The Role of Water in Atmospheric Dynamics and Climate

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Abstract

From its beginnings nearly 2000 years ago until the end of the nineteenth century, the science of meteorology focused strongly on the role of water and its change of phase; indeed the very word "meteorology" betrays this focus. As synoptic observation networks began to reveal rotary weather systems and fronts, however, the conceptual picture of large-scale atmospheric dynamics changed dramatically to one in which water and its change of phase were considered embellishments on a world view of dry, adiabatic dynamics. This view persists today, even to some degree in the tropics, where phase change of water is a dominant physical process. After reviewing this historical progression, I will highlight both the advances made possible by this dry, adiabatic world view, and the roadblocks to a more complete understanding that this has created. The paper concludes with a discussion of the role of water in the climate system, and the need for scientists better trained in thermodynamics to solve many outstanding problems in weather and climate.

1. Historical overview[1]

To the average person, the word "weather" entails the variation of wind, temperature, clouds and precipitation. Almost all text books in atmospheric science state that "weather" is confined to the troposphere because, although winds, pressure and temperature vary considerably above the tropopause, there are essentially no clouds or precipitation there. Water is clearly central to the notion of weather.

The earliest natural philosophers were preoccupied with explaining clouds and precipitation, which are of paramount significance in any agrarian economy. Thales, whom tradition regards as the first known philosopher of the natural world, lived in the seventh century, B.C., and held that water is the central element that lies at the basis of all creation, from the sky and the earth and through all living things. It took more than 200 years for Greek philosophers to add earth, fire and air to the list of central elements. (It was Thales' follower, Anaximander, who first ascribed wind to the flow of air, a fact not accepted for centuries and still regarded with suspicion by many entering graduate students.) Anaxagoras (499-427 B.C.) sought to explain why hail often occurs in summer, in spite of high surface temperatures. From experience on mountains, he observed that temperature decreases with altitude and deduced that hail must form high up within clouds. Noting that air and debris tend to shoot upward above fires, Anaxagoras speculated that tall clouds result from vigorous heating of air near the ground, showing the value of logical inference from observation, even in the complete absence of any guiding theoretical principles. But theory would soon have its day in the sun.

In his famous treatise *Meteorologica*, written around 340 B.C., Aristotle focused on the natural causes of clouds, rain, floods and thunder. Much like today's global warming naysayers, Aristotle took much delight in attacking accepted wisdom. Using a somewhat convoluted argument, he categorically rejected the idea that wind is moving air and spent considerable effort debunking Anaxagoras's theory that hail forms high up within clouds. If hailstones formed so high within clouds, Aristotle argued, then surely their fall through so much air would render them perfect spheres by the time they reached the ground. Since this was clearly not the case, hail must therefore form near the ground. How to explain that hail is made from ice, which even then was

[1] In this overview, I have relied heavily on the historical work of Frisinger (1977) and Kutzbach (1979).

generally recognized as being cold? Why, it was because water falling through the air must compress and thereby turn into ice. This was perhaps the first instance (but by no means the last) of what happens when the mechanistically inclined try to do thermodynamics. By denying that wind is moving air and that hail forms above the freezing level, Aristotle, the theoretician, set back meteorology by more than 2000 years.

As global exploration and trade became increasingly important during the sixteenth and seventeenth centuries in western Europe, the global distribution of wind became a natural subject of attention among natural philosophers. It is perhaps not surprising that the well known treatises on the origin of the trade winds by Edmund Halley and George Hadley, at the beginning of the 18th century, occurred near the prime of the Age of Sail. This, together with the publication of the Euler equations in 1755 and their extension to the case of motion on a rotating planet in 1860 marked the early advent of dynamical meteorology. But the problem of the origin of cyclones served to re-focus attention on the importance of thermodynamics in general, and of phase change of water in particular.

The characterization of cyclones as rotary storms was well in place by the middle of the 18th century, owing mostly to the observational work of Benjamin Franklin and Elias Loomis. In an attempt to explain their physical origin, the American scientist James Pollard Espy began development of what was to be called the thermal theory of cyclones, beginning in the 1830s. Observing that cyclones are invariably associated with clouds and precipitation, Espy came to believe that such storms are powered by the liberation of the latent heat of vaporization, and undertook extensive laboratory experiments designed to determine what we now refer to as the moist adiabatic lapse rate. His work is particularly remarkable when it is recognized that the formulation of the science of thermodynamics took place during the 1840s and 1850s, and the first law of thermodynamics was not introduced to meteorology until the 1860s. But already in 1841, Espy stated that

> *"When the air near the surface of the earth becomes more heated or more highly charged with aqueous vapor, its equilibrium is unstable, and up-moving columns or streams will be formed. As the columns rise, their upper parts will come under less pressure, and the air will therefore expand; as it expands, it will grow colder about one degree and a quarter for every one hundred yards of its ascent. The ascending columns will carry up with them the aqueous vapor which they contain, and, if they rise high enough, the cold produced by expansion from diminished pressure will condense some of its vapor into cloud. A soon as cloud begins to form, the caloric of elasticity of the vapor or steam is given out into the air in contact with the little particles of water formed by the condensation of the vapor. This will prevent the air, in its further progress upwards, from cooling so fast as it did up to that point; that is, about five-eighths of a degree for one hundred yards of ascent, when the dew point is about 70 degrees."*

Espy went on to deduce that if the environmental lapse is greater than the moist adiabatic lapse rate, convection may occur, and he believed that it was such convection that led to the formation of middle latitude cyclones. He had an important ally in Elias Loomis, who in 1843 wrote that

> *"The heat liberated in the formation of this cloud raises the thermometer, causing a more decided tendency of the air inward toward the region of condensation....Relative elevation of temperature under the cloud gives increased velocity to the inward current of air. More cloud is thus formed, heat liberated....Thus the storm gains violence by its own action."*

This proposed explanation for the origin of middle latitude cyclones, which depended entirely on latent heat release, bears an uncanny resemblance to the theory of Conditional Instability of the Second Kind, developed 120 years later by Charney and Eliassen (1964) to explain the development of tropical cyclones:

> *"We should consider [the depression and the cumulus cell] as supporting one another---the cumulus cell by supplying the heat for driving the depression, and the depression by producing the low-level convergence of moisture into the cumulus cell."*

Although Espy went too far in relying on latent heating as a power source for extratropical cyclones, his work on moist convection marked the first progress on this topic since that of Anaxagoras, more than 2200 years earlier and anticipated by more than a century a prominent theory of tropical cyclones.

