POLITECNICO DI MILANO

Cambiamenti Climatici e Adattamenti negli Ecosistemi e nelle Società

Dr. Alessandro Ceppi

Academic Year 2023-2024

Università di Padova

1222-2022 800 ANNI Università degli Studi di Padova

Climate Justice Jean Monnet Centre of Excellence

Ocean and Sea Level

NASA/Goddard Space Flight Center Scientific Visualization Studio

The ocean covers over 70% of Earth's surface, and it holds 97% of its water.

Its high heat capacity, fluid motion, and abundant life mean the ocean plays a key role in regulating climate.

Sunlight, wind, and convection (the buoyant rising of warm water followed by sinking as it cools) mix heat through the ocean vertically.

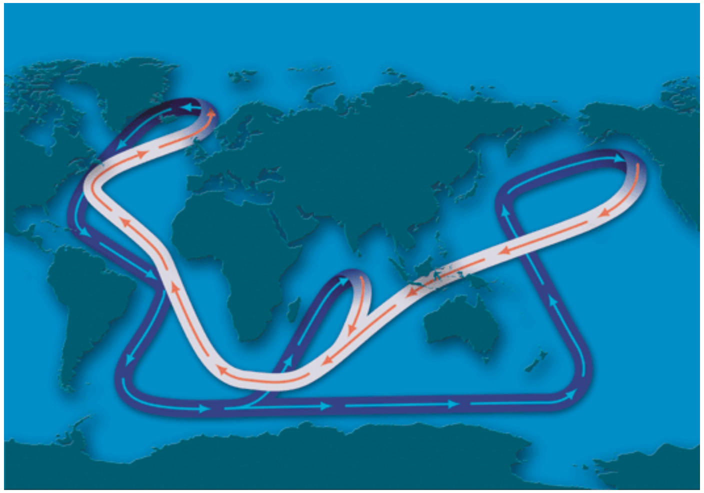
The ocean's heat content influences sea surface temperatures and exerts a strong influence on climate.

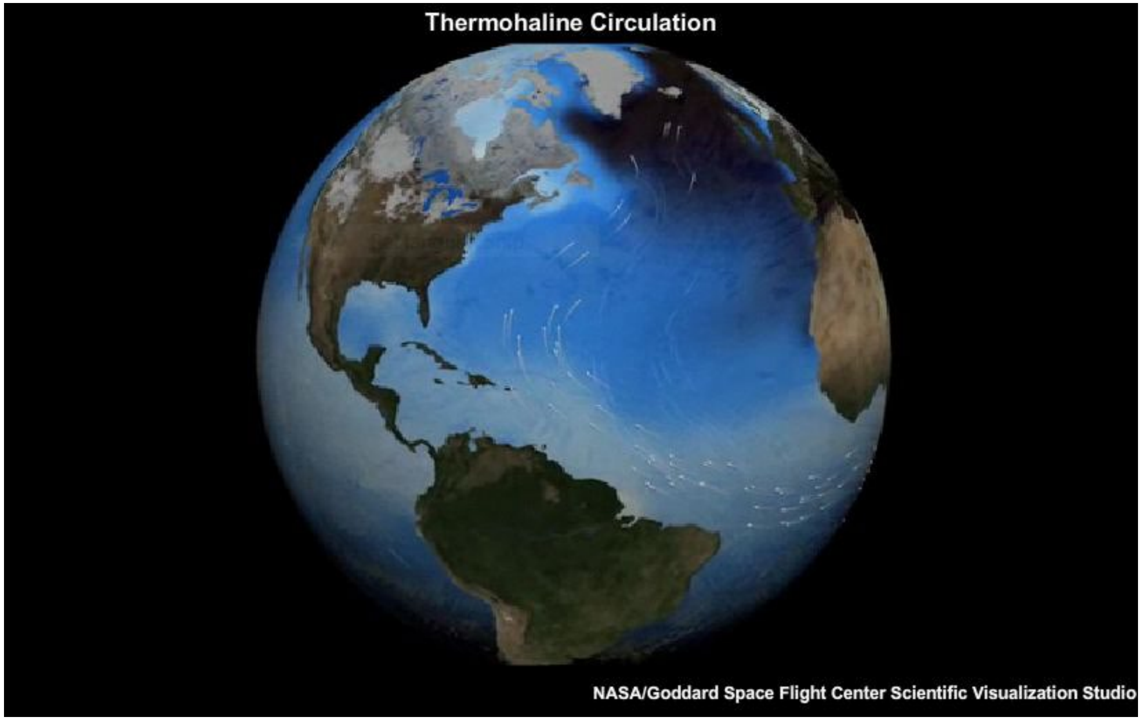
Reservoirs of water	Mass	Residence time
Atmosphere	0.01	Days
Fresh water (lakes and rivers)	0.6	Days to years
Fresh water (underground)	15	Up to hundreds of years
Alpine glaciers	0.2	Up to hundreds of years[a]
Greenland ice sheet	5	10,000 years[b]
Antarctic ice sheet	53	100,000 years
Oceans	2,700	
Crust and mantle	20,000	10^{11} years

Masses of the various reservoirs of water in the Earth system (in 10^3 kg m^{-2}) averaged over the surface of the Earth, and corresponding residence times

The oceans are mostly composed of warm salty water near the surface over cold, less salty water in the ocean depths. These two regions don't mix except in certain special areas.

The ocean currents, the movement of the ocean in the surface layer, are driven mostly by the wind.

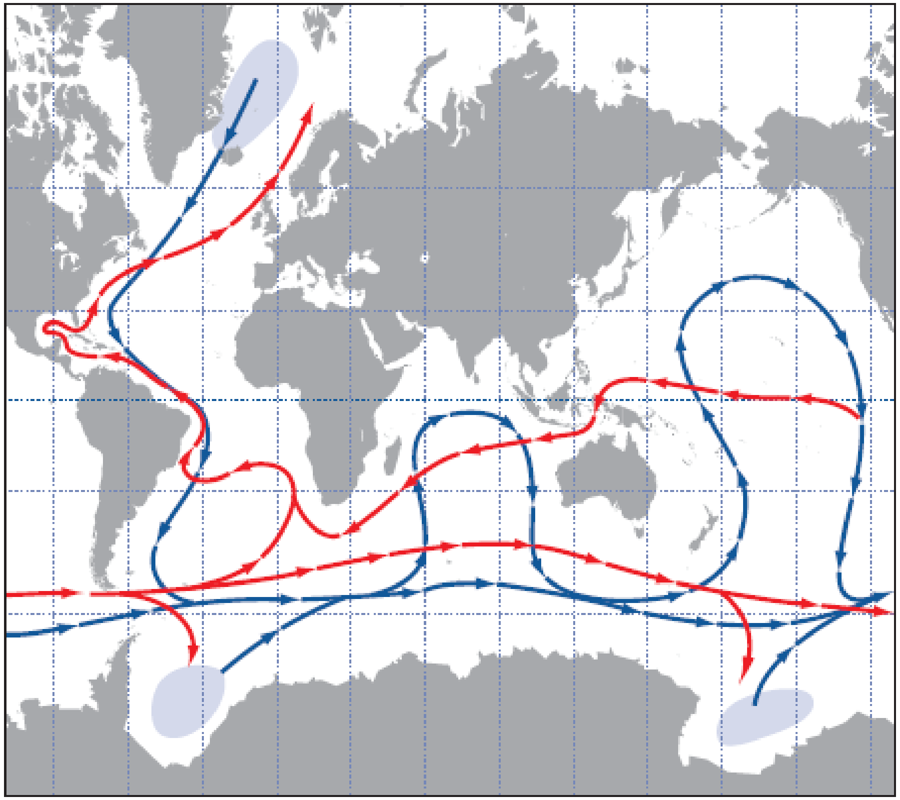




Thermohaline Circulation

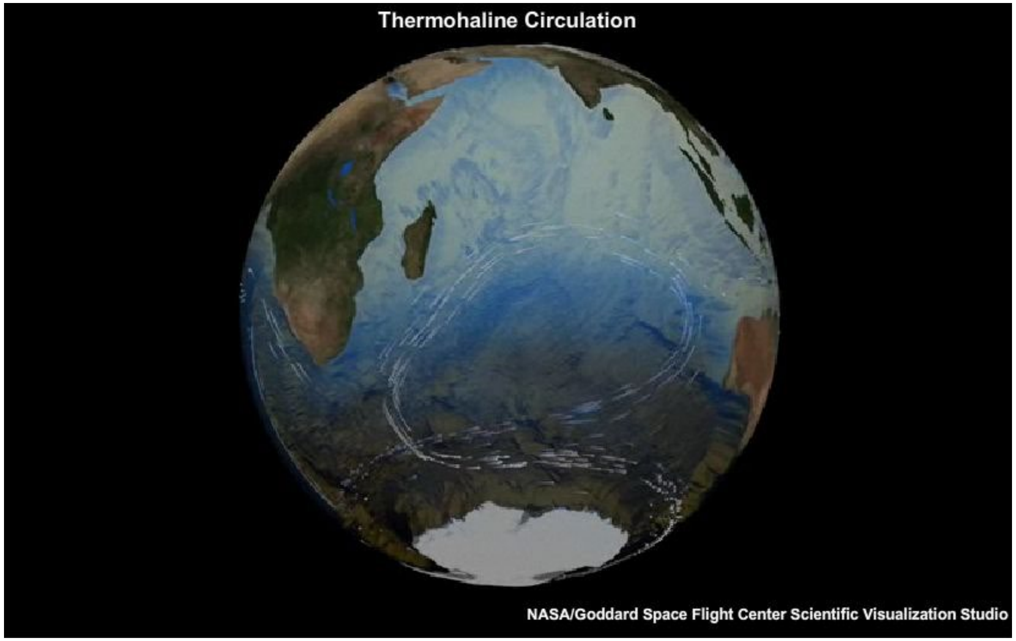
In certain areas near the polar oceans, the colder surface water also gets saltier due to evaporation or sea ice formation.

Thermohaline Circulation



Highly simplified schematic of the thermohaline circulation. Shading denotes regions of downwelling, blue arrows denote transport of bottom water, and red arrows denote the return flow of surface water.

Thermohaline Circulation



In the polar regions, the surface water becomes dense enough to sink to the ocean depths.

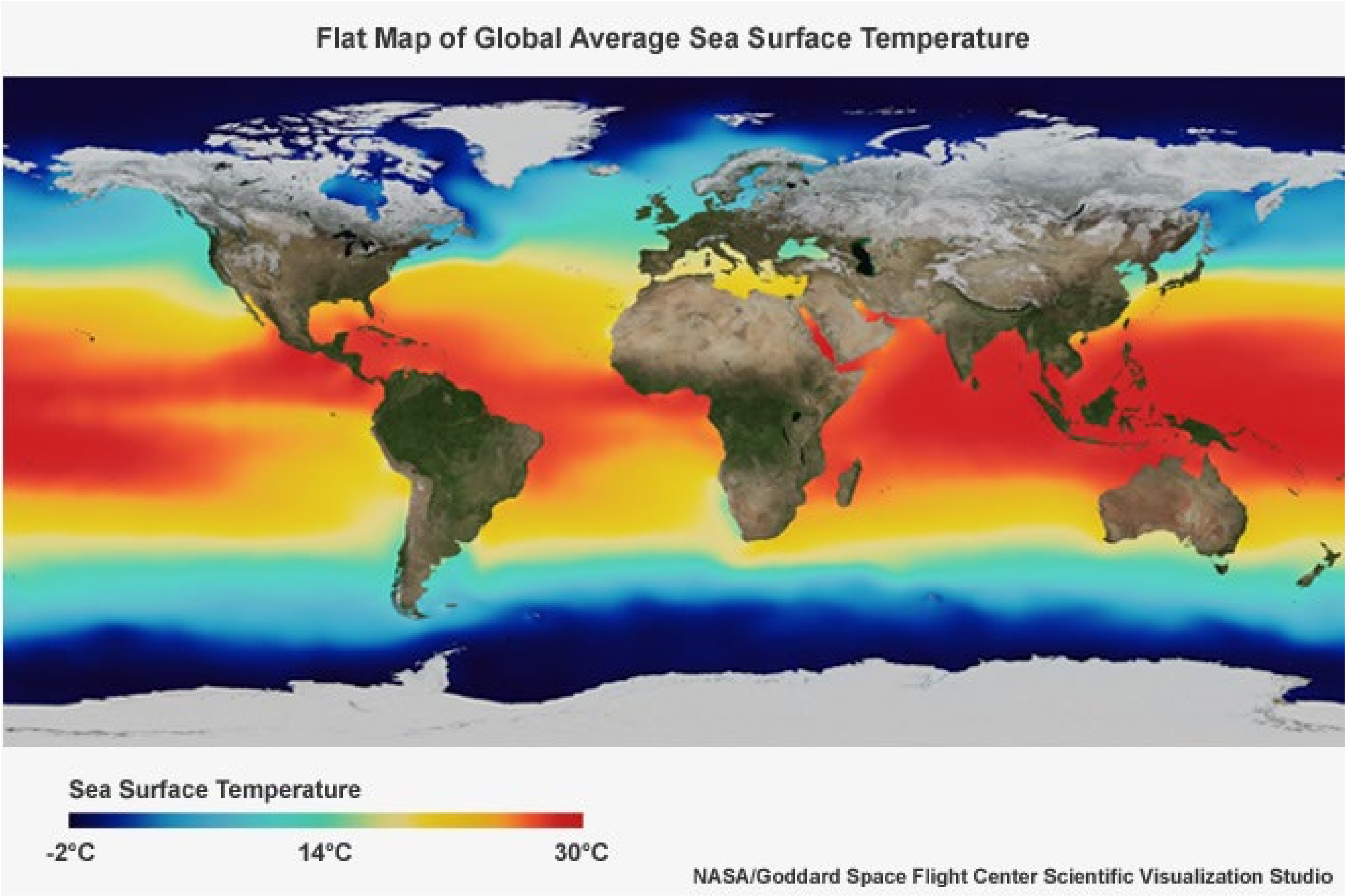
The pumping of surface water into the deep ocean forces the deep water to move horizontally.

The deep ocean water must find an area on the world where it can rise back to the surface. This closes the current loop.

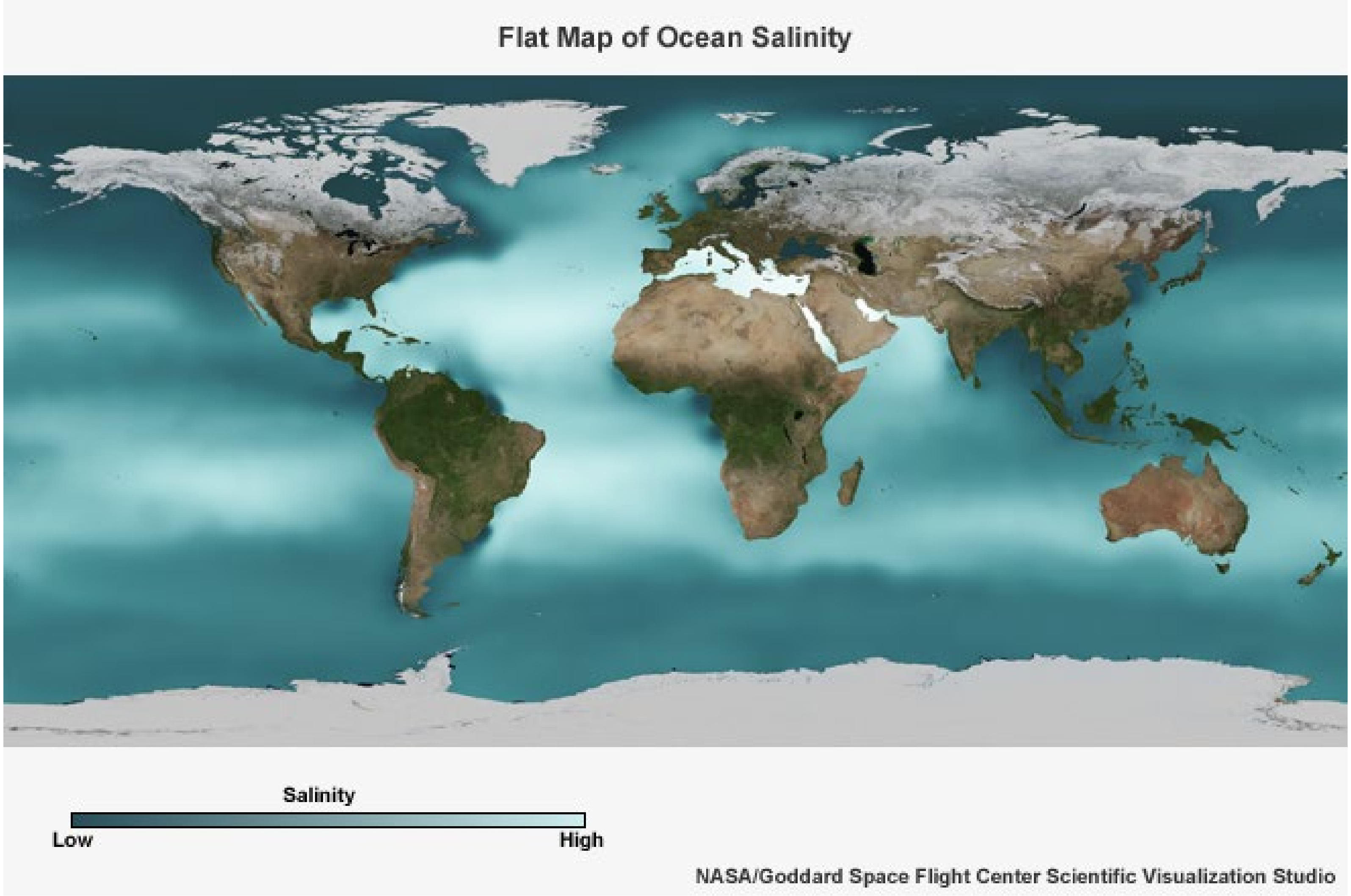
This process usually occurs in the equatorial ocean, mostly in the Pacific and Indian Oceans.

This very large, slow current is called the thermohaline circulation because it is caused by temperature and salinity (haline) variations.

Sea Surface Temperature

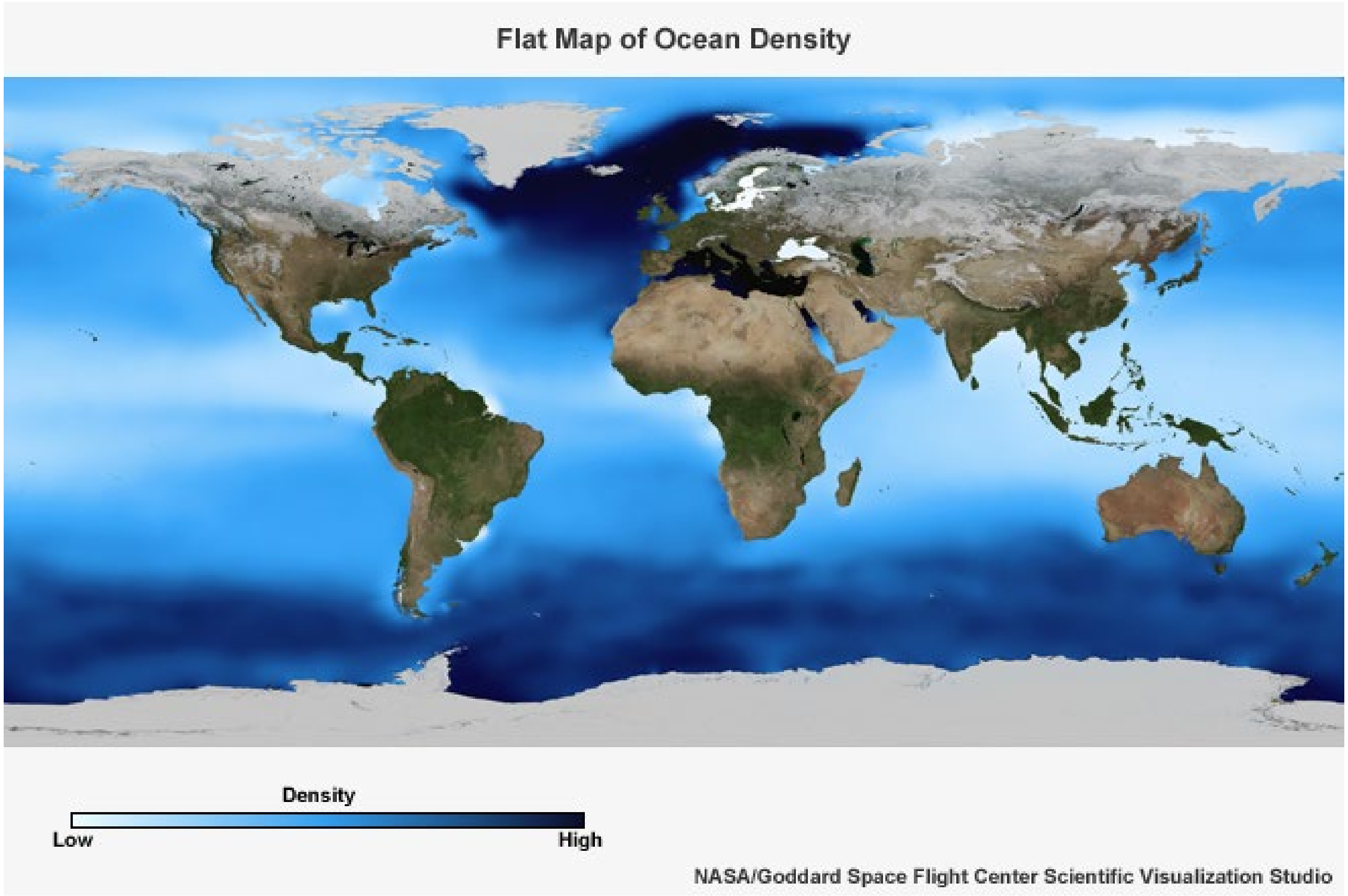


Adding Heat Alters Ocean Dynamics



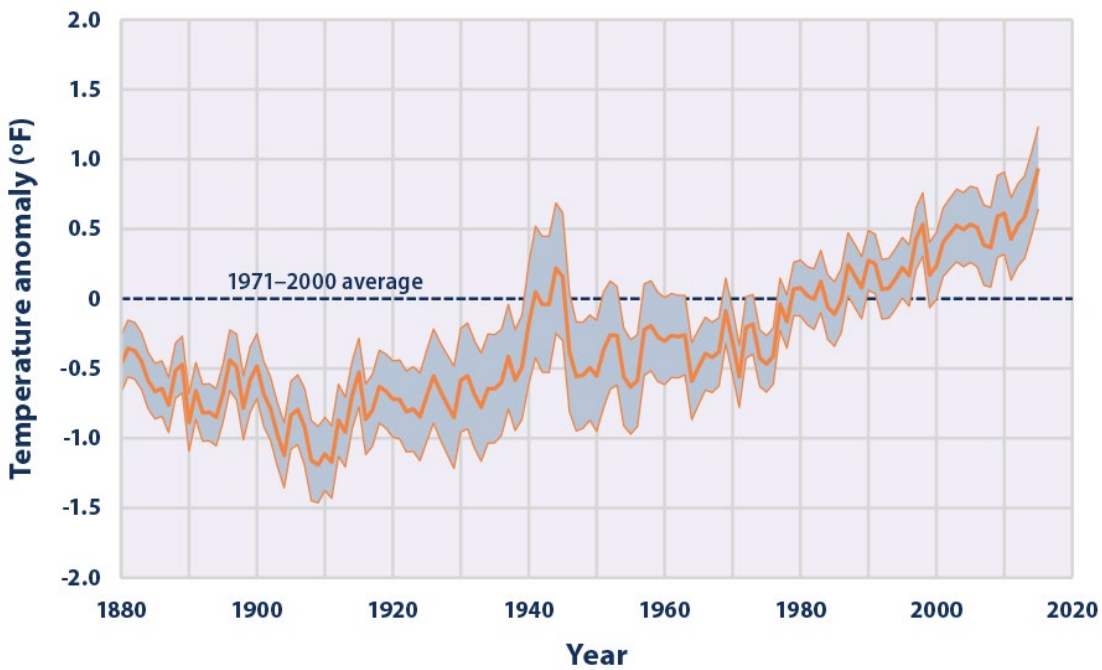
This map shows ocean salinity. The white regions have the highest salinity and the dark regions have the lowest.

