Climate Science

Climate Change and Radiative Forcing / The Ocean in Earth's Climate System

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WATCHING THE SEASONS -- PHENOLOGY OBSERVATIONS AND CLIMATE CHANGE

Background:

For centuries, various peoples in Europe and the Orient have kept track of recurring biological events such as the budding and flowering of plants or migration of wildlife that appeared related to the seasonal cycle. More recently, people across North America have become aware of phenology, which represents an organized and systematic effort to monitor the well-defined seasonal phases in plant and animal life. In addition to these biotic events, several abiotic or non-living events would also fall within the realm of phenological observations, such as watching for the freezing and "ice out" (or opening) of lakes in northern latitudes. Thus, phenology can be used in the scientific study of the influence of climate upon the periodic annual phenomena of plant and animal life. In the addition, phenology can be employed to see how long-term changes in these seasonal events change in response to long-term changes in climate.

The origin of the term "phenology" is either from the contraction of the word phenomenology or from the Greek words "phaino" (to show or appear) and "logos" (to study). The origins of phenology came from observations of recurring phenological events made by early agrarian cultures that attempted to monitor the progress of the natural calendar. Some of these observations resulted in proverbs and sayings that were meant to forecast future weather events or trends, especially for those that could affect the planting and harvesting of crops. Some historians suggest that the Chinese may have had written records dating back to approximately 974 BC. The Japanese were making observations of the timing of the peak in the blossoming of cherry trees at the Royal Court in Kyoto since approximately 705 AD. While some phenological societies in Europe have been around for more than a century, interest in phenology has developed in this country. The USA National Phenology Network, which is sponsored by NOAA, NASA and the US Fish and Wildlife Service, is a nationwide network consisting of citizen scientists, government agencies, non-profit groups, educators and students willing to monitor the impacts of climate change on plants and animals in the United States. Stimulated by the National Phenological Network, a program called Project BudBurst has been developed at the National Center for Atmospheric Research (NCAR) and represents "a national phenology and climate change campaign for citizen scientists."

So how are recognizable phenological events related to climate? Consider the onset of spring growth, which usually depends upon various climates and weather factors. Invariably, the lengthening daylight and higher sun angles should warm the air and ground, permitting the reemergence of spring foliage across the northern sections of the country. The Swedish botanist Carolus Linnaeus (1707-1778) compiled annual calendars of leaf opening, flowering and fruiting together with concurrent weather conditions for 18 locations in Sweden over many years. He was one of the first scientists to make a connection between phenological events and climate. Furthermore, by comparing these phenological observations over a wide area, we can also monitor how these events move geographically over the year, responding primarily to the seasonal changes in the sunlight with latitude. Andrew D. Hopkins, an entomologist with the U.S. Department of Agriculture during the early 20th century (and no known relation to this author), attempted to correlate phenological phenomena of plants and animals with the various climate elements across the nation. According to the relationship that he proposed (now known as Hopkins Law), most phenological events tend to progress northward and upward in altitude during spring, while southward and downward in fall. A delay is also noted in the eastward direction. This empirical relationship suggests that the time for the peak flowering of a certain plant species, would progress northeastward at a rate of 4 days per 1 degree of latitude and upward at 1 day for 100 feet of altitude. We should note that this relationship was valid for the United States during the early 20th century.

Since some biotic and abiotic events are sensitive to small variations in temperature or other atmospheric factors, climate scientists and historians have attempted to use phenological records as a proxy indicator of past climates prior to the instrumental records. For example, researchers studying the records of grape harvests in Europe were able to reconstruct growing season temperatures extending back for more than 500 years, well before the invention of the thermometer. Inspection of the long-term phenological records has also revealed a phenomenon that some people refer to as "season creep," which represents the earlier observed timing of seasonal events in spring. The famous cherry blossoms around the Tidal Basin in Washington. DC currently tend to bloom at the start of April, earlier than the mid-April peak blooms of earlier decades. This season creep appears to be associated with the general increase in temperature across the globe.