By the late 1860s, it was generally accepted that the heat liberated when water vapor condenses is the major source of power for extratropical cyclones. For example, in 1868 the Scottish scientist Alexander Buchan wrote that

> *"The chief disturbing influences at work in the atmosphere are the forces called into play by its aqueous vapour."*

Clearly, water played a central role in conceptions of atmospheric physics through much of the 19th century. But beginning in the mid 1870's new observations began to cast the thermal theory into doubt. In 1874, Julius Hann, later the director of the Austrian weather service, pointed out that heavy tropical rains appeared to have no effect on the surface pressure. a fact also noted in the next century by Charney and Eliassen (1964). Loomis (1877), in stark contrast with his earlier beliefs, stated that

> *"It seems safe to conclude that rainfall is not essential to the formation of areas of low barometer, and is not the principal cause of their formation or their progressive motion".*

But at this time, skepticism about the thermal theory was not widespread, and attempts were made to reconcile the new observations with the theory. In 1874, Hann pointed out that latent heat release must lead to inflow, but if that inflow were not given a vertical motion, the pressure would not fall. Here was perhaps the first hint that latent heating, as it is an *internal* process, need not be associated with the generation of kinetic energy, a fact that is difficult for some to accept even today.

The desiccation of atmospheric science began in earnest as a result of more detailed observations of extratropical cyclones, undertaken in Europe in the 1880s and 1890s. These observations revealed that extratropical cyclones are always associated with substantial horizontal temperature gradients. The fact that such gradients are associated with a reservoir of potential energy was established by the French scientist Margules at about this time. These developments paved the way to the 1916 work of Vilhelm Bjerknes, who is credited with the idea that extratropical cyclones result from the dynamical instability of the baroclinic currents found in middle latitudes. Bjerknes' work marked a transition away from a preoccupation with energetics and toward a focus on stability.

More then any other development, it was the application of linear stability theory to the problem of baroclinic instability that initiated a long period during which the effects of water in atmospheric dynamics were virtually ignored. In linear formulations, it is awkward, at best, to include the strong irreversibility of the process of precipitation, which removes water from the system and thereby causes descending air to be unsaturated. In his seminal paper on baroclinic instability, Charney (1947) argued that

> *"As long as one is concerned with waves of small enough amplitude, the vertical motions will not be of sufficient magnitude to cause condensation, so that this factor may also be ignored."*

Charney here appears to argue not that condensation is unimportant, but that it can be ignored during the early stages of baroclinic development. Nevertheless, he recognized that "condensation can produce appreciable errors" in calculations of baroclinic growth rates and structure. Eady (1949) noted that baroclinic growth rates calculated by ignoring condensation are too small. In a widely ignored portion of his otherwise well-known paper, Eady included the effects of a pre-existing, zonally oriented band of saturated air in his linear analysis of baroclinic growth, and noted the strong tendency toward frontogenesis at the boundaries of the cloudy zone as well as an increase in the rate of growth.

As is often true in science, it is the neglect of secondary effects that permits a focus on the essence of a phenomenon and leads to true progress in understanding it. This was clearly the case in the development of the theory of baroclinic instability, which led to the first coherent and physically consistent view of extratropical dynamics. By neglecting the secondary effects of condensation and friction, one can view the dynamics is terms of the evolution of the adiabatic invariants potential temperature and potential vorticity, as nicely summarize in the work of Hoskins, McIntyre and Robinson (1985).

A casual survey of the literature published during the 1960s and 1970s reveals far more concern with the effect of nonlinearity associated with the finite amplitude of real baroclinic systems than with irreversible processes such as phase change of water and friction. It was not until the 1980s that extensive attempts were made to incorporate these effects in idealized models and theory.

Water in its various phases plays a critical role in the climate system. As early as the late 18th century, Jean Baptiste-Joseph Fourier described the warmth of the earth's surface in terms of a "hothouse" effect, and by the middle of the 19th century, the Englishman John Tyndall recognized that much of the absorption of infrared radiation in the atmosphere is owing to the presence of water vapor. The central importance of water vapor in the greenhouse effect was established quantitatively by Svante Arrhenius (1896), using primitive measurements of absorption coefficients. In the 20th century, it came to be realized that clouds are responsible for much of the reflection of solar radiation by the earth system, as well as being strong absorbers of infrared radiation.

2. Water in Atmospheric Dynamics

a. Zonally symmetric equilibrium states

There is a long tradition in dynamical meteorology of considering the evolution of small perturbations to an equilibrium state. In their classical treatises on baroclinic instability, Charney (1947) and Eady (1949) took the equilibrium states to be zonally oriented flow with vertical shear, satisfying hydrostatic and geostrophic (and therefore thermal wind) balance.

It is interesting to note that while such states satisfy the equations of motion, they are not in thermodynamic equilibrium. In order to satisfy thermodynamic as well as dynamic balance, such states would have to be in radiative equilibrium. We know from detailed calculations of radiative equilibrium, holding water vapor and clouds at their climatological values, that most of the lower troposphere would have super-adiabatic lapse rates. Besides being unphysical, such states would render untenable the mathematical problem of linear baroclinic instability.

