Summary and Brief Analysis of Lectures Given by Prof. Joellen Russell at the Santa Fe Global Sustainability Summer School (12th to 25th July 2005)

By

F. Ona, M. Zellner, S. Borgeson and Y. Bamutaze

1.0. Overall Context

Oceans circulate enormous volumes of water, which in turn transports massive amounts of energy globally. The scale of energy transport is particularly notable when compared to the mass and heat flows of the atmosphere. Thus oceans play an important role in shaping the general character of global climate and weather patterns. Since global CO_2 levels have been elevated beyond pre-industrial levels, oceans have also become massive sinks of CO_2 and atmospheric heat[1]. It is no exaggeration to say that oceans will determine the long term trajectory of climate change.

While oceans transport and sequester energy and CO_2, the flow patterns and strength of their currents are determined largely by persistent westerly winds that also shape weather patterns. The way storm tracks are influenced by the Westerlies and the interaction between Westerlies and the Antarctic Circumpolar Current (ACC) in the Southern Hemisphere are emerging as important drivers of the global climate and in understanding future climate change. Thus the observed disagreements in major models about the strength and location of Westerlies and the southern ocean are shaping up to be among the largest sources of error in projecting climate change.

2.0 Lecture I: Southwest Climate, the Westerly Winds and Climate Model Projections (Monday 13th July 2009, SFI GSSS)

Dr. Russell's first lecture emphasized the role of climate models in improving our understanding and prediction of atmosphere and climatic characteristics. The lecture included a regional analysis of the climate dynamics of the US southwest. The major topics of Russell's first lecture were:

1. The poleward migration of the Westerlies
2. The Westerlies and the ozone hole over Antartica
3. Weather patterns and the Westerlies

2.1 Migrating Westerlies (Temporal dynamics of the Westerlies)

Based on atmosphere/ocean coupled climate model projections, the effects of climate change are recognized to be strongly connected to the poleward shift of mid-latitude Westerlies that in turn affect the precipitation patterns, ocean circulation, and temperatures. This shift, which was also validated with satellite imagery data first obtained in 1976, is believed to be continuing. Model results indicate that the migration

[1] It is estimated that 85% of anthropogenic carbon enters the oceans.

of Westerlies is a consequence of cooling in the upper atmosphere (stratosphere) over the poles which creates low pressure zones that tilt the Westerlies pole-ward and intensify their winds[2]. The stratospheric cooling is a result of the heat trapped by Greenhouse Gases (GHG) in the lower atmosphere (troposphere) failing to reach the stratosphere and the diminished capability of the ozone depleted stratosphere to absorb incoming UV radiation[3].

2.2 Westerlies and Antarctica

The Southern Hemisphere Westerlies form a vortex circulating around the South Pole. The vortex acts as a barrier to air circulation into or out of its interior and thus isolates the atmosphere over Antarctica. As the Westerlies shift poleward, they are causing decreased temperatures over the Eastern Antarctica; while increasing temperatures over western Antarctica and the Antarctic Peninsula, which poke out beyond the vortex into warmer air. As a consequence, Eastern Antarctica is experiencing increased ice coverage while the ice in Western Antarctica is in increasing danger of melting.

Although concentrations of CFCs in the atmosphere have stabilized since the Montreal Protocol, the hole in the ozone layer over Antarctica has persisted and grown. There is evidence that this is due to its interactions with the Southern Hemisphere Westerlies and GHGs. The reactions that break down stratospheric ozone are catalyzed by ice crystals. So the cooler the stratosphere is the more ozone gets broken down. Because GHGs are actively absorbing infrared radiation from the earth in the troposphere, they effectively cool the stratosphere. In addition to increasing the breakdown of ozone, the increased temperature gradient between the pole and lower latitudes helps to shift the Westerlies by dragging towards the maximum temperature gradient. The tighter, stronger Westerlies form a sort of barrier to warm air mixing into the polar vortex which intensifies the cooling and bottles up the CFCs. The temperature trend is not changing much in the north, so we could wind up with a warm north and probably a cold south.

