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A Methodology for Applying Conditional Nonlinear Optimal Perturbation and Natural Cybernetics to Tropical Cyclone Mitigation

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Abstract: Investigations into tropical cyclone mitigation, especially those made by Ross Hoffman, are introduced in the beginning to elicit the weather control version of 4-Dimensional Variation (4D-Var) as a nonlinear optimal control technique and the theory of natural cybernetics. Subsequently, the concept of Conditional Nonlinear Optimal Perturbations (CNOP) and the existing connotation of natural cybernetics related to weather modification are briefly presented. After that, the primary application of CNOP, improved by comparison with 4D-Var, are stressed upon, which can make use of the observational data during the controlling process, thereby having some advantages over 4D-Var in weather control. The technique may be called 'nonlinear optimal forcing variation calculus (NOFV)' or 'nonlinear optimal forcing perturbation (NOFP)' approach, which could make controlling as close to the observation as possible. Moreover, two other applications of CNOP, i.e. inversion of the initial perturbation evolving into a tropical cyclone and the solution of perturbation yielding maximum vertical wind shear with CNOP, are further investigated. Subsequently, the application of natural cybernetics to tropical cyclone mitigation and control, is analyzed in comparison with precipitation enhancement. Meanwhile, the means to realize tropical cyclone control and mitigation are synoptically reviewed. The investigation and analysis show that CNOP approach and natural cybernetics are useful in tropical cyclone mitigation and control.

Keywords: Conditional Nonlinear Optimal Perturbations (CNOP), Tropical Cyclone Mitigation, Natural Cybernetics, 4-Dimensional Variation (4D-Var), Nonlinear Optimal Forcing Perturbation (NOFP)

1. Introduction

Although tropical cyclone (TC), an extreme meteorological event and marine weather phenomena with great destructive power, has been always been watched closely in all social circles, it has only been in terms of its natural intensity evolution and travel route forecast. While tropical cyclone mitigation and control may be topics of interest, at present, they are limited to our imagination and science fiction movies. However, with the development of meteorology, mathematics, computer science, engineering, satellite technology and many relevant sciences and technologies, it may be possible to realize this dream in the near future, which would be very significant for coastal areas destroyed by tropical cyclones every year, especially the economically developed coastal cities.

In fact, Americans have been exploring the theories behind and the feasibility of hurricane mitigation for a long time, having launched an outfield experiment called "Stormfury"

[1, 2] to mitigate hurricane during 1962–1983. However, due to many discrepancies in theoretical and practical effects, the experiments were stopped eventually. Scientists seem to think that it is because the theories were limited to the cloud seeding theory, without an in-depth understanding of tropical cyclones before attempting these experiments. However, with the development of numerical simulation and computer technology, we can avoid such outfield experiments, in which numerical simulations were made in advance. More importantly, it may be impossible and unnecessary to counter atmospheric motions with equal amounts of energy because the atmosphere is a complex nonlinear system. The chaos theory put forward by Lorenz while investigating meteorological prediction—with the common form being the well-known 'butterfly effect'—shows that the atmosphere is very sensitive to initial values. After simulating a hurricane that occurred in the past, Ross Hoffman et al. [3] changed one or more of its characteristics at any given time and examined the effects of these perturbations. It was found that most of these alterations simply die out. Only interventions with special characteristics—a particular pattern or structure that induces self-reinforcement—will develop sufficiently to have a major effect on a storm. The challenge is to find just the right stimuli—changes to the hurricane—that will yield a robust response, leading to the desired results.

