Greenhouses, hot water bottles, cycles and the future of New Zealand climate

W.P. DE LANGE
Department of Earth & Ocean Sciences, University of Waikato
delange@waikato.ac.nz

Abstract

The Greenhouse Effect acts to slow the escape of infrared radiation to space, and hence warms the atmosphere. The oceans derive almost all of their thermal energy from the sun, and none from infrared radiation in the atmosphere. The thermal energy stored by the oceans is transported globally and released after a range of different time periods. The release of thermal energy from the oceans modifies the behaviour of atmospheric circulation, and hence varies climate. Based on ocean behaviour, New Zealand can expect weather patterns similar to those from 1890-1922 and another Little Ice Age may develop this century.

Introduction

The moisture and varying temperature of the land depends largely upon the positions of the currents in the ocean, and it is thought that when we know the laws of the latter we will, with the aid of meteorology, be able to say to the farmers hundreds of miles distant from the sea, "you will have an abnormal amount of rain during next summer," or, "the winter will be cold and clear," and by these predictions they can plant a crop to suit the circumstances or provide an unusual amount of food for their stock (Lt. John E. Pillsbury from *The Gulf Stream*, Appendix 10, US Coast & Geodetic Survey report, 1891).

Geological evidence indicates that the earth has had oceans and an atmosphere for the last 3.8 billion years, and during this time climate has always been varying. The most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) was that since AD 1950, Anthropogenic Global Warming (AGW), which is now referred to as *Climate Change* in the media, has superseded natural climate change. The dominant factor is inferred to be an increase in the radiative forcing associated with the Greenhouse Effect, due to an increased concentration of some greenhouse gases resulting from human activities. However, there are other anthropogenic factors that may influence climate, such as land use changes and the discharge of particulates into the atmosphere. Further, the analysis is based on the assumption that only radiative forcing involving outgoing infrared radiation has a significant effect on global climate.

Greenhouse effect

The Greenhouse Effect involves the interaction of infrared or long-wave radiation (0.8-1000 µm wavelengths) emitted by the earth, with most types of molecules in the atmosphere. The Greenhouse Effect is most effective between 3 and 20 µm (longer wavelengths are associated with colder temperatures, with 14 µm corresponding to snow and ice), although there are some wavelengths in this range where there is almost no interaction. Infrared radiation is absorbed by the molecules, and eventually re-emitted at longer wavelengths, resulting in a reduction in the rate at which outgoing longwave radiation (OLR) escapes from the atmosphere. Assuming that all other components of the earth's climate system remain constant, and given an infinite flat earth and well-mixed atmosphere, an increase in greenhouse gas concentration leads to an increase in the equilibrium temperature of the earth.

Assuming a spherical finite earth, the result is less clear-cut, and suggests that increasing concentrations may have little effect. However, both approaches indicate that the direct increase in temperature due to an enhanced Greenhouse Effect is relatively small, and positive feedback mechanisms are invoked to predict higher temperature responses.

Ocean thermal energy

Concurrently with increasing global air surface temperature, there has been an increase in global sea surface temperatures, and the total thermal energy in the upper 700 m of the oceans (often referred to as *Ocean Heat*). Some studies have shown that the increases and decreases in ocean heat precede the rise and fall of atmospheric surface temperatures over continents, and major weather fluctuations such as the El-Niño Southern Oscillation (ENSO) also follow changes in the quantity and distribution of ocean heat.

The oceans derive 99.9% of their thermal energy from solar short-wave radiation (0.4-1 µm), with most of the remaining 0.1% due to the geothermal heat flux from within the earth. A small amount of thermal energy is produced by the dissipation of waves, particularly long-period tidal waves. The amount of energy absorbed at infrared wavelengths (>1 µm) is negligible, implying that the Greenhouse Effect does not heat the oceans to any significant degree.

