The physics of hurricanes

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1 Introduction

Hurricanes have been in the news recently amid concerns that as a result of global warming their frequency and intensity might increase. Indeed, the dramatic increase in the number of intense storms affecting the United States in the last two years has heightened these fears. Hurricane Katrina that devastated New Orleans in August 2005 was the costliest on record with 1300 lives lost and a damage bill estimated at about 125 billion US dollars. Hurricane Wilma in October 2005 was the third most damaging storm in US history and holds the record for the storm with the lowest central pressure ever observed. Estimating the potential effects of global warming on hurricane activity is a topic of active research, which I will discuss later. The main focus of this article is on the physics of hurricanes, an understanding of which is important for assessing future trends in hurricane activity. I will begin with a brief review of the main observed features of these storms. I will then show how we can understand some these features in terms of classical physics, i. e. Newton's second law of motion and the thermodynamics of moist air.

2 Observations of Hurricanes

Hurricanes are cyclonically-rotating[2] low-pressure weather systems that develop over the warm oceans, mostly in the Tropics where sea surface temperatures exceed about 27^{o}C. At upper levels in the troposphere the winds rotate anticyclonically beyond a few hundred kilometres from the centre. The term hurricane is used for storms that occur over the Atlantic Ocean, Caribbean

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[2]i.e. counterclockwise in the NH, clockwise in the SH

Sea, Gulf of Mexico and northern Pacific Ocean east of the dateline. Over the Western North Pacific Ocean these these weather systems are called typhoons and in most other places tropical cyclones, except over the North Indian Ocean and Bay of Bengal where they are referred to simply as cyclones. These storms are confined mostly to the summer and autumn months except in the Northwest Pacific when they can occur at any time, albeit most frequently in summer. About 80 storms form globally each year. They do not usually form within about five degrees of the equator, an indication that the Earth's background rotation is important in their development.

Hurricanes usually develop from pre-existing regions of disturbed weather such as areas of persistent thunderstorms. A storm is classified as a hurricane or typhoon when the sustained[3] wind speed at 10 m above the surface exceeds 119 km per hour or 33 m s^{-1}. Most readers will be familiar with satellite images of these storms such as that in Fig. 1a. Characteristic features are the dense high-level cirrus clouds surrounding the storm and the eye, the region surrounding the rotation axis that is free of deep clouds. Eye sizes can vary considerably - some intense storms have eye diameters as low a few kilometres, while some large storms have eyes exceeding 100 km in diameter. The high-level cirrus overcast is fed largely by an annular region of deep convective clouds, referred to as the eyewall clouds because their inner edge form an outward sloping "wall" to the eye. One obtains a good impression of the eyewall slope in the close up satellite image of the eye in Fig. 1b and in the photograph taken from within the eye by a research aircraft in Fig. 1c. The eyewall clouds are a source of very heavy precipitation.

Much of our knowledge of hurricane structure has been obtained from aircraft measurements, which are routinely carried out in Atlantic and Caribbean storms. Figure 2a shows a photograph of one of the United States National Oceanic and Atmospheric Administration's P3 research aircraft that is used for such measurements. The underbelly of the aircraft has a radar that scans horizontally and detects the pattern of precipitation during the flight. A typical radar image is shown in Fig. 2b. Regions of high radar reflectivity correspond with regions of heavy precipitation. The eyewall clouds are prominent features of radar images as are the spiral rainbands that form at larger radii. Figure 2c shows a typical profile of flight level winds measure by the aircraft as it flies through the storm at an altitude of one and a half to three kilometres. Winds are light in the eye, rising rapidly to a maximum and then declining steadily with radius. Maximum wind speeds are found at low levels under the eyewall clouds. In weaker storms the eyewall may not extend completely around the eye. To a first approximation, the flow in the inner core region, typically within 100-200 km from centre, is symmetric about the axis. While air parcels are rotating about the central axis, those at low and middle levels, up to perhaps 5 km, have a radially-inward component and those at upper levels, above 10 km, have an outward component. Thus air parcels spiral in at low and middle levels and out at upper levels. The inflow is largest in a shallow layer, typically 500 m to 1 km deep, adjacent to the sea surface. Reasons for these features are discussed below.

[3] "Sustained" refers to a 10 minute average, although a few countries including the United States uses a 1 minute average.