From this, Ross Hoffman and his colleagues developed a new method and technology for controlling hurricanes, with the basic idea that using nonlinear optimal control techniques gives a hurricane or its surrounding atmosphere a suitable perturbation to control its travel route through its own nonlinear effect. However, to match the tremendous energy of the hurricane, the perturbation also needs a large amount of energy, which may be provided by the space solar power station in the future. Most of their papers on this topic were published from 2004 to 2006 [4, 5]. However, 10 years since, their team does not seem to have made any significant progress, with America not launching any programs regarding outfield experiments. We believe that this is likely because of the following reasons. First of all, the nonlinear optimal control technique used by Hoffman is the weather control version of the 4-Dimensional Variation (4D-Var) method, which, as a data assimilation technique, has proved to be advanced, but problematic when directly applied to weather control. During the control process, the numerical model simulating tropical cyclones is assumed to be perfect, with no model errors. In reality, however, numeric models always consist of model errors. In particular, scientists have not understood the intensity and internal structure of tropical cyclones so far. Moreover, although in their ideal numerical simulations, the control vectors were changed across all layers, in the outfield experiment, Hoffman concentrated only on changing the environmental field surrounding the TC, because to change the structure of TC and then shift its route or intensity, required accurate structure simulation and data assimilation. Before 2006, there were technological bottlenecks with regard to such aspects, which may have caused the estimated route to be significantly different from the actual route after the modification. Last, but not the least, there may have been some difficulty in breaking through the numerical simulation, due to which they may have had to wait for the lift-off of satellites to emit enough energy. America had planned to build the first practical Solar Power Satellite via Arbitrarily Large Phased Array (SPS-ALPHA), designed to be completed within 25 years. However, they have not launched any satellite this year. Apparently, NASA has not been able to raise sufficient funds for this project.

As a matter of fact, weather modification could be regarded as one category of cybernetics [6, 7]. Academician Zeng Qingcun [8] from China has suggested 'natural cybernetics', which provides a new way to further investigate weather modification in science. Natural cybernetics research is the mechanism of automatic and artificial control of the natural environment and the theory, means and technology of manual regulation and control, in order to solve environmental and evolutionary problems, thus attaining harmony and the substantial development of human beings with their natural environment. From a new point of view, weather modification can incorporate traditional cloud dynamics, micro physics and weather modification theory with recent and rigorous cybernetics and programming methodology. It takes advantage of the existing achievements of meteorology and augments some new methods, such as feedback control, optimal programming, etc., thus opening up a quantitative and verifiable research technique to control weather.

Just like the development of 4D-Var, nonlinear optimal methods have been increasingly developing in meteorology and oceanography. Due to the complexity and nonlinearity of the atmosphere and ocean, Mu Mu and Duan Wansuo [17] introduced the concept of Conditional Nonlinear Optimal Perturbations (CNOP), so as to explore the impact of nonlinearity on the predictability of atmosphere and oceanic motions. The CNOP approach has been used to study the nonlinear dynamics of ENSO predictability [9, 10, 11, 12, 21, 22, 23], the sensitivity of ocean circulation [18] and ensemble prediction [19]. Furthermore, the CNOP approach has been used to determine the 'sensitive area' in target observations for TC [20]. These studies have shown that CNOP is a useful tool for studying the nonlinear evolution of weather and climate. Therefore, could it be used for the nonlinear optimal control of TC, similar to the 4D-Var approach?

In this paper, the concept of CNOP approach and the existing, related connation of natural cybernetics are briefly introduced in Section 2. After that, the principle usage of CNOP, improved by comparison with 4D-Var, is analyzed in Section 3. In Section 4, other uses of CNOP are further explored. Then, the application of natural cybernetics to TC mitigation is analyzed in Section 5. Towards the end, the methodology and prospects are summarized and discussed.

2. Synopsis of CNOP and Natural Cybernetics

2.1. The Concept of Conditional Nonlinear Optimal Perturbations

Conditional Nonlinear Optimal Perturbation (CNOP) is an initial perturbation that satisfies a given constraint and has the largest nonlinear evolution at the time of prediction. The CNOP approach, which is a natural generalization of the Linear Singular Vector (LSV) approach to a nonlinear regime, can be briefly reviewed here [11].