Hot water bottle effect

Water has a high heat capacity, which gives it the ability to absorb, store and emit thermal energy; hence, the use of hot water bottles to provide warmth. The top 3.2 m of the ocean has the same total heat capacity as the entire atmosphere, which means that the oceans store most of the energy in the global climate system. The hot water bottle effect describes the movement of heat. The ocean warms up if it absorbs heat faster than it loses heat, and it cools down if it loses heat faster than absorbing it. This is clearly evident in the annual cycle of both surface water temperatures and sea level. At the tropics and higher latitudes, maximum surface temperatures and the associated maximum thermal expansion occur in late summer to early autumn, with the corresponding minima in late winter to early spring.

At longer time scales, variations in the rate of solar warming are associated with: fluctuations in solar output in terms of both the amount of energy available, and the distribution of energy across the different wavelengths; and the amount of solar energy transmitted to the oceans, which fluctuates with orbital distance, the orientation of earth, and changes in atmospheric absorbance and albedo (mostly the solar energy absorbed and reflected by clouds). Although variations in Total Solar Irradiance (TSI or visible light) appear to be small, there is growing evidence that these small changes are amplified by both: pressure fluctuations in the stratosphere linked to absorption of UV by ozone; and variations in evaporation rates affecting cloud clover, and hence albedo, in cloud-free subtropical areas. Further, variations in solar activity are not confined to TSI; much larger variations have been observed in the strength of the sun's magnetic field, and it's likely they cause fluctuations in the earth's albedo through changes in cloud cover.

General Circulation Models (GCMs) used to project future climate have significantly different equilibrium climate sensitivities, ranging from 2 to 5°C for a doubling of effective carbon dioxide. Much of this difference is attributed to different treatment of clouds and associated feedbacks, particularly those associated with deep convective clouds (the tallest clouds), and thin marine layer (low level) clouds. GCMs treat deep convective clouds as a positive feedback (warming), while thin marine layer clouds are ignored or treated as a weak negative feedback. Initial satellite data (Nimbus-7 1980-84) suggested that, on average, clouds cover 51.8% of the earth. However, with the steady improvement in sensor resolution and spectral sensitivity, the coverage has been revised to 62.7% (ISCCP C2 1984-88), and more recently 77.6% (MODIS 2000-06). Most of the extra coverage represents thin marine layer clouds, suggesting GCMs underestimate the negative feedback associated with these clouds.

Although the data presented above may suggest an increase in global cloud cover, analysis of the individual datasets indicates that overall cloud coverage has declined from 1980-2006, contrary to the positive feedback assumed in GCMs. It has been hypothesised that the reduction was due to a declining availability of ionised nuclei required for cloud formation, since the sun's stronger magnetic field reduced the concentration of galactic cosmic rays (GCRs) entering the atmosphere. In particular, the GCR flux is thought to affect the distribution of thin marine layer clouds, and hence the shortwave radiation fluxes into the oceans. However, since the solar maximum during Solar Cycle 23 (2000-2002), there has been a dramatic drop in both the sunspot and overall solar magnetic field, coinciding with extended periods of no sunspot activity, which may be contributing to increased marine layer cloud formation, leading to cooling. In addition to there being very few sunspots, the strength of the sunspots that do occur is much less than 20 years ago.

Ocean currents redistribute the heat entering the ocean from the sun. There is a higher solar flux near the equator than at the poles, so both the oceans and atmosphere are warmer near the equator. Atmospheric and oceanic circulation both transport energy from the equator to the poles as a result of the thermal gradient. However, due to the presence of land masses that constrain ocean circulation, the transport in the oceans is not uniform. Presently, the oceans effectively transport thermal energy from the North Pacific Ocean to the North Atlantic, resulting in a higher evaporation rate in the North Atlantic, which is balanced by a higher precipitation rate in the North Pacific. This results in the water in the North Atlantic being warmer and saltier than the water in the North Pacific. Cold fresher water can freeze more easily than warm saltier water, so the formation of sea ice in the arctic is controlled by the relative inflows of Pacific and Atlantic water into the Arctic Ocean. There are similar, but less pronounced salinity/temperature anomalies around Antarctica, that rotate around the continent (Antarctic Circumpolar Wave) and influence sea ice formation.