A continuation of phenological observations should help track the effect of climate change on organisms and help scientists make predictions concerning the future health of the ecosystems. If springtime temperatures across a region increase over the years, the timing of specific phenological events, such as the budding, leafing and fruiting of plants could occur earlier. A drastic change in the timing of these events could result in fewer seeds and insects, which could also have an impact on other animals that depend upon the seeds and insects.

CLIMATE CHANGE AND RADIATIVE FORCING

Driving Questions: *What is climate change and how can it be determined? What is radiative forcing and what makes it important to climate science?*

Educational Outcomes: To define climate change and ***radiative forcing***. To identify factors that affect climate, the agents and mechanisms which exert forcings that alter climate, the relative magnitude of each factor, and the evaluation of the total radiative forcing from the group of factors.

Objectives: After completing this investigation, you should be able to:

- Describe climate change and how it is objectively determined.
- Explain the IPCC concept of radiative forcing as a way to commonly describe the influence of various factors that can cause climate change.
- List and explain the principal causes of climate change, including their relative impacts leading to warming or cooling.

Climate Change

The scientific consensus arrived at by the Intergovernmental Panel on Climate Change (IPCC) is that climate change is very likely occurring as it is “unequivocal” that global Earth is warming. Here we consider how we can quantify the changes in boundary conditions that bring about this temperature increase.

As stated in the first week of this course, **our global climate is fundamentally the story of solar energy received by Earth being absorbed, deflected, stored, transformed, put to work, and eventually emitted back to space.** Climate describes the slowly varying aspects of the atmosphere-hydrosphere-land surface system. It encompasses and bounds the broad array of weather conditions and impacts that arise from the complex interplay of the subsystems of Earth’s climate system in response to this energy flow.

The relative amounts of incoming and outgoing energy, on a global basis, determine whether or not Earth is in a steady-state condition, cooling, or warming. Earth’s climate system, essentially an open physical system regarding energy, is sustained by a continuous supply and removal of energy. It achieves a steady-state condition when its properties (e.g., temperature) do not vary in statistically significant ways when averaged over time. **Climate change refers to a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, that persists for an extended period, typically decades or longer.** Climate change results from natural causes and/or human (anthropogenic) activities.

Radiative Forcing

To give focus to climate change, the IPCC in its First Assessment Report (1990) emphasized a new concept, ***radiative forcing*****.** Radiative forcing refers to the change in the net vertical radiation flow (expressed in W/m^2) in the climate system at the top of Earth’s troposphere that is caused by the addition of greenhouse gases (e.g., CO_2) or other changes (including solar radiation, Earth’s surface albedo, and aerosols). The IPCC describes radiative forcing as a modeling concept that is a simple but important means of estimating and comparing the impacts of different natural and anthropogenic radiative causes on the surface-troposphere climate system.

Radiative forcing is the change in net (difference between downward solar and upward longwave) radiant energy flow at the upper limit of the planet’s atmosphere, assumed on Earth to be at the tropopause, under a specified set of conditions. When the net flow of energy is into the planetary climate system, it produces positive radiative forcing; when the net flow is to space, the radiative forcing is negative. In the case of Earth, radiative forcing values are typically changes measured relative to the mean state of Earth’s climate system at the start of the industrial era (about 1750).

Follow the Energy! The essentials of radiative forcing are embodied in various AMS CEM scenarios, included those first presented in *Investigation 1*’s **Follow the Energy!** Go to the RealTime Climate Portal and click on “AMS Conceptual Energy Model”.

1. Set the AMS CEM at One Atmosphere, Sun’s Energy: 50%, 200 Cycles, and Introductory

Mode. Run the model. It shows that the mean energy content in the planet's climate system was **[(*0.5*) (*2.3*)(*4.7*)(*10.7*)]** energy units.

2. Now change only the model's Sun's Energy setting from 50% to 100%. This is analogous to doubling incident solar radiation. After running the model at this higher rate of solar irradiance, it is seen that the mean energy content in the planet's climate system changed to **[(*0.5*)(*2.3*)(*4.7*) (*10.7*)]** energy units.

3. Comparing the two runs of the model shows that increasing the amount of solar energy entering the planet's climate system would produce positive radiative forcing and attendant warming. Change in the rate at which the Sun delivers energy to the planet is an example of a(n) **[(*natural*) (*anthropogenic*)]** climate change.

