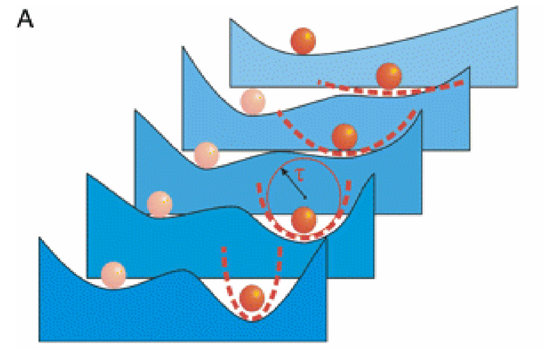
Earth Gauge

A National Environmental Education Foundation Program

Tipping Elements and Feedbacks

Holocene Earth: Earth's environment is characterized by distinct features. Large ice masses cover the poles. Predictable seasonal wind regimes, like the Indian Monsoon, bring wet and dry seasons. Prominent ocean currents such as the Gulf Stream control sea surface temperatures and drive weather systems. Desert covers North Africa while rainforest covers equatorial South America. These basic climatic features that characterize Earth today have been prevalent for the past 10,000 years, a time frame known as the *Holocene epoch*. Analysis of climatic changes on longer glacial-interglacial (tens to hundreds of thousands of years) time scales suggests that these features are not stable and even small changes in background conditions can trigger processes causing these features to shift to qualitatively new states. What does this mean?

Metastable States: A canoe has two *metastable* states: the right-side-up state, which is best for holding passengers, and the upside-down state. A canoe will remain in one of these states until a disturbance pushes it to the other. Passengers moving about a canoe cause it to rock, but as long as the rocking does not cross a certain threshold or *tipping point*, the canoe will remain in the right-side-up state. Once it does cross this *tipping point*, the canoe turns over and catastrophically switches to the upside-down state.



Above: Wells represent potential metastable states. The shallowing of the right well (dark to light blue) represents environmental changes favoring the left well as the attractive state. Image Lenton, et al., 2008. Please see copyright notice on the third page.

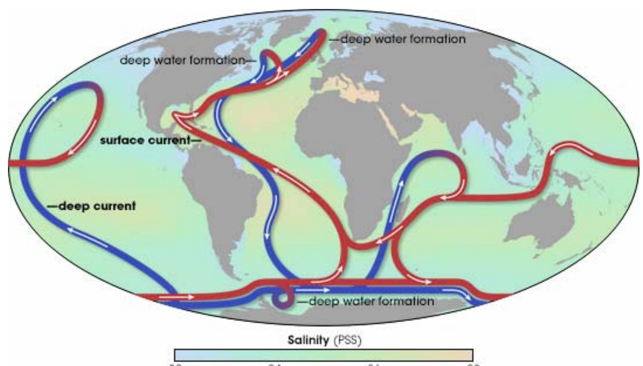
The canoe example has several parallels to the Earth system: a) many features of the Earth system have *metastable* states like the two states of the canoe, b) these states can be separated by a specific threshold – when this threshold is passed, the resulting changes can be difficult or impossible to reverse and c) small perturbations can have disproportionate impacts.

Positive feedbacks**:** Positive feedback loops are systems where initial triggering events, potentially even small ones, trigger other events that exacerbate the impact of the initial event – provide the mechanism through which small perturbations can have disproportionate impacts. One example of a positive feedback is melting atop major ice sheets, such as those covering most of Greenland. Melting lowers the ice sheet's elevation, exposing the ice to warmer air and resulting in even more mass loss and lower ice sheet elevations.

POTENTIAL *TIPPING ELEMENTS* OF HOLOCENE EARTH

The Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) can be considered the "engine" of the Earth's ocean *thermohaline circulation system* (see image right, courtesy of NASA), or the system of currents driven by differences in temperature and salinity. Currents of near-surface waters originating from the Southern Ocean around Antarctica make their way northward through the Atlantic basin. The Atlantic Basin exports water vapor to the Pacific and Southern Oceans, leaving salty (and therefore dense) water on its surface. The cooling of these already dense waters around Greenland makes them even more dense, causing them to sink or "overturn" to depths of 8000 feet where they become southern-moving cold currents.



As the Earth came out of the last ice age, melting glaciers in the AMOC region sent pulses of freshwater into the North Atlantic, periodically causing sharp drops in salinity. Once the salinity and density dropped below a threshold needed to induce sinking, the AMOC turned from an "on" state to an "off" state. This shutdown caused major changes in ocean circulation and the weather patterns that these ocean currents drive. Freshwater inputs can come from glaciers, rainfall over the ocean and river runoff. A total increase in freshwater input of between 0.1 and 0.5 sverdrups (26 and 132 million gallons per second, or between 500 and 2200 times the discharge of the Mississippi River) from all or any of these sources is estimated to be the freshwater threshold needed to stop the AMOC.