There are also processes that affect the rate at which oceans lose thermal energy. On average oceans lose 53% as latent heat due to evaporation, 41% as infrared emissions, and 6% by conduction to the atmosphere. However, these losses can vary in response to the amount of turbulence and extent of cloud cover, which provide a feedback mechanism to limit the total amount of ocean heat in the upper ocean. Over long time periods, the location of the pycnocline (the boundary between warmer surface waters and colder deep waters) is quite stable, indicating that the total amount of thermal energy stored in the surface and deep oceans is relatively constant. At shorter time periods, there do appear to be fluctuations, particularly in the surface oceans, that are associated with climate variability.

Ocean-atmosphere interactions and climate variability

The Pacific warm pool

The international TOGA COARE project conducted in 1992-93 measured ocean-atmosphere interactions involving the "warm pool" region of the western Pacific. This area contains some of the warmest ocean surface waters on earth and plays an important role in global climate variability, particularly ENSO. COARE found that several processes limited the maximum surface temperature of the pool, and also the total volume of warm water.

As the surface temperature increased in response to solar forcing, there was an increase in evaporation that ultimately resulted in an increase in precipitation, transferring energy from the ocean to the atmosphere. The precipitation also predominantly fell back into the ocean, creating a cold fresh pool on the ocean surface that cooled the warm pool as it mixed with the underlying warmer saltier water. More recent studies have shown that as the ocean surface temperature increases, the strength of convection in the overlying atmosphere also increases. This results in taller but narrower clouds, so although the thickness of the cloud layer increases, the area covered decreases, allowing more OLR to leave the atmosphere, hence cooling the ocean. The Earth Radiation Budget Experiment (ERBE) has observed that within the tropics, an increase in sea surface temperature does increase OLR, contrary to the assumed response in GCMs.

The warm pool occasionally flows eastward along the equator, resulting in anomalously warm waters in the eastern Pacific Ocean, particularly off the Southern American coast. This is associated with changes in the strength and direction of atmospheric circulation systems, collectively known as an El Niño event within the ENSO cycle. The redistribution of the waters of the warm pool results in an increase in OLR and consequently an increase in the global air surface temperature after a lag of about 7 months. The magnitude of the El Niño event is related to the volume of the warm water pool and the proportion that flows eastward (the largest volume measured to date preceded the 1998 super-El Niño). Following an El Niño event warm anomalies have been observed propagating around the oceans, eventually arriving in the North Atlantic.

The discredited "Hockey Stick" reconstruction of global temperature over the past millennium disputed the existence of a global temperature maximum known as the Mediaeval Warm Period. It was argued that the multiplicity of proxy data showing such a warm period were due to regional effects, not global warming. The Pacific Warm Pool has undergone temperature fluctuations over the last millennium that supports both a Mediaeval Warm Period and a Little Ice Age, followed by a Modern Warm Period that is no warmer than the Mediaeval Warm Period. Given the global impact that the Warm Pool has on climate and the increasingly global proxy evidence, it is clear that the Mediaeval Warm Period was global, and the "Hockey Stick" interpretation is incorrect.

Ocean circulation and climate oscillations

Water density is an important factor controlling ocean circulation, and is a function of temperature, salinity and pressure. Water masses with different temperatures and salinities can have the same density and therefore occur at the same depth in the ocean. Below the surface, the temperature and salinity of water masses change slowly, mostly in response to mixing. Further, water masses move more easily horizontally, since vertical movement requires a change in density. At the surface, interactions with the atmosphere can result in rapid changes in temperature and salinity, which can result in density changes, or the temperature changes are compensated for by salinity changes resulting in no density change (known as changes to the *spiciness* of the water). Typically, warming at the surface is associated with an increase in salinity, while cooling is associated with a decrease in salinity. This phenomenon results in warmer, saltier (*spicy*) water masses with the same density as cooler, fresher (*non-spicy*) water masses, which all flow at the same depth and provide a "memory" of the ocean/atmosphere interactions that created them.

