Notes on Three Lectures by Matthew England

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Part I: A Climate Physics Primer

At the broadest level, we can classify the drivers of climate change into two categories. First, extraterrestrial factors play and important role. The output of the sun varies over many timescales, such as the multi-decadal sunspot cycles that cause solar radiation to fluctuate. In turn, the Earth absorbs different amounts of solar radiation depending on the orbital geometry of the planet. The Earth's orbit is somewhat eccentric, and the planet also "wobbles" on its axis, resulting in regular variations of the planet's climate over many thousands of years. Finally, stellar dust can affect the Earth's climate as well.

The second broad category is terrestrial factors. On a geologic timescale, the formation and degradation of mountain ranges can affect climate by physically altering atmosphere circulation patterns. Erupting volcanoes release large amounts of sulfur aerosols into the atmosphere, which reflect incoming solar radiation, cooling the planet. Over millions of years, the slow process of continental drift can change patterns of oceanic or atmospheric flow.

Generally speaking, these drivers are not affected by human activity, but several other terrestrial factors are. Changes to the albedo, or reflectivity, of the planet can occur either in the atmosphere (such as the emission of sulfur aerosols from volcanoes or fossil fuel pollution) or through changes in land cover. An example of the latter is degradation of a forest into a desert: viewed from space, the original forest would be dark, indicating that it absorbs much of the light that strikes it. However, a desert would be much lighter, indicating that a greater fraction of the incoming radiation is reflected. And finally, the best-known driver of climate change is atmospheric chemistry–in particular, the concentrations of greenhouse gases such as carbon dioxide and methane.

Carbon dioxide (CO_2) is the primary greenhouse gas associated with global warming, due to the influence of human activity on its atmospheric prevalence. Through samples from ice cores, coral reefs, and other natural records, we know that CO_2 levels and global temperatures are tightly correlated. Over the last 400,000 years (spanning several glacial cycles), CO_2 has naturally varied from 190-290 parts per million. However, since the industrial revolution, that concentration has risen above 380 parts per million. The rates of change in recent decades are faster than any observed in the last 200,000 years or so. (Similar stories are true for other greenhouse gases.)

Only in the last 150 years or so have direct temperature records (using thermometer data) been available. Unfortunately, the last decade has been significantly warmer than any period in the last 100 years, which is cause for some concern, as our greenhouse gas emissions are steadily increasing. When scientists run climate models using historical data, "natural" drivers–such as volcanoes, orbital cycles, and solar output–cannot explain recent observed temperature trends. These trends can only be reproduced when the models are given CO_2 emissions from human activity on top of the natural variability.[1]

When scientists speak about global warming or warming trends, they are referring to statistical patterns over several decades or centuries. It is important to take a long-term view, as global weather can change rapidly from year-to-year. What is important is not the relationship between one year and its predecessor, but the trend over many years. Indeed, the temperature record over the last 150, 100, and 50 years conclusively shows that the planet is steadily warming, though individual years or regions may experience cooler conditions. The most recent years have been the warmest, and in particular, the last decade has been extremely hot by historical standards.[2]

Although many factors influence the temperature of the planet, scientists are able to use computer models to reproduce historical observations. These models show a clear role for greenhouse gases to alter the climate, particularly if we continue emitting them at increasing rates. But warming isn't the only concern. Changes in precipitation patterns are likely to ensue as well. The historical record is more complicated with precipitation trends than with warming trends, but in general, scientists expect wetter areas to get wetter, and drier areas to get drier.

Turning to the crysophere–the world's ice and snow–the story is even grimmer. Significant and rapid change is underway in both the Antarctic and Arctic regions. In the Antarctic, the Larsson-B ice shelf collapsed quite suddenly in 2002, encompassing an area of 5,000 km^2. Although this did not affect sea levels–sea ice floats–it suggests that the continental West Antarctic ice sheet is at greater risk than was previously thought. If this sheet melted entirely, it would raise the sea levels by 15 m. This is unlikely to occur in the immediate future, but even spread over decades, the impacts would be immense. The Eastern ice sheet, which is more protected from a warming climate, contains almost 70 m of sea level rise if it were to melt.

In the Arctic, the Greenland ice sheet is even more worrisome. Many scientists believe the question of melting is not a matter of "if", but "when". If the full sheet melts, it would add 5-6 m of sea level rise. In addition, since the Greenland ice sheet is replenished from snowfall in the center of the formation, it could be a permanent transition. If the ice sheet

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[1] We know that much of the CO_2 in the atmosphere comes from fossil fuels through carbon dating. Living creatures uptake C^{14}, an isotope of carbon that has a half-life of about 5,000 years. Fossil fuels contain biological material that is typically millions of years old, so it has very little C^{14}. If the CO_2 in the atmosphere was from natural sources, we would expect higher levels of C^{14}, but in fact we observe the opposite.

