REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 15, 1996	Final - March 1, 1990 - June 30, 1996

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Tropical Cyclone Motion in the Western Pacific	Grant N00014-90-J-1383
6. AUTHOR(S) Thomas A. Schroeder Bin Wang	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Hawaii 2525 Correa Road Honolulu, HI 96822	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Marine Meteorology 800 North Quincy Street Arlington, VA 22217-5000	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unlimited

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

19960912 002

13. ABSTRACT (Maximum 200 words)

A systematic examination of the physics of beta-drift of tropical cyclones has been undertaken. Sequentially we analysed beta-drift of a vortex with baroclinic structure, explored the physics of development and gyration of beta gyres and then exposed the vortex to environmental shears. Through this work we have: identified physical factors controlling drift of a baroclinic vortex in a quiescent environment, identified variability of drift due to vortex structure, developed a kinetic energy theory to explain gyre formation, identified the effect of horizontal shears on beta-drift, proven that shear strain rate of environmental flow alters drift speed and shown the mechanisms by which environmental shear changes beta-drift direction. A theory has been developed for dependence of beta-drift on environmental shear and initial vortex structure.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Tropical cyclone, beta-drift, vortex motion	10
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

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

DTIC QUALITY INSPECTED 1

FINAL REPORT

to

OFFICE OF NAVAL RESEARCH

MARINE METEORLOGY

July 15, 1996

Principal Investigators:
Thomas A. Schroeder, Bin Wang

Project Title:
Tropical Cyclone Motion in the Western Pacific

Project Number: N00014-90-J-1383

Address: Department of Meteorology
University of Hawaii
2525 Correa Road
Honolulu, Hi 96822

E-mail: **Schroeder: tas@soest.hawaii.edu**
Wang: bwang@soest.hawaii.edu

Phone: Schroeder: (808) 956-7476 Fax: (808) 956-2877

I. ABSTRACT

A. Long-term Goals:

To improve ability to predict tropical cyclone motion with specific application to the western Pacific Ocean.

B. Scientific Objectives:

To develop our understanding of the physics of the interaction between a tropical cyclone and its environment ("beta-drift")

C. Approaches:

Numerical experiments and theoretical analysis.

D. Tasks completed:

a. Analysis of the physics of beta-drift of a tropical cyclone with **baroclinic**structure (1990-1991).

b. Study of the cause of development and gyration of beta-gyres (**beta-gyre dynamics**) (1992-1993)

c. Impacts of horizontal environmental shears upon beta-drift (1994-1995)

E. Most significant scientific accomplishments:

Our systematic study of the physics of tropical cyclone motion have resulted in the following accomplishments:

1. We have identified the physical factors which control beta drift direction and speed of a tropical cyclone with baroclinic vertical structure in a quiescent environment. (Wang and Li,1992)

2. For initial vortices of differing strutures, we have identified a variety of possible beta-drift tracks (quasi-steady, wobbling, and cycloidal) in accordance with beta-gyre evolution . (Li and Wang, 1994)

3. We have developed a kinetic energy theory which explains the fundamental cause of beta-gyre development. We used asymmetirc streamfunction tendency analysis to explain the cause of beta gyre gyration. (Li and Wang, 1994)

4. We have demonstrated the mechanism through which horizontal shears and the relative vorticity gradients of environmental flows affect beta-drift speed. (Wang and Li, 1995)

5. We have discovered and theoretically proven that the shear strain rate of an environmental flow alters beta drift speed. (Li and Wang, 1996)

6. We have shown the mechanisms by which environmental shear flows change beta-drift direction. We developed a theory for dependence of beta-drift direction on initial vortex structure and environmental shears. (Wang *et al*, 1996).

