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Uncertainty in Predictions of Hurricane Frequency and Intensity in Relation to the Greenhouse Effect

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Introduction

In 1992 Hurricane Andrew came ashore just south of Miami, Florida. In its wake it left just over sixteen billion dollars in insured damage. In the same year, the United Nation's Intergovernmental Panel on Climate Change issued a report declaring that "global warming is inevitable."[1] These two ominous events have fueled concern that global warming may lead to devastating hurricanes. However, some have argued that much of this concern is "demonstrably unfounded [and] being embellished by politics."[2] What is needed is to fill the gap between existing scientific knowledge and public policy, for it is the responsibility of public policy makers to be concerned with questions in which science cannot come to definitive conclusions. Central to this effort is an understanding of the uncertainty involved in scientific conclusions concerning hurricanes. This paper will review the current literature regarding the predictions of hurricane intensity and frequency in a greenhouse situation and discuss the uncertainty arising from conclusions found in the literature.[3]

Current Hurricane Theory

A basic understanding of hurricanes is important to understand the models that predict hurricane intensity and frequency, for many models predict only the factors relevant to hurricanes and not hurricanes themselves. Current thinking about hurricanes seems to be split into several branches, each of which studies a different part of hurricane theory. This paper will concentrate on two main branches and their subsets. Focus upon the intensification factors of already developed hurricanes will allow for a study of the factors involved in hurricane intensity. Attention to the genesis factors, another branch of hurricane research, will allow for study of the factors involved in hurricane frequency.

Intensity

Two types of processes drive hurricane intensification. The first type to be discussed is internal and can be appropriately described as the thermodynamics of the system. The second type is the external atmospheric conditions necessary for intensification.

In 1988, Kerry Emanuel, an MIT meteorologist, claimed hurricanes were "an elegant example of a natural Carnot heat engine."[4] A heat engine is a system that removes heat from one reservoir, releases some of that heat to another reservoir at a different temperature, and does work in the process. A hurricane is a heat engine. It draws heat from the ocean, releases some of it to the atmosphere via radiative cooling, and does work during this process.

The Carnot engine, a machine by which heat energy (Q) is changed into mechanical energy at some efficiency (ε), is the hurricane (Figure 1). Q_1 and Q_2 represent the flow of Q into and out of the machine. The temperatures at which this flow occurs are T_1 and T_2, lower stratosphere temperature and sea surface temperature (SST), respectively. According to Carnot's theory the efficiency of a heat engine is:

$$\varepsilon = 1 - (T_1 / T_2) \quad \text{where } T_1 < T_2$$

Therefore, the efficiency of a hurricane converting Q into mechanical energy is a function of the temperature of the lower stratosphere and the SST. Furthermore, Carnot's theorem shows that the total energy (E) available is:

$$E = \varepsilon T_2(S_B - S_A)$$

where S = total entropy at points A and B

Emanuel goes on to show that the lower bound of pressure "is a function of ε, SST, and relative humidity" at point B.[4] He shows that much of the Atlantic Hurricane Basin[5] (AHB) has SSTs high enough to produce storms with central pressures between 910mb and 895mb (calculations from mean September conditions). However, these storms are very rare; only three recorded hurricanes in the AHB have ever reached this potential or lower.

Why, then, do hurricanes not intensify to their thermodynamic potential? R. T. Merrill offers a set of external atmospheric conditions that preclude hurricanes from reaching this potential. Merrill discusses several differences between the atmospheric conditions surrounding intensifying hurricanes (IH) and non-intensifying hurricanes (NIH). The features atmospheric features surrounding NIH are:

> *"stronger mean environmental flow relative to the hurricane motion, unidirectional flow over and near*

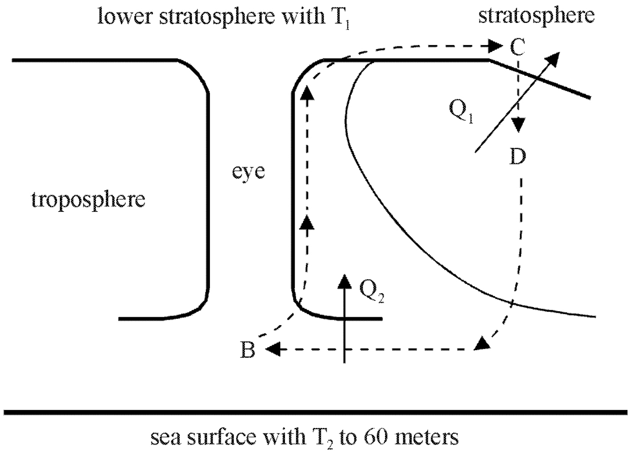

Figure 1. The Carnot heat engine hurricane.

