References to Clouds in the IPCC Report AR4

TS.1 - **Key uncertainties include aspects of the roles played by clouds**, the cryosphere, the oceans, land use and couplings between climate and biogeochemical cycles.

TS.2.2 - Anthropogenic aerosols effects on water clouds cause an indirect cloud albedo effect (referred to as the fi rst indirect effect in the TAR), which has a best estimate for the fi rst time of –0.7 [–0.3 to –1.8] W m–2. The number of global model estimates of the albedo effect for liquid water clouds has increased substantially since the TAR, and the estimates have been evaluated in a more rigorous way. The estimate for this radiative forcing comes from multiple model studies incorporating more aerosol species and describing aerosol-cloud interaction processes in greater detail. Model studies including more aerosol species or constrained by satellite observations tend to yield a relatively weaker cloud albedo effect.
Despite the advances and progress since the TAR and the reduction in the spread of the estimate of the forcing, there remain large uncertainties in both measurements and modelling of processes, leading to a low level of scientifi c understanding, which is an elevation from the very low rank in the TAR. {2.4, 7.5, 9.2}
Other effects of aerosol include a cloud lifetime effect, a semi-direct effect and aerosol-ice cloud interactions. These are considered to be part of the climate response rather than radiative forcings. {2.4, 7.5}

TS.4.5 - Cloud feedbacks (particularly from low clouds) remain the largest source of uncertainty.

Box TS.8 - Although the large-scale dynamics of these models are comprehensive, **parametrizations are still used to represent unresolved physical processes such as the formation of clouds and precipitation**, ocean mixing due to wave processes and the formation of water masses, etc. **Uncertainty in parametrizations is the primary reason why climate projections differ between different AOGCMs.**

TS.6.4.2 - Large uncertainties remain about how clouds might respond to global climate change.

2 - Executive Summary - The total direct aerosol RF as derived from models and observations is estimated to be –0.5 [±0.4] W m–2, with a medium-low level of scientifi c understanding. The RF due to the **cloud albedo effect** (also referred to as fi rst indirect or Twomey effect), in the context of liquid water clouds, is estimated to be –0.7 [–1.1, +0.4] W m–2, with a **low level of scientifi c understanding**.

2.4 - The TAR considered the cloud albedo effect to be a key uncertainty in the RF of climate but did not assign a best estimate of the RF, and showed a range of RF between 0 and –2 W m–2 in the context of liquid water clouds.
[...]
The TAR also discussed the impact of anthropogenic aerosols on the formation and modification of the physical and radiative properties of ice clouds (Penner et al., 2001), although quantification of an RF from this mechanism was not considered appropriate given **the host of uncertainties and unknowns surrounding ice cloud nucleation and physics**.

2.4.4.7 - Finally, cloud contamination of satellite products, aerosol absorption above clouds, not accounted for in some of the measurement-based estimates, and the complex assumptions about aerosol properties in both methods can contribute to the present discrepancy and increase uncertainty in aerosol RF.
[...]
As mentioned above, uncertainty in the vertical position of absorbing aerosol relative to clouds can lead to large uncertainty in the TOA aerosol RF.

3 - Executive Summary - Surface and satellite observations disagree about total and low-level cloud changes over the ocean.

3.4.3 - Clouds play an important role in regulating the flow of radiation at the top of the atmosphere and at the surface. They are also integral to the atmospheric hydrological cycle via their integral influence on the balance between radiative and latent heating. **The response of cloud cover to increasing greenhouse gases currently represents the largest uncertainty in model predictions of climate sensitivity** (see Chapter 8).

