Directorate
Monterey, CA 93943-5006

Hampton N. Shirer

The Pennsylvania State University
University Park, PA 16802

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 ψ and perturbation temperature T (Haack and Shirer 1991). These expansions are composed of two parts: roll circulation patterns given by T_r and ψ_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 β:

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

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 ν 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 κ 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 β 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 β 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 β and a (or L), give the preferred or

p. 107

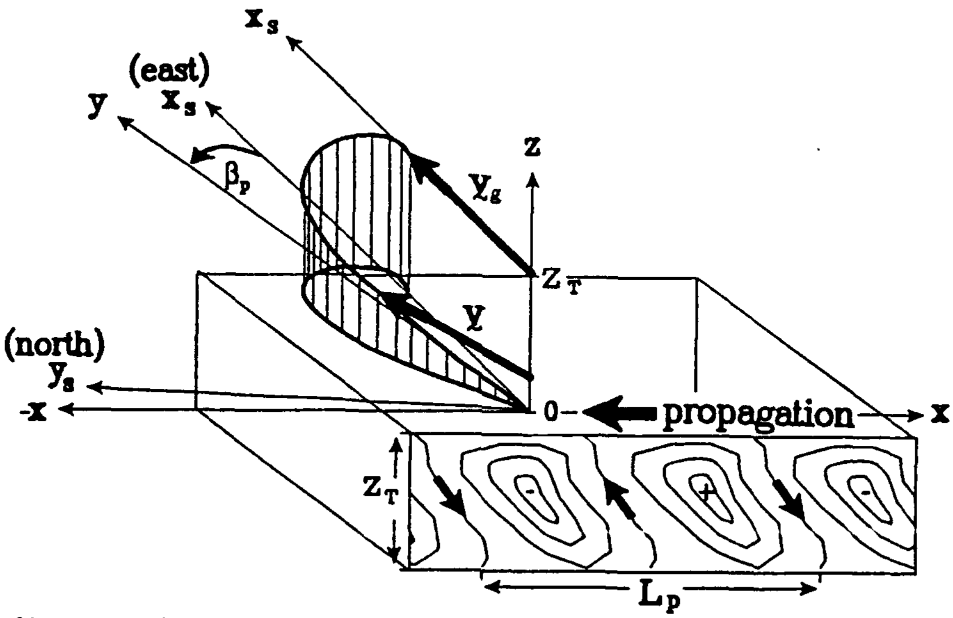
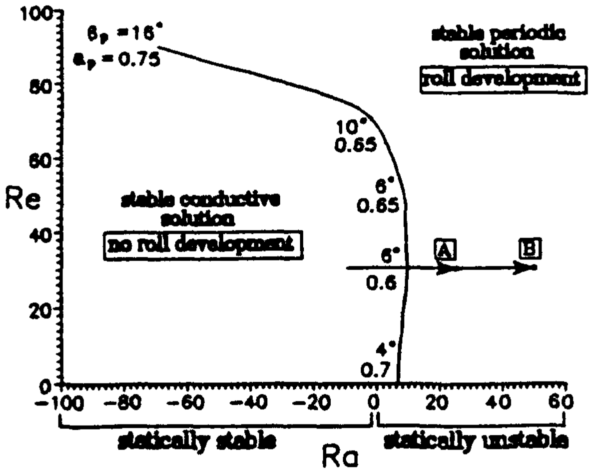


Figure 1. Schematic depiction of a propagating roll stream function pattern given by the 14-coefficient model of Haack and Shirer (1991). Here a small positive orientation angle β_p is shown for a case with a standard Ekman profile that has a westerly geostrophic wind vector V_g. The axes (x_s, y_s) 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 β_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 β 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 ψ_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 β_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.

