# Model tropical cyclone behaviour in experiments related to modification attempts

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ABSTRACT

A numerical model of tropical cyclone development (Sundqvist, 1970*a*) has been used to study and compare the effects on the cyclone intensity by cloud seeding and spatial variations of sea surface temperature. The cloud seeding is simulated by taking into account heat released by freezing for temperatures below 0°C at selected radii of the convective area. The movement of a cyclone over a sea surface with a non-homogeneous temperature distribution is simulated in this axi-symmetric model by changing the sea temperature from one period of time to another inside a certain radius. The results indicate that the maximum winds of the symmetric model tropical cyclone rather have a tendency to intensify than to decrease when cloud seeding is employed. The results of the experiments simulating a fluctuating sea surface temperature show that even rather small scale (even smaller than the size of the convective region) variations significantly affect the intensity of a tropical cyclone.

## Introduction

In a recent paper (Sundqvist, 1970*a*; henceforth named P 1) the writer presented a numerical model of tropical cyclone development. A detailed study of the results of an integration revealed that the model cyclone exhibited a great deal of realistic features and that the system possessed a satisfying consistency energetically. It was thus inferred that the model could be used with confidence in various comparative experiments. In a later paper (Sundqvist, 1970*b*; P 2) a few such experiments were described. One of these was a study of the influence of sea surface temperature on the evolution and another was an investigation into how the intensity of the vortex was affected by an artificially strengthened convection in part of the precipitation area. In the discussion of these two specific experiments it was pointed out that they provide information that partly has direct practical implementation, despite the model not being applicable to actual atmospheric data.

The numerical integrations revealed that the intensity of the model tropical cyclone markedly depends on the sea surface temperature, which is in close agreement with earlier conclusions based on empirical studies (Palmén, 1948; Bergeron, 1954).

The experiment with artificially augmented release of latent heat was meant to give some idea of how effective cloud seeding could be in a mature tropical cyclone. The inclusion of the additional latent heat was made in a very simplified way, however, and hence was not a simulation of cloud seeding in that respect. The amount of extra heat given to the system was, however, judged to be at least as great as one may expect to be brought about by a seeding process. Still, practically no change in intensity of the model vortex was observed. Similar results (Gentry, 1969) have evidently been obtained in modification experiments with the numerical model at the National Hurricane Research Laboratory in Miami. These preliminary experiments thus indicate, as inferred in P 2, that any appreciable reduction of the maximum winds of a mature hurricane is unlikely to occur as a result of cloud seeding[2].

On the other hand, regarding the data obtained from the modification experiments on hurricane Debbie in August 1969 (Gentry, 1970), those suggest that cloud seeding might

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[2] Recently Rosenthal (1971) has studied the response of a hurricane model to artificially enhanced heating. This study was not brought to the author's attention until this paper was in press. Consequently, no comparative discussions are included here.

possibly have a reducing effect on tropical cyclone intensity. The fact that shortly after *each one of the two* seeding occasions—which took place 48 hours apart—a conspicuous decrease of the maximum winds was observed, seems to be one of the strongest indications that the human interference may have contributed to that decrease. Gentry (1970) also states, however, that it cannot be said with any certainty whether or not the observed changes were caused by the seeding.

Variations in hurricane intensity of the kind observed in the Debbie experiment may very well be caused or at least contributed to by several natural factors of which the sea surface temperature is probably the most dominant one. The behaviour of individual tropical cyclones in relation to the temperature of the underlying ocean surface has been studied and discussed in several papers (e.g. Fisher, 1957; Perlroth 1962, 1967). These show that there exists a noticeable correlation between changes in sea surface temperature along the path and changes in tropical cyclone intensity. Even a relatively small scale temperature pattern—which in fact characterizes the western equatorial Atlantic—appears to have a distinct influence on the hurricane intensity. During a 48-hour period say, it is hence conceivable that one or more fluctuations from low to rather high values of central surface pressure may be observed, because the cyclone passes over several bands of warm and relatively cool water in the same time.

It thus seems to be of value to get an idea of the relative importance of cloud seeding and fluctuating ocean temperature for the intensity of tropical cyclones, since then a more confident judgement of the effect of seeding in real cases should be possible. The purpose of the present paper is to compare the influences of the two above mentioned factors on the mature model cyclone.

As the model vortex is axially symmetric, a motion in over cool and warm waters cannot be simulated, but merely the effect due to their different extensions under the system can be studied. The simulation of cloud seeding is done here in a more realistic way than in the earlier experiment (P 2).