[2] Warming has been isolated to the stratosphere, the lower part of the atmosphere that ranges from the surface to a few kilometers high. In contrast, the upper atmosphere (the stratosphere) has been cooling, due both to the destruction of ozone (which absorbs ultraviolet rays and releases them as infrared radiation, heating the upper atmosphere) and the greenhouse gases in the troposphere that trap heat from the surface from reaching the stratosphere.

melts too much, the elevation will fall, and the precipitation will come as rain, not snow, leading to the dissolution of the ice sheet. Unfortunately, none of the models used to assess ice sheets are able to reproduce the melting rates observed in the last few years. That is, the ice sheets are melting faster than our models can predict, suggesting that the models are too optimistic with respect to projections for melting and sea level rise.

Although the global climate has seen substantial changes in the past century, few can be explained through known modes of natural vulnerability. Only by accounting for the significant role of human activity–particularly the emission of greenhouse gases–can scientists account for the observed changes. Air temperature, rainfall, oceanic properties, ice sheets, sea level, and storm trends have all been affected. Looking to the future, these changes will likely accelerate unless humanity takes aggressive action to reduce its greenhouse gas emissions.

Part II: The Ocean's Role In Climate and Climate Change

1. The ocean's role in the Earth's climate system

Oceans play a critical role in determining the climate of the Earth. Covering roughly 70% of the Earth's surface and extending in depths greater than 5000 meters, the capacity for the oceans to absorb and release solar radiation is profound. Unlike its terrestrial counterpart, which is typically able to store solar energy to a shallow depth of 1 meter, oceans can absorb solar radiation up to ~1000 meters in depth. While their ability to store energy is partly facilitated by surface water mixing, the density and temperature differentials in ocean surface waters, along with wind patterns, create ocean currents that create downwelling of warm water in some locations and upwelling of cool water near Antarctica. Effectively these surface and deepwater currents transport stored solar energy throughout the Earth's oceans, and correspondingly influence local weather systems and global climate.

The degree to which we can observe climate alteration by oceans is best illustrated by the annual range of monthly mean temperatures in locations in proximity to oceans versus those found in the terrestrial interior. Continental areas have large differences between average winter daily temperatures and average summer daily temperatures (up to 20-25 degrees C), whereas more coastal locations have less variation (a range of about 8 degrees C). Oceans essentially buffer coastal climates. Oceanic currents can also shift regional climates. For example, the Gulf stream that travels up the east coast of North America transports warm equatorial water north towards the east coast of Iceland. As the warm water evaporates it is transported eastward by the prevailing Westerlies (strong winds), which leads to an increase in air temperatures across Scandinavia and parts of Western Europe. These effects influence the livelihoods and even energy consumption of the local populations, who face a milder climate than what would otherwise be present without today's ocean currents.

Oceans themselves are greatly affected by salinity gradients. The evaporation of warm water traveling north as part of the North Atlantic current has a relatively low salinity

(~34 parts per thousand). As the water travels between Iceland and the United Kingdom it begins to evaporate, which increases the salinity (~37 parts per thousand) and creates a density gradient that causes a downwelling of the newly cooled and denser ocean waters. This downwelling acts in part to pull warm and less dense surface water into that area as it begins its travel toward Antarctica. The movement of warm surface water up the eastern coast of North America is driven by Easterlies near the equator. New cool surface water travels down the west coast of Europe and Africa to replace the warm waters travelling west near the equator and complete the North Atlantic gyre. Gyres are found throughout the oceans of the Earth and typically correspond in latitude to global wind patterns (e.g. Hadley or tropical, mid-latitude, and polar cells). The duration for water to completely circulate a gyre is on the order of decades (sometimes 10-15 yrs). In contrast the vertical ocean changes based on the thermohaline as discussed above may take 1000's of years to complete a cycle. [[Maybe add a picture from the lecture to illustrate this paragraph?–Danny]]

Several factors could contribute to altering the North Atlantic current and therefore global climate. One possibility is that increasing temperature alters the ocean's density through thermal expansion and causes a shift in the North Atlantic current. A second possibility is the slowing or shifting of the North Atlantic current due to a change in salinity. If the Greenland ice sheets were to melt, due to global warming, the waters entering the ocean would decrease ocean salinity and therefore slow down, shift the location south, and possibly halt the North Atlantic current. Rahmstorf and Ganopolski (1999) used a climate model to show that such an alteration of the North Atlantic current would lead to cooling in northern latitudes and create a full blown ice age . Furthermore, in the case of a complete shutdown of the current, the ocean may reorganize itself and not reestablish the North Atlantic Deep Water (NADP) current.

At the other end of the earth, warm water traveling from the equator toward the South Pole is diverted east and back towards the equator before reaching the Antarctic. Blocked by the Antarctic circumpolar current, this current protects the Antarctic ice sheet from the possibility of thawing. However, this wasn't always the case: approximately 35 million years ago the tip of South America was connected to Antarctica. This connection directed warm ocean currents further south puncturing into the protective circumpolar current, which caused a thawing of the ice sheets that subsequently reduced the albedo and altered the climate of the region significantly. Now the gap that exists between South America and Antarctica–the Drake Passage–is the narrowest point of the Southern ocean.