2.3 Weather patterns and the Westerlies

The shift of the Westerlies poleward has altered precipitation patterns and temperatures. In general, models predict that dry areas will become dryer and wet areas wetter, but there is not nearly as good agreement on the spatial distribution of precipitation as there is on temperature between models. Specific to the Southwest, winter storms, which are crucial sources of water for the region, track along the path of the Westerlies and have been pulled northward. This creates a drier and hotter climate throughout the region. For example, in Phoenix Arizona, the effects of hotter temperatures and drier conditions are expected to produce summers with 40 additional 100 degree days if CO_2 emissions follow the IPCC A1F1 scenario to reach quadrupled concentrations over pre-industrial levels by 2050. Measured emissions are currently tracking slightly higher than the A1F1

[2] It is estimated that the Westerly winds have moved pole-ward almost 6 degrees of latitude in the southern hemisphere, 3-4 degrees in the northern hemisphere during the past 30 years.
[3] It is currently estimated that 60-70% of Antarctic cooling is from the hole in the ozone layer, with the balance attributable to GHGs.

scenario and rapid population growth and greater dependence on water for agricultural uses can be expected to increase the negative impact of this climate change in the region.

The following are noteworthy in the understanding the outcomes of climate simulations:

1. The state of the latest climate models which include modules for simulating the atmosphere, oceans, ocean chemistry, ocean biology, land surface, terrestrial biology (plants) and sea ice can be coupled or run independently to understand the whole earth climate. There are a variety of global climate models simulating 25 different observed climate features. Despite their differences, all the models robustly agree on warming and precipitation trends.

2. There are ongoing efforts and prospects in the scientific community to develop robust dynamic vegetation models to illustrate how vegetation changes with respect to ocean biogeochemistry and terrestrial forcing. Results from the current model attempts reveal transitions from forest to grassland under climate stress conditions.

3. There are huge feedbacks emanating from withdrawing nutrients from the ocean by intensive whaling or fishing which reduces krill populations. This affects the functioning of the oceans and their capacity to produce O^2. Ocean sinks are decreasing because of warming and mixing.

4. The growth and density of tropical forests as sinks are generally underestimated. It is important to observe that re-growth after deforestation is much faster than initially thought.

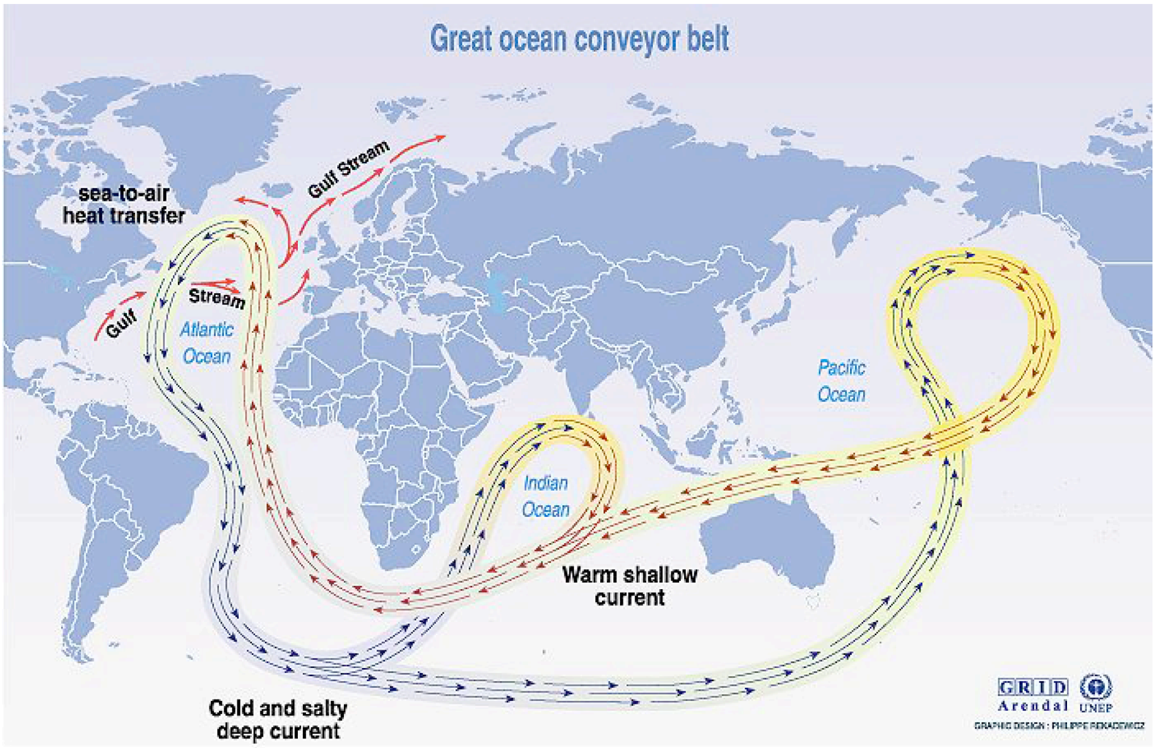
3.0 Lecture II: The Once and Future Battles of Thor and the Midgard Serpent or The Southern Hemisphere Westerlies and the Antarctic Circumpolar Current (Tuesday 14th July 2009, SFI GSSS).