## Model, parameters and reference case

The model tropical cyclone is assumed to be an axially symmetric vortex in which hydrostatic and gradient balance exists. The heating due to release of latent heat through convection is parameterized and determined by the convergence of water vapor in the boundary layer; the vertical distribution of the heat released is a function of the temperature at the lifting condensation level and the stratification above. The tangential wind and the specific humidity are the two dependent variables predicted, while those remaining, i.e. the radial and vertical velocities and the temperature, are obtained diagnostically. The potential temperature, representative of the boundary layer, is, however, given by a prognostic equation in which variations of the surface pressure are taken into account. The vertical fluxes of momentum, sensible heat and water vapor at the air–sea interface are expressed respectively in the forms

$$\tau_s = -\varrho_s c_D |V| v$$
$$h_s = \varrho_s c_p c_D |V| (T_w - T_s)$$
$$m_s = \varrho_s c_D |V| (q_w - q_s)$$

where $c_p$ is the specific heat at constant pressure, $c_D$ the drag coefficient, $\varrho_s$ the air density, $V$ and $v$ the total and tangential winds (at 900 mb) and $T_s$ and $q_s$ are the temperature and the specific humidity in the boundary layer; $q_w$ is the saturation value of $q$ at the temperature of the sea surface, $T_w$.

In the actual integrations the computational region ranges from the center of the vortex to radius $r_{max} = 600$ km (where inflow and outflow is allowed) and from the ground ($p \cong 1\,000$ mb) to the 100 mb surface. The grid size is $\Delta r = 25$ km in the horizontal and $\Delta p = 100$ mb in the vertical.

For a more detailed description of the model, the reader is referred to P 1.

The basic values of the parameters are the following.

$f = 5 \times 10^{-5}\ 5^{-1}$; the Coriolis parameter at latitude 20° N
$c_D = 1.5 \times 10^{-3}$
$T_w(r_{max}) = 27.5°C$
$q_w(r_{max}) = 23.6$ g/kg

Furthermore we have

$T_s(r_{max}) = T_w(r_{max})$;
$p_s(r_{max}) = 1\,010$ mb; surface pressure at $r = r_{max}$

In addition to the previously mentioned relation between $T_w$ and $q_w$, the latter is by definition inversely proportional to $p_s$.

The same reference case is used in the present studies as in the experiments of P2. That is, the evolution of a vortex with initial conditions of barotropy and hurricane season stratification (Jordan, 1958). The parameter values, with $T_w = T_w(r_{max})$ independent of radius, are those given in the preceding paragraph.

## Simulation of cloud seeding

In a discussion in P1 it was concluded that an extra heat source introduced into the tropical cyclone system at a great distance—compared to the radius of maximum wind say—from the centre would reduce the cyclone intensity effectively. As the method of cloud seeding requires that clouds already exist, it cannot be applied farther out than in the outskirts of the main convective region of the system. The convection at that distance is relatively weak however, so that the additional heat release probably would be of little significance. The optimum distance thus lies between the last mentioned radius and the one at which the convective activity has its maximum. If seeding is applied at still smaller radii the differential heating will increase, which in turn favours an intensification.

The basic question thus is: can this type of intervention bring about so large an outward shift of the maximum of the heat release that the differential heating in the core region becomes significantly decreased despite the process involving an overall increase of the heating?

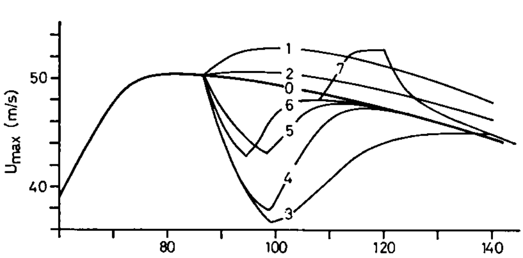


*Fig. 1.* Variation of maximum tangential wind for various experiments. Curve no. (0) control case; (1) cloud seeding experiment S1; (2) cloud seeding experiment S2; (3) through (7) show results of experiments with varying sea temperature as described in text and Table 1: (3) STP 2; (4) ST 5; (5) ST 2; (6) ST 4; (7) ST 7.

