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Impact of tropical cyclones on a baroclinic jet in the ocean

The initial evolution of a baroclinic jet under influence of a barotropic flow induced by the tropical cyclones is considered using a two-layer model and the thin-jet approximation. In spite of antisymmetric structure of the barotropic flow, the jet meander growth due to the barotropic flow advection is shown to favor an anticyclonic meander to the right of the storm track. This enhancement of the anticyclonic meander is found to be related to the dispersion properties of frontal waves along the jet described by the thin-jet theory and coupling with deep eddies developing in the lower layer during the jet meandering.

Keywords: baroclinic jet, tropical cyclone, anticyclonic meander, thin-jet theory.

Introduction

Tropical cyclones (TC) provide the most intense atmospheric forcing to the ocean generating both barotropic and baroclinic currents. Here the barotropic current is defined as a depth-averaged flow. The baroclinic currents are what remain after substraction of the depth-averaged flow and are associated with the ocean stratification. J.E. Geisler [1] was the first to reveal distinctively different nature of the barotropic and baroclinic responses of the ocean to a moving TC because the barotropic gravity wave speed is much larger than the baroclnic one. Typically, the TC translation speed (5 m/s) is greater than the baroclinic wave speed and much smaller than the barotropic wave speed. Therefore, the baroclinic response is characterized by upwelling with oscillating narrow wake behind the TC, formed by slow propagating, near-inertial baroclinic waves, while fast propagating barotropic waves produce a broad barotropic flow.

In a deep ocean, the depth-averaged TC-induced currents are essentially weaker than the baroclinic currents concentrated in the upper ocean. Due to strong vertical shear, mixing processes and upwelling are able to reduce the surface temperature by several degrees that was pointed out in pioneering works by A.I. Felzenbaum with colleagues (e.g., [2]). The TC-induced mixing and decrease of the ocean temperature was shown to be enhanced to the right from the storm track due to resonance between inertial oscillations and rotating wind direction during TC passage [3, 4]. Ocean cooling under TC provides an important negative feedback to the TC intensity [5]. Therefore, coupled TC – ocean models are used now for prediction of TC evolution [6].

The most important features of the ocean response to TC with initially horizontally homogeneous ocean conditions which have been widely studied as summarized by A.P. Khain and G.G. Sutyrin [7]. However, when a TC crosses frontal regions with strong ocean currents such as the Gulf Stream or Kuroshio, the ocean response is more complicated (e.g., [8 – 11]). Here we focus on a baroclinic jet meandering forced by a TC using a two-layer model and the thin-jet theory (see [12] and references therein).

Formulation of the problem

Let's consider a TC uniformly moving in *y*-direction at the speed U_h over a stratified ocean with a baroclinc jet flowing in the *x*-direction at the *f*-plane. As shown by I. Ginis and G. Sutyrin [13] for initially horizontally homogeneous ocean, the depth-averaged TC-induced flow behind the storm is antisymmetric, being positive to the right from the storm track (in the direction of TC motion) and negative to the left. It can be characterized by the depth-averaged velocity maximum, v_m and its distance from the storm track, x_m :

$$v_m = a_1 \frac{L\tau_L}{\rho_0 H_0 U_h}, \qquad x_m = a_2 L, \tag{1}$$

where the characteristic TC scale L is defined as the radius where the wind stress torque R_d reaches its maximum, τ_L is the wind stress at this radius, H_0 is the ocean depth, ρ_0 is the ocean density. It was found for several typical radial distributions of the wind stress in TC [14] that the coefficient a_1 ranges between 2 and π, and a_2 ranges between 0.65 and 1. Here we prescribe the typical cross-track distribution of the depth-averaged velocity as (thin line in Fig. 3)