3.4.3.2 - Analyses of the spatial trends in ISCCP cloud cover reveal changing biases arising from changes in satellite view angle and coverage that affect the global mean anomaly time series (Norris, 2000; Dai et al., 2006). The ISCCP spurious variability may occur primarily in low-level clouds with the least optical thickness (the ISCCP 'cumulus' category; Norris, 2005a), due to discontinuities in satellite view angles associated with changes in satellites. Such biases likely contribute to ISCCP's negative cloud cover trend, although **their magnitude and impact on radiative flux calculations using ISCCP cloud data are not yet known.** Additional artefacts, including radiometric noise, navigation and rectification errors are present in the ISCCP data (Norris, 2000), but **the effects of known and unknown artefacts on ISCCP cloud and flux data have not yet been quantified. Other satellite data sets show conflicting decadal changes in total cloud cover.** For example, analysis of cloud cover changes from the HIRS shows a slight increase in cloud cover between 1985 and 2001 (Wylie et al., 2005). However, spurious changes have also been identifi ed in the HIRS data set, which may affect its estimates of decadal variability. One important source of uncertainty results from the drift in Equatorial Crossing Time (ECT) of polar-orbiting satellite measurements (e.g., HIRS and the Advanced Very High Resolution Radiometer; AVHRR), which aliases the large diurnal cycle of clouds into spurious lower-frequency variations. After correcting for ECT drift and other small calibration errors in AVHRR measurements of cloudiness, Jacobowitz et al. (2003) found essentially no trend in cloud cover for the tropics from 1981 to 2000.

While the variability in surface-observed upper-level cloud cover has been shown to be consistent with that observed by ISCCP (Norris, 2005a), the variability in total cloud cover is not, implying differences between ISCCP and surface-observed low cloud cover. Norris (2005a) shows that even after taking into account the difference between surface and satellite views of low-level clouds, the decadal changes between the ISCCP and surface data sets still disagree. The extent to which this results from differences in spatial and temporal sampling or differences in viewing perspective is unclear.

In summary, while there is some consistency between ISCCP, ERBS, SAGE II and surface observations of a reduction in high cloud cover during the 1990s relative to the 1980s, there are substantial uncertainties in decadal trends in all data sets and at present there is no clear consensus on changes in total cloudiness over decadal time scales.

3.4.4.1 Top-of-Atmosphere Radiation - [long discussion including reference to Palle] - In summary, although there is independent evidence for decadal changes in TOA radiative fluxes over the last two decades, **the evidence is equivocal**. Changes in the planetary and tropical TOA radiative fluxes are consistent with independent global ocean heat-storage data, and are expected to be dominated by changes in cloud radiative forcing. **To the extent that they are real, they may simply reflect natural low-frequency variability of the climate system.**

7.5.2 - **Cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates and the relatively poor simulation of boundary layer clouds in the present climate is a reason for some concern (see Chapter 8). Therefore the results discussed below need to be considered with caution.**

8 - Executive Summary - In some models, simulation of marine lowlevel clouds, which are important for correctly simulating sea surface temperature and cloud feedback in a changing climate, has also improved. Nevertheless, **important deficiencies remain in the simulation of clouds and tropical precipitation (with their important regional and global impacts)**.

[...]

Recent studies reaffirm that **the spread of climate sensitivity estimates among models arises primarily from inter-model differences in cloud feedbacks. The shortwave impact of changes in boundary-layer clouds, and to a lesser extent midlevel clouds, constitutes the largest contributor to inter-model differences in global cloud feedbacks. The relatively poor simulation of these clouds in the present climate is a reason for some concern. The response to global warming of deep convective clouds is also a substantial source of uncertainty in projections since current models predict different responses of these clouds. Observationally based evaluation of cloud feedbacks indicates that climate models exhibit different strengths and weaknesses, and it is not yet possible to determine which estimates of the climate change cloud feedbacks are the most reliable.**

[...]

Significant uncertainties, in particular, are associated with the representation of clouds, and in the resulting cloud responses to climate change.

[...]

Models continue to have significant limitations, such as in their representation of clouds, which lead to uncertainties in the magnitude and timing, as well as regional details, of predicted climate change.

