ON THE IMPORTANCE OF THE SEA-SURFACE TEMPERATURE ON HURRICANE DEVELOPMENT. NUMERICAL EXPERIMENTS

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RESUMEN

Una de las más claras interacciones océano-atmósfera se observa en la relación entre la temperatura del mar y la intensidad de los vientos máximos de los huracanes. En este trabajo, se hace una breve descripción de la forma en que un aumento de la temperatura de la superficie del mar, induce un aumento de la presión del vapor de agua en el aire cercano a la superficie, lo cual a la vez produce un aumento de calor latente disponible. Esto último genera nubes y un calentamiento que produce una disminución de la presión barométrica. Se mencionan casos en que este fenómeno se ha observado, con referencia al Golfo de México y el Pacífico Nororiental. Se hace referencia también a un modelo numérico, simétrico y balanceado de un huracán, mediante el cual se ha probado la hipótesis mencionada. Los resultados que se han obtenido verifican, en esencia, la validez de la teoría y al mismo tiempo dan confianza al modelo. Estos resultados señalan valores críticos de la temperatura de la superficie del mar y del ángulo de entrada de los vientos de niveles bajos como condiciones necesarias para la formación del huracán.

ABSTRACT

This paper contains a brief description of how an increase in sea-surface temperature induces a decrease in surface pressure which, in turn, causes an increase in the hurricane maximum winds. Some observational support for this process is obtained from case-studies of hurricanes in the Gulf of Mexico and the norteastern Pacific. A numerical model of a balanced, symmetric hurricane is used for theoretical tests of the process. Results of the tests verify, in essence, the validitv of the reasoning and, at the same time, give credence to the model. Experiments using our numerical model show that critical values of sea-surface temperature and, in addition, of the inflow angle are necessary conditions for hurricane development.

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INTRODUCTION

Hurricanes represent a clear-cut example of air-sea interaction. It is known that some conditions are needed for hurricane development. These conditions are well known to tropical meteorologists and have been published in several books; e.g. Palmen and Newton (1969). The necessary (but not sufficient) climatological-geographical conditions are:

1) A sufficiently large maritime area having such a high sea-surface temperature value that moist air-masses lifted from the lowest layers of the atmosphere (almost at sea-surface temperature) remains considerably warmer than the surrounding undisturbed atmosphere while expanding pseudo-adiabatically up to at least 12 km.

2) A Coriolis parameter larger than a minimum value, which precludes hurricane formation in a belt of about 5° to 8° latitude on either side of the Equator.

3) A weak vertical wind shear and, correspondingly, a weak baroclinicity in the basic current over a deep tropospheric layer.

It is felt that some of these necessary but insufficient conditions need further study on a synoptic rather than on a climatological basis.

IMPORTANCE OF THE SEA-SURFACE TEMPERATURE

Palmén (1948) mentioned that for a hurricane to form it is necessary that such a formation occurs over oceanic regions away from the Equator where the sea-surface temperature is above 26-27° C. Because the atmosphere has "a relatively poor memory", its capacity "to remember" is obtained through the interaction with the ocean which has a large capacity for energy storage (Adem 1973). The energy is released by atmospheric phenomena, being the hurricane –among them– one of utmost importance.

Several situations have been observed in which a hurricane enters an area having a higher sea-surface temperature than that of the surrounding areas. In these situations, a major intensification has been observed. One example is that of Hurricane Hilda, 1964. According to Hawkins and Rubsam (1968), Hilda became a full hurricane only after the originally weak storm moved over the warm waters of the Gulf of Mexico. Another example is that of Hurricane Beulah, 1967, reported by Sugg and Pelissier (1968). After crossing over the northeast portion of the Yucatan peninsula, Beulah moved back to sea on a northwesterly track. Beulah intensified very significantly over the warmer waters of the central Gulf of Mexico, reaching a central pressure of 923 mb which is one of the lowest values recorded in hurricanes. It is known that northeastern Pacific hurricanes loose in intensity as they move over generally cool waters to the west of the Baja California peninsula. However, some hurricanes have made landfall on the peninsula and have even emerged to the Gulf of Cortes when sea-surface temperatures were not too cool.