4. Now compare the two runs of the model in terms of its response if the rate at which the Sun delivers energy to the planet had been the opposite, that is, it decreased from 100% to 50%. The comparison shows that the reduced incident solar radiation would result in **[(*positive*) (*negative*)]** radiative forcing of the planet's climate system, with accompanying global cooling.

Adding an Atmospheric Layer: Switching the Atmospheres setting from One Atmosphere to Two Atmospheres subjects energy units passing through the atmospheric component of the model to a another application of the model's **Rule 2**, which states, "During each cycle, any energy unit in the atmosphere will have an equal chance of moving downward or upward." A rising energy unit from the planet's surface will first reside in the first (lower) atmosphere. In the next cycle of play, it will move upward to the second (higher) atmosphere or downward to the planet's surface. Once in the second (higher) atmosphere, it has during the subsequent cycle equal chances of escaping upward to space or moving downward to the first (lower) atmosphere.

5. Set the AMS CEM at Two Atmospheres, Sun's Energy: 100%, 200 Cycles, and Introductory Mode.
Run the model. After running the model with the two-atmosphere configuration, the mean energy content in the planet's climate system is **[(*0.5*)(*2.3*)(*4.7*)(*10.7*)]** energy units.

6. Compare the mean energy content in the planet's climate system from Item 2, which was set at One Atmosphere, Sun's Energy: 100%, 200 Cycles, and Introductory Mode, with the two-atmosphere value from Item 5. The comparison shows that adding a second atmosphere [(***increases***)(***decreases***)] the energy content of the planet's climate system.

7. The change from One Atmosphere to Two Atmospheres in the model settings results in **[(*positive*) (*negative*)]** radiative forcing of the planet's climate system.

8. The change from the One Atmosphere setting to Two Atmospheres in the AMS CEM is analogous to a doubling of heat-absorbing greenhouse gases in Earth's atmosphere. Comparison of the amounts of energy residing in the planet's climate system before and after the doubling shows that such an enhanced greenhouse effect is an example of radiative forcing that **[(*increases*) (*decreases*)]** the energy content of the planet's climate system.

9. This change in the energy content of the planet's climate system would result in a

[(*colder*) (*constant*)(*warmer*)] mean global temperature.

10. The addition of greenhouse gases to Earth's atmosphere is an example of climate change largely due to **[(*natural*)(*anthropogenic*)]** causes.

Comparing Principal Radiative Forcing Components: The strength of the concept of radiative forcing is that the influence of different factors that cause climate change can be quantified using common units (W/m^2), which allows them to be compared and tracked. This is an essential prerequisite to better understanding the agents and forcing mechanisms that can produce climate change, and to scientifically predict climate change beyond simply extrapolating observed current climate trends into the future.

Figure 1 summarizes the principal components and impacts of the radiative forcing of climate during the industrial era between 1750 and 2005. Their forcing is reported in W/m^2, with positive forcings leading to warming of climate and negative forcings leading to cooling. The dots at the end of the thick bars indicate the best estimates of the values and the thin horizontal bars passing through the dots represent the judged possible variation of the particular value, referred to as a "range of uncertainty."