Adding Heat Alters Ocean Dynamics



This is a map of ocean density [g/ml]. Light blue regions indicate the least dense waters; dark blue regions are the most dense.

The Sea's Surface and Global Climate



Global sea surface temperature has increased over the 20th century

From 1901 through 2009, temperatures rose about 0.12° F (0.07° C) per decade.

In the last 30 years, surface waters have warmed even more quickly, at an average rate of 0.21° F (0.12° C) per decade.

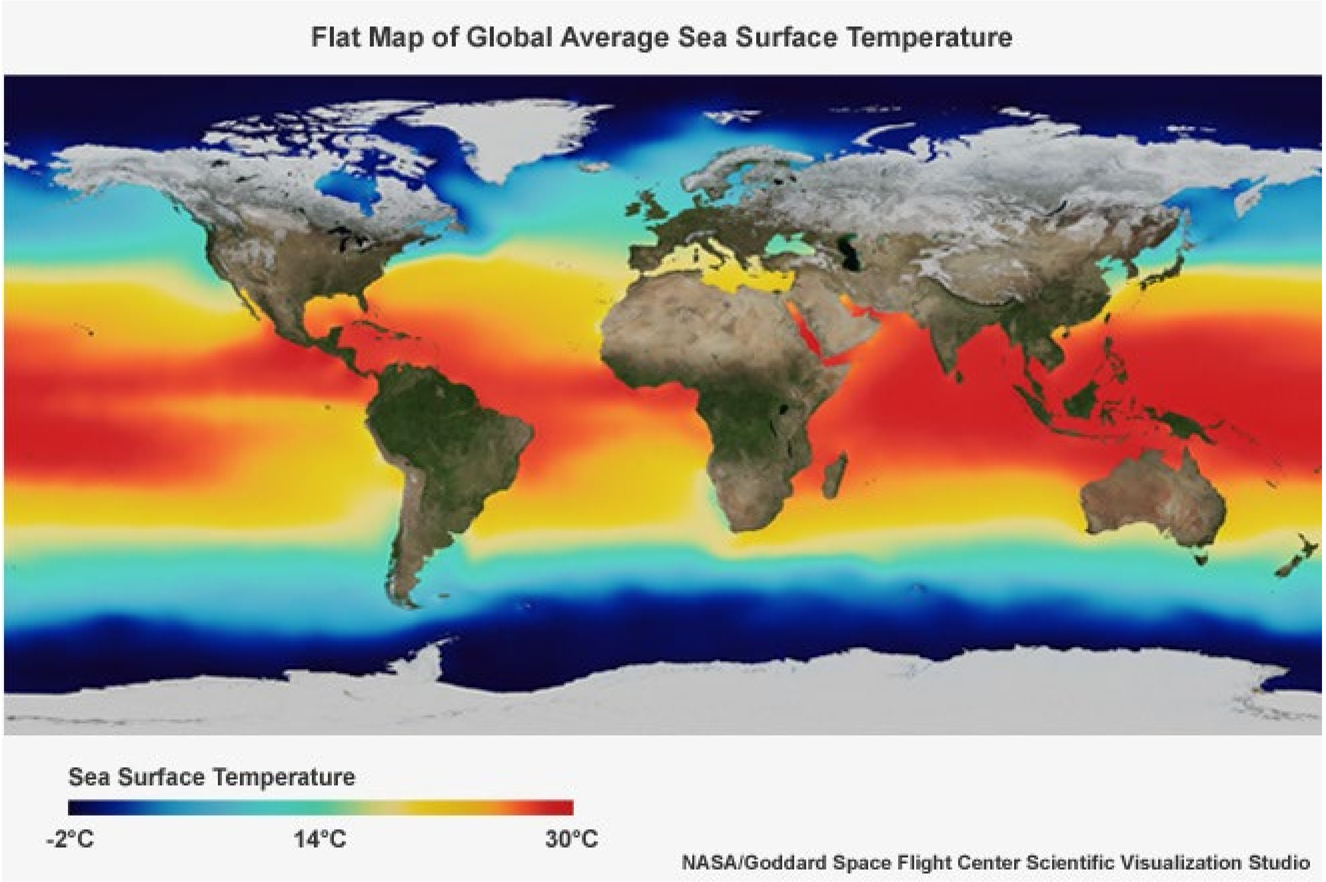
Sea surface temperatures have been higher over the past 30 years than at any other time since at least 1850, and probably for millennia.

The largest increases in sea surface temperature occurred in two key periods: between 1910 and 1940, and from 1970 to the present.

Adding Heat Alters Ocean Dynamics

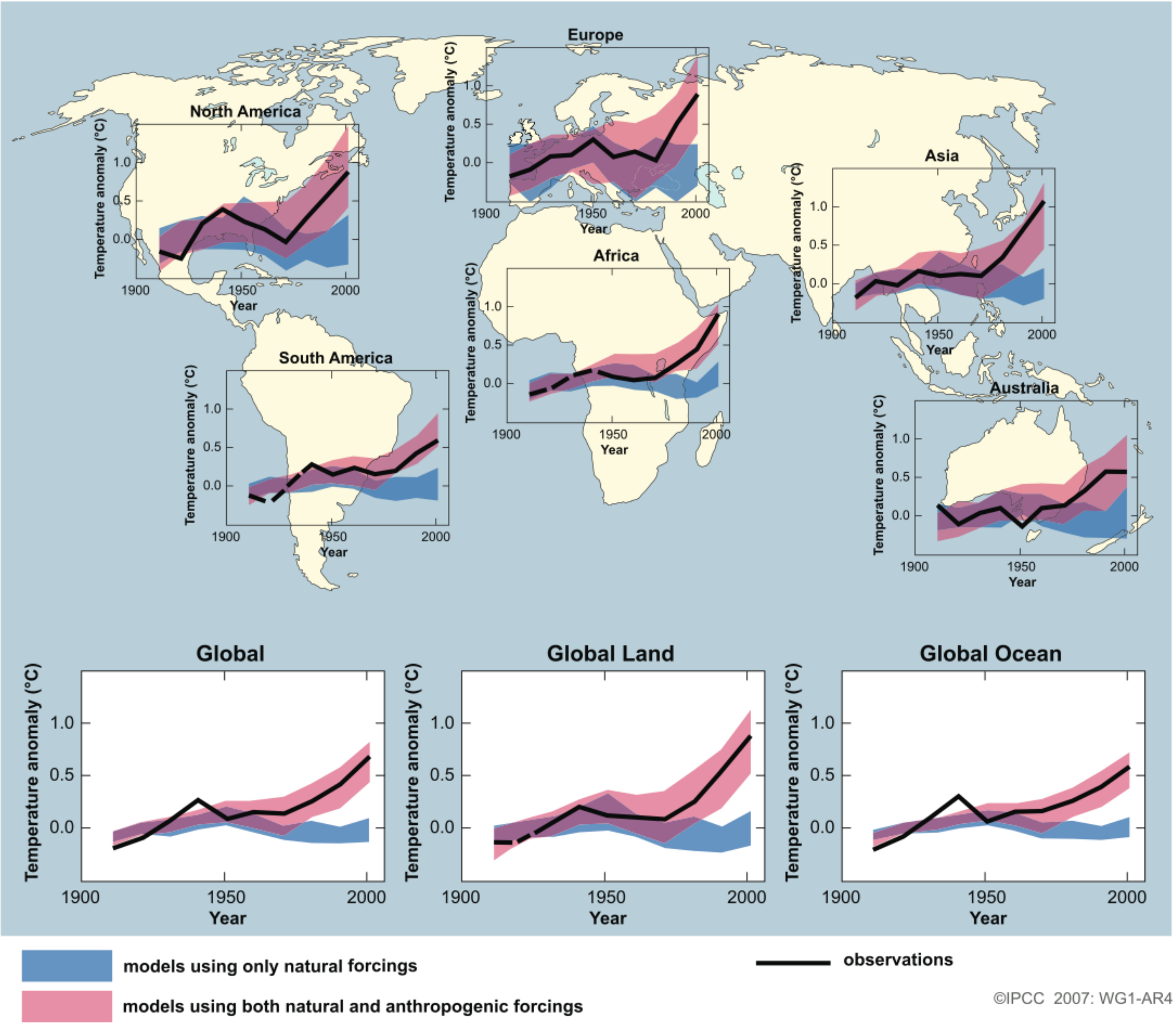
Added heat changes ocean dynamics, as many currents are driven by subtle differences in temperature (and salinity). Currents influence climate and ecosystems.

At high latitudes, warming waters have additional impacts: they melt sea ice and coastal ice shelves.



In addition, water expands as it warms, so as ocean temperatures climb, sea levels also rise. The conceptual animation to the right illustrates this process. As the burner puts increasing heat on the beaker, the water it contains warms and expands, eventually overflowing out of the vessel.

Global Warming: Increasing of sea/land temperatures



Rates of rise

Sea level rise will not rise at the same pace everywhere.

Depending on local conditions, sea level rise could be much less than a meter, or much more.

Average Global Sea Level

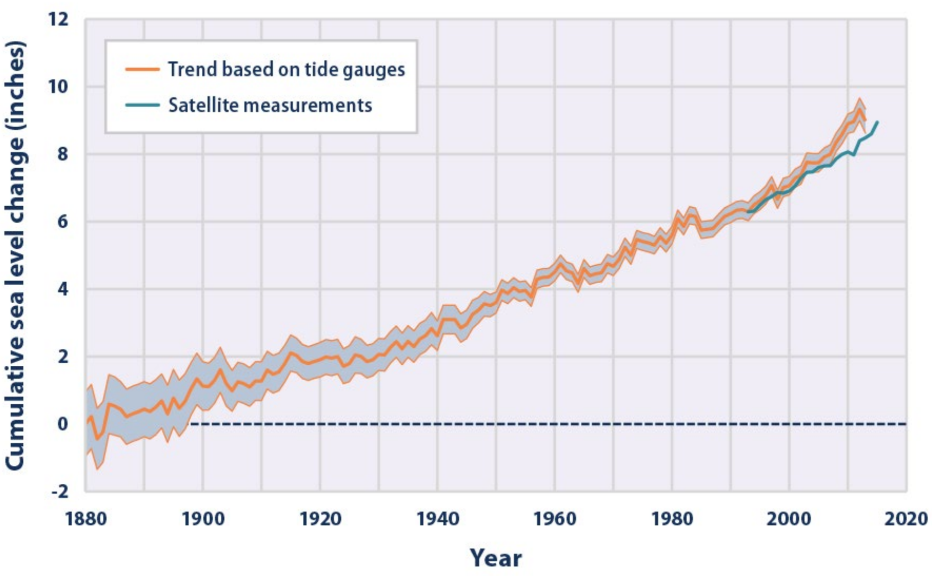
After roughly 2000 years with little change, average global sea levels rose throughout the 20th century, and in recent years the rate of change has accelerated.

When averaged over all the world's oceans, absolute sea level has increased at an average rate of 0.06 in. (0.15 cm) per year from 1870 to 2008.

From 1993 to 2008, average sea level rose roughly twice as fast as the long-term trend, at a rate of 0.11 to 0.13 in. (0.28 to 0.33 cm) per year.

The average absolute sea level of the world's oceans has risen about 20 cm since 1870.

Data are based on a combination of long-term tidal gauge measurements and recent satellite measurements.



Rising Seas

Only a few centimeters of sea level rise can produce major changes for coasts.

In low-lying areas, a half a meter vertically can translate to inundation far from the present shoreline.

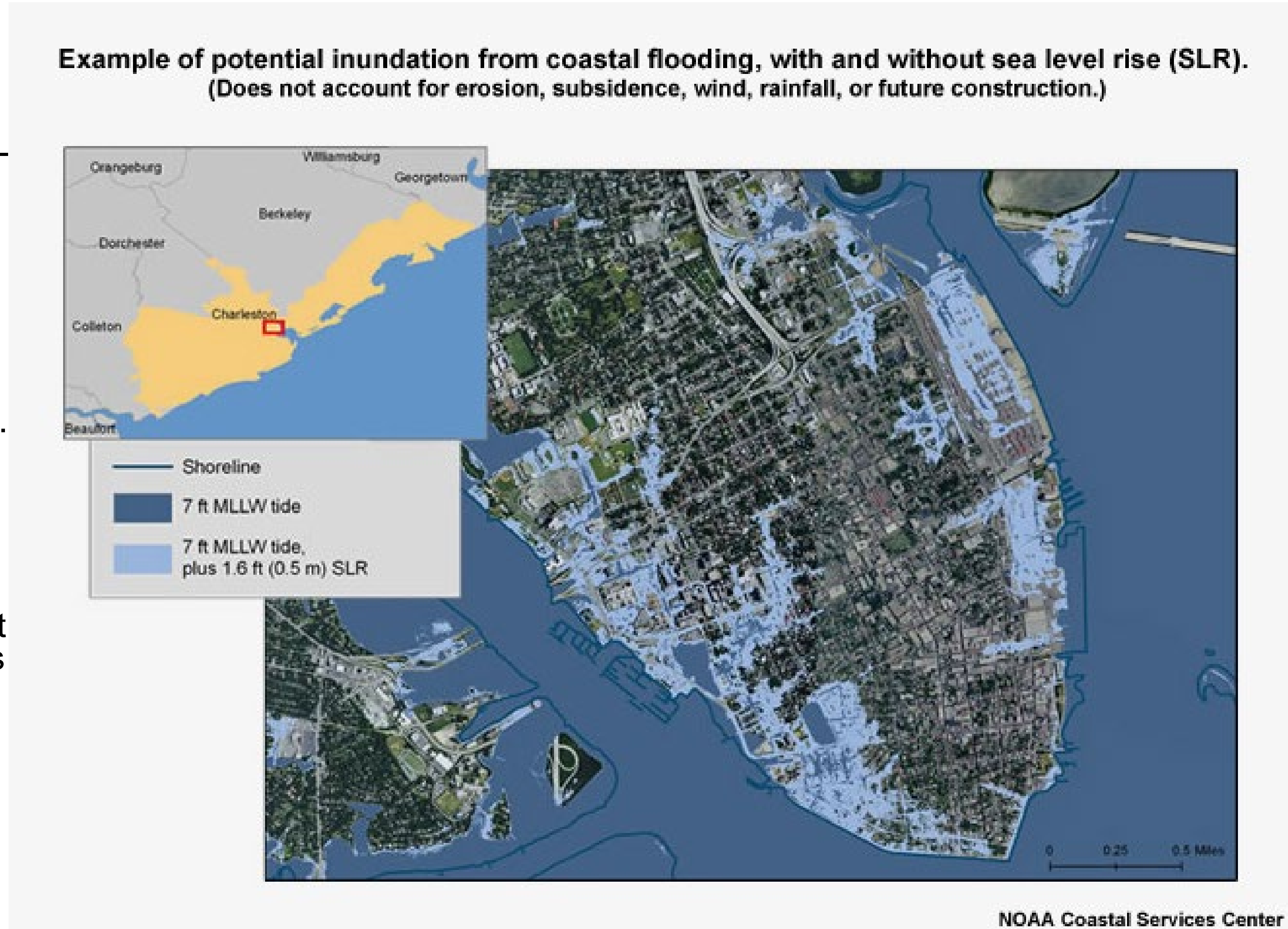
On the scale of centuries, a few degrees of global warming could generate 10s of centimeters of global sea level rise.

Cost of Rising Seas

The consequences of sea-level rise may be expensive.

A separate study more recently calculated that a rise of almost 20 in. (0.5 m) by 2100 would cause $23-170 billion in damage.

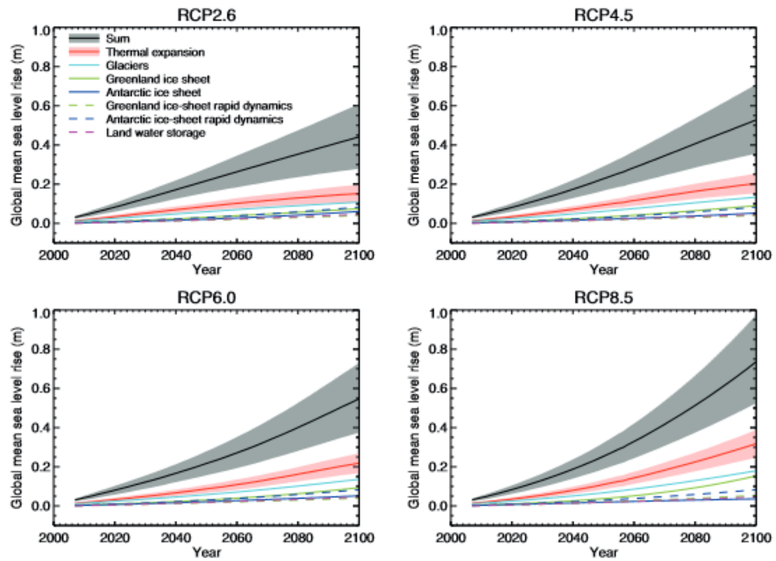
It is also worth remembering that sea level rise will not stop in 2100. Without significant deviation from our present course of greenhouse gas emissions, sea level rise will continue for several thousand years.



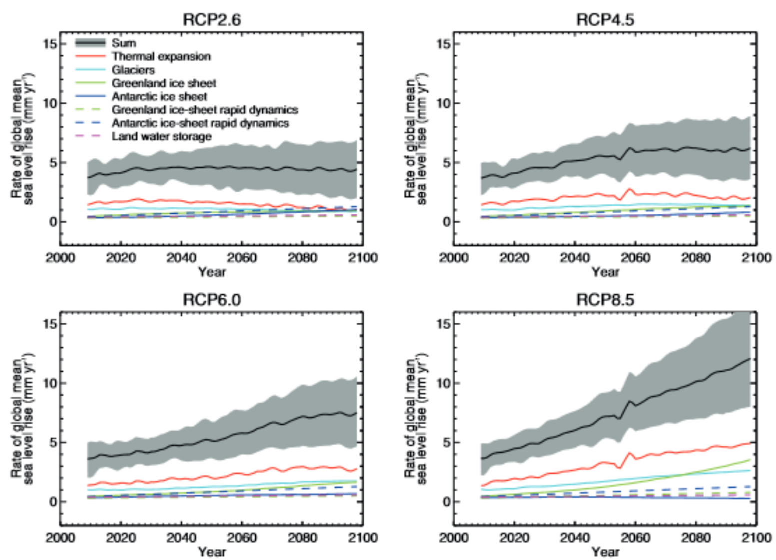
In 1991, the Federal Emergency Management Agency calculated that a one-foot (about 30 cm) sea level rise by 2100 would increase annual flood damage to insured property by 36-58%.

Projections

Global mean sea level rise [m]



Rate of global mean sea level rise [mm/year]

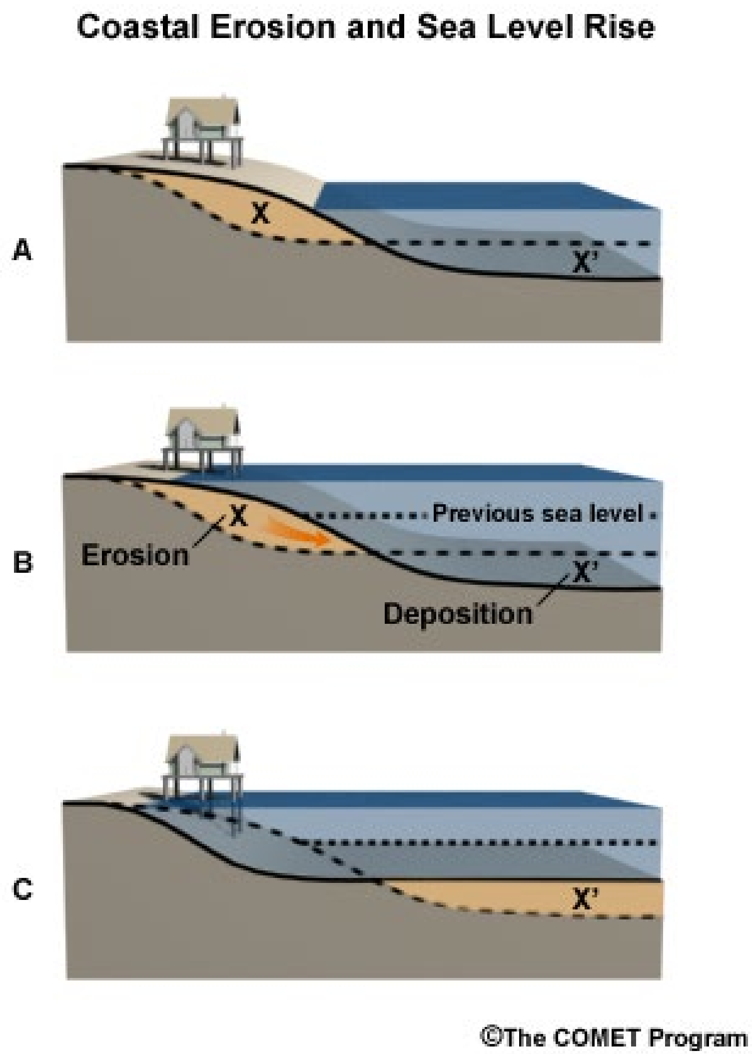


Rising Seas

Ice Age (10000 years ago)

Today

Influences on sea level rise



Land can sink when it is whittled by erosion

What can water offer you? Courtesy of Maria Nickolova

Most people first think of all the difficulties and the problematic situations and cannot see the unlimited opportunities that could be found only in this place.

