SCIENCE OF CLIMATE CHANGE I

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First, a game: CREATE YOUR OWN SCIENTIFIC EPONYM...
(From *The Science Creative Quarterly*)

Eponym: An eponym is the name of a person, whether real or fictitious, which has (or is thought to have) given rise to the name of a particular place, tribe, era, discovery, or other item

$$G = n^{-1}(f + 1)$$

Ng's Score

Where n = the number of cup holders a vehicle has.

Where f = the frequency per year where all cup holders are in use during vehicle use.

Examples:

My Honda Civic: Has two cup holders (n=2), and I would predict that both are in use during traveling at least 20 times each year (f=20). This means the Ng's Score for this particular '97 Civic calculates to a score of 11.5

A Ford Expedition: Apparently has 10 cup holders (n=10). Which I'm going to guess the vast majority of Ford Expedition owners have never had the opportunity to use all at once during the course of even owning the vehicle (f=0). Therefore, an Ng's Score here would calculate to 0.1

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Scientific Method:

As asked, hopefully all of you have had the chance to read over the "Intergovernmental Panel on Climate Change Fourth Assessment Report. Synthesis Report (from the three working groups). Summary for Policymakers."
(http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf)

In section 3, we have a part of the report specific for upcoming trends and how certain scenarios (SRES "special report on emission scenarios") factor in. Two figures from this report are shown in the overhead - one that looks at the different scenarios in terms of Greenhouse gas emissions, as well as projected temperature rise. And the other showing more locality temperature trends projected at the 2090 to 2099 mark (the big one of course is noted the major changes in the northern parts of the world).

But how is such data generated? Why would you believe it? Should you believe it? Where do these uncertainty values come from? And what do they mean? Because they are a large part of the discourse that exists over climate change in particular.

(reading:) Section 1.2. Historical Overview of Climate Change Science. Chapter One of the Working Group 1 of the 4AR of the IPCC.
(http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter1.pdf)

"Science may be stimulated by argument and debate, but it generally advances through formulating hypotheses clearly and testing them objectively. This testing is key to science. In fact, one philosopher of science insisted that to be genuinely scientific, a statement must be susceptible to testing that could potentially show it to be false (Karl Popper, 1934). In practice, contemporary scientists usually submit their research findings to the scrutiny of their peers, which includes disclosing the methods that they use, so that their results can be checked through replication by other scientists. The insights and research results of individual scientists, even scientists of unquestioned genius, are thus confirmed or rejected in the peer-review literature by the combined efforts of many other scientists. It is not the belief or opinion of the scientists that is important, but rather the results of this testing."

Einstein anecdote from same chapter. When told that a book called "100 Authors Against Einstein" was coming out, he remarked "If I were wrong then one would have been enough!"

"Thus science is inherently self correcting; incorrect or incomplete scientific concepts ultimately do not survive repeated testing against observations of nature. Scientific theories are ways of explaining phenomena and providing insights that can be evaluated by comparison with physical reality. Each successful prediction adds to the weight of evidence supporting the theory, and any unsuccessful prediction demonstrates that the underlying theory is imperfect and requires improvement or abandonment. Sometimes, only certain kinds of questions tend to be asked about a scientific phenomenon until contradictions build to a point where a sudden change of paradigm takes place (Thomas Kuhn, 1996). At that point, an entire field can be rapidly reconstructed under a new paradigm."

"Despite occasional major paradigm shifts, the majority of scientific insights, even unexpected insights, tend to emerge incrementally as a result of repeated attempts to test hypotheses as thoroughly as possible. Therefore, because almost every new advance is based on the research and understanding that has gone before, science is cumulative, with useful features retained and non-useful features abandoned."

And it most often takes a freaking long time to move forward. PhD timescale example for a dissertation in biochemistry or molecular biology. 3 month example vs the 5 years it actually takes to complete. Even there, it's much faster than "faith" example.

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Thermodynamics, baby, thermodynamics:

It should surprise no-one (in the sciences, anyway), that we would begin this discussion with a bit about thermodynamics. This is one of those things that has such underlying value in the physical sciences that in many respects, it is hard to escape – you might not necessarily be aware of its presence, being distracted by other sciency things – but it is there nevertheless. It is also a good representative of how the "physical" in the "physical sciences" works,

Particularly if we look at our weather or our climate (the terminology which we'll go into later), or some other such term that tends to mean a variety of different things to different people.