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> *the hurricane center, and slightly weaker radial outflow and/or more pronounced anticyclonic flow surrounding the center in the upper troposphere.*"[6]

These are features of the upper troposphere that tend to dominate over the thermodynamic drive of the storm. Thus both the thermodynamics and the atmospheric conditions influence the intensification of a storm.

Frequency

Scientists use criteria for hurricane creation to predict the frequency of hurricanes. I will concentrate on two types of criteria. The first is the Seasonal Genesis Parameter (SGP), and the second is the rainfall in the Sahel and New Guinea areas of Western Africa.

Gray provides six components that are necessary but not sufficient for hurricane genesis. These factors are grouped into two sets of potentials, one thermal and the second dynamic. The two sets are then multiplied together to yield the SGP.[7]

The thermal potential involves three factors multiplied together. The first part is the thermal energy of the ocean. This parameter requires the ocean to have a temperature of 26 degrees Celsius to a depth of 60 meters, and provides the thermal energy for the storm. The depth requirement is most likely to prevent cooling of the ocean surface due to upwelling caused by tropical disturbances.[4] The second part is the "role of surface to middle troposphere [temperature] gradient."[7] This gradient is responsible for the creation of convection, and hurricane genesis needs a 10 degree difference between surface and middle troposphere. This parameter helps to distinguish between summer and winter genesis in the sub-tropical latitudes. The last part of the thermal potential is the relative humidity (RH) of the middle troposphere. The RH is important "because entrainment of moist air into updraughts inhibits their growth less than entrainment of dry air."[7]

The dynamic potential also contains three factors multiplied together. The first is vorticity. Hurricanes form "only in regions with positive low-level vorticity."[7] The second is the Coriolis parameter. This parameter takes into account that the rotation of the Earth creates weak pressure gradients near the Equator and that these gradients get stronger farther away from the Equator. These weak gradients do not allow for sufficient wind acceleration, for "wind acceleration is related to the magnitude of the pressure gradient."[7] Wind acceleration is important as it must balance the frictional dissipation of the storm. Thus, the stronger the Coriolis parameter, the more likely hurricane genesis becomes. The final parameter is vertical wind shear. Vertical wind shear is merely the vertical component of wind flow. If vertical wind shear is too high, then it prevents the "accumulation of enthalpy and moisture."[7]

When arbitrary units are added to the individual parameters to cover the possible daily variations, the SGP gives, in Gray's words, "very close correspondence between predicted and observed seasonal cyclone frequency."[7] The SGP is a powerful tool to predict the frequency of hurricanes.

Another indicator of hurricane frequency in the Atlantic Basin is the amount of rainfall in the Sahel and New Guinea regions of Western Africa. A comparison given by Gray between the ten wettest and the ten driest years in those regions and the number of category 3, 4, and 5 hurricanes in the Atlantic Hurricane Basin shows a strong correlation—the wetter the year in those regions (based on the Saffir-Simpson scale; Table 1), the greater the incidence of intense hurricanes.[8, 9] The ten driest seasons in Western Africa had an average of 1.0 intense hurricanes, while the ten wettest seasons had an average of 4.8 intense hurricanes. However, the number of tropical storms and weak hurricanes changes very little between wet and dry years.[10] Thus the influence of Western African rainfall is to increase intense hurricane formation frequency.