In the Pacific Ocean, there are at least four layers in which spiciness anomalies can move and affect weather and climate. At the very surface, anomalies propagate slowly eastward in association with a 30-60 day weather cycle known as the Madden-Julian Oscillation (MJO). The MJO involves periods of both increased convection that can spawn tropical cyclones and greatly reduced convection that can create drought conditions. At slightly greater depths, there is an eastward flow associated with ENSO. This flow is deeper in the central Pacific and surfaces in the eastern Pacific (re-emergence), where it produces anomalously high sea surface temperatures and an increase in OLR as discussed earlier.

The deeper layers are less well understood and involve more complicated flow paths. Immediately above the major density boundary in the ocean (the pycnocline) are anomalies linked to the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO). These phenomena have periods of 60-80 years, which is consistent with the movement of water around the oceans along the pycnocline. The pycnocline is bowl-shaped, so it is deepest in the mid-ocean basins of the North and South Pacific and Atlantic oceans, and nears the surface at high latitudes and the Equator. Anomalous water masses created at high latitudes, particularly the North Pacific and North Atlantic, flow horizontally along the pycnocline, and rotate around the ocean basins, eventually re-emerging at high latitudes. Depending on weather conditions when the water masses re-emerge, the spiciness anomalies can be strengthened or diluted.

In the Pacific Ocean it is also evident that due to the shallow pycnocline, anomalous spiciness associated with the PDO can interact with the overlying water masses associated with ENSO. If a spicy PDO anomaly coincides with the warm pool, it can significantly increase the volume and warmth of the pool and strengthen the subsequent El Niño event. Similarly, a non-spicy PDO anomaly will weaken El Niño events and favour neutral or La Niña conditions. Proxy and historical data indicate that this pattern has consistently occurred for the last 400 years, and most probably occurred for the last several millennia.

Spiciness also occurs in Intermediate Waters located just below the pycnocline in the oceans. These waters originate at higher latitudes than the anomalies involved in the PDO, particularly around Antarctica where they are affected by the extent of sea ice and the strength of circum-Antarctic circulation. At this stage it is unclear what role the anomalies play in global climate, but they may be associated with the 1470 year Bond Cycles evident in the palaeoclimate record. Bond Cycles are most pronounced during glacial times when they are linked to the influx of coarse sediment into the deep ocean, particularly in the North Atlantic. The pattern of Warm Periods and Little Ice Ages over the last few millennia has been linked to Bond Cycles, although the mechanisms involved are not known.

Although the Intermediate Water spiciness anomalies lie beneath the pycnocline, which restricts vertical mixing, these waters can re-emerge at high latitudes, and near the equator they can interact with surface waters due to the shallowness of the pycnocline. This suggests that these anomalies can interact with the Pacific Warm Pool in a similar fashion to those associated with the PDO. Analysis of millennial scale proxy data for the Pacific Warm Pool provides evidence that since the Last Glacial Maximum there have been fluctuations in extent and maximum temperature of the pool consistent with Bond Cycles. This may provide a mechanism to drive warm/cool climate variability at millennial time scales.

New Zealand climate variability

New Zealand climate, particularly rainfall and wind patterns, shows systematic variations at different time periods. Due to the short instrumental record, most of the identified variation is strictly weather and not climate, and includes: a quasi-biennial oscillation (QBO) associated with sea-level pressure and meridional (north-south) flow around New Zealand; the ENSO pattern with periods of 3-8 years; a decadal pattern strongly correlated with the 11 year Schwabe sunspot cycle; and cycles with periods of 18-22 years that also correlate well with the Hale magnetic solar cycle. A 70-80 year pattern linked to the PDO is also evident, which some have correlated to the 60-120 year Gleissberg cycle that is associated with modulation of the Schwabe cycle amplitude. Proxy data also suggest the presence of a 200-220 year de Vries solar cycle (also known as Seuss Cycle).

It is recognised that both the QBO and ENSO undergo sudden phase shifts that affect their amplitude and influence on New Zealand, as do the strong circum-Antarctic (zonal) westerly winds (ZWW) to the south of New Zealand. Some of these phase shifts correlate well with the Schwabe solar cycle, and others with the phase shifts of the PDO. In particular, three major climate shifts have been identified for New Zealand from instrumental data: 1922-1944 positive PDO; 1946-1977 negative PDO; and 1978-1998 positive PDO. Since 2002, there has been a shift to a negative PDO.