8.3.1.1 [re mean surface temperature] - **Outside the polar regions, relatively large errors are evident in the eastern parts of the tropical ocean basins, a likely symptom of problems in the simulation of low clouds. The extent to which these systematic**

model errors affect a model's response to external perturbations is unknown, but may be signifi cant (see Section 8.6).

8.3.1.1.2 - At most latitudes, the difference between the multi-model mean zonally averaged outgoing SW radiation and observations is in the annual mean less than 6 W m–2 (i.e., an error of about 6%; see Supplementary Material, Figure S8.5). Given that clouds are responsible for about half the outgoing SW radiation, **these errors are not surprising, for it is known that cloud processes are among the most difficult to simulate with models** (see Section 8.6.3.2.3).

8.3.4.3 - In comparison to global surface observations, Wild (2005) concluded that many climate models overestimate surface absorption of solar radiation partly due to **problems in the parametrizations of atmospheric absorption, clouds and aerosols**.

8.6.3.2 - **In many climate models, details in the representation of clouds can substantially affect the model estimates of cloud feedback and climate sensitivity** (e.g., Senior and Mitchell, 1993; Le Treut et al., 1994; Yao and Del Genio, 2002; Zhang, 2004; Stainforth et al., 2005; Yokohata et al., 2005). **Moreover, the spread of climate sensitivity estimates among current models arises primarily from inter-model differences in cloud feedbacks** (Colman, 2003a; Soden and Held, 2006; Webb et al., 2006; Section 8.6.2, Figure 8.14). **Therefore, cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates.**

8.6.3.2.1 [***note clouds being considered only as "feedbacks"***] - The Earth's cloudiness is associated with a large spectrum of cloud types, ranging from low-level boundary-layer clouds to deep convective clouds and anvils. Understanding cloud feedbacks requires an understanding of how a change in climate may affect the spectrum and the radiative properties of these different clouds, and an estimate of the impact of these changes on the Earth's radiation budget. Moreover, since cloudy regions are also moist regions, a change in the cloud fraction matters for both the water vapour and the cloud feedbacks (Pierrehumbert, 1995; Lindzen et al., 2001). Since the TAR, there have been some advances in the analysis of physical processes involved in cloud feedbacks, thanks to the combined analysis of observations, simple conceptual models, cloud-resolving models, mesoscale models and GCMs (reviewed in Bony et al., 2006).
[...]

Therefore, **understanding of the physical processes that control the response of boundary-layer clouds and their radiative properties to a change in climate remains very limited.**
[...]
The sign of the climate change radiative feedback associated with the combined effects of dynamical and temperature changes on extratropical clouds is still unknown.
The role of polar cloud feedbacks in climate sensitivity has been emphasized by Holland and Bitz (2003) and Vavrus (2004). **However, these feedbacks remain poorly understood.**

8.6.3.2.3 - **An observational test focused on the global response of clouds to seasonal variations has been proposed to evaluate model cloud feedbacks (Tsushima et al., 2005), but has not yet been applied to current models. These studies highlight some common biases in the simulation of clouds by current models** (e.g., Zhang et al., 2005). This includes the over-prediction of optically thick clouds and the under-prediction of optically thin low and middle-top clouds. However, **uncertainties remain in the observational determination of the relative amounts of the different cloud types** (Chang and Li, 2005). For mid-latitudes, these biases have been interpreted as the consequence of **the coarse resolution of climate GCMs and their resulting inability to simulate the right strength of ageostrophic circulations** (Bauer and Del Genio, 2006) and the right amount of sub-grid scale variability (Gordon et al., 2005). **Although the errors in the simulation of the different cloud types may eventually compensate and lead to a prediction of the mean CRF in agreement with observations (see Section 8.3), they cast doubts on the reliability of the model cloud feedbacks.** For instance, given the nonlinear dependence of cloud albedo on cloud optical depth, the overestimate of the cloud optical thickness implies that a change in cloud optical depth, even of the right sign and magnitude, would produce a too small radiative signature. Similarly, the under-prediction of low- and mid-level clouds presumably affects the magnitude of the radiative response to climate warming in the widespread regions of subsidence. **Modelling assumptions controlling the cloud water phase (liquid, ice or mixed) are known to be critical for the prediction of climate sensitivity. However, the evaluation of these assumptions is just beginning** (Doutriaux-Boucher and Quaas, 2004; Naud et al., 2006). Tsushima et al. (2006) suggested that observations of the distribution of each phase of cloud water in the current climate would provide a substantial constraint on

