EU Cloud Intercomparison, Process Study and Evaluation Project
EUCLIPSE
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Report of the Main Results and Legacy

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Abstract

The FP7 European Union Cloud Intercomparison, Process Study and Evaluation Project (EUCLIPSE) helped propel European climate science to the forefront of the field internationally. EUCLIPSE germinated one of the most important new international climate science initiatives, the World Climate Research Programme's grand science challenge on clouds, circulation and climate sensitivity, and made major scientifc contributions which underpinned, and in some cases have already eclipsed, the fifth assessment report of the IPCC (AR5). As a result of EUCLIPSE it is now understood why climate sensitivity, a simple measure of the expected average warming of the Earth from a doubling of atmospheric CO2, remains the most vital issue in climate science. Cloud feedbacks have ceased to be a riddle rapped in a mystery inside an enigma, and by linking cloud processes to the structure of the atmospheric circulation and its propensity to change, a foundation has been laid for understanding regional climate changes. Building on the legacy of earlier EU projects (EUClouds and EUROCS) EUCLIPSE has bridged the gaps between distinct cultures, irreversibly linking experts in atmospheric processes to broader questions of climate change, in so doing it has helped develop a uniquely European expertise on some of the most critical questions in climate science, by organically linking activities and interests of Europe's leading climate research laboratories with one another, and with broader expertise within the university community.

1 Introduction

The wealth of results that came out of the EUCLIPSE project have been published in more than 70 peer reviewed articles, of which more than 10 have been used in the fifth assessment report of the IPCC (AR5). All European climate models that participated in EUCLIPSE run now routinely with satellite simulators making more objective evaluations of these climate models with satellite products possible on a routine basis. These climate models have all been participating in a large number of model experiments as described in the second phase of the Cloud Model Feedback Intercomparison Project (CFMIP2). The output of these model experiments are all archived for a period of at least 10 years and freely accessible, and advanced diagnostic tools that can be used to analyse climate model results have been made available. The purpose of this document to provide an short overview of the most important results of the EUCLIPSE project and summarizing the legacy of the project.

1 Climate Sensitivity

Equilibrium Climate Sensitivity, which defines the global-mean surface temperature change associated with a doubling of CO_2 in the atmosphere, conditions the response of many aspects of the climate system to forcing, both at global and regional scales. The spread of Climate Sensitivity has not reduced over the last three decades, but much progress has been done in interpreting it. The seminal study of climate sensitivity of the EUCLIPSE model ensemble and the CMIP5 models more broadly was that by Vial et al. (2013). This paper played an important role in the AR5 and is a definitive milestone in model based estimates of climate sensitivity. The study goes beyond previous work by understanding and quantifying the contributions of adjustments to inter model spread in climate sensitivity.

The CMIP5 multimodel results are shown in Figure 1. When the multimodel mean of 3.45 K is decomposed into regions, it shows that the main contribution comes from the tropics. In terms of processes, 43% of the global warming is associated with the direct response to CO2 forcing. (36% for the stratosphere-adjusted forcing and 7% for the adjustments), and 57 % from the feedbacks: 32 % of the warming arises from the combined water vapour/lapse rate, 10 % from clouds, 8 % from surface albedo and 7 % from the feedback residual term. The cloud adjustments are generally positive and can hence be associated with a reduced strength of the cloud feedback.

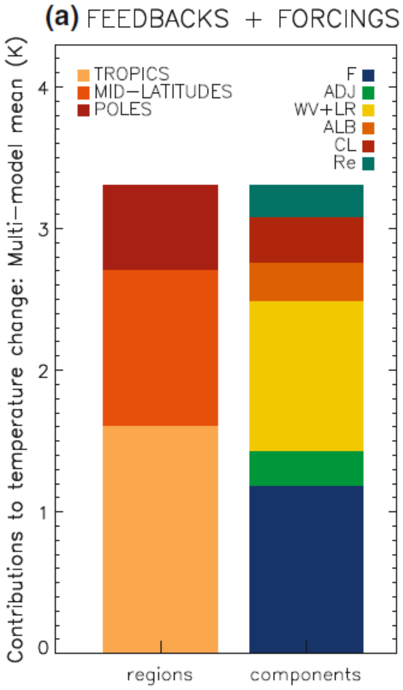

Figure 1: a multi-model mean of the climate sensitivity separated into regional contributions: the tropics (between 30_S and 30_N), the mid-latitudes (between 30_and 60_ in each hemisphere) and the poles (between 60_ and 90_ in each hemisphere) (left) and into its different components, including the Planck response to stratosphere-adjusted forcing (F), the Planck response to the adjustments to CO2 forcing and land surface warming (ADJ), the combined water vapour/ lapse rate (WV/LR). (Figure from Vial et al. 2013)

Nonetheless the large feedback differences between models, primarily originates from clouds in weakly subsiding regions of the tropics, accounting for most (70 %) of the inter model spread (see Figure 2)