There is a Norse myth about Thor disguising himself as a boy and joining the Giant Hymir as he went on a fishing trip. Thor brought an ox head as bait and managed to catch his nemesis, the Midgard Serpent, which was large enough to circle the world and bite its own tail and was believed to be holding the world together. As Thor prepared to kill the serpent, Hymir grew concerned and cut him loose. Thor, having shed his disguise, threw Hymir in the ocean as his nemesis escaped. In the context of our modern understanding of climate dynamics, it is tempting to speculate that Thor, god of wind, thunder and storms was really fighting with the Antartic Circumpolar Current…

Russell's second lecture explained the interactions between the Southern Hemisphere Westerlies and the Antartic Circumpolar Current and underscored the importance of the south polar sea as an enormous heat and carbon sink that dramatically affects global climate. She emphasized the sensitivity of climate model outcomes to the quality of simulated interaction between the winds and ocean currents and made the case that the difference between modeled outcomes represent the biggest global uncertainty about carbon sinks and therefore merits focused attention.

3.1 The Antarctic Circumpolar Current

Ocean flows have traditionally been illustrated using “conveyor belt" circulation diagrams as illustrated in Figure 1. Notably, there is limited activity in the southern ocean around Antarctica.



Source: Broecker, 1991, in Climate change 1995, Impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.

Figure 1: Typical “conveyor belt” diagram of ocean circulation. Note that the Antarctic Circumpolar Current is entirely absent.

Although they don’t show up in the conventional diagram and are not often discussed in text books, flows in the southern ocean, known as the Antarctic Circumpolar Current (ACC) are very large. Powered by the Southern Hemisphere Westerly winds, the ACC circumnavigates the globe from west to east uninterrupted by land across the range of latitudes that pass through Drake’s Passage (the narrowest part of the southern ocean). The current is so strong that it reaches the ocean floor at depths of up to 5000 meters and sustains a flow rate of 145 million m^3 s^{-1}. The depth and flow are unprecedented elsewhere on earth. In addition to this direct forcing, the Westerlies, which are deflected by the “coriolis force” also drive a steady flow of surface water northward away from the pole in all directions around Antarctica. As the surface water moves northward, ocean water is drawn to the surface from as deep as 2,000m below the surface to replace the northward flowing water. Isotopic analyses reveal that the deep water is often surfacing for the first time in a period of approximately 800 years. This upwelling is bigger than the North Atlantic sink.

Deep ocean waters are rich in carbon of biological origin, but current and future atmospheric concentrations of CO_2 create a gradient sufficient to drive further absorption. The cold deep water also absorbs heat from the atmosphere when it surfaces. After a fairly brief appearance, the heat and CO_2 laden water circulates back into the deep ocean, effectively sequestering atmospheric CO_2 and heat in the ocean. Based on observations of dissolved CFCs and CO_2, it is estimated that the southern ocean accounts for 40% of the CO_2 absorbed by the oceans and controls the air-sea gas fluxes associated with the biological pump. Because dissolved CO_2 forms carbonic acid, the carbon rich deep ocean waters are already relatively acidic when they surface and are even more so after their exposure to the elevated CO_2 levels in the atmosphere.

