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Conceptualizations and High School Earth Science Educational Guides of Tropical Cyclone Motion and Development

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요 약

태풍의 운동과 발달에 관하여 개념적 모형과 수치적 모형을 사용하여 조사하였고, 또한 고등학교 지구과학 교육과정을 위하여 이와 관련된 교육적 지침을 제공하였다. 절대 와도 보존에 근거를 둔 개념적 모형은 볼텍스(vortex)의 동쪽과 서쪽에 각각 위치한 일차적으로 유도된 고기압성 및 저기압성 자이어(gyre)가 β-평면상에서의 순압 볼텍스 운동에 주된 역할을 한다는 것을 제시한다. 비발산 순압모형을 이용한 수치 실험 결과, 중첩되어 일차적으로 유도된 고기압성 자이어의 강도와 위치가 볼텍스 운동과 밀접히 관련되어 있음을 알았다. 축 대칭 태풍 모형을 이용한 수치 실험 결과, 따뜻한 열대 해상에서 충분한 진폭을 가진 잘 구성된 초기 볼텍스만이 태풍으로 발달할 수 있음이 밝혀졌다. 과학교육의 목적을 달성할 수 있도록 제작된 실험 활동의 하나로써 태풍의 진로 추적이라는 제목을 가진 교과 내용물을 제시하였다. 제시된 내용물은 고등학교 지구과학 교과 과정에 포함될 수 있으리라 생각한다.

ABSTRACT

Some aspects of tropical cyclone motion and development are investigated using a conceptual model and numerical models and some related educational guides are provided for the high school earth science curriculum. A conceptual model based on the absolute vorticity conservation suggests that the primarily induced anticyclonic and cyclonic gyres located just to the east and west of the vortex, respectively, play a key role in the barotropic vortex motion on a β-plane. The nondivergent barotropic model simulations show that the intensity and location of the superposed primarily induced anticyclonic gyre are closely linked with the vortex motion. The axisymmetric tropical cyclone model simulations indicate that a well-organized vortex with sufficient amplitude over the warm tropical oceans is a prerequisite required for the initial vortex to intensify into a tropical cyclone. Subject contents with a title of typhoon tracking as an experimental activity are presented in such a way that the activity can achieve many objectives of science education. The presented materials can be potentially incorporated into the high school earth science curriculum.

INTRODUCTION

Tropical cyclones, called typhoons in the northwestern Pacific areas, are intense mesoscale vortices developed and maintained by vortex-ocean interactions. Because of their fascinating and destructive nature in our atmosphere, the physical processes associated with the genesis, intensification, maintenance and decaying of tropical cyclones have been studied extensively during the past three decades. Some of the observed features of tropical cyclones such as low central pressure, high wind speed, torrential rainfall and

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calm eye have been well known to most people, especially those who live in the influential areas of storms. The purpose of this paper is twofold. The first one is to investigate some aspects of tropical cyclone motion and development, which should be clarified for our further understandings of tropical cyclones. The second is to set up earth science subject contents with some educational guides on tropical cycone motion and development for high school students.

The nondivergent barotropic vorticity equation is one of simple equations which has physical significance in the large-scale atmospheric motion and it has been successfully used to explain many aspects of tropical cyclone motion. Many numerical studies performed with barotropic models have indicated that the motion of tropical cyclone is related to the vortex structure as well as the absolute vorticity gradient of the steering current. For an isolated vortex, the speed and direction of the drift depend on the vortex structure(DeMaria and Baik, 1987). The vortex track is more sensitive to size changes than to intensity changes(DeMaria, 1985; Chan and Williams, 1987).

Much efforts have been made to explain the preferred direction and speed of the vortex due to the β-effect. Rossby(1948) showed that an isolated cyclonic vortex is subjected to a resultant poleward force because of the latitudinal gradient of the planetary vorticity assuming that the surrounding atmosphere does not affect the vortex motion. Rossby's assumption did not allow the reaction effect of pressure around the moving vortex, so that it probably has little bearing on the long-term drift of the vortex(Kitade, 1981; Anthes, 1982). Adem(1956) obtained a solution to the nondivergent barotropic vorticity equation by means of a Taylor series expansion and concluded that the vortex would accelerate westward initially and gradually turn northward as the higher order time derivatives become important. Anthes and Hoke(1975) studied the vortex movement on a β-plane using the nondivergent and divergent barotropic models. Their results showed that both model vortices drifted in a general northward direction with speeds of 1.4-2.8 m/sec and an anticyclonic gyre developed east of the cyclone in both models. Fiorino and Elsberry(1987) used a nondivergent barotropic model with a moving grid and pointed that the nonlinear advective effects control the northward and westward components of the vortex drift through a rotation of the asymmetric flow gyres around the vortex. These previous studies provide a general idea that the β-effect causes the vortex to move towards the northwest in the northern hemisphere with speeds of 1-3 m/sec.

In the first part of this paper, we combine these earlier findings of the β-effect on the tropical cyclone track together and present a conceptual model of barotropic vortex motion on a β-plane assuming that there is no surrounding large-scale flow. Then, this conceptual model is tested through nondivergent barotropic spectral model simulations. Also, the sensitivity of the vortex motion to β is investigated.

Emanuel(1986) emphasized that the intensification and maintenance of tropical cyclones can be exclusively resulted from a finite-amplitude air-sea interaction instabiliby without any contribution from ambient conditional instability. Accordingly, in order for an initial disturbance to grow by self-induced mechanism without preexisting conditional instability, considerably organized surface heat flux is needed. This requires a well-organized initial vortex with sufficient finite-amplitude. The intensification of axisymmetric model tropical cyclone starting from neutral thermodynamic environment did not occur when the initial vortex amplitude was reduced from 12 to 2 m/sec(Rotunno and Emanuel, 1987) or 15 to 5 m/sec(DeMaria and Pickle, 1988). The objective of the second part of this paper is to decide a minimum initial vortex amplitude and a threshold sea surface temperature necessary for simulating the tropical cyclone development when the Betts convective adjustment scheme(Betts, 1986) is employed to parameterize cumulus convective processes and the Jordan's hurricane season sounding (Jordan, 1958) is used for an initial thermodynamic field. For these purposes, an axisymmetric finite difference tropical cyclone model is employed.

The third part of this paper presents subject contents with a title of typhoon tracking as an experimental activity. The presented materials can be potentially incorporated into the high schoool earth science curriculum and might help students draw an attention on typhoons which they experience every summer, and understand the basic concepts of tropical cyclone motion and development. Also, a brief suggestion on the environmental education is given in connection with the meteorology part of the high school earth science curriculum.