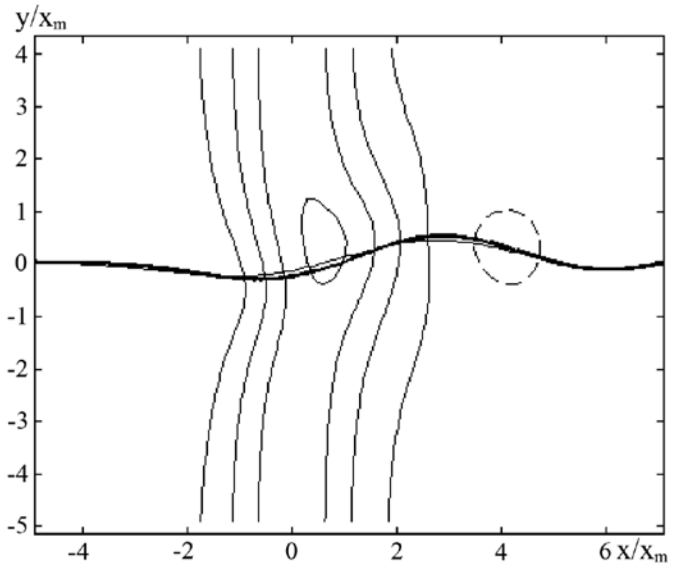
$$\frac{V}{v_m} = \frac{x}{x_m}\exp\left(\frac{1}{2} - \frac{x^2}{2x_m^2}\right). \tag{2}$$

Evolution of an initially straight baroclinic jet is considered under influence of such barotropic ocean flow.

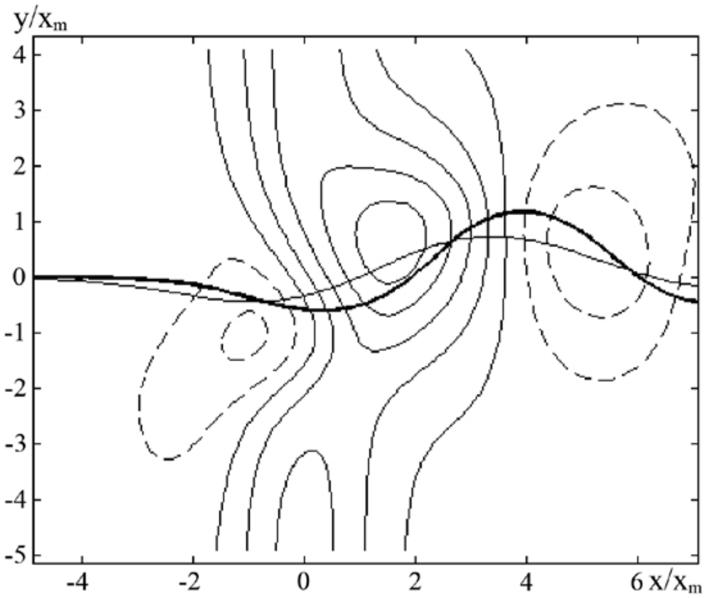
Numerical simulations using a two-layer model

For numerical simulations we use the two-layer intermediate geostrophic model [15]. The initial setup includes an upper-layer jet without meanders plus the barotropic flow (2) in both layers over a flat bottom. The baroclinc jet in the upper layer is initialized by the potential vorticity jump at $y = 0$ along the *x*-axis. Choosing x_m as the spatial scale and v_m as the velocity scale, the flow evolution depends on three nondimensional parameters: the jet intensity, u_m / v_m, the jet width, R_d / x_m, and the depth ratio H / H_0, where u_m is the maximum jet velocity, R_d is the baroclinic radius of deformation, H is the upper layer depth.

Typical results for $u_m / v_m = 8$, $R_d / x_m = 1/2$, $H / H_0 = 1/6$ are shown in Fig. 1 for $t = x_m / v_m$ and in Fig. 2 for $t = 2x_m / v_m$. It can be seen that in spite of antisymmetric structure of the barotropic flow (2), the jet meander growth due to the barotropic flow advection favors an anticyclonic meander to the right of the storm track in qualitative agreement with numerical simulations by S. Lee [11]. To evaluate physical mechanisms behind this effect we use a thin-jet theory.



F i g. 1. The mid-jet path (thick line) superimposed by the stream function in the lower layer (dash line shows positive (anticyclonic) deep eddies) of the two-layer model for $t = x_m/v_m$; solution (11) – (13) is shown by a thin line



F i g. 2. The mid-jet path (thick line) superimposed by the stream function in the lower layer (dash lines show positive (anticyclonic) deep eddies) of the two-layer model for $t = 2x_m/v_m$; solution (11) – (13) is shown by a thin line