F. Significance of accomplishments and transition items:

Prediction of tropical cyclone motion based upon environmental steering currents exhibits systematic errors which can, to a large extent, be accounted for by the so-called beta-drift. We have identified the controlling factors of this beta-drift. These factors provide a useful guide for prediction of beta-affected track deviations from the track predicted from environmental steering. For instance, our results suggest that (1) beta-drift is faster (slower) near a subtropical ridge (monsoon trough) or in a saddle field with anticyclonic (cyclonic) circulation to its east and south.; (2) beta-drift direction is more influenced by longitudinal shear of the meridional wind than by the meridional shear of zonal environmental flows. In the western rim of a subtropical high where meridional shear decreases eastward, the beta-drift component will be directed more northward. The environmental shear favors tropical cyclone recurvature. These rules may be a useful guide for prediction of beta-drift track deviations.

The theory of beta-gyre dynamics has furthered our understanding of the interaction among the primary vortex, secondary asymmetric circulations, and the environmental flow in the presence of the earth's vorticity gradient.

G. Abstracts of the major scientific results:

See attached abstracts.

II. STATISTICAL SUMMARY

A) Refereed publications acknowledging ONR Grant

Wang, B., and X. Li, 1992: The beta drift of three-dimensional vortices: A numerical study. *Mon, Wea.Rev.*, 120, 579-593.

Wang, B., and Y. Xue, 1992: Behavior of a moist Kelvin wave packet with nonlinear heating. *J.Atmos.Sci.*, 49, 549-559.

Li, X., and B. Wang, 1994: Barotropic dynamics of beta gyres and beta drift. *J.Atmos.Sci.*, 51, 746-756.

Wang, B., 1994: Climate regimes of the tropical convection and rainfall. *J.Atmos.Sci.*, 6, 1109-1118.

Fletcher, C.H., B.M. Richmond, G.M. Barnes and T.A. Schroeder, 1995: Marine flooding over the coast of Kaua'i during Hurricane Iniki: hindcasting inundation components and delineating washover. *J.Coastal Res.*, 11, 188-204.

Wang, B., and X. Li, 1995: Propagation of a tropical cyclone in a zonal flow with meridional shear: an energetics analysis. *J. Atmos.Sci.*, 52, 1421-1433.

Li, X. , and B. Wang, 1996: Acceleration of hurricane drift by shear strain rate of the environmental flow. *J.Atmos.Sci.*, 53, 327-336.

Wang, B., and Y. Wang, 1996: Temporal structure of the Southern Oscillation. *J. Climate*,9, 1586-1598.

Wang, B., X. Li, and L. Wu, 1996: Deflection of hurricane drift by the presence of environmental flow. Submitted to *J.Atmos.Sci.*

Wang, B., and X. Xie, 1996.: A model for boreal summer intraseasonal oscillation. *J. Atmos.Sci.*, in press.

Wang, B., and X. Xu, 1996: Northern Hemisphere summer monsoon singularity and climatological intraseasonal oscillation. Submitted to *J.Climate.*

Smith, R.B., X. Li, and B. Wang, 1996: A hurricane drift law including meridional shear. Submitted to *Tellus.*

B. Postdoctoral fellow/ graduate students supported:

Graduate students: X. Li, L. Wu., R. Wu
Postoctoral Fellow: X. Li (1994-1995).

Reprinted from MONTHLY WEATHER REVIEW, Vol. 120, No. 4, April 1992
American Meteorological Society

The Beta Drift of Three-Dimensional Vortices: A Numerical Study

BIN WANG AND XIAOFAN LI

Department of Meteorology, School of Ocean and Earth Sciences and Technology, University of Hawaii at Manoa, Honolulu, Hawaii

(Manuscript received 20 March 1991, in final form 12 August 1991)

ABSTRACT

The beta effect on translation of cyclonic and anticyclonic vortices with height-dependent circulation (the beta-drift problem) is investigated via numerical experiments using a dry version of a multilevel primitive equation model (Florida State University model).

The vertical structure of vortex circulation influences steady translation in a manner similar to that of the horizontal structure. Both spatially change the mean relative angular momentum (MRAM) of the vortex. The translation speed and its meridional component are both approximately proportional to the square root of the magnitude of MRAM of the initial (or quasi-steady-state) symmetric circulation. The latitude is another important factor controlling the speed of the beta drift. The meridional component decreases by about 45% when the central latitude of the vortex increases from 10° to 30°N.