To set the tone for all: that being the scientists, the humanists, and the artists in our audience, let's first begin with some choice quotes from folks who are more famous than you or I:

A theory is the more impressive the greater the simplicity of its premises, the more different kinds of things it relates, and the more extended its area of applicability. Therefore the deep impression that classical thermodynamics made upon me. It is the only physical theory of universal content which I am convinced will never be overthrown, within the framework of applicability of its basic concepts.
-A. Einstein.

Once or twice I have been provoked and asked the company how many of them could describe the Second Law of Thermodynamics. The response was cold: It was also negative. Yet I was asking something which is about the scientific equivalent of "Have you read a work of Shakespeare's?"
-C.P. Snow.

The law that entropy always increases - the second law of thermodynamics - holds I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations--then so much worse for Maxwell equations. If it is found to be contradicted by observation--well these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of Thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation.
-Sir A.S. Eddington.

Lisa, get in here. In this house we obey the laws of thermodynamics!
-Homer Simpson.

(quotes found from From Prof. W. Craig Carter course notes, MIT - http://ocw.mit.edu/OcwWeb/Materials-Science-and-Engineering/3-00Thermodynamics-of-MaterialsFall2002/Syllabus/index.htm)

Nice right? Hopefully, you're convinced. More so, we can assume by what C.P. Snow said, rather than by what Lisa Simpson said, but we'll take whatever we can get here.

Thermodynamics is a branch of science, which more or less looks at things like temperature, pressure, and volume, particularly as they relate to a mathematical representation of things like energy or motion.

For fun, you can also look at the root meaning of the word, by imagining yourself playing charades and envisioning the unfortunate instance of being handed the word "thermodynamics." Most likely, you'll attempt to break the word down into its two constituent parts – *thermo* and *dynamics*. "Thermo" of course, implies something to do with "heat" but from a strictly scientific vantage, the term "heat" is akin to the "movement of energy." Think of what happens when you put a burning coal next to an ice cube – there is clearly a change of temperature in both players as the energy is transferred from one to the other - that energy in transit is referred to heat.

And it is a big deal. So much so, that like certain celebrities, it is given its own special symbol – a nice one too, in this case, the letter "*Q*."

But back to charades. You're thinking, how do I mime *dynamics*? And it hits you – that *dynamics* is really just a fancy word for "motion." You gesture wildly with the hopes that your audience gets your word.

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Maybe, right now, a poem would help.

Weather
by Ambrose Bierse

Once I dipt into the future far as human eye could see,
And I saw the Chief Forecaster, dead as any one can be--
Dead and damned and shut in Hades as a liar from his birth,
With a record of unreason seldome paralleled on earth.
While I looked he reared him solemnly, that incandescent youth,
From the coals that he'd preferred to the advantages of truth.
He cast his eyes about him and above him; then he wrote
On a slab of thin asbestos what I venture here to quote--
For I read it in the rose-light of the everlasting glow:
"Cloudy; variable winds, with local showers; cooler; snow."

Here's the point, at least in the context of this lecture. Temperature, pressure, volume, motion – these are all things that play into how our climate and weather *goes*. These are thing that relate to the action of heat on the air, the water, and the land. So, in many respects, a weather forecast or a projection of climate is an exercise in understanding thermodynamics.

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But how does one understand thermodynamics? Well, lucky for us, most agree that a good place to start is to take a look at the *laws of thermodynamics*. These form a basic framework, a list of rules if you like, much like the Ten Commandments that Moses hauled around - although one might argue that these scientific arguments are a lot more elegant in their brevity.

We'll focus on the first law, because in many respects, it represents a good glimpse of how a lot of climate science is surveyed. Here, the first law of thermodynamics can be expressed in a number of different ways. In science speak, it may come out:

The first law of thermodynamics defines the internal energy as equal to the difference of the heat transfer into a system and the work done by the system.