The evolution equations for the state vector w, which may include sea surface temperature, zonal wind and relative humidity, among others, can be inserted into a nonlinear model:

$$\begin{cases} \dfrac{\partial w}{\partial t} = N(w) \\ w|_{t=0} = w_0 \end{cases}, \tag{1}$$

where N is the nonlinear operator. The solution for equation (1) in time t can be written as

$$w(t) = M_t(w_0), \tag{2}$$

where w_0 is the initial value of the model and M_t is the "propagator" that "propagates" the initial value w_0 to a future time t. If u_0 is the initial perturbation superimposed on a reference state $U(t)$, which is the solution to the nonlinear model and satisfies $U(t) = M_t(U_0)$ (U_0 being the initial value of the reference state), the evolution of u_0 can be obtained using the following equation:

$$u(t) = M_t(U_0 + u_0) - M_t(U_0) \tag{3}$$

For a chosen norm $\|\bullet\|$, an initial perturbation, $u_{0\delta}$ is called the CNOP, if and only if the following is true:

$$J(u_{0\delta}) = \max_{\|u_0\| \le \delta} \|M_t(U_0 + u_0) - M_t(U_0)\|, \tag{4}$$

where $\|u_0\| \le \delta$ is an initial constraint defined by the norm $\|\bullet\|$ and J is the objective function.

CNOP is the initial perturbation, whose nonlinear evolution attains the maximal value of the cost function J at time t. In predictability studies, CNOP represents the initial error that has the worst effect on the prediction result at the optimization time (Mu and Duan, 2003). In our investigation, CNOP should be changed slightly, as discussed in the following section.

2.2. General Formulation of Natural Cybernetics and Connotation Related with Weather Modification

Natural Cybernetics [8] investigates the self-controlling behavior of the natural environment and the potential mechanism of anthropogenic control, developing a theory, method and technology for anthropogenic control, which will facilitate the solution of problems related to "environment and development", leading to the harmonious co-existence of mankind and the environment, with the sustainable development of mankind. In the abstract, the general formulation of its mathematical expression can be stated briefly as follows.

Consider a collectivity of some variables in the natural environment that we want to exploit or regulate. The variables interacting with them form the set *X(P,t)*, which could alter with spatial point *P* and time *t*. Given that *X* consists of components X_i *(i= 1, 2,..., m),* and the human activities related to them are humanistic variables *y(p,t)*, which is an n-dimensional vector, whose components are Y_j *(j= 1, 2,..., n)*. These variables directly or indirectly affect the natural environment variables *X(P,t)*, thereby changing or disturbing the evolutionary process of *X(P,t)*. As a result, the evolution of the natural environment X is determined by itself and the humanistic variable *Y*. The regularity of this evolutionary process is restricted by differential equations (usually partial differential equations), defined as,

$$\frac{\partial x}{\partial t} = L(X, Y, t), \tag{5}$$

in addition to initial conditions and boundary conditions. Obviously, human activities are confined by their own abilities, such as funds. Therefore, *Y* is restricted by some function or norm || • ||, i.e.

$$\|Y\|_e \le C, \tag{6}$$

where *C* is a limiting constant. Or the distance between the natural environment after change and the environment most suitable for human life is minor, so that some norm || • || of *X-Xp* should satisfy a certain restrictive condition

$$\|X - X_p\|_p \le D, \tag{7}$$

where D is a restrictive constant.

Natural cybernetics attempts to find the most appropriate human activity Y under the circumstances (6) or (7) or [(6) + (7)], so as to optimize some socio-economic benefit. The benefit is decided by the altered environmental variable, X and the humanistic variable, Y, which can be marked as *F(X,Y)*. Therefore, we require

$$F(X, Y) = optimal, \tag{8}$$

where the meaning of 'optimal' may be 'maximum' (for example, maximum economic benefit) or 'minimum' (for example, minimum expenditure or minimum contamination).