Table 1. The Saffir-Simpson Scale for Hurricane Intensity

Category	*Central pressure (mb)*	*Max. sustained winds (km/h)*
1	> 980	119 - 151
2	979 - 965	152 - 176
3	964 - 945	177 - 209
4	944 - 920	210 - 248
5	< 920	> 249

Western African rainfall may, however, be only a manifestation of changing atmospheric conditions that are favorable to intense hurricane formation. Several other conditions are observed along with increased rainfall. Two of these are important to the intensification of hurricanes: a) increased SST and b) changes in upper tropospheric wind. One of these conditions is an atmospheric feature that Merrill describes as a factor surrounding hurricane intensification or non-intensification.[6] Upper tropospheric wind flow becomes westerly over the Western Atlantic during periods of increased rainfall, and, as described above, "stronger mean environmental flow relative to the hurricane motion" decreases the chance of hurricane intensification. Thus as hurricanes move from East to West the westerly upper tropospheric flow decreases the flow around the hurricane relative to its motion. Warmer SST in the Atlantic increases the thermodynamic efficiency of the storm and the total energy available to it as discussed above.

It seems that Western African rainfall is a strong predictive tool for the frequency of intense hurricanes during the following hurricane season. However, there is little conclusive knowledge concerning the causes of this correlation. Thus, at this time, Western African rainfall is merely a tool for prediction.

Hurricane Prediction and GCMs

GCMs (General Circulation Models) are one of the most important tools for climate and weather research. GCMs are combinations of atmospheric models and slab ocean models. These two models are based on "non-linear partial differential equations" whose solutions must be determined by numerical methods.[11] The models simulate climate by breaking the Earth and oceans into horizontal grids (e.g., 200 km squares) and vertical layers (from 2 to 19). The models are integrated forward in time to produce predictive results.

There are two ways to attempt to predict hurricane frequency and intensity in a greenhouse situation. The first is to predict frequency and intensity from changes predicted by GCMs that are environmental precursors for hurricane formation and intensification. The second way is to examine the predictions of GCMs that attempt to model hurricanes themselves as tropical disturbances.

Ryan et al. use a GCM model to predict the Yearly Genesis Parameter in a greenhouse situation.[12, 13] The Yearly Genesis Parameter increases approximately by a factor of three in the greenhouse situation run as compared with the control. The authors point out, though, that the result is possibly an overestimate. The increase in the Yearly Genesis Parameter results mainly from an increase in the thermal part of the equation. Specifically, the increases in thermal energy of the ocean and the increases in the temperature gradient between the surface and the middle troposphere produce the bulk of the change. An increase in SST creates both of these changes. Uncertainty arises from criticism of the thermal energy requirement in the Genesis Parameter.

McBride shows that the thermal energy requirement for hurricane genesis is met over much of the tropical oceans during hurricane genesis seasons.[14] The Genesis Parameter is also extremely sensitive to the ocean energy parameter, for just a 0.5 degree change in SST produces a twenty percent change in storms predicted.[12] Thus it should be the dynamic part of the Genesis Parameter that should more accurately predict daily occurrence of hurricanes.

Parts of the Yearly Genesis Parameter are the subject of another experiment by Larson and Henderson-Sellers.[2] The authors used two GCMs to predict the change in the dynamic portion of the Yearly Genesis Parameter in a greenhouse situation. Both of the models showed little change in the values of the dynamic potential. In the control run, though, both of the models were unable to reproduce anything like the observed dynamic potential. The authors did report a significant increase in SST that would invariably cause an increase in the thermal portion of the Genesis Parameter, as mentioned above.

Emanuel uses the results from a GCM to predict the theoretical maximum intensity of hurricanes in a greenhouse situation.[15] As above, Emanuel predicts the minimum central pressure in mature storms; however, he uses different inputs to the system. The results are that much of the Atlantic Hurricane Basin has predictive values below 900mb, a small deviation from values predicted with normal conditions. However, the minimum pressure decreases from 895mb to 820mb over the entire Gulf of Mexico. These results suggest that the area in which hurricanes reach devastating intensity will be greatly increased. These results also depend upon the SST predicted by a GCM.

Tropical disturbances predicted from GCMs are the focus of experiments by Haarsma et al.[16] These experiments use a GCM to predict actual tropical disturbances rather than the environmental conditions with which they are associated. For the Atlantic Hurricane Basin they predict an increase by a factor of 1.5 of the number of intense tropical disturbances (tropical storms). Furthermore, they do not predict an increase in the area of tropical cyclone formation; the occurrence of tropical disturbances is roughly the same. The GCM predicts a 2.5^o increase in SST; this alone could explain the increase in intense tropical disturbance frequency.