Which is kind of confusing. As an equation, it usually looks a little like this:

$$dU = dq - dw$$

Even if you did know that the ***d*** was representative of a "change in", and that "***U***" was "internal energy" and then guess that "***w***" had something to do with "work," I'm totally sure if this way of illustrating the law really helps. Actually just to make things even more confusing, in math land it's sometimes written differently – such as:

$$dU = dq + dw,\ dU = -dq + dw, \text{ or } dU = -dq - dw$$

Anyway, if you were running a PR firm you might go with:

We are all about the conservation of energy.

Which, well like a lot of PR, is a bit on the vague side.

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Here's an interesting sidebar – the PR take can also be stated as:

"Energy can be neither created nor destroyed"

...although it can be converted from one form to another. This is why the math equation has its different uses of positive (+) and negative (-) signs. It's such a central tenant of science that often this first law gets the limelight as one of the most important "laws of nature." Irrefutable, unless of course, you consider (in a certain way) some of the beliefs held in religion. But that's another story...

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Let's pause here for a bit to look at these expressions a little more closely. Better yet, let's see if we can find a sort of a "Thermodynamics for Dummies" expression. Curiously, Wikipedia does a decent job of doing this (not a commentary on Wikipedia!). It succinctly describes the first law in the following manner:

"The increase in the internal energy of a system is equal to the amount of energy added by heating the system, minus the amount lost as a result of the work done by the system on its surroundings."

Better? Kind of.

The first thing that makes these expressions confusing is the continued use of the word "system" and the word "work." You're probably going "What is a system?", "What do they mean by work?", and perhaps even "Why did they pick these terms in the first place? They kinda suck."

Anyway, a "system" is just jargon for a *part of the universe under consideration*. Although this sounds grand, it essentially sets a boundary of what you are looking at. This boundary could be small (like thermal coffee cup) or big (like the Earth), and the boundary can be sealed (sort of like our coffee cup with its lid closed) or open (like the sun being able to heat the Earth). It's just a parameter.

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Actually, if we're throwing jargon around, here's a handy list that let's you talk a little more about thermodynamic systems (I've been told that this is suitable for cocktail party conversations).

Isolated (The Universe)	No energy and no matter may be passed through the boundaries.

Closed (A free Pinball Machine)	Energy can pass through the boundaries, but matter cannot pass through the boundaries.
Adiabatic (A perfect Thermos)	No heat (and therefore no matter that can carry heat) can pass through the boundaries.
Open (An Aquarium)	Both energy and matter may be passed through the boundaries.

NOTE to class: if you do use it as a pick up line, let me know how it goes.

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The word “work” signifies the energy as transferred by a force, as in pushing, pulling – it more or less implies a form of movement. But don’t forget that as much as a piston can move, so can air and water particles, so can atoms, so can electrons, so in principle the word “work” could have many connotations.

So what do we have so far?

Well, maybe we can rewrite it as:

The energy in a particular part of the universe (that we happen to be looking at) is dependant on the amount of heat (a kind of energy) and the amount of work (another kind of energy) present/coming in/going out for that particular part of the universe.

Now. hopefully, it’s starting to sound kind of obvious, but in many respects that’s the whole point. This first law is akin to a form of bookkeeping – which is why sometimes, there is the notion of conservation of energy in this law. Here, the bookkeeping idea is kind of key – let’s use a fancier font and make it bigger:

bookkeeping

Bookkeeping also allows you to make calculations, and calculations can be especially powerful when you have a good handle on some physical laws. Here’s one worth knowing– it’s called the Ideal Gas Law. Wait, let’s bold that even. **The Ideal Gas Law**.

Benoît Paul Émile Clapeyron in 1834 came up with that one. It’s really quite pretty and states that:

$pV = nRT$

Where:

p is the absolute pressure [Pa], (Pressure (symbol: 'P') is the force per unit area applied on a surface in a direction perpendicular to that surface.)
V is the volume (in cubic meters) of the vessel containing n moles of gas
n is the amount of substance of gas (in moles again – not the animal, a unit of “numbers” of molecules)

R is a constant, specifically the gas constant. It is equal to 8.314472 $m^3 \cdot Pa \cdot K^{-1} \cdot mol^{-1}$.
T is the temperature in kelvins (a unit of temperature, like a shifted over version of celcius)

If you reflect on this, hopefully you nail home the point that things like temperature can affect volume, and pressure. i.e. if you have a vessel and you know the volume, and you put a gas in it (and you're able to measure how much), and you play around with the temperature of the vessel – you can mathematically work out the pressure in that vessel. And in effect, things like pressure and a change in volume can "move" things and ultimately enact a degree of work.