3. Primary Application of CNOP Improved by Comparison with 4D-Var

Ross Hoffman et al. used the weather control version of the 4D-Var approach, which is ordinarily used in data assimilation. Hence, we briefly introduced his method, adding some of our comprehension. In a target experiment, Hoffman et al. [5] sought a controlled state close to the observed state at the initial time ($t = t_0$), such that at a later time ($t = t_1$), the controlled or targeted simulation—that in our comprehension is the simulation added to perturbation—is close to a target atmospheric state. To mathematically define the objective function that will be minimized by 4D-Var, the unperturbed simulation U, is defined from time t_0 to t_1, with the corresponding states $U(t_0)$ and $U(t_1)$. Subsequently, the goal state $G(t_1)$ is defined, in which the tropical cyclone is repositioned approximately 100 km to the west of the position in $U(t_1)$. Then, 4-Var is used to find the optimal controlled or targeted simulation T, by simultaneously minimizing the difference between the goal (i.e., $T(t_1)-G(t_1)$)—which, based on our comprehension, is the difference between the perturbed state and the goal state at time t_1—and the initial states (i.e., $T(t_0)-U(t_0)$)—which is the difference between the perturbed state and non-disturbed state at the initial time, i.e. the initial perturbation itself. In other words, $T(t_0)-U(t_0)$ is the minimal perturbation to get within $T(t_1)-G(t_1)$ of the goal. With this end in view, we understand that the parallelism in the 4D-Var approach between weather control version and data assimilation application is as follows: the non-disturbed state in the former corresponds to the ambient field, which is apriori in the latter, while the former perturbed state (i.e. the optimal controlled simulation) resembles the latter numerical model solution. In addition, the goal state in weather control is similar to the observation field in data assimilation.

In their preliminary experiments, both, the goal state mismatch and the size of the initial perturbation, were represented in the cost function by a simple quadratic norm

$$J(t)=\sum_{x,k}\frac{1}{S_{xk}^2}[\sum_{i,j}\{T_{xijk}(t)-G_{xijk}(t)\}^2], \qquad (9)$$

where they use 4D-Var to minimize the sum $J(t_0)+J(t_1)$. Here, x defines the model variables (for example, temperature or horizontal wind components), i, j and k index the grid points in the three spatial dimensions, while t denotes time (either t_0 or t_1). The goal at t_0 is to stay close to the unperturbed initial conditions. Therefore, $G(t_0)\equiv U(t_0)$. In the equation, the flux or "coupled" form of the variables is used since this is the form of the primitive equations in MM5.

The control vector is a list of all the quantities that are allowed to be varied by the minimization. An example of an element of the control vector is the temperature at a particular grid point. In principle, one could minimize J with respect to the entire model state vector (i.e., all prognostic variables at all grid points). For MM5, these are the three-dimensional fields of p', P^*u, P^*v, p*T, p*q and P^*W (perturbation pressure, coupled with eastward and northward wind components, temperature, specific humidity and vertical velocity, respectively). The 4D-Var may be configured so that all variables are allowed to vary even though only temperature, horizontal wind and humidity observations are used. It is obvious that the weather control version of the 4D-Var approach is a substantially nonlinear optimal control technique.

In this way, we can initially follow their method to carry out some numerical simulations, where the model upgrades from MM5 to WRF. At the same time, during the process of solving with the 4D-Var approach, we can make use of DRP-4D-Var, established by Wang Bin et al. [26] at the Chinese Academy of Sciences, or compare it with solving by adjoint model, thus yielding some conclusions. Although we could probably ascertain some controlled simulation or effective perturbation, these works would not improve substantially, compared with those carried out by Hoffman.