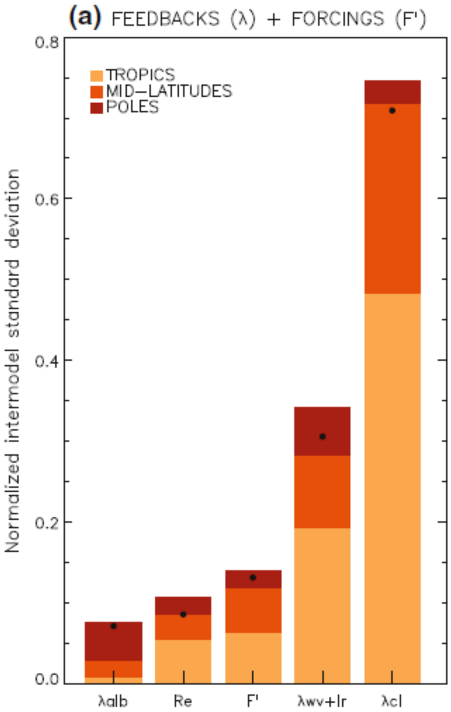

Figure 2: The inter-model standard deviation of climate sensitivity of the feedback responses estimates associated with the atmosphere-adjusted forcing based on six model that have a small residual contribution for this decomposition method). (Figure from Vial et al. 2013)

.Brient and Bony (2012, 2013) analyzed the processes underlying the strong low-cloud feedbacks in the IPSL model. They found that the feedback processes were exaggerated by an overly strong low-cloud radiative effect, something termed the beta effect. By constraining this amplification of the low-cloud feedback they showed that the low-cloud feedback of the IPSL-model is overestimated by about 50% owing to its over-estimate of cloud-radiative effects. Accounting for a smaller cloud feedback would reduce the IPSL model climate sensitivity from a value of about 3.9 K as cited in Vial et al. (2013), to a value nearer to 3 K.

Mauritsen and Stevens (2014) introduced a crude representation of the effects of convective organization on the precipitation efficiency of convection under the presumption, based on process models, that convection organizes more readily in a warmer climate. This reduced the climate sensitivity of the MPI-ESM from about 2.8 to about 2.2 K, although the coupled version of the same model has a higher base sensitivity (3.7 K in Vial et al. (2013) and between 2.9 and 3.7 K in Stevens et al. (2013)) In this revised version of the ECHAM model the changes in tropical upper tropospheric temperatures were more readily reconciled with observations, and the hydrological sensitivity increased, also more in line with (admittedly disputed) inferences from observations. The study suggests however that convective processes that are currently not included in models could lead to a substantial (20%) reduction in the climate sensitivity. Much larger reductions in the climate sensitivity from such processes have been hypothesized in the literature, and were initially targeted with the introduction of a temperature dependent precipitation efficiency, but because of compensating long and shortwave cloud effects these end up being very difficult to realize in the climate system.

Stevens and Bony (2013) surveyed the existing literature on feedback parameters and separated feedbacks from what they termed robust processes from processes which are much less certain. Examples of robust feedbacks include the combined lapse-rate and water vapor feedback, the surface albedo feedback, and the feedback from changes to tropical high-clouds associated with the tendency of the tropical tropopause to maintain a fixed temperature. They showed, (see Fig. 3, that only accounting for robust feedbacks leads to an estimate of the equilibrium climate sensitivity of about 2.7 K as compared with the average equilibrium climate sensitivity of 3.45 K of the CMIP5 multimodel ensemble with a large spread as a result of a poor understanding of the basic feedbacks in climate models, and partly as a result of cloud processes other than those of the rising tops of tropical ice clouds.

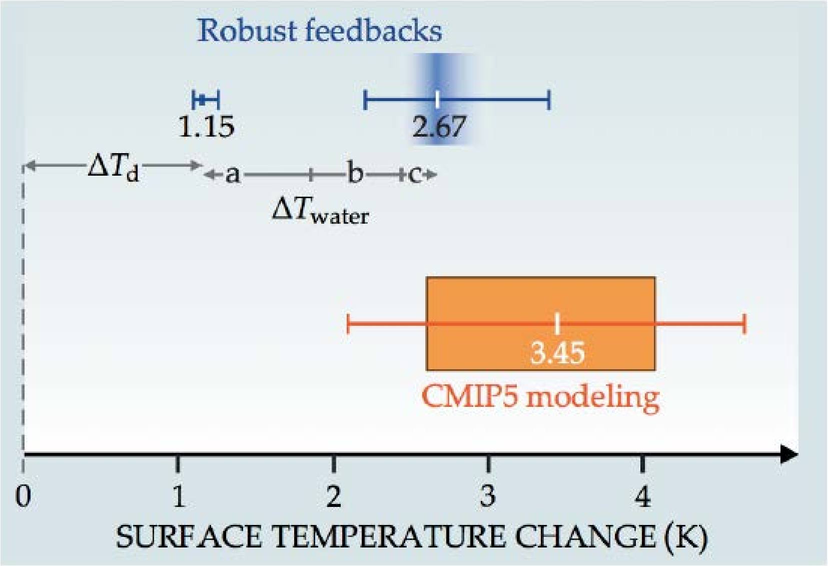

Figure 3: Different measures of the equilibrium climate sensitivity. Taken from Fig.4 of Stevens and Bony (2013).

