APPENDIX A

IPCC Fourth Assessment Report Climate Projections

(Supplemental to Chapter 2)

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These robust conclusions, which we believe also apply to the climate projections from the SAP 2.1a scenarios (Clarke *et al*., 2007), are taken primarily from the Executive Summary of Chapter 10 of the IPCC's Fourth Assessment Report (Meehl *et al*., 2007) as well as some details extracted from the body of Chapter 10, and are summarized below.

A.1 MEAN TEMPERATURE

All Atmosphere-Ocean General Circulation Models (AOGCMs) in Chapter 10 of the Fourth Assessment Report (AR4) (Meehl *et al*., 2007) project increases in global mean surface air temperature (SAT) throughout the twenty-first century, with the warming proportional to the associated radiative forcing. There is close agreement among globally averaged SAT multi-model mean warming for the early twenty-first century for the three SRES (B1, A1B and A2) scenarios as well as for SAP 2.1a Level 2 through 4 scenarios out to 2050. The warming rate over the next few decades in Chapter 10 (Meehl *et al*., 2007) is affected little by different scenario assumptions or different model sensitivities, and is similar to that observed for the past few decades. By mid-century (2046 to 2065), the choice of SRES scenario becomes more important and they start to separate, though the range among the collection of AOGCMs is comparable. By the end of the twenty-first century, the SATs generated by MAGICC using the 12 SAP 2.1a scenarios in Chapter 2 as well as the full spread of all of the AOGCMs for the A2, B1 and Committed projections have completely separated, though A1B still has some overlap with A2 and B1.

In general, geographical patterns of projected SAT warming show greatest temperature increases over land (roughly twice the global average temperature increase) and at high northern latitudes, and show less warming over the southern oceans and North Atlantic, consistent with observations during the latter part of the twentieth century. These patterns are similar across the B1, A1B, and A2 scenarios (see Figure 10.8 in Chapter 10 of the AR4; Meehl *et al*., 2007) only increasing in magnitude with increasing radiative forcing. Results for the stabilization emission scenarios similar to those studied here should show the same pattern similarities at least out to 2100 (Dai *et al*., 2001a,b). It should be noted that, in none of the cases considered here, has the climate stabilized by 2100; for the higher stabilization levels this may take centuries. Temperature change patterns may differ as one approaches closer to a stable climate.

A.2 TEMPERATURE EXTREMES

It is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly in a future warmer climate. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the mid and high latitudes, with a comparable increase in growing season length (Meehl *et al*., 2007).

A.3 MEAN PRECIPITATION

Globally averaged mean atmospheric water vapor, evaporation and precipitation are projected to increase. By 2100, precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific in particular, with general decreases in the subtropics, and increases at high latitudes as a consequence of a general intensification of the global hydrological cycle. The geographical patterns of precipitation change during the twenty-first century are not as consistent across AOGCMs and across scenarios as they are for surface temperature (Meehl *et al.*, 2007).

A.4 PRECIPITATION EXTREMES AND DROUGHTS

Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation. There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions. Precipitation extremes increase more than the mean in most tropical and mid- and high-latitude areas (Meehl *et al.*, 2007).

A.5 SNOW AND ICE

As the climate warms, snow cover and sea ice extent decrease; glaciers and ice caps lose mass owing to dominance of summer melting over winter precipitation increases. There is a projected reduction of sea ice in the twenty-first century both in the Arctic and Antarctic with a large range of model responses. Widespread increases in thaw depth over much of the permafrost regions are projected to occur in response to warming over the next century (Meehl *et al.*, 2007).

Note: All of the AR4 predictions for precipitation, snow cover, and sea and land ice are less certain and more variable across the suite of AOGCMs than they are for both the global average and the more robust geographic patterns of temperature.

A.6 CARBON CYCLE

Under the SRES illustrative emissions scenarios, for central carbon-cycle model parameters, CO_2 concentrations are projected to increase from its present value of about 380 ppm to 540 to 970 ppm by 2100. The SAP 2.1a Reference scenarios give 2100 concentrations of 740 to 850 ppm (Clarke *et al.*, 2007). There is unanimous agreement among the simplified climate-carbon cycle models that future climate change would reduce the efficiency of the Earth system (land and ocean) to absorb anthropogenic carbon dioxide. The higher the stabilization emission scenario warming, the larger is the impact on the carbon cycle. Both MAGICC and two of the three integrated assessment models used in SAP 2.1a contain simplified carbon cycle models comparable to those in Chapter 10 of the AR4 (Meehl *et al.*, 2007).

A.7 OCEAN ACIDIFICATION

Increasing atmospheric CO_2 concentrations lead directly to increasing acidification of the surface ocean. Multi-model projections based on SRES scenarios give reductions in pH of between 0.14 and 0.35 units over the twenty-first century, adding to the present decrease of 0.1 units from preindustrial times.