TROPICAL CYCLONE MOTION

A CONCEPTUAL MODEL ON THE β-EFFECT

The physical basis of the nondivergent barotropic vorticity equation is the conservation of absolute vorticity which is given by

$$\frac{\partial \zeta}{\partial t} + u\frac{\partial \zeta}{\partial x} + v\frac{\partial \zeta}{\partial y} + \beta v = 0 \tag{1}$$

where ζ is the relative vorticity, u and v are the nondivergent wind components in the eastward and northward directions, respectively, and β is the northward gradient of the Coriolis parameter. The ζ, u and v can be expressed in terms of streamfunction ψ as follows.

$$\zeta = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} \tag{2}$$

$$u = -\frac{\partial \psi}{\partial y}, \; v = \frac{\partial \psi}{\partial x} \tag{3}$$

Equation (1) means that the local change of relative vorticity is a sum of the nonlinear relative vorticity advection and the linear planetary vorticity advection. There are observational evidences(e.g., Chan, 1984) which indicate that vorticity advection is the primary mechanism for the tropical cyclone motion. This fact can be a justification in using the barotropic vorticity equation for the study of vortex motion. We will proceed the following arguments of barotropic vortex motion on a β-plane in the context of a conceptual initial value problem and assume that there is no surrounding large-scale flow.

First, suppose that an axisymmetric cyclonic vortex is put on an f-plane on which there is no variation of the Coriolis parameter(β=0). Because of the absolute vorticity conservation and a constant planetary vorticity, an air parcel moving around the vortex must have the same relative vorticity along the path. This implies that the path of the air parcel is a circle and the velocity vector is perpendicular to the gradient of relative vorticity. Therefore, the nonlinear relative vorticity advection term is exactly zero and the local change of relative vorticity is zero. Hence, the position of the vortex center at any time is the same as that of the initial vortex center. In the case of an f-plane, the initial vortex structure remains unchanged and the vortex is not drifted with time.

Next, consider an axisymmetric cyclonic vortex put on a β-plane. For the purely horizontal nondivergent motion, it can be shown from the equations of motion that resultant forces acting on the vortex in the x and y directions are given by

$$F_x = -\int_c (p - \rho f \varepsilon) \sin \theta dl \tag{4}$$

$$F_y = \int_c (p - \rho f \varepsilon) \cos \theta dl - \rho\beta \int_A \psi dA \tag{5}$$

here, p is the pressure, ρ a constant air density and f the Coriolis parameter. The A represents the area of a vortex with a closed boundary c, ε the streamfunction at the vortex boundary and θ the angle between x-axis and line element, dl, on c. The acceleration force due to the variation of planetary vorticity, the second term in Eq.(5), was introduced by Rossby(1948). This term is positive for an arbitrary cyclonic vortex, so the vortex is always subjected to a resultant force directed northward in the absence of the first terms in Eqs.(4) and (5). The force acting on a vortex through the boundary, the first terms in Eqs.(4) and (5), was introduced by Kitade(1981) who argued that the pressure field around the vortex is also important in the prediction of the vortex movement in addition to the Rossby acceleration force.

Let us imagine the moment that an axisymmetric cyclonic vortex is just put on a β-plane. At that moment, it can be easily shown that the first terms in Eqs.(4) and (5) are zero. Therefore, the only force acting on the vortex is the Rossby acceleration force and the vortex will experience northward force. After that moment, consider an air parcel with a small value of absolute vorticity in the eastern part of the vortex where southerly wind exists. As the air parcel moves northward, it will experience anticyclonic circulation because of the physical constraint of the absolute vorticity conservation. The resultant phenomenon is a formation of an anticyclonic gyre east of the vortex. To the east of the anticyclonic gyre induced by the vortex, northerly wind exists and an air parcel moving southward will acquire cyclonic circulation by the absolute vorticity conservation, resulting in a cyclonic gyre. This cyclonic gyre can induce an anticyclonic gyre in the eastern part and so on. With the same reasoning, a cyclonic gyre can be induced west of the vortex. This cyclonic gyre can produce a cyclonic gyre to the west and so on. During this process, the intensity of the induced gyre is weaker than that of the already existing adjacent gyre. In the regions between successive gyres east of the vortex, the flow directions of two gyres are the same. On the other hand, the flow directions are opposite west of the vortex.

The idealized schematic diagram on the above arguments is shown in Fig. 1. For the illustrative purpose, the induced gyres are drawn in circles and same

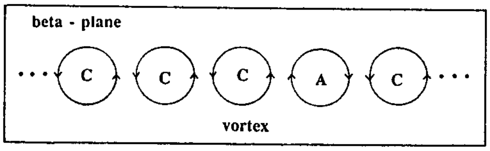

Fig. 1. The idealized schematic diagram of the induced gyres. The C and A indicate cyclonic and anticyclonic, respectively.

size and aligned parallel to x-axis. In an f-plane case, the vortex cannot induce gyres because of a constant relative vorticity along an air parcel trajectory. Once the vortex begins to induce gyres, the initial symmetric pattern of the vortex is destroyed and the first terms in Eqs.(4) and (5) no longer become zero. The forces act on the vortex in both x and y directions. Accordingly, the nonlinear relative vorticity advection term interacts with the linear planetary vorticity advection term to give rise to the relative vorticity tendency.

The point is that the gyres induced by the vortex just to the east and west play a key role in the vortex drift on a β-plane. Those gyres will be called the *primarily induced anticyclonic gyre* and the *primarily induced cyclonic gyre*, respectively. The primarily induced anticyclonic and cyclonic gyres remain asymmetric after the symmetric component of the vortex at any integration time is removed. However, if the symmetric component of the vortex and the primarily induced anticyclonic and cyclonic gyres are superposed, the resultant features are asymmetric vortex and much more distorted gyres. In this study, no attempt is made to decompose any total field into the symmetric vortex and the asymmetric gyre fields. Instead, only the total field will be considered. The primarily induced anticyclonic gyre which appears in the superposed total field will be called the *superposed primarily induced anticyclonic gyre*. We will identify the characteristics of the superposed primarily induced anticyclonic gyre in its relation to the vortex drift through the numerical model simulations.

DESCRIPTION OF NONDIVERGENT BAROTROPIC SPECTRAL MODEL

The model equations (1)-(3) are solved numerically on a doubly-periodic 3600 km square domain with a β value evaluated at 20°N(unless otherwise mentioned) using a spectral method with Fourier component basis functions. The Adams-Bashforth time differencing scheme is used to solve the spectral amplitude form of Eq.(1). The model is truncated with wavenumber 31 (unless otherwise stated) in both x and y directions and the time step is 240 sec. Further details of the model are described by DeMaria(1985). The initial condition is an axisymmetric cyclonic vortex given by

$$V = V_m\left(\frac{r}{r_m}\right)\exp\left\{\frac{1}{b}\left[1-\left(\frac{r}{r_m}\right)^b\right]\right\} \tag{6}$$

where V is the tangential wind speed and r the radial distance from the vortex center. The parameters of the vortex are specified as V_m = 30 m/sec, r_m = 125 km and b = 1.224. The parameter basically determines the vortex structure beyond the radius of maximum wind and is chosen so that the tangential wind speed at r = 300 km becomes 15 m/sec, which is a typical value at that radius for tropical cyclones. Equation (6) yields a maximum tangential wind speed of 30 m/sec at a radius of 125 km. The above vortex is initially positioned at the center of domain for the time integration. We define the vortex center as the streamfunction minimum.