By constructing a simple model of aerosol forcing which captures the main properties of much more comprehensive models Stevens (2014) explored the time history of aerosol forcing. Using the fact that the aerosol forcing established itself earlier in the industrial period than did greenhouse gas forcing he argued that an aerosol forcing more negative than -0.9 Wm^{-2} is implausible and that a net aerosol forcing of about -0.5 Wm^{-2} is a more plausible central estimate. A smaller magnitude for the aerosol forcing implies a climate sensitivity toward the smaller end of the accepted range, and something more consistent with what was inferred from the observational record by (Otto et al., 2013). Accepting the results from Mauritsen and Stevens (2014) which deliberately attempted to modify processes that would lower the climate sensitivity in their model, but were not able to produce a model with a climate sensitivity of less than 2 K the above results suggest that a climate sensitivity of between 2 and 3 K, smaller than the range (1.5-4.5 K) adopted by AR5. A difficulty with this developing story line of a somewhat lower climate sensitivity, is that convective aggregation processes are poorly understood, and whether or not the ansatz developed by Mauritsen and Stevens (2014) is a reasonable one is very much an open question. Likewise the use of the observational record to infer smaller sensitivities generally fails to account for studies that show feedbacks strengthening as equilibrium is approached.

Other work points, particularly work on emerging constraints, points to a climate sensitivity nearer 4K or even higher. Among these studies perhaps the most convincing is one, which was conducted at LMD (an EUCLIPSE laboratory) with two EUCLIPSE investigators, Sherwood et al. (2014) and is based in large part on ideas developed during the EUCLIPSE project, that shows how models with a climate sensitivity larger than 4 K are more consistent with available data. However, the constraint employed in this study had to be evaluated with the help of reanalyses, and involved a process, lower tropopsheric mixing, which is not well constrained by the observations going into the reanalysis. On the other hand, work on emergent constraints which is less dependent on the reanalyses also points to higher sensitivities, and a great deal of experience shows that it is much easier to build a model with a higher, rather than a lower climate sensitivities. Because the emergent constraint literature articulates specific hypotheses, it provides a basis for evaluating processes thought to be responsible for a particular model's climate sensitivity (many of which build on EUCLIPSE work) and thus a route for reconciling the apparently contradictory story line between a high and low climate sensitivity.

Work within the EUCLIPSE project has been a major advance in our understanding of climate sensitivity. But because much of it appeared concurrently with, or even after, the preparation of the AR5, these advances are not fully reflected in that report. To help communicate these advances to the broader community a special workshop is being organized at the instigation of EUCLIPSE investigators (Bony, Stevens, Webb) to revisit the assessment of climate sensitivity. This workshop is being organized through the WCRP grand challenge on clouds, circulation and climate sensitivity, and will take place after the end of the EUCLIPSE project, but is only possible as a result of the advances and collaborations developed through EUCLIPSE. At the workshop the strengths and weaknesses of story lines for a high versus low climate sensitivity will be explored in more depth.

One might think that is easy to think that the question of the equilibrium climate sensitivity CO2 is passee, an academic abstraction largely irrelevant to policy makers, planners, or the broader society. EUCLIPSE has made important contributions to helping us understand that this is far from the case. Many of the more fine-grained aspects of the climate system appear to be directly related to the equilibrium climate sensitivity. For instance, projections of changes in European temperatures, particularly during the summer, are directly proportional to the climate sensitivity (Cattiaux 2013, see Figure 4). More broadly, although different models predict different patterns of changes, the amplitude of a particular models projected climate change pattern scales remarkably well with the change in the globally averaged surface temperature. Finally uncertainty in changes in globally averaged precipitation have been shown to be dominated by uncertainty in globally averaged surface temperature changes, i.e., the equilibrium climate sensitivity (Bony et al 2013). This work, through EUCLIPSE, contributes to work by others in the broader community, which shows that the climate sensitivity is associated with physiological limits to adaptation, and that the transient climate response is both proportional to and controlled by the same factors as that of the equilibrium climate sensitivity. Hence narrowing climate sensitivity remains the single most vital question of climate science, as no other single number conditions so many aspects of climate change.

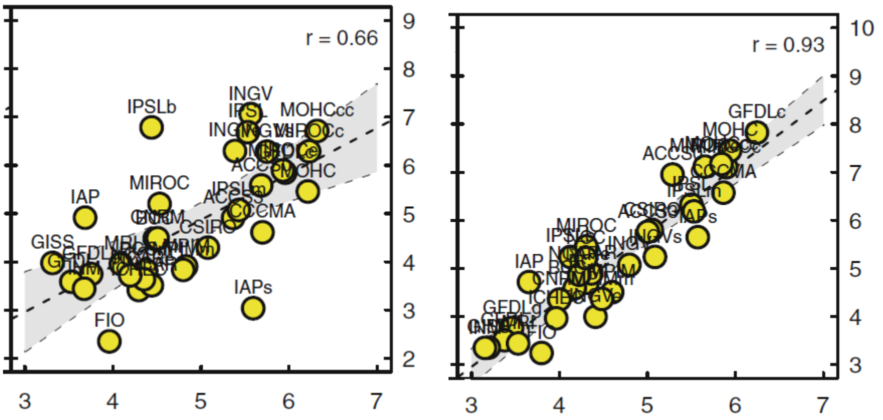

Figure 4: Left: European averages of the differences between winter temperature changes (rcp8.5 –present) plotted versus global projected changes. Right: same for summer temperature differences. Note the strong correlation between global and regional temperature differences.(from Cattiaux et al. 2013)

3 Low Cloud Feedback

Of the major feedbacks on radiative forcing, most (like the surface albedo or water vapour feedback) were identified more than a century ago, when scientists first begin thinking about climate change. The idea that clouds might be an important in determining the equilibrium climate sensitivity really only was raised a few decades ago, and even then there were no clear ideas why clouds should change with a changing climate - a point that gains emphasis when it is realized that then, and now, it has been widely assumed that relative humidity will not change markedly with warming. EUCLIPSE is responsible for the most important new ideas in decades as to why and how climatologically important low-clouds might change in a changing climate, even if the processes that regulate the large-scale patterns of relative humidity change little.

