Hello. It is a pleasure to have this opportunity to speak with you about what I refer to as the “threat” of climate change.

To start let me share with you a few general observations.

Climate change is:

- An issue that periodically generates considerable political and media interest - sound and sometimes fury but not always signifying much;
- An issue with an almost continuous round of international meetings and great promises but as yet little real action;
- An issue which, despite significant scientific progress and clear indications that climate change is accelerating, is still not being addressed with the necessary urgency;
- An issue that can be simply understood but yet represents possibly one of the greatest scientific challenge of our times;
- An issue of morality where actions today and in any one country will benefit people on other shores and of future generations (who we will never meet) and which sometimes defies simple economic accounting;
- An issue that presents a new kind of challenge - uncertain in its form and extent, insidious rather than (as yet) directly confrontational, long term rather than immediate.
- An issue which has been around for a long time and will not go away…
The scientific understanding of climate change is not new – quantum mechanics and relativity are much newer. The story can be traced back to the French mathematician Fourier who as long ago as 1824 discussed the link between the climate and the existence of certain gases in the atmosphere. He argued that the Earth should be considerably colder than the planet actually is if warmed only by the incoming solar energy – about 30 degrees colder. He considered the possibility that the Earth's atmosphere might act as an insulator of some kind. This idea contributed to the metaphor of the “greenhouse effect”.

Fourier’s hypothesis was taken up some years later by a Swedish chemist Svante Arrhenius. In 1896 he calculated how changes in the levels of carbon dioxide could alter the surface temperature of the Earth. He was the first person to predict that emissions of carbon dioxide from the burning of fossil fuels (primarily coal at that time) were large enough to cause a warming of the planet.

This idea was later taken up by Guy Callendar in the UK. He estimated that with the then current fossil fuel use carbon dioxide concentrations would reach 314 ppm by the year 2000. In fact we reached that concentrations in the late 1950’s. The concentration in 2000 was close to 370 ppm. Today’s concentrations are close to 400 ppm. That is almost a 40 % increase from pre-industrial levels of 280 ppm when we replaced human and animal power by mechanical power fuelled by burning first wood then coal, oil and gas - the era of dark satanic mills.
• As Arrhenius and others have shown the presence of *Greenhouse Gases* in the atmosphere creates conditions that allows for human civilization to exist on this planet. They act like a blanket around the Earth, they trap heat and raise the temperature of the Earth making this planet inhabitable. They thus significantly affect our climate. This diagram illustrates some of the principles. Our understanding is based on well-established physics. There is no scientific controversy regarding the Greenhouse Effect although there are still some elements, such as the behaviour of clouds, that are still not fully understood.

• As some climate change nay-sayers will claim the climate has always changed. They are correct. The climate is driven mainly by the path of the Earth around the Sun, but in a slow, predictable manner. By contrast, the changes we have seen recently have been unusually rapid and are dominated by our burning of fossil fuels.

• Although water vapour is a strong greenhouse gas, we cannot as humans directly affect the amount of water vapour in the atmosphere. It varies from day to day depending on the weather. What we can and have influenced is the amount of carbon dioxide in the atmosphere through the burning of fossil fuels and the destruction of forests. The additional carbon dioxide warms the atmosphere allowing it to hold more water vapour which adds further heat until it reaches equilibrium. This is what we call a positive feedback.
The root cause of the problem is shown in this graph. It shows the results from careful observations of the concentration in the atmosphere of carbon dioxide from Mauna Loa in Hawaii made by Charlie Keeling of NOAA. These measurements were begun in 1957, several years before climate change had become a public policy concern. It was already obvious in the early 1970’s that carbon dioxide concentrations were rising above pre-industrial levels. This has inexorably and ominously continued. In fact the rate of increase itself has risen.