RESULTS AND DISCUSSION

The wind vector field near the tropical cyclone cen-

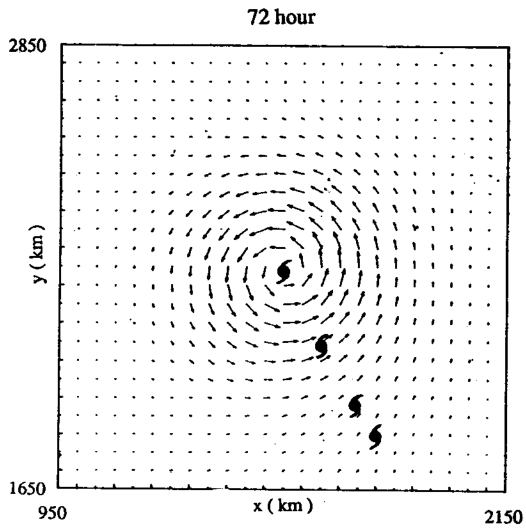

Fig. 2. The wind vector field at 72 hour. The 24 hourly storm positions are marked by the synoptic symbols for tropical cyclones. The magnitude of the maximum wind vector is 31.9m/sec.

ter at 72 hour is shown in Fig. 2. It can be seen that the initially symmetric wind pattern experiences a little distortion in the vicinity of the storm center. The wind speed east of the storm center is higher than that west because of the influence of the primarily induced anticyclonic gyre located just to the east of the storm. The maximum wind speed is 30.3 m/sec at 0 hour after the vortex structure given by Eq.(6) is represented by the spectral truncation of wavenumber 31 and 31.9 m/sec at 72 hour. This implies that the peak of wind speed is conserved very well. The peak values of relative vorticity and streamfunction were also very little changed during the time integration. DeMaria(1985) showed that phase errors in finite difference model result in fairly large errors in the prediction of the tropical cyclone track and sometimes computational dispersion is so severe that the vortex center can no longer be identified. The spectral model reduces the effect of computational dispersion considerably. Therefore, the spectral method appears to be more powerful than the finite difference method in the barotropic tropical cyclone track prediction model. The speed of the vortex gradually increases up to 54 hour. Afterwards, the vortex moves at a nearly constant speed of 2.5-2.6 m/sec. The storm moves towards between northwestward and northward directions(see Fig. 6).

In the previous subsection, a conceptual model on the induced gyres was presented under the physical constraint of absolute vorticity conservation on a β-plane. In order to figure out the gyres, the streamlines, which are independent of flow speed and give a better picture of circulation pattern, at 24, 48 and 72 hour are shown in Fig. 3. At 24 hour, the induced cyclonic gyre west of the vortex is superposed on the vortex circulation because the flow directions in the region between the vortex and the induced cyclonic gyre are in the opposite sense. As the storm moves towards the north-northwest, the portion of the advancing gigantic cyclonic circulation gyre superposed on the vortex reaches the model western boundary and disappears. The separated cyclonic flow pattern associated with the storm is observed at 72 hour. A gigantic asymmetric anticyclonic gyre east of the vortex(superposed primarily induced anticyclonic gyre) is clearly seen during the storm drift on a β-plane. The scale of the superposed primarily induced anticyclonic gyre is much greater than the vortex scale. The gyre moves together with the strom. The solid lines in Fig. 3 represent the lines connecting centers of the vortex and the superposed primarily induced anticyclonic gyre. A

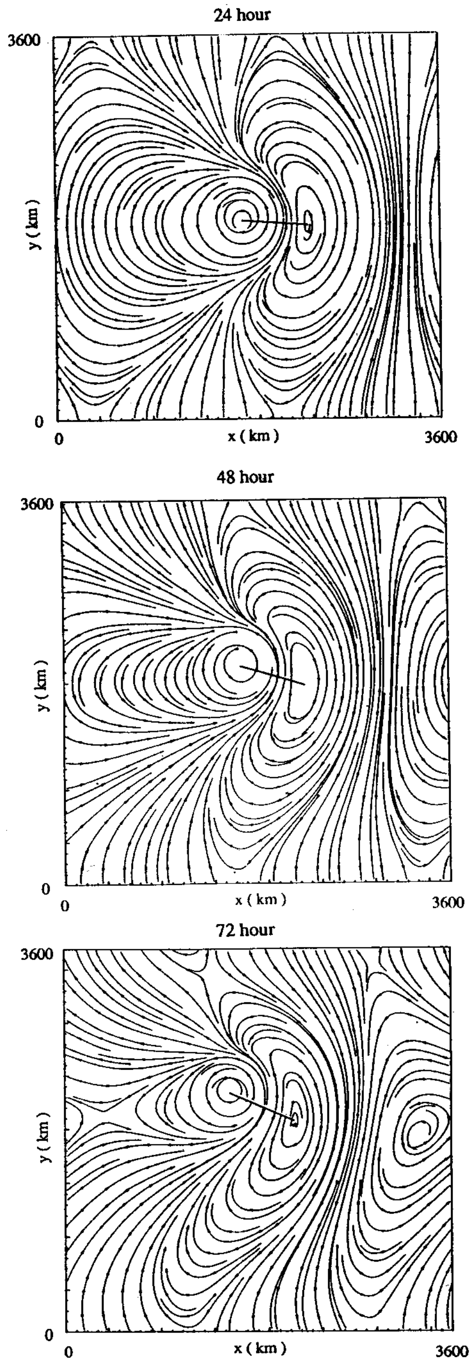

Fig. 3. The streamline fields at 24, 48 and 72 hour. The solid lines indicate the lines connecting centers of the vortex and the superposed primarily induced anticyclonic gyre.

closer inspection indicates that the line is gradually tilted from east-westward direction as the storm moves.

A cyclonic gyre east of the superposed primarily induced anticyclonic gyre appears as the time integration proceeds. The present spectral model employs a doubly-periodic boundary condition. So, there is a possibility that a portion of the advancing cyclonic circulation gyre towards the western boundary can reappear through the eastern boundary. Another possible condition already mentioned is that an air parcel moving southward acquires cyclonic circulation and this results in a cyclonic gyre. For the 3600 km square domain, it is not clear to decide which factor is more responsible for the formation of that gyre. However, it is believed that two factors are combined in forming the gyre in the present model simulation.

Figure 4 shows isotach fields corresponding to Fig. 3. This figure shows that the intensity of the superposed primarily induced anticyclonic gyre increases with time. Note that the center of the induced gyre does not coincide with the location of the maximum wind speed of the gyre like the vortex.

In order to investigate the effect of model domain size on induced gyres, two experiments are performed. One has a 1800 km square domain with wavenumber truncation of 15 in both x and y directions and the other has a 5700 km square domain with 49 wavenumber truncation. Therefore, the horizontal resolution in physical space in these two experiments is similar to that in the previous experiment with the 3600 km square doamin and the wavenumber truncation of 31. The streamline fields at 72 hour are shown in Fig. 5. For the smaller doamin size(upper panel), only a small portion of the cyclonic gyre east of the superposed primarily induced anticyclonic gyre is seen. For the larger domain(lower panel), the cyclonic gyre is in a complete form and the effect of periodic boundary condition is observed near the northern and southern boundaries. This figure imlies that the number of induced gyres depends on model domain size.