The beta-drift speed is intimately related to the axially asymmetric pressure field. During quasi-steady vortex translation the asymmetric pressure field maintains a stationary wavenumber 1 pattern in azimuthal direction with a high in the northeast and a low in the southwest quadrant of a Northern Hemisphere cyclone. The beta-drift velocity is approximately equal to the geostrophic flow implied by the asymmetric pressure gradient at the vortex center. If the Rossby number associated with the asymmetric flow is small, to the lowest order, the asymmetric pressure gradient force at the vortex center is balanced by the Coriolis force associated with the beta drift of the vortex.

1. Introduction

Beta drift is a basic component of tropical cyclone motion. It arises from the interaction between the gradient of earth's vorticity (or in more general terms, the absolute-vorticity gradient) and the vortex circulation. Beta drift may create a deviation from environmental steering and may play a dominant role if the ambient steering current is weak or indefinite, particularly in the deep tropics. Study of beta drift also provides fundamental understanding of nonlinear interaction between the vortex dynamics and the environment.

The investigation of motion of an isolated barotropic vortex in a quiescent environment dates back to Rossby (1948). Using a solid-body-rotation vortex and assuming a balance between the integrated pressure force by the surrounding fluid and the Coriolis force associated with the vortex translation, Rossby argued that an axially symmetric cyclonic vortex is driven poleward due to the latitudinal variation of the Coriolis parameter. Adem (1956) reexamined the translation of a geostrophic vortex on beta plane in terms of a Taylor expansion of streamfunction in time. In the Northern Hemisphere, a cyclonic vortex was shown to first move westward then turn northward. Adem first noticed a relation between vortex translation and its horizontal structure: the initial westward and subsequent northward components are proportional to the vortex radius and the maximum wind speed, respectively.

Numerical experiments using barotropic models all indicate that an initially symmetric vortex on a beta plane moves consistently northwestward in the Northern Hemisphere (e.g., Anthes and Hoke 1975; Madala and Piacsek 1975) rather than northward or first westward then northward. Recent numerical studies of barotropic beta drift have further focused on the effects of the horizontal vortex structure on the beta drift. DeMaria (1985) showed that the vortex track is much more sensitive to changes in the outer region (size change) than to changes in the inner regions (intensity change). Holland (1983, 1984) postulated that the vortex motion depends on cyclone–environment interaction at an effective radius of interaction, which is an envelope defined by the region of rapid increase in inertial instability. He intuitively predicted that the maximum wind variation should not affect the motion, while the changes in the size and strength of the outer circulation affect the motion by changing the effective radius. On the other hand, Chan and Williams (1987) showed that for a constant-shape vortex the northward movement increases with both the maximum wind

Corresponding author address: Dr. Bin Wang, University of Hawaii, School of Ocean & Earth Science & Technology, 2525 Correa Rd. Honolulu, HI 96822.

Barotropic Dynamics of the Beta Gyres and Beta Drift

XIAOFAN LI AND BIN WANG

Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii

(Manuscript received 27 April 1993, in final form 16 August 1993)

ABSTRACT

The movement of a symmetric vortex embedded in a resting environment with a constant planetary vorticity gradient (the beta drift) is investigated with a shallow-water model. The authors demonstrate that, depending on initial vortex structure, the vortex may follow a variety of tracks ranging from a quasi-steady displacement to a wobbling or a cycloidal track due to the evolution of a secondary asymmetric circulation. The principal part of the asymmetric circulation is a pair of counterrotating gyres (referred to as beta gyres), which determine the steering flow at the vortex center. The evolution of the beta gyres is characterized by development/decay, gyration, and radial movement.

The beta gyres develop by extracting kinetic energy from the symmetric circulation of the vortex. This energy conversion is associated with momentum advection and meridional advection of planetary vorticity. The latter (referred to as "beta conversion") is a principal process for the generation of asymmetric circulation. A necessary condition for the development of the beta gyres is that the anticyclonic gyre must be located to the east of a cyclonic vortex center. The rate of asymmetric kinetic energy generation increases with increasing relative angular momentum of the symmetric circulation.