A more practical approach is to allow what we are calling the equilibrium state to contain small-scale convection and then consider the stability of such states to macro-motion on scales much larger than those characterizing the convective eddies. Thus we may consider the equilibrium state to be one of *radiative-convective* equilibrium. The first detailed calculations of radiative-convective equilibrium that included moist convection were described by Manabe et al. (1965). Such states have nearly moist adiabatic lapse rates in the troposphere and are thus quite stable to dry adiabatic displacements. These states are not only baroclinically unstable, but unstable to slantwise moist convection everywhere that the horizontal temperature gradient is non-zero.

Slantwise moist convection has time and space scales that are intermediate between the scales of upright moist convection and of baroclinic instability (Emanuel, 1983). If we continue to be interested in the stability of equilibrium states to baroclinic motion, then may also regard the slantwise convection in the same way we handled upright moist convection: we assume that the convection adjusts the macro-flow to nearly neutral equilibrium on time scales small compared to the time scales over which radiation, surface fluxes and synoptic-scale flows destabilize the atmosphere to slantwise convection. (This is not as good an assumption as in the case of vertical convection, and may break down in the ascent regions of strong extratropical cyclones.) Thus we may regard the equilibrium state as one of *radiative-slantwise convective* equilibrium. That the baroclinic atmosphere is close to such a state is shown in the observational analyses by Emanuel (1988). Note that in strongly baroclinic regions, such states are decidedly stable to purely vertical displacements.

Given the latitudinal distribution of moist entropy in the boundary layer together with the stipulation that the zonal wind vanish at the surface, the thermal and kinematic structure of the radiative-slantwise convective equilibrium state is completely determined. If the tropopause is determined by matching the troposphere to the radiative-equilibrium of the stratosphere, then the tropopause height is also completely determined. Given the observed, zonally averaged distribution of moist entropy at the surface, the tropopause height, so determined, is very close to the observed height, as shown in Figure 1. The sharp descent of the tropopause across the jet is captured, as well as the gradual decline in tropopause height toward the pole.

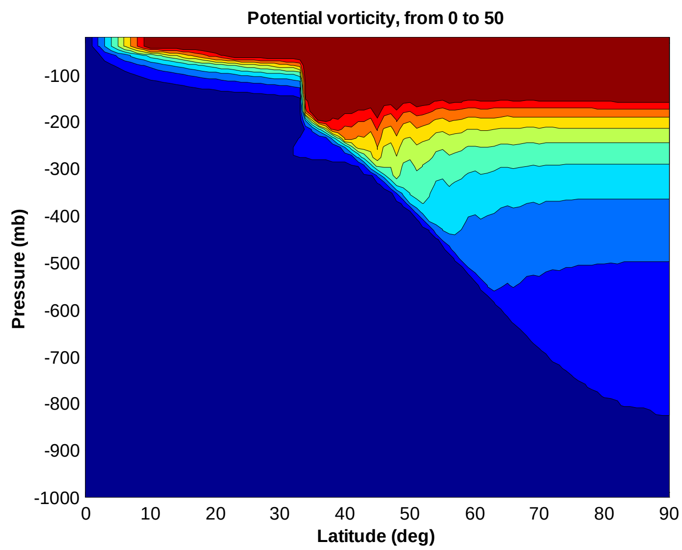

Figure 1: Potential vorticity in a radiative-slantwise convective equilibrium state, with an assumed isothermal stratosphere. The troposphere is assumed to be neutral to slantwise moist convection and to have vanishing zonal wind at the surface; the wind distribution above the surface is determined from the thermal wind equation.

The dynamically inclined like to state that the height of the tropopause outside the tropics is determined by dynamics (e.g. see Lindzen, 1993). This sentiment is based in part on the false idea that moist convection is confined to the tropics. In fact, middle and high latitudes experience a great deal of deep convection, over the continents in summer and over the oceans in winter. The residence time of air over the oceans in winter or the continents in summer is more than sufficient for convection to establish moist adiabatic lapse rates (along angular momentum surfaces, as required by theory of slantwise moist convection), while the transit of air over continents in winter or oceans in summer is not so long that radiative cooling can appreciably change the lapse rates, except near the surface. Thus the only places one finds appreciably sub-moist adiabatic lapse rates (along angular momentum surfaces) is in polar regions and in boundary layers over continents in winter or oceans in summer.

b. Baroclinic instability

In assessing the stability of the equilibrium zonal flow, to be consistent, one should consider flows that satisfy thermal wind balance *and* radiative-convective equilibrium. It is formally inconsistent to neglect phase change of water in the linear stability problem, when the flow whose stability is being assessed is itself convecting. Thus, the classical problem of baroclinic instability is, in an important sense, ill-posed. The static stability is taken to be the observed stability, which is established by moist convection, but phase changes of water are neglected in the perturbations.

The problem of the stability of convecting atmospheres to motions on scales much larger than those characterizing the spacing between cumulus clouds was addressed by Emanuel et al. (1994). They used as a starting point the observation that ascending regions are moister than descending regions, so that not all the moisture convergence into ascending regions is compensated by precipitation; some must be used to moisten the atmosphere. Thus not all of the adiabatic cooling associated with large-scale ascent can be compensated by latent heating and there is net cooling of ascending air. Emanuel et al. (1994) argued on this basis that to a first order of approximation, the dynamics of large-scale motions in convecting atmospheres are the same as those of dry atmospheres, but with a greatly reduced effective static stability. When applied to baroclinic instability, this would give horizontal scales less than, and growth rates greater than the classical values by about a factor of 5.