In the following paragraphs, we improve upon the nonlinear optimal control technique—the weather control version of the 4D-Var approach. The presumption made by Hoffman et al. during their experiments with the 4D-Var approach, that the numerical model is perfect and the non-disturbed state is an accurate prediction, i.e. disregarding model errors, is a major defect. We wanted to consider model errors and attempt to utilize CNOP approach, which has been used in weather and climate prediction, target observation, initial perturbation of ensemble forecast, sensitivity of thermohaline circulation and so on. However, the approach has never been used to control weather. Hence, we do not know whether it can succeed to a certainty. However, it is very analogous to the 4D-Var approach as, for example, both of them are nonlinear optimal methods; both are correlated with numerical models and initial perturbations; the algorithms of numerical solution are also similar, such as using the adjoint model to compute gradient, using SQP or SPG algorithm to seek extreme values of the functions, etc. Only the 4D-Var approach is used to reduce the discrepancy between the model state after perturbation and the goal state to a minimum, whereas the CNOP approach is used to maximize the evolution of initial perturbation. How can it be related to the goal state, then?

Firstly, let us see the difference in cost function between 4D-Var and CNOP approaches. The cost function in 4D-Var represents the discrepancy between the model state after perturbation and the goal state, while that of perturbation evolution in CNOP represents the distance between the model state after perturbation and the non-disturbed state. Therefore, the difference between them represents the discrepancy between the goal state and the non-disturbed state. Moreover, the CNOP approach aims to achieve the maximum value, while 4D-Var aims to achieve the minimum. Therefore, their difference provides an extreme value. Nevertheless, the issue is to portray this difference

appropriately. We could start by checking if the simplest situation is appropriate. If the goal state was expressed as the non-disturbed state plus some constant, i.e. $G_{i,j,k}(t) = U_{i,j,k}(t) + C$, then the difference in cost function is a constant, which serves no purpose. Even if the constant is described a little more in detail to convert it into a time-invariant quantity, it would still be inappropriate. With regard to real circumstances, the non-disturbed state is not an accurate prediction or observation. Therefore, the goal state should be depicted as the observation field plus a time-invariant quantity, i.e. $G_{i,j,k}(t) = O_{i,j,k}(t) + I_{i,j,k}$. Then, the difference between the goal state and the non-disturbed state can be described as the model error plus the time-invariant quantity, as

$$G_{i,j,k}(t) - U_{i,j,k}(t) = E_{i,j,k}(t) + I_{i,j,k}, \quad (10)$$

where E represents the model errors; I symbolizes the time-invariant quantity; i, j and k index the grid points in the three spatial dimensions; and t denotes time. Due to the ease of calculation of the time-invariant quantity, the difference could be portrayed with model error.

As regards the model error, we considered combining 4D-Var with Optimal Forcing Vector (OFV) approach [12], which is close to the CNOP approach. Our preliminary consideration was to first use OFV to determine the model error that optimally matches the observation. Subsequently, there are two processing methods. One involves applying the 4D-Var approach to superimpose the cybernation for the equation on the optimal model error. Another method, as stated before, involves utilizing the optimal model error to determine the difference between goal state and non-disturbed state, subsequently applying the CNOP approach for cybernation. Here, the cost function is defined as the perturbed model state minus the non-disturbed state, subtracting these values once more.

This kind of technique amounts to {[OFV] ⊕ [4DVar]} or {[OFV] ⊕ [CNOP]} approach, which might be called the 'nonlinear optimal forcing variation calculus (NOFV)' or the 'nonlinear optimal forcing perturbation (NOFP)' approach. The greatest advantage of this approach, compared with the weather control version of the 4D-Var approach used by Hoffman et al., is to take model error into account, i.e. to make use of the observational data during the controlling process. Of course, the approach used by Hoffman might also have indirectly utilized observational data, in the process of solving the non-disturbed state with the numerical model. Therefore, our approach can make use of observational data twice, thus ensuring the controlling process is as close to the observations as possible.