Hurricanes come in a range of sizes and, for reasons that are not fully understood, there appears to be little relationship between their size, as measured for example by the radial extent of gale-force winds (sustained wind speed greater than 17 m s^{-1}), and intensity, as measured by the maximum wind speed.

3 Dynamics and thermodynamics of a mature hurricane

In the following description I will try to isolate and explain important aspects of the dynamics and thermodynamics of a mature hurricane, but I need to begin with a note of caution. The different elements discussed below are not independent, but tightly coupled and 'cause and effect' arguments can easily lead one astray. The best one can hope for is to try to present a consistent picture of the various elements that make up the hurricane. In considering the dynamics of hurricanes it is convenient to distinguish between the primary circulation, i. e. the tangential flow rotating about the central axis, and the "secondary circulation" or "in-up-out circulation" (low and middle level inflow, upper-level outflow), although when these two components are combined, the picture emerges of air parcels spiralling inwards, upwards and outwards.

The primary circulation

Hurricanes, like other large-scale weather systems are approximately in hydrostatic balance. That means that the normal decrease in pressure with height, which corresponds with an upward force acting on each air parcel, is nearly balanced by the weight of the air parcel. Thus the vertical acceleration of air parcels is a result of the small difference in these forces.

A similar situation occurs in the radial direction. Aircraft measurements have shown that above a height of between 500 - 1000 m, the radial forces acting on an air parcel in a hurricane are nearly in balance also. This means that the inward-directed force on an air parcel that is associated with the decrease in pressure with decreasing radius is approximately balanced by the sum of the outward-directed centrifugal and Coriolis forces acting on the parcel. The centrifugal force per unit mass of air is equal to the square of the tangential wind speed divided by the radius and the radial component of the Coriolis force per unit mass is proportional to the tangential wind speed and the sine of the latitude. The Coriolis force arises in the equations of motion because Newton's second law is expressed in coordinates fixed relative to the rotating Earth and not fixed in space. In the atmosphere it is the local horizontal component of this force that is important and in the Northern Hemisphere the Coriolis force on an air parcel acts in a direction to the right of the parcel's motion (i.e. radially outwards for a cyclonically-rotating vortex). *The pressure at any given radius is equal to that at large radii minus a radial integral of the sum of the centrifugal* *and Coriolis forces times the density.* One very important implication of this result is that *where the primary circulation decreases with height beyond a given radius, the pressure at this radius will increase with height more slowly than that in the storm environment.* Then, hydrostatic balance implies that the density is less than that at large radii.

The approximately balanced state described above is called *thermal-wind balance.* Strict thermal-wind balance describes a state in which the forces associated with the weakening of the tangential circulation with height are exactly balanced by those associated with a decrease in the density with radius. If the balance of forces were exact, there could be no secondary circulation in the vortex, i. e. no radial or vertical motion as there would be no forces to drive it. To understand the forces that give rise to the secondary circulation of a hurricane we must consider the processes that give rise to small imbalances in the forces described above.

The secondary circulation

In a shallow layer of air near the surface, typically 500 - 1000 m deep, frictional stresses reduce the tangential wind speed and thereby the centrifugal and Coriolis forces, while it can be shown that the force associated with the radial increase of pressure remains largely unchanged. We call this layer the friction layer. The result of the force imbalance is a net inward force that drives air parcels inwards in this layer. One can demonstrate this effect by placing tea leaves in a beaker of water and vigorously stirring the water to set it in rotation. After a short time the tea leaves congregate near the bottom of the beaker near the axis as shown in Fig. 3: they are swept there by the inflow in the friction layer. Slowly the rotation in the beaker declines because the inflow towards the rotation axis in the friction layer is accompanied by radially-outward motion above this layer. The depth of the friction layer depends on the viscosity of the water and the rotation rate and is typically only on the order of a millimetre or two in this experiment. Because the water is rotating about the vertical axis, it possess angular momentum about this axis. Here angular momentum is defined as the product of the tangential flow speed and the radius. As water particles move outwards above the friction layer, they conserve their angular momentum and as they move to larger radii, they spin more slowly. The same process would lead to the decay of a hurricane if the frictionally-induced outflow were to occur just above the friction layer, as in the beaker experiment. What then prevents the hurricane from spinning down, or, for that matter, what enables it to spin up in the first place? Clearly, if it is to intensify, there must be a mechanism capable of drawing air inwards above the friction layer, and of course, this air must be rotating about the vertical axis and possess angular momentum so that as it converges towards the axis it spins faster. The only conceivable mechanism for producing inflow above the friction layer is the upward "buoyancy force" in the clouds, the origins of which we examine below.