3.1 Shallow Cumulus Clouds

A number of studies of EUCLIPSE investigators point to the fact that low shallow clouds will tend to have a positive feedback when subjected to warming. Rieck et al (2012) showed using Large Eddy Simulations that warming of marine cumulus topped boundary layer with an increased amount of water vapour such as to have an initially constant relative humidity, leads to an increase of the latent heat surface flux, just sufficient to sustain a constant relative humidity. These increased surface latent heat fluxes deepens the cloudy boundary layer, thereby lowers the relative humidity in the boundary layer and a associated decrease of cloud amount, suggesting a positive cloud feedback (see Fig. 5)

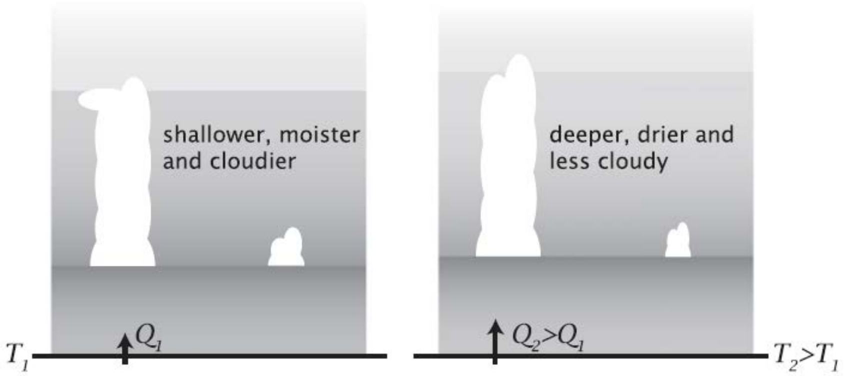

Figure 5: Schematic diagram showing the main response of the cloud-topped boundary layer to a change in temperature, assuming large-scale processes act to keep the humidity constant (taken from Rieck et al 2012)

showed how water vapor fluctuations, an important driver of turbulent mixing in the lower troposphere, increase with warming if the relative humidity stays constant, and that this implies more efficient lower tropospheric mixing which would tend to deepen and dry the lower layers of the troposphere, reducing cloudiness over the ocean, and amplifying warming.

Florent and Brient (2012) have proposed and tested another physical mechanisms for controlling the positive in climate change from an energetic perspective (see Fig. 7). In the present-day climate, tropical marine low clouds primarily occur in regimes of large-scale subsidence. In these regimes, the moist static energy (MSE) of the PBL is increased by surface turbulent fluxes, and decreased by clear-sky radiative cooling, cloud-radiative cooling, and by the downward advection of low MSE from the free troposphere (the typical profile of MSE deficit on the right -defined as the difference between the MSE profile and the 1,000 hPa MSE- shows that the MSE minimum occurs around 700--850 hPa in weak subsidence regimes). Shallow cumulus clouds contribute to the vertical transport of humidity from the PBL to the lower free troposphere, and deep convection controls the free tropospheric temperature profile of the tropical belt. In a warmer climate, the change in the moist-adiabatic stratification of the tropical atmosphere, the enhanced vertical transport of humidity by shallow convection and the deeper PBL due to enhanced surface fluxes all tend lead to a decrease of the vertical gradient of MSE. However, the non-linearity of the Clausius-Clapeyron relationship leads to a larger increase in specific humidity at high temperatures and low altitudes than at lower temperatures and higher altitudes. This leads to an enhanced vertical gradient of specific humidity and MSE between the PBL and the lower free troposphere, and thus an enhanced import of low-MSE and dry air from the free troposphere down to the PBL. This decreases the low-level cloud fraction and weakens the cloud radiative cooling within the PBL. This argument applies mainly for BL cumulus clouds where to cloudtop radiative cooling does not play a decisive role.