The counterclockwise rotation of inner beta gyres (the gyres located near the radius of maximum wind) is caused by the advection of asymmetric vorticity by symmetric cyclonic flows. On the other hand, the clockwise rotation of outer beta gyres (the gyres near the periphery of the cyclonic azimuthal wind) is determined by concurrent intensification in mutual advection of the beta gyres and symmetric circulation and weakening in the meridional advection of planetary vorticity by symmetric circulation. The outward shift of the outer beta gyres is initiated by advection of symmetric vorticity by beta gyres relative to the drifting velocity of the vortex.

1. Introduction

Tropical cyclone motion is primarily controlled by nonlinear vorticity advection. Theoretically, two distinctive mechanisms can be identified that affect adiabatic motion of a barotropic vortex: steering by environmental flows, and advection by an asymmetric flow induced by interaction of the vortex circulation with the environmental absolute potential vorticity gradient. An ideal example of the environmental steering is given by Adem and Lezama (1960), who proved that a barotropic symmetric vortex embedded in a uniform flow on an f plane moves exactly with the velocity of the environmental flow. The presence of the environmental absolute potential vorticity gradient, however, may generate asymmetric circulation through interaction with a symmetric vortex. The secondary asymmetric flow thus generated can further advect symmetric relative vorticity, causing another type of motion, which was termed as propagation by Holland (1983). An ideal problem of propagation was first investigated by Rossby (1948), who showed that an isolated rigid-body-rotation vortex on a beta plane will undergo a poleward acceleration due to the increase of the Coriolis force with latitude. The movement of a vortex embedded in such a quiescent environment on a beta plane is now commonly referred to as beta drift. Rossby's solution, however, did not consider the effects of secondary circulation and compensating pressure gradient forces and hence was not in full agreement with subsequent numerical solutions (e.g., Anthes and Hoke 1975).

A fundamental theoretical problem is to explain the mechanisms causing beta drift. Adem (1956) first worked out a series solution for a barotropic nondivergent vorticity equation, which suggested a beta effect–induced asymmetric circulation that drives the vortex first westward and then poleward. Holland (1983) argued that the advection of earth vorticity by symmetric azimuthal winds could produce asymmetric vorticity (which, on the one hand, drags a cyclone westward and, on the other hand, creates two counterrotating gyres—counterclockwise to the west and clockwise to the east) that is often referred to as beta gyres. The resulting poleward wind over the vortex center [referred to as "ventilation flow" by Fiorino and Elsberry (1989)] would advect the cyclone poleward. The roles

Corresponding author address: Dr. Xiaofan Li, School of Ocean and Earth Science and Technology, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822.

Reprinted from JOURNAL OF THE ATMOSPHERIC SCIENCES, Vol. 52, No. 9, 1 May 1995
American Meteorological Society

Propagation of a Tropical Cyclone in a Meridionally Varying Zonal Flow: An Energetics Analysis

BIN WANG AND XIAOFAN LI

Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii

(Manuscript received 27 September 1993, in final form 10 October 1994)

ABSTRACT

Tropical cyclone propagation (the beta drift) is driven by a secondary circulation associated with axially asymmetric gyres (beta gyres) in the vicinity of the cyclone center. In the presence of the beta effect, the environmental flow may interact with the symmetric circulation and beta gyres of the cyclone, affecting the development of the gyres and thereby the cyclone propagation. An energetics analysis is carried out to elucidate the development mechanism of the beta gyres and to explain variations in propagation speed of a barotropic cyclone embedded in a meridionally varying zonal flow on a beta plane. Two types of zonal flows are considered: one with a constant meridional shear resembling those in the vicinity of a subtropical ridge or a monsoon trough, and the other with a constant relative vorticity gradient as in the vicinity of an easterly (westerly) jet.