Now, we relate the speed and direction of the vortex(see Fig. 6) to the characteristics of the superposed primarily induced anticyclonic gyre. Two are noticeable. First, the intensity of the gyre is closely correlated to the vortex speed. As the gyre becomes intensified with time, the storm is gradually accelerated. Second, an examination of the degree of tilting in the solid lines(Fig. 3) with time reveals that the locations of the gyre, relative to the vortex center, somewhat

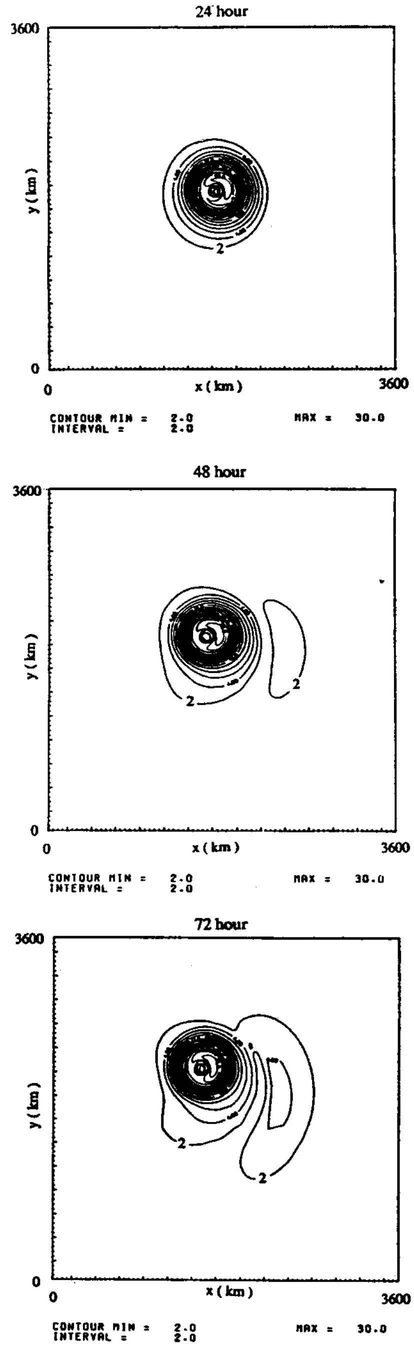

Fig. 4. The isotach fields in unit of m/sec corresponding to Fig. 3.

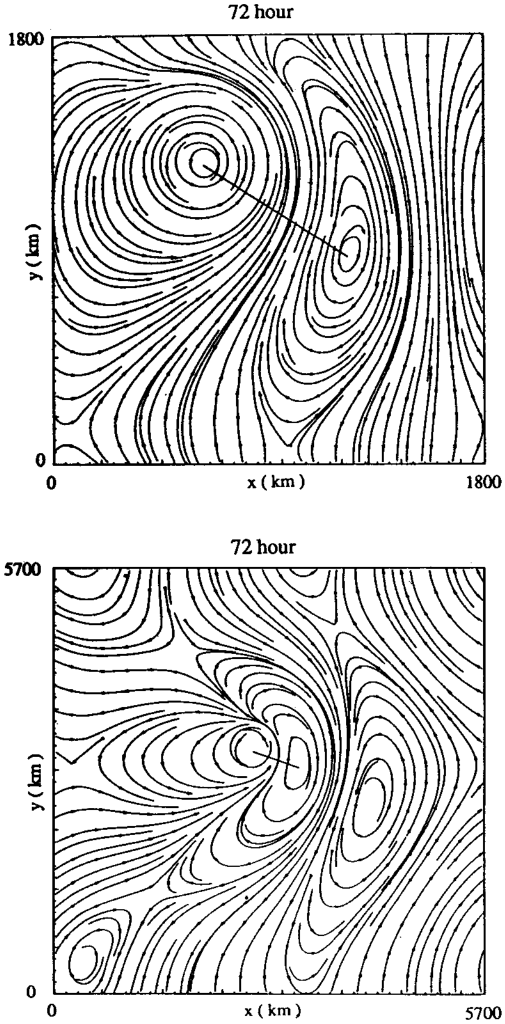

Fig. 5. The streamline fields at 72 hour for the smaller(upper panel) and the larger(lower panel) domain sizes. The solid lines have the same meaning as those in Fig. 3.

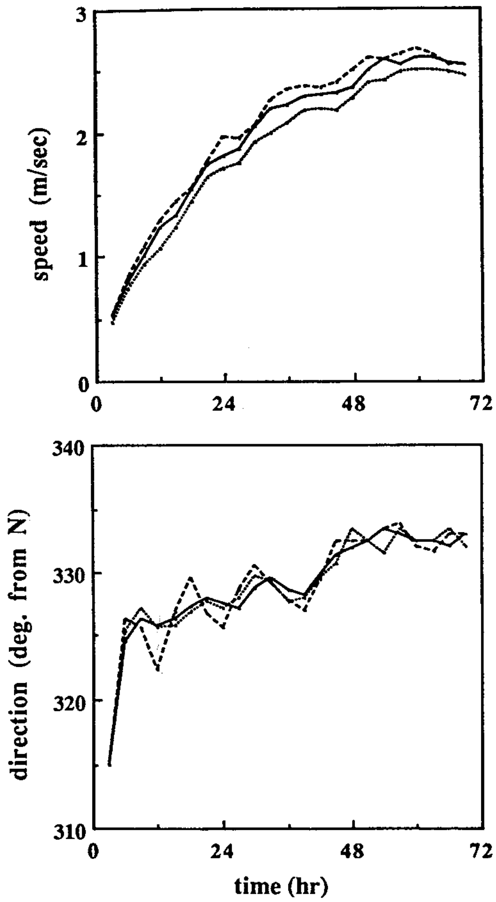

Fig. 6. The vortex speed(upper panel) and direction (lower panel) as a function of time. The dashed, solid and dotted lines correspond to β values evaluated at 10, 20 and 30°N, respectively.

reflect small changes in the vortex direction. The small tilting tendency towards the north-south direction with time gives a little change of the vortex direction towards the north. The superposed primarily induced anticyclonic gyre was induced by the initially symmetric cyclonic vortex due to the absolute vorticity conservation on a β-plane, moves with the storm and experiences intensity and location changes with time. The nonlinear relative vorticity advection term no longer becomes zero because of the asymmetric wind field and interacts with the linear planetary vorticity advection term. The gyre provides normal force through the vortex boundary and this force has both x and y components according to Eqs.(4) and (5). The magnitude of this force term is closely linked with the and provides northerly and westerly components of the vortex drift.

Next, the sensitivity of the vortex drift to β is investigated. For this purpose, 11 cases are simulated with different values of β, which are evaluated at latitudes between 10°N and 30°N with a 2° latitude increment. Figure 6 shows the vortex speed and direction as a function of time. The calculation was done using the three-hourly positions of storm centers. For the sake of clarity of figure, only three cases (10, 20 and 30°N) are plotted. These figures indicate that the increased β value results in a small increase in the vortex speed and the storm direction seems to be insensitive to changing β values. Figure 7 shows the mean vortex speed and direction during 72 hours as a function of β. It is interesting to note that the relation between the mean vortex speed and β is almost perfectly linear, although the difference in speed due to change in β is small compared with the vortex speed. Also, it is striking that the mean vortex direction is independent of β.

