A Climate of Curiosity

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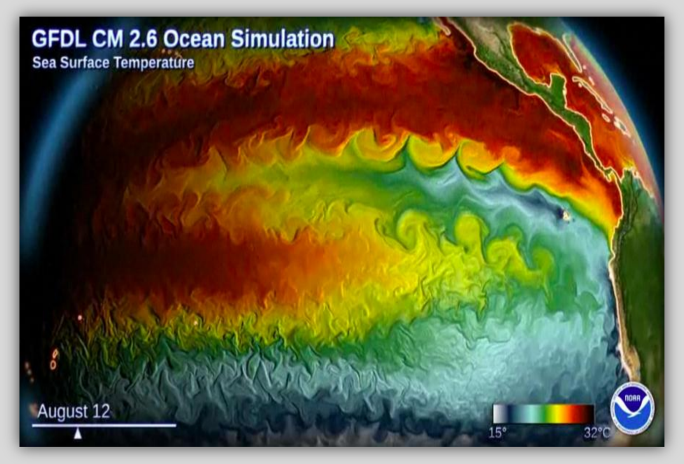
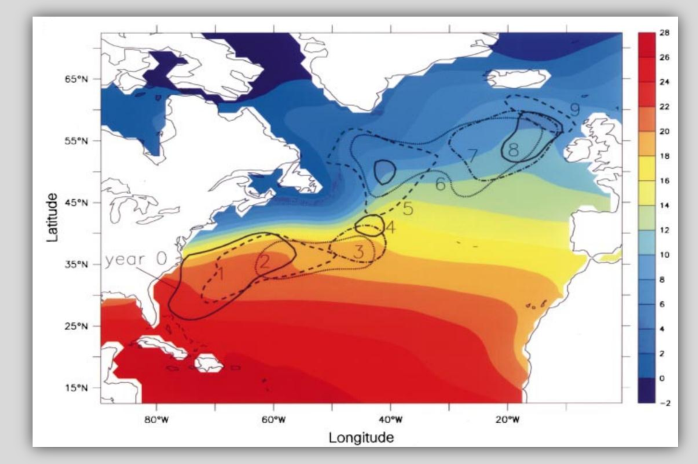
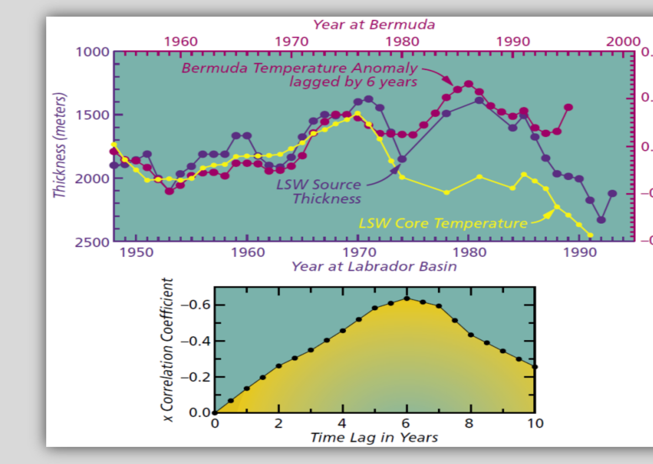
1. The iconic *Earthrise* photograph inspired a collective awareness of the complexity and vulnerability of the Earth's climate system. The picture was taken by astronauts aboard NASA's Apollo 8 mission on December 24th 1968. It is often credited with sparking an environmental movement, including the formation of the Environmental Protection Agency in 1970, and the establishment of Earth Day on April 22nd of every year. More recently, the academic study of climate dynamics has been humbled by the discovery of mathematical curiosities such as turbulence and chaos.



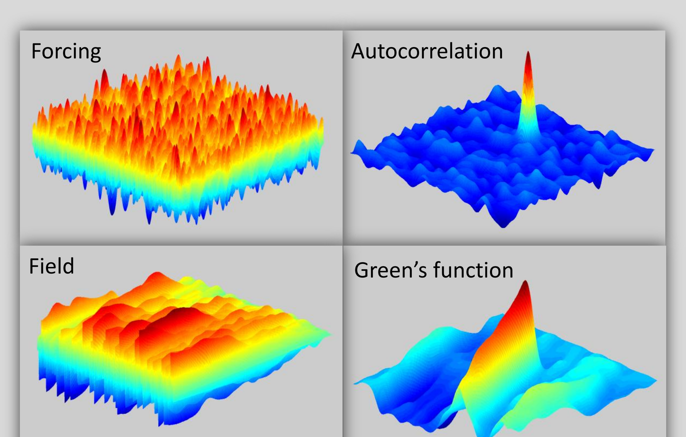
2. Scientists are becoming increasingly aware of the interconnected dynamics between the ocean and atmosphere. One example of the coupled system is the El Niño phenomenon illustrated above. Global patterns of precipitation are altered as warm sea surface temperatures migrate from the Western (La Niña) to Eastern (El Niño) Pacific. An example in the Atlantic is the Gulf Stream bringing heat from the equator to the European continent. However we do not have a complete understanding of coupled atmosphere-ocean dynamics. This is partly because ocean currents are chaotic and difficult to characterize.