The problem with this approach is that observations show rather clearly that waves of even very small amplitude have sufficient downward motion in their descent phases to utterly wipe out convection there. (An interesting exception may be the case of a certain variety of “polar lows”, which appear to be examples of baroclinic instability in strongly convecting atmospheres, usually in very cold air flowing out over relatively warm ocean or lake waters. In these cases, deep convection can often be found in all quadrants of the disturbances.) Thus, in this particular sense, the waves become nonlinear almost immediately. One way of dealing with this problem is to assume that the ascent regions of the growing disturbances are saturated, or convectively adjusted, while the descent regions are subsaturated. Formally, one has to assume in the “linear” models that this moist-up, dry-down condition is the *only* important nonlinearity in the system during its early growth. This approach was taken by Emanuel (1985) in an analytic model of frontal circulations, by Thorpe and Emanuel (1985) in nonlinear models of frontogenesis, and to linear and nonlinear baroclinic instability by Emanuel et al. (1987) and Fantini (1993). The first three of these works used semigeostrophic models, for which the potential vorticity plays the same mathematical role as static stability in quasigeostrophic models. Slantwise neutrality implies zero effective potential vorticity, so in these works the potential vorticity was taken to be very small in the ascent regions of the waves and fronts.

The main conclusion of these studies is that while condensation in the ascent regions of the waves increases frontogenesis and the growth rate of baroclinic waves (the latter by as much as a factor of two), the main effect is on the structure of the waves, with the ascent regions generally confined to thin, sloping sheets, in contrast with broad regions of descent. The overall horizontal wavelength of baroclinic disturbances is reduced by roughly a factor of two, and fronts form much more quickly at the lower than at the upper boundary when condensation is accounted for. Later work by Fantini (1993) showed that the sensitivity of growth rates to very small moist potential vorticity is somewhat exaggerated by semigeostrophic models; when the primitive equations are used the increase in growth rates by condensation are even more modest. Nevertheless, the structural differences remain, and Fantini (1995) showed that condensation favors relatively stronger warm fronts.

Some aspects of the asymmetry introduced by condensation in baroclinic waves are illustrated in Figure 2, which shows the distribution of surface pressure and precipitation in developing baroclinic waves when the effective static stability is reduced by 90% in ascending regions of the disturbances. Note the concentration of precipitation into relatively thin bands and small patches surrounding the surface low pressure areas.

The complex and important role of water in baroclinic disturbances is nicely illustrated by the observational studies conducted by Browning (1986, 1990, 1994) and Parsons and Hobbs (1983) amongst many others. It is clear that, in addition to contracting the main regions of ascent associated with the fronts and the cyclones, the presence of moisture gives rise to a rich spectrum of mesoscale phenomena, including mesoscale precipitation bands and squall lines. These mesoscale phenomena constitute a large measure of what the average person considers to be “weather” and pose at least as a great a challenge to forecasters as prediction of the surface pressure field did a generation ago.

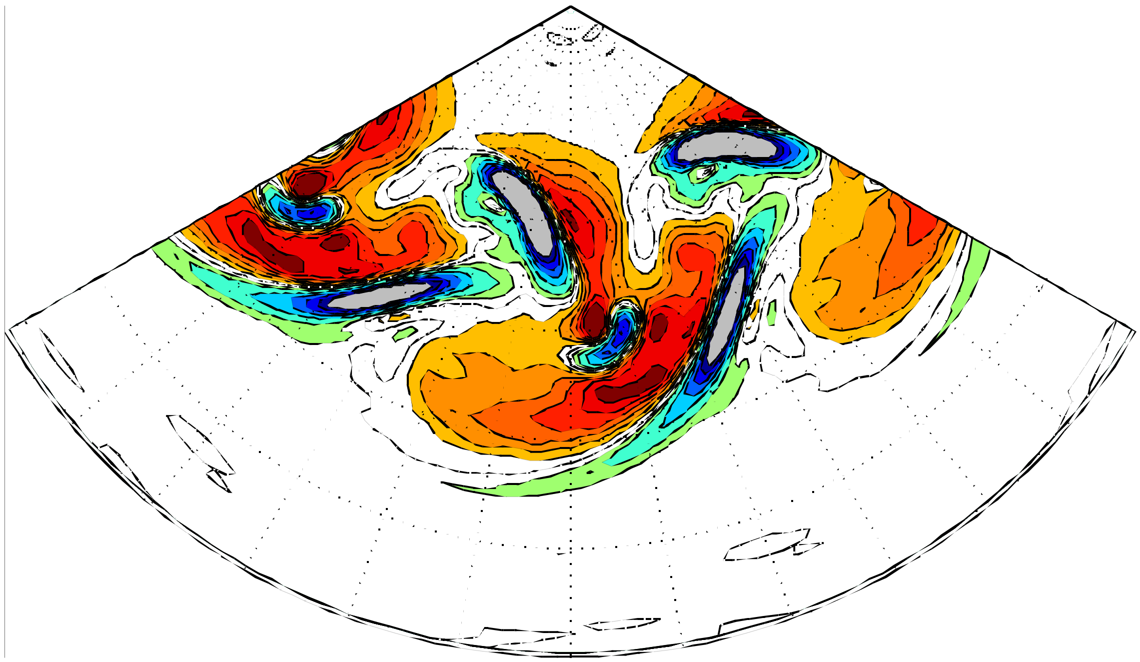

Figure 2: Distribution of vertical velocity over a third of the Northern Hemisphere in a primitive equation model simulation, in which condensation is represented by applying a reduced static stability to upward moving air. Cool colors represent upward motion; warm colors represent downward motion. (Model designed by and figure courtesy of Tieh Yong Koh.)

c. The Tropics

Compared to the extratropical atmosphere, progress in understanding and predicting tropical weather systems has been slow. In contrast with extratropical weather systems, most tropical systems are dominated by diabatic processes such as condensation, radiation, and surface fluxes. The training of graduate students, which in many schools is dominated by instruction in adiabatic, quasigeostrophic dynamics, leaves them largely unprepared to tackle the Tropics, for which a solid grounding in moist thermodynamics is essential. Progress in this century will be made by those who do not shrink from acquiring comprehensive backgrounds in both dynamics and thermodynamics.