Water homes are much more flexible than the conventional fixed ones, because they are prefabricated and the major part of their structure is very easily transported.

A whole class of floating architecture, the houseboats, has their own motor, so the dwellers are able to go to trips and change their location.

Stilt house

Floating village on Tonlé Sap Lake

Build on water

Another excellent aspect of the “life in the water” is the possibility to choose between complete privacy and close neighborhood relations.

As a result of the threatening fast rising of the sea level, the aquatic architecture, i.e. floating houses, communities, habitats, and brand new islands has been becoming more and more popular and adequate solution for the global catastrophe.

Build on water

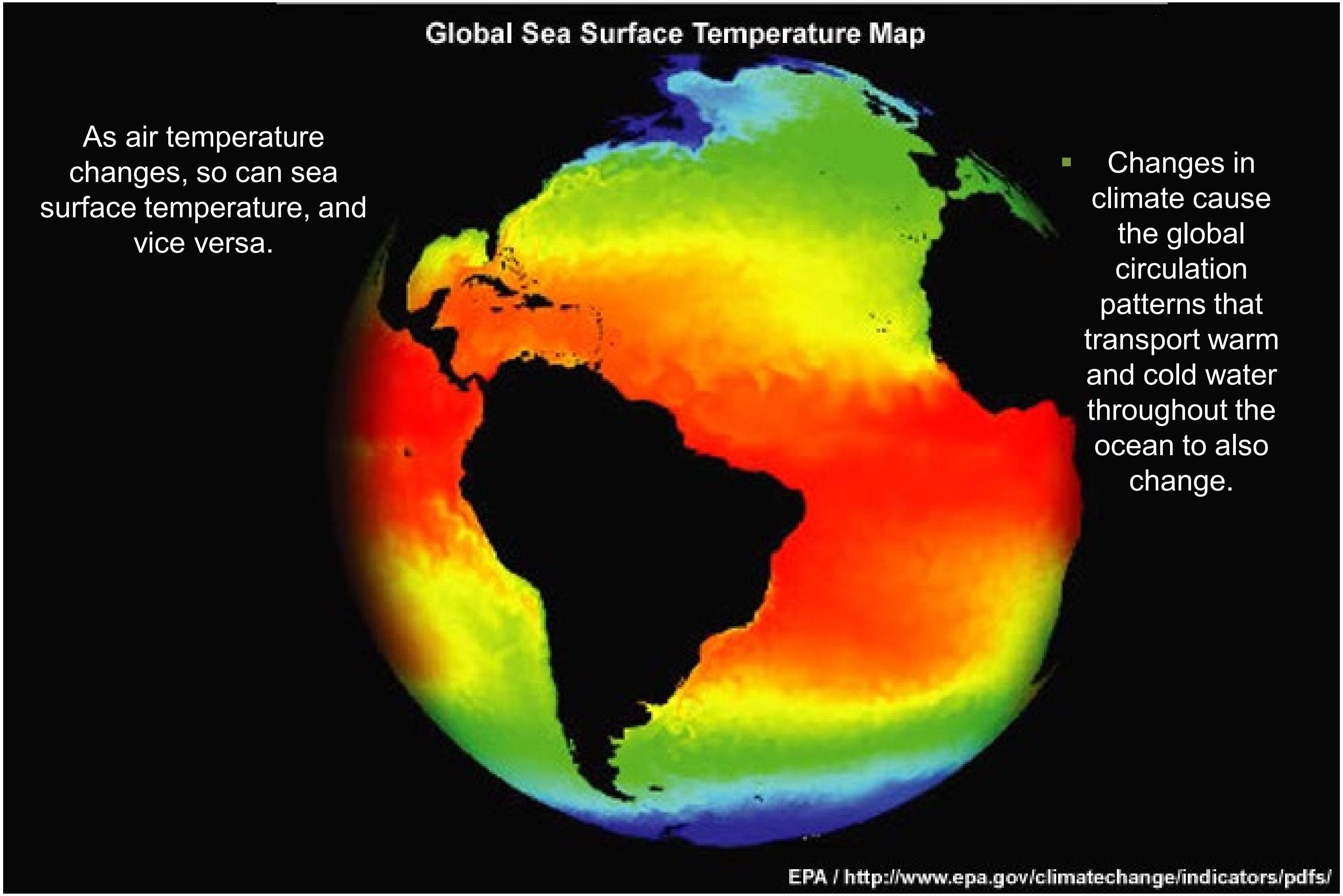
Nowadays one of the most sustainable examples of living units is exactly the floating green homes and the self-sufficient water cities.

Build on water

Even such a complex project like an international airport is possible to be built on water. Those two pictures show the cases of some of the biggest airports and they are constructed on artificial islands. The first one is the International Terminal Kansai, Osaka, Japan, designed by Renzo Piano. The second is the Honk Kong International Airport, a project by Foster and Partners. Both of them demonstrate the complete compatibility of the water with the building world.

The small islands of Venice Lagoon are artificial islands

Dynamic Surface Waters



As air temperature changes, so can sea surface temperature, and vice versa.

- Changes in climate cause the global circulation patterns that transport warm and cold water throughout the ocean to also change.

New Dynamics

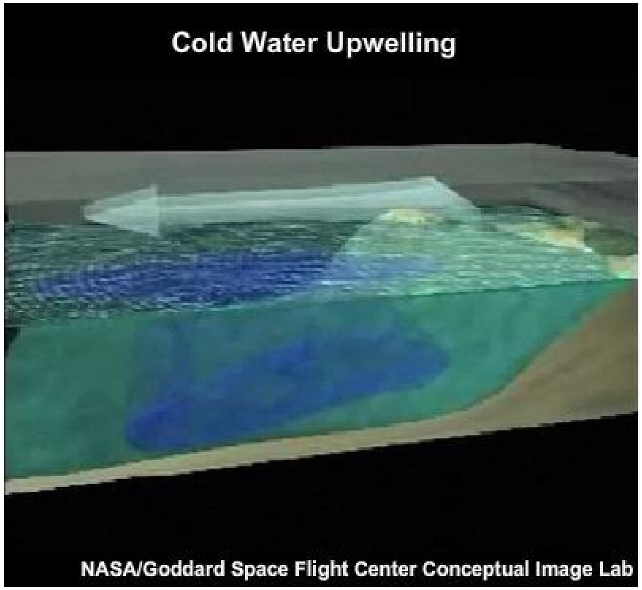
Climate change will also likely alter wind and ocean circulation patterns.

A warmer ocean surface will increase temperature stratification, inhibiting the upwelling of nutrients and oxygen available to phytoplankton, the food source for fish.

For example, a 2.7° F (1.5° C) sea surface warming off the coast of California between 1951 and 1993 resulted in a 70% decline in zooplankton.

Changing winds can also increase or decrease upwelling as they blow on surface waters.

Where upwelling might increase because of climate change-related wind shifts, ecosystem productivity could increase.



This illustration shows the process of coastal upwelling.

Winds coming off principal land masses push surface layers of water away from the shore.

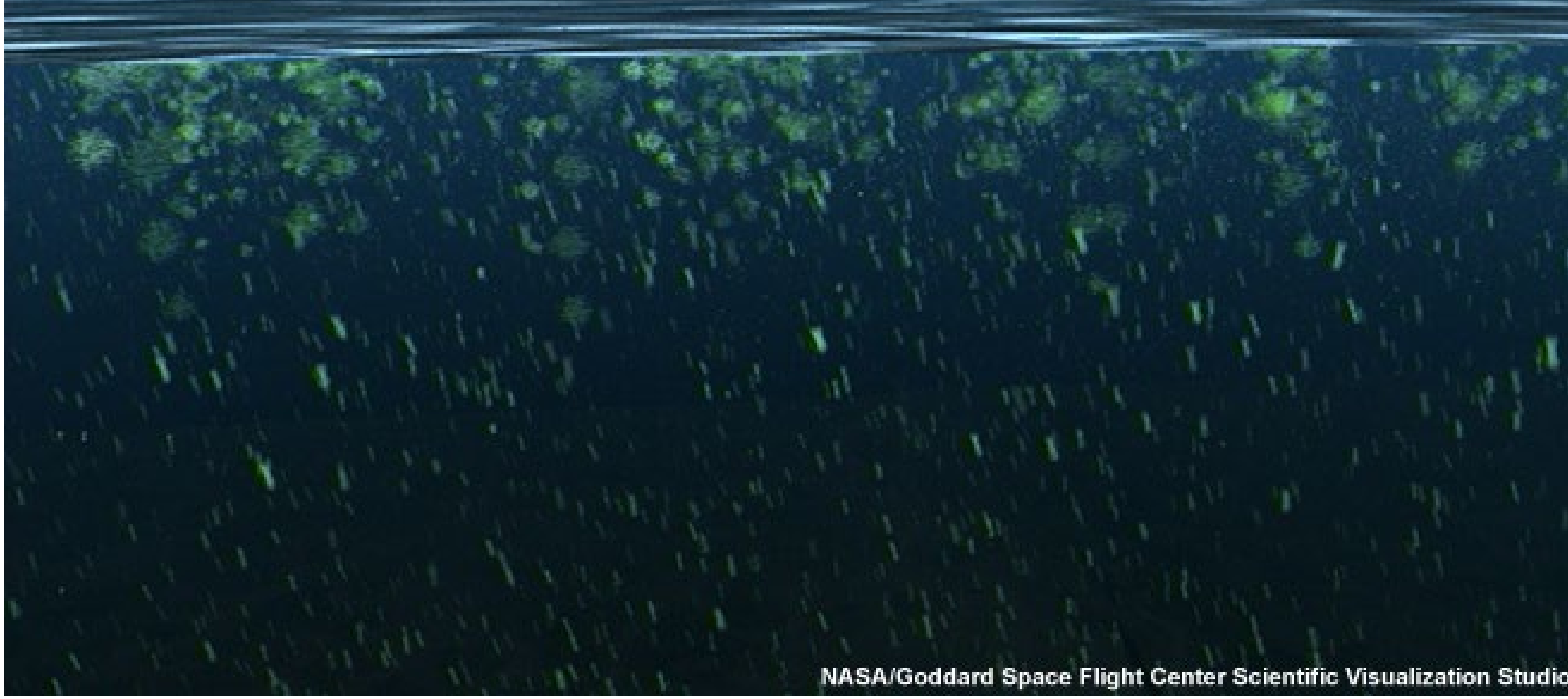
Deeper water underneath the surface layers rush in toward the coast, filling the void left by the wind and bringing nutrients that fuel phytoplankton growth.

The Ocean and Carbon

Because the concentration of CO_2 is higher in the air than in the ocean, it diffuses into seawater.

The tiny photosynthetic microbes called phytoplankton (shown here) absorb CO_2 and use it to make food.

Half of the world's oxygen is generated by phytoplankton.



More carbon, more acid water

The ocean absorbs 22 million metric tons/day of CO_2, altering ocean chemistry.

As atmospheric CO_2 increases as more fossil fuels are burned, the ocean absorbs more and more CO_2 in response.

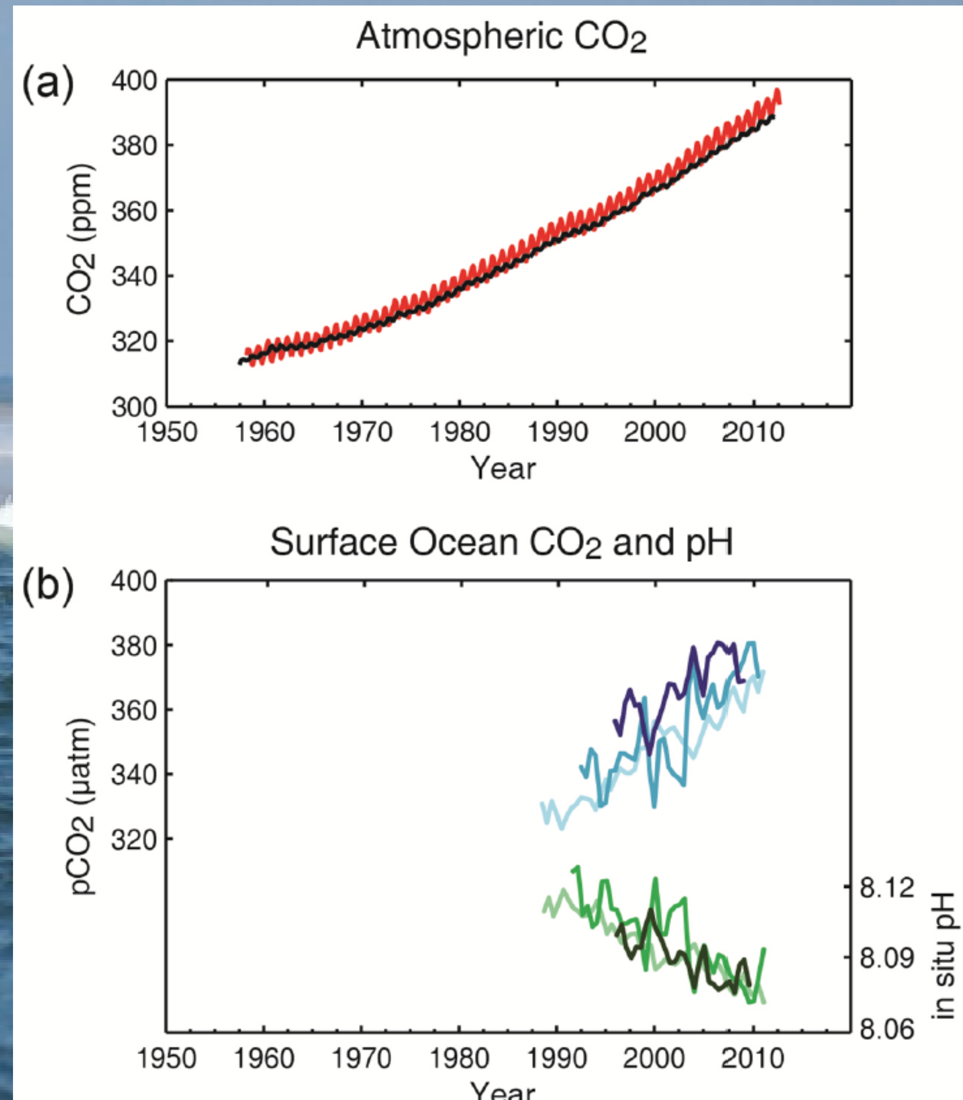
CO_2 dissolved in water produces carbonic acid (H_2Co_3) which increases the ocean’s acidity.

More carbon, more acid water

Warmer sea surface temperatures have caused phytoplankton productivity to decrease in the last century.

Less phytoplankton means less absorption of CO_2.

More CO_2 entering the ocean and less of it consumed by phytoplankton means that surface seawater is acidifying faster.



Another feedback loop:

Rising of Temperatures -> less Phytoplancton -> less CO_2 absorbed

More CO_2 in the ocean -> faster acidification

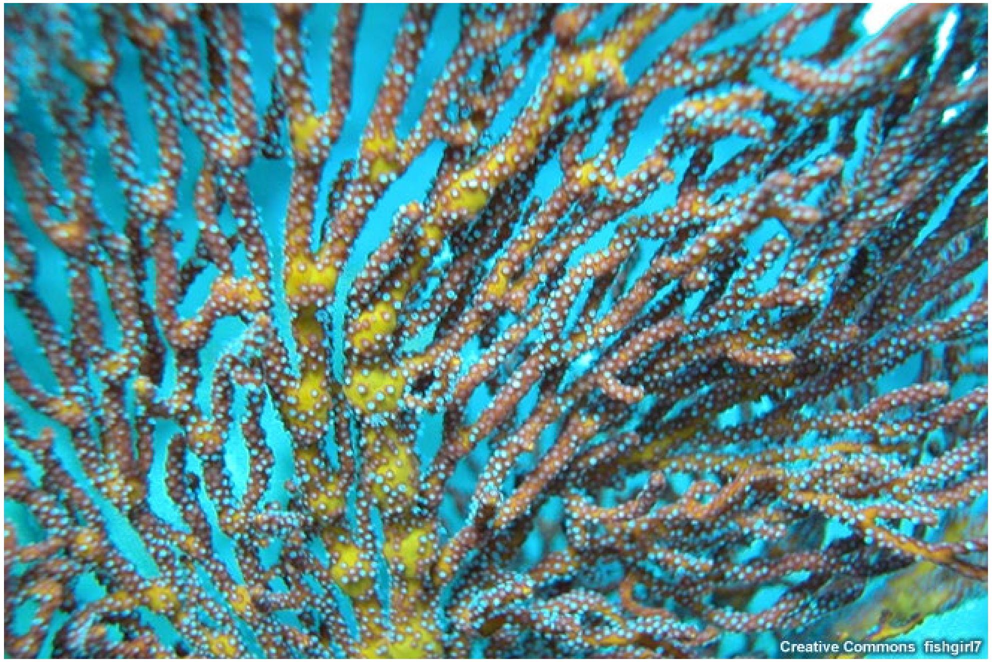
More CO_2 in the atmosphere -> More CO_2 in the ocean -> more acid waters

Acidified seawater has less of the carbonate ions which marine organisms need to make calcium carbonate.

Corals, crabs, and other creatures all rely on this important molecule to make their skeletons and shells, radically altering marine ecosystems and ocean geochemistry.

Higher temperatures prompt corals to expel their photosynthetic partner algae, a traumatic event known as bleaching.

Dynamic Surface Waters



Warm surface waters can prevent critical deep-sea nutrients from cycling upward, potentially causing fish populations to decline.

Changes in sea surface temperature have a tremendous impact on the marine ecosystem including:

- influencing where plants and animals live;
- altering migration or breeding patterns;
- threatening ocean life;
- affecting the frequency, intensity, and location of algal blooms.

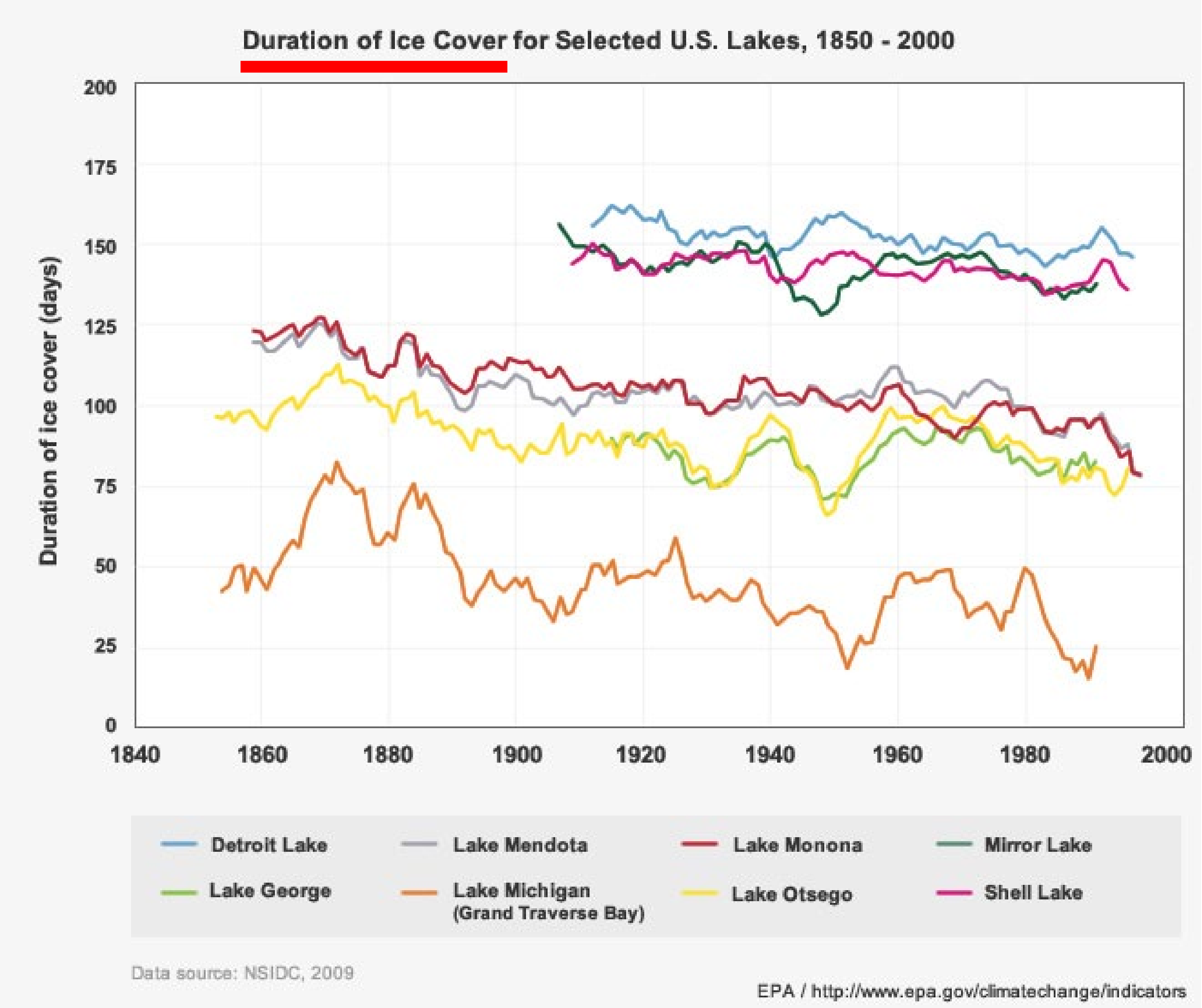
Global Lakes Heat Up

Like air and seawater, lake water is warming too.

Lakes in the U.S., Canada, and Europe warmed more than those near the equator.