The Greenland Ice Sheet

During the last interglacial period (the Eemian), temperatures in Greenland were an estimated 6.3 degrees Fahrenheit warmer and sea levels were between 13 and 20 feet higher than today. Between six and 10 feet of this increased sea level rise is believed to have come from the Greenland Ice Sheet, which partially melted before stabilizing. While the positive feedback of warming temperatures leading to melting ice, lowered ice sheet height and even more ice loss is believed to be strong, warmer temperatures also mean more atmospheric moisture is present, which can lead to more snowfall and more ice sheet growth. Over the past few decades of warming, the balance between these two forces has favored of ice mass loss. Since 2000, Greenland has been losing about 200 gigatons (200 billion tons) of ice each year, and loss rates accelerated after 2006. Greenland's ice sheet holds about 2.5 million gigatons of ice – enough to raise sea levels by seven meters.

The West Antarctic Ice Sheet

About 530,000 cubic miles of ice compose the West Antarctic Ice Sheet. Unlike the East Antarctic and Greenland Ice Sheets, the West Antarctic Ice Sheet mostly sits below sea level, making it especially vulnerable to warmer ocean waters and rising sea levels. A strong positive feedback appears to exist involving ice sheet retreat and sea level rise, allowing more ocean water to penetrate into the basin and "undercut" the ice sheet. This "undercutting" allows ocean water to serve as a lubricant between the ice and the rock, leading to even more discharge of ice into the ocean and even more sea level rise. The ice sheet has significantly retreated at least once during past interglacial periods and may have disappeared entirely. It is believed that between four and 13 feet of the Eemian sea level rise came from Antarctica, with most of this contribution coming from West Antarctica.

The Amazon Basin

Because of its size – 1.7 billion acres, far larger than the lower 48 United States – the Amazon Basin is a major component of Earth's hydrologic cycle. Between 15 and 20 percent of Earth's freshwater flow comes out of the basin, and changes here are felt in weather patterns around the world. The region is also a major reservoir of carbon, so changes in the Amazon's ecological structure have implications for the global carbon cycle. During past glacial periods, the tropics were drier, meaning that there was less annual rainfall and longer dry seasons in the Amazon Basin, which favored the survival of grasses over tree species. During the last glacial maximum (21,000 years ago), about 20 percent less of the basin was covered with forest, and much of the forest that did remain became seasonal forest as opposed to the evergreen rainforest that has been dominant during the Holocene. This decrease in forest cover occurs through a positive feedback cycle of drying at the fringes of the basin, which leads to grass cover expansion. More grass cover leads to less evapotranspiration, less rainfall and more fires – all factors that favor further expansion of grass cover and the retreat of forest cover.