2. The ocean's capacity to modulate climate change

The relatively low thermal capacitance of land surfaces renders land unable to buffer the greenhouse effect. This is evidenced by a simple comparison of the temperature of sand at the top of a soil profile in the desert versus that the temperature if one was to dig down a meter. It would be much more comfortable to stand on the soil found one meter below the ground than to stand on top of the soil profile. In contrast, the ocean offers a large capacity to buffer climate change. Ocean temperatures remain relatively constant for depths of ~50 m and subsequent water temperature changes are only slight and change in smooth transitions with increasing depth up to 1000 m.

In addition to modulating climate as a heat storage and transfer mechanism, oceans act as a carbon sink. The ocean absorbs CO_2 through two processes, which are termed the solubility pump and the biological pump. The solubility pump describes the oceans' capacity to absorb CO_2 through diffusion from the atmosphere into the oceans through mixing at the surface boundary layer. The rate of solubility of CO_2 into the ocean has an inverse relationship with air temperature, so that with cooler temperatures there is a greater ability for CO_2 to dissolve into the oceans. As atmospheric CO_2 increases, more CO_2 can be dissolved in the oceans, increasing the acidity of the ocean, which significantly alters ocean ecosystems. The solubility pump is further enhanced by the downwelling of CO_2 rich ocean waters, which are able to store carbon for 1000s of years.

A second mechanism, known as the biological pump, also facilitates the oceans ability to moderate climate change. Algae and other biotic organisms metabolize CO_2 and incorporate it into the food chain of the ocean. The fecal matter of these organisms and in some cases their bodies, upon death, precipitate down to the bottom of the ocean to create a pool of carbon. It is estimated that this biological pump sequesters approximately one third of anthropogenic emissions in the ocean. While some have experimented with enhancing the biological pump through iron fertilization, it is not known if the biological pump naturally increases with increased atmospheric CO_2.

3. The ocean's capacity to bite back

While the oceans have a tremendous capacity to moderate global climate change they also have the capacity to disrupt our systems. With warmer ocean temperatures the intensity of precipitation events, hurricanes, and cyclones increase. The warming of the ocean also alters its density and creates thermal expansion of ocean waters. It has been estimated that the thermal expansion of ocean waters with a two degree centigrade warming would result in approximately a one-meter increase in global sea levels. A further and much more substantial sea level rise would occur with the melting of the Greenland and western Antarctic ice sheets. Rises in sea level would greatly alter coastal ecosystems and inundate terrestrial lands causing significant economic costs and disruption of local livelihoods.

Part III: Climate Models–How Do They Work and Why Should We Trust Them?

An overview was first given about the definition, classification, characteristics and benefits of a climate model. The process of building a model extends to verification, validation and assessment.

Computer models are advantageous in terms of expense, comprehensiveness, logic, accessibility, flexibility (capable of examining, sensitivity analysis, parameter tuning etc).

There are 6 governing equations in climate models: for ocean there are 3 of momentum, conservation for heat, salt, and mass and the same is for the atmosphere with humidity instead of salt. They have as many equations as unknowns.

Forcing conditions represent only processes at the top of the atmosphere for full blown climate models. Running submodels or subcomponents of the Earth requires many more forcing conditions that need to be addressed. Hence it is harder to run submodels rather than a whole model.

It would be interesting to track down the progress, quantitatively and qualitatively, of the scientific modeling community.

For the most part models are run on FORTRAN90. The language is better in picking out errors in floating points.

What kind of grid is employed determines what kind of dynamics it will represent effectively.
In the late 80s, the resolution is (4 degrees by 4 degrees) 400km by 400km. Now it is about 1 degree by 1 degree. When we can't get what we want, we go down to a finer resolution by nesting a sub-grid of finer scale on top of the coarse grid. Sometimes we have to change the model or some models give us the option of where to zoom in. The option of nesting different resolutions allows for adding the affects of cities, etc that are quite small but can effect local weather/climate significantly.

The vertical vs. horizontal resolution is another issue. A spectral grid is such that the lines are parallel along the y axis but bend along the x axis. 1D e.g. that about an air column in the atmosphere and 2D models e.g. Henry Stommel's 2-boxes models still have good uses on their own. 3D models employ spectral grids which minimize numerical errors in atmospheric models.

The process of running a model to get its output and spatial visualization are separate.
Having models is one thing, having interfaces where researchers will simply walk in and use is another option and there are some good ones.

There are good models and fake ones that look like real. This is not a parade. Open access is important.

CFC invade the ocean in very specific way and they act as tracers in ocean circulation experiment. As these were introduced, the presence/level of CFCs in deep water provides an excellent sense of movement and mixing. This can be used to double-check the accuracy of ocean models, being more precise than temperature and salinity checks...
To assess uncertainties in existing models, Greenland ice is a big uncertainty (1.6m is likely sealevel rise, 85cm from land ice). Another is sulfite aerosols–a pollutant that has helped to keep things cooler. as we clean up our combustion, this will change–the impacts of this are uncertain

References

Rahmstorf, S. and A. Ganopolski, 1999. Long-term global warming scenarios computed with an efficient coupled climate model. Climatic Change 43: 353 – 367.