4. Other Applications of CNOP

4.1. Inversion of Initial Perturbation Evolving into Tropical Cyclone with CNOP

As everybody knows, it is necessary for the formation of tropical cyclone to have atmospheric perturbation. Statistically speaking tropical cyclones originate from mainly 4 kinds of initial perturbations. The vortexes in the inter-tropical convergence zone occupy most of them about 80 percent; the easterly waves take up about 10 percent; the shearing-off lows or upper-air vortexes occupy about 5 percent; the baroclinic perturbations take up about 5 percent. Therefore, tropical cyclones are evolved from initial perturbations, which could be found out with CNOP approach. This is an inverse problem. For that matter, scientists in China has succeeded in the inversion of initial perturbation evolving into rainstorm with CNOP. That is to say, the rainstorm or tropical cyclone could be regarded as an intense perturbation under ordinary weather and using CNOP approach could reverse the perturbation. In this way, as long as human are able to attenuate the initial perturbation, the rainstorm or tropical cyclone could abate.

This application may include some problems. In the first place, there are so many perturbations in the tropical area and thus how to ensure the inverse initial perturbation precise without mistake? In the second place, when we solve the inversion the tropical cyclone has actually come into being. Whether it is too late to discuss the initial perturbation of tropical cyclone? Or what is the meaning? Give another consideration instead. Could we find out the common pattern of initial perturbations evolving into tropical cyclones? Just like the pattern of ENSO with positive sea surface temperature anomaly (SSTA) in the east and negative SSTA in the west or vice versa. If we could find the pattern out, we are able to eliminate or attenuate the tropical cyclone.

4.2. Solution of Perturbation Yielding Maximum Vertical Wind Shear with CNOP

Strong environmental vertical wind shear (VWS) is known to be one of the major reasons for the failure of generation and weakening of tropical cyclones (TCs) [13, 16, 25]. Observational studies suggested that the shear must be below some threshold value in order for a TC to develop, and statistical relations have been obtained in some previous studies. For example, Zehr [29] found that a shear value of 12.5 m s^{-1} prevents development of TCs in the western North Pacific while Gallina and Velden estimated the critical shear for TC development in the Atlantic to be 7–8 and 9–10 m s^{-1} in the western North Pacific. They also identified time lags between the shear and the change in TC intensity. Wang et al. [28] find that the low-level shear between 850 (or 700) and 1000 hPa is more negatively correlated with TC intensity change than any deep-layer shear during the active typhoon season, whereas deep-layer shear turns out to be more influential than low-level shear during the remaining less active seasons. Further analysis covering all seasons exhibits that a TC has a better chance to intensify than to decay when the deep-layer shear is lower than 7–9 m s^{-1} and the low-level shear is below 2.5 m s^{-1}.

Based on these studies, we put forward the following consideration. If we could seek out an extremely unstable point, perturbing which would make the vertical wind shear abrupt change, then the cirrus cap will be blown away and the warm core of TC may be destroyed. Thereby the tropical

cyclone will abate. This means is probably more remunerative than simple seeding cloud. At present, the means of weather modification are in principle seed freezing nucleus and hygroscopic nuclei to realize desired purposes. However, some scholars have pointed out the effect of 'explosion' on cloud body. After the operation of explosion or dynamical perturbation, some observational phenomena are difficult to illustrate with seeding cloud effect but they could be explained by dynamical perturbation. Therefore, we can find out this extreme unstable point with CNOP approach by numerical model of tropical cyclone to make vertical wind shear reach maximum at anticipated time. As a consequence, the intensity of tropical cyclone will abate.