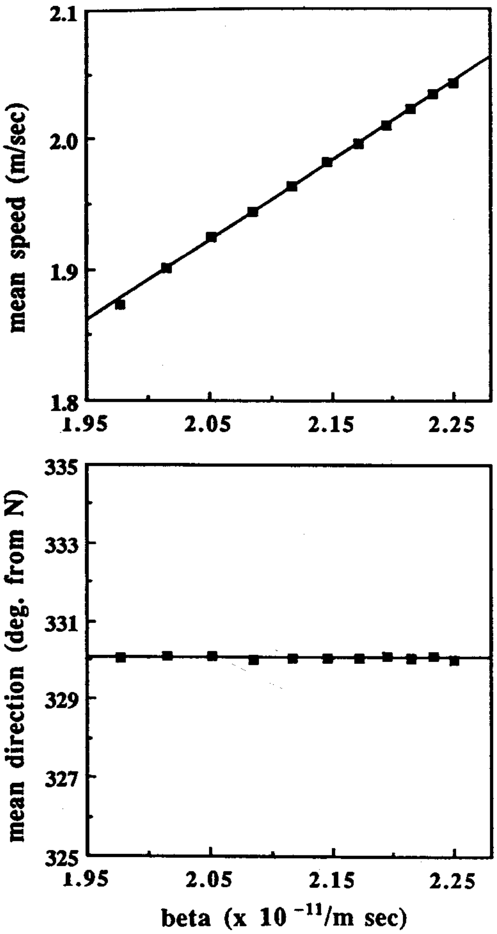

Fig. 7. The mean vortex speed(upper panel) and direction(lower panel) during 72 hours, which are indicated by the black square symbols, as a function of β. The solid lines represent linear regression lines.

TROPICAL CYCLONE DEVELOPMENT

DESCRIPTION OF AXISYMMETRIC FINITE DIFFERENCE MODEL

The axisymmetric tropical cyclone model used in this study is identical to that of Baik et al.(1990a), so only the essential features of the model will be repeated. The numerical model includes the conservation equations for momentum, mass, energy and water vapor and the equation of state. The vertical momentum equation is assumed to be hydrostatic. The system of equations is written with σ-coordinate in the vertical and axisymmetric polar coordinates in the horizontal on an f-plane. The model atmosphere is divided nto 15 layers with non-uniform thickness and has a uniform horizontal resolution of 20 km. The horizontal domain size is 1000 km. This optimal domain size for the primitive equation axisymmetric tropical cyclone simulations could be obtained by implementing a spectral radiation boundary condition, which employs a different gravity wave speed for each vertical mode. The governing equations are solved numerically using the finite difference method.

The model contains subgrid-scale horizontal and vertical diffusion, air-sea interaction, simple radiation, grid-scale phase change, dry convective adjustment and subgrid-scale moist convective processes. The air-sea interaction processes of momentum, heat and water vapor are parameterized using the bulk aerodynamic method. The exchange coefficient for heat and water vapor is assumed to be equal to that of momentum, which is calculated iteratively assuming that the lowest level(level 15) wind is in the constant stress layer.

The cumulus convection is implicitly represented by the Betts convective adjustment scheme(Betts, 1986). The basic idea behind the scheme is that under the presence of cumulus clouds the local thermodynamic structures are constrained by cumulus convective activity and adjusted towards an observed quasi-equilibrium state in nature. A crucial observational basis for deep scheme is that in the existence of penetrative deep convection a quasi-equilibrium temperature profile below the freezing level parallels a moist virtual adiabat, which includes parcel buoyancy correction due to cloud water, rather than a moist adiabat. For deep scheme, we construct first-guess reference profiles and then correct them to satisfy the conservation of moist static energy. The observational basis for shallow scheme is that in shallow cloudy region a quasi-equilibrium thermodynamic profile closely follows a mixing line which connects the saturation point of subcloud air and that of air above cloud layer. For shallow scheme, we construct first-guess reference profiles and then correct them to satisfy enthalpy and moisture constraints in such a way that integrated heating and moistening in the vertical are zero(hence, there is no convective precipitation in shallow clouds). If the computed convective precipitation rate in deep scheme is found to be negative, cloud top is specified and shallow scheme is applied.

The model is initialized with a cyclonic vortex in gradient wind balance and zero radial wind. The Jordan's(1958) hurricane season sounding for the West Indies area is used for an initial thermodynamic state at the model lateral boundary. The relative humidity sounding data above level 8 are not available. So, we insert RH = 40% at level 7 and RH = 20% at level 1 and a linear interpolation with respect to pressure is made to obtain relative humidity data at levels 2-6. No moisture perturbation near the storm is added. The initial surface pressure at the boundary is given as 1015.1 mb, which is the surface pressure in the Jordan's sounding. Note that inside the lateral boundary the temperature field and the surface pressure distribution are calculated by the initialization procedure. However, the initial relative humidity field is a function of height (σ) only. The Coriolis parameter is evaluated at 20°N.

RESULTS AND DISCUSSION

To find a minimum initial vortex amplitude necessary for the initial disturbance to intensify into a tropical cyclone when the Betts convective adjustment scheme is coupled with the Jordan's sounding, the model is time-integrated up to 10-day. The sea surface temperature is set to 28°C. Note that at initial time there are only shallow clouds over the entire model domain.

Figure 8 shows the time evolution of the maximum tangential wind speed at the lowest model level for the initial vortex amplitudes(denoted by v_m) of 4, 6 and 8 m/sec. The storms with v_m = 4 and 6 m/sec did not develop into tropical cyclones, while the storm with v_m = 8 m/sec did develop. Precipitation analyses(not shown here) indicate that convective precipitation begins at 77, 54 and 41 hour and grid-scale precipitation starts at 133, 95 and 77 hour for v_m = 4, 6 and 8 m/sec, respectively. These mean that the time period required for shallow clouds to become deep cumulus clouds is shortened as the initial vortex amplitude is increased and that subgrid-scale convective precipitation precedes grid-scale precipitation. For the three simulations, when there are only shallow clouds, storm development is slightly decelerated. Only after deep cumulus clouds appear in the model atmosphere, storms begin to develop. However, because of the low wind speed latent heat supply from the ocean is not large enough for the storms starting from v_m = 4 and 6 m/sec to become tropical cyclones within 10 days, implying that tropical cyclones cannot form out of weak random perturbations. It took a considerably longer time period for the initial vortex with v_m = 8 m/sec to intensify into a tropical cyclone compared with other model storms(e.g., Yamasaki, 1977).