Moist convection is a turbulent, chaotic process, with characteristic eddy turnover times on the order of an hour. For this reason, the predictability time scale of convection on the scale of the individual convective cell is no more than a few hours. As in the case of classical turbulence, there is some hope that larger scale phenomena that interact with the turbulence can be predicted on longer time scales, if there is a well-defined relationship between the macro-flow and the statistics of the turbulence. Part of the historical problem in treating the Tropics can be traced to a failure to distinguish between the behavior of individual convective elements and that of large scale systems that interact with whole ensembles of convective elements.

This problem of predictability is nicely illustrated by the case of radiative-convective equilibrium. In recent years, it has become possible to simulate such states explicitly, with three-dimensional, nonhydrostatic models that simulate the convection explicitly, albeit with marginally adequate horizontal resolution. In one such experiment, the radiative cooling of the troposphere is simply specified, and classical bulk aerodynamic formulae are used to calculate fluxes of heat, moisture and momentum from a sea surface of fixed temperature. The simulation is conducted in a doubly periodic domain of horizontal dimensions on the order of 100 km, so as to encompass many individual convective cells. Since the radiative cooling is specified, and since in equilibrium the domain average latent heating must equal the radiative cooling, the statistically averaged amount of convection is specified in this experiment. Thus, for example, the amount of precipitation integrate over the whole domain and averaged in time, is constant. If one considers space-time subdomains of the precipitation, on the other hand, there is considerable fluctuation of the precipitation. Figure 3 shows the ratio of the standard deviation of precipitation to the mean precipitation in such subdomains as a function of their size and length of averaging time. It would appear from this experiment that to achieve a stable statistical relationship between the convection and the large-scale forcing (in this case, just the radiative cooling), one has to average over at least 30 km and several hours. Thus we may hope that for weather systems with space and time scales larger than these, there may be a stable statistical relationship between the convection and the weather system in question.

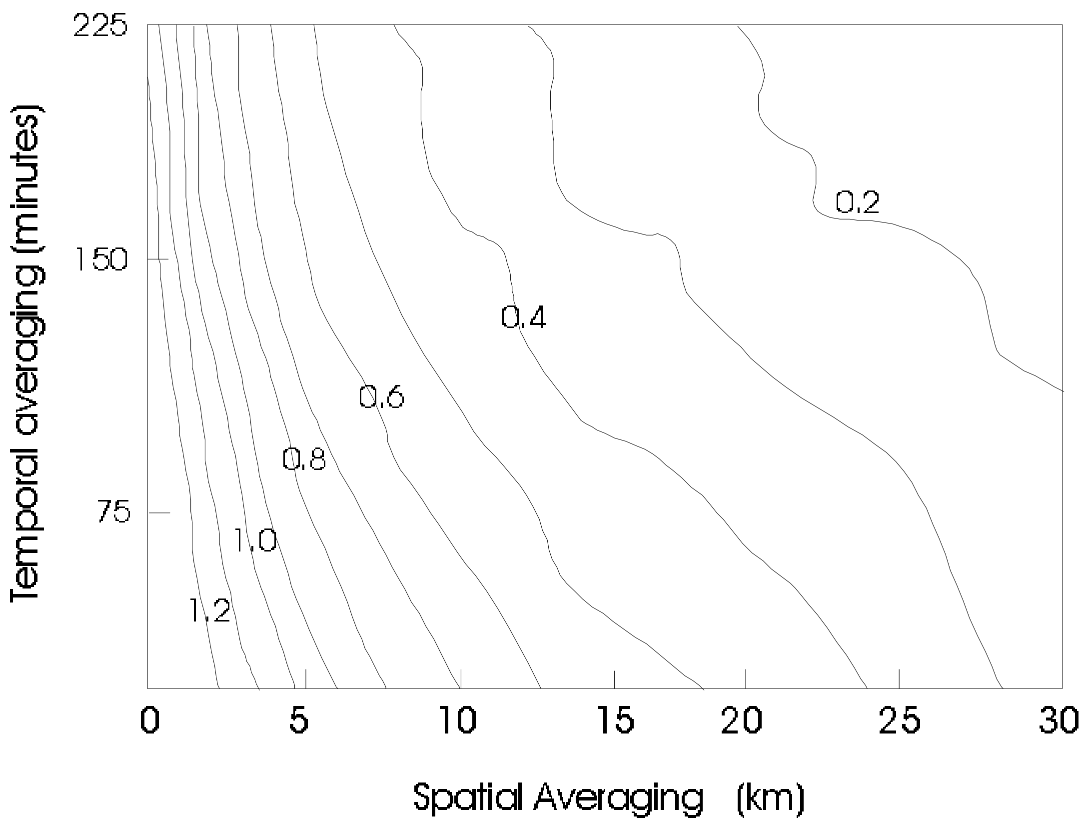

Figure 3: Ratio of the variance to the domain average of the precipitation in a three-dimensional numerical simulation of radiative-convective equilibrium over a water surface, as a function of space-time averaging. The ordinate is the length of time averaging; the abscissa is the length of averaging in space. This ratio asymptotes to $\sqrt{2}$ for short averaging intervals. (From Islam et al., 1993.)

The radiative-convective equilibrium state is a natural basic state to use for thinking about the tropical atmosphere, and which to use as a basic state in linear perturbation analysis. The failure to recognize this and to regard the tropical atmosphere as basically dry with moist perturbations led to such historical anomalies as the theory of Conditional Instability of the Second Kind (CISK).