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 β 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 β_p are altered by a maximum of 14° at low values of Re. This error in β_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

This research has been partially supported by the National Science Foundation through Grants ATM86-19854 and ATM89-09947, the National Aeronautics and Space Administration through Contract NAS8-36150 and Grant NAG8-780, and the Office of Naval Research through Contract N00014-86-K-06880. NOARL contribution no. 91:111:432. Approved for public release; distribution is unlimited.

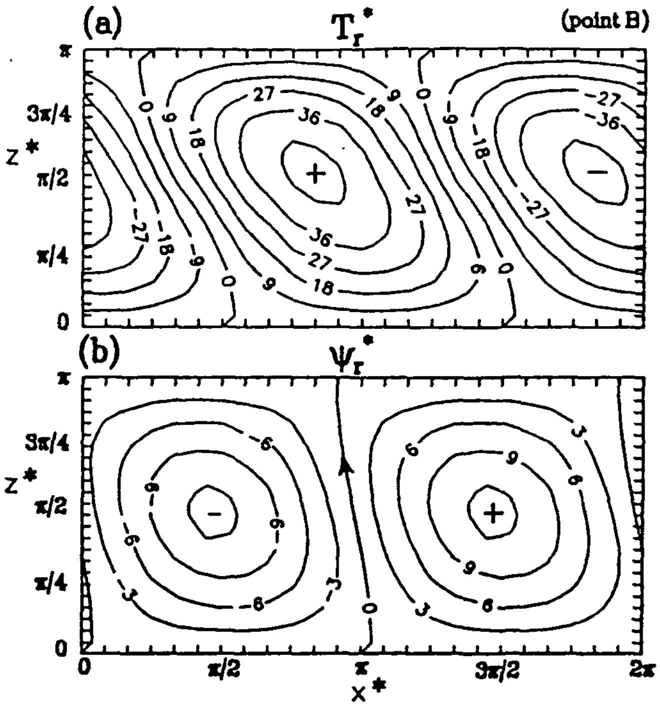


Figure 3. Patterns of dimensionless roll temperature T_r^* in (a) and stream function ψ_r^* in (b) for point B in Fig. 2.

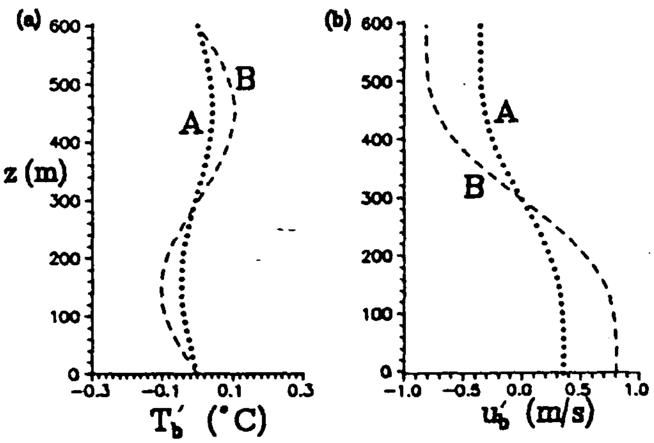


Figure 4. Profiles of dimensional roll temperature modification T_b' in (a) and roll wind modification u_b' in (b) for points A and B in Fig. 2.

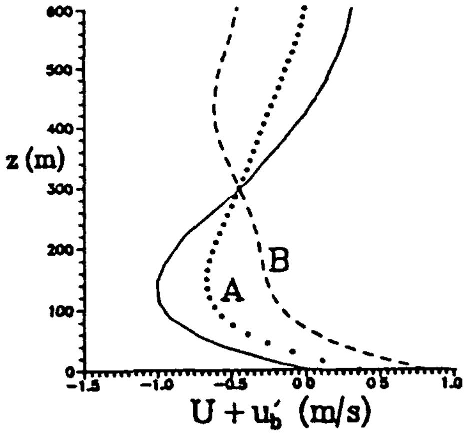


Figure 5. The original cross-roll Ekman wind profile (solid) when $\beta = 6^\circ$, and the roll-modified Ekman profiles for points A (dotted) and B (dashed) in Fig. 2.