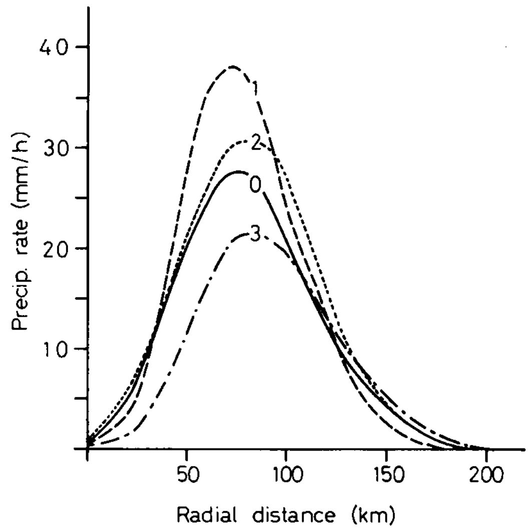


*Fig. 2.* Radial distribution of the rate of precipitation drawn to show the differential heating at $96^h$ in four different experiments. Curve no. (0) control case; (1) cloud seeding experiment S1; (2) cloud seeding experiment S2; (3) experiment ST3 with varying sea temperature.

In the quantitative study of the impact of cloud seeding on the model tropical cyclone it is assumed that the efficiency of the artificial freezing nuclei is complete. That is, the heat released by freezing is taken into account at all levels with a temperature below 0°C at those radii where seeding is simulated. Note that no additional external heat source is introduced, but merely a more efficient release of the latent heat in the region in question. Thus, the *resulting increase* in heating by condensation is determined by the dynamics of the model system; i.e., via the thermodynamics governing the convection, and the latter's interplay with the large scale motion. I seems that this approach is fairly analogous to the seeding of tropical cyclones.

The evolution of the maximum tangential wind of the model vortex is shown for two different seeding experiments by the curves (1) and (2) in Fig. 1; the curve (0) depicts the control case. The simulated seeding starts for both cases at $87^h$ of the control experiment and goes on during the whole period of time shown in the figure.

In the *experiment S1*, producing curve (1) it

Table 1. *Combinations of $T_A$, $r_A$ and $\Delta t_A$ in experiments with a varying sea surface temperature*

| Name of exp. | $T_A$ °C | $r_A$ km | $\Delta t_A$ hours |
|---|---|---|---|
| ST 1 | 26.0 | 175 | 12 |
| ST 2 | 26.0 | 75 | 12 |
| ST 3 | 25.5 | 75 | 12 |
| ST 4 | 25.5 | 75 | 7 |
| ST 5 | 24.5 | 75 | 12 |
| ST 6 | 24.5 | 75 | 7 |
| ST 7 | 29.5 | 75 | 7 |

is assumed that silver iodide is spread around both the radius of maximum precipitation rate ($r_p$) and the radius one grid distance *inside* $r_p$; i.e. in an annulus of width 50 km. It is seen that the model cyclone in this case intensifies to a new mature stage in which the maximum wind is almost 10 % higher than in the control case.

The rate of precipitation as a function of radius (reflecting the differential heating) nine hours after the seeding was started is shown for different experiments in Fig. 2 (curves 0, 1 and 2 correspond respectively to 0, 1 and 2 in Fig. 1). We notice, as discussed above, that the action of experiment S1 has resulted in a marked increase in the differential heating leading to an intensification as shown in Fig. 1.

In *experiment S2* (curve (2) in Figs. 1 and 2) the cloud seeding is applied around the radii one and two grid distance *outside* $r_p$. Fig. 1 shows that the model storm intensifies even in this case. However, the increase of the maximum wind is now much less pronounced than in S1.

The increased rate of precipitation of S2 outside $r_p$ is clearly demonstrated in Fig. 2. The consequent reinforcement of water vapor inflow causes a strengthening of the heating, even around $r_p$. Therefore, in this case also, the differential heating becomes somewhat stronger than in the control experiment, despite a slight outward shift of the condensation region is noted.

In another experiment (not shown in the present figures) the simulated cloud seeding was imposed at the two outermost gridpoints of the convective region. The additional heating thereby brought about was however very small because of the relatively weak activity of the basic convection in this part of the system. Consequently no significant departures from the control case were observed.

The results of these experiments thus indicate that in order to significantly affect the intensity of the axi-symmetric model tropical cyclone by cloud seeding it has to be applied in the part of the convective region where the basic activity is well developed. Because of this, and because of the relatively small radial extent of the condensation area, it appears that an increase rather than a decrease in the differential heating is more likely to occur. Consequently the effect—if any—of cloud seeding seems to be a tendency to intensify winds.

It is also of interest to mention that a couple of experiments have been performed where the cloud seeding ceases at $120^h$ in S1 and S2. The further evolution of the storm in those cases gradually (in about 20 hours) becomes practically identical with the one of the control case. This indicates that the cloud seeding does not act as a trigger mechanism, but can merely give a certain effect on the storm's development for that period of time during which it is being employed.