Calculations show that for tangential wind profiles characteristic of a mature hurricane, the inflow in the friction layer turns upwards before it reaches the hurricane centre. The maximum upflow at the top of the friction layer is near to the radius of maximum tangential wind speed. This explains why the eyewall clouds form in a ring away from the central axis. The inflowing air acquires moisture from the sea surface and as it rises out of the boundary layer the water vapour condenses to form the deep clouds surrounding the eye. The density of the ascending cloudy air at a particular height and radius decreases with the amount of moisture it contains when it left the friction layer. This is a result of the latent heat that is released when the water vapour progressively condenses in the cloud. To understand the radial variation of density of the ascending air we need to examine the moisture transfer from the sea surface.

The rate of evaporation of moisture from the sea to the air depends on the relative humidity of the air, being larger when the relative humidity is low and zero when the relative humidity is 100%, i.e. when the air is foggy. The rate of evaporation increases also with the temperature of the sea, but for fixed sea surface temperature and relative humidity, the rate increases rapidly as the surface wind speed increases and the surface pressure decreases. It turns out that the latter effects are paramount so that the moisture content of air converging in the friction layer and ascending out of it increases rapidly with decreasing radius. Therefore the density of the cloudy air above the friction layer decreases also with decreasing radius. Being lighter than the air at larger radii at the same height, we might expect it to rise. In fact it will only rise if it is less dense than the air in a hypothetical vortex that is in strict thermal wind balance with the tangential wind field distribution that exists at the particular instant of time. If that is the case we can say that it has an upward buoyancy force relative to its immediate surroundings. This force prevents the air flowing outwards immediately above the friction layer as in the beaker experiment, i. e. it maintains the secondary circulation of the mature storm. During the intensification stage, the buoyancy force leads to inflow above the friction layer. Because the air is rotating about the axis, it possess angular momentum and above the friction layer, air parcels approximately conserve their angular momentum when they are displaced radially. Where they spiral inwards, they spin faster and where they spiral outwards, they spin more slowly.

As air exits the friction layer most of it flows upwards and eventually outwards, which explains why the eyewall slopes outwards. The ascending air parcels approximately conserve their angular momentum so that as they move away from the rotation axis, they spin more slowly. Thus the tangential wind speed in the hurricane decreases with height above the friction layer. Because of the contribution of the Earth's background rotation to the angular momentum measured relative to the rotating Earth, the direction of rotation actually reverses at large radii in the upper-level outflow from the storm and the flow eventually becomes anticyclonic. One can think of the Coriolis force acting on the radial component of flow acting to decelerate and reverse the direction of the tangential component of flow.

The decrease in tangential wind speed with height has important consequences for the dynamics. We saw earlier that it is associated with a downward pressure gradient force relative to that in the environment. This force is approximately balanced by the buoyancy force associated with the warm core region so that it is really the net of these two forces that drives the secondary circulation.

The eye of the storm

We have seen that the mature hurricane has a largely cloud-free eye. The lack of deep clouds in the eye is a result of subsiding motion in the eye. When an air parcel subsides, its pressure increases causing it to warm. Recall how your bicycle pump warms up when you pump up your tyres! The warming results from the temperature increase of the air that is compressed. As the subsiding air warms in the hurricane eye, any water drops or ice crystals (i.e. clouds) that might have been in it rapidly evaporate. Despite the pressure rise, the density rises less than it does in the storm environment so that the air becomes buoyant relative that in the environment. Therefore it has to be forced down. How does this happen?

We have seen that associated with the decline in the tangential wind speed with height at all radii, there is a reduced upward force acting on air parcels compared with that at large radii. If the vortex were exactly in balance, the air density would be less also and there would be no net force to drive vertical motion. This is thought to be nearly the case in a mature hurricane and it would appear that the subsidence near the axis of a hurricane occurs mainly during the intensification stage. As the tangential circulation intensifies, the density of an air parcel in the eye must be slightly larger than it would be in the exactly balanced state in which case the air slowly subsides. When the tangential circulation weakens, the density is slightly less than in the exactly balanced state and the air slowly rises.