The importance of sea-surface on hurricane formation has been stressed in recent articles by personnel of the National Hurricane Center, Miami, Florida; e.g. Hebert and Frank (1974). The lack of hurricanes in the 1972 and 1973 seasons is explained by the lower-than-normal sea-surface temperatures which were observed in the western Atlantic. In contrast, warmer temperatures were recorded near the intertropical convergence zone over the east equatorial Pacific and many hurricanes formed in the northeastern Pacific in 1972 and 1973.

THE CISK THEORY

In recent years, a theory about hurricane formation has been formulated by Charney and Eliassen (1964). This theory has been called CISK, initial letters for Conditional Instability of the Second Kind. The theory, which is well accepted in Tropical Meteorology states, in essence, that the original disturbance produces humidity convergence in the lower levels. Due to mass continuity, upward vertical motion is induced. As air masses over the sea have a large relative humidity value, condensation occurs and latent heat is liberated. Part of the liberated latent heat is going to increase the kinetic energy. This, in turn, increases the convergence and, so, a chain of events is established. Of course, the large the sea-surface temperature, the larger the humidity content of the convergent air-masses and, also, the larger the latent heat liberation.

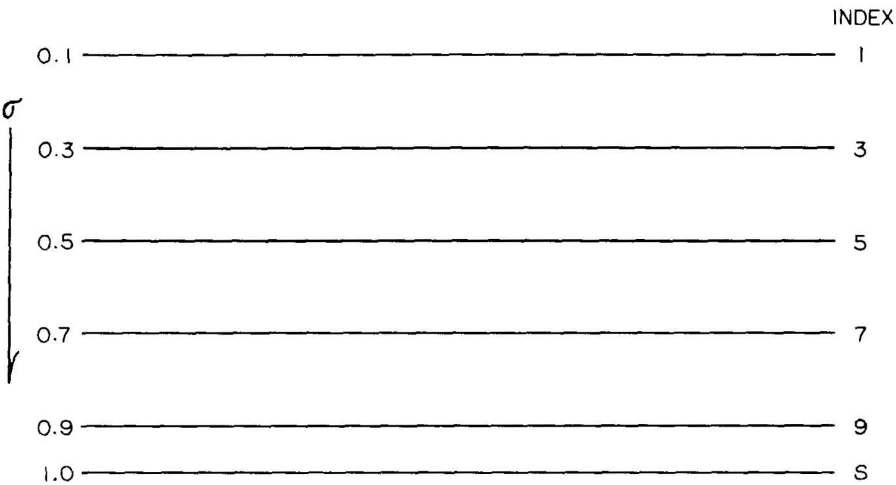
From an assumed sea-surface temperature value and by using an integrated form of the Clausius-Clapeyron equation, it is possible to obtain the saturation vapor pressure, e_S, of the air-masses close to the sea surface. From e_S and p (pressure), the saturation mixing ratio, w_S, is obtained by using the approximation

$$w_S \simeq 0.662\ e_S/p.$$

The actual mixing ratio is calculated after prescribing a relative humidity value. The mixing ratio is used in computing the equivalent potential temperature. This latter parameter (equivalent potential temperature) is the one used in our formulation of a heating function for modeling purposes.

THE HURRICANE MODEL

In the sense that it is possible to perform experiments of atmospheric phenomena with a reasonable degree of control by making use of models, Meteorology has become an experimental science in recent years. Regarding hurricanes, several models have been formulated and have helped seek a better understanding of the physics of hurricane development and maintenance. Generally these models are numerically integrated; e.g. Ooyama (1969), Rosenthal (1970), Sundquist (1970). We do not have many computer facilities in Mexico. However, a simplified model –which is suitable for the computers available to a Mexican University– has been developed and several experiments with the model have produced satisfatory results. This model, in spite of being a simplified one, contains the fundamental physics of the CISK theory. The model is symmetrically balanced and is formulated in the sigma system. The model has four levels in the free troposphere and a level in the friction layer. The vertical distribution of the model is schematically presented in the following diagram.