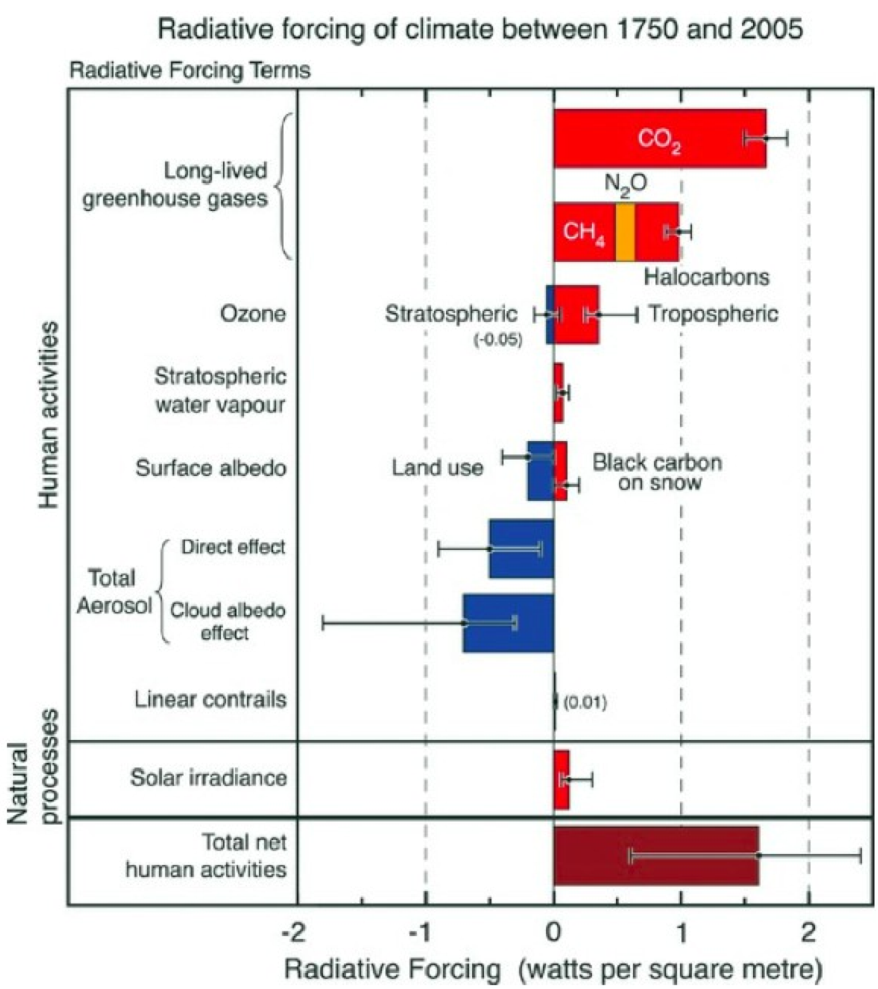

Figure 1.
Summary of the principal components of the radiative forcing of climate between 1750 and 2005. Solar irradiance refers to incident solar radiation. [IPCC *Climate Change 2007, The Physical Science Basis*, FAQ 2.1, Figure 2]

11. According to the list of radiative forcing terms along the left in Figure 1, the only natural process that produced radiative forcing during the industrial era is **[(*stratospheric water vapor*)(*surface albedo*)(*solar irradiance*]**. The figure shows the forcing is positive; therefore, it has a warming impact. [Note: According to the IPCC, this particular forcing component has increased slightly during the industrial era.]

12. Violent volcanic eruptions (discussed in Investigation 11A), which occur infrequently, are not listed in Figure 1 as radiative forcing agents. This is because **[(*they cannot cause global-scale temperature changes*)(*the global temperature changes they can cause are typically observable only for a year or two*)]**.

13. According to Figure 1, the major positive radiative forcing (warming) arises from anthropogenically-produced **[(*albedo changes due to land use*)(*total aerosol effects*) (*carbon dioxide*)]**.

14. According to Figure 1, the total radiative forcing due to human activities during the industrial era is equivalent to a positive (warming) **[(*0.6*)(*1.0*)(*1.6*)(*2.4*)]** W/m^2. This value is within a range of uncertainty between about 0.6 and 2.4 W/m^2 as shown by a horizontal line in the graph. This range of uncertainty concerning the value is a major reason why the global temperature increases predicted for the 21st century under different scenarios include the best estimate of temperature and likely range.

15. Given the value for total radiative forcing from the previous question, scientists would predict that the combined anthropogenic and natural perturbations present today would result in a troposphere today and into the future that is **[(*warmer than*)(*the same as*) (*cooler than*)]** the troposphere of the year 1750. And they would be able to make a prediction regarding the range of future tropospheric temperatures based on the magnitude of the total radiative forcing value.

[Note: How do these radiative forcings compare with the average solar energy intercepted by Earth? The value of average incident solar radiation at Earth's surface is determined as follows. The total solar energy intercepted by Earth is equal to the solar constant (1368 W/m^2) times the cross-sectional area of the planet. Because Earth's total surface area is four times its cross-sectional area (area of circle = πr^2, area of sphere = 4 πr^2), the average solar energy received per square meter over the entire surface of the globe is one-quarter the solar constant (i.e., 342 W/m^2).]