the model cloud feedbacks at middle and high latitudes.
As an attempt to assess some components of the cloud response to a change in climate, several studies have investigated the ability of GCMs to simulate the sensitivity of clouds and CRF to interannual changes in environmental conditions. When examining atmosphere-mixed-layer ocean models, Williams et al. (2006) found for instance that by considering the CRF response to a change in large-scale vertical velocity and in lower-tropospheric stability, a component of the local mean climate change cloud response can be related to the present-day variability, and thus evaluated using observations. Bony and Dufresne (2005) and Stowasser and Hamilton (2006) examined the ability of the AOGCMs of Chapter 10 to simulate the change in tropical CRF to a change in SST, in large-scale vertical velocity and in lower-tropospheric RH. They showed that the models are most different and least realistic in regions of subsidence, and to a lesser extent in regimes of deep convective activity. **This emphasizes the necessity to improve the representation and the evaluation of cloud processes in climate models, and especially those of boundary-layer clouds.**

8.6.4 - **A number of diagnostic tests have been proposed since the TAR (see Section 8.6.3), but few of them have been applied to a majority of the models currently in use. Moreover, it is not yet clear which tests are critical for constraining future projections. Consequently, a set of model metrics that might be used to narrow the range of plausible climate change feedbacks and climate sensitivity has yet to be developed.**

9.2.2.2 (discussion of outgoing SW flux) - **Wielicki et al. (2002) explain the observed downward trend by decreases in cloudiness, which are not well represented in the models on these decadal time scales** (Chen et al., 2002; Wielicki et al., 2002).

10.3.2.2 - The change in mean cloud radiative forcing has been shown to have different signs in a limited number of previous modelling studies (Meehl et al., 2004b; Tsushima et al., 2006). **Figure 10.11a shows globally averaged cloud radiative forcing changes for 2080 to 2099 under the A1B scenario for individual models of the data set, which have a variety of different magnitudes and even signs.** The ensemble mean change is –0.6 W m–2. **This range indicates that cloud feedback is still an uncertain feature of the global coupled models** (see Section 8.6.3.2.2).

Box 10.2 - Confidence has increased in the strength of water vapour-lapse rate feedbacks, whereas **cloud feedbacks (particularly from low-level clouds) have been confirmed as the primary source of climate sensitivity differences** (see Section 8.6).

10.5.4.3 - Soden and Held (2006) find that **differences in cloud feedback are the dominant source of uncertainty** in the transient response of surface temperature in the AR4 ensemble (see also Section 8.6.3.2), as in previous IPCC assessments. Webb et al. (2006) compare equilibrium radiative feedbacks in a 9-member multi-model ensemble against those simulated in a 128-member perturbed physics ensemble with multiple parameter perturbations. They find that the ranges of climate sensitivity in both ensembles are explained mainly by differences in the response of shortwave cloud forcing in areas where changes in low-level clouds predominate. Bony and Dufresne (2005) find that marine boundary layer clouds in areas of large-scale subsidence provide the largest source of spread in tropical cloud feedbacks in the AR4 ensemble. Narrowing the uncertainty in cloud feedback may require both improved parametrizations of cloud microphysical properties (e.g., Tsushima et al., 2006) and improved representations of cloud macrophysical properties, through improved parametrizations of other physical processes (e.g., Williams et al., 2001) and/or increases in resolution (Palmer, 2005).

11.8 - **Processes that are not particularly well represented in the models are clouds**, planetary boundary layer processes and sea ice.