A.8 SEA LEVEL

"Sea level is projected to rise between the present (1980 to 1999) and the end of this century (2090 to 2099) under the SRES B1 scenario by 0.28 m for the multi-mode average (range 0.19 to 0.37 m), under A1B by 0.35 m (0.23 to 0.47 m), under A2 by 0.37 m (0.25 to 0.50 m) and under A1FI by 0.43 m (0.28 to 0.58 m). These are central estimates with 5 to 95 percent intervals based on AOGCM results, not including uncertainty in carbon-cycle feedbacks. In all scenarios, the average rate of rise during the twenty-first century very likely exceeds the 1961 to 2003 average rate (1.8 ± 0.5 mm per year). During 2090 to 2099 under A1B, the central estimate of the rate of rise is 3.8 mm per year. For an average model, the scenario spread in sea-level rise is only 0.02 m by the middle of the century, and by the end of the century it is 0.15 m (Meehl *et al.*, 2007)". The projections of sea-level rise for the 12 SAP 2.1a scenarios by MAGICC are within the range reported by AR4 (Wigley *et al.*, 2007).

"Thermal expansion is the largest component, contributing 60 to 70 percent of the central estimate in these projections for all scenarios. Glaciers, ice caps and the Greenland ice sheet are also projected to contribute positively to sea level. GCMs indicate that the Antarctic ice sheet will receive increased snowfall without experiencing substantial surface melting, thus gaining mass and contributing negatively to sea level. Further accelerations in ice flow of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams could substantially increase the contribution from the ice sheets. Current understanding of these effects is limited, so quantitative projections cannot be made with confidence (Meehl *et al.*, 2007)".

A.9 OCEAN CIRCULATION

a. There is no consistent change in the ENSO for those AOGCMs with a quasi-realistic base state.
b. Among those models with a realistic Atlantic Meridional Overturning Circulation (MOC), while it is very likely that the MOC will slow by 2100, there is little agreement among models for the magnitude of the slow-down. Models agree that the MOC will not shut down completely (Meehl *et al.*, 2007).

A.10 MONSOONS

Current AOGCMs predict that, in a warmer climate, there will be an increase in precipitation in both the Asian monsoon (along with an increase in interannual variability) and the southern part of the West African monsoon with some decrease in the Sahel in northern summer, as well as an increase in the Australian monsoon in southern summer. The monsoonal precipitation in Mexico and Central America is projected to decrease in association with increasing precipitation over the eastern equatorial Pacific. However, the uncertain role of particles complicates the projections of monsoon precipitation, particularly in the Asian monsoon (Meehl *et al.*, 2007).

A.11 TROPICAL CYCLONES (HURRICANES AND TYPHOONS)

The Summary for Policymakers finds it *likely* that intense hurricanes and typhoons will increase through the twenty-first century as it warms. Results from embedded high-resolution models and global models, ranging in grid spacing from 1 degree to 9 km, generally project increased peak wind intensities and notably, where analyzed, increased near-storm precipitation in future tropical cyclones (Meehl *et al.*, 2007). However, these questions of changes in frequency and intensity under global warming continue to be the subject of very active research (CCSP, 2008; Emanuel *et al*., 2008; Knutson *et al*., 2008).

A.12 MIDLATITUDE STORMS

Model projections show fewer midlatitude storms averaged over each hemisphere, associated with the poleward shift of the storm tracks that is particularly notable in the Southern Hemisphere, with lower central pressures for these poleward-shifted storms. The increased wind speeds result in more extreme wave heights in those regions (Meehl *et al.*, 2007).

A.13 RADIATIVE FORCING

"The radiative forcings by long-lived greenhouse gases computed with the radiative transfer codes in twenty of the AOGCMs used in the AR4 have been compared against results from benchmark line-by-line (LBL) models. The mean AOGCM forcing over the period 1860 to 2000 agrees with the mean LBL value to within 0.1 W per m^2 at the tropopause. However, there is a range of 25 percent in longwave forcing due to doubling CO_2 from its concentration in 1860 across the ensemble of AOGCM codes. There is a 47 percent relative range in longwave forcing at 2100 contributed by all greenhouse gases in the A1B scenario across the ensemble of AOGCM simulations. These results imply that the ranges in climate sensitivity and climate response from models discussed in this chapter may be due in part to differences in the formulation and treatment of radiative processes among the AOGCMs (Meehl *et al.*, 2007)".

A.14 CLIMATE CHANGE COMMITMENT (TEMPERATURE AND SEA LEVEL)

"Results from the AOGCM multi-model climate change commitment experiments (concentrations stabilized for 100 years at year 2000 for twentieth century commitment, and at 2100 values for B1 and A1B commitment) indicate that if greenhouse gases were stabilized, then a further warming of 0.5°C would occur (Meehl *et al.* 2007)".

"If concentrations were stabilized at A1B levels in 2100, sea-level rise due to thermal expansion in the twenty-second century would be similar to the twenty-first, and would amount to 0.3 to 0.8 m above present by 2300. The ranges of thermal expansion overlap substantially for stabilization at different levels, since model uncertainty is dominant; A1B is given here because most model results are available for that scenario. Thermal expansion would continue over many centuries at a gradually decreasing rate, reaching an eventual level of 0.2 to 0.6 m per degree of global warming relative to present (Meehl *et al.*, 2007)".