Summary: Climate scientists are demonstrating considerable progress in identifying the factors that affect climate, the agents and mechanisms which exert forcings that alter climate, the relative magnitude of each factor, and the evaluation of the total radiative forcing from the group of factors.

This consideration of the Earth environment as a system is powerful in its potential to better understand climate and climate change. The highly complementary empirical and dynamic approaches to climate study reveal the workings of Earth's climate system. As stated at the beginning of this course, the empirical approach allows us to construct descriptions of climate, and the dynamic approach enables us to seek explanations for climate. Each has powerful applications. In combination, the two approaches enable us to explain, model, and predict climate and climate change.

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THE OCEAN IN EARTH'S CLIMATE SYSTEM

Driving Questions: *How important is the ocean in the climate system and climate change? How are oceanic conditions changing?*

Educational Outcomes: To describe why the ocean is the major component of Earth's climate system in terms of mass and energy. To show the significant increase in the energy content in Earth's climate system, particularly in the ocean, in recent decades that evidence climate change. To explain what changes are occurring in the ocean and their observed impacts on Earth's climate system.

Objectives: After completing this investigation, you should be able to:

- Explain why the ocean is the dominant energy and mass reservoir and most influential component of Earth's climate system.
- Describe what influences the ocean has on and receives from the rest of the climate system.
- Explain what changes are occurring in the ocean and what the consequences may be for Earth's climate system.

The Ocean Component of Earth's Climate System

Earth's climate system, which has been the subject of this course, encompasses the "spheres" of the atmosphere, hydrosphere (including the ocean), cryosphere, geosphere, and biosphere along with their interactions and the variability and changes within and because of boundary conditions. Traditional climate studies have often been restricted to conditions at Earth's surface primarily due to the workings of the atmosphere. We are culminating our primary investigations of Earth's climate system by focusing on the ocean, the system's major component in terms of mass and energy.

While we live on the land and interact most with the atmosphere, the major component of Earth's climate system in terms of mass and energy is the ocean. The ocean covers about 71% of Earth's surface and makes up 99.8% of the mass of the fluid portions of Earth's system (air and water). The high specific heat of water combined with the size of the ocean reservoir gives the ocean exceptional capacity to store and transport heat. Therefore, just from the mass and energy characteristics, the variability of the fluid portions of the planet implies that the ocean merits major consideration when seeking understanding of Earth's climate system and its changes.

Change in Heat Content of Climate System Reservoirs: Figure 1 shows the estimated heat energy content changes in various parts of the climate system for two periods: 1961-2003 (blue bars) and 1993-2003 (red bars). All of these values represent increases in the heat storage of those portions of the climate system during the respective time periods. The heat units are in 10^{22} J. [Note: 1 joule (J) = 0.239 calorie]