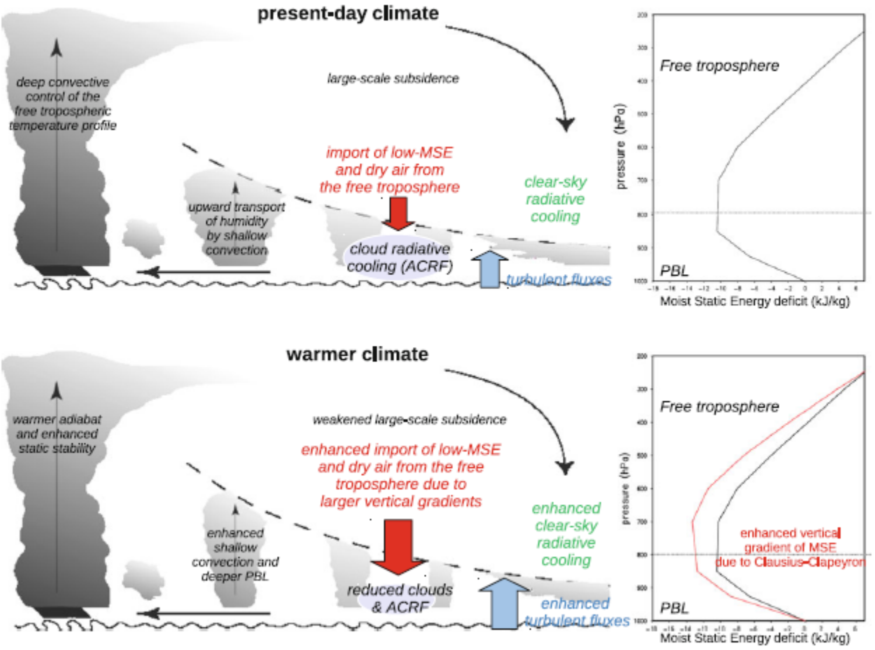

Figure 7: Schematic of the physical mechanisms controlling the positive low-cloud feedback of the IPSL-CM5A-LR OAGCM in climate change analyzed from an energetic perspective (Taken from Brient and Bony 2012)

Finally as part of CFMIP/GASS Intercomparison of Large-Eddy and Single-Column Models (CGILS), a collaboration between two organizations, the Cloud Feedbacks Model Intercomparison Project (CFMIP) and the Global Atmospheric Systems Studies (GASS), within the World Climate Research Program and EUCLIPSE, a number of idealized cases were designed for shallow cumulus (S6), cumulus under stratocumulus (S11) and stratocumulus (S12) over the subtropical ocean. The cases were simulated under state state conditions by Large Eddy Simulation (LES) and repeated under warmer SST conditions. The resulting Cloud Radiative Effect (CRE) of the shallow cumulus clouds (see Figure 9, S6) of all the LES codes are small but all positive and thus qualitatively in line with the hypotheses and results of Rieck et al (2012) and Brient and Bony 2012).

3.2 Stratocumulus

The climate response of stratocumulus to global warming is more complicated, because of the strong interaction of the radiation with the stratocumulus at cloud top. Within EUCLIPSE the stratocumulus response has been investigated with Mixed Layer Models and Large Eddy Simulations and the conceptual picture emerging from these studies (Dal Gesso 2014a, Dal Gesso 2014b) is shown in Fig. 8 (from after Dal Gesso et al 2014). Similar as in Rieck et al (2012) a warmer SST leads to a larger surface evaporation, which makes the boundary layer more energetic and will promote a stronger entrainment at the top of the stratocumulus. If this would be the only mechanism it would lead to a growth of the cloud top height, but also to a decrease of relative humidity, corresponding to a increase as well of cloud base height as well but not so much as the cloud top height so that the net effect is a cloud thickening and hence a negative cloud feedback. But the entrainment at cloud top also depends on the longwave cloud radiative cooling which is a main driving force for stratocumulus. In a wamer atmosphere, the free troposphere is more humid, so that the radiative longwave cooling at the top of the stratocumulus will be less strong leading to a reduction of the top-entrainment and hence to a reduced growth of the cloud top height. Finally there is the effect of subsidence: weaker (stronger) subsidence leads to thicker (thinner) clouds. In summary, there are different cloud responses that also work in different directions. The overall result of a series of mixed layer model studies is that in the absence of subsidence a warmer SST leads to a decreasing cloud thickness and hence to a positive cloud feedback. Moreover increasing SST also promotes the break up of stratocumulus into cumulus, associated with a decrease of cloud cover and hence a positive feedback.

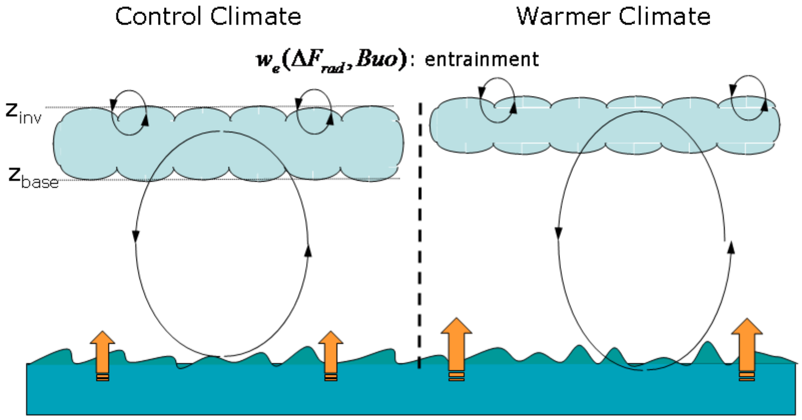

Figure 8: Conceptualisation of how stratocumulus clouds respond to a warming SST based on Mixed Layer Model studies. (inspired from Dal Gesso et al 2014a)

These results are consistent with the Large Eddy Simulations of CGILS for cumulus under stratocumulus (see fig. 9). The stratocumulus case (S12) shows suggests a negative cloud feedback, but this is due to face of a strongly weakened subsidence in the perturbed climate for that case. In Blossey et al 2012) S12 is also simulated with a warmer SST but without a weakened subsidence. In that case all the LES results give indeed a positive cloud feedback in accordance with the Mixed Layer Model results. These results do show however, how delicate the response of stratocumulus depends on the precise nature of the perturbed climate.