Application of a thin-jet theory

In works [16, 17] the authors investigated meandering of thin ocean jets using a reduced-gravity shallow water model (valid for small depth ratio) by expanding the governing equations in terms of a small parameter, the radius of deformation multiplied by the meander curvature. In the leading approximation, the mid-jet path: at the *f*-plane can be described by a self-contained set of equations:

$$\frac{\partial Y}{\partial t} = V_{\text{jet}}(X,Y), \quad \frac{\partial X}{\partial t} = U_{\text{jet}}(X,Y), \tag{3}$$

$$\frac{\partial X}{\partial s} V_{\text{jet}} - \frac{\partial Y}{\partial s} U_{\text{jet}} = a\frac{\partial K}{\partial s} \ , \tag{4}$$

$$\left(\frac{\partial X}{\partial s}\right)^2 + \left(\frac{\partial Y}{\partial s}\right)^2 = 1, \quad K = \frac{\partial X}{\partial s}\frac{\partial^2 Y}{\partial s^2} - \frac{\partial Y}{\partial s}\frac{\partial^2 X}{\partial s^2}, \tag{5}$$

where the jet velocity (U, V) is defined by (3), X and Y are Cartesian coordinates of the jet, s is the distance along the jet, K is the curvature, t is the time, and the coefficient a is defined by the cross-jet structure

$$a = \frac{g'^2}{f^2(h_1 - h_2)} \int h \left(\frac{dh}{dn}\right)^2 dn \ , \tag{6}$$

where g' is the reduced gravity, h is the layer thickness, h_1 and h_2 are the thickness values at both sides far from the jet, n is the cross-jet coordinate.

Equation (4) indicates that the normal velocity of the baroclinic jet segment is proportional to the rate of change of centrifugal force along the path ($\partial K/\partial s$). Introducing the local azimuth of the jet, so that

$$\frac{\partial X}{\partial s} = \cos(\theta), \quad \frac{\partial Y}{\partial s} = \sin(\theta), \quad K = \frac{\partial \theta}{\partial s}, \tag{7}$$

from equations (3) – (6) a single equation can be obtained:

$$\frac{\partial \theta}{\partial t} = a\frac{\partial^2 \theta}{\partial s^2} + \frac{a}{2}\left(\frac{\partial \theta}{\partial s}\right)^2 + c_0(t)\frac{\partial \theta}{\partial s}. \tag{8}$$

The function $c_0(t)$ is determined by the boundary conditions at the inflow and /or by the initial condition. For an initial value problem in an unbounded domain when a localized perturbation of the jet is considered, this equation can be further transformed into the modified Korteweg – de Vries (mKdV) equation for the curvature. The mKdV equation is known to describe a variety of long, nonlinear waves, where the dispersive and nonlinear terms (the first and second terms in equation (8)) balance. The envelope solitary wave, or «breather», is particularly interesting as it describes a transformation of cyclonic meanders into anticyclonic ones and vise versa inside a breather [18].

Taking into account motion in active lower layer when the depth ratio is not too small, the velocity in the lower layer has to be included into equations (3):

$$\frac{\partial Y}{\partial t} = V_{\text{jet}}(X,Y) + \frac{\partial p}{\partial x}, \; \frac{\partial X}{\partial t} = U_{\text{jet}}(X,Y) - \frac{\partial p}{\partial y}. \tag{9}$$

Here p is the geostrophic stream function in the lower layer. Developing meanders at the initial stage can be interpreted using the formulation (4), (5) and (9) where p is defined initially by the TC-induced velocity (2). When the meander amplitude $|Y|$ remains small, a linearized version of (4), (5) can be considered assuming $X \sim s$:

$$\frac{\partial Y}{\partial t} = a\frac{\partial^2 Y}{\partial s^2} + V(s). \tag{10}$$

Its solution can be found by Fourier transforms to describe forcing of dispersing meanders:

$$Y(s,t) = \frac{1}{2\pi}\int \vec{Y}(k,t)\exp(iks)dk\,, \tag{11}$$

$$\hat{Y} = [1 - \mathrm{e}^{-i\omega t}]\frac{\hat{V}(k)}{i\omega}, \qquad \omega = ak^2\,, \tag{12}$$