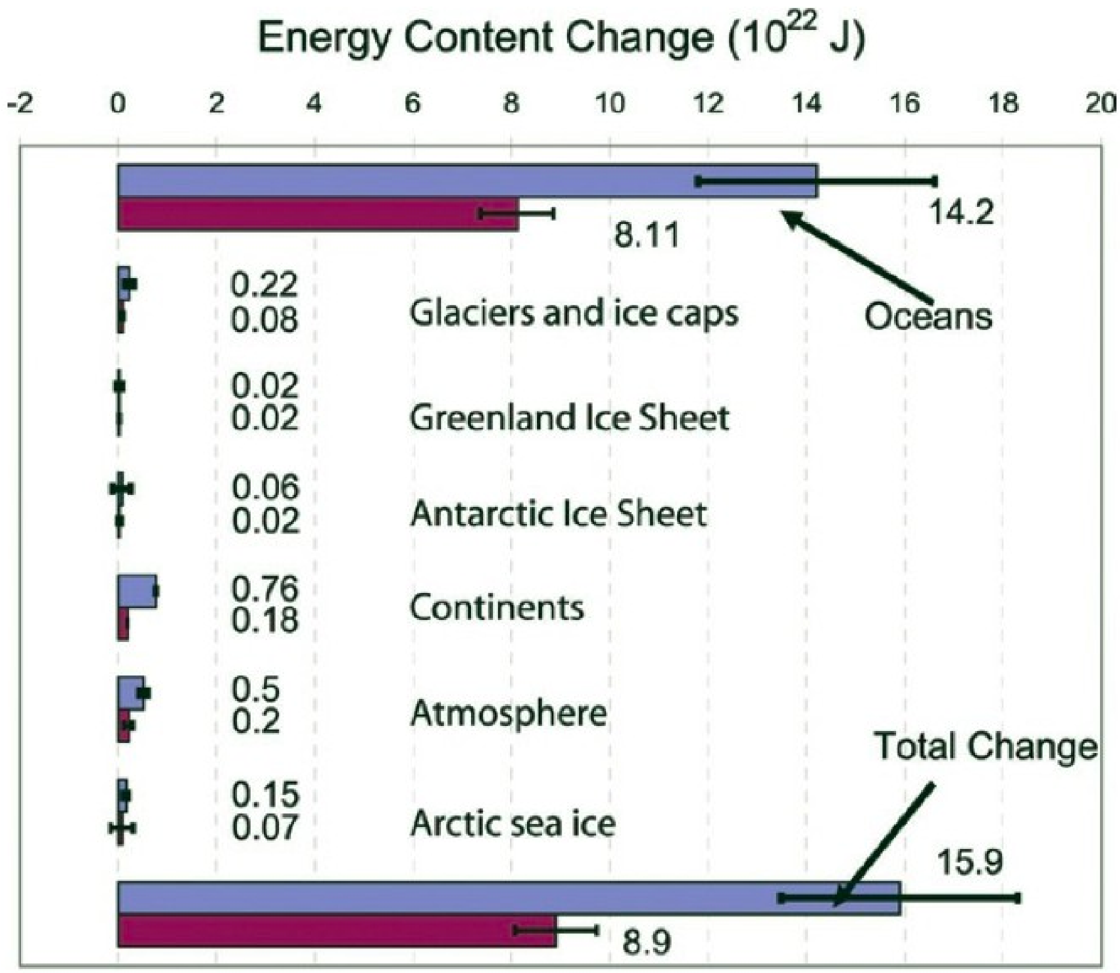

Figure 1.
Energy content change of portions of the climate system, from 1961-2003 (blue) and from 1993-2003 (red). (IPCC)

1. For all of the energy content changes shown in Figure 1, the values varied considerably in magnitude. However, the estimated values were all positive. What does the positive energy change from 1961 to 2003 imply about these parts of the climate system?
   [(*all cooled*)(*some cooled and some warmed*)(*all warmed*)]

2. The total change in the energy content of the components of Earth's climate system shown in Figure 1 from 1961 to 2003 was **[(*14.2*)(*15.9*)(*24.8*)]** x 10^{22} J.

3. Figure 1 indicates that in the 1993-2003 time period a total of 8.9 x10^{22} J were added to Earth's climate system's heat content. Therefore, the climate system's heat content must have increased **[(*7.0*)(*8.11*)(*15.0*)]** x 10^{22} J during the earlier time period from 1961 to 1993.

4. Comparison of the 1961-1993 total change with the 1993-2003 total change implies that the annual rate at which heat energy was being added to Earth's climate system was generally **[(*decreasing*) (*steady*)(*increasing*)]** from year to year.

5. Compare the numbers for the energy content changes in the continents and the atmosphere over the period 1993-2003 (*red bars*). For these two portions of the climate system over this latter period, the energy content change(*s*) of **[(*continents were much greater*) (*continents and atmosphere were about equal*)(*the atmosphere was much greater*)].**

6. Combining the values for the ice components of the system (*glaciers, ice sheets and sea ice*) provides a total energy content change of 0.45 x 10^{22} J during the 1961-2003 time period. Compared to the energy content change for the continents and atmosphere during the same time period, the total ice energy content change was nearly equal to the change within the **[(*atmosphere*)(*continents*)]** component.