The problem of the behavior of even linear perturbations to radiative-convective equilibrium is far from solved. Computer speeds and capacities are only just now becoming large enough to simulate radiative-convective equilibrium over large enough domains to examine the behavior of synoptic-scale tropical disturbances while still explicitly simulating cumulus clouds. As mentioned in the preceding section, this problem was looked at from a theoretical standpoint by Emanuel et al. (1994), who argued that linear perturbations to radiative-convective equilibrium should behave very much like adiabatic linear perturbations, except that they would experience an effective static stability about an order-of-magnitude less than that of their adiabatic counterparts, and that the perturbations would be damped in proportion to their frequency, owing to the finite time scale over which convective clouds respond to changes in their environment. More recently, Wheeler and Kiladis (1999) have shown that observed anomalies of outgoing longwave radiation in the equatorial region indeed follow have dispersion characteristics very much like adiabatic modes of the equatorial waveguide, but with greatly reduced equivalent depths, as shown in Figure 4. It remains to identify the mechanisms that serve to excite such modes, and many have been proposed in the literature.

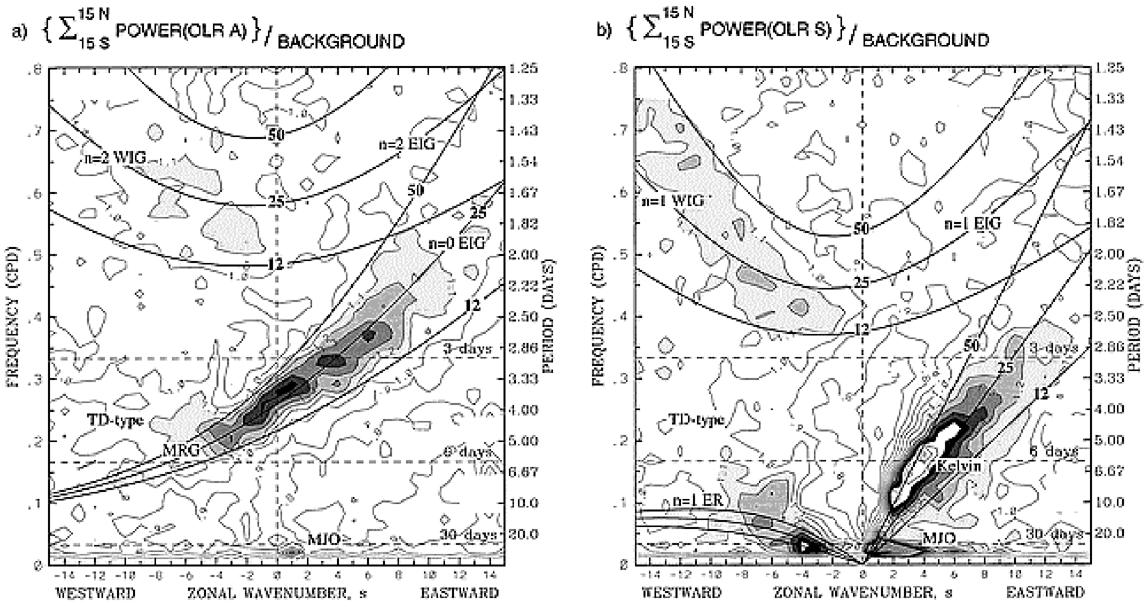

Figure 4: Spectra in the wavenumber-frequency domain of satellite-measure outgoing longwave radiation measured over a period of several years in a latitude belt extending from 5 S to 5 N. A background red noise epectrum has been subtracted from these fields. At right are components that are symmetric about the equator; the left panel shows asymmetric modes. The solid curves represent the dispersion curves of equatorially trapped waves, labelled by their equivalent depths. (From Wheeler and Kiladis, 1999.)

By considering moist convection as a statistical equilibrium process, latent heating must be regarded as an internal process and large-scale circulations must be regarded as arising from dynamical processes and from thermodynamic energy input from the lower boundary or from cloud-water vapor-radiation interactions. One must regard the conversion of thermodynamic to mechanical energy in terms of sources and sinks of the moist entropy, not the conversion between latent and sensible forms of enthalpy. Thus, tropical cyclones are driven by the wind-induced transfer of moist enthalpy from the sea surface, not by the release of latent heat in cumulus clouds, which is no more than a transfer process. (By analogy, automobiles are driven by engines, not by drive shafts, even thought the latter are essential components for transferring motive power to the wheels.)

Clearly, water plays an essential role in tropical meteorology, and many tropical weather systems are gradually becoming better understood. Yet there remain fundamental problems. For example, there exists no theory for the Madden-Julian Oscillation that is general accepted and can account for all of its observed characteristics. Perhaps even more troubling, we lack a theory for moist convective spacing and vertical velocity scales, even in radiative-convective equilibrium states. (Theories have been proposed by Rennó and Ingersoll (1996) and Emanuel and Bister (1996), but these were based on the assumption that the main irreversible entropy source in radiative-convective equilibrium is mechanical dissipation. This was shown to be a bad assumption by Pauluis and Held (2000), thus leaving us without a viable theory for moist convective scaling.) We do not understand nor can we predict with any real skill the genesis of tropical cyclones. Are tropical cloud clusters examples of self-organized convection, as in the case of squall lines, or do they represent the ascent phase of tropical waves? Problems like these make the Tropics the last great frontier in meteorology.

3. Water in the Climate System

Perhaps the most mysterious role of water in the earth system is its regulation of climate. Evaporation of water from the surface keeps the average surface temperature far cooler than it would otherwise be, but water vapor is also the most important greenhouse gas in the atmosphere and condensed water in the form of clouds is also an important absorber of longwave radiation. On the other hand, much of the Earth's albedo is owing to clouds. The difficulty of correctly handling water in its various phases is probably the main source of uncertainty in model-based predictions of global warming.