A non-uniform ("stretch") grid was designed for economical reasons. Such a grid allows us a better resolution in the central part and a coarse resolution in the outward portion of the model hurricane. This satisfies the resolution needs for reproducing the observed fields of real hurricanes. The grid-point radial distribution is given by the following expression:

$$r = \frac{10^3}{2} S(S + 3), \quad S = 0, 1, 2, \ldots n$$

where r represents radial distance (in meters) and S varies from 0 to a prescribed integer n. Additional details of the model are described in an unpublished Spanish version of the research done by the author at Florida State University; the more relevant results are in a Spanish publication by Serra (1972).

A heating function is designed for modeling purposes. This heating function is formulated to be directly proportional to the equivalent potential temperature θ_e, and to the vertical motion at the lowest level and inversely proportional to the integrated value (over all the troposphere) of the equivalent potential temperature difference between θ_e at a particular level and at the lowest level, θe_9. When the sea-surface temperature increases, the heating function tends to increase.

The vertical motion in the model is computed from a stream-function which, in the lowest level, is derived from an assumed distribution of the inflow angle. This angle follows the distribution of reciprocal spirals and it has been shown that its maximum value heavily influences the rate of hurricane development.

EXPERIMENTS

Experiments with the model were performed in order to investigate the relative importance of the sea-surface temperature and the maximum value of the inflow angle on hurricane formation. In essence, the inflow angle represents in some way the degree of organization of the model storm. Therefore, values of this angle were assumed to be relatively large even for the first steps of integration. By so doing, computer time was saved.

Results of the experiments are presented in subsequent paragraphs.

Figure 1 shows the surface tangential velocity distribution along the radius after 24 hours of physical time integration. The surface tangential velocity distribution is shown for two sea-surface temperature values (other variables in the model being held unchanged). There is not much of a development for the value 292° K; the maximum velocity after 24 hours is only about 20 m/sec. When the sea-surface temperature is changed to 300° K, the maximum surface velocity reaches over 60 m/sec in 24 hours; in this case, the maximum is located closer to the center of the storm. To study in detail this change in tangential velocity, experiments were conducted by using successive 2° K sea-surface temperature increases (for the range 292-300° K). The results of these experiments are illustrated in Figure 2. The maximum velocity does not vary much for sea-surface temperature values between 296° and 300° K. The curves for 292°

and 294° K show only a little development and they almost overlap. This indicates that for the prescribed values of inflow angle and relative humidity used in the experiment (an initial inflow-angle of 17.87° and 95% relative humidity for the lowest level), the critical value of sea-surface temperature for hurricane development is 296° K. This critical value is smaller than the one proposed by Palmén (1948).

Figure 3 shows the time variation of maximum tangential velocity for sea-surface temperatures of 290° and 302° K. The initial inflow angle and the inflow angle values which are assumed after 24 hours of integration are also shown in the figure. The development associated with 290° K is minimum whereas the development associated with 302° K produces velocities of hurricane intensity. To investigate these findings in more detail, succesive 2° K-interval increments are used over the 290-300° K range. Results of this investigation are illustrated in Figure 4. Not much variation occurs for 290-294° K sea-surface temperatures; the maximum velocity which is obtained in these cases is slightly over 20 m/sec. For 296-302° K sea-surface temperatures and for the same inflow angle as for the cases in Figure 2, velocities corresponding to full hurricane intensity are obtained. The relatively large inflow angle is responsible for hurricane intensity to develop in a short time when the sea-surface temperature is above the critical value. The important fact is, however, that our numerical experiments show the existence of a sea-surface temperature critical value for hurricane formation.