7. Compared with the energy content change for oceans for either period, the changes of all the other portions of the climate system combined were **[(*much smaller*)(*about the same*)(*much greater*)].**

8. Using the value for the ocean change over the 1993-2003 period compared to the system's total change for the same 1993-2003 time period (*red bars*), the ocean accounted for about **[(*10%*) (*25%*)(*50%*)(*75%*)(*90%*)]** of the total energy content increase in the system. This demonstrates the prominent role the ocean must play in determining climate and climate change.

Global Warming Impacts on the Ocean: The *IPCC AR4, Climate Change 2007: Physical Science Basis, Technical Summary*, p. 47, states, "Warming is widespread over the upper 700 m of the global ocean." Further, "The world ocean has warmed since 1955, accounting over this period for more than 80% of the changes in the energy content of the Earth's climate system." This ocean warming has several critical impacts on the climate system.

9. The temperature change of ocean water leads to changes in evaporation and density. Evaporation from the ocean drives the global water cycle. Warmer water has more energy available for evaporation. In locations where precipitation is less than evaporation, we would expect that excess evaporation would lead to surface ocean waters that become **[(*less*)(*more*)]** saline (as salts are left behind in the evaporation process).

"There is now widespread evidence for changes in ocean salinity at gyre and basin scales in the past half century with the near-surface waters in the more evaporative regions increasing in salinity in almost all ocean basins. These changes in salinity imply changes in the hydrological cycle over the oceans." (IPCC AR4, *Physical Science Basis, Technical Summary*, *p.48*)

10. As seawater warms, it becomes less dense. Less dense water means that the same mass of water would occupy a greater volume. The result of a warming ocean would be **[(*rising*) (*lowering*)]** sea level.

"The global average rate of sea level rise measured by TOPEX/Poseidon satellite altimetry during 1993 to 2003 is 3.1 ± 0.7 mm yr^{-1}." (IPCC AR4, *Physical Science Basis, Technical Summary*, p.49

11. Another crucial gas dissolved in the ocean is oxygen. Dissolved oxygen is essential to the oceanic biosphere. With a warmer ocean, **[(*more*)(*less*)]** O_2 would be dissolved in the water.

In fact, the IPCC states, "The oxygen concentration of the ventilated thermocline (about 100 to 1000 m) decreased in most ocean basins between 1970 and 1995. These changes may reflect a reduced rate of ventilation linked to upper-level warming and/or changes in biological activity." (IPCC AR4, *Physical Science Basis, Technical Summary*, p.48)

Although there is no known evidence at present of its occurrence, one fear is that the warmer, less dense water may resist sinking in the North Atlantic Ocean basin. It is that sinking that drives the global meridional overturning circulation, a massive inter-basin heat engine for the ocean system. And, warmer ocean surface waters in tropical regions could lead to greater tropical cyclone activity through an increase in the number of storms, by storms becoming more intense, or both.

Ocean Acidification: Associated with the changes already mentioned is the impact of increased carbon dioxide in the atmosphere and ocean.

Of the carbon dioxide that is emitted into the atmosphere, about 56% is taken up by dissolving in the ocean. The ocean is normally slightly alkaline. The CO_2 that dissolves in ocean waters forms a weak acid solution that increases the acidity of the waters, causing pH values to decrease (the lower the pH, the higher the acidity). One consequence is that the calcium carbonate shells or structures of many ocean creatures become more soluble in more acidic waters. Ocean life will have difficulty living in a more acidic ocean. "The uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic, with an average decrease in surface pH of 0.1 units." (IPCC AR4, *Physical Science Basis, Technical Summary*, p.48)

Figure 2 is a summary of these interrelated effects over the global ocean. Red arrows represent heat and carbon dioxide changes, blue arrows indicate the net water mass movements (evaporation versus precipitation), black arrows signify changes in the thermocline and calcium carbonate dissolution level and yellow circles represent the decreasing pH values. Above the colored portion of the sea along with ice extent is the latitudinal rise of sea level. Much of that increase is due to the warming of seawater. The rise of sea level due to thermal expansion is referred to as *thermosteric* or *steric* sea level change.