4 Hurricane motion

As a result of an intensive research effort in the late 80's and early 90's, we now know a lot about the dynamics of in hurricane motion. To a first approximation, hurricanes are carried along by some vertical average of the larger scale flow in which they are embedded. Thus at low latitudes, storms tend to move westwards with the trade wind flow, but even if the flow is exactly towards the west, they have also a poleward drift, an effect that can be shown to result from the increase in the local vertical component of the Earth's angular velocity with increasing latitude. Often this poleward motion is accentuated by the larger-scale flow, such as when the storms are on the western side of (anticyclonically-rotating) subtropical high pressure systems. In such situations, storms recurve and begin moving towards the east, aided by the westerly winds at higher latitudes.

About 40% of Atlantic hurricanes recurve as they move out of the tropics and then move eastwards or northeastwards, some of them becoming intense extra-tropical cyclones.

Short-term (24-48 hour) hurricane track forecasts have greatly improved during the last decade, in part because the numerical weather forecasting models that predict the large-scale flow have become more accurate, but there are still occasions when individual forecasts go astray and involve large errors. Nevertheless, the accuracy is still often unacceptably large beyond about 72 hours, which can be a problem when a major storm is threatening a large populated area as was the case with Hurricane Katrina (the forecasts made 72 hours and less before the event were exceptionally good, but the 4 and 5 day forecasts were not so good). In the Atlantic during 2004, the National Hurricane Center's mean track errors after 24, 48, 72, 96 and 120 hours were 107 km, 187 km, 280 km, 395 km and 546 km, respectively.

5 Intensity change

We have a reasonably good understanding of at least some of the individual processes that cause the intensity of a hurricane to change. Nevertheless, current forecasts of intensity change have little skill and this is a problem of active research. We know that vertical wind shear, i. e. a change in the large-scale wind speed with height, has a detrimental effect both on the formation and intensification of hurricanes. It can have an effect also on the storm motion and is one factor that causes the storm centre to wobble about some mean track. If the shear is strong enough, as often happens when storms move polewards into the middle latitudes, the warm air in the eye gets "blown away" from the low-level centre of circulation and the storm weakens.

The ocean is another factor. We have seen that the storm gains its energy from the moisture it picks up at the sea surface and this, in turn, determines the temperatures that can be attained in the eyewall clouds and hence the buoyancy of these clouds relative to the storm environment. We have seen also that the moisture supply depends strongly on the ocean surface temperature. The large breaking waves generated by the hurricane-force winds produce turbulent motions in the warm layer and the ensuing mixing draws cooler subsurface water upwards into this layer. This mixing reduces the sea-surface temperature and lowers the surface evaporation, which of course feeds back to affect the hurricane. The amount of cooling depends on the depth of the warm layer before the storm hits and on the length of time the storm lingers over a particular spot. It is therefore largest for slow-moving storms.

Another detrimental effect on hurricane intensity is the presence of dry air that may be drawn into their circulation. This dry air provides a more unfavourable environment for the deep convection in the storm.

6 The demise of hurricanes

Hurricanes always decay in intensity as they move over land, not so much because the frictional stresses at the surface are increased, but because the life line to the moisture supply from the sea surface is cut off. From the discussion above one can see that this will lead to a reduction of the temperature, and hence the upward buoyancy force in the eyewall clouds that is responsible for maintaining the secondary circulation. Even when the winds have reduced in strength and the surface moisture supply has greatly diminished, hurricanes can still produce copious amounts of rainfall. Slow moving storms can cause very heavy falls locally, which can lead to flash flooding. Also, because hurricanes constitute regions rich in rotation about a vertical axis, they often spawn tornadoes on making landfall. Tornadoes are very intense small-scale vortices that are produced in certain types of thunderstorms which have rotating updrafts. They are typically only a few hundred meters across, but wind speeds can exceed 100 m s^{-1}.

Hurricanes that move to higher latitudes over the sea often form intense extra-tropical low-pressure systems. The extra-tropical transition of storms as they move polewards over cooler water and suffer increasing vertical wind shear is an active area of research.