Figure 5 illustrates the nature of the problem. This shows the distribution of clouds and of upper tropospheric water vapor as revealed by satellite-sensed radiation in the 6.7 µm band. Note the almost bimodal distribution of water in this picture: there are very dry areas interleaved with very wet areas, with sharp gradients separating the two. The dry areas denote broadly descending air; they are dry because precipitation has removed most (but not all) of the water from ascending air.

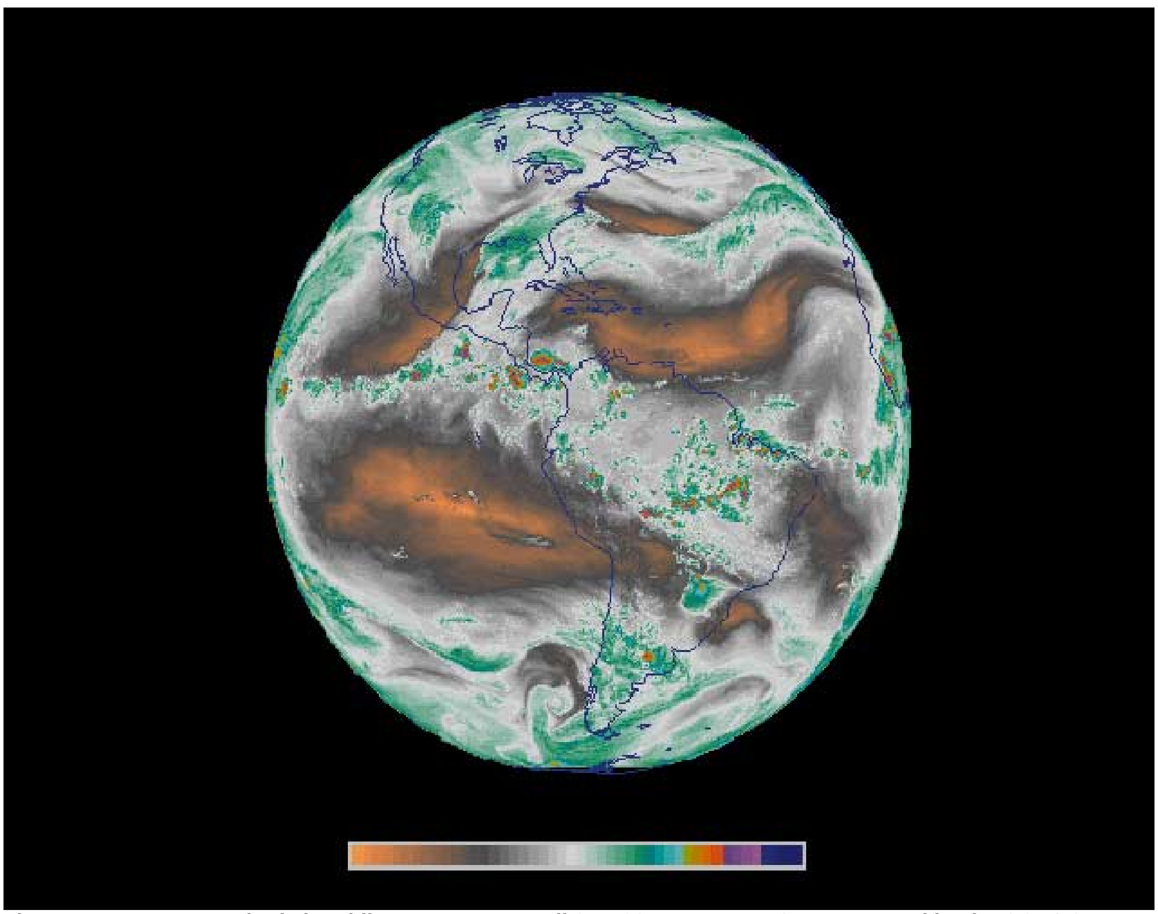

Figure 5: Upper tropospheric humidity patterns on April 27, 1995, at 1745 UTC as measured by the GOES 8 satellite. The 6.7 µm data are related to water vapor, with a peak signal between about 550 and 350 mb. The data are influenced by high clouds. (Image courtesy of A. Gruber and R. Achutuni, NOAA National Environmental Satellite Data and Information Service.)

It is not, in fact, difficult to replicate this first-order characteristic of the water distribution: wet ascent and dry descent. Simple advective-diffusive models will suffice; it has even been shown that a simple model that removes supersaturation and does nothing more replicates the moist-dry patterns seen in Figure 5. But this seemingly simple solution masks the crux of the problem: How does water respond to changes in global temperature? Here we are looking for comparatively subtle, but climatically important, changes in the humidity of the dry and moist regions and in the relative areas occupied by each.

It is not difficult to see that the sensitivity of the water distribution to global climate change depends crucially on cloud microphysical processes. For example, if precipitation formation were microphysically impossible, then the atmosphere would be saturated everywhere and filled with cloud. The amount of water in the actual atmosphere depends on just how efficient the removal of water by precipitation is, as argued by Emanuel (1991) and demonstrated conclusively by Rennó et al. (1994). While the spatial distribution of water in the atmosphere is strongly affected by large-scale circulation, such circulation cannot remove the sensitivity of the overall water content to cloud microphysics and turbulence. However, this sensitivity *is* effectively removed by the expedient of having insufficient vertical resolution in models, as demonstrated by Emanuel and Zivkovic-Rothman (1999), who showed that numerical resolution of water vapor requires at least 50 mb. resolution through the troposphere, and microphysical sensitivity declines with vertical resolution. Today's climate models do not achieve this resolution, and their water vapor feedback is thus similar among all the models (Cess et al., 1990) and insensitive to the way cumulus clouds are treated. Figure 6 shows the tropical climate sensitivity of radiative-convective equilibrium in a model using the microphysically based convective scheme of Emanuel and Zivkovic-Rothman, as a function of vertical resolution. The relatively low sensitivity seen in the high resolution model is owing to the strong dependence of stochastic coalescence on adiabatic water content, which is in turn a strong function of temperature. Thus the warmer the climate, the greater the fraction of condensed water that is converted to precipitation. On this basis, one would expect the relative humidity of the upper troposphere in regions of large-scale ascent to decline with increasing temperature.