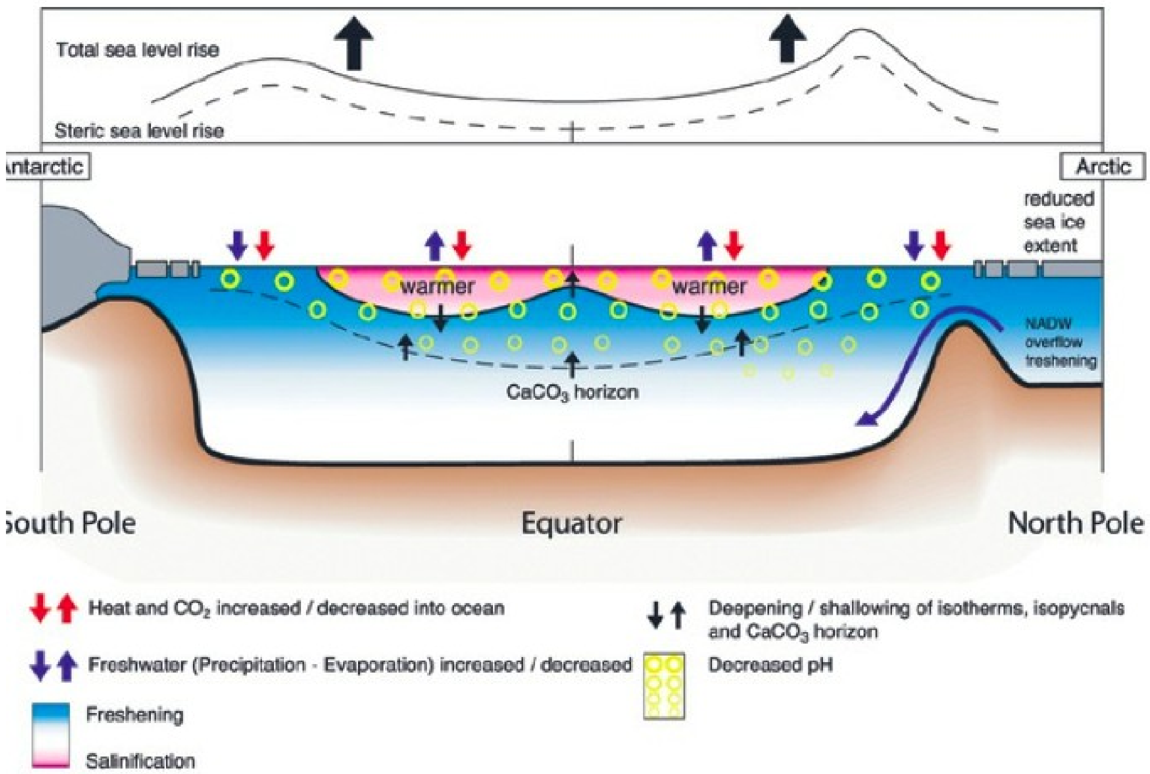

Figure 2.
Schematic of ocean changes including temperature, carbon dioxide absorption, evaporation effects. [IPCC]

12. As seen in this investigation, we **[(*can*)(*cannot*)]** ignore the role of the ocean if we want to more completely understand Earth's climate system and climate change.

13. The ocean plays a **[(*minor*)(*major*)]** role in the climate system through its cycling of mass and energy.

Summary: We now go back to reconsider the **Earth's Climate System paradigm**, which was addressed in Investigation 1A. This statement provided us with a guiding definition of climate, the climate system and the ways humans interact with and affect that system of which they are a part. *"Climate can be explained primarily in terms of the complex redistribution of heat energy and mass by Earth's coupled atmosphere/ocean system*." Many of the investigations in this course examined the boundary conditions that derived from the physical processes at work on and in the climate system. We also looked at the mean state of the system and its variability within those boundaries.

"Scientific research focusing on key climate processes, expanded monitoring, and improved modeling capabilities are already increasing our ability to predict the future climate." A major environmental monitoring effort is underway, called GEOSS - the Global Earth Observation System of Systems. Data from this effort has provided the insight for the ocean changes we noted previously. And, it will provide the basis for understanding the changes currently occurring as well as the computer models that will inform policy decisions for future human activities in our climate system.

Your knowledge of Earth's climate system will be enhanced by considering both its empirical and dynamic perspectives. The more we know about the environment in which we live, the more informed we will be to work toward making it a better place for everyone.