- Incidentally, the annual variability in this curve is the Earth breathing.
- I have added some important markers to this graph. It seems the increase in atmospheric concentrations of greenhouse gases is insensitive to the rounds of negotiations we have had since governments started to discuss if not tackle this threat.
• Let’s put this increase in perspective.
• This diagram shows results from a 3-kilometre long ice-core drilled into the Antarctic ice-sheet. Annually the ice captures in its crystals samples of the air at the time snow was deposited. Each layer records the atmospheric concentration of the time. The blue curve is the temperature record and the green curve is the carbon dioxide concentration. As you can see, the concentration has varied over time. It has been lowest during an ice age and highest during an interglacial period. Note that the difference between an ice age and an interglacial is about 5°C. Note also that the last interglacial period was some 2 °C warmer than our present one.
• When we go back over the past several ice-ages we can see that we have now taken the concentration of carbon dioxide in the atmosphere to levels that we have not seen for almost a million years. The concentration has not gone above 280 ppm during all that time; as I mentioned it has now reached 400 ppm and it is still increasing. This is evidence that we have clearly taken the atmosphere into uncharted territory. That is the basis of the threat that we face.
What the previous slide showed us is that we have upset the balance of the carbon cycle—that is the flow of carbon through the atmosphere, oceans and biosphere. We have done this by pumping more carbon (in the form of carbon dioxide) into the atmosphere than the Earth’s systems can absorb. Until we bring this carbon cycle into balance again atmospheric concentrations will continue to rise. Thus in order to start to address the threat of climate change we have to rebalance the carbon budget.

This diagram illustrates the carbon budget. We have been pumping every year some 8.3 Gt of carbon into the atmosphere through burning of fossil fuels (and cement production). We are presently also adding some 1.0 GtC through land-use changes—primarily deforestation in the tropics. These figures are for 2010, the most recent estimate of global emissions is closer to 9.7 GtC per year.

This input is somewhat balanced by the up-take of carbon in the terrestrial and ocean biospheres as well as straight-forward physical and chemical dissolving of CO$_2$ in the oceans. This later process is increasing the acidity of the oceans with potentially damaging effects on the ocean ecosystems. Current estimates suggest that some 2.6 GtC are being taken up by forest re-growth and 2.5 GtC are being taken up in the oceans.

We are pumping more carbon into the atmosphere than is being taken up by the land and oceans. The difference stays in the atmosphere. This increase is now estimated to be some 4.2 GtC per year.

A useful analogy is the bath tub. As long as the rate of flow into the tub is lower that the rate at which water flows out, the tub will not over-flow but as soon as the inflow is just a little bit greater the level of the water will rise—until it overflows.
• Let us examine some of the inputs into the carbon budget.
• As this diagram illustrates the rate of increase of our emissions from the burning of fossil fuels and deforestation have recently been around 3% per year. This is twice as rapid as it was at the end of the last millennia.
• There was a short decrease around 2008; this occurred at the time of the global financial crisis. People didn’t have so much money to spend, economic activity declined and the use of fossil fuels dropped. But this didn’t last very long and emissions went up again.
• If emissions don’t start to decline there is clearly no way the concentrations will go down and be stabilized at a level that avoids “dangerous climate change”.
• If we continue on the present “business as usual” track by the end of the century carbon dioxide concentrations could be as high as 900 ppm with global average temperatures some 4 °C above pre-industrial levels.

Emissions at or above current rates would induce changes in all components in the climate system, some of which would very likely be unprecedented in hundreds to thousands of years. (AR5, WGI, SPM).
Let’s now consider the drivers of climate change – the factors that have lead to the unprecedented increase in atmospheric concentrations of greenhouse gases.

It is useful if we examine a fairly simple formula that was developed by a Japanese scientist – Koichi Kaya. He postulated that there are four main factors governing the emissions of greenhouse gases from the combustion of fossil fuels.

In principle we can influence each of these factors in order to affect the greenhouse gas emissions; all of which are dependent on our values and hence are politically charged (some more than others). The focus has been on improving energy efficiency and de-carbonizing our energy supply.
There are different ways in which we can look at carbon emissions – we are not all equal.

The first column shows the total carbon emissions for a range of countries. China is now the largest emitter having passed the United States a few years ago.

The second column shows the cumulative emissions of carbon since the beginning of the industrial revolution some 250 years ago. It is not surprising that the largest cumulative emissions are from the industrialized world, Europe and the United States. Cumulative emissions are important as we shall see later – they determine the ultimate level of warming of the climate. Hence, there is an historic legacy of past emissions.

The third column shows the emissions per capita. The North American emissions per capita are still twice what they are in Europe (with an equivalent standard of living), some four times greater than China (where the standard of living is growing rapidly) and nearly ten times that of India (and most developing countries).
• Since the beginning of the Industrial Revolution the global average surface temperatures have risen by almost a degree – recall the difference between an ice-age and an inter-glacial period is about 5 °C.

• In the words of the IPCC’s 2007 Fourth Assessment Report: “warming of the climate system is now unequivocal”. The Fifth Assessment Report adds further confidence to that statement.