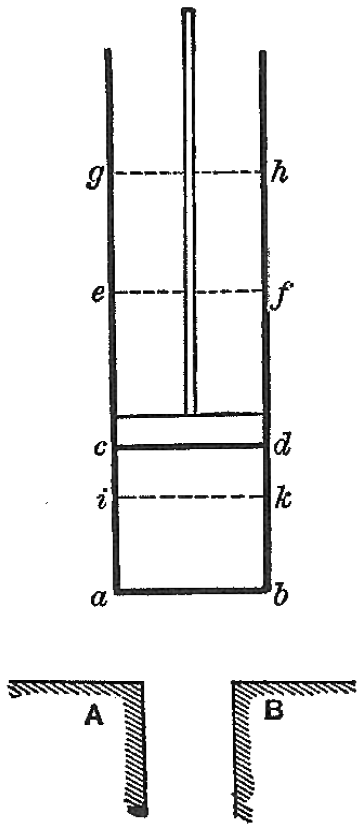
Kind of like how heat moves a piston in a motor (he says somewhat innocently). Actually, truth be told, an engine was more or less what started this whole thermodynamic thing, in particular with an individuals like Sadi Carnot working stuff out to make engines better. He published "*Reflections on the Motive Power of Fire, a discourse on heat, power, and engine efficiency*" in 1824, and although he didn't personally coin the word "thermodynamics" (James Joules did that in 1858), he's pretty much revered as the "Father of Thermodynamics."

This, of course, was a big deal at the time, what with all of this happening when the steam engine was front and center in history. Here, of course, we're referring to the Industrial Revolution, which happened around the late 18^{th} century to the early 19^{th} century (more or less the same as Carnot's efforts).

Basically he was interested in working out how to maximize the work energy produced in the energy as a reflection of the amount of heat energy (shoveling the coal) provided.

Anyway, back to the science. Right... physical laws, systems, work, energy...

Here, take a look at this:



What you're looking at is one of the original images used by Carnot to "work stuff out." Now that you're armed with a few terms, think of the system denoted by *abcd* as being a "closed" system (heat can be transferred but not matter), where the line between *c* and *d* implicates the surface of a piston. Now assume that A and B are blocks of a certain temperature, specifically where either A is hot and B is cold (in a steam engine scenario, A would be the coal fire pit, and B would be the rest of the engine except for that *abcd* space. What happens here, of course, is a transfer of heat energy between A and B, and also between A and *abcd*. The latter is good – it will drive the piston, the former not so much, it's just heat transfer that is diverted elsewhere.

The beautiful thing about the first law of thermodynamics and its bookkeeping properties is that you can now start to calculate what will happen to that *abcd* system. i.e. heat is transferred and it will affect whatever happens to be inside *abcd*. Assuming it's air in the most general of senses (i.e. a gas), then facets of the Ideal Gas Law can take place. Heat going in will raise the temperature and with that a subsequent breakdown of what will happen to the volume and pressure of that air in that particular system can be seen, calculated, and/or predicted. As you can easily surmise, if *cd* happens to be a component of a piston, the resultant increase in pressure will make it move - which basically leads to a form of work. This in turn can also be calculated, but we'll spare you the many equations involved in this instance (as in what happens when there are friction forces impeding the work of the piston, as in what if some of the heat energy in *abcd* escapes back out to B, as in what happens when there is a pressure applied on the other end of the piston. etc, etc, etc – you get the picture).

In other words: $\boldsymbol{dU = dq + dw}$

In all, what one realizes is that such calculations are indeed quite powerful. You can use them to make things work better, and more to the point for us, you can use them to make pretty decent predictions.

To many, this whole notion of what such calculations can do is actually thought of as being “pretty”: in fact, the word “elegant,” in particular, is often used. In agreement to this, there exists many an academic argument that proclaims mathematical expression as a form of creativity in its purest form.