Experiments by varying the initial value of the inflow angle were also performed. A fixed value of 302° K for sea-surface temperature was used in these experiments (Figure 5). This fixed value is larger than the critical one by 6° K. Initial values for the maximum inflow angle and for the inflow angle after 24 hours of integration are indicated in Figure 5. Note that, for a fixed sea-surface temperature, the rate of hurricane development depends very heavily on the assumed value for the inflow angle. Due to the large value for the assumed sea-surface temperature (302° K), maximum velocities over

40 m/sec were obtained in all cases. Note, however, that the smaller the inflow angle, the larger the time required for development. It is possible, therefore, that even in the presence of high sea-surface temperature values, the hurricane may not develop at all because of too small values of the inflow angle. Thus, critical values of sea-surface temperature and, in addition, of the inflow angle are necessary conditions for hurricane development. This is in agreement with the findings by Fisher (1958) which were based on actual data.

CONCLUSION

The sea-surface temperature is an important factor for hurricane development. It is possible to suggest from our experiments a critical sea-surface temperature value of 296° K for a hurricane to form. However, an adequate sea-surface temperature value is not enough to induce hurricane formation. Experiments with our model show that above-critical values of both the sea-surface temperature and the inflow angle are necessary conditions for hurricane formation. If one of these conditions were poor or absent, the hurricane would need more time to develop or it would not develop at all even if other climatological-geographical requirements were met.