Scientists studying thermal infrared satellite images of lakes for the past 25 years calculated that around the world, over 100 of the largest lakes on Earth warmed an average of 0.81° F (0.45° C) per decade, or 2° F (1° C) over 25 years.

Global Lakes Heat Up



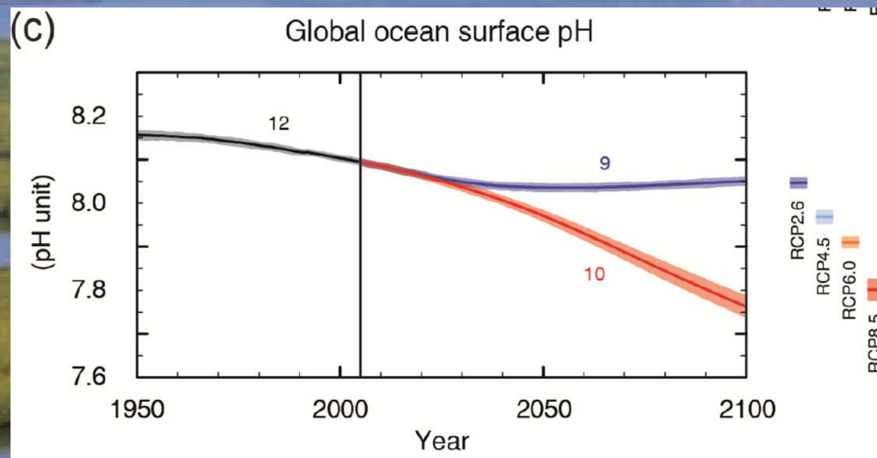
Lakes are also suffering ice loss, with freezing dates arriving later and thaw dates earlier since the mid 1800s.

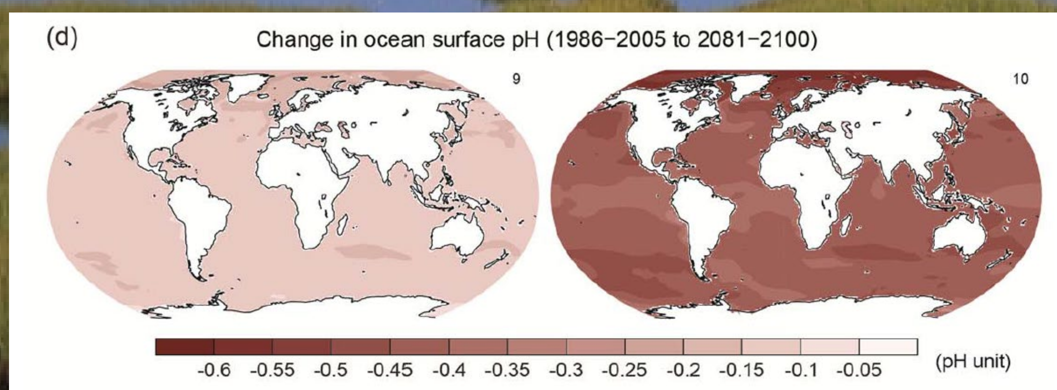
On the whole, lakes have stayed frozen one to two days fewer per decade.

Vulnerable Ecosystems

Wetlands, estuaries and coral reefs are the most vulnerable marine ecosystems to climate change.

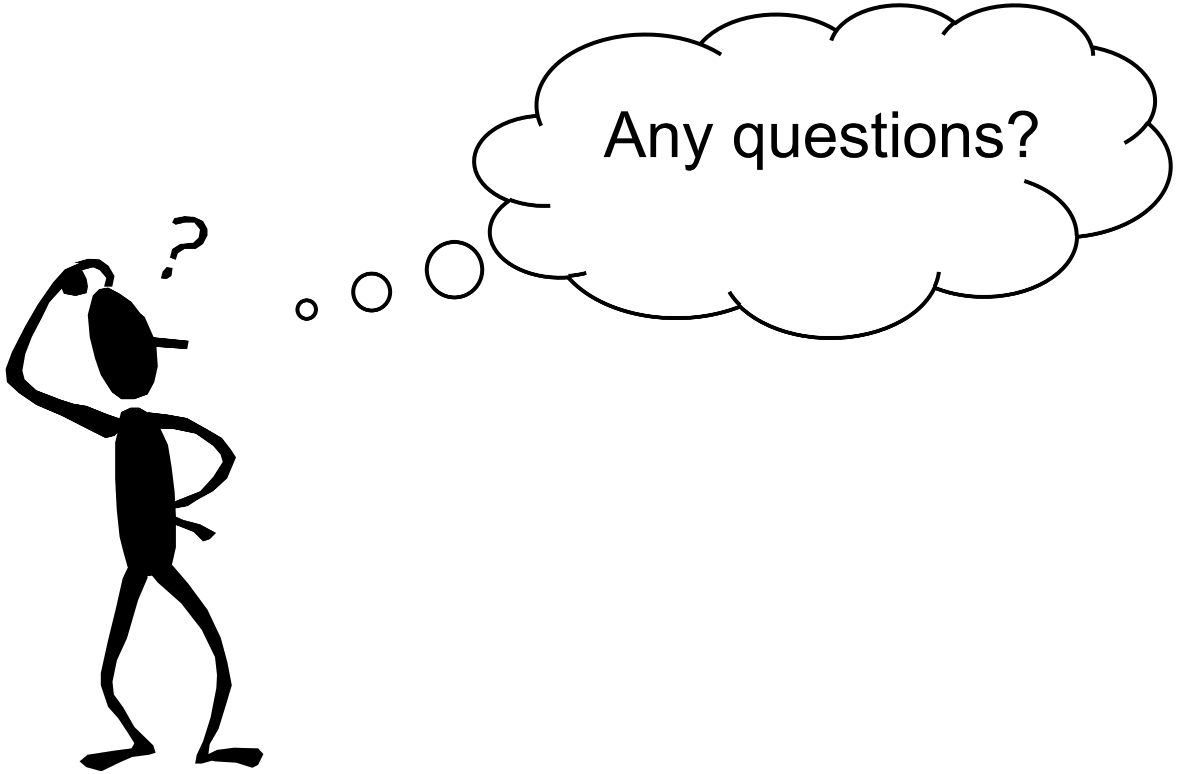
Ocean acidification has a lot to do with this, since decreasing pH makes it harder for corals to build and maintain their skeletons.



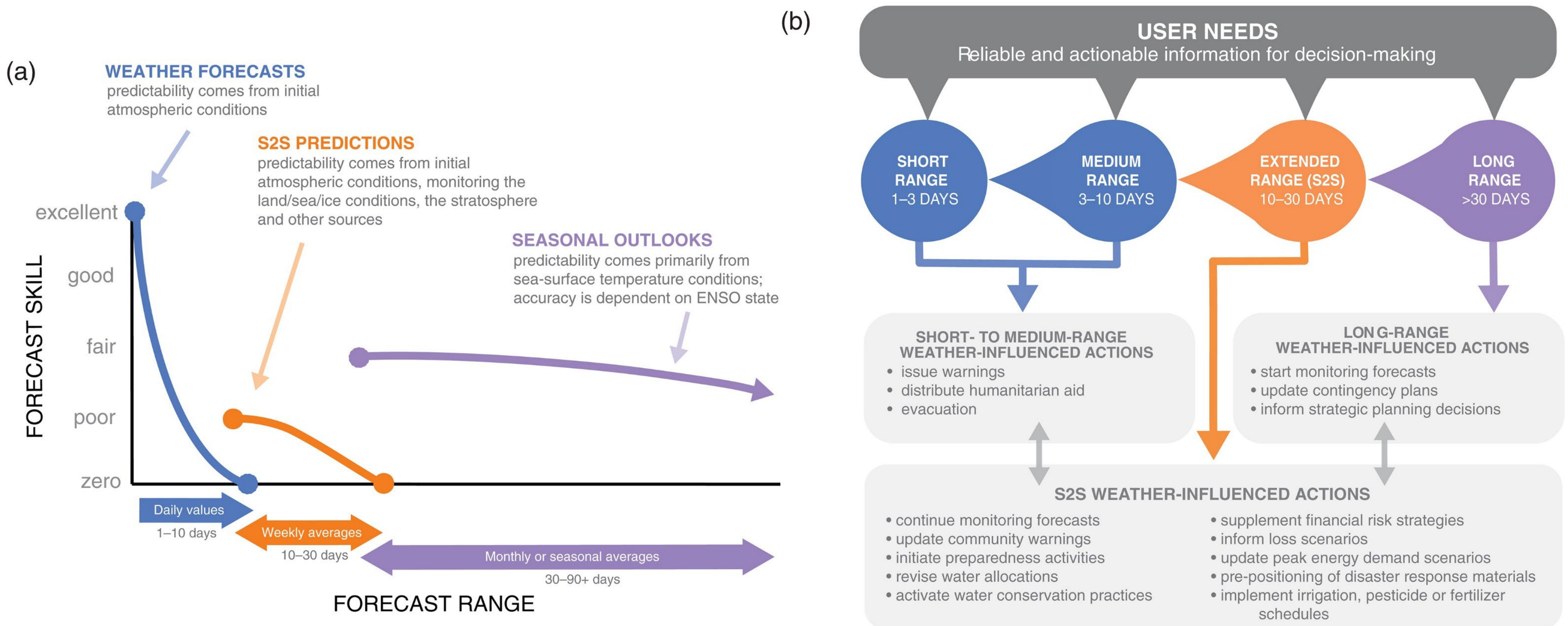


Vulnerable Ecosystems

Scientists have calculated that under doubled CO_2 conditions, coral reefs will experience on average a 20 - 30% decrease in calcification.


Any questions?

Weather & Climate forecasts



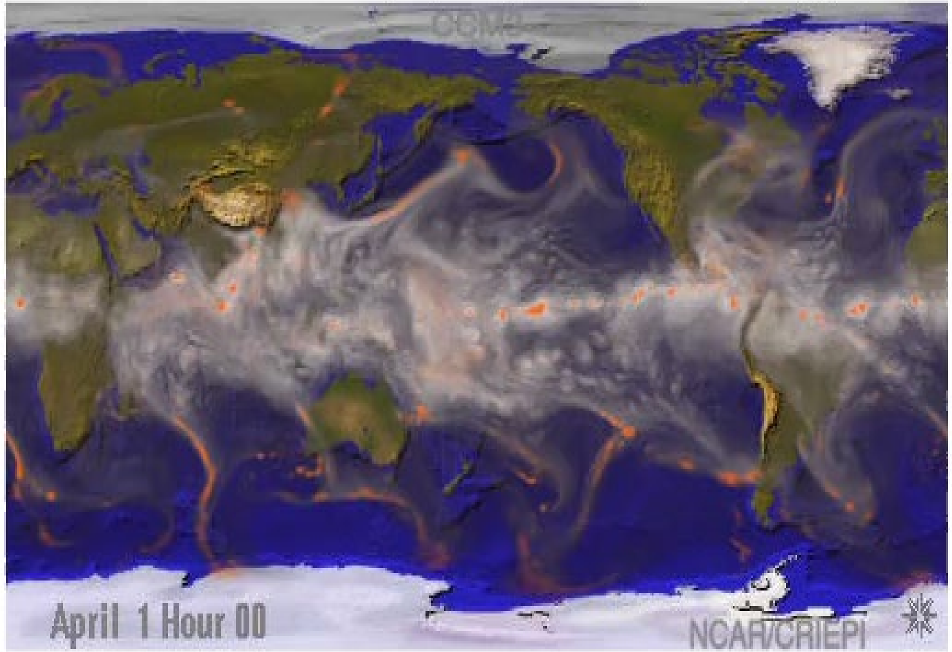
White et al., 2017

Introduction to climate models

Weather forecasters depend on numerical weather prediction (NWP) models to produce timely, accurate forecasts. We depend on these forecasts to make all manner of decisions from recreation choice to emergency response. As a community, weather forecasters understand the strengths and weaknesses of NWP models better than just about any other group. Every forecaster knows, for example, that model skill drops sharply with time and that NWP models struggle to produce accurate and precise forecasts more than a week into the future.
Climate models share a common heritage with NWP models. For example, this animation shows water vapor and precipitation for a period of several days. We see the same weather patterns produced by NWP models and observed in satellite images. **In a climate simulation, the model would run for decades or centuries, rather than days. As a result, forecasters frequently wonder how a climate model can produce an accurate projection decades or centuries in the future, when NWP models cannot produce an accurate forecast at 10 days.** The answer lies in the questions the respective models seek to address.

Community Climate System Model (**CCSM**)

CCSM3 Simulation of Water Vapor (white) and Precipitation (orange) for April



©UCAR 2002

Why model the Earth system?

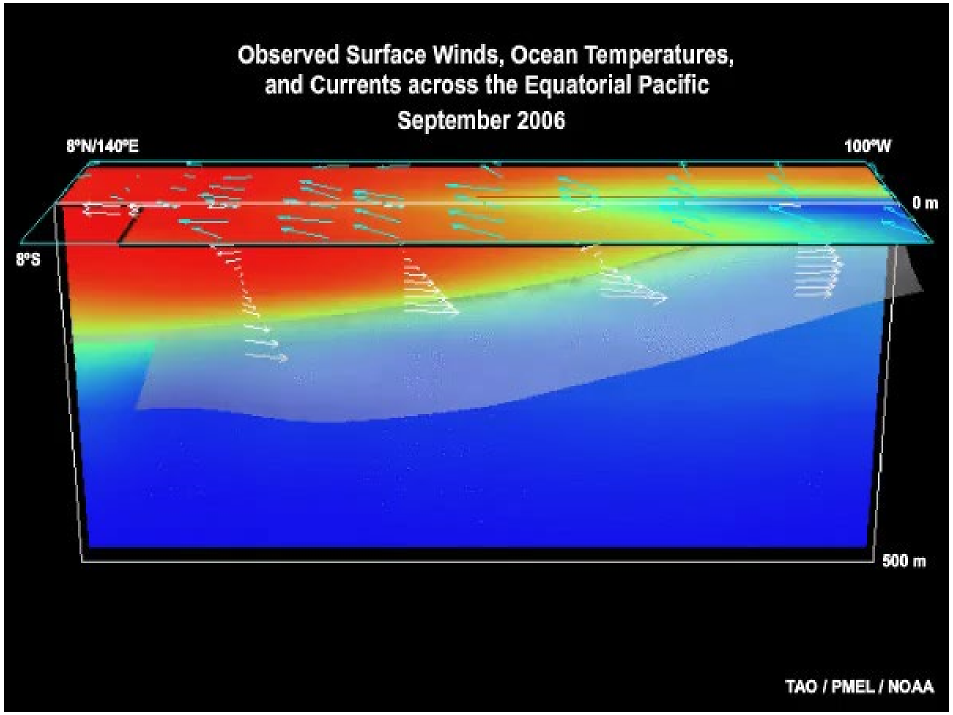
We also use models as a tool to look into the future, just as we use weather forecast models to make predictions. Both weather and climate models provide information for societal needs. **For example, planning for future water and hydrologic needs requires looking far into the future.**

Why model the Earth system?

Why do we model the climate system?
Since the start of the Industrial Revolution, greenhouse gases, principally carbon dioxide, have increased substantially in the atmosphere. The past several decades have seen a significant rise in global surface temperatures. **The climate change associated with this warming may have profound impacts for society**. For example, the frequency of extreme events, like flooding and heat waves, may increase with a high toll on society.

Why model the Earth system?

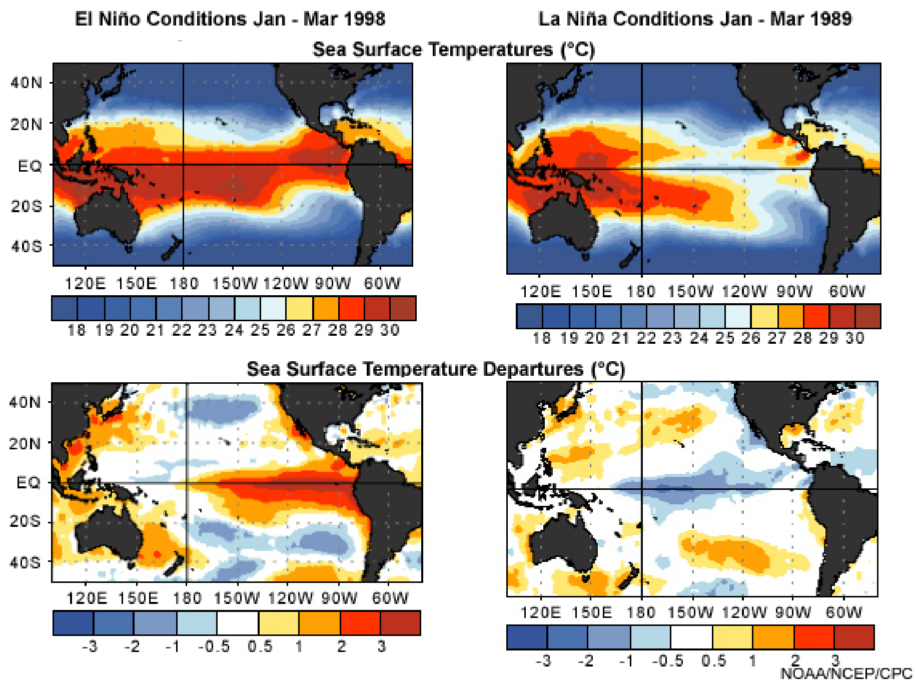
Understanding how climate changes in response to changes in the composition of the atmosphere and other factors drives climate research. Climate models provide a tool to understand how processes work and interact with each other. For example, El Nino/Southern Oscillation (ENSO) is a mode of climate variability that strongly influences weather in North America and beyond. It results from a complex interaction of atmosphere and ocean. This animation shows observed winds, ocean temperatures, and currents across the Equatorial Pacific through five years of an ENSO cycle. **Successfully modelling the complex interactions that result in ENSO allows researchers to understand the roles of the processes involved and how they interact.**

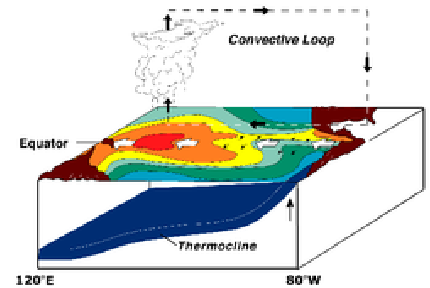


Synoptic-scale climate drivers: Air-Sea Interactions: El Niño and La Niña

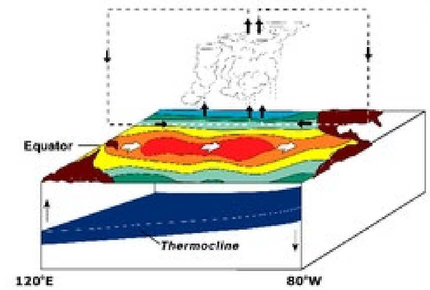
• Over the past few decades, scientists have gained a greater appreciation for the effect of ocean temperatures and currents on global weather patterns and climate.

• Two of the most well known phenomena are El Niño and La Niña. The top graphics (below) show sea surface temperatures during both types of years. Scientists use graphs of sea surface temperature anomaly data (bottom graphics) to detect each of these events. As you can see, El Niño is characterized by anomalously warm sea surface temperatures in the eastern, equatorial Pacific while La Niña is associated with an unusually cold water tongue in the Eastern Pacific.

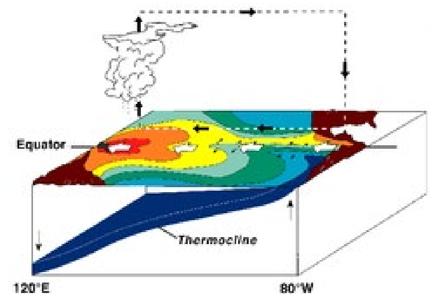




Normal Pacific pattern. Equatorial winds gather warm water pool toward west. Cold water upwells along South American coast.



El Niño Conditions. Warm water pool approaches South American coast. Absence of cold upwelling increases warming.

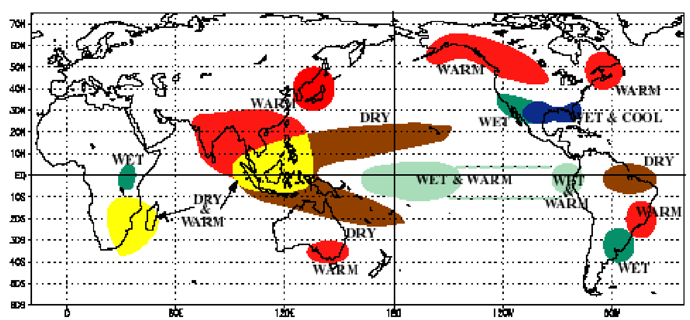


La Niña Conditions. Warm water is farther west than usual.

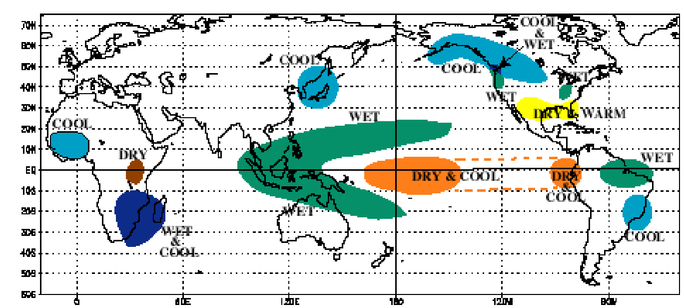
• Synoptic atmospheric circulation patterns are often altered from climatological norms during El Niño and La Niña episodes, resulting in noticeable deviations from normal weather conditions in some locations.

• This schematic shows areas whose temperatures and precipitation patterns tend to be affected by El Niño and La Niña. The areas are wetter, drier, warmer, or cooler than normal, or some combination thereof. Winds are often affected since there is less difference in air pressure across the Pacific.