Broccoli and Manabe also use a GCM to predict the frequency of hurricanes, rather than extrapolating their existence from environmental predictions.[17] The authors use number of storm days as their measurement of hurricane frequency in a greenhouse situation. Two different cloud parameter schemes were used, with conflicting results. They report an increase of 18.9% in the global numbers of storm days using a model with fixed clouds. However, they also report a decrease of 13.1% in the global number of storm days using a model with variable clouds. The role cloud feedback is a major source of uncertainty for GCMs.[18] Both models also report an increase in SST of 1.5^o and 2.5^o respectively.

In conclusion, the GCMs all have one thing in common—they all predict an increase in SST that leads to two assumptions, depending on what the model is studying. The first assumption is that through an increase in ocean thermal energy, the frequency of hurricanes will increase. The second is that, by virtue of an increase in SST, the maximum amount of energy available for hurricane intensification will increase.

Using predictions of rainfall in Western Africa as a prediction of intense hurricane frequency, a decrease in these types of storms can be expected. A five to ten percent decrease in the amount of precipitation in Western Africa is predicted by three GCMs in a greenhouse situation.[11] The conclusion of a decrease in intense hurricane frequency is at best tentative. If the causes are from changes in the atmospheric conditions affecting the rainfall, then it is more likely that there will be a decrease in hurricanes. However, the causes of the decrease in Western African rainfall during greenhouse situations are not known. Lighthill et al. suggest that there is no reason to suppose that a greenhouse situation would change the atmospheric conditions that arise from the Western African monsoons giving birth to intense hurricanes in the Atlantic Hurricane Basin.[19] Much future work in this area needs to be done.

Uncertainty

The UN's Intergovernmental Panel on Climate Change (IPCC) has studied climate changes in depth. One of the main results of their GCM studies has been a "generally satisfactory portrayal of aspects of variability of the atmosphere, for instance those associated with variations in sea surface temperatures."[11] As we have seen, SSTs are an important part of the predictions issued for hurricanes. However, it is premature to assume that the conclusions drawn about hurricane intensity and frequency from SSTs have the same degree of confidence as those simply predicting SSTs.

There is no theoretical justification for the lower bound of the ocean thermal energy requirement of 26 degrees Celsius in the Genesis Parameter. There is even speculation that the lower bound may increase in a greenhouse situation.[12] Even more uncertainty arises when the area in which the Genesis Parameter is favorable increases due to the increasing SSTs in the middle latitudes. Some of these areas are unlikely to produce hurricanes because of the external atmospheric conditions with which they are associated. For example, hurricanes are very unlikely to form above 20° latitude. Here the "role of surface to middle troposphere [temperature] gradient,"[7] mentioned above as a part of the thermal potential of the Genesis Parameter, is not conducive to hurricane formation. Even though a greenhouse situation may well bring on increases in SSTs, the link between hurricane frequency and SSTs is poorly understood. Thus, conclusions about increased hurricane frequency based on SSTs do not warrant the same degree of confidence as that placed in SSTs alone.

Emanuel's claim that there is a theoretical maximum potential intensity of hurricanes based on SST reveals little overall about hurricanes in a greenhouse situation. While his claims may be true, there is evidence that hurricane intensification depends on external atmospheric conditions, as argued by Merrill.[6] Adverse atmospheric conditions preclude hurricanes from reaching their theoretical maximum. An examination of the Atlantic Hurricane Basin atmospheric conditions related to