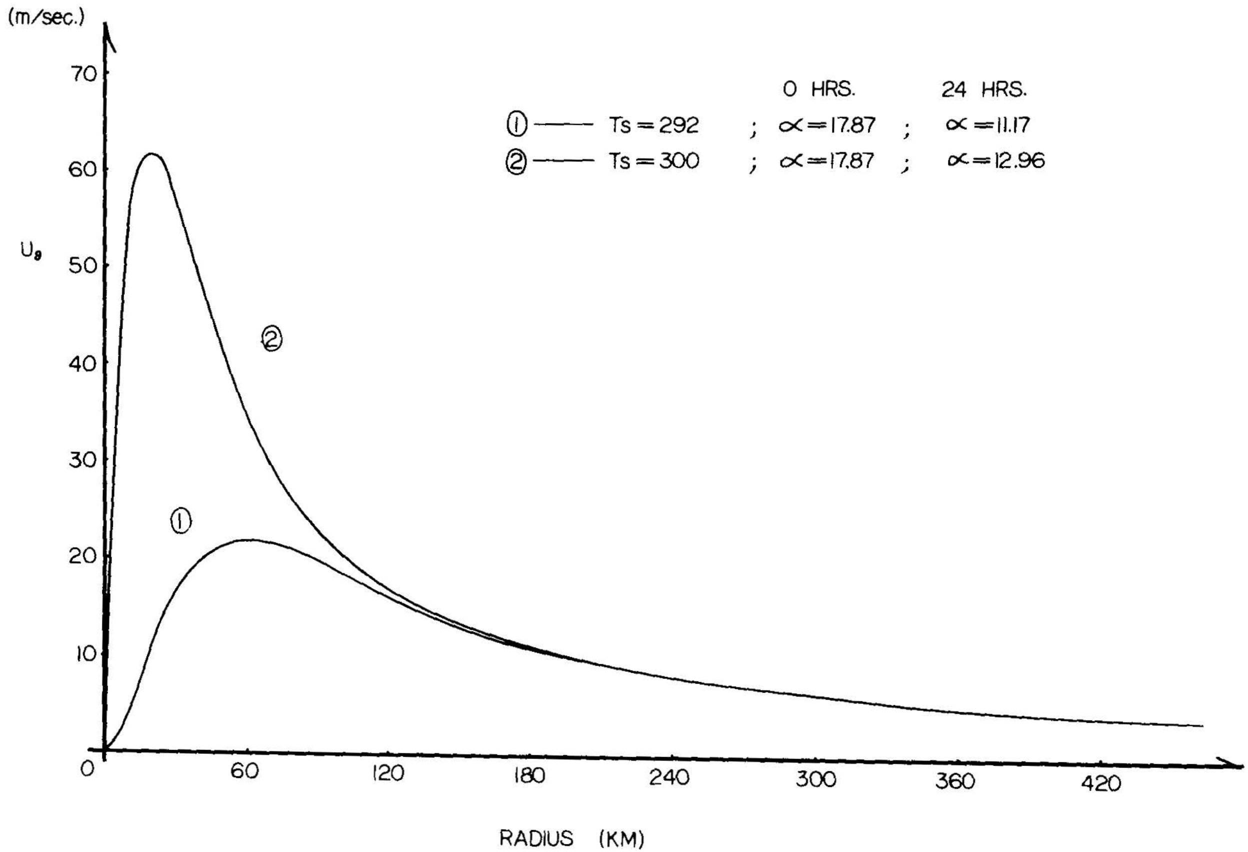


Figure 1. Tangential velocity distribution along the radius for two different sea-surface temperature values. The distribution is for the lower level after 24 hours of physical time integration.

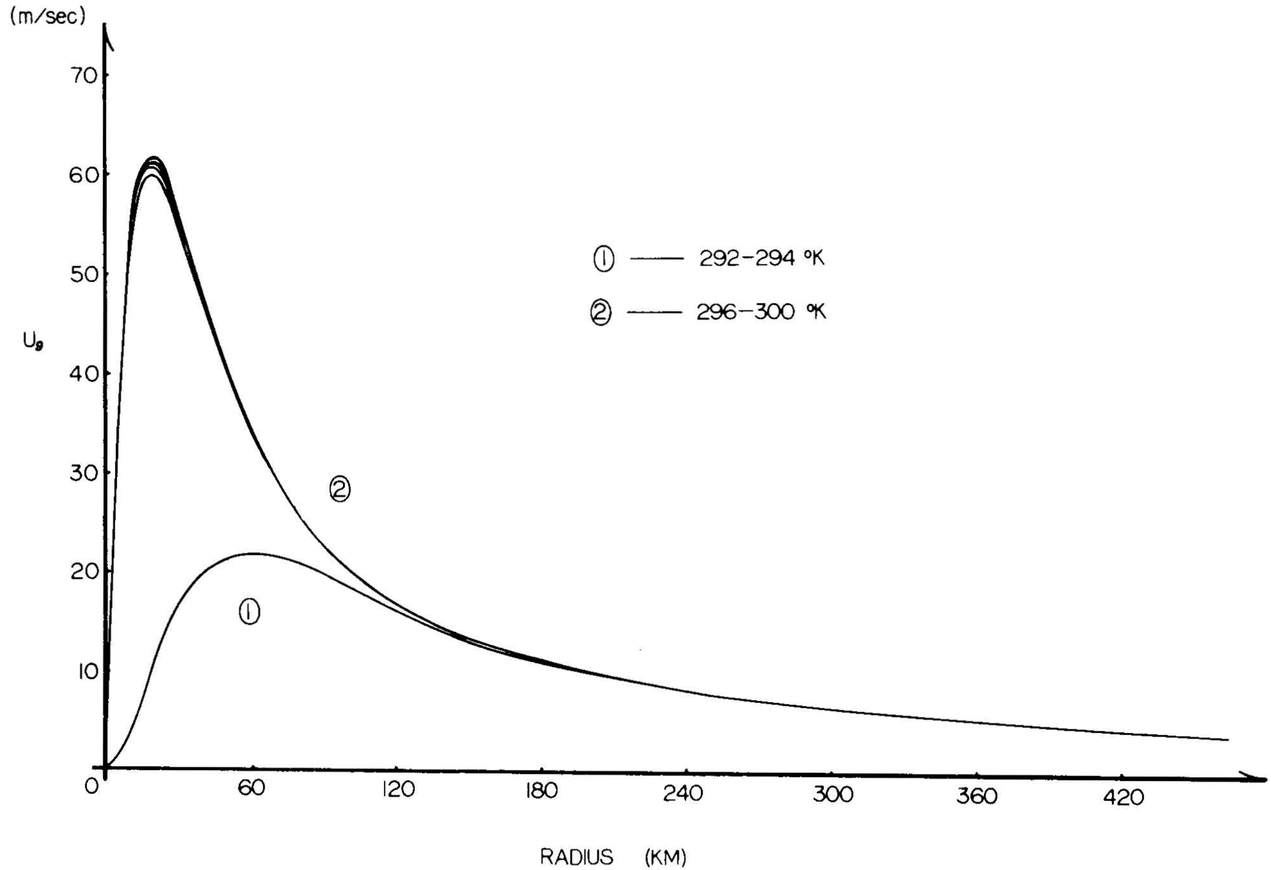


Figure 2. Same as figure 1, but for sea-surface temperature values at 2° K intervals within the range 292-300° K.