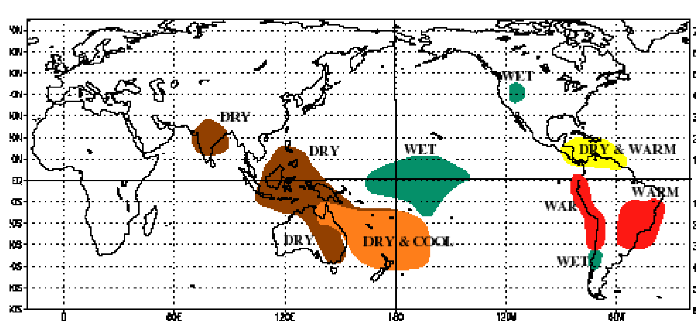
WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



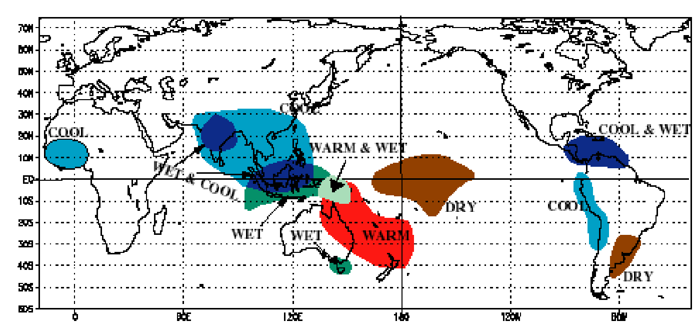
COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



WARM EPISODE RELATIONSHIPS JUNE - AUGUST

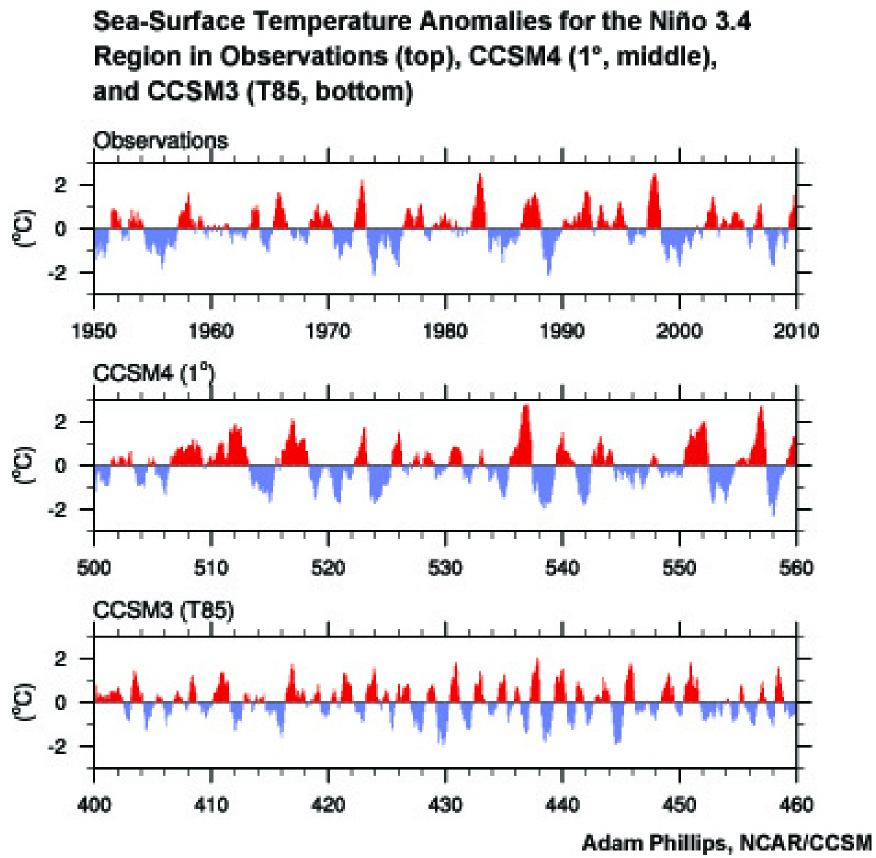


COLD EPISODE RELATIONSHIPS JUNE - AUGUST



ENSO

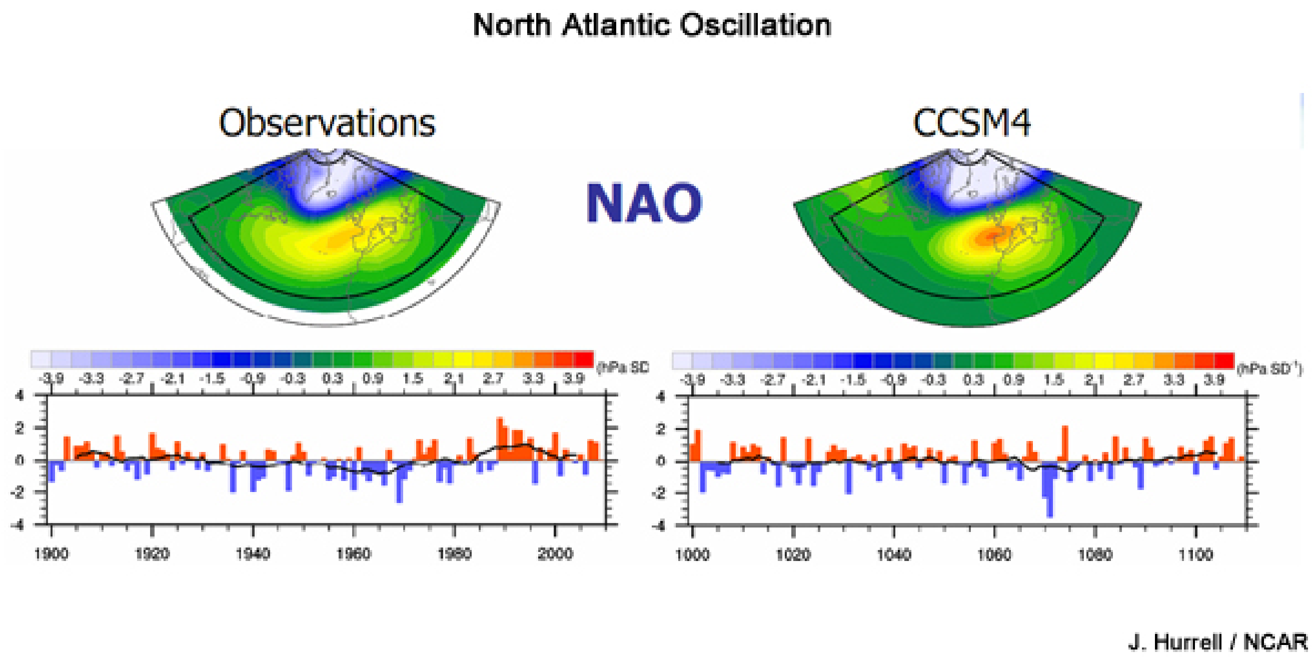
A similar argument can be made for ENSO. We know that ENSO plays a very important role in seasonal weather phenomena, especially in tropical regions and some extratropical regions, especially in the cold season. Therefore, getting a good simulation of ENSO leads to a more realistic climate simulation and more robust climate statistics. This plot of SST anomalies shows the improvement in both the magnitude and periodicity of ENSO variability between the older CCSM3 and newer CCSM4 simulations.
Overall, it's very important to get a climate model that is not just simulating mean temperature and moisture distribution, but also simulating these various modes of variability.



Natural Variability: North Atlantic Oscillation

Climate statistics encompass more than just the mean state for climate. They also include measures of natural variability, including the location, timing, and strength of oscillations within the climate system. For example, fully coupled models generate variability on the same time and spatial scales as ENSO, the North Atlantic Oscillation (NAO), and Pacific Decadal variability, among others.

This is a plot of one mode of variability found in the climate system, the North Atlantic Oscillation (NAO), which is a pressure oscillation between the Arctic region and the subtropics. The plot on the left shows the annual mean NAO in the real atmosphere from 1900 to 2008, while the plot on the right shows the annual mean NAO in a fully coupled model over a 109-year period. The results are strikingly similar.



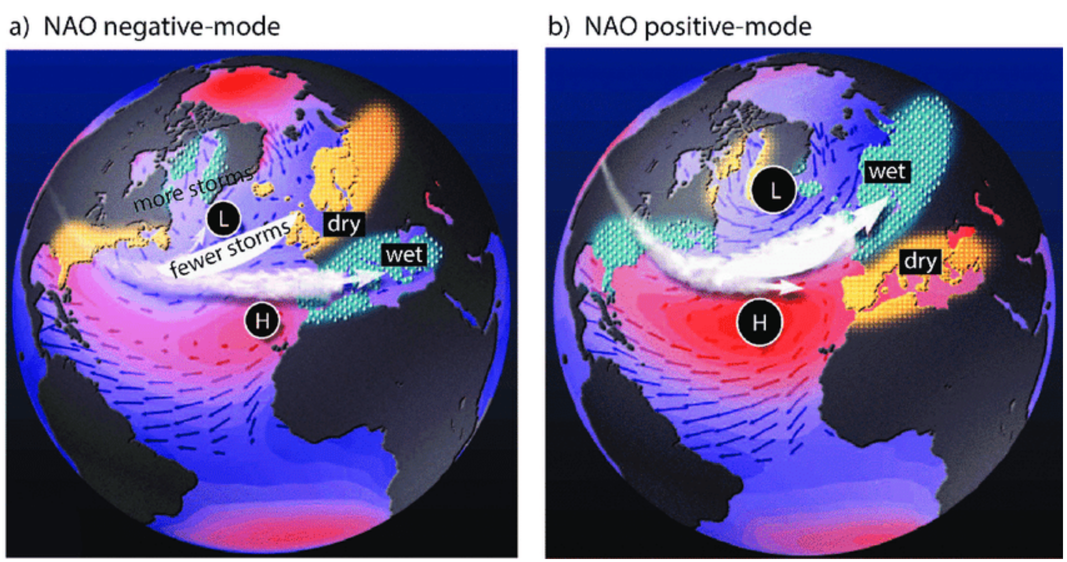
It's important to note that this variability is not externally forced. This is a natural mode of variability of the Earth's climate system that happens to play a very important role for seasonal weather. Here we see typical global weather patterns associated with positive and negative modes of NAO.

NAO (North Atlantic Oscillation)

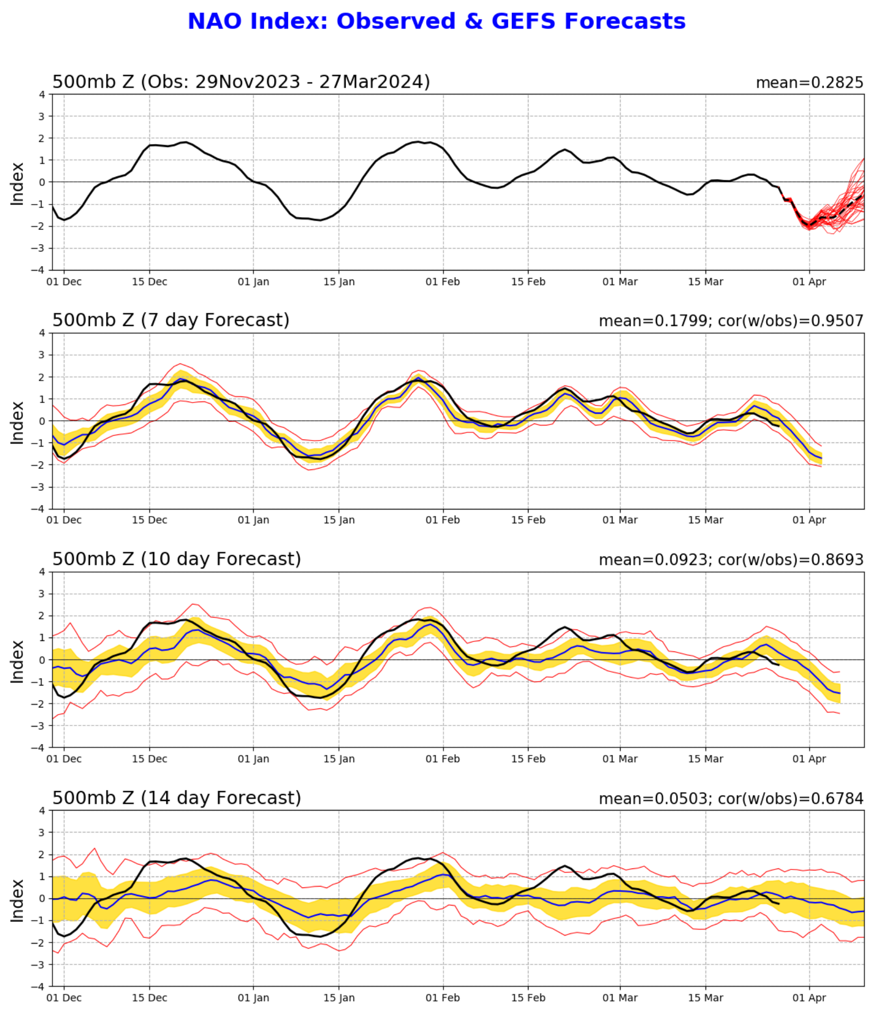
In the general circulation of the atmosphere we identified an Iceland low and Azores (or Bermuda) high on the map of average sea-level pressure (SLP).

The NAO is a variation in the strength of the pressure difference between these two pressure centers. Greater differences (called the positive phase of the NAO) correspond to stronger north-south pressure gradients that drive stronger west winds in the North Atlantic — causing mid-latitude cyclones and associated precipitation to be steered toward N. Europe. Weaker differences (negative phase) cause weaker westerlies that tend to drive the extratropical cyclones toward southern Europe.

An NAO index is defined as $\Delta P^* = P^*_{Azores} - P^*_{Iceland}$, where $P^* = (P - P_{clim})/\sigma_P$ is a normalized pressure that measures how many standard-deviations (σ_P) the pressure is from the mean (P_{clim}). The winter average (Dec - Mar) is often most relevant to winter storms in Europe.



Forecast: NAO (North Atlantic Oscillation)



https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao_index_ensm.shtml

Earth’s climate system

Before we look at how climate models work, we first take a brief look at what they simulate. **The ultimate goal of climate modelling is to accurately simulate the flow of energy through the climate system via many interacting processes.** In light of that, we start with the big picture: global energy flows.

For the climate system to be in a steady state, the long-term average energy coming in must balance the long-term energy going out. At the surface, the amount of energy absorbed through radiation has to balance that lost through the combined effects of radiation, latent heat, and sensible heat.

This is analogous to a checking account. If, over time, you're putting more money into a checking account than you're taking out, then money will accumulate in the bank. On the other hand, if you take more out than you put in, then you'll eventually deplete your account. If you put in as much as you take out over time, then the balance will stay constant.

Solar energy drives the Earth's climate system. Based on measurements from satellites and other instruments, we can trace the flow of energy through the climate system.

Global energy flows

Energy comes into the climate system as shortwave solar radiation. Some of that energy reflects off clouds and the atmosphere back to space. Some more is absorbed by the atmosphere.

The rest makes its way to the surface, where most is absorbed but some is also reflected. The difference between the incoming and the reflected energy is the total available to the Earth's climate system. About two-thirds of that is absorbed by the surface, while the rest is absorbed by the atmosphere.

Solar energy absorbed at the surface warms the surface, which radiates thermal, or longwave, radiation.

Some of that radiation makes it directly out to space through the so-called atmospheric window and some more is absorbed by clouds. There are also greenhouse gases in the atmosphere, particularly water vapor and carbon dioxide, that very efficiently absorb longwave radiation and radiate it.

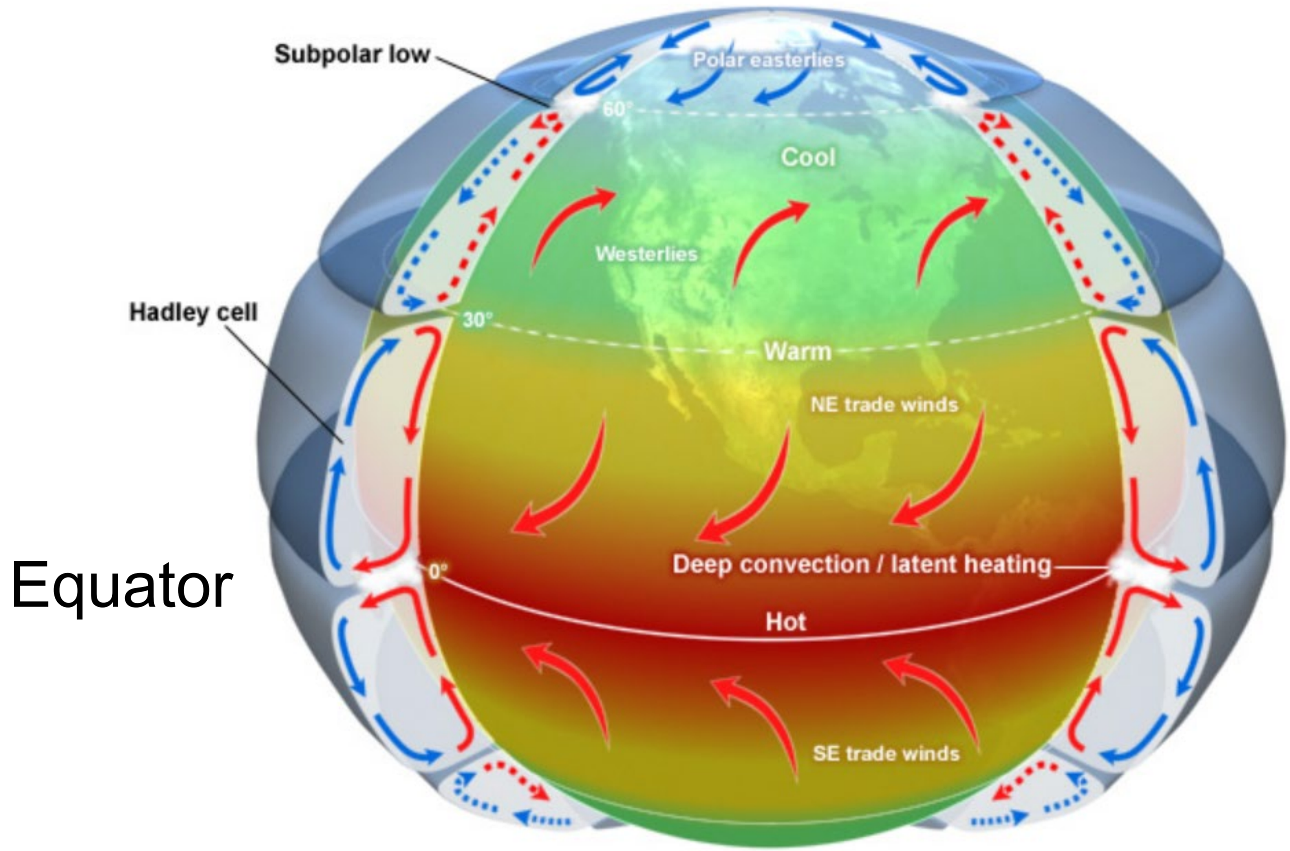
Greenhouse gases radiate in all directions so that some radiated energy is directed upward toward space, with the remainder directed downward toward the surface.

Radiative transfer isn't the only way that energy moves between the surface and the atmosphere. The surface also loses energy through evapotranspiration from plants and wet surfaces (latent heat), and through conduction (sensible heat).

Climate models need to account for all the processes that modulate this flow of energy. For example, clouds reflect, absorb, and radiate energy. Therefore, the cloud processes need to be accurately simulated in climate models. Similarly, vegetation strongly modulates energy flow by affecting albedo and evapotranspiration.

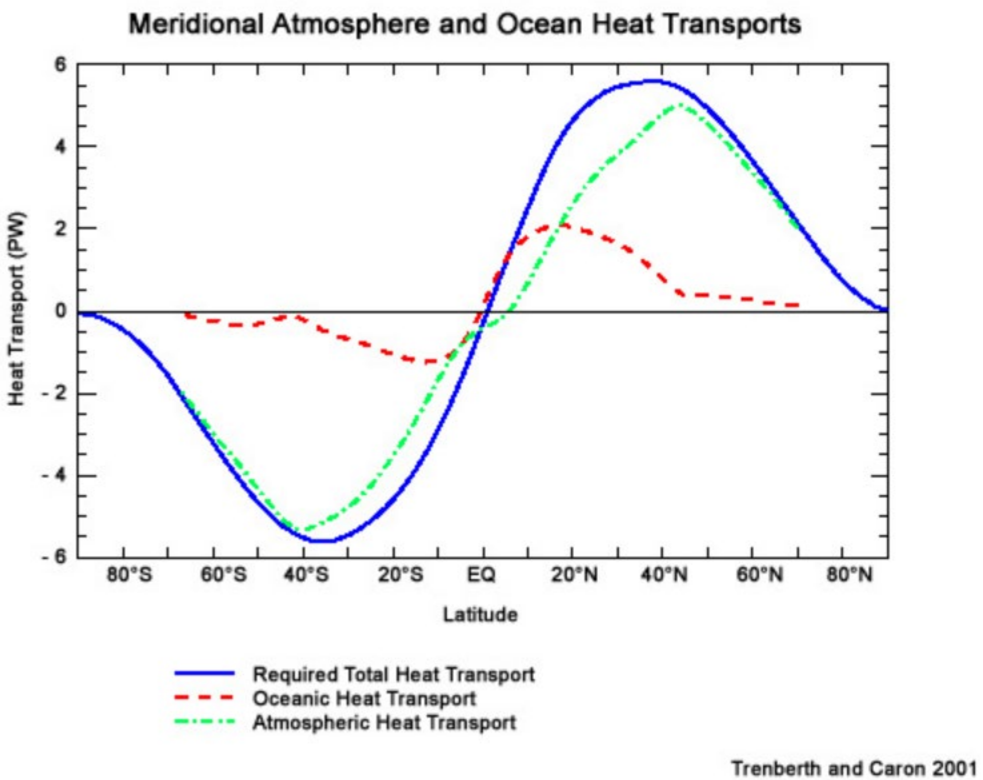
Earth’s atmospheric dynamics

Incoming solar radiation is much stronger near the equator than near the poles. Atmospheric circulations develop in response to this unequal distribution. These circulations attempt to equalize this distribution by moving heat from warmer to colder regions. **Climate models have to account for these large-scale circulations, such as Hadley cells, and the convective heating shown in this figure**.



Earth's Heat Transport

The result of long-term climatological circulation and short-term storm systems is the net transport of heat from low latitudes to high latitudes. This figure, based on observations, shows the total amount of energy (in petawatts or 10^{15} of watts) that's transported toward both poles by the atmosphere, shown in green, and by the ocean, shown in red. While the atmosphere transports most of the heat out of the tropics and toward the poles, the ocean also plays a significant role. **Thus, climate models need to simulate oceanic processes in addition to atmospheric ones.**



The key difference between weather and climate is really a matter of time scale.

- **Weather is what we experience over the course of hours, days, and weeks.**

- **Climate is the average of weather over years, decades, and longer.**

Or, as the old adage goes: climate is what you expect, weather is what you get.