7 Potential Intensity

An interesting question from a theoretical perspective is what sets the maximum intensity a storm can achieve in a given environment? Professor Kerry Emanuel at the Massachusetts Institute of Technology has likened the mature hurricane to a Carnot heat engine that acquires heat energy, primarily in the form of latent heat, at the sea surface temperature (typically 26^{o}C to 30^{o}C) and exports this heat to the upper troposphere at some mean temperature (typically -60^{o}C to -70^{o}C) near the tropical tropopause, which lies around 15-16 km. By making various assumptions he showed how to calculate the maximum intensity that a storm can achieve in a given location at a particular time. Such calculations are important not only to forecasters, but also for making assessments of the impact of global warming on hurricane intensity. While the accuracy of the theory has been called into question on the basis that numerically-simulated hurricanes in models with sufficiently high resolution can exceed the calculated maximum intensity, it seems that majority of observed storms do not and that most have significantly lower intensities than the predicted maximum. The inference is that there are frequently processes at work in the atmosphere that are detrimental to intensification.

8 Current research

I have already mentioned two areas of active research on hurricanes, but of course there are others. One challenging area of current research is to improve our understanding of, and ability to predict the intensity change of storms: will a storm intensify or weaken in the immediate future? Intensity forecasts are critically important when storms are close to making landfall. Such improvements are likely to come about by improved representations of physical processes in forecast models, a task that calls for a better understanding of some of these processes. An example is the the problem of concentric eye-wall cycles. Strong hurricanes often undergo periodic intensity changes when a new eyewall forms outside the current eyewall and moves radially inwards. One possibility is that the subsidence associated with the outer eyewall weakens the convection in the inner eyewall, allowing the inner core region to spin down on account of friction. Another possibility is that air converging into the inner eyewall is redirected to the outer eyewall, reducing its supply of absolute angular momentum and moisture. As the new eyewall continues to contract, the storm re-intensifies. The processes that trigger these eyewall cycles are not well understood.

We have seen the importance of surface moisture supply to the hurricane, but we are unsure how to accurately quantify the rate of moisture supply at the high wind speeds that are found in the hurricane core. Measurements at these extreme wind speeds are extremely difficult (and hazardous) to make. During the last few Atlantic hurricane seasons, the National Oceanic and Atmospheric Administration's Hurricane Research Laboratory in Miami has been trying to acquire the necessary measurements by making low altitude flights over the sea. The aim is to try to determine the so-called exchange coefficients that are required to represent the moisture supply and the surface exchange of momentum in hurricane models. At the same time there has been a large effort to gather ocean data before and after the passage of a hurricane. The sophisticated hurricane forecast model developed by the Geophysical Fluid Dynamics Laboratory in Princeton is linked to a forecast model for the ocean and aims to represent the changes in ocean structure brought about by the hurricane and the feedbacks that result.

While the dynamics of hurricanes can be understood to a first approximation in terms of processes that are axisymmetric about the rotation axis, it is recognized that nonaxisymmetric processes are important also during all stages of the life cycle. Large-scale asymmetries arise from the interaction of storms with their environment and these asymmetries have an important effect, especially on storm motion and perhaps also on storm intensity. The radial structure of tangential winds in the inner region of a hurricane is such that the vortex is able to support different types of waves in which air parcels move radially inwards or outwards during a wave cycle. One particular type of wave propagates anticyclonically relative to the tangential wind and has analogous properties to large-scale planetary waves in the atmosphere and ocean. The large-scale waves are also called Rossby waves after the Swedish meteorologist Carl Gustav Rossby, who discovered them. For this reason the waves on a vortex are referred to as vortex Rossby waves. They are almost certainly excited by moist convection, but also by external influences such as changes in the large-scale vertical wind shear. Vortex Rossby waves have been shown to propagate radially, to transport angular momentum radially, and can play an important role in the intensification of hurricanes. The waves may become unstable as well and it is thought that the instability may be an important mechanism for producing mixing of angular momentum and heat across the eyewall into the eye itself. Pioneering studies of these waves and the instabilities they produce have been carried out over the last decade by Professors Michael Montgomery and Wayne Schubert at Colorado State University and are continuing. During the last Atlantic hurricane season, a major experimental programme was carried out to document the asymmetries in hurricanes, and especially the structure of the spiral rainbands and their influence on hurricane intensity. The observations involved in situ measurements using multiple research aircraft and the results from the wealth of data collected are forthcoming.