• The temperature increase has not been smooth, indeed we have seen periods in which surface temperatures declined or were stationary as we seem to have had over the last decade. The plateau we have seen over the last decade has been used by the nay-sayers to argue that climate change is over. But there is evidence that recently more of the heat trapped in the atmosphere has in fact gone into the oceans so for the climate system as a whole there really has not been any pause in the warming of the planet. Furthermore, we have to look at the long-term trend and there the trend (as shown in this graph) is undeniable.

• The coloured lines show the rates of temperature increases over different time periods. What is noticeable and most worrying is that the rate of change has increased. You can see this from the increasing slope of the straight lines – the closer one comes to the present so the steepness of the straight lines increases. This is evidence that climate change may well be accelerating.
There have been worrying changes in other climate variables, for example in sea-ice extent and volume. This diagram shows what has been happening to sea-ice extent. The red points are the observations for September, when the sea-ice extent is at its lowest, and the black points are for March when it is at its maximum. The reduction of Arctic sea-ice in 2007 was unprecedented during the period for which we have reliable comprehensive measurements. 2012, saw even less ice than in 2007. This year the decline is not so marked but still below the long-term average. Although we may have had an unusually cold winter the Arctic was warmer than normal.

The trend in sea-ice extent is clear – not only is the decline obvious but you can’t put a convincing straight line through the September data points for the past 30 years. In fact the Arctic sea-ice is declining faster than our models were projecting as you can see in the insert. Basically we have under-estimated the feedback processes involved – the key one arises from the fact that by melting the sea-ice we are replacing a white reflecting surface by a dark absorbing surface. This is a positive feedback – it enhances the warming of the water and leads to more melting.

In some estimations late-summer Arctic sea ice could disappear almost entirely within the next few decades rather than by the end of the century as was previously thought. According to the IPCC Fifth Assessment Report, a nearly ice-free Arctic Ocean in September before mid-century is likely with the IPCC’s most extreme the GHG concentration scenario – a scenario that is close to our current “business as usual” trend.
• But it is not only the extent of sea-ice in the Arctic that is declining, it is also the volume and this may be decreasing at an even faster rate. This slide shows the decline since the beginning of satellite observations – a little over three decades. We now have only some 20% of the sea-ice volume we had 35 years ago.

• Much of the ice in the Arctic is now one-year old ice, not the multi-year old ice that used to be the bane of ships in the Arctic. The ice today is thin and soft.
• It has been evident for some years that the Greenland Ice Sheet has been shrinking particularly around its edges where the glaciers flow into the sea. Some of these glaciers have been accelerating at surprisingly fast rates – you can actually see the flow in some places. Our estimates are now much more reliable with data from satellites that can measure small variations in gravity due to the differences in the ice cover. We are still trying to fully understand the mechanisms responsible for this rapid decline. In fact we have been forced to rethink the physics of glacier flow.

• During the summer, ice on the surface melts and forms large pools of water which get warmer and melt more ice. This melting is enhanced by airborne particles that are blown in from far away. Eventually some of this water finds its way into deep crevices and flows down to the bedrock. The surprising thing is that this water stays liquid, pushes up the ice and lubricates the flow of the glacier.

• Melting of the Greenland Ice-Sheet is contributing about a third of the sea-level rise that we have seen in recent decades. There is enough water in the Greenland Ice Sheet to rise global sea-levels by 5 m.

• While overall the ice cover over Antarctica seems to be stable the worry is that the glaciers that drain into the surrounding ocean may not be so stable in fact once initiated their decline may be unstoppable. Melting of these glaciers could lead to a global rise in sea-level of several meters. This would threaten the vulnerability of millions of people living in coastal cities.
• Let's spend a little time discussing climate extremes.
• Climate change is more than a steady global rise of temperature. That is why I prefer to use this term and not global warming (and therein lies an interesting debate). In general we can expect an increase in the frequency and severity of extreme events.
• This may be much more of a concern. It is often the extreme events, short though they may be in duration, that cause the most damage. Changes in extreme events are already observed to be having impacts on socioeconomic and natural systems. Two or more extreme events that occur over a short period reduce the time available for recovery. Adapting to changes in extreme events will be challenging.
• There has been a significant increase in the damages from such events over the last 50 years. In a recent Economist article it is claimed that the frequency of weather disasters has tripled since the 1960’s and insured losses have risen ten-fold.
• One must be careful not to attribute all this damage to climate change alone for there are other factors to consider – for example a dramatic increase in exposure and value of property in flood plains and coastal areas. Furthermore, we must also be prudent in attributing every or any individual climate or weather extreme to climate change. However, as Jim Hansen said recently: "We now know that the chances these extreme weather events would have happened naturally – without climate change – is negligible." We have loaded the dice.
• We deduce from simple statistics, as the top left figure shows, that we can expect increases in extreme events, in this case heat waves, as global temperatures rise.