Forecast models are used to predict specific weather events. To do that, they start with the initial conditions and simulate how those conditions will evolve with time. Getting the initial conditions right turns out to be very important in forecasting weather events. **The goal of those who develop and use these weather forecast models is to predict weather with enough accuracy to help those who may be affected by it.**

On the other hand, climate models are used to generate the statistics (such as the mean and variability) of weather phenomena, not predict the time and place at which the phenomena will occur. So, while climate models simulate weather phenomena, they are not dependent on initial atmospheric conditions to the extent that weather forecast models are. **Initial ocean conditions can affect the simulated climate over the course of several years (eg. El Nino/La Nina) to a decade or more.**

Already proposed by Murphy in 1993, good forecasting is not only a matter of "getting it right", but also to make the receivers understand it, and, above all, to be able to draw conclusions from it [Persson et al., 2013].

- Murphy, A. What is a good forecast? An essay on the nature of goodness in weather forecasting. Weather Forecast. 1993, 8, 281–293.

- Persson, A. Abstract: The ultimate criterion of a "good" forecast is always the decisions made from it. In Proceedings of the 9th HEPEX Webinar: Five Points to Remember in Risk Forecasting, 24 October 2013.

Weather models

The most obvious weather changes emerge from the interplay among a fairly limited set of ingredients in the atmosphere: pressure, temperature, moisture, wind and clouds. Weather is also shaped by other factors in the surrounding environment, such as ocean temperature, vegetation and sea ice. But these latter factors don't change much over the course of a few days, so a weather model can focus on tracking the atmosphere while keeping the rest of the environment constant.

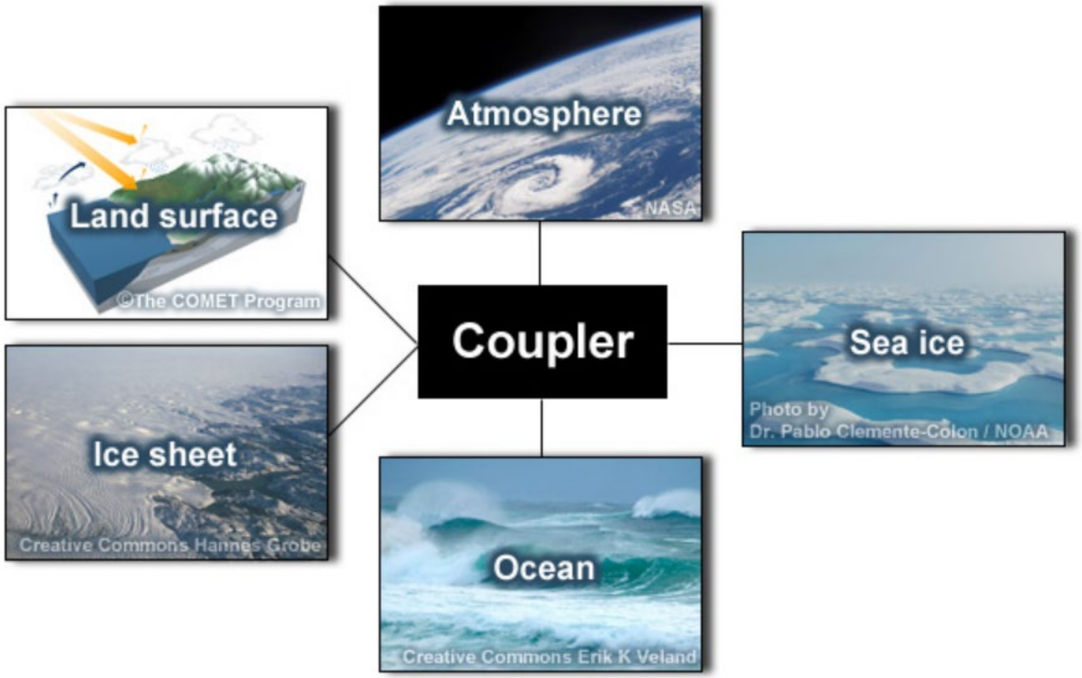
Climate models

Climate models don't have that luxury. As the weeks roll into months, vegetation thrives and decays. Sea ice comes and goes. Greenhouse gases accumulate. The ocean gradually absorbs heat from our warming atmosphere, sometimes releasing it in giant pulses during El Nino events. In the very long term, even the topography of Earth changes. All of these variations "feed" into the atmosphere and influence weather, often so subtly that the effect isn't obvious until it's been playing out for years. For all of these reasons, it's extremely difficult to go beyond a weather model's focus on the atmosphere and to depict Earth's whole environment accurately in a **global climate model**.

Model components

The components that go into a climate model include an atmosphere model, ocean model, land model (including snow and land ice), and sea ice model. A coupler manages the interactions between the different components, accommodating different grids, resolution, and time steps.

In contrast, NWP models mostly include just the atmosphere. The ocean, land, and ice are prescribed quantities with values derived from current satellite observations, climatology, or a mix of both. These values do not change much over the course of a weather forecast period, so they can be fixed.

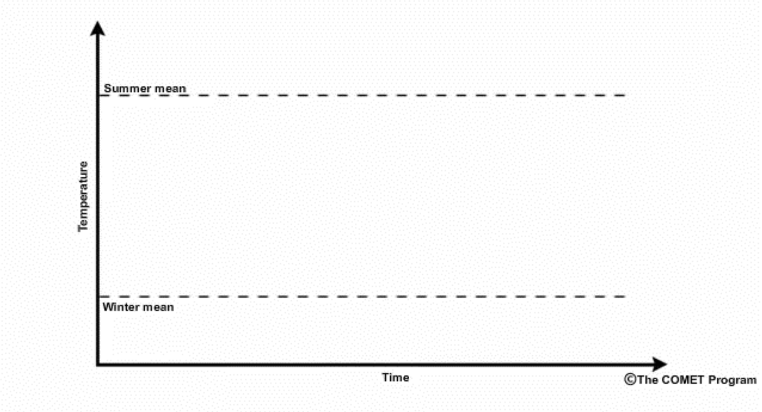


Initial Condition vs Boundary Condition

In modelling terms, the difference between weather and climate is what we call an initial condition problem versus a boundary condition problem.

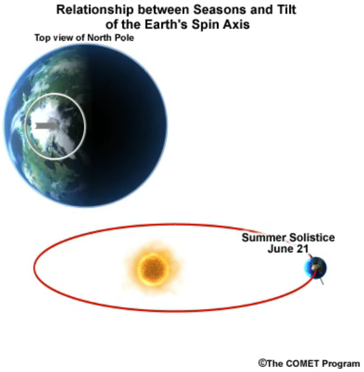
- **Initial conditions are the starting point, the initial state of variables like wind, temperatures, pressure, and moisture.**
- **Boundary conditions, in contrast, are values prescribed by the modeler. Examples include the intensity of solar radiation and composition of the atmosphere. Weather depends on initial conditions, while climate on decadal and longer time scales depends primarily on boundary conditions.**

Imagine we are looking at two forecast model runs starting from the same initial value, representative of the spring or fall season in either the Northern or Southern Hemisphere: Let's force one set of forecasts with summer incoming solar radiation. The result is a prediction of temperature that oscillates up and down and gradually warms.
Now take that model and run it several more times with summer solar forcing, starting each run with slightly different initial conditions, just like weather forecasters do with model ensembles. The forecasts diverge with time, but stay within some gradually warming forecast envelope. The details of the forecast, just like weather, depend critically upon the initial conditions of the model run.
Next, repeat the process, but use winter solar forcing. It quickly becomes clear that the summer state is significantly warmer than the winter state.
The variance within the summer and winter ensembles results from slight changes in the initial conditions.
The difference between the summer and winter forecasts, or seasonality, results from a difference in boundary conditions.



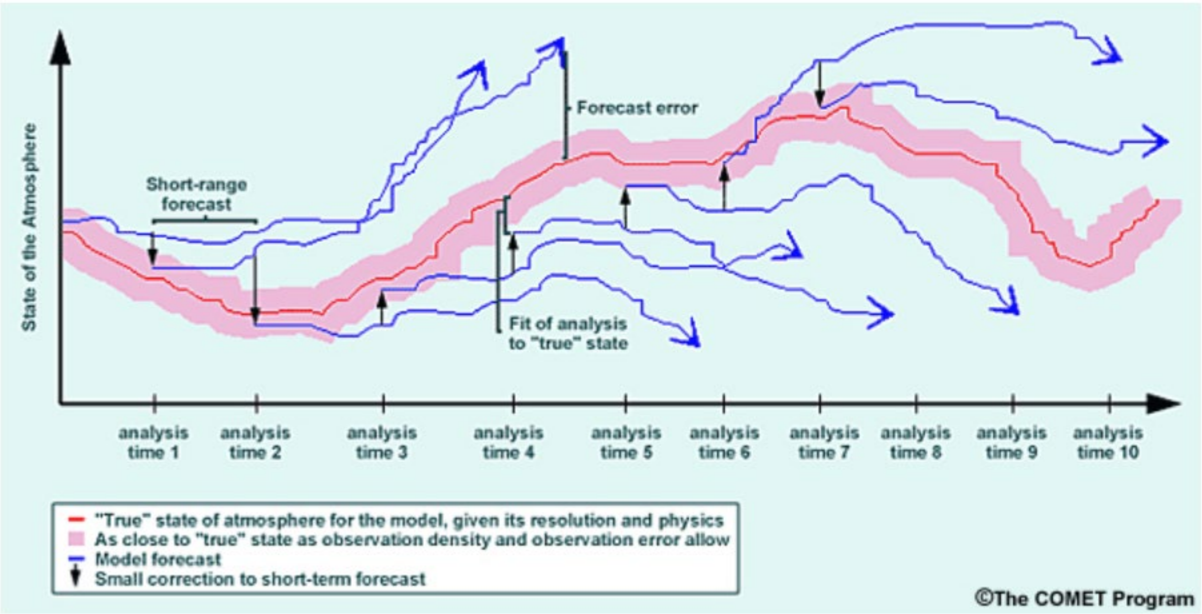
Initial Condition vs Boundary Condition

If this were a location in the U.S., we know that it will be warmer in the summer, on average, than in the winter. The boundary condition that differs from summer to winter is the intensity and daily amount of incoming solar radiation reaching the Earth's surface, which is directly related to the tilt of the Earth with respect to the sun. Seasonality is a boundary condition. The Northern Hemisphere gets more sunlight in summer than in winter.



On the other hand, the drift and spread between different forecasts within the summer and winter ensembles reflects a difference in initial conditions. This graphic illustrates how model forecasts continually drift away from the true state of the atmosphere. As a result, forecasters frequently re-initialize weather models to better match current observations, typically several times per day.

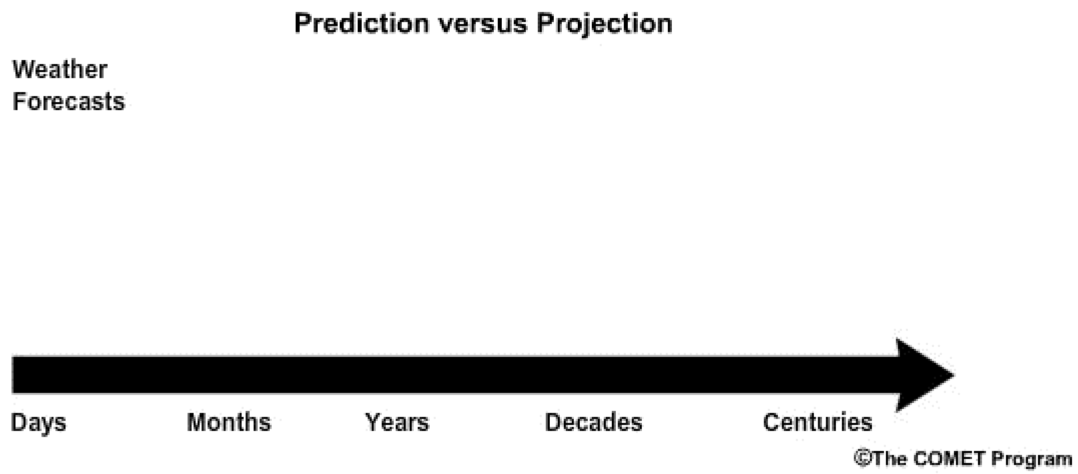
For climate models, it's the boundary conditions that matter. Initialization does not affect the long-term statistics that the models are designed to generate for periods of decades to centuries.



Prediction vs Projection

Another way to look at weather versus climate is looking at it as a forecast challenge.
Weather forecasters have a strong grasp of the fundamental mechanics of their task. If you know the initial conditions, you can predict how the weather is going to evolve for some time going forward. **This is why so much effort is expended obtaining and assimilating observations for numerical weather prediction.** And by extension, a crucial step in the forecast process is to evaluate the model initialization by comparing the model analysis against current observations.
Making an ENSO forecast or a seasonal outlook of precipitation is structurally no different than making a daily weather forecast. Why? Because they both assume you have a good understanding of how the basic system works. And because you know how it works, if you know the initial conditions, you can predict how it's going to vary going forward for some time into the future. Whether that's a 24-hr forecast or a seasonal outlook, it's structurally the same. The objective of such a forecast is the same, too: to produce a prediction for a given location for a given time period.
But there's a limit to predictability. You've undoubtedly heard of Lorenz's Butterfly: the allegory of how the flap of the butterfly's wings over Brazil leads to a thunderstorm a week later. Small differences in the initial conditions, things we can't even measure, will grow and contaminate the solution for a forecast. As a result, forecasters can't predict if there will be snow on New Year's day or rain on the summer solstice next year. That's not because the weather model is no good, or we don't understand the physics well enough. It's due to the chaotic nature of the system.
When it comes to longer-term climate problems, those determined over decades to centuries, it's a different challenge. We're not interested whether in the year 2083 we're going to have El Nino or La Nina, so the initial conditions don't concern us. We're interested in how the statistics of the climate system will change in response to changing boundary conditions.
Using our knowledge of how the climate system works, we want to know how factors that change the flow of energy will change the climate statistics. If the sun gets brighter, incoming energy increases. If the amount of carbon dioxide in the atmosphere increases, it changes how the atmosphere absorbs infrared radiation and, hence, changes the flow of energy through the system. If forest, which is dark, is replaced by crops and pastures that are brighter, the surface albedo changes. These are all examples of changes in boundary conditions. The physics are the same as those in weather prediction, but we're solving a different problem.
To distinguish between the questions addressed by weather and climate models, scientists use different terms. **Projection refers to how the statistics of the climate system will change in response to changing boundary conditions. Prediction refers to the short-term evolution of the climate system from an initial state under constant boundary conditions.**

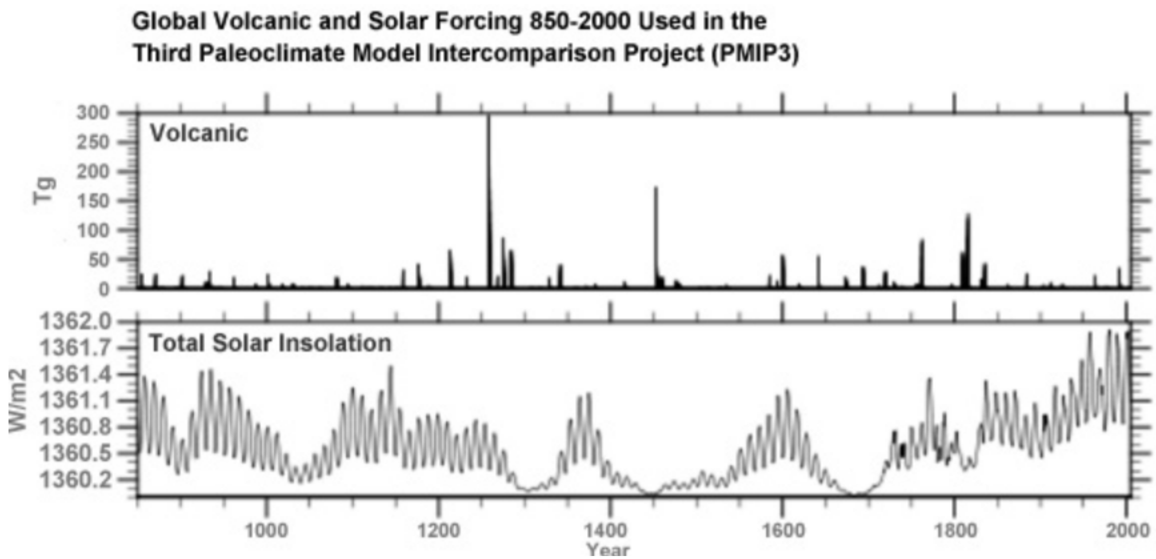
Boundary Conditions



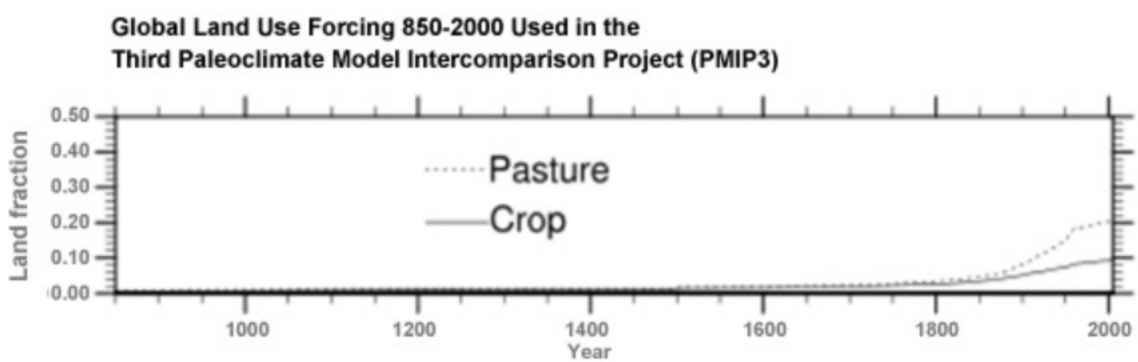
Boundary conditions in climate models all affect the way that energy is absorbed or exchanged in the climate system. Boundary conditions are not predicted by the model and must be specified. Some boundary conditions are natural, and others are influenced by human activities.

What are the boundary conditions in climate models?

Boundary Conditions



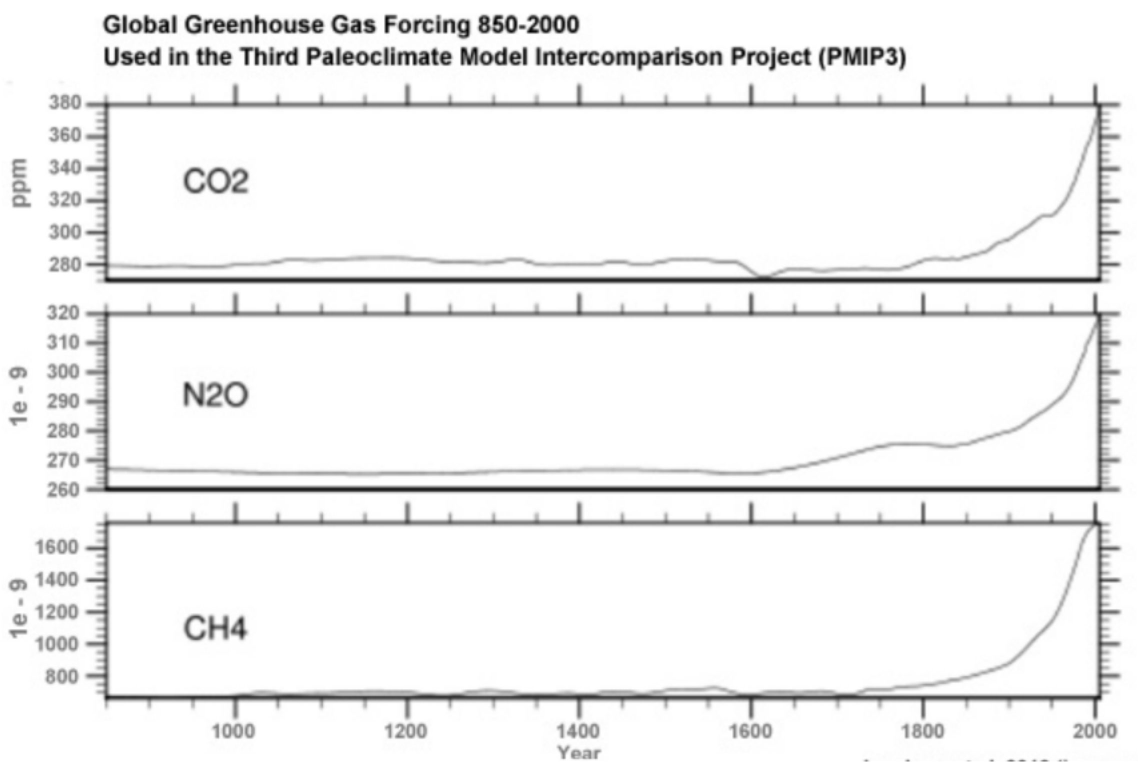
Natural boundary conditions include solar radiation and volcanic aerosols. Total solar insolation, observed at the top of the atmosphere, has varied by about 2 W/m^2 around an average of about 1361 W/m^2 over the past 1150 years. Large volcanic eruptions episodically inject large quantities of aerosols into the atmosphere, which reflects incoming solar radiation.



Human-influenced boundary conditions include changes at the surface and changes in the atmosphere. At the surface, cutting forest for pasture and crops changes surface reflectivity and moisture, heat, and momentum exchanges between land and atmosphere.

