Synopsis of IPCC Sixth Assessment Report, by Ronn Smith, August 2021

The debate is settled. For the first time, the Intergovernmental Panel on Climate Change (IPCC) has stated that since systematic scientific assessments began in the 1970s, the influence of human activity on the warming of the climate system has evolved from theory to established fact. The Earth is warming faster than previously thought, and we are collectively responsible. Meanwhile, outspoken deniers of human caused climate change have turned strangely silent. Some have even denied their denial, as if past statements were not a matter of public record. Their backup strategy: discount the dangers of climate change and exaggerate the cost of confronting it.

But the science leaves no excuse for ignorance or inaction. The IPCC just released the first installment of its Sixth Assessment Report (AR6), *Climate Change 2021: The Physical Science Basis*. This report updates the fifth assessment (AR5, 2013) with new findings, a broader context, and stronger evidence. AR6 states, "The robustness of IPCC assessments stems from the systematic consideration and combination of multiple lines of independent evidence. In addition, IPCC reports undergo one of the most comprehensive, open, and transparent review and revision processes ever employed for science assessments." A total of 234 scientists from 66 countries contributed to the latest report, building on more than 14,000 scientific papers to produce a 3,949-page report, which has been approved by 195 governments.

AR6 assesses new scientific evidence relevant to a world whose climate system is rapidly changing, overwhelmingly due to human influence. Compared to AR5, this new report reflects significant advances in scientific understanding, computer modeling, and instrumental observations (particularly in ocean observing networks and remote sensing systems). It also provides more in-depth regional analyses and predictions. Above all, it establishes higher levels of confidence in the human causes and the consequences of climate change identified in previous assessments. For example, from AR5 to AR6 the attribution of water cycle changes to anthropogenic influences strengthened from "likely" to "high confidence."

AR6 shows improved consistency between independent estimates of climate drivers, the combined climate feedbacks, and the observed energy and sea level increases. This enables the conclusion, "It is unequivocal that the increase of CO_2, methane, and nitrous oxide in the atmosphere during the industrial era is the result of human activities and is the principal driver of many of the changes observed across the atmosphere, ocean, cryosphere, and biosphere." This should come as no surprise to the millions of Americans inhaling wildfire smoke for months on end, or the millions more ravaged by record rainfall events and flooding, or the thousands of farms and municipalities in the American Southwest drying up from persistent drought and increased evapotranspiration.

Another improvement in AR6 is the emergence of stronger climate signals since AR5. The passage of time has made human influence stand out from natural variability. With eight more years of evidence, it is "virtually certain" that Earth has warmed at least 0.95°C and most likely 1.09°C (2°F) since preindustrial times, that human activities are the primary cause, and that this warming has affected the climate and oceans. Evidence of intensifying extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and in particular, their attribution to human influence, has strengthened since AR5. AR6 states with high confidence that mean temperatures and heat extremes have emerged above natural variability in almost all land regions.

Current climate impacts will only get worse – how much worse is up to us. AR6 concludes that at least 1.5°C of global mean surface temperature increase (from the 1850-1900 baseline) is baked in as "committed warming" even under the most optimistic mitigation scenario. If the world aggressively reduces greenhouse gas emissions, we will still most likely observe the 1.5°C milestone in less than 20 years. An IPCC supplemental report in 2018 advised policy makers that exceeding this threshold could result in disproportionate climate impacts as nonlinear feedback mechanisms become more ascendent.

When AR5 was published, a so-called hiatus in global warming (from 1999 to 2012) fueled the debate over climate change. Skeptics cited this short-term slowdown in atmospheric warming as evidence that natural temperature fluctuations overwhelm any man-made warming. AR6 dispels this fallacy as an artifact of a too-narrow spatial and temporal scope. AR6 attributes the temporary slowdown to internal and naturally forced variability (such as incoming solar radiation, volcanic activity, orbital cycles, and global biogeochemical cycles) that partly offset the anthropogenic surface warming. But it notes that over this same period heat uptake continued to steadily increase in the oceans, which absorbs 93% of the surplus heat caused by human emissions (the atmosphere absorbs only 1%). Since 2013 a tiny fraction of that excess ocean heat may have returned to the air and accelerated atmospheric warming, since the past five years (2016–2020) mark the hottest five-year period in the instrumental record. The hiatus of the early twenty-first century is long forgotten, along with the voices of denial it stirred.

In contrast to the skeptics' myopia, AR6 examines multiple lines of evidence over long periods. It establishes convergence between direct observations, understanding of physical processes, modeling, and paleoclimate studies. The deep past provides a useful context for present-day observations and predictions. AR6 states with high confidence that in 2019, atmospheric CO_2 concentrations were higher than at any time in at least 2 million years. Since 1750, increases in CO_2 (47%) and methane (156%) concentrations far exceed the natural changes between glacial and interglacial periods over at least the past 800,000 years. AR6 states this with "very high confidence" because reconstructions of past climate conditions have less uncertainty than in previous reports.

Paleoclimate data, along with recorded observations from the last century or more demonstrate that atmospheric CO_2 concentrations and global mean temperatures are strongly coupled. Earth's net positive radiative imbalance has increased linearly with CO_2 concentrations, to its current value of 0.79 watts per square meter (2006-2018 average, with high confidence). Over the period 1850–2019, a total of 2,390 billion tons of anthropogenic CO_2 was emitted, and those emissions are increasing by nearly 2% every year. The last time global surface temperature was sustained at a level more than 2.5°C higher than the 1850–1900 average was over 3 million years ago. Yet, that level is likely to recur in this century.