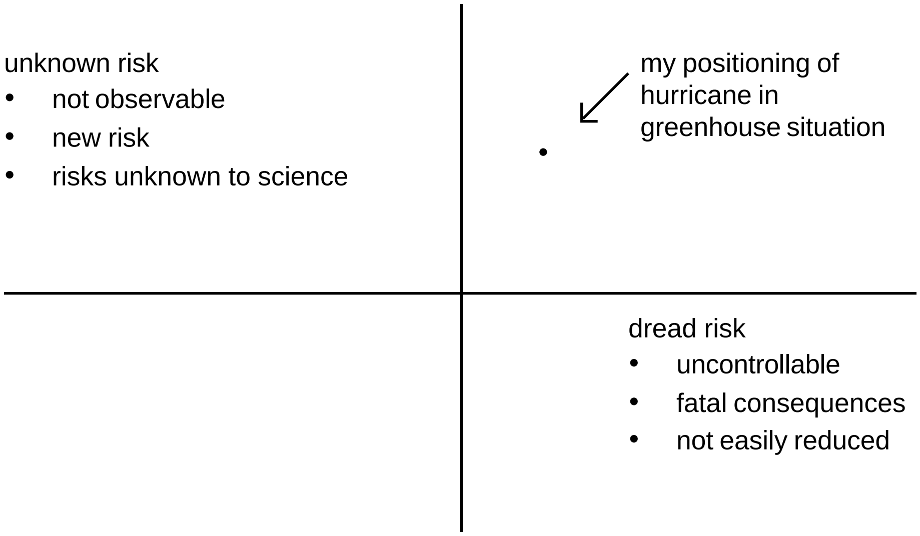

Figure 2. A factor-analytic diagram. The vertical axis represents the extent of the "unknown" factor; the horizontal axis represents the extent of the "dread" factor. Adapted from: Slovic, P. 1987. "Perception of Risk." In: Susan, C., ed. 1994. *Environmental Risks and Hazards* (New Jersey: Prentice Hall).

hurricane intensification in a greenhouse situation was attempted via an inspection of rainfall in Western Africa. As the rainfall was expected to decrease, the atmospheric conditions for hurricane intensification could become more adverse. Again, however, this is at best tentative.

Overall, predictions of hurricane frequency in the Atlantic Hurricane Basin during a greenhouse situation are weak, and feature a large degree of uncertainty. Though still containing significant uncertainty, increases in maximum intensity that could possibly be attained in a greenhouse situation are somewhat more likely.

Measurement of the risk involved in these situations is illustrative. Risk is the probability of a given set of consequences occurring during a prescribed time period.[20] There are two sets of considerations for understanding future hurricane risk. The first consideration is that even without the possible effects of a greenhouse situation upon hurricane intensity and frequency, there is still the prospect of hurricane consequences. The second consideration is the probability of change in hurricane intensity and frequency in a greenhouse situation. Since future risk of hurricanes must, by definition, take into account the probability of hurricane occurrence, it is safe to say that future hurricane risk at this time is low. There is too much uncertainty associated with future hurricane frequency and intensity to form more specific conclusions.

Discussion of Risk

Gilbert White studied mankind's attempt to adjust to the risk associated with natural disasters by studying the policies concerning river flooding during the mid-1900s in the US. During the 1930s the United States government embarked upon a series of projects to control river flooding. The extensive dams in the Columbia River Basin and the Tennessee River Valley were among the results of this policy. Two important results from White's study concern the types of adjustments to natural disasters and the evolution of a decision-making model in the face of natural hazards.

There are three types of adjustments to natural hazards. The first is an attempt to modify the causes. The second is an effort to modify the losses. The final adjustment is an endeavor to distribute the losses incurred.[21] Studies of the decision-making processes of individual areas led to the development of a "bounded rationality" model of decision-making. In this model, a decision-maker receives input from both the environment and the human side of the situation. The decision-maker then conducts a cost-benefit analysis to yield an appropriate plan of action. Critical to this process is the fact the plan of action is subject to the decision-maker's perception of the risks involved.[21]

These conclusions applicable to the hurricane risk in a greenhouse situation. Modification of the causes of hurricanes is normally an area that cannot be pursued. However, in a greenhouse situation, the causes of hurricanes can certainly be modified via carbon dioxide reduction. Nonetheless, the uncertainty associated with hurricane risk is historically too high to warrant action, for action on the flood risk during the 1930s did not come until prompted by increasing loss of life from floods. On the other hand, other effects of the greenhouse situation will most likely cause action to be taken (e.g., sea level rise). White observed another adjustment to natural hazards in his research of river flooding—modification of losses.[21] Amelioration of losses from hurricane damage is an area where little has been accomplished. Therefore, it seems that the certainty of future risk will have to be great for action to be taken in this area. Distribution of losses occurs in the flooding situation via public relief and insurance. These measures are already in place for hurricane dangers. However, there is much concern as to whether or not the insurance industry will be able to bear the burden of increased hurricane damage.[22] Considering the uncertainty in the likelihood of increased hurricane frequency and intensity in a greenhouse situation, it seems unreasonably cautious to go through major reforms for this reason alone.