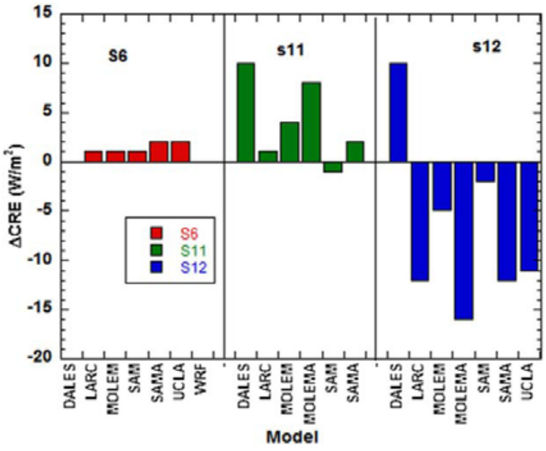

Figure 9: Change in cloud radiative effect for a number of Large Eddy Simulations for shallow cumulus cloud conditions (S6), cumulus under stratocumulus (S11) and stratocumulus (S12). Figure taken from Zhang et al 2013) and simulations are described in Blossey et al (2012).

3.3 Low Cloud Response Mechanisms in Climate Models

Climate models tend to produce a widespread positive low-cloud feedback, but the change in low-cloud varies greatly depending on the model, causing most of the overall spread in climate sensitivities among GCMs. An interpretation of both the positive sign and of the inter-model spread of low-cloud feedback is now emerging, which relates the low-cloud feedback to vertical mixing of humidity in the lower troposphere. In GCMs, this mixing occurs both at the small-scale through transports by shallow cumulus clouds, and at the larger scale through shallow atmospheric circulations (left panel). The mechanism relating mixing to low-cloud feedback is that the low-tropospheric mixing transports moisture vertically and dehydrates the low-cloud layer at a rate that increases as the climate warms, and this rate of increase scales with the initial mixing strength. The simulated strength of convective mixing between the lower and middle tropical troposphere (referred to as *LTMI* in the right-hand side panel) varies substantially among GCMs, and differences explain about half of the variance in climate sensitivity across climate models. The mixing inferred from observations appears to be sufficiently strong to imply a climate sensitivity of more than 3 degrees for a doubling of carbon dioxide (Sherwood et al., Nature, 2014).

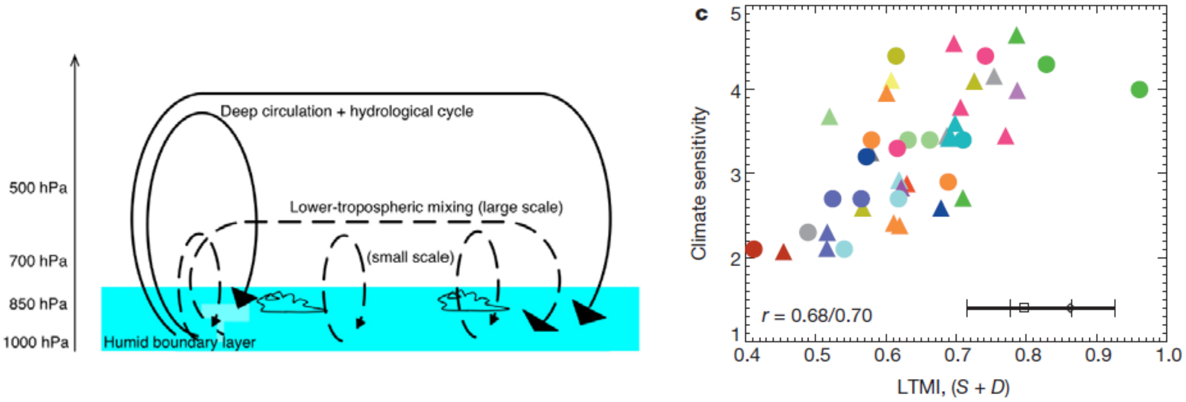

Figure 10: Left: Deep overturning strongly coupled to the hydrological cycle and atmospheric energy budget is shown by solid lines; lower-tropospheric mixing is shown by dashed lines.Right: Relation between the intensity of low tropospheric mixing (LTMI) and the climate model sensitivity for a number of climate models (from Sherwood et al 2014)

3.4 Low Cloud feedback: Not a riddle anymore

All the ideas that arose frome EUCLIPS and were described in the previous sections have proven powerful in understanding the response of climate models to forcing, and helped break a long-standing deadlock in our understanding of the climate system, namely whether or not clouds are contributing to or mitigating against forced changes in the climate system. Because of work in EUCLIPSE it is now thought that clouds act to amplify warming, although to what degree remains open. Before EUCLIPSE it was not understood why cloudiness might depend on Earth's surface temperature, let alone in which sense. Clouds, once a riddle wrapped inside a mystery inside and enigma, are no longer enigmatic, and while riddles remain, even some of the mystery has been removed.