5. Application of Natural Cybernetics for Tropical Cyclone Mitigation

Zeng Qingcun et al. [30], based on the theory of natural cybernetics, suggested a framework for artificial weather modification and its verification. The framework consists of observations and prediction (both before and during the operation), the quasi-continuous decision-making during operation (controlling) with feedback cycle, operation and verification. All the links are closely correlated to each other in the system. The scheme of operation is given by solving a relevant optimization problem. Accordingly, cybernetics is meant to control the entire system. Lei Hengchi et al. [15] re-surveyed the current situation of weather modifications using natural cybernetics and proposed that the direct, as well as inverse problems for weather modification should be investigated. Based on a case study, the optimal problem for controlling the weather modification operation is discussed. The inverse problem, i.e., the optimal controlling problem for weather modification, should be studied. The kernel problem of natural cybernetics is considered to be the optimal controlling problem for ascertaining the control method and establishing the control scheme, which is a kind of inverse problem. Another type of inverse problem mentioned in the paper is, seeking out the mode, range and intensity of the initial model perturbation, which is what the nonlinear optimal control technique attempts to solve. Therefore, the nonlinear optimal control technique could be ascribed to natural cybernetics, with the weather control version of the 4D-Var approach as a nonlinear optimal control technique, which could also be regarded as a control technique in natural cybernetics. From another point of view, the controlling of operational points is a type of 'local controlling', while the effective perturbation found by nonlinear optimal control technique is 'global controlling' before operation. Of course, this 'global controlling' is only a one-time event, whereas the 'local controlling' of operation points can be repeated multiple times.

As stated above, seeking out optimal perturbation by the nonlinear optimal control technique can be attributed to natural cybernetics, as it is essentially an inverse problem. In addition, from the research on cybernetics and weather modification, the application framework of natural cybernetics in precipitation enhancement operation (i.e. control of the entire operation process) can be used for the mitigation and control of TC. To explain briefly, with natural cybernetics method, we could regard the regulation of TC as a control engineering system that disposes and integrates prediction and regulation (i.e. operation) with observation and verification, composing them into an objective, sequential and closely-joined engineering system. Each link is not an independent or incoherent event because the feedback circuit correlates all of them in the system. The system includes the following links: (1) observation and prediction before operation; (2) enactment and execution of the preliminary scheme to operate; (3) observations set up and undertaken for the forthcoming operation, with complete course tracing of the operation and effect verification; (4) enactment and execution of tumbling-type or quasi-continuous operation scheme, which is the role of the feedback circuit and tumbling amendment of operations; (5) effect verification methods. The inlet of the feedback circuit and the optimal operation scheme were used to construct a distributed controlling problem that correlates to partial differential equations. Given the atmospheric state variables (including initial conditions and boundary conditions) and specified means of implementation, which is the seeding dose of catalytic agent for precipitation enhancement and TC regulation, solving the evolution of the atmospheric state (including micro-physical characteristics of cloud and rainfall) is a direct forecasting problem. Nevertheless, the means of implementation should be determined by the optimal effect. In this regard, there are concomitant equations of 'optimal operation scheme' or 'optimal controlling scheme', which could also be called the control problem or the inverse problem. The corresponding problems are usually the so-called 'adjoint equations', which are closely related to the original problems (i.e. direct problems).

It is important to explain the two aspects. Firstly, it is much more dangerous to artificially mitigate and control TC than to enhance precipitation. A wrong or failed regulation may have catastrophic consequences. Therefore, before engineering the operation, we should determine the effective perturbation as accurately as possible by the nonlinear optimal control technique. This means, numerical simulation should be undertaken before everything else. With regard to global and local, global controlling should take precedence over local controlling. Secondly, there are more methods of regulating TC than artificial precipitation enhancement. However, its project scale is much larger than that of precipitation enhancement, with much more complex feedback circuits than those of precipitation enhancement. The conditions for precipitation enhancement with natural cybernetics have been provided. For example, the observations can cover a large spatial range, with more progressive resolution and fineness than ever. The efficiency of catalysts has also increased, with the ability to manufacture in bulk. Meso-scale and regional weather predictions, as well as the equations for cloud and rainfall

evolution can largely describe cloud microphysics and rainfall precipitation. High-speed computers are more accessible, with the ability to be placed in the operational command position, while their arithmetic speed can satisfy the aging requirement. As long as observations, predictions, regulation schemes, operational commands and effect verifications are set up and organized well, such precipitation enhancing experiments can certainly be carried out. However, TC control and mitigation do not satisfy these conditions for the time being. They depend on further developments in engineering techniques and satellite techniques.