It is shown in Fig. 8 that within the present model framework and for the sea surface temperature of 28°C the initial vortex amplitude should exceed 6 m/sec to simulate the development of a tropical cyclone with the Jordan's initial thermodynamic state when the Betts convective adjustment scheme is employed to parame-

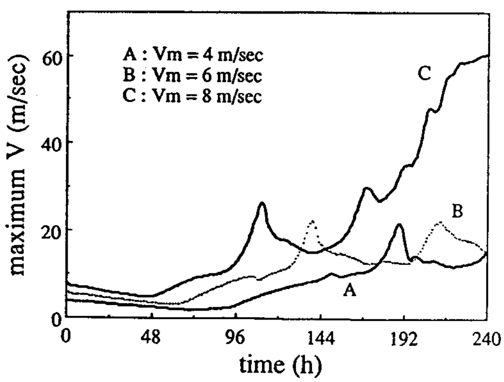

Fig. 8. The time evolution of the maximum lowest level tangential wind speed for the initial vortex amplitudes of 4, 6 and 8 m/sec.

terize cumulus convective processes. This implies that a well-organized strong vortex is initialy necessary for the intensification of the vortex into a tropical cyclone. In nature, such a strong starting disturbance may be occasionally provided by large nonlinear vorticity advection in tropical waves(Shapiro, 1977).

To decide a criterion of sea surface temperature necessary for simulating the development of a tropical cyclone with the present numerical model and investigate the response of model storm to high sea surface temperature, several experiments are performed with varying sea surface temperatures. Figure 9 shows the time evolution of the maximum lowest level tangential wind speed for the sea surface temperatures of 25, 27 and 30°C. In these experiments, the initial vortex amplitude is specified as 8 m/sec.

The model storms with sea surface temperatures of 25°C and 27°C did not intensify into tropical cyclones. For the 27°C case, although the maximum lowest level tangential wind speed is as large as 23.7 m/sec at 132 hour, the minimum surface pressure is only 1004.7 mb and the maximum lowest level tangential wind is located at 250 km radius from the center at that time step. On the other hand, the storm with 28°C sea surface temperature did develop into a tropical cyclone (see the case C with v_m = 8 m/sec in Fig. 8). From these results, it is found that a threshold value of sea surface temperature required for the simulation of a tropical cyclone using the present model with the Betts convective adjustment scheme and the Jordan's initial thermodynamic state is between 27°C and 28°C.

When the sea surface temperature is increased to

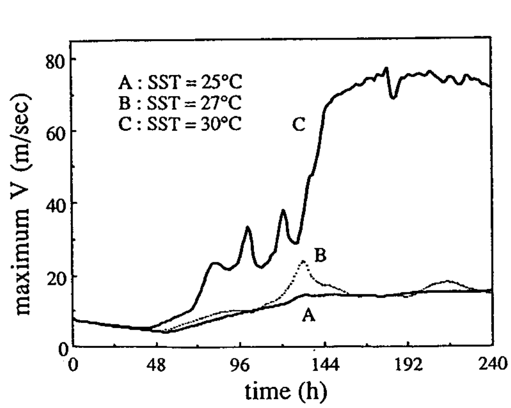

Fig. 9. The time evolution of the maximum lowest level tangential wind speed for the sea surface tem peratures of 25, 27 and 30°C.

30°C, the storm evolution is dramatic during the one-day period starting at 128 hour. The minimum surface pressure drop during that time period is about 79 mb. At the mature stage(from 168 to 240 hour), the maximum lowest level tangential wind speed and the minimum surface pressure are about 74 m/sec and 868 mb, respectively. This value of the simulated minimum surface pressure is nearly equal to the low-pressure record of 870 mb for the extremely extraordinary intense typhoon Tip which occurred on October 1979. Even though for the given sea surface temperature axisymmetric numerical models(Rotunno and Emanuel, 1987; Baik et al., 1990b) can produce a maximum possible intensity close to the theoretically estimated intensity(Emanuel, 1988), the real tropical atmosphere over the warm tropical oceans usually produces less intense storms. This is because the vertical shear of the horizontal wind and the sea surface temperature decrease due to oceanic mixing and upwelling can prohibit storm intensification(DeMaria et al., 1992).

HIGH SCHOOL EARTH SCIENCE EDUCATIONAL GUIDES

Using the conceptual model and the nondivergent barotropic model, we gave an explanation of why tropical cyclones tend to move northwestward in the northern hemisphere in the absence of large-scale environmental flow. In nature, there always exist large-scale circulations around tropical cyclones, which also affect tropical cyclone tracks. Although many complicated factors are responsible for tropical cyclone motion, one can say, as a good approximation, that a combination of the β-effect and the large-scale environmental flow patterns determines tropical cyclone motion. This fact, together with a need for well-designed experimental activities in the high school earth science course(An and Lee, 1991), motivates some earth science educational guides on tropical cyclone motion and development, which might be instructive to high school students. The subject title is *typhoon tracking,* which can be utilized as an experimental activity. The contents can be described as follows.

1. Instructor prepares typhoon track and wind data and tracking chart. The typhoon track and wind data contain day, time, position in latitude and longitude and maximum wind speed of the storm every synoptic time interval(12 hour interval). Table 1 shows one

example for the hurricane Erin, which occurred over the Atlantic ocean on Auguest 1989. Note that tropical cyclones over the Atlantic areas are called hurricanes and the maximum wind speed is in unit of kt because hurricane intensities are officially reported in kt with last digit having 0 or 5. Choose the typhoon which moved northwest in the subtropical region, then turned and moved towards the northeast in the midlatitudes (one of typical typhoon tracks) and affected the Korean peninsula and its surrounding areas. The typhoon tracking chart is a map of the northwestern Pacific areas with latitude and longitude lines drawn. An example of the hurricane tracking chart can be found in Paul(1986).

2. Students plot the typhoon positions on the tracking chart and connect the positions. Also, students plot the time evolution of the maximum wind speed on graph. Instructor helps students compute the mean typhoon speed and direction at any synoptic time by providing a simple formula for distance calculation given two locations on the earth. As references, the 1989 Atlantic tropical cyclone tracks are plotted in Fig. 10, the life-time maximum wind speeds and duration times are given in Table 2 and the time evolution of the maximum wind speed for the hurricane Erin (1989) is plotted in Fig. 11.

3. Instructor helps students find and understand that in large part the typhoon motion is determined by the large-scale environmental flow patterns, that is, the prevailing easterly wind in the tropical or subtropical regions causes the typhoon to move westward and the prevailing westerly wind in the midlatitudes causes the typhoon to move eastward. Also, instructor explains that an isolated tropical cyclone moves northwestward in the northern hemisphere due to the latitudinal variation of the Coriolis parameter in a simple context that students can understand with an aid of other subject contents in the earth science curriculum. Instructor mentions that tropical cyclone motion can be determined by a combination of the large-scale environmental flow and the effect of the latitudinal variation of the Coriolis parameter.

4. By examining the typhoon track chart and the time evolution graph of the maximum wind speed, instructor helps students understand that tropical cyclones form and intensify over the warm tropical oceans and lose their powerful intensities as they move into the midlatitude oceans with relatively lower sea surface temperatures or make landfalls. By doing this, students might understand implicitly that the energy source to drive tropical cyclones comes from the oceans.