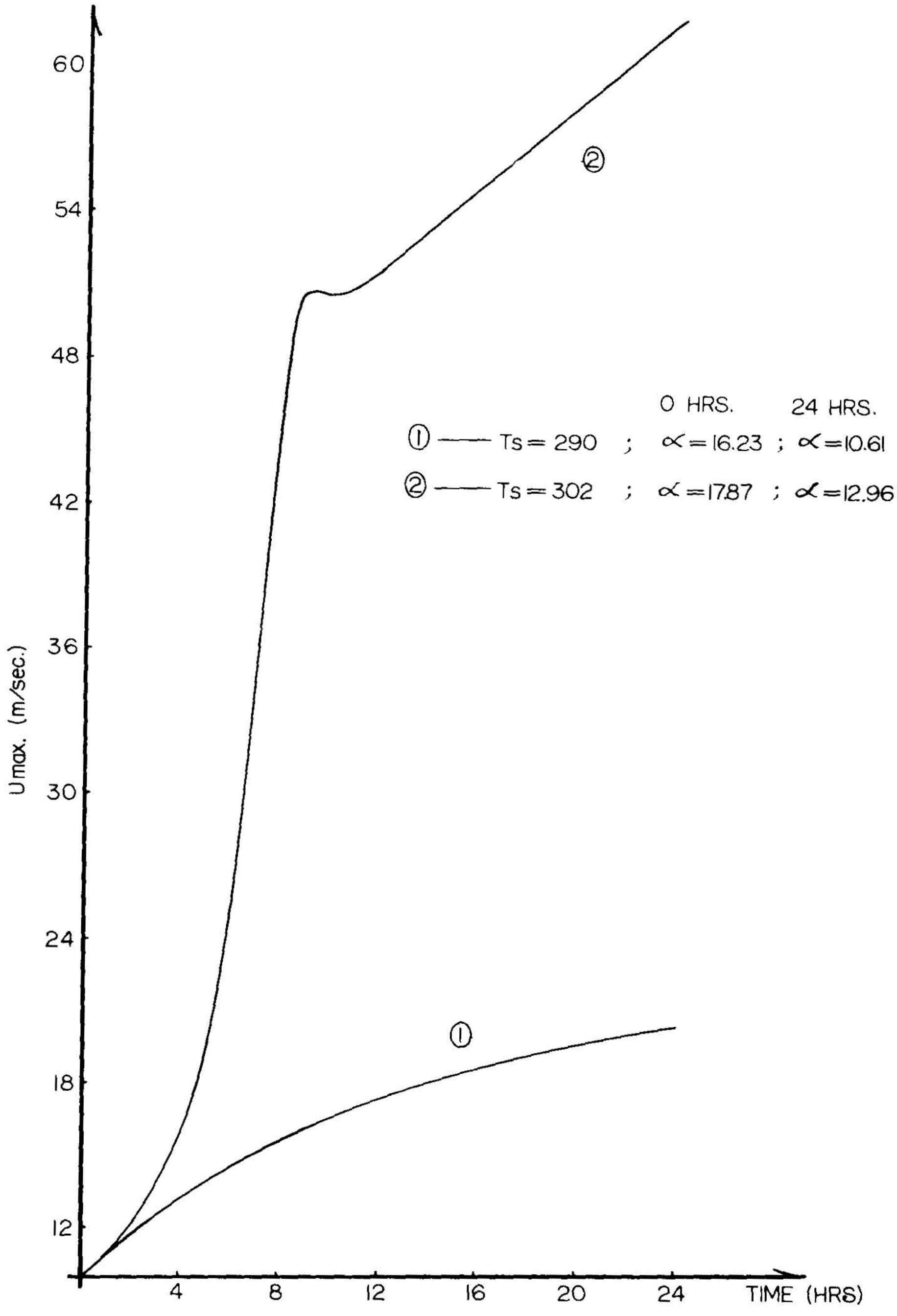


Figure 3. Maximum tangential velocity vs. time for the indicated values of sea-surface temperature and inflow angle.