6. REFERENCES

Brown, R. A., 1970: A secondary flow model for the planetary boundary layer. *J. Atmos. Sci.*, 27, 742-757.

Haack, T. and H.N. Shirer, 1991: Mixed convective/dynamic roll vortices and their effects on initial wind and temperature profiles. Submitted to *J. Atmos. Sci.* for review.

Shirer, H.N. and B. Brümmer, 1986: Cloud streets during KonTur: a comparison of parallel/thermal instability modes with observations. *Contrib. Atmos. Phys.*, 59, 150-161.

Shirer, H.N. and T. Haack, 1990: The modification of large-scale wind profiles by roll circulations. *Proc. Seventh Conf. Atmos. Rad.*, Amer. Met. Soc., J113-J118.

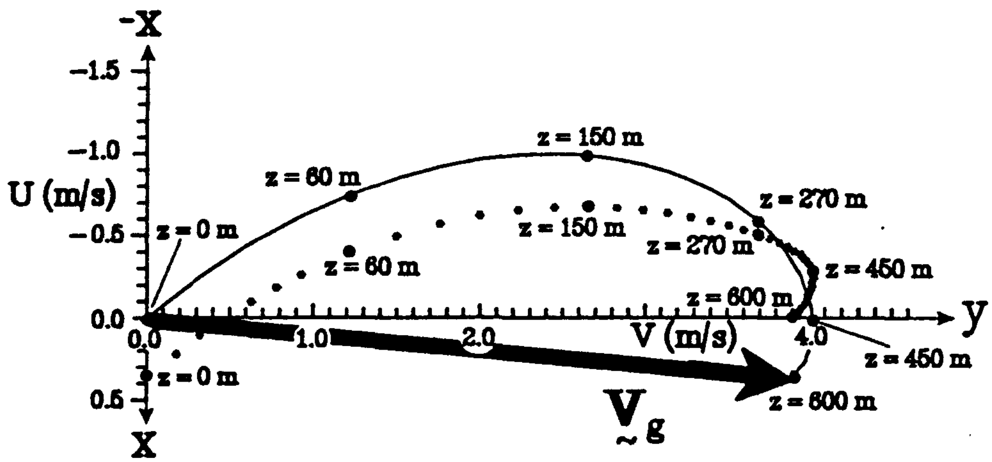


Figure 6. Roll coordinate depiction of the original Ekman spiral (solid) and the geostrophic wind vector $\underset{\sim}{V}_g$ when $\beta = 6^\circ$, and the roll-modified Ekman spiral (dotted) for point A in Fig. 2.

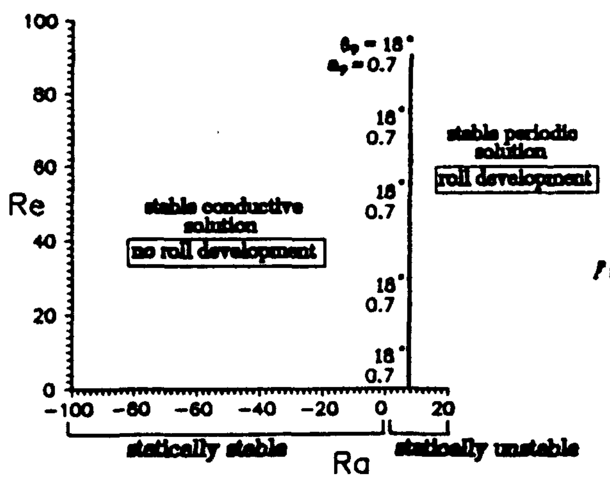


Figure 7. Transition curve representing the minimum values of critical forcing needed for roll development when using the roll-modified Ekman wind profile given in Fig. 5 for point B. Preferred values of roll orientation angle β_p and aspect ratio a_p differ substantially from those shown in Fig. 2 for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

p. 110