• Physical considerations also suggest that as the climate system warms and becomes more energetic there will be more extremes.

• The bottom right slide shows that such a shift in extremes has been observed. It shows the distribution of summer temperatures for each decade from the 1950’s to today. The distribution shifts to the right – to higher temperatures – as predicted. Roughly speaking, extreme temperatures have gone up by at least 2 degrees which is more than twice the global mean. We are currently observing twice as many record hot days as record cold days – and yes, there will be cold extremes as we had in this part of North America due to unusual changes in weather patterns.
• Consider the 2003 heat wave in Europe (see diagram) that resulted in some 70 thousand additional deaths.

• In a future climate, heat waves are expected to be more intense, longer-lasting and more frequent. By the middle of this century a day so hot that it is currently experienced only once every 20 years would occur every five years over most of Canada. By the end of the century, it would occur every other year or more.

• It has to be noted that as a result of this shift to higher extreme temperatures there will also be a decrease in frost days and a lengthening of the frost-free season. This could be a good thing for farmers but many plants are very susceptible to extreme temperatures at critical periods of their growth.
There was a similar heat-wave in Russia in 2010. Indeed, this heat-wave was even more intense than that in 2003 as can be seen in the diagram in the top-left and the plot in the lower right of this slide.

The 2010 heat-wave shattered all the records both in terms of the deviation from the average temperatures and its spatial extent. The temperatures were as much as 13.3°C above the average. Daytime temperatures of 38.2°C were recorded and it didn't get much cooler at night. The heat-wave covered around 2 million km². As in 2003 it was the unabating night-time temperatures that caused many of the additional deaths.

Fortunately the estimates of additional deaths was much lower than in 2003 – around 15 thousand. This may be due to difference in social factors. However, the heat-wave was accompanied by a large number of wild fires, covering an area of 1 million hectares, that sent huge plumes of acrid smoke over cities such as Moscow causing severe air quality problems and adding to the death totals.

The effects of the heat-wave were to reduce Russia’s GDP by an estimated $15 billion. Because of the effects on agriculture the Russian government embargoed grain exports.
• To bring you up-to-date this diagram collects some of the most recent results in the IPCC Fifth Assessment Report. Future warming depends on two factors, future emissions and what we refer to as the climate sensitivity. The emissions scenarios in the AR5 are not the same as those in the Fourth Assessment Report which were based on socio-economic story-lines whereas those in the Fifth Assessment Report are based on proscribed concentrations.

• The climate sensitivity is defined as the increase in temperatures for a doubling of CO$_2$ concentrations. Our best estimate is 3 °C. Thus, if we allow CO$_2$ concentrations to reach twice pre-industrial levels (2x280 ppm or 560 ppm) we will have exceeded the 2 °C level governments have deemed as “dangerous”.

• The scenario with the lowest temperature increase (RCP 2.5) reaches a stable temperature towards the end of the century of about 1-2 °C warmer than present. The most extreme scenario (RCP 8.5) is the one that most closely parallels our current “business as usual” track.

• The top panel shows projected temperatures to the year 2100. It shows that if our emissions continue to rise as at present then temperatures by the end of the century will reach 4 °C (concentrations are likely to be around 900 ppm!).

• The second panel shows projections for Arctic sea-ice. You can see that even with the most optimistic scenario there is a possibility that by mid-century all sea-ice could be gone by the end of summer.

• The bottom panel shows projections for ocean acidification caused by the dissolving of carbon dioxide in sea water. This is an additional threat caused by increased atmospheric concentrations of carbon dioxide. It threatens any hard-bodied organisms in the ocean.
The changes we have made to the climate system may well be irreversible over human (not geological) time scales. This is due to the inertia of the climate system.

Consider this slide which uses some of the results of a climate model run performed by the CCCma group in Victoria. In these experiments they assume emissions follow the “business as usual” path but then they abruptly ceased all emissions at a certain point in time: in one at 2010 and in another at 2100 – this is shown by the cumulative emissions plot in the top panel.

In both experiments once emissions stop the CO₂ concentrations in the atmosphere decline rapidly over roughly a century and then level out somewhat as can be seen in the middle panel. However, even after 2 millennia there is still some 50% of the original gas remaining in the atmosphere. Carbon dioxide can stay in the atmosphere for as long as 1000 years all the time absorbing radiation, getting warmer and changing the climate.