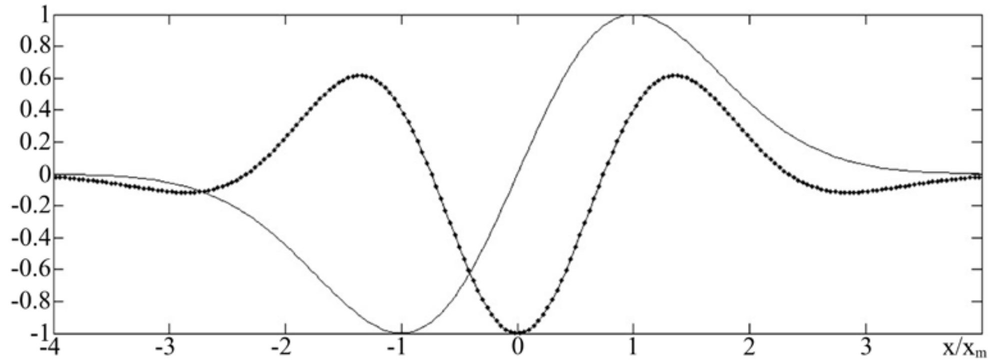
$$\hat{V}(k,t) = \int V(s)\exp(-iks)ds\,, \tag{13}$$

here hat denotes Fourier transforms, k is the wavenumber, ω is the frequency and i is the imaginary unit. In order to illustrate the asymmetry in developing meanders, we consider Taylor expansion in time. The first two orders show the meander growth proportionally to TC- induced velocity and modification of meanders due to dispersive effects

$$Y \sim tV(s) + \frac{at^2}{2}\frac{d^2V}{ds^2} + \ldots\,. \tag{14}$$

Fig. 3 shows V/v_m according to equation (2) in comparison with the second term (dotted line) normalized by its extremum value to illustrate that the anticylonic meander growth is enhanced while the cyclonic meander growth is reduced due to the dispersion properties of frontal waves along the jet.

The linearized solution (11) – (13) agrees well with the numerical solution during an initial period up to $t = x_m/v_m$ (Fig. 1). Advection of the jet by deep eddies coupled with meandering jet due to well-known baroclinic instability mechanism becomes noticeable in further enhancement of anticyclonic meander (Fig. 2). This kind of vertical coupling during growth of baroclinic meanders has been widely investigated (see, e.g., [19] and references therein).



F i g. 3. TC-induced barotropic velocity (2) (thin line) and the normalized dispersive term in equation (14) (dotted line)

Discussion and summary

The initial evolution of a baroclinic jet under influence of the TC-induced barotropic flow is considered using a two-layer model and the thin-jet approximation. In spite of antisymmetric structure of the barotropic flow, the jet meander growth due to the barotropic flow advection is shown to favor an anticyclonic meander to the right of the storm track in qualitative agreement with numerical simulations by S. Lee [11]. This enhancement of anticyclonic meander is found to be related to the dispersion properties of frontal waves along the jet described by the thin-jet theory during the initial stage. In order to consider further amplification of meander growth, the effects of vertical coupling have to be taken into account, e.g., using a two-layer model with both active layers as illustrated in Fig. 2.

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АНОТАЦІЯ У рамках двошарової моделі та в наближенні тонкого струменя розглядається еволюція бароклинного струменя, викликаного баротропною течією, індукованою тропічним циклоном. Показано, що, не дивлячись на антисиметричну структуру баротропної течії, її адвекція призводить до меандрування бароклинного струменя та до зростання головним чином антициклонічного меандру праворуч від штормтрека. Знайдено, що посилення антициклонічного меандру пов'язане з дисперсійними властивостями фронтальних хвиль (які описуються у рамках теорії тонкого струменя) і з взаємодією з глибинними вихорами, які розвиваються в нижньому шарі океану при меандруванні бароклинного струменю.

Ключові слова: бароклинний струмінь, тропічний циклон, антициклонічний меандр, теорія тонкого струменя.

АННОТАЦИЯ В рамках двухслойной модели и в приближении тонкой струи рассматривается эволюция бароклинной струи, вызванной баротропным течением, индуцированным тропическим циклоном. Показано, что, несмотря на антисимметричную структуру баротропного течения, его адвекция приводит к меандрированию бароклинной струи и к росту главным образом антициклонического меандра справа от штормтрека. Обнаружено, что усиление антициклонического меандра связано с дисперсионными свойствами фронтальных волн (описываемых в рамках теории тонкой струи) и с взаимодействием с глубинными вихрями, развивающимися в нижнем слое океана при меандрировании бароклинной струи.

Ключевые слова: бароклинная струя, тропический циклон, антициклонический меандр, теория тонкой струи.