Still this expression is kind of vague, especially in light of what this section is suppose to be about – i.e. earth science, the climate, the atmosphere. That vagueness is o.k. It’s one of the weird things about the laws of thermodynamics, especially as they are presented in their most simplest form.

“Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you any more.”
- Arnold Sommerfeld

So now let’s try to massage that first law into a form more reflective of looking at our climate.

Let’s take a break here (cue in results from “Getting your own Scientific Eponym” exercise). Hopefully, there are two or more that can “relate” to one another. i.e. the possiblility of taking two of the mathematical eponyms to create a more inclusive, possibly more useful new equation.

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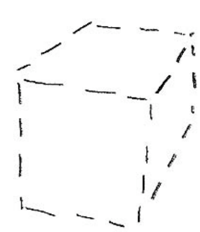
CLARIFY WITH AN OVERHEAD: that this math part is not necessary for course grades.
Reference text: “*Fundamentals of Atmospheric Modeling*” Mark Z Jacobson.

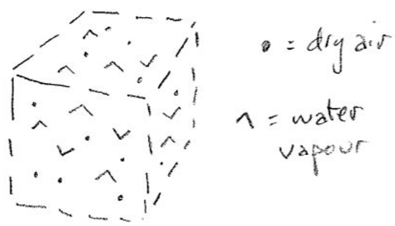
Now it’s time to go into Breakfast of Champions mode. Let’s take the $dU = dq - dw$ expression and change it a little. We’ll make it:

$$dq^* = dU^* + dw^*$$

All I’ve done here is rearrange the variables a bit, and there have been some small stars added, because we want to present some specific nomenclature to the system we’re dealing with. In this case, the system will a parcel of air, basically a box of particles suspended in the atmosphere like this:



We'll even call this parcel M_a which is just a succinct way of saying this is a particular **M**ass of **a**ir. We could even go so far as to say that $M_a = M_d + M_v$ where M_d is the dry air mass (like dust bunnies, oxygen, etc) and M_v is the mass of the water vapor. Here, let's draw that out like this:



(In the remainder of this exercise, I'm not going to incorporate the $= M_d + M_v$ feature since it just makes these expressions even busier, but keep in mind that you can)

I'm also interested in putting ***dq**** up front of the equation because I'm curious about the transfer of heat energy between this parcel of air and the environment surrounding it. Anyway, since ***dq**** (with the star) is reflective of the change in heat energy in our **particular system** (i.e. the parcel of air), you could also say that the value of heat energy change per mass of air (or ***dq*** – without the *) is equal to the following:

$$dq = \frac{dq^*}{M_a}$$

By analogy:

$$dw = \frac{dw^*}{M_a} \qquad dU = \frac{dU^*}{M_a}$$

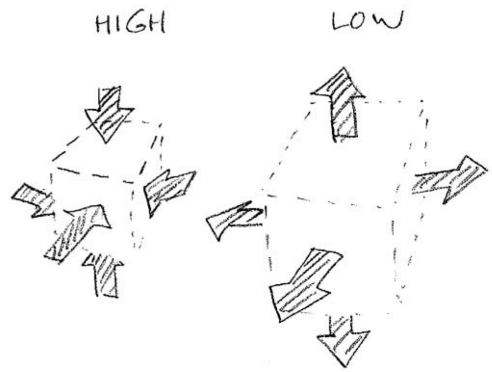
Which actually all leads back to the mother equation which is:

$$dq = dU + dw \qquad (1)$$

That's good. Circular rational thinking is a good thing in science. (Anyway, still with me?) O.K. let's focus specifically on the work component. As the air expands, work will be done by the air. There's actually a formula to calculate the amount of work done here. It looks like this:

$$dw^* = p_a\, dV$$

(Do you see similarities to the Ideal Gas Law here). This simply says that the amount of work that that packet of air will do is equal to the pressure of that packet of air times the change in volume (i.e. if it expands, it's moving out, forcing things out). From a more visual sense, think of the packet of air rising to an area of lower pressure: here work is done by the air (forces out), since the change in volume (or dV) is greater than 0. Likewise, when your packet of air sinks to higher pressure, the packet will compress – work is done on it, and dV < 0.