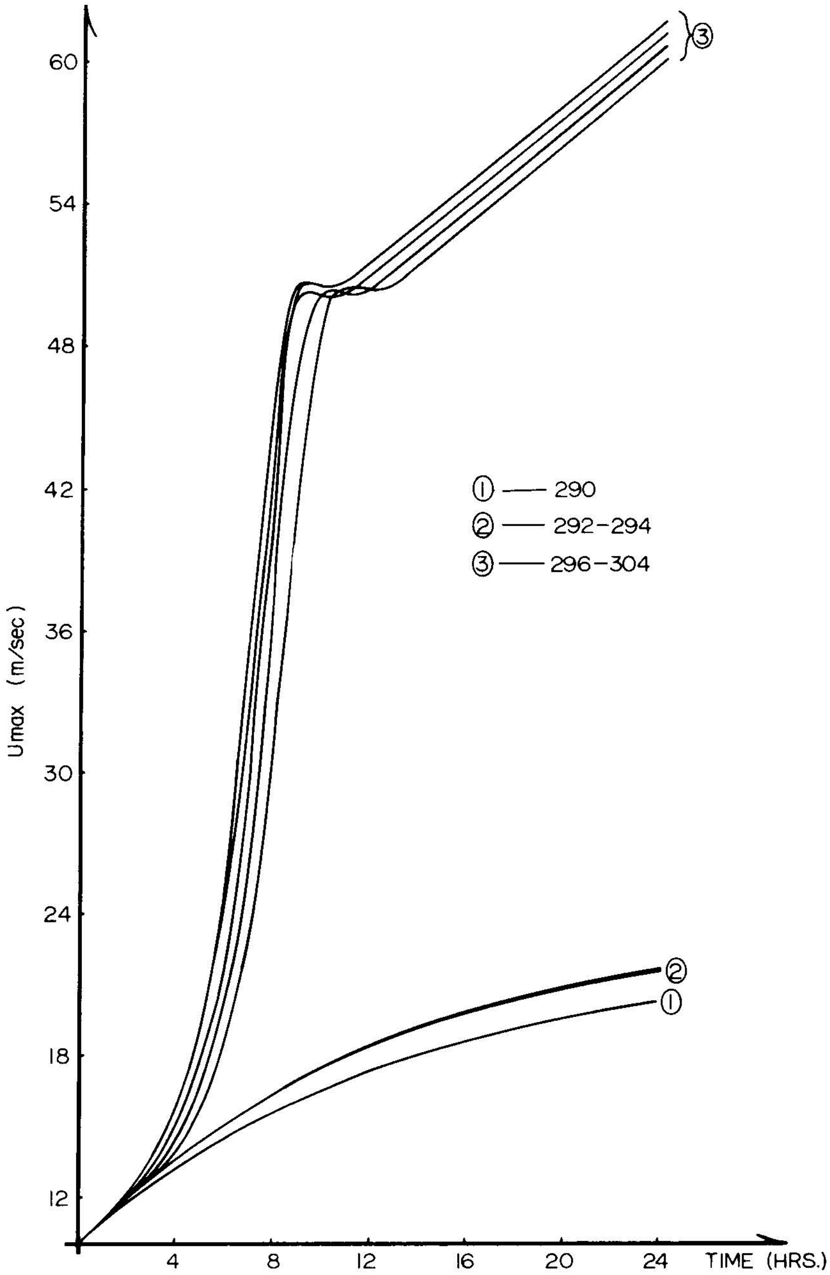


Figure 4. Maximum tangential velocity vs. time for several sea-surface temperature values.