The decision-maker's perception of risk in the "bounded rationality" model of natural hazards decision-making is subject to many influences. The decision-maker must define an acceptable relationship between perceived risk, perceived benefit, and acceptance of risk. These relationships are influenced by "[perceived] characteristics such as familiarity, control, catastrophic potential, equity, and level of knowledge."[23] These characteristics are easily represented in factor-analytic representations. Such representations plot unknown risk on the vertical axis and dread risk on the horizontal axis (Figure 2). Slovic shows that the higher the score on the vertical and horizontal the "greater the desire for strict regulation to reduce risk."[23] It seems that the placement of hurricanes during a greenhouse situation would fall high on the vertical axis (the unknown risk) and just to the right of the middle on the horizontal axis (dread risk). Since dread risk is considered more important than unknown risk in determining public desire for regulation, it follows that hurricane risk posed by the greenhouse situation justifies little action in the eyes of the public.

Another factor in the consideration of perceived risk is the discrepancy between lay and scientific perceptions. "[T]he public sees the world in a different way from the scientific community and technical community."[20] Decision-makers receiving input from the scientific community must be able to help bridge this gap in perceptions. While science often views risks in terms of number of deaths, the lay public perceives risk by considering such factors as dread and unknown risk, as described above.[23] Facilitating tolerance of these different perceived risks is one of the roles of the decision-maker in a democratic society. Thus for hurricanes, decision-makers must tread a line between complete dismissal of public fears and complete acceptance of scientific uncertainty.

Unfortunately, comparisons of the amount of risk associated with earthquakes in California shows that the uncertainty associated with hurricanes in the greenhouse situation is of little concern to the U.S. government. Estimates show that there is a "67 percent probability of one or more earthquakes of magnitude 7 or greater in the San Francisco Bay area by 2020."[24] The U.S. government's policy position on earthquakes is that the federal agencies should a "primarily informational role."[24] As the current state of research concerning hurricane possibilities during a greenhouse situation is in no position to give numerical probabilities, there is likely to be no response from the U.S. government.

The considerable uncertainty connected with the likelihood of increased hurricane frequency and intensity during a greenhouse situation scientifically warrants little action in the terms of adjustment to the hazard. However, there should be further research into the field of hurricane frequency and intensity before scientists support specific policy recommendations. Scientists are adverse to supporting false propositions; they are much more likely to reject a proposition on the basis of little evidence that may later turn out to be true than risk supporting a wrong one. These types of errors are labeled Type I and Type II errors.[25, 26] Sometimes, the scientific desire to avoid Type I errors can have serious consequences. If hurricanes do increase in both intensity and frequency during the next century without scientists having predicted it, preparation will probably be quite inadequate, resulting in dire consequences. Thus it seems to be the responsibility of policy makers to understand the uncertainty associated with hurricanes and to pursue a reasonable course of action.

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(13) The Yearly Genesis Parameter is merely the Seasonal Genesis Parameter for the whole Earth for an entire year.

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(18) In nature, the role of clouds is paradoxical. Clouds heat the climate systems of the Earth by reducing inferred emissions to space. However clouds also cool the climate system of the Earth via "reflection and reduction in absorption of solar radiation."[11] In the present climate the overall effect of clouds is to cool the Earth. There are three components that govern the cloud influence upon the climate: (a) cloud amount, (b) cloud altitude, and (c) cloud water content. In a greenhouse situation these cloud components may change to feed the system either positively (increases warming) or negatively (increased cooling). GCMs model clouds by either fixing the amount, altitude, and water content of clouds at present day levels or containing "interactive cloud parameterizations" which allow for variation. "The latter are more detailed but not necessarily more accurate as more parameters have to be specified....[Thus] one of the largest sources of uncertainty in the simulation of equilibrium climate change lies in the prediction of clouds."[11]

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(26)A Type I error is endorsing a position which later turns out to be false. A Type II error occurs when a position is not endorsed that later turns out to be true.