Now, twiddle these expressions a bit more and you get this:

$$dw = \frac{p_a dV}{M_a}$$

In the world of atmospheric sciences, folks will often use the term **specific volume of air** (defined as what is the volume of air per mass of said air), which can be given the symbol α. That means that in our particular system, our particular packet of air, you can write:

$$\alpha_a = \frac{V}{M_a} \quad \text{or} \quad d\alpha_a = \frac{dV}{M_a}$$

Don't forget that the little "***d***" is indicative of "change in"

Anyway...do rework these expressions and you get:

$$dw = p_a d\alpha_a \qquad (2)$$

Moving on:

If we were to suppose that energy transfer occurs between our packet of air and the environment, we should be able to say that ***dq*** is not zero. And we should also note that there is a lot going on in the atmosphere that could affect the movement of heat, whether its radiative heating, or cooling, or what happens to the energy when things like evaporation, or freezing occur.

Anyway, the change in internal energy of this air is its change in temperature, which is dependant on the amount of energy required to change its temperature by one degree celcius (1K). The proper way to express mathematically the "amount of energy required to change its temperature by one degree can be written as:

$$c_{v,m}$$

The little "v" and little "m" is provide some constraints on this term. It says let's look at this value assuming that we're still dealing with the same Ma, and also assuming that the volume doesn't change. You do that because, for example, if the volume can change, then obviously that will affect the pressure, and thereby affect the temperature. i.e. it makes this value dependant on too many things, which just makes it even more complicated than it needs to be.

Anyway, this term has the honor of being called the **specific heat of moist air at constant volume**. And is equivalent to the energy required to raise the temperature of 1g of air 1 degree celcius at constant volume. It is a constant, i.e. has a define value that depends on amount of water vapor present (the whole M_v thing).

This constant is handy, because you can now calculate the change in internal energy (or dU) as long as you can calculate the change in temperature in that packet of air. i.e. the change in internal energy (dU) is dependant on this constant times the actual change in temperature. This gets to look like:

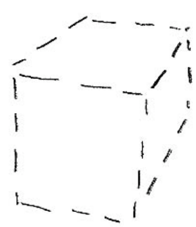
$$dU = c_{v,m}\, dT \qquad (3)$$

At this junction, many of you are probably thinking, "Dear Lord, what is the point of all of this?" Well, the point is that by using all of this analysis, we have the ability to fancy up our first law of thermodynamics. More specifically, if we use (1), (2) and (3), we get:

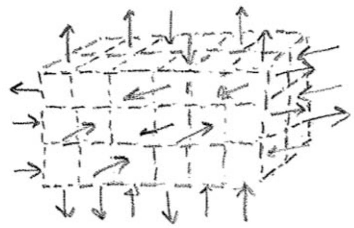
$$dq = c_{v,m}\, dT + p_a d\alpha_a$$

This is actually a more formal rendition of the first law of thermodynamics for the atmosphere, and here's the thing (so so important), many of the variables and constants denoted in this new expression can be measured and/or modeled.

Think of it like this. How much heat energy is being transferred in this packet of air? Well if I know that the temperature is just so, and that the pressure is also just so, I should be able to fit those values in to figure out my ***dq***. You might even be confident enough to do some back of the envelope calculations for that single packet of air- you know this one (since the equation is really just a bunch of multiplication and addition – nothing too crazy hard):



But what about this:



(whoa)
Here the transfer of heat and work between packets are obviously going to affect each other. Clearly, this isn't a back of the envelope calculation anymore, but it could be one that a computer can handle.

That's really what a climate model is trying to look at.

Models are composed of algorithms (a step by step calculation), which in turn are based on processing mathematical expressions, which in turn are derived from physical laws, which in turn are derived from the things people see and do and measure everyday and throughout history.

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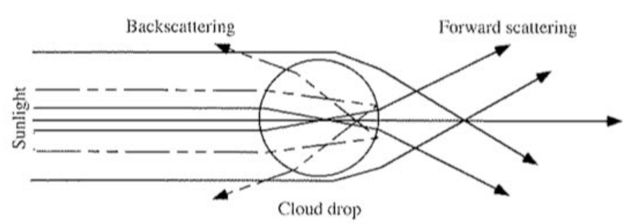
However, if you want to make a kick ass model, one way to do it is to make your algorithm include as much as possible. This is where it's kind of mind boggling. The better the model, the better it reflects reality, and reality can have all sorts of things to reflect. Things like:

- Equations of state (ideal gas law): how do pressure, temperature, volume influence each other,
- Processes related to moisture. evaporation, condensation, formation and dispersal of clouds.
- Processes related to absorption, emission, reflection of solar and thermal radiation.