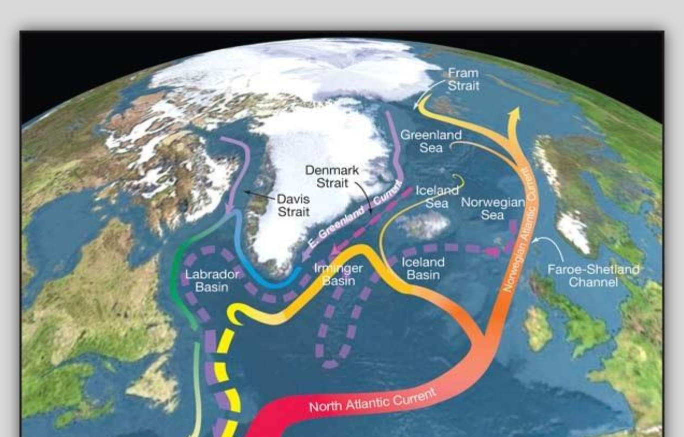
3. One way of characterizing ocean currents is by correlating small scale fluctuations in temperature measurements. The ocean's surface is heated and cooled by random fluctuations in atmospheric conditions. The image above shows how Gulf Stream speeds are inferred from propagating patterns of sea surface temperatures (Sutton and Allen, *Nature*, 1997). The colors indicate average surface temperature. The numbers and contours are the year at which the region had the highest correlation with the year-0 area. Given the distance traveled, and the time of peak correlation, an average advection speed of 1.7 cm/s is suggested.



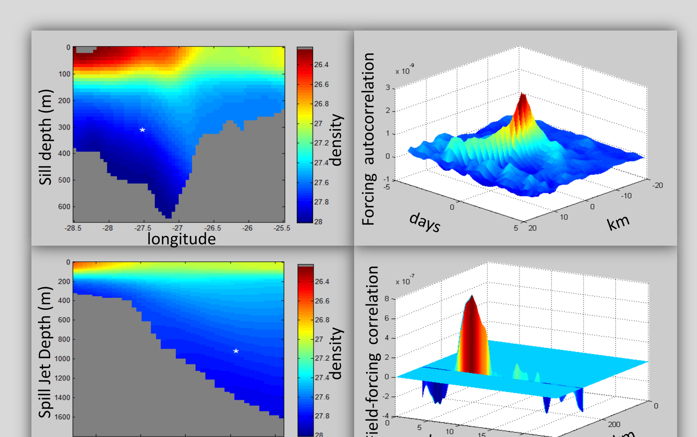
4. However correlation does not imply causation, thus it is unclear how to interpret correlation in terms of the underlying fluid dynamics. In the image above, Curry and McCartney (1996) suggest that atmospheric conditions in the Northern Atlantic become imprinted into the Labrador Sea and then transported to Bermuda. The plot of correlation coefficient as a function of time-lag suggests a six year transit time in the Deep Western Boundary Current. Unfortunately it is unclear how the peak and width of the correlation plot should relate to physical fluid transport mechanisms such as advection and diffusion.



5. We have shown that correlation functions can be related to physical transport mechanisms using an advanced mathematical technique known as a Green's function. Fluid transport processes such as advection and diffusion are defined by linear partial differential equations between forcing and field variables. These equations have Green's function solutions which contain complete information about the transport. Some functions of time-lagged correlation between forcing and field variables will converge to the Green's function if the scale of forcing autocorrelation is small.



6. We are currently applying correlation methods to characterize the flow of dense water through the Denmark Strait. Many scientists believe that the currents in this region play a critical role in maintaining climate stability. As the warm and salty North Atlantic Current mixes with the cold and fresh water flowing down from the Arctic region, dense water forms and then sinks to the bottom of the ocean. The massive sinking action drives the global overturning circulation and transports heat around the world. Characterizing the flow of dense water through the Denmark Strait will help us better understand this dynamic.



7. A correlation analysis in a Denmark Strait model suggests an average current speed of 0.6 m/s and diffusivity of 5×10^3 m^2/s. Using a high resolution simulation of the Denmark Strait overflow, we correlate fluctuations in density related variables flowing downstream. The image above shows the average density field at the Denmark Strait Sill (top left) and 285 km downstream at the Spill Jet (bottom left). The autocorrelation of the forcing at the Sill (top right) is contained within 5 days and 10 km. The forcing-field correlation (bottom right) shows Sill – Spill Jet transit times between 5 and 10 days.

Summary

The *Earthrise* photograph inspired an awareness of the complexity and vulnerability Earth's climate. Today scientists are studying the interconnected dynamics between the ocean and atmosphere. One way of characterizing chaotic ocean currents is by correlating small scale fluctuations in observations. Current speeds in the Gulf Stream and the Atlantic Deep Western Boundary Current have been estimated by correlating atmospheric conditions imprinted into the ocean's surface and transported to remote regions. However since correlation does not imply causation, it was previously unclear how to relate correlation functions to the underlying physics of fluid transport. We have made this relationship clear using an advanced mathematical technique known as a Green's function. We are now applying correlation functions to estimate transit times in the Denmark Strait Overflow. Improving our characterization of the dense water currents in this region will help us understand how it contributes to the global overturning circulation.