Zonal flow with a constant meridional shear changes the generation rate of the gyre kinetic energy through an exchange of energy directly with the gyres. The momentum flux associated with gyres acting on the meridional shear of zonal flow accounts for this energy conversion process. Zonal flow with an anticyclonic (cyclonic) shear feeds (extracts) kinetic energy to (from) the gyres. The magnitude of this energy conversion is proportional to the strength of the meridional shear and the gyre intensity. As a result, the gyres are stronger and the beta drift is faster near a subtropical ridge (anticyclonic shear) than within a monsoon trough (cyclonic shear).

Zonal flow with a constant relative vorticity gradient affects gyre intensity via two processes that have opposing effects. A southward vorticity gradient, on the one hand, weakens the gyres by reducing the energy conversion rate from symmetric circulation to gyres; on the other hand, it enhances the gyres by indirectly feeding energy to the symmetric circulation, whose strengthening in turn accelerates the energy conversion from symmetric circulation to gyres. The effect of the second process tends to eventually become dominant.

1. Introduction

Tropical cyclone motion normally differs from an environmental steering (George and Gray 1976; Chan and Gray 1982; Carr and Elsberry 1990). The difference is attributed to a propagation component that arises from the interaction of the tropical cyclone circulation with embedded environment. Current understanding of the nature of the propagation is primarily gained from theoretical and numerical modeling studies.

Theoretically, the translation of an initially axially symmetric vortex embedded in a spatially varying environmental flow may be advantageously partitioned into two components: a steering caused by the advection of axially symmetric vorticity by the environmental flow, and a propagation induced by the advection of the symmetric vorticity by axially asymmetric flows near the vortex center. The asymmetric flows result from interactions between the vortex circulation and the planetary vorticity gradient (the beta effect) and the relative vorticity gradient of the environmental flow.

An example of pure steering was given by Adem and Lezama (1960), who showed that a barotropic symmetric vortex embedded in a uniform environmental flow on an f plane moves precisely with the uniform flow. An example of pure propagation was first studied by Rossby (1948), who showed that the beta effect can drive a rigid-body rotation cyclone northward in the absence of environmental flows. Recent numerical investigations have established that in a quiescent environment on a beta plane, the propagation of a barotropic symmetric vortex (the beta drift) is determined by the advection of symmetric vorticity by the asymmetric flow between a pair of counterrotating gyres (the beta gyres); the beta gyres are generated by the advection of planetary vorticity by the symmetric vortex circulation (Chan and Williams 1987; Willoughby 1988; Fiorino and Elsberry 1989; Peng and Williams 1990; Shapiro and Ooyama 1990; Smith et al. 1990; Li and Wang 1994; and others).

In the presence of both the beta effect and environmental flows, vortex translation is a combination of steering and propagation. In the simplest case, in which the environmental flow is uniform and time indepen-

Corresponding author address: Dr. Bin Wang, School of Ocean and Earth Science and Technology, University of Hawaii, 2525 Correa Rd., Honolulu, HI 96822.

Reprinted from JOURNAL OF THE ATMOSPHERIC SCIENCES, Vol. 53, No. 2, 15 January 1996
American Meteorological Society

Acceleration of the Hurricane Beta Drift by Shear Strain Rate of an Environmental Flow*

XIAOFAN LI AND BIN WANG

Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii

(Manuscript received 7 November 1994, in final form 21 July 1995)

ABSTRACT

An energetics analysis is presented to reveal the mechanisms by which the environmental flows affect hurricane beta-gyre intensity and beta-drift speed. The two-dimensional environmental flow examined in this study varies in both zonal and meridional directions with a constant shear.

It is found that a positive (negative) shear strain rate of the environmental flow accelerates (decelerates) beta drift. The horizontal shear of the environmental flow contains an axially symmetric component that is associated with vertical vorticity and an azimuthal wavenumber two component that is associated with shear strain rate. It is the latter that interacts with the beta gyres, determining the energy conversion between the environmental flow and beta gyres. A positive shear strain rate is required for transfering kinetic energy from the environmental flow to the beta gyres. As a result, the positive shear strain rate enhances the beta gyres and associated steering flow that, in turn, accelerates the beta drift.