3.2 Modeling and Predictions

The dynamics linking intensifying Westerlies migrating towards higher latitudes, the ACC and the cycling of deep ocean water to the surface in large volumes are strongly suggested by observational data and are present in most of the recent generation of climate models. However, there is disagreement among climate models on the location and intensity of the Westerlies and consequent ACC, upwelling, and follow-on on effects. For example, none of the models show peak winds as far south as the observations and many are up to 10 degrees out of place. As a consequence, there is a wide range in the estimates of the cumulative uptake of CO_2 and heat in the southern ocean. In general, models predict that the area of deep ocean upwelling will decrease as the Westerlies move closer to the pole, but their migration is also expected to increase the rate of upwelling. These two effects together appear to cancel out or even increase the CO_2 uptake, implying that the southern ocean should prove to be a fairly durable sink. However, with sufficient warming, some models predict layers of warm water at the surface thick enough to interfere with and even prevent upwelling, effectively compromising the large CO_2 sink. The good news is that the cumulative carbon and heat storage is higher in the model with more realistic winds (the effect is on the order of a 20% cut in emissions!) and thus the better models have a lower climate sensitivity index than the others. Because the dynamics in the southern ocean have the potential to place a substantial drag on the climate system and therefore decreasing the climate sensitivity to GHG forcing, developing a clear understanding of the dynamics related to the ACC is an important research goal for climate modelers.

3.3 CO_2 and Temperature in the Paleo-Climate Record

Ice core data used to reconstruct the paleo-climate record shows a remarkable correlation between CO_2 levels and temperature. Although the correlation alone is sufficient to raise major concerns about current CO_2 levels, modelers have lacked a definitive theory explaining the causal connection. The scale of CO_2 flux flags the oceans as the only possible reservoir of CO_2 during glacial periods and biological processes (raining carbon down into the ocean from the photosynthetic layer near the surface) are believed to provide the capture and storage mechanism. Today, the interaction between the Southern Hemisphere Westerly winds and the ACC give a compelling explanation of this phenomenon, including the triggering of transitions between glacial and interglacial periods. During the interglacial periods, the upwelling caused by the ACC provides copious nutrients to support biological activity that captures CO_2 from the atmosphere and "pumps" it into the deep ocean as organisms die and sink to the bottom.

As atmospheric CO_2 levels drop, so do temperatures which ultimately trigger a gradual onset of the ice age. The cooler conditions cause the ACC to relax, and it no longer drives deep water mixing. The more stagnant, stratified ocean lacks the nutrients to support large amounts of biological activity, thus CO_2 sequestration effectively slows to a halt. In this manner, the ocean has been primed during approximately 80K years of carbon accumulation and by this point the deep ocean has very high levels of CO_2 which off gas when it is cycled to the surface. When natural variations in the patterns of the Westerlies intensify the ACC, temporarily driving upwelling, CO_2 is reintroduced into the atmosphere. This starts a positive feedback with atmospheric temperature that leads to the continued intensification of the ACC and upwelling that rockets the climate back out of the glacial period.

The foregoing explanation is vindicated by three distinct tests that the paleo record presents: (1) coincident CO_2 and temperature changes (2) Antartic temperatures that rise several hundred years before CO_2 at the end of glacial periods (3) the deep Atlantic carrying a large burden of biotic CO_2. Furthermore, measurements of carbon concentrations deposited at various ocean depths from southern ocean seamount cores indicate that there was deep carbon during interglacial periods.

3.4 Ramifications

Because of the magnitude of ocean current flow and the degree of atmosphere/ocean coupling they feature, the Southern Hemisphere Westerlies and the ACC are clearly driving several important climate processes. The following ramifications are notable:

- Migration of the Southern Hemisphere Westerlies is redirecting the jets that steer storm tracks and driving precipitation patterns away from sub tropical regions towards the poles.
- The interaction between the SHW and ACC provides a plausible mechanism for and time keeper of glacial periods.
- The shifting winds are likely to lead to the degradation of Adele? penguin habitat leading to the possibly extinction in some areas.
- The strengthening of the ACC is likely to introduce stresses on Minke whales as they travel further in search of food.
- Acidification of the oceans will impact the crustaceans and unicellular organisms at the base of the food web.
- The interaction between the SHW and the ozone hole will lead to further cooling of the Antarctic interior while preserving or even expanding the hole in the ozone layer.
- Similarly, the migration of the SHW will lead to warming of west Antarctica and the peninsula.

Many of these changes are one way trips and we must keep in mind that further surprises are likely since we are way beyond CO_2 levels of the standard cycle.