5. The experimental activities on the construction and interpretation of weather map and the interpretation of satellite photograph will be included in the 6th high school earth science curriculum according to the

Table 1. The day, time, position and maximum wind speed of the hurricane Erin(1989)

day	time (GMT)	position latitude (°N)	position longitude (°W)	wind (kt)
20	12	19.8	37.6	30
21	00	22.0	40.7	40
21	12	22.1	42.4	40
22	00	25.0	43.0	40
22	12	29.4	44.2	65
23	00	30.5	46.5	65
23	12	31.5	46.2	65
24	00	32.5	45.8	70
24	12	34.1	44.7	75
25	00	36.3	42.3	85
25	12	38.8	39.8	85
26	00	41.7	36.6	75
26	12	47.0	35.9	65

Table 2. The names, dates and life-time maximum wind speeds of 1989 hurricanes

name	date (day/month)	wind (kt)
Allison	6/24-6/27	45
Barry	7/09-7/14	45
Chantal	7/30-8/03	70
Dean	7/31-8/08	90
Erin	8/18-8/27	90
Felix	8/26-9/09	75
Gabrielle	8/30-9/13	125
Hugo	9/10-9/22	140
Iris	9/16-9/21	60
Jerry	10/12-10/16	75
Karen	11/24-12/04	50

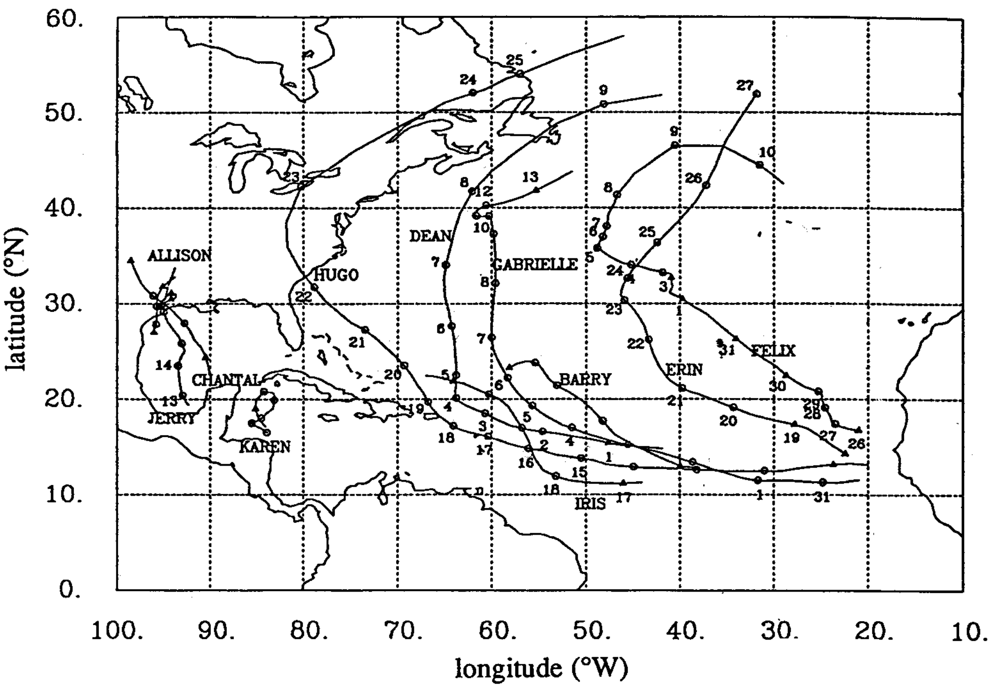

Fig. 10. The Atlantic tropical cyclone tracks during 1989. The 00 GMT positions are represented as a circle(triangle) when the storm intensity was greater(less) than tropical storm strength. The numbers next to the storm positions are the day of the month.

Korean Ministry of Education(1992). In connection with these activities, instructor preparers the weather map and satellite imagery of the typhoon. Students examine and interpret the satellite view of the typhoon and investigate how the typhoon track was affected by the large-scale environmental flow patterns on the weather map.

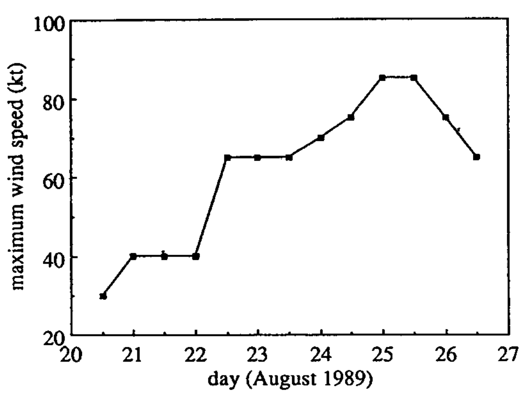

Fig. 11. The time evolution of the maximum wind speed for the hurricane Erin(1989).

6. Instructor selects a typhoon which made landfall over the Korean peninsula and prepares the typhoon tracking chart on which the typhoon positions are already plotted and connected, but are terminated on the chart near the southern ocean of the Cheju Island. Instructor also prepares the weather map near the termination time. Students predict next typhoon track based on the provided weather map and the effect of the latitudinal variation of the Coriolis parameter. Student compare the predicted tracks with the actual track. Finally, open discussions on tropical cyclone motion and development between instructor and students are made and instructor summarizes and concludes the typhoon tracking subject.

The experimental activity described above might be categorized into the Schwab's first inquiry level because the problem and some processes to solve the problem are given to students. However, based on the Klopfer's classification of science education objectives, the presented activity enables students to obtain abilities of the data analysis and interpretation, the problem recognition and search for resolution and the application of scientific knowledge and method as well as the knowledge and comprehension. Especially, the presented activity can induce students' interests in association with science and real life because typhoon is one of most familiar meteorological phenomena to Koreans.

The climate of the earth has been changed continuously by the natural processes with different time scales. These processes include the movements of continents, the collisions of large objects such as asteroids with the earth, the earth's orbital changes with which the beginnings and ends of ice ages can be explained, the volcanic eruptions etc. However, recently there has been increasing evidences for supporting the global warming tendency(greenhouse warming) caused by the non-natural processes, especially the increased carbon dioxide content ejected into the atmosphere by human activities. Since the greenhouse warming can change the earth's environment towards the undesired ways, a great demand is required to save our planet by educating people and reducing greenhouse gases.

The environmental education is interdisciplinary and can be perfomed in all curricula including earth science. Future earth science textbooks for high school students should contain the environmental problems we are encountering, for example, in terms of interrelated system of atmosphere, hydrosphere, cryosphere and biosphere. Students might quickly recognize the seriousness of man-made environmental changes if they learn how the weather and climate will be dramatically changed as a result of the global warming and how the changed weather and climate will affect mankind. One of such examples is with tropical cyclones. If the global warming in the atmosphere continues, the sea surface temperature also increases. As shown in Fig. 9, the increased sea surface temperatures can yield more intense tropical cyclones. The landfalls of more intense typhoons in changing climate over the Korean peninsula undoubtedly will cause more loss of property and life.

SUMMARY AND CONCLUSIONS

This paper investigated some aspects of tropical cyclone motion and development and provided some related educational guides for the high school earth science curriculum.