It is simply not credible that models that cannot replicate the observed water vapor distribution can nonetheless be expected to reproduce the correct distribution and climate sensitivity of clouds. That climate models fail to replicate basic aspects of the water vapor and cloud distributions has been demonstrated by Sun and Oort (1995) and Lindzen et al.(2000).

Progress toward understanding climate today is impeded by a culture of climate modeling that has increasingly emphasized a single measure of success, the simulation of global mean temperature, over the skeptical attention to failures that has traditionally served as a critical component of scientific progress. One can only hope that the barrier that now exists between climate modelers and cloud physicists will gradually erode as the intricacies of the role of water in climate become more apparent.

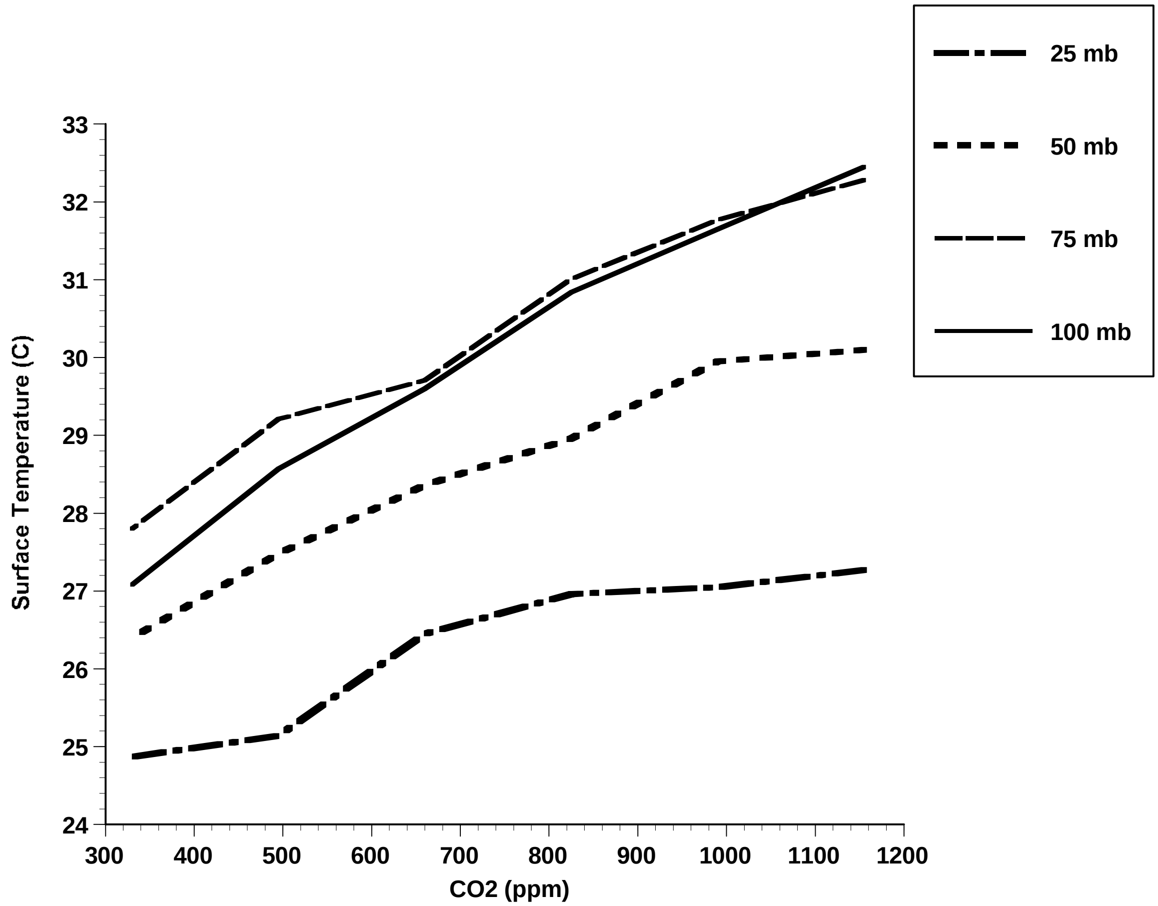

Figure 6: Dependence of surface temperature in radiative-convective equilibrium on atmospheric CO2 content, for four different vertical resolutions, using the convection scheme described by Emanuel and Zivkovic-Rothman (1999) and the radiation scheme of Chou et al. (1991).

4. Summary

The critical role of water in weather and climate was a focus of natural science from the time of the ancient Greeks through the end of the 19th century. This role was temporarily de-emphasized by the success of adiabatic theories in explaining the basic behavior of middle latitude weather systems, beginning in the 1940s, but has enjoyed a resurgence of interest in recent decades owing to the obvious importance of clouds and precipitation in the characterization of weather, but also because of the important effect of latent heating on the dynamics and structure of weather systems. The marriage of research in cloud physics to numerical weather prediction is a happy one, producing increasingly fruitful results in the form of better weather forecasts. We are now just beginning to see the benefits of accounting for cloud physics in understanding and modeling climate.

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