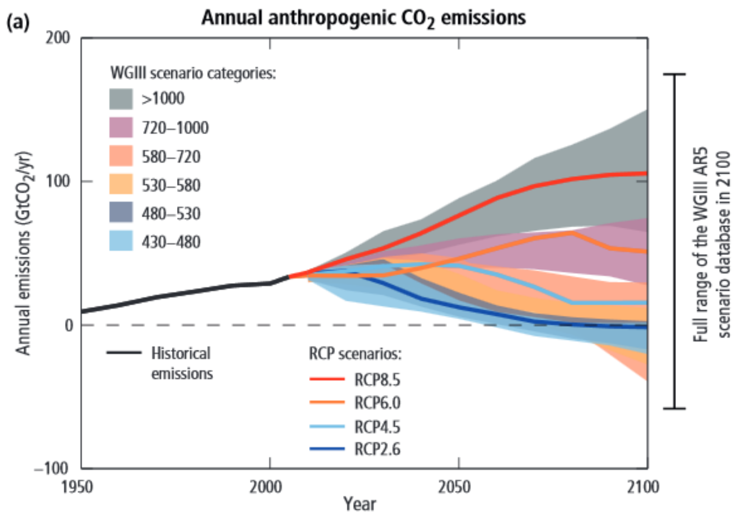
Boundary Conditions

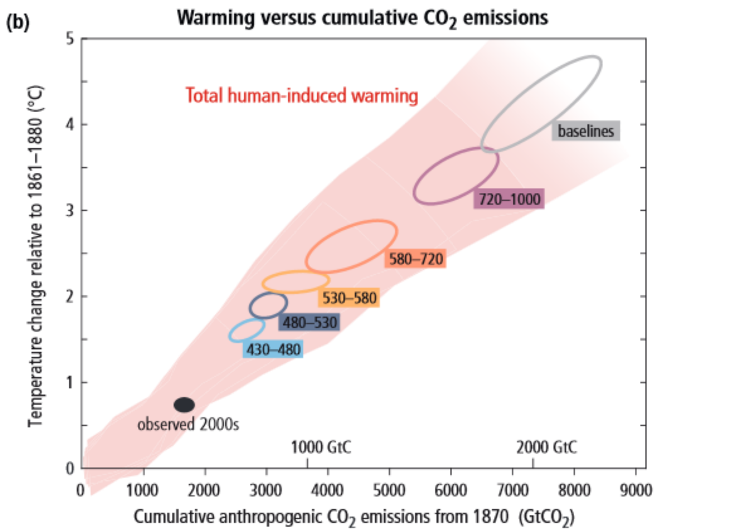
In the atmosphere, the most important changes are those that affect greenhouse gases. Greenhouse gases, principally water vapor and carbon dioxide, keep Earth habitable by absorbing enough long-wave radiation to keep surface temperatures tens of degrees Celsius warmer than they would be otherwise. These graphs show a rapid rise in different greenhouse gases over the past 2 centuries, primarily due to burning of fossil fuels.
Human emissions of atmospheric aerosols also alter the Earth's energy balance. Depending on the composition of the aerosols and where they are, they contribute to both warming and cooling of the climate. Overall, aerosols are thought to contribute a cooling effect equal to about half of the warming caused by greenhouse gases when averaged over the globe.



Future scenarios: model predictions

Advances in climate change modelling now enable best estimates and likely assessed uncertainty ranges to be given for projected warming for different emission scenarios.





Anthropogenic GHG emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. The Representative Concentration Pathways (RCPs), which are used for making projections based on these factors, describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP 6.0 and RCP8.5 (Figure a). RCP2.6 is representative of a scenario that aims to keep global warming likely below 2° C above pre-industrial temperatures.

Multiple lines of evidence indicate a strong, consistent, almost linear relationship between cumulative CO_2 emissions and projected global temperature change to the year 2100 in both the RCPs and the wider set of mitigation scenarios analysed in WGIII (Figure b). Any given level of warming is associated with a range of cumulative CO_2 emissions, and therefore, e.g., higher emissions in earlier decades imply lower emissions later.

Models: think in a probabilistic way!

- It may seem confusing to think of a temperature range and a probability at the same time, but that's the direction modellers are heading, and it's the type of output that's most useful in making decisions.

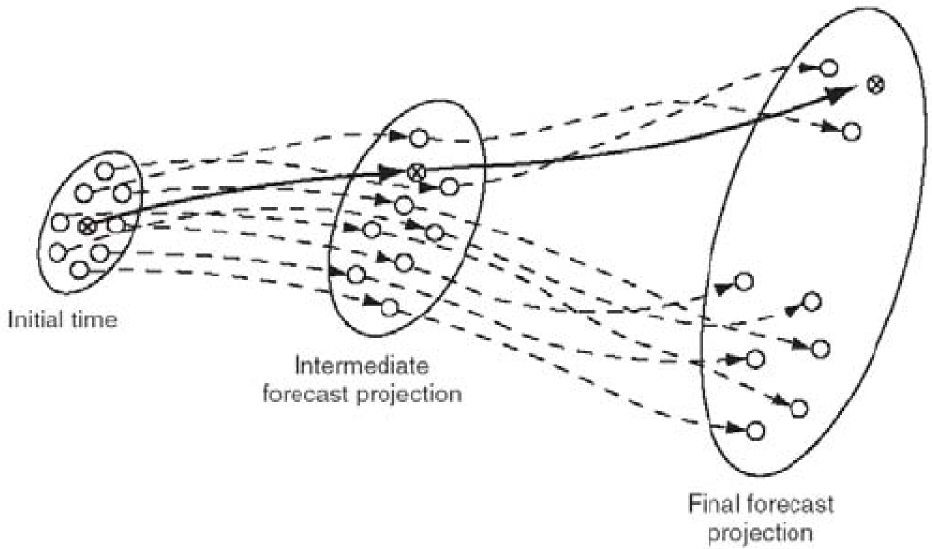
- Once upon a time, weather forecasts would call for "possible showers" or "a chance of snow" without ever specifying a number. That made it hard to tell exactly how likely it was that your picnic would get rained out. It wasn't until computing become widespread in the 1960s that a new set of statistical weather models enabled forecasters to look at a wide range of outcomes and assign likelihoods.

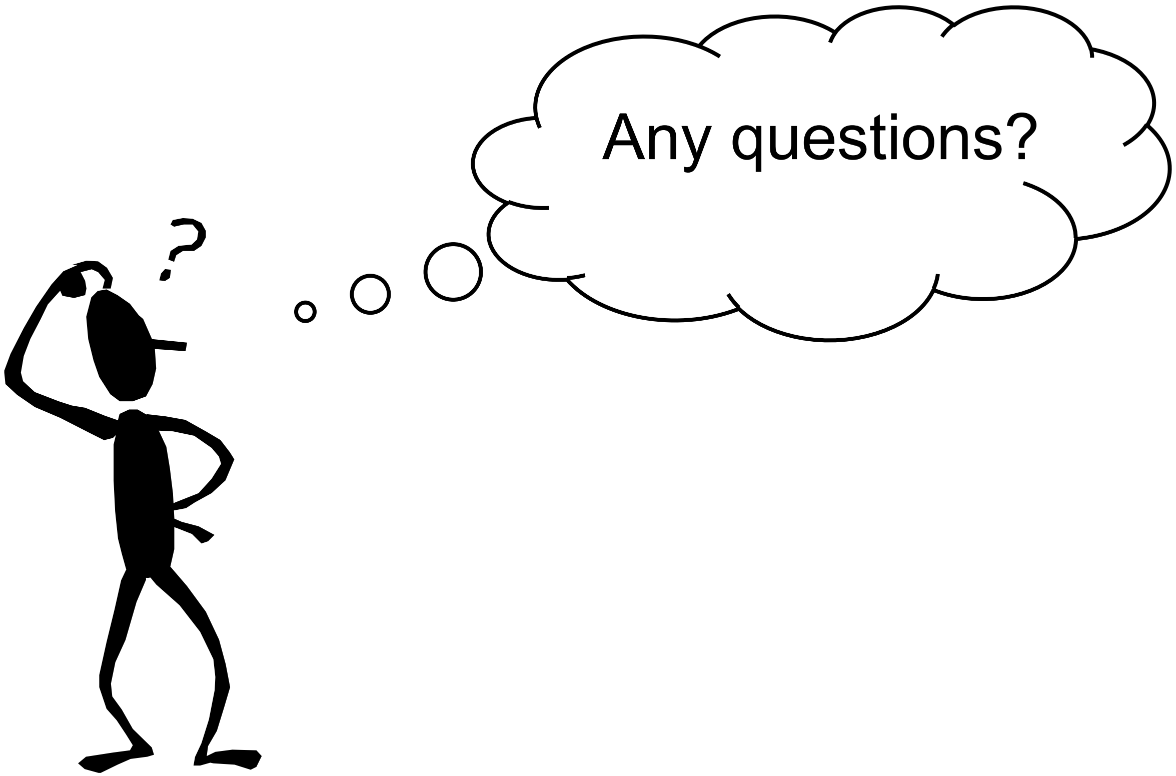
- By the 1970s, "probabilistic" forecasts were the norm and people had grown accustomed to phrasings such as "a 30% chance of rain." In much the same way, climate modelling is now affordable enough that some high-end models can be run a number of times.

Models: think in a probabilistic way!

• Each run might use a different rate of CO_2 increase, for example, to show the many ways the climate might unfold depending on how serious we get about reducing emissions. Or the model might simulate the same CO_2 increase a number of times, but with starting conditions that vary slightly, in order to see how natural variations in climate affect the results.

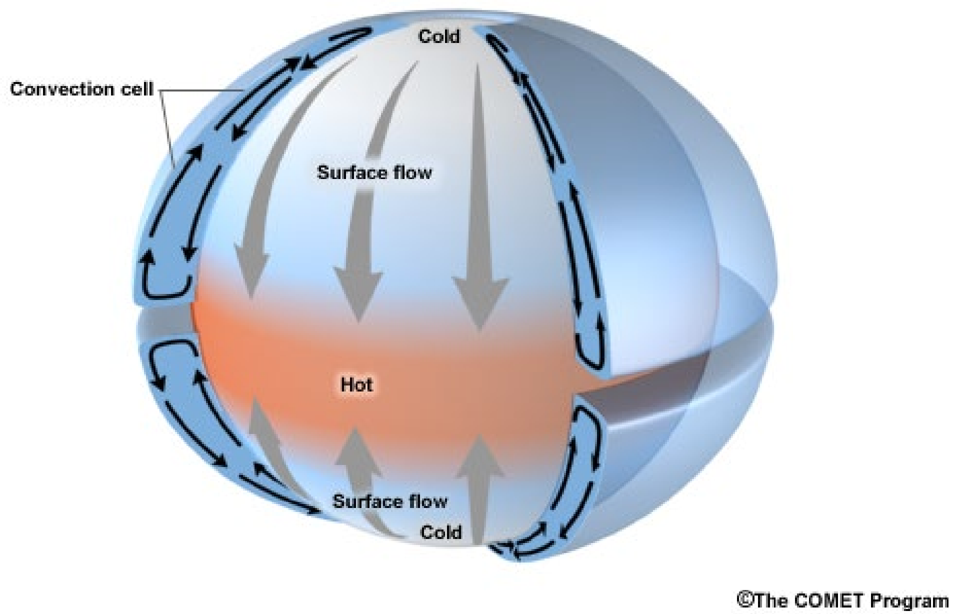
• These large sets of simulations are called **ensembles**, and they've become increasingly important in climate modelling. Some ensembles include more than one thousand simulations, which was unheard of as recently as the late 1990s. The sheer size of these ensembles allows scientists to calculate statistics and probabilities that a single model run (**deterministic forecast**) can't provide.



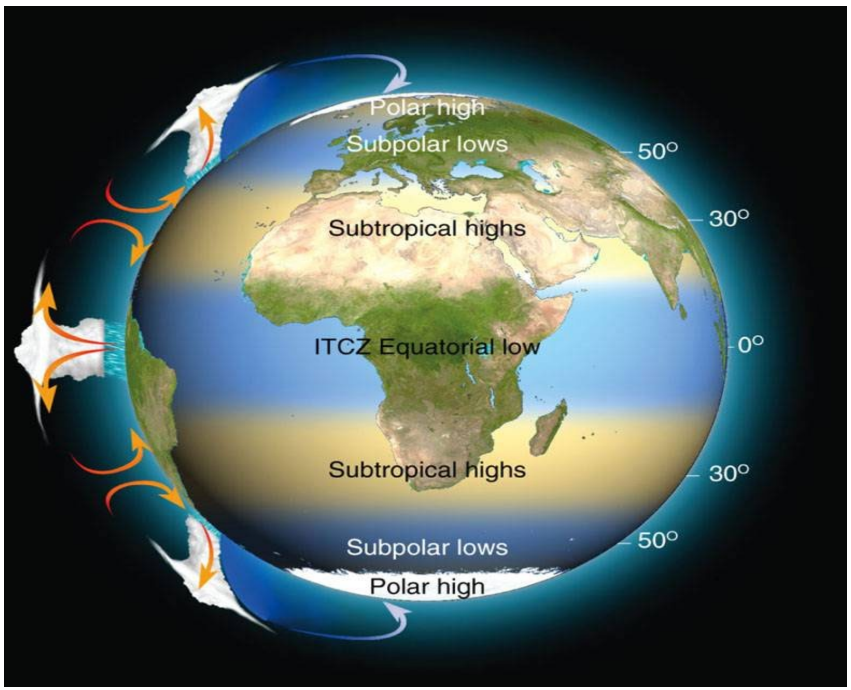

Any questions?

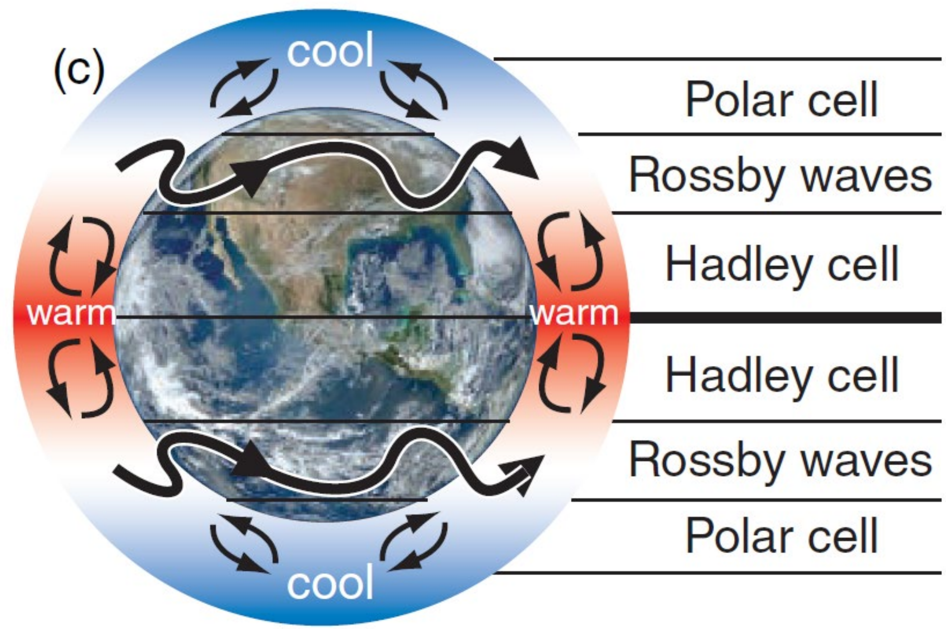
General circulation of the atmosphere

A spatial imbalance between radiative inputs and outputs exists for the earth-ocean-atmosphere system. The earth loses energy at all latitudes due to outgoing infrared (IR) radiation. Near the tropics, more solar radiation enters than IR leaves, hence there is a net input of radiative energy. Near Earth's poles, incoming solar radiation is too weak to totally offset the IR cooling, allowing a net loss of energy.
The result is **differential heating**, creating warm equatorial air and cold polar air. This imbalance drives the global-scale **general circulation** of winds.

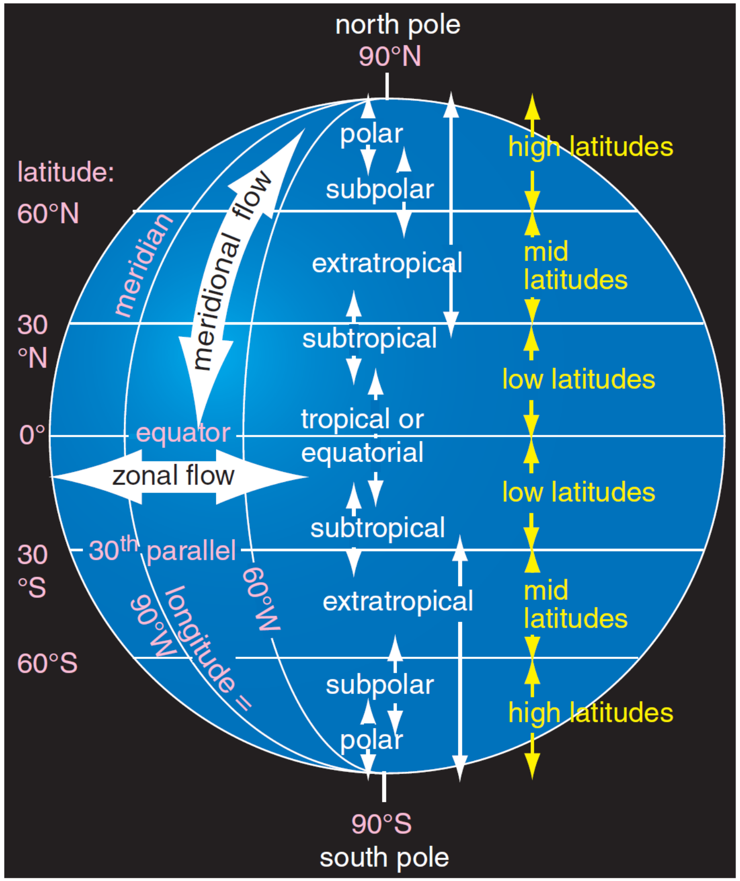


Because buoyancy causes warmer air to rise and colder air to sink, you might guess that equator to pole overturning would exist. Instead, the real general circulation has three bands of circulations in the Northern Hemisphere.



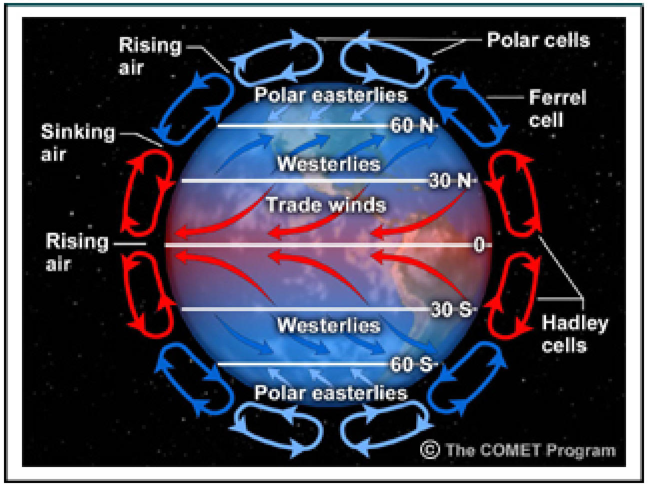


Lines of constant latitude are called **parallels**, and winds parallel to the parallels are identified as **zonal flows** (Figure). Lines of constant longitude are called **meridians**, and winds parallel to the meridians are known as **meridional flows**. Between latitudes of 30° and 60° are the **midlatitudes**. **High latitudes** are 60° to 90°, and **low latitudes** are 0° to 30°. Each 1° of latitude = 111 km. **Tropics**, **subtropics**, **subpolar**, and **polar** regions are as shown in Figure. Regions not in the tropics are called **extratropical**; namely, poleward of about 30° N and about 30° S. For example, **tropical cyclones** such as **hurricanes** are in the tropics. Low-pressure centers (**lows**, as indicated by on weather maps) outside of the tropics are called **extratropical cyclones**.



At low latitudes are broad bands of persistent easterly winds ($U \approx -7$ m s^{-1}) called **trade winds**, named because the **easterlies** allowed sailing ships to conduct transoceanic trade in the old days.

These trade winds also blow toward the equator from both hemispheres, and the equatorial belt of convergence is called the **intertropical convergence zone** (**ITCZ**).



On average, the air at the ITCZ is hot and humid, with low pressure, strong upward air motion, heavy convective (thunderstorm) precipitation, and light to calm winds except in thunderstorms.

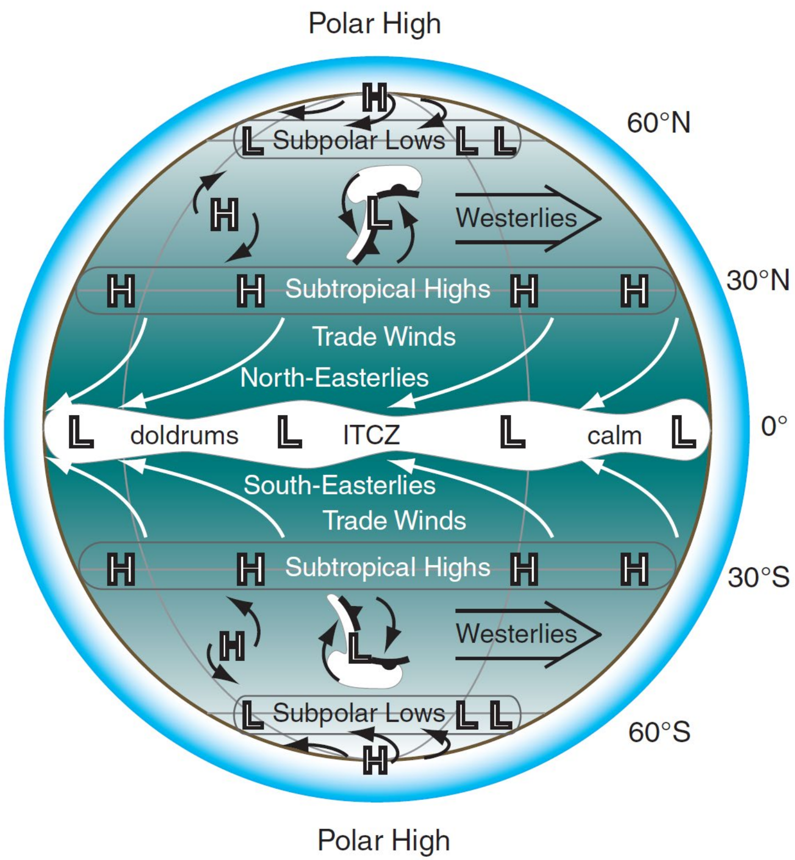
This **equatorial trough** (low-pressure belt) was called the **doldrums** by sailors whose sailing ships were becalmed there for many days.

General circulation of the atmosphere

At 30° latitude are belts of high surface pressure called **subtropical highs.** In mid-latitudes are transient centers of low pressure (**mid-latitude cyclones, L**) and high pressure (**anticyclones, H**).