A broader perspective also recognizes that human activities do not alter Earth's physical systems in linear fashion. For example, AR6 points out the limited buffering capacity of earth systems due to saturation effects. Land and oceans have absorbed 56% of manmade CO_2 emissions (leaving 44% to the atmosphere). However, there is high confidence that the proportion of greenhouse gases taken up by land and oceans will decrease with increasing atmospheric concentrations, leaving a larger proportion to remain in the atmosphere.

Developments in the latest generation climate and Earth system models include new and better representation of physical, chemical, and biological processes, as well as higher resolution. The Coupled Model Intercomparison Project Phase 6 (CMIP6) has improved the simulation of recent climate change. CMIP6 includes over 100 independent models. By combining many different models, IPCC can extract

information about the full range of possible future climate changes and the associated uncertainties. While the models differ in particulars, the CMIP6 multi-model mean global surface temperature change over the last century and a half is close to the best estimate of the observed warming. CMIP6 has corrected deficiencies in prior models that resulted in underpredicting global temperature increases. For example, there has been a 50% reduction in uncertainty of cloud feedback, which is now believed to amplify warming 20% more than assumed in CMIP5.

AR6 offers important insights into the ocean's response to climate change. Under past global warming levels of around 2.5°C–4°C relative to 1850–1900, as predicted for the 21st century, sea level was 5 to 25 meters (16 to 80 ft.) higher than today. It may take several centuries to millennia for global mean sea level to rise by those amounts, but it would require a similar amount of time to reverse course even under large net negative CO_2 emissions (high confidence). Global mean sea level increased by 20 centimeters between 1901 and 2018 and could rise another meter or more by 2100. Human influence is very likely the main driver of this increased rate of sea level rise. Thermal expansion explained 50% of sea level rise during 1971–2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land water storage 8%.

It is virtually certain that the global upper ocean (0–700 meters) has warmed since the 1970s and extremely likely that human influence is the main driver. The rate of increase in thermal stratification in the upper 200 meters of the ocean from 1970-2018 is double that reported in AR5. Ocean stratification inhibits vertical mixing that would otherwise moderate shallow temperature buildup and the salinity gradient, as well as oxygen distribution to support aquatic life. Projected oxygen loss from the oceans in 2080-2099 is substantially greater than previously assessed. It is also virtually certain that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean.

In the cryosphere, AR6 considers it very likely that human influence is the main driver of the global retreat of glaciers since the 1990's and has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades. There is only limited evidence, with medium agreement, of human influence on the Antarctic Ice Sheet mass loss. Nonetheless, the impact of such mass loss on rising sea levels could be catastrophic because the ice sheet contains some 30 million cubic kilometers.

AR6 poses five shared socioeconomic pathways, or future scenarios ranging from very low greenhouse gas emissions to high emissions. Modeling these pathways establishes a cause-effect chain, from anthropogenic emissions, to changes in atmospheric concentration, to changes in the Earth's energy balance, to changes in global climate and ultimately regional climate and climatic impact drivers. Modeling yields best estimates of future climate conditions (decadal and century), and a range of global warming levels corresponding to emission scenarios. AR6 predicts a minimum of 1.4°C warming for the lowest emissions scenario, temporarily overshooting to 1.6°C in the next decades. It predicts a 21st-century warming of 4.4°C for the high emissions scenario. The intermediate scenario yields 2.7°C (4.9°F) of total warming by 2100. Even this scenario is optimistic – roughly represented by national commitments made so far under the 2015 Paris Agreement.

While the 2021 installment of AR6 by Working Group I (WGI) assesses the physical science basis of climate change, WGII will assess associated impacts, vulnerability, and adaptation options. WGIII will assess mitigation response options and explore synergies and tradeoffs between mitigation and adaptation. WGII and WGIII reports won't be released until 2022, but they are expected to call for

urgent action. The AR6 WGI report expresses high confidence that additional ecosystem responses to warming are not yet fully included in climate models, such as CO_2 and methane fluxes from wetlands, permafrost thaw and wildfires, which will further increase concentrations of these gases in the atmosphere. Such feedbacks will accelerate with warming temperatures. AR6 also states with very high confidence that changes in global ocean temperature and deep ocean acidification are irreversible on centennial to millennial time scales. This makes human action both more imperative and more tempting to postpone.

Along with fossil fuel curtailment, the option of direct carbon removal will no doubt be addressed by WGII. But its prospects for implementation in the near term appear bleak. Except for natural carbon sinks like vegetation, permanently removing CO_2 directly from the atmosphere presents a daunting challenge. The demands of efficiency and scalability render currently available technologies unrealistic.

Despite the already built-in warming of the planet and lasting impacts of human emissions to date, AR6 offers some hope. It is virtually certain that global surface temperature rise, and associated climate changes can be limited through rapid and substantial reductions in global greenhouse gas emissions. But the opposite is also true. Inaction will compound currently observed climate trends. Modeled outcomes for a broad range of indicators increasingly diverge through the 21st century across the different scenarios. Due to the slow response of the deep ocean and ice sheets, this divergence continues long after 2100. 21st century emissions choices will not only dictate climate change for the next few generations but will have implications for sea level rise for centuries to millennia.

The human response to climate change will likely be driven by social and political forces more than by technological advances. AR6 recognizes that scientific knowledge interacts with pre-existing conceptions of weather and climate, including values and beliefs stemming from ethnic or national identity, traditions, religion or lived relationships to land and sea. But it also asserts that science has values of its own, including objectivity, openness, and evidence-based thinking. Despite (or perhaps because of) the preponderance of evidence presented in AR6, social values may guide the choices made over the coming decades.