6. Discussion

Maybe what people concerned most are still the means to realize TC control and mitigation. The most probable reason is that tropical cyclones have too huge energy to be controlled. The heat quantity released by a mature TC every hour probably amount to energy capacity exploded by more than 2600 atomic bombs blown up in Japan. Even if energy capacity required by initial perturbation with the help of nonlinear optimal control technique could be less two or three order of magnitude than that of the tropical cyclone itself. It is also very breathtaking to manufacture such energy artificially. Once someone brought forward that detonating a bomb in the centre of tropical cyclone is possible to break up cloud wall and break down TC finally. In fact it is impossible. On the one hand, this means underestimate the energy of TC far and away. On the other hand, it also neglects the fact that TC mainly be fluid and the impact of inner and outer circulation. Due to the temporal transitoriness of single collision, even if some cloud and rain were dispersed, the circulation will supplement soon. There are some other means such as cold water pump, liquid nitrogen ship, giant steamer full of black carbon, membrane covering sea area and so on. Nevertheless, these means all need extremely gigantic scales because they are mostly carrying out around the TC, while it needs too huge energy to change outer circulation or the environmental field. As a result, they are mainly impossible to realize and so more feasible way is to alter the inner circulation or internal structure. At the present time, the actualizing means inside TC chiefly include several kinds as follows. The first one is explosion; the second one is seeding cloud; the third one is radiation from outer space; the fourth one is conducting thunder to discharge. Among them the most possible way to achieve the energy rank required by TC mitigation and control is to radiate from outer space. The space solar power station could be used to irradiate microwaves which could be absorbed by water vapor to heat local atmosphere so as to form perturbation, which is one of effective perturbations shown by numerical simulations. Simulation results from Hoffman indicate that a temperature increase of nearly 2°C causes the route modification or the reduction of the tropical cyclone. Isabelle Dicaire et al. [14] compute that under the following assumptions: (i) a transmission power is 1.5 GW with one space platform, (ii) the target is only water vapor, and the absorption rate of the power is 100%, (iii) the density of the water vapor is 5g/m^3, and (iv) the irradiation area has a circular, cylindrical shape with a 100-km diameter and 10-km height, heating a tropical cyclone by 2°C with an irradiation duration of 5 d by five SPSs. It is too long for 5 days but if only the irradiation power enhance the required radiation period would shorten. We believe that with the development of high power microwave or strong electromagnetic impulse this is completely realizable. In fact it is not necessary for such a large domain of atmospheric cylinder. Under the nonlinear effect, the range of sensitive area may just need 20-km diameter and 1-km height. Considering that the water vapor volume account for about 4 percent of the whole atmosphere, it just needs half a day for microwaves to irradiate. Of course, these are very idealistic presumptions whereas the factual circumstances are much more complex. During the process, the CNOP approach and natural cybernetics are able to issue the prospectus and unfold the grand plan greatly.

7. Conclusion

In this paper, we started with the work carried out by Ross Hoffman to elicit the nonlinear optimal control technique and natural cybernetics. Subsequently, we briefly introduced the concept of CNOP and the existing connotation of natural cybernetics related to weather modification. After that, we emphasized the primary application of CNOP, improved by comparison with 4D-Var, followed by further investigation of the other applications of CNOP. Subsequently, we analyzed the application of natural cybernetics in TC mitigation and control. From our investigation and analysis, it can be seen that the CNOP approach and natural cybernetics are very useful, whether in theory, method or technique, for TC mitigation and control.

Having said that, TC is an extremely complex and powerful subject, which even meteorologists and oceanographers have not fully understood, especially its intensity and internal structure. Therefore, the responsibility of mitigating and controlling TC is very onerous. As the saying goes, 'the way ahead is long; I see no ending, yet high and low I will search, with my will unbending'. As academician Zeng Qingcun explained using an old Chinese phrase ‘men can conquer Nature’, only those who can stabilize themselves can conquer Nature. We hope that our discussion acts as a catalyst for bringing together scientists researching TC mechanism and weather modification technology, with engineers. We believe that this dream can be realized some day in the near future.

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