One of the most controversial topics at present concerns the possible effects of global warming on the frequency and intensity of hurricanes and there has been a number of recent papers on this subject. A particular problem of attributing the changes in tropical cyclone frequency and intensity to global warming is the large natural variability in the frequency of storms. Nevertheless, Peter Webster at the Georgia Institute of Technology and coworkers examined 35 years of tropical cyclone records in all ocean basins and reported a large increase in the number of intense storms in most basins, the smallest percentage increase being in the North Atlantic Ocean. In contrast they reported that the number of cyclones and cyclone days has decreased in all basins except the North Atlantic during the last decade. They note that averaged sea surface temperatures have increased in all basins during the period, typically by about 0.5^{o}C, the implication being that this may account for the increase in intense storms. Kerry Emanuel has pointed out that while the frequency of tropical cyclones is an important scientific issue, it is not an optimal measure of tropical cyclone threat. He notes that the wind damage produced by cyclones rises roughly as the cube of the wind speed as does the amount of power dissipated by the storm over its lifetime. Emanuel defines a power dissipation index that is equal to the cube of the maximum wind speed integrated over the life of the storm. He has shown that fluctuations in this index correlate rather well with fluctuations in regional mean sea surface temperatures in the North Atlantic and North Pacific, the two basins which have the most reliable data on storm intensities. The inference is that if the oceans warm as is expected to occur in conjunction with a global warming of the atmosphere, the damage potential of storms will increase. In view of the population growth in many coastal areas that are prone to hurricanes, the research to date points to a worrying scenario that damaging storms like Hurricanes Katrina and Rita in 2005 may become the norm in the next decades. Some researchers including Chris Landsea at the National Hurricane Center in Miami and Professor William Gray at Colorado State University have expressed skepticism about these results, pointing to the deficiencies in the data base used for these studies. In fact Professor Gray claims that there has been no significant increase in the number of intense hurricanes in all basins except in the Atlantic over the last twenty years and there has even been a slight decline in the Northwest Pacific during this period.

Acknowledgements

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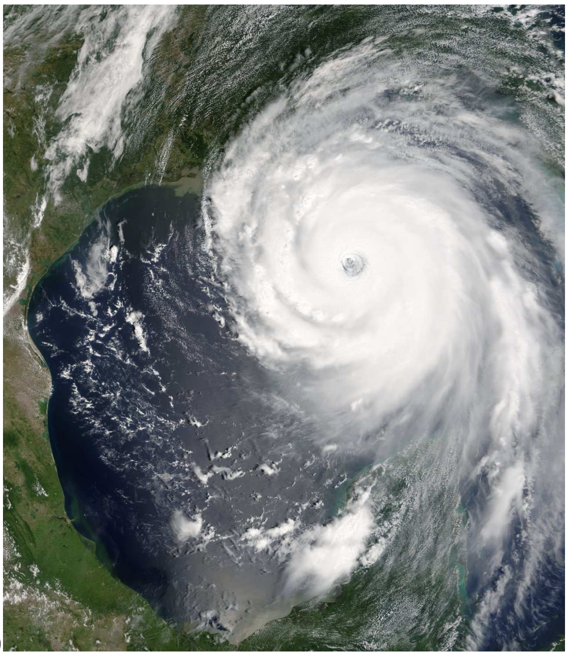
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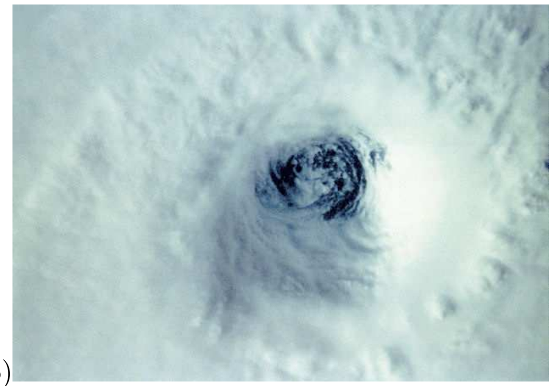
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Figure 1: (a) Visible satellite imagery of Hurricane Katrina on September 2005 shortly before making landfall in New Orleans. (b) Close up satellite image of the eye of a hurricane. (c) Aerial photograph inside the eye of Hurricane Isabel (2003), showing the sloping eyewall clouds. (Courtesy Sim Aberson, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratories Hurricane Research Division)