* And truth be told, it really is quite remarkable the degree of finesse these calculations can take place. For instance, heat is coming from the sun, hits the ground, bounces back, some retained longer due to things like greenhouse effects. Here's a fancy detail related to deflecting radiative heat from water in particular:

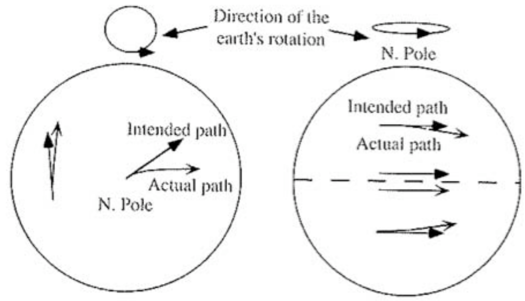


Diffraction patterns of water droplets! Now that's nuanced!

Let's keep going...

- Processes related to convection (i.e. such as heat transfer nuances).
- Processes related to momentum, heat and water exchange at the surface.

Here's a cool one related to momentum:



Introducing, the coriolis effect. What's this?

You may know it as that urban myth responsible for the direction of the water spiral when you flush the toilet, and how it would differ in different hemispheres.

Well, wiki says:

"The Coriolis effect is the apparent deflection of moving objects from a straight path when they are viewed from a rotating frame of reference. The effect is named after Gaspard-Gustave Coriolis, a French scientist who described it in 1835, though the mathematics appeared in the tidal equations of Pierre-Simon Laplace in 1778. One of the most notable examples is the deflection of winds moving along the surface of the Earth to the right of the direction of travel in the Northern hemisphere and to the left of the direction of travel in the Southern hemisphere. This effect is caused by the rotation of the Earth and is responsible for the direction of the rotation of large cyclones: winds around the center of a cyclone rotate counterclockwise on the northern hemisphere and clockwise on the southern hemisphere."

But because the Earth does rotate, there are forces which can nuance the work done on that isolated packet of air.

And, well, these details can go on and on. You have viscosity issues, the fact that the atmosphere settles itself into discrete layers, work being transferred into sonic energy, the effect of heat transfer when you're on top of a land mass versus on top of a water mass, on top of vegetation versus ice; the angle of the sun at particular times of the day, atmospheric chemical reactions dependant on the temperature of that packet that may lead to changes in the content.

And somewhere out there, there are formula and attempts at formula that conceptualize in a calculable fashion all of these things. The trick of course is to bring it all together. And whether it's a good trick is dependant on the robustness of your expressions (i.e. do they work), and of course, the inherent awesomeness of the computer system you are using to look at this.

Goofy math question: Which is real? Both real, neither real? Equation of lifespan and month of birth, equation of carbon emissions for divorced vs married scenarios.

Anyway, hopefully you have a better sense of what this "modeling" business is all about, but's it's worth finishing today on a fundamental reason why modeling is an important part of this scientific process.

It boils down to this:

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“A characteristic of Earth Sciences is that Earth Scientists are unable to perform controlled experiments on the planet as a whole and then observe the results.”

[doodle] So true, it’s not like you can go: “Like, I have this awesome experiment – you over there, take that Earth, release 14 billion tons of carbon dioxide, and then I got my little thermometer over here, and will see what happens. Oh, and you over there, you create another planet earth, so that we can have an appropriate control, where we don’t release 14 billion tons of cabon dioxide...”

BUT this nuance is important, because if you were able to do such things (whole Earth, system scale experiments, incorporating the full complexity of interacting processes and feedback), then wouldn’t that be ideal to verify or falsify hypotheses?

However, empirical tests can be performed on various nuances of the system (all the details mentioned above). And in concert, along with the ability to trust your models (which again are founded on these empirical observations), the community has built a massive and refined body of Earth Science knowledge.

“likely, very likely...”