The El Niño–Southern Oscillation

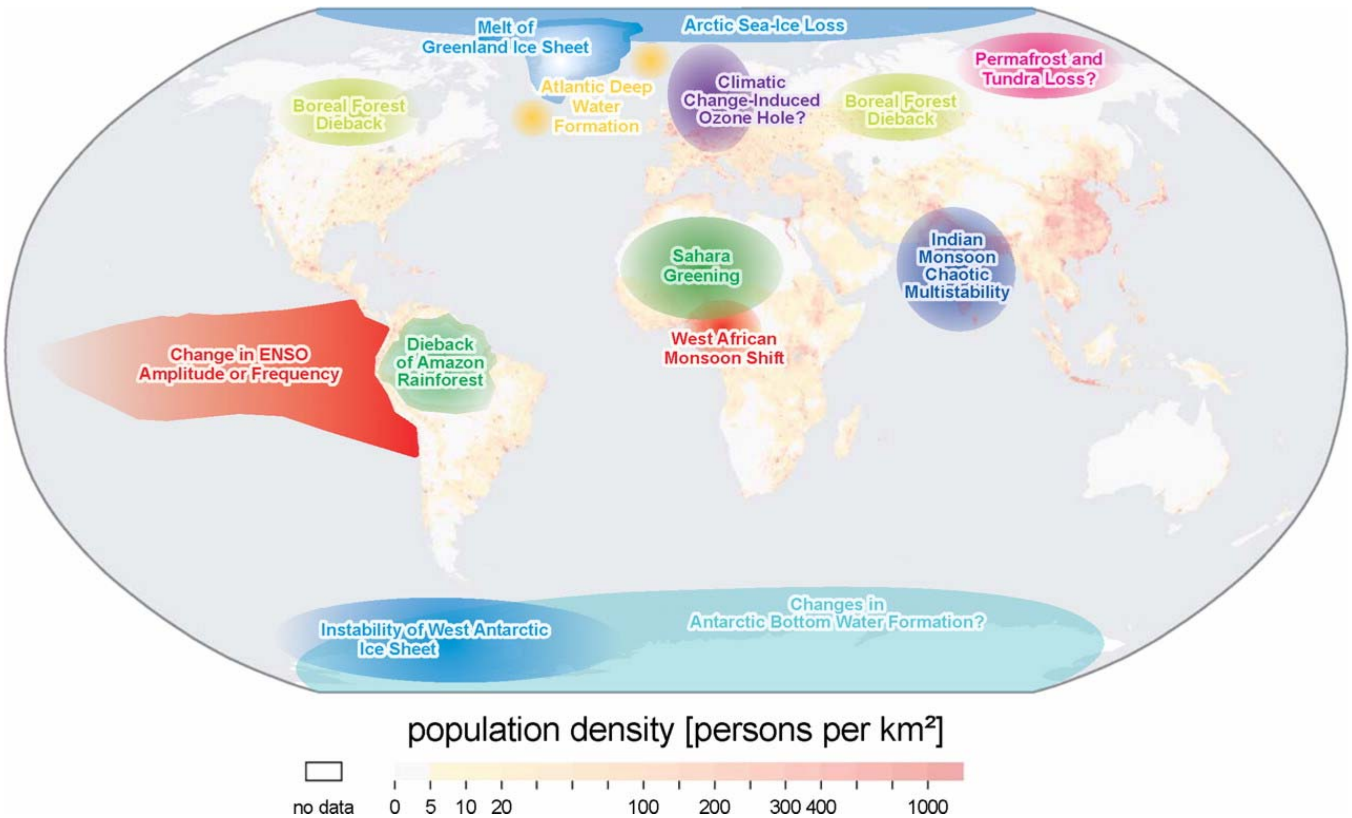
The El Niño–Southern Oscillation (ENSO) is considered the strongest and most ubiquitous source of inter-annual variability in Earth's climate. ENSO is a system of positive feedbacks - strong easterly winds in the equatorial Pacific pull nutrient rich cold water from the ocean depths, driving a temperature contrast between the eastern and western tropical Pacific, which further strengthens the easterly winds. This system is reinforced by circulation in the upper atmosphere that moves in the opposite direction. Strengthening or a weakening of any of these components triggers feedbacks that lead to strengthening or relaxing of the entire system, leading to at least two metastable states (the El Niño or La Niña states are the two strongest states). ENSO's behavior during Earth's past is poorly understood. Some believe that during the much warmer Pliocene (five to 1.8 million years ago), ENSO was in a persistent El Niño state (relaxed tropical Pacific circulation system), and it was the development of La Niña states (strong tropical Pacific circulation system) that caused storm tracks to shift north and precipitation at high latitudes to increase, making high latitude glaciers and ice ages possible. Because the effects of ENSO range widely across the globe, shifts in ENSO conditions – regardless of direction – can lead to tipping points in other systems.

Other Potential Tipping Elements

Other elements of the Holocene climate believed to be sensitive to changes in background conditions include the Arctic sea ice, the Indian or South Asian monsoon, the Sahara/Sahel and West African Monsoon, and the boreal forest cover. The South Asian monsoon circulation, for example, is driven by strong solar heating in South Asia's interior. This heating generates rising columns of air and the moist marine air that blows in to fill the gaps this rising air leaves at the surface brings rainfall. An initial drying on land can cause a transition from forest to grassland, which can cause a local cooling in a manner similar to that observed in the Amazon. This cooling can reduce the strength of the rising air in the continent's interior, leading to less powerful currents of marine air, less rainfall, and further drying. Hundreds of millions of people depend directly on the monsoon rains for their livelihoods.

Interaction among Tipping Elements

Changes in the state of one tipping element may influence the state of another tipping element. Changes in ENSO, for example, affect water vapor transport to the Atlantic Ocean. This water vapor transport can affect rainfall levels and the amount of freshwater entering the Atlantic, influencing the behavior of the AMOC. Changes in sea surface temperatures due to a change in the AMOC can cause changes in precipitation in the Amazon Basin. This can lead to changes in the Amazon ecosystem structure, with ramifications for the global carbon cycle. Changes in the global carbon cycle can affect all of these tipping elements.



Above: The global distribution of some key commonly identified tipping elements, overlaid on a population density map. Image: Lenton, et al., 2008. Please see copyright notice below.

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