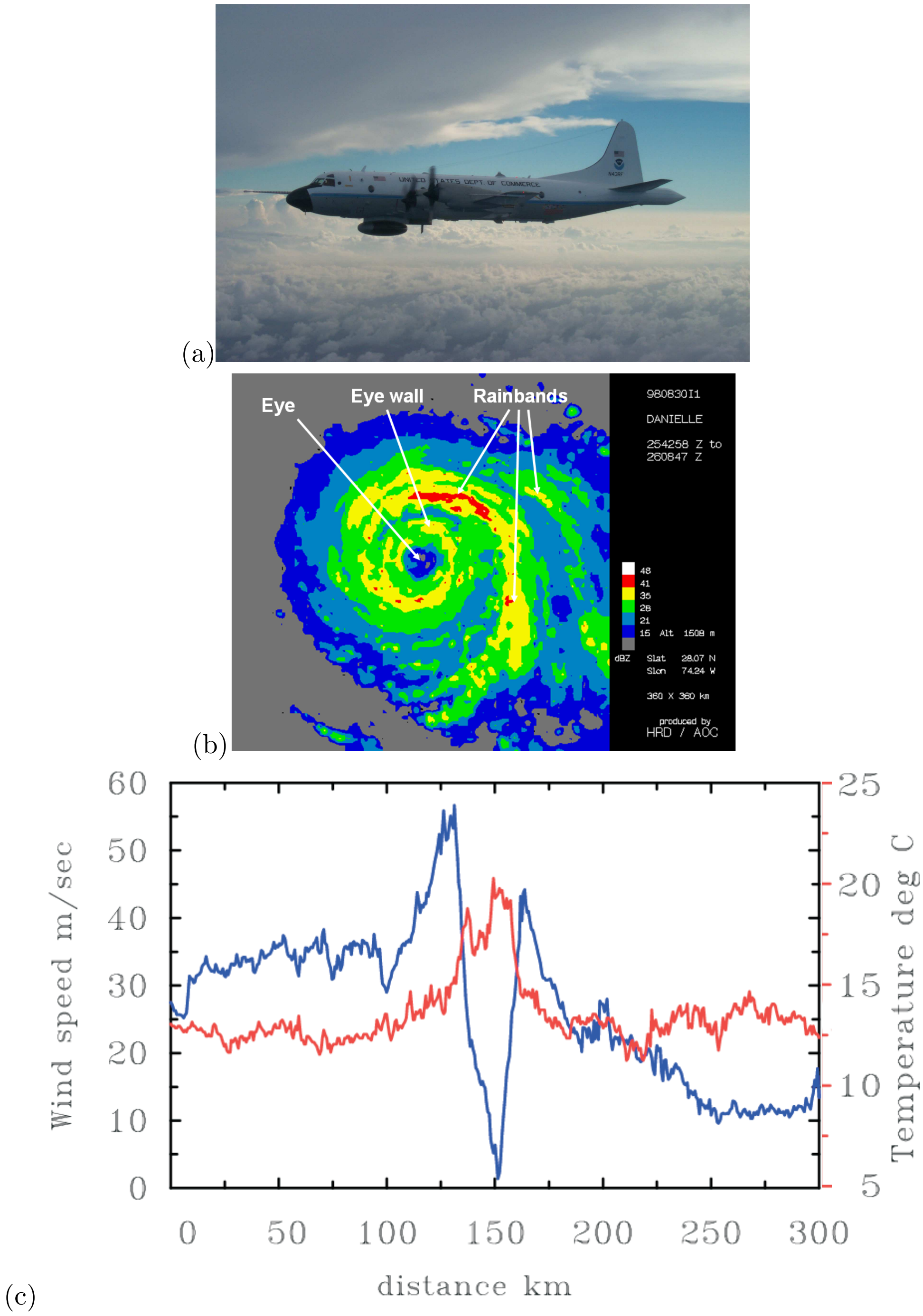

Figure 2: (a) United States National Oceanic and Atmospheric Administration's P3 research aircraft used to collect data in hurricanes. (b) Radar image of Hurricane Danielle (1998), based on a horizontal scan from the belly radar. The colour scale characterizes the radar return signal in decibels, which increases in strength with the intensity of the precipitation. The spiral rainbands, the eyewall convection and the central eye, which is largely free of precipitation, are prominent features. (c) Typical profile of flight-level wind speed and temperature measured during a transect of Hurricane Ivan (2004) by a research aircraft. Note the calm winds and the maximum temperature in the eye and the maximum winds surrounding the eye. (Courtesy National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratories Hurricane Research Division)

(a) 

Figure 3: The beaker experiment showing the effects of frictionally-induced inflow near the bottom after the water has been stirred to produce rotation. This inflow carries tea leaves to form a neat pile near the axis of rotation.