In the first part of this paper, the β-effect in the nondivergent barotropic tropical cyclone motion was studied assuming that there is no surrounding large-scale flow. The conceptual model suggested that gyres can be induced by adjacent vortex or gyres under the absolute vorticity conservation on a β-plane and the primarily induced anticyclonic gyre located just to the east of the votex and the primarily induced cyclonic gyre just to the west of the vortex play a key role in the vortex drift. The conceptual model was tested using the nondivergent barotropic spectral model. The model results showed that it is possible to figure out induced gyres. The scale of the superposed primarily induced anticyclonic gyre was much larger than the vortex scale. This implies that numerical modesl with relatively coarse horizontal resolution may track tropical cyclones. The results also showed that the intensity and location of the superposed primarily induced anticyclonic gyre are closely linked with the vortex drift. The sensitivity experiment with different values of β indicated that the increased β value results in a small increase in the vortex speed and the vortex direction is insensitive to changing β values. It was also shown that the mean vortex speed is a linear function of β and the mean vortex direction is independent of β. To understand the mutual interactions between the vortex and the primarily induced gyres is a key to the barotropic vortex drift on a β-plane. Further work is needed to examine the influence of different initial vortex structures on the intensity and location of the gyres.

In the second part of this paper, the Jordan's mean hurricane season sounding was used for an initial thermodynamic state in the axisymmetric finite difference tropical cyclone model which includes the Betts convective adjustment scheme to parameterize shallow convection as well as deep convection. Emphasis was put on deciding a minimum initial vortex amplitude and a threshold sea surface temperature necessary for the simulation of tropical cyclone development. The model results indicated that for the sea surface temperature of 28°C the initial vortex amplitude should exceed 6 m/sec to simulate the tropical cyclone development and for the initial vortex amplitude of 8 m/sec the threshold sea surface temperature lies between 27°C and 28°C. These results imply that a well-organized vortex with sufficient amplitude over the warm tropical oceans is a prerequisite required for the initial vortex to intensify into a tropical cyclone.

In the third part of this paper, some earth science educational guides for high school students were presented under the subject title of typhoon tracking. The subject contents as an experimental activity are organized in such a way that students can understand the basic factors responsible for tropical cyclone motion and deduce the energy source to drive tropical cyclones by plotting the typhoon track and maximum wind speed, computing the typhoon speed and direction and analyzing the results in connection with the large-scale atmospheric circulations on the weather map and the sea surface temperature. Also, included is the activity of forecasting typhoon track. It was suggested that when the environmental problems plan to be included in the meteorology part of the high school earth science textbooks, an attention should be paid on how the weather and climate can change in response to the global warming and how the changed weather and climate can affect mankind. Thus, students can recognize the seriousness of global warming by human activities.

Tropical cyclones are spectacular and intense vortices that fascinate atmospheric scientists in so many ways and much of what we had learned in the past from tropical cyclone research, especially cloud microphysics and convection, have been applied to other atmospheric phenomena. Although the basic dynamics and thermodynamics of tropical cyclones are fairly well understood, there still remains a lot of problems to be resolved, including tropical cyclogenesis and intensity change problems. Continuous research and educational efforts are required to better understand the nature of tropical cyclones and help students be familar with and interested in typhoons, which are most destructive among all natural disasters, but provide essential rainfalls over the Korean peninsula.

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REFERENCES

Adem, J., 1956, A series solution for the barotropic vorticity equation and its application in the study of atmospheric vortices, Tellus, 8, p.364-372.

An, H. S., and Lee, H. C, 1991, The problem and the improvement of experimental activities in the high school earth science course, Jour. Korean Earth Sci., 12, p.346-354.(in Korean)

Anthes, R. A., 1982, Tropical cyclones: Their evolution, structure and effects, Meteor. Monogr., No. 41, Amer. Meteor. Soc., 208p.

Anthes, R. A., and Hoke, J. E., 1975, The effect of horizontal divergence and the latitudinal variation of the Coriolis parameter on the drift of a model hurricane, Mon. Wea. Rev., 103, p.757-763.

Baik, J.-J., DeMaria, M., and Raman, S., 1990a, Tropical cyclone simulations with the Betts convective adjustment scheme. Par I: Model description and control simulation, Mon. Wea. Rev., 118, p.513-528.

Baik, J.-J., DeMaria, M. and Raman, S., 1990b, Tropical cyclone simulations with the Betts convective adjustment scheme. Par II: Sensitivity experiments, Mon. Wea. Rev., 118, p.529-541.

Betts, A. K., 1986, A new convective adjustment scheme. Part I: Observational and theoretical basis, Quart. J. Roy. Meteor. Soc., 112, p.677-691.

Chan, J. C. L., 1984, An observational study of the physical processes responsible for tropical cyclone motion, J. Atmos. Sci., 41, p.1036-1048.

Chan, J. C. L., and Williams, R. T., 1987, Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: Zero mean flow, J. Atmos. Sci., 44, p.1257-1264.

DeMaria, M., 1985, Tropical cyclone motion in a nondivergent barotropic model, Mon. Wea. Rev., 113, p. 1199-1210.

DeMaria, M., and Baik, J.-J., 1987, The effect of the vortex structure on barotropic hurricane track forecasts, 17th Conference on Hurricanes and Tropical Meteorology, Miami, Amer. Meteor. Soc., p.52-54.

DeMaria, M., and Pickle, J. D., 1988, A simplified system of equations for simulation of tropical cyclones, J. Atmos. Sci., 45, p.1542-1554.

DeMaria, M., Baik, J.-J., and Kaplan, J., 1992, Upper level eddy angular momentum fluxes and tropical cyclone intensity change, J. Atmos. Sci.(in press)

Emanuel, K. A., 1986, An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance, J. Atmos. Sci., 43, p.585-604.

Emanuel, K. A., 1988, The maximum intensity of hurricanes, J. Atmos. Sci., 45, p.1143-1155.

Fiorino, M., and Elsberry, R. L., 1987, The role of vortex structure in barotropic tropical cyclone motion, 17th Conference on Hurricanes and Tropical Meteorology, Miami, Amer. Meteor. Soc., p.55-59.

Jordan, C. L., 1958, Mean soundings for the West Indies area, J. Meteor., 15, p.91-97.

Kitade, T., 1981, A numerical study of the vortex motion with barotropic models, J. Meteor. Soc. Japan, 59, p. 801-807.

Paul, R. A., 1986, Meteorology exercise manual and study guide, Macmillan Publishing Co., 262p.

Rossby, C. G., 1948, On displacements and intensity changes of atmospheric vortices, J. Mar. Res., 7, p. 175-187.

Rotunno, R., and Emanuel, K. A., 1987, An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a nonhydrostatic axisymmetric numerical model, J. Atmos. Sci., 44, p.542-561.

Shapiro, L. J., 1977, Tropical storm formation from easterly waves: A criterion for development, J. Atmos. Sci., 34, p.1007-1021.

Yamasaki, M., 1977, A preliminary experiment of the tropical cyclone without parameterizing the effects of cumulus convection, J. Meteor. Soc. Japan, 55, p.11-31.

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