## Model storm response to a fluctuating sea surface temperature

In P2, the studies of the importance of the sea surface temperature for the evolution of the model tropical cyclone revealed that a drop in the surface temperature causes a weakened convection, which is most dominant in the inner part of the precipitation area. This is a consequence of the convective instability reduction, which becomes more pronounced the lower the pressure, since, for a given change of temperature, the change in surface air equivalent potential temperature increases with decreasing pressure. Therefore it was inferred that variations in sea surface temperature of a rather small horizontal scale (about the size of the core region) along the path of a storm may affect its intensity. Furthermore as mentioned in the introduction, observations reveal a correlation between fluctuations in ocean temperature and central surface pressure of mature tropical cyclones.

It thus appears to be of interest to obtain a quantitative measure of the effect from a non-homogeneous surface temperature on the

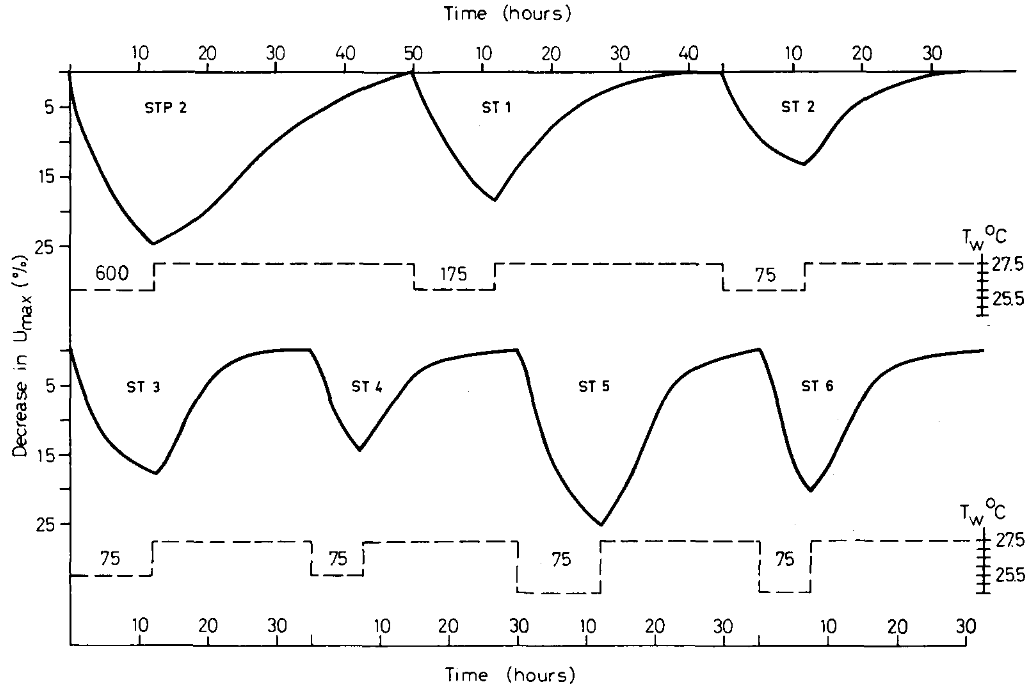


*Fig. 3.* Time variation of the percentage deviation of the maximum tangential wind from that of the control case for—in order from upper left corner to lower right corner—the experiments STP 2 and ST 1 through ST6. The relative time scale starts with zero each time a drop in $T_w$ occurs. The dashed line indicates the variation of $T_w$ and the numbers on this line give the radial extent of the $T_w$ drop.

model storm and then to compare this effect with that brought about by the simulated cloud seeding.

The motion of a real tropical cyclone over a certain distribution of sea surface temperature, $T_w$, can only be crudely simulated with the model storm because it is axi-symmetric. In the present experiments, the simulation is accomplished by assigning one value $T_A$ to $T_w$ between the centre and a radius $r_A$ and another value $T_B$ outside $r_A$. A temporal variation is introduced by setting $T_A$ different from $T_B$ during a limited period of time, $\Delta t_A$.

In all the present experiments $T_B = 27.5°C$, i.e., equal to $T_w$ of the control case. The integrations are started with $T_A \neq T_B$ from the $87^h$ state of the control case. The combinations of $T_A$, $r_A$ and $\Delta t_A$ that have been run are shown in Table 1. The experiment ST 7 is started from $107^h$ of ST 4 but is otherwise performed in the same way as the others.

For comparison we shall also look at the experiment in P 2 where $T_w = 26°C$ for 12 hours; the parameters of that case, which we here will call STP 2, thus are: $T_A = 26°C$, $r_A = r_{max} = 600$ km, $\Delta t_A = 12$ hours.