The effect on temperatures is that they stay roughly constant for millennia as can be seen in the bottom panel. This is due to the heat stored in the oceans being slowly transferred to the atmosphere.

The situation over the medium term is also worrying. We cannot change overnight our systems for producing and using fossil fuels. Furthermore, because of the inertia in the climate system there is estimated to be another 1-2 °C in the pipeline – this is regardless of what we might do in the next few decades to limit our emissions. That part of history is already written - we have essentially made a commitment to future climate change. And recall we have already seen almost a 1 °C increase since the beginning of the Industrial Revolution. Nevertheless, we can make a start today. The longer we delay the riskier and more costly will become. As Lord Stern argued in his book on the economics of climate change the costs of inaction are likely to be greater than the costs of taking action.
• It we want to eventually stabilize the climate, to arrest the increase in global temperatures and avoid “dangerous interference with the climate system”, then we are going to have to stabilize the concentrations of greenhouse gases in the atmosphere. We are going to have to rebalance the carbon budget so that the amount of carbon dioxide being emitted into the atmosphere is equal to that being taken up by the biology of the planet Earth.

• In order to stabilize the concentrations, emissions will need to peak and decline thereafter. The lower the stabilization level, the more quickly this peak and decline would need to occur. The choice of a target is political; science can inform that choice but ultimately it is one that one depends on our values debated in a democratic process.

• In order to have a more than even chance of meeting the 2 °C target which governments have settled on, it is estimated that global emissions need to peak by 2015 and be at least 50% of current levels by 2050. As mentioned earlier today’s annual emissions are estimated to be around 9.7 Gt C and growing at some 3% per year. Under business-as-usual projections, global emissions could reach 15 Gt C in 2020. Even with the most ambitious interpretations of current national pledges, emissions in 2020 are estimated to be 14 GtC. We are not going in the right direction.
Let me get back to the issue of cumulative emissions. This is something that the IPCC discusses for the first time in the 5th Assessment Report. It turns out that the temperature increase depends, in an almost linear fashion, on cumulative emissions – the sum of all emissions since the Industrial Revolution. This can be seen in this graph. Choosing a temperature target gives us a budget – a limit on emissions and hence the fossil fuels we can burn.

In 2009 governments at a Conference of the Parties under the UN/FCCC in Copenhagen set a target of avoiding more than a 2°C temperature increase. We have already used up over half of the corresponding budget. At current rates of emissions we will overshoot this budget in 50 years (16 years if emissions keep rising).

We are essentially dumping our fossil fuel wastes freely into the atmosphere. This is a great market failure. Sooner or later we will put a price on carbon. This will lead to a constraint on fossil fuel use – the dirtiest will become uneconomical – unburnable.

Aggressive investments in fossil fuel infrastructure are inconsistent with any serious attempt to responsibly address climate change. To meet the 2°C target we will have to leave a significant portion of known fossil fuel reserves in the ground. Fossil fuel assets including infrastructure will become stranded assets.

We are going to have to wean ourselves off our addiction to fossil fuels. The Stone Age did not end because we ran out of stones but because we made a transition to a new technology. Inaction is not a rational option.
• In November 1936, Winston Churchill stood before the United Kingdom’s House of Commons and placed a period at the end of the misguided debate over the nature of the “gathering storm” on the other side of the English Channel: "Owing to past neglect, in the face of the plainest warnings, we have entered upon a period of danger. . . . The era of procrastination, of half measures, of soothing and baffling expedience of delays is coming to its close. In its place, we are entering a period of consequences. . . . We cannot avoid this period; we are in it now."

• But I remain optimistic. There are encouraging signs – maybe not in Canada at this time but elsewhere. Technologically, the cost of solar panels has come down from $76 per watt of electricity generated in 1977 to $0.74 today. The costs of electricity generated by wind turbines has also declined significantly. These energy sources are now rivalling those from coal-fired power plants. In fact almost half of new electricity generating capacity in the USA in 2012 came from renewables. And there are potential savings; according to the International Energy Agency the costs of decarbonizing our energy systems is estimated to be less than a third of the costs of the fuel saved.

• On a political front the Chinese government, which really take climate change seriously, has suggested that it will put an absolute cap on its emissions. The Indian government is somewhat behind but the new Prime Minister has written a solid book on climate change. Meanwhile, back in Canada……