4 Clouds, Precipitation and Circulation

The overall distribution of dry and wet areas over the globe is primarily related to the large-scale atmospheric circulation. In the tropics for instance, wet areas are located in the moist, ascending branches of the tropics (associated with what are known as the Hadley and Walker Circulations) where moisture converges and rises, giving rise to precipitation, while dry areas are located in the descending branches of this circulation. A reason why climate models exhibit great difficulties in predicting the regional distribution of tropical rainfall over a large range of timescales is that they fail to represent this large-scale circulation properly. EUCLIPSE helped understand why this is so, and proposed ways to improve models. The long-standing tendency of models to produce a double ascending branch of the tropical circulation over equatorial oceans instead of a single one as shown by observations (sometimes called the 'double-ITCZ' problem) could be alleviated by increasing the amount of turbulent mixing between clouds and the environmental air around them, and better capturing their coupling to patterns of surface evaporation (Oueslati and Bellon, 2013, Moebis and Stevens 2012).

These studies, and others supported by EUCLIPSE, also showed that a more realistic representation of the tropical convergence zones also improved the representation of important modes of tropical variability, including phenomena such as the Madden-Julian Oscillation and ENSO, both of which are critical to patterns of weather well away from the tropics (i.e. Crueger et al. 2013) .

EUCLIPSE studies also showed how low-cloud radiative effects play an important role in determining the aridity of the arid regions of the tropics, and the strength of the tropical circulation and its response to external forcing, such as might accompany an increase in aerosols in the northern hemisphere as a result of human activity (Fermepin et al. 2014, Voigt et al. 2014).

Climate change affects the regional distribution and amount of precipitation through thermodynamical (ΔP_{therm} and dynamical effects (ΔP_{dyn}). The multi-model mean ΔP_{ther} exhibits a wet-get-wetter, dry-get- drier regional pattern (Fig. 11).

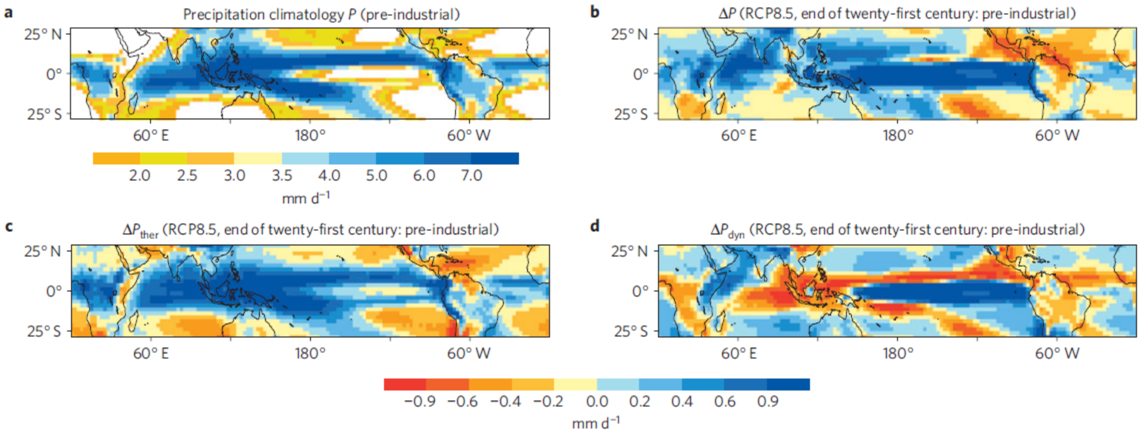

Figure 11 Multi-model mean projection of tropical precipitation changes at the end of the twenty-first century. ***a****, Climatological multi-model mean annual precipitation simulated by sixteen CMIP5 climate models in the pre-industrial climate.* ***b–d****, Multi-model mean change in annual precipitation (in mmd^{-1}) projected by the same models (****b****) and its decomposition ($\Delta P = \Delta P_{ther} + \Delta P_{dyn}$) into thermodynamic ($\Delta P_{ther}$;* ***c****) and dynamic (ΔP_{dyn};* ***d****) components at the end of the twenty-first century in a climate-change scenario without mitigation (RCP8.5).(Figure from Bony at al. Nature Geoscience 2013)*

EUCLIPSE has shown that thermodynamical effects could be diagnosed and understood by investigating the change in precipitation with surface temperature for given circulation regimes (characterized here by their vertical-mean large-scale vertical velocity ϖ). Rising temperatures increase the amount of water vapor in the atmosphere through the Clausius-Clapeyron relationship and enhance surface evaporation. Enhanced evaporation increases precipitation in all regimes, but the change in humidity increases moisture convergence and thus precipitation in convective regimes while it increases moisture divergence and decreases precipitation in subsidence regimes. As a result of both effects, all climate models predict an increase of precipitation with surface temperature in convective regimes, and little change or a decrease of precipitation in subsidence regimes (the solid line shows the multi-model mean and vertical bars the inter-model standard deviation). This thermodynamical response, which can be well approximated by assuming that water vapor increases by 7.5 %/K and surface evaporation increases by 2 %/K (dashed line), explains the 'wet gets wetter, dry gets drier' patter