There are three regions of coherent sea surface temperature around New Zealand: the Tasman sea to the west; and two areas towards the east, north and south of the Chatham Rise (which constrains the location of the Sub-Tropical Front (STF) separating waters sourced from high and low latitudes). ENSO events affect the sea surface temperatures in the Tasman Sea (cooler during El Niño), and the PDO affects sea surface temperatures east of New Zealand around the STF. In turn these affect the temperature and pressure gradients across New Zealand.

A positive PDO coincides with an increase in mean sea level pressure (SLP) over the Tasman sea (west of 170°W), a decrease in sea surface temperature east of New Zealand, and the South Pacific Convergence Zone (SPCZ) moving northeast. This results in an increased west to southwest wind flow across New Zealand, a reduction in precipitation in the north of the North Island, and an increased precipitation for the north, west, south and southeast of the South Island.

Storm surges are smaller and less frequent, and there is a reduction in the frequency of waterspouts (coastal tornadoes) and mesoscale storms. The opposite occurs during a negative PDO.

The transition from one state to the other of the PDO coincides with a step-like increase/decrease in sea level, which appears to match a similar increase/decrease in global surface air temperature and upper ocean temperature, consistent with thermal expansion being the main driver of sea-level change. Globally, a positive PDO is associated with higher temperatures, and a negative PDO with cooler conditions. New Zealand's temperature response is more complicated, as increased southwest wind flows tend to lower temperatures.

Future New Zealand climate

The IPCC developed a range of scenarios to estimate future concentrations of Greenhouse Gases, and these were used as the basis of projections of future climate. They are not forecasts in the same sense as weather forecasts, and therefore it is difficult to assess the significance of any particular projection. It is clear that all the scenarios used have overestimated the concentrations of the Greenhouse Gases considered for the first decade of this century, even though it is argued that the estimated emissions have exceeded the assumed emissions for some scenarios.

Based on the projections, the IPCC considered the most likely rate of increase in global temperature this century to be 0.2° per decade, and the rate of sea level rise to be 4 cm per decade. The other projections of climate change vary widely between models and there is no consistent projection that can be applied to New Zealand. Hence, NIWA assume that until about 2050, climate change in New Zealand will be similar to that which occurred during the 20th century (i.e. dominated by natural climate variability), and any climate change associated with AGW will predominantly occur later. So far this century, the measured global air surface temperature and sea level are "rising" at a much lower rate than predicted (New Zealand has cooled by 0.2°C and sea level has fallen 3 cm).

Alternatively, based on ocean-atmosphere interactions, it is possible to predict future climate, because the spiciness anomalies that contribute to climate change already exist in the oceans. Therefore, they can be measured and it is possible to predict their eventual re-emergence. The available data indicate that a negative PDO is established, and the AMO is also switching to a negative mode in the Atlantic Ocean. This has been contributing and will continue to contribute to global cooling for another 20-25 years. As the oceans cool, global sea levels should fall although continued retreat of glaciers will slow the drop.

New Zealand will experience a climate consistent with a negative PDO, probably most like the pattern that existed between the mid 1890s and 1922 with relatively weak ENSO fluctuations. This will mean more intense rainfall events in some areas, particularly the upper North Island, increased frequency and magnitude of storm surges, and more frequent waterspouts and mesoscale storms. Drought frequency is likely to increase for most parts of the South Island. Snowfall is likely to increase in the North Island and eastern parts of the South Island, and decrease for the western side of the Southern Alps.

After 2030, there should be a switch to a positive PDO. It is unclear whether this will result in warming. During the 20th century, increasing solar activity and decreasing low level clouds have contributed to an increase in ocean heat content. Since the solar maximum in Cycle 23, solar activity has decreased and ocean heat content has also been falling. Extrapolation of known solar cycles (particularly the Gleissberg and Seuss cycles) predicts solar activity will continue to decline this century. If this is correct, then global climate is moving towards another Little Ice Age.

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