The time variation of the maximum tangential wind in some of the above mentioned experiments is shown in Fig. 1 (curves 3 through 7). First we notice that the departures from the control case are more acute in these experiments than in those with cloud seeding. We furthermore note that the return to the control case intensity after $T_A$ has become equal $T_B$ proceeds faster for smaller $T_A$ and/or for a greater preceeding difference between $T_A$ and $T_B$.

Comparing the changes of the maximum wind for different experiments it is seen that a drop of 2°C lasting for seven hours causes an intensity reduction that is as large as that caused by a drop of 1.5°C lasting for twelve hours when the radial extent of the lower temperature is the same in the two cases (curves 5 and 6 in Fig. 2). Similarly, the strongest winds of the model cyclone decrease at practically the same rate during a period of twelve hours whether the storm system is exposed to a 1.5°C lower sea surface temperature throughout the radial extent, or to a 3°C lowering of $T_w$ inside a radius of 75 km (curves 3 and 4 in Fig. 2). We furthermore observe in Fig. 1 that a rise in sea surface temperature in the core region results in an intensification which is as pronounced as is the weakening brought about by a corresponding drop in $T_w$ (curves 6 and 7).

Another aspect of the response in the intensity of the model tropical cyclone to a fluctuating sea surface temperature is given i Fig. 3. The percentage deviation of the maximum tangential wind from that of the control case is plotted against time for the experiments STP 2 and ST 1 through ST 6. The time scale is relative, starting with zero when the drop in $T_w$ occurs for each case. The variation of the sea surface temperature is indicated by the dashed line at the bottom of each half of the figure and the numbers on that line give the radial extent (in km) of the $T_w$ drop. The composite shows that sea surface temperature variations, with amplitudes of a realistic magnitude, cause the maximum wind of the model storm to alternate between values that may differ by as much as 15 to 25 %. The frequency of these alternations depend on the horizontal scale of the temperature drop (or rise). Nevertheless it is quite possible to observe one or several high and lower intensity states within a span of the order of 40–60 hours.

## Concluding comments

The quantitative results of the model experiments, which have been presented in the two preceeding sections, indicate that fluctuations in sea surface temperature along the paths of tropical cyclones distinctly influence their intensity. Furthermore it is indicated that a more likely effect of cloud-seeding is an increase rather than a reduce of the intensity of a storm. In any case, it appears that the latter kind of intensity changes are of smaller magnitude than those induced by a varying sea surface temperature.

It is thus quite conceivable that possible outcomes of cloud seeding may be obscured by effects that are produced by variations in sea surface temperature. This must naturally make the evaluation of seeding experiments more difficult. Consequently, it seems, a good number of such experiments will have to be performed before the results of those make a judgement or conclusion of significant certainty possible. A conservative interpretation thus implies that in connection with hurricane modification attempts it is necessary to know the temperature of the sea. At any rate, we may state that such a knowledge will noticeably improve the possibilities of confidently assessing the consequences of cloud seeding in nature.

There are instruments available today, with which the surface temperature can be measured with an accuracy that is acceptable in the experiments discussed above (see e.g. Smith et al., 1970). For the purposes that we have in mind here it is not a very accurate absolute temperature measurement that matters most, but an indication of how the sea surface temperature changes from one place to another. Radiometer measurements from satellites may become vitiated in the vicinity of a tropical cyclone because of clouds. This deficiency can probably be remedied by measuring from airplanes in the area in front of (with respect to an expected path) the storm system and possibly also beneath it. The model experiments presented above suggest that such efforts to obtain the temperature of the sea surface are worth-while considering.

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## МОДЕЛЬ ПОВЕДЕНИЯ ТРОПИЧЕСКОГО ЦИКЛОНА В ЭКСПЕРИМЕНТАХ ПО ИСКУССТВЕННОМУ ВОЗДЕЙСТВИЮ

Численная модель эволюции тропического циклона (Сундквист, 1970а) была использована для изучения влияния искусственного воздействия на облака и пространственных изменений температуры моря на интенсивность циклона. Воздействие на облако моделировалось путем учета тепла, освобождаемого при замерзании при температуре ниже 0°C на некоторых выбранных радиусах в области конвекции. Движение циклона над поверхностью моря с неоднородной температурой моделировалось в данной осесимметричной модели путем изменения со временем температуры моря внутри некоторого радиуса. Результаты показывают, что максимальные ветры в симметричной модели тропического циклона имеют тенденцию к интенсификации, а не к ослаблению при искусственном воздействии. Результаты экспериментов, моделирующих флуктуации температуры поверхности моря, показывают, что изменения весьма малых пространственных масштабов (даже меньших размера конвективной области) значительно влияют на интенсивность тропического циклона.