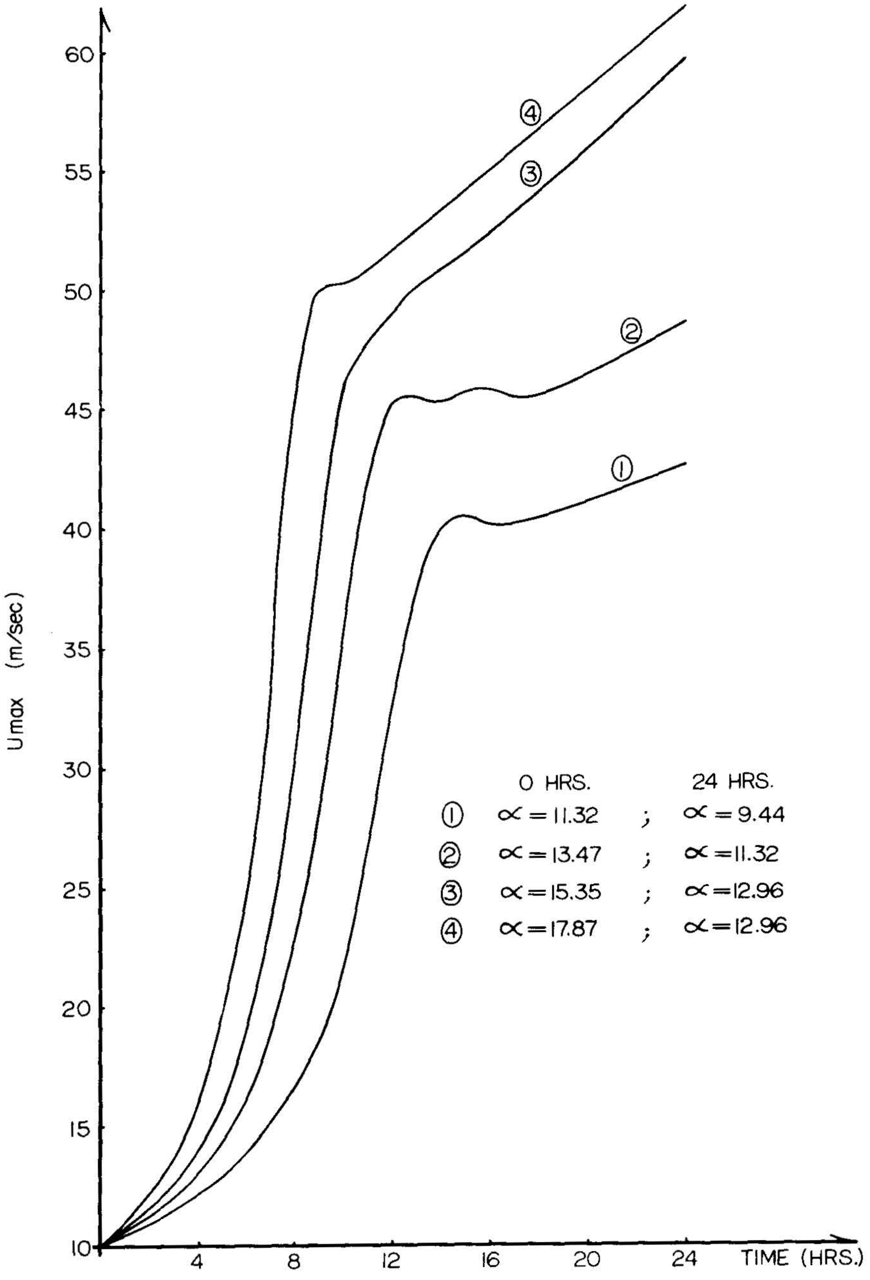


Figure 5. Maximum tangential velocity vs. time for a fixed sea-surface temperature (302° K) and for several values of inflow angle.

ACKNOWLEDGMENTS

The experiments discussed in this paper were performed at "Centro de Cálculo de la UNAM", and the author wishes to express his gratitude to the Centro for the facilities given to him during his research work. The author also wishes to express his recognition to Mr. Alfonso Estrada for his valuable assistance.

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