1. Introduction

The presence of an environmental flow affects hurricane motion not only by advecting axially symmetric vorticity (steering) but also by changing axially asymmetric beta gyres. The beta gyres result from interactions between the symmetric circulation and the gradients of planetary vorticity (the beta effect) or environmental relative vorticity (e.g., Holland 1983). The circulation associated with the beta gyres advects symmetric vorticity and induces a propagation component (beta drift). The beta drift often represents a deviation from the steering. It is thus of fundamental importance to understand how the presence of a horizontally varying environmental flow influences the beta drift of tropical cyclones.

Previous studies of the effects of environmental flow on hurricane motion have focused on a special environmental flow: zonal flows with meridional shears (e.g., Sasaki 1955; Kasahara 1957; DeMaria 1985), partially because the environmental relative vorticity gradient associated with zonal flows is able to enhance or offset the beta effect. It was found, however, that even without a relative vorticity gradient a zonal flow with a constant anticyclonic (cyclonic) shear can also accelerate (decelerate) beta drift (Ulrich and Smith 1991; Smith 1991) by enhancing (weakening) the beta gyres (Williams and Chan 1994).

Wang and Li (1995, hereafter WL95) developed an energetics theory to explain the physical mechanisms by which a *zonal* flow affects the development of the beta gyres and beta drift. They showed that a zonal flow with an anticyclonic meridional shear feeds kinetic energy to the beta gyres, enhancing the gyre-induced steering flow and accelerating the beta drift. In contrast, a zonal flow with a cyclonic meridional shear extracts energy from the beta gyres and slows down the drift.

The mean tropical flows surrounding a tropical cyclone are not purely zonal and often contain a substantial meridional component. For instance, the vertically averaged winds between 300 and 850 hPa, derived from the European Centre for Medium-Range Weather Forecasts analyses for the period of 10–17 July 1987 (Fig. 1), show that the mean flow consists of a subtropical ridge around 28°N, a monsoon trough to its south, and a westerly trough to its north. The maximum easterly wind along the line AB (Fig. 1) and the maximum northerly wind along the line CD have the same order of magnitude. It is, therefore, necessary to examine influences on beta drift of a more general environmental flow that has both zonal and meridional components.

Since the mean divergent wind is negligibly small compared to the rotational wind, we may approxi-

* School of Ocean and Earth Science and Technology Contribution Number 3956.

Corresponding author address: Prof. Bin Wang, School of Ocean and Earth Science and Technology, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822.

On Hurricane Beta Drift Direction in Horizontally Sheared Flows

Bin Wang[1], Xiaofan Li, and Liguang Wu

Department of Meteorology
School of Ocean and Earth Science and Technology
University of Hawaii at Manoa, Honolulu, Hawaii 96822

March, 1996

Submitted to J. Atmos. Sci.

[1] Corresponding author address: Dr. Bin Wang, University of Hawaii, School of Ocean and Earth Science and Technology, 2525 Correa Road, Honolulu, HI 96822

Abstract

The impacts of environmental shears on beta drift direction is assessed through numerical experiments with a barotropic divergent model. We found that cyclonic (anticyclonic) shears make the beta drift more westward (northward) in the Northern Hemisphere. In addition, the longitudinal shear of meridional flows ($\partial V/\partial x$) is much more effective than the meridional shear of zonal flows ($\partial U/\partial y$) in deflection of the beta drift.

An analytical model for beta drift angle is advanced to interpret the numerical model results. The theoretical model predicts: (1) Beta drift direction does not depend on the planetary vorticity gradient; (2) In a quiescent environment, the drift angle is primarily determined by the outer azimuthal flows of the vortex; (3) In a sheared environmental flow, the deflection of beta drift induced by environmental shears depends mainly on the longitudinal shear of meridional flows. It is shown that the environmental shear changes beta drift angle by advection of beta-gyre vorticity and planetary vorticity that affects beta gyre orientation.