Winds around lows **converge** (come together) and circulate **cyclonically** — counterclockwise in the N. Hemisphere, and clockwise in the S. Hemisphere. Winds around highs **diverge** (spread out) and rotate **anticyclonically** — clockwise in the N. Hemisphere, and counterclockwise in the S. Hemisphere. The cyclones are regions of bad weather (clouds, rain, high humidity, strong winds) and fronts. The anticyclones are regions of good weather (clear skies or fair-weather clouds, no precipitation, dry air, and light winds).

a) Near Surface

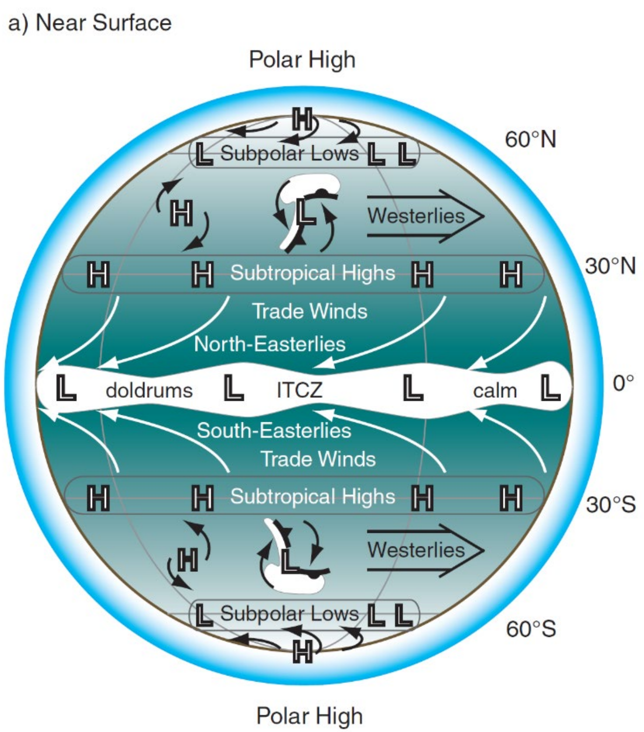


General circulation of the atmosphere

The high- and low-pressure centers move on average from west to east, driven by large-scale winds from the west. Although these **westerlies** dominate the general circulation at mid-latitudes.

Near 60° latitude are belts of low surface pressure called **subpolar lows.**

Near each pole is a climatological region of high pressure called a **polar high.**

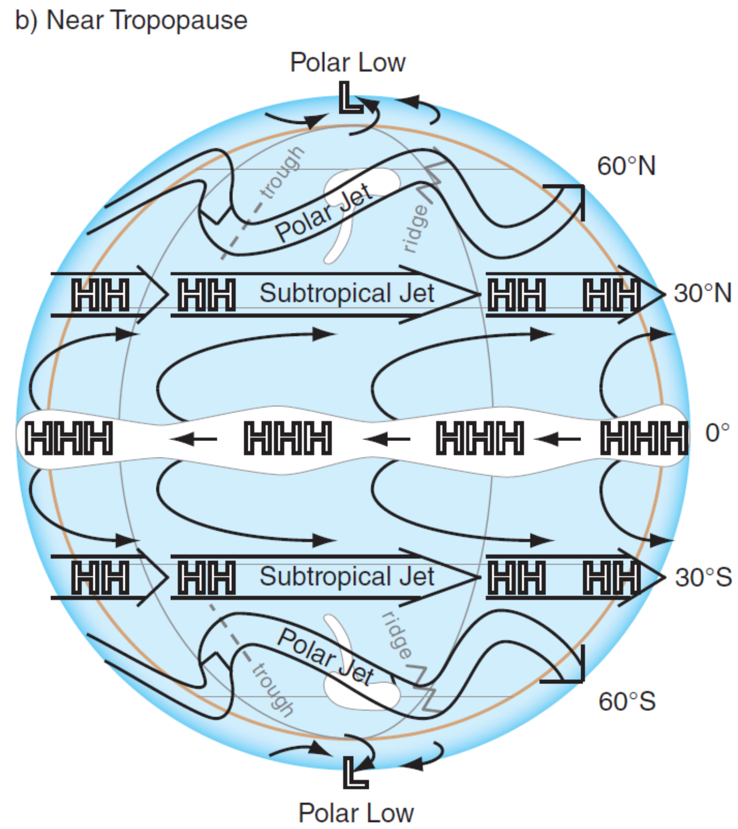


General circulation of the atmosphere

In the tropics is a belt of very strong equatorial high pressure along the tops of the ITCZ thunderstorms.

In mid-latitudes at the tropopause is another belt of strong westerly winds called the **polar jet**. The centerline of the polar jet meanders north and south, resulting in a wave-like shape called a **Rossby wave** (or **planetary wave**).

Near 30° latitude in each hemisphere is a persistent belt of strong westerly winds at the tropopause called the **subtropical jet**. This jet meanders north and south a bit. Pressure here is very high, but not as high as over the equator.

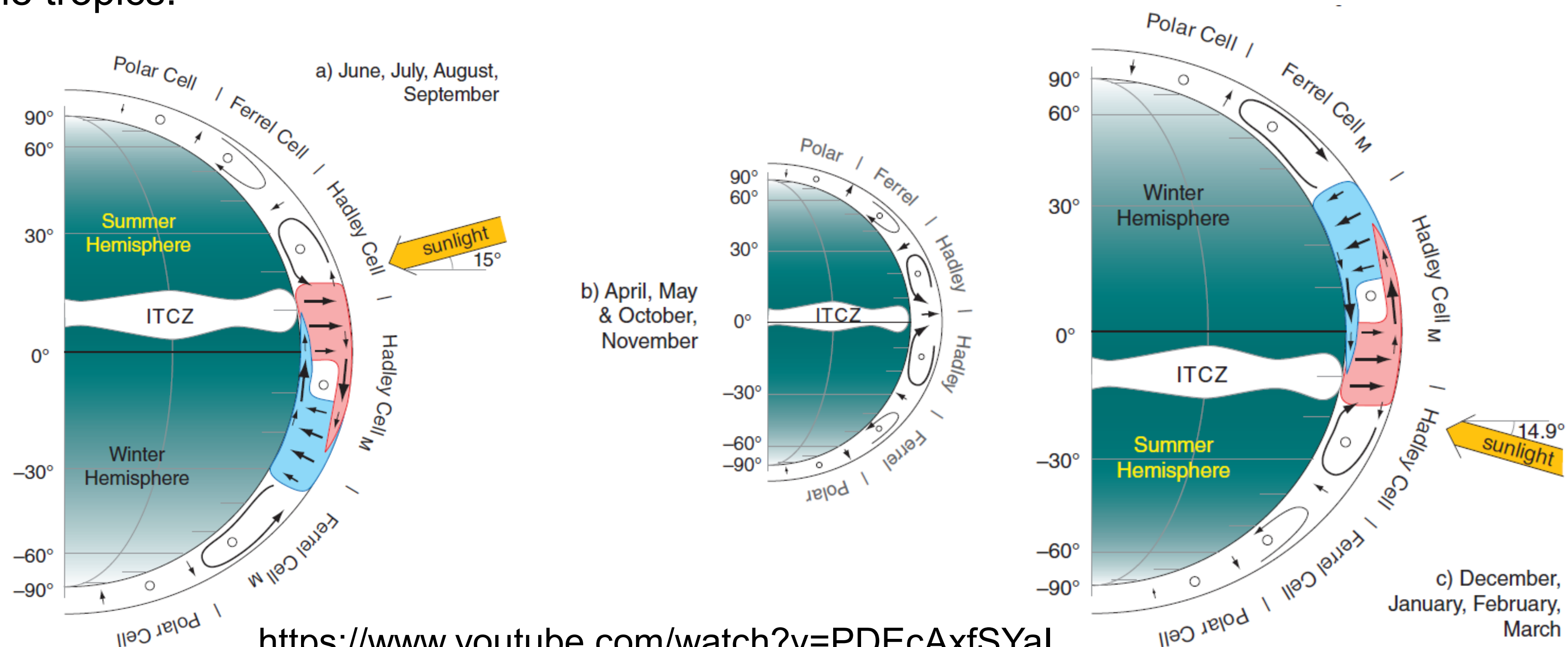


The equatorward portions of the wave are known as low-pressure **troughs**, and poleward portions are known as high-pressure **ridges**.

Near 60° at the tropopause is a belt of low to medium pressure. At each pole is a low-pressure center near the tropopause, with winds at high latitudes generally blowing from the west causing a cyclonic circulation around the **polar low.**

General circulation of the atmosphere

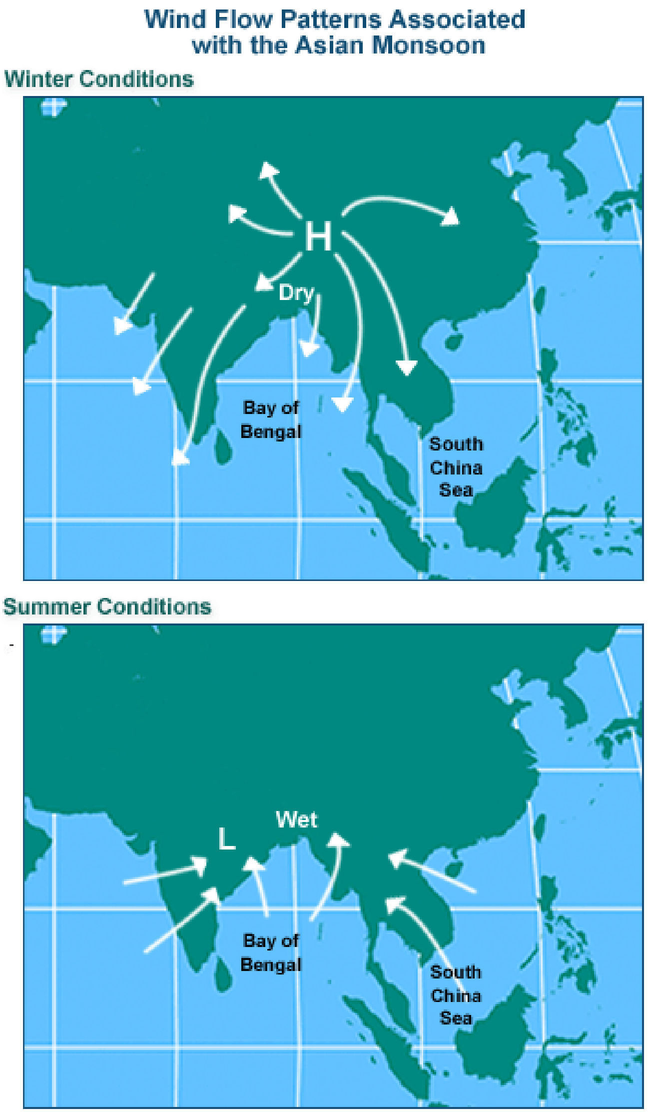
Vertical circulations of warm rising air in the tropics and descending air in the subtropics are called **Hadley cells** or **Hadley circulations.**
At the bottom of the Hadley cell are the trade winds. At the top, near the tropopause, are divergent winds. The updraft portion of the Hadley circulation often contains thunderstorms and heavy precipitation at the ITCZ. This vigorous convection in the troposphere causes a high tropopause (15 – 18 km altitude) and a belt of heavy rain in the tropics.



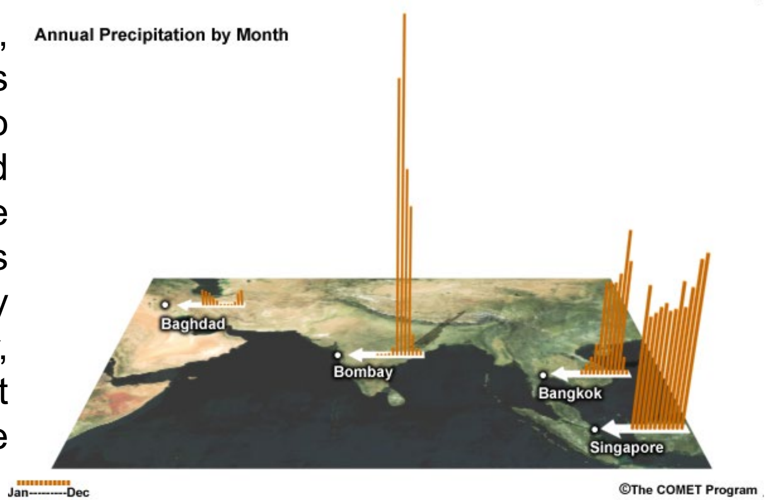
https://www.youtube.com/watch?v=PDEcAxfSYaI

Synoptic-scale climate drivers: Monsoons

- A monsoon circulation is a seasonal change in wind direction caused by a change in the dominant atmospheric pressure pattern. The largest monsoon system is in Southeast Asia, which is dominated by synoptic-scale uplift and upslope winds in summer and downslope winds in winter.
- Monsoonal tropical cities experience copious amounts of summer rain, followed by dry winters, and parched conditions before the monsoon season hits again. The rhythms of the monsoon regime dictate the areas' weather and therefore their climate.



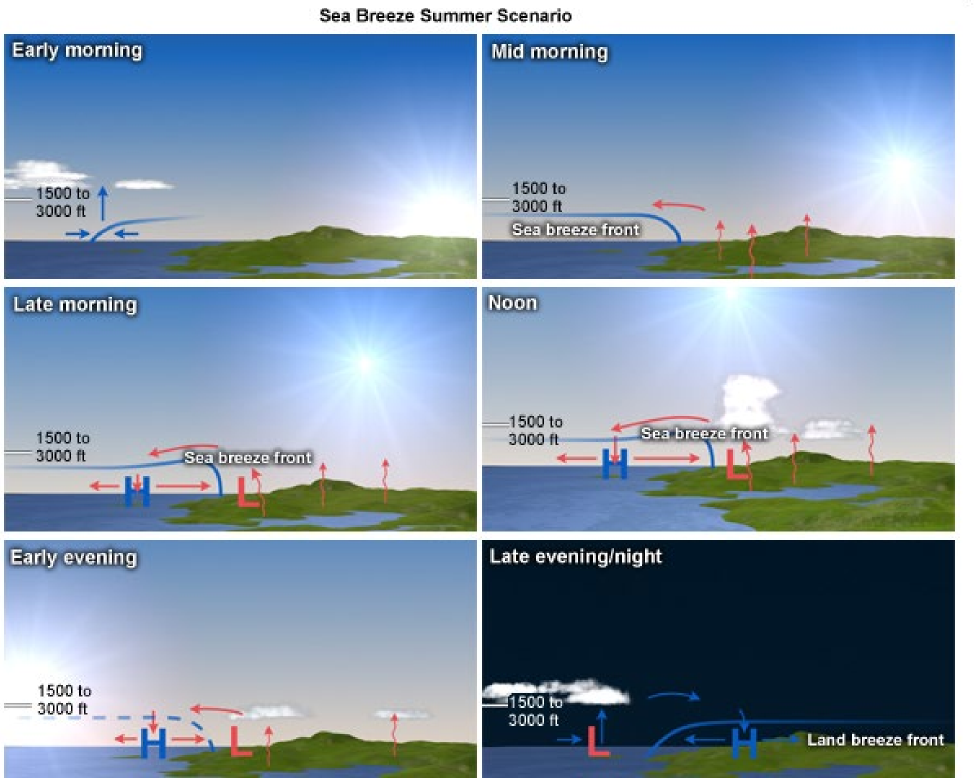
As the graphic shows, Bombay, India experiences monsoonal flow in contrast to Baghdad, Bangkok, and Singapore, which do not. The summer monsoon rains occur in Bombay primarily from June to September, while dry conditions persist throughout the rest of the year.



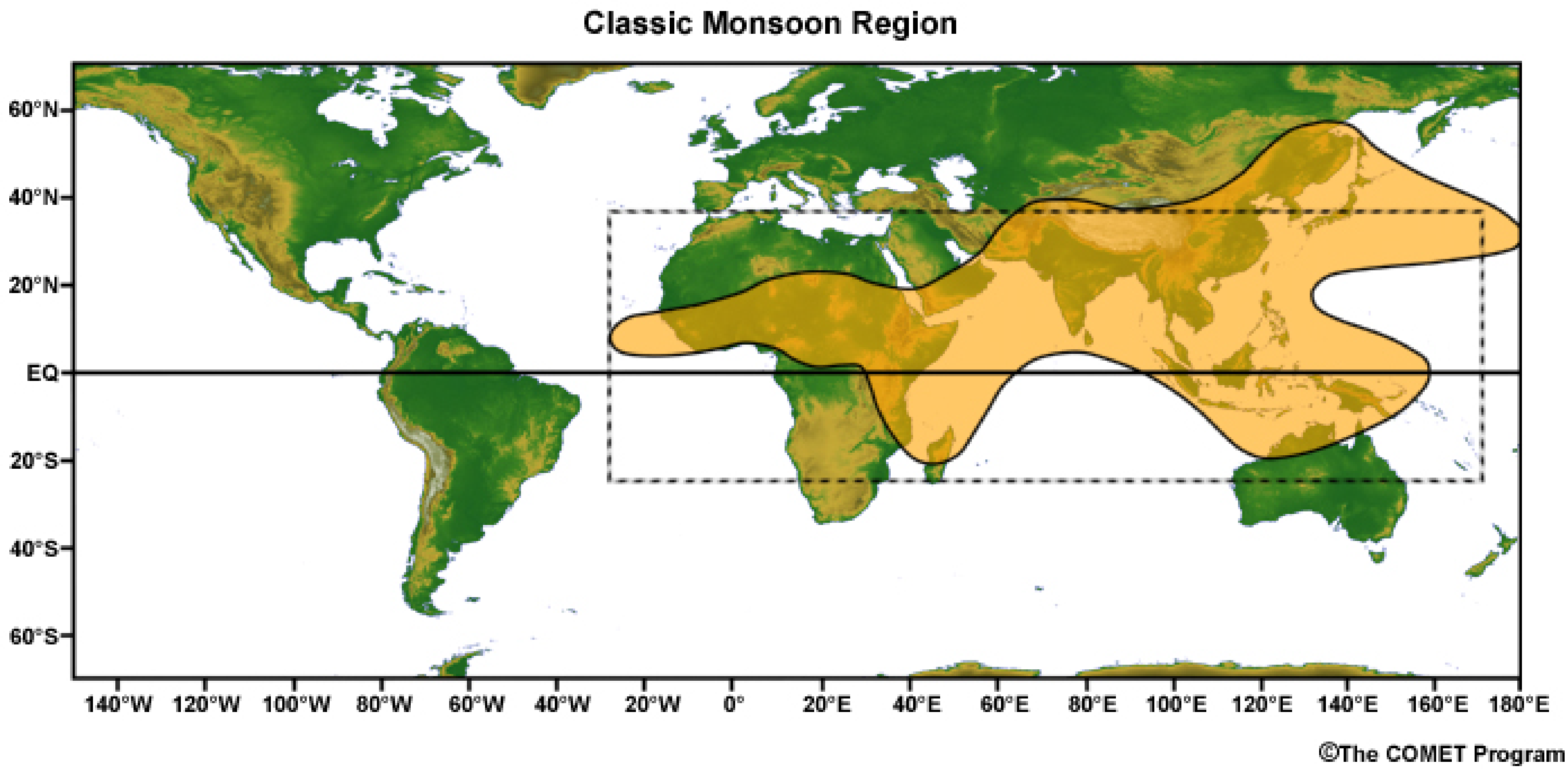
Sea/land breezes

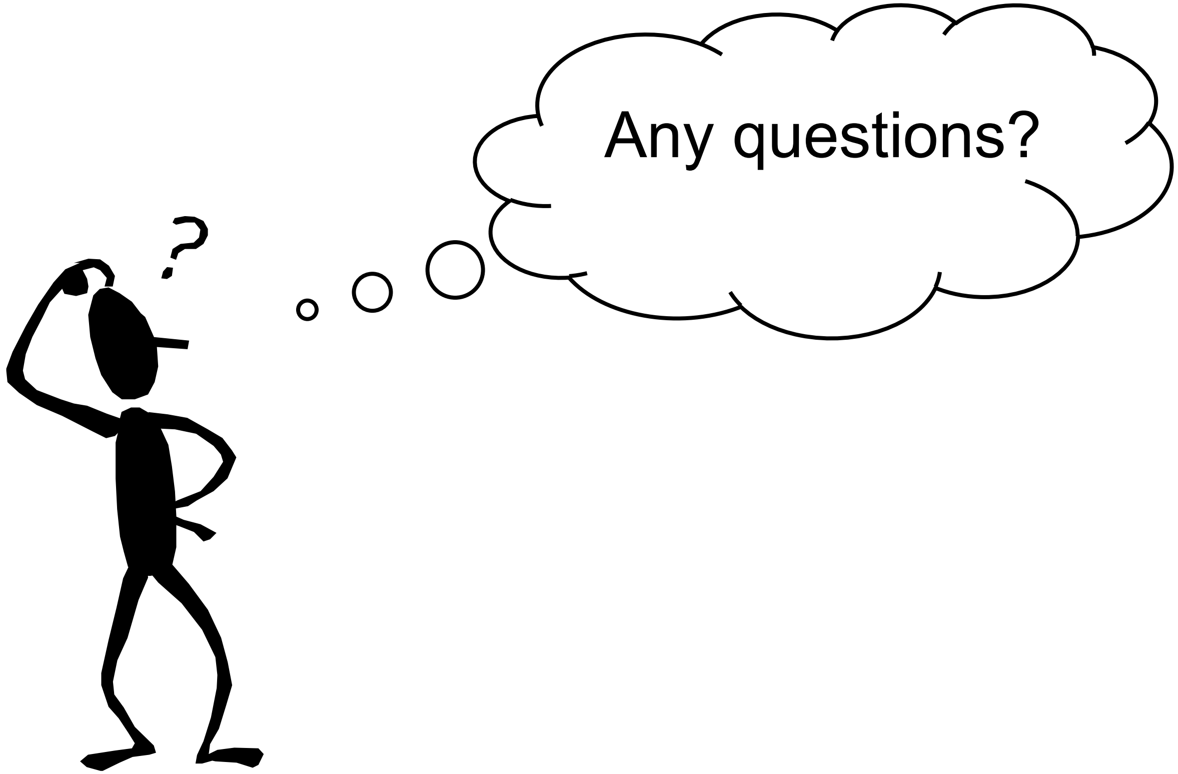
• Areas near coasts and lakes often experience sea or lake breezes as a result of heating differences between water and land surfaces. Since land heats more quickly than water during the day, the air over land warms and therefore rises, causing low-pressure, convergence, and onshore flow. The resulting circulation has return flow aloft over the water with subsiding air just offshore, which causes high pressure and divergence at the surface.

• The rising air over land helps to promote the generation of afternoon clouds and thunderstorms, while the sinking air just off the coast tends to dampen their development. Sea breeze circulations typically weaken and then reverse themselves at night when the land cools faster than the water.



Synoptic-scale climate drivers: Monsoons




Any questions?