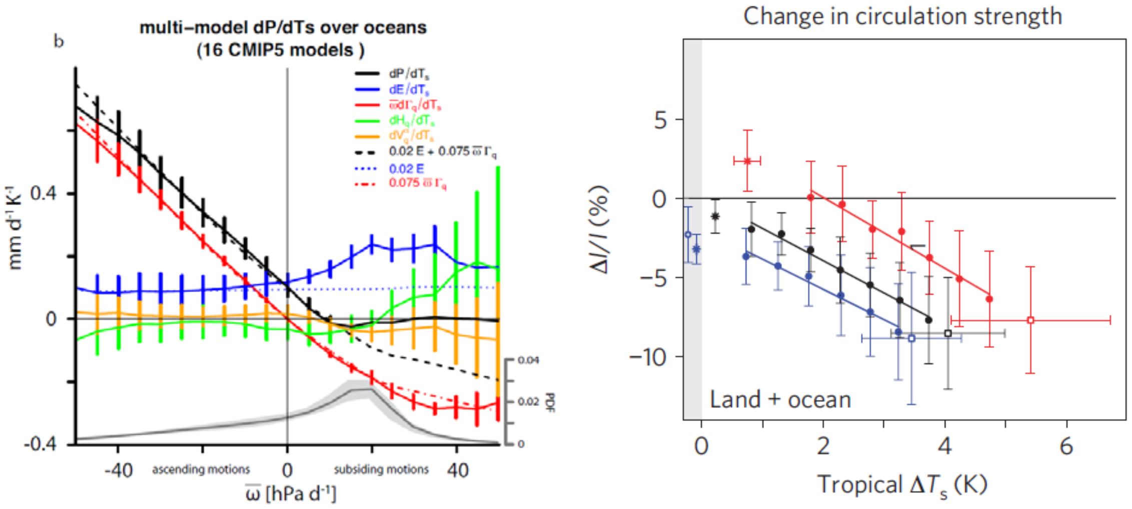

Figure 12 left: Sensitivity of precipitation, and of its different components, to sea surface temperature changes estimated through linear regression from abrupt4xCO2 simulations. Right: Response of the tropical atmospheric circulation to increased CO2 in a range of CMIP5 experiments. For land (red) and ocean (blue) areas, evolution with surface warming of the multi-model mean fractional change (compared with pre-industrial) in the strength of the overturning circulation. (From Bony et al. 2013 Nature Geoscience)

Dynamical changes primarily relate to changes in the strength of the tropical overturning circulation under CO_2 and temperature increases. By analyzing a full suite of CMIP5 simulations (coupled, atmosphere-only, aqua-planet, scenario) EUCLIPSE has shown that increased CO_2 amounts in the atmosphere exert a direct impact on the strength of large-scale vertical motions in the atmosphere even in the absence of global-mean surface temperature change: over land, increased CO_2 strengthens rising motions while increased temperatures weaken them; over ocean, increased CO_2 and temperature both weaken circulation. The understanding of these contrasted responses of the atmospheric circulation to CO_2 and temperature increases over land and ocean has helped interpret regional patterns of precipitation changes in the Tropics.

Few aspects of the climate system matter as much for humankind as the large-scale distribution, amount and variability of rainfall over the globe, EUCLIPSE has greatly contributed to understanding how and why the representation of cloud and cloud-radiative processes in models is so critical for predicting these aspects of the large-scale circulation, and hence why models have struggled to represent such changes more robustly.

5. Impact and Legacy

5.1 WCRP Grand Challenge

To guide its efforts over the coming decade the World Climate Research Programme launched an initiative of six Grand Science Challenges. One of these, on Clouds Circulation and Sensitivity germinated from the EUCLIPSE project, as its two lead coordinators are EUCLIPSE workpackage leaders, and of the twelve coordinators, five are from Europe, and of these four formed the core team within EUCLIPSE. This particular Grand Science Challenge will be the focus of WCRP attempts understand the physical climate system, as such it is helping prioritize new satellite missions, experimental strategies within projects such as CMIP (the coupled model inter-comparison project) and activities within the core projects of WCRP, through its leadership of the Grand Science Challenge EUCLIPSE has helped give European scientists a leading role within the initiative. (Bony and Stevens 2013)

5.2 Guidance for parameterization:

EUCLIPSE developed new parameterizations, new approaches for parameterizations, and a deeper understanding of some of the critical issues facing parameterization. For future parameterization EUCLIPSE demonstrated how important the coupling's among parameterizations are, whether it be between circulation and convection, convection and clouds, turbulence and convection, or clouds and radiation. As a rule, the couplings among the parameterizations were shown to plays as much, or more, of a role than the specifics of any particular parameterization. EUCLIPSE demonstrated the power of numerical weather prediction techniques, single column model approaches, and high-resolution process modeling for advancing parameterization. One prime example is the parameterization for the cloud overlap; Virtually all weather and climate models use the maximum-random overlap function whereas both observations and Large Eddy Simulation show that such an approximation gives a very strong underestimation of the total cloud cover, since the overlapin reality for broken clouds is much less effective. As a result this will lead to larger cloud fractions and less bright clouds, thereby removing the “too few too bright” bias (Neggers and Siebesma 2013).

5.3 New Modeling Hierarchy Frameworks for studying climate change

EUCLIPSE advanced the integration of existing frameworks, and the development of new frameworks, to study climate change. The use of a hierarchy of models, from single column models, to high-resolution process models, to short time integrations of advanced climate models EUCLIPSE has shown how this hierarchy of models must be used in combination to solve important problems in climate science. Finally EUCLIPSE advanced the model hierarchy by showing the power of new idealizations, ranging from three dimensional calculations of radiative convective equilibrium using Earth System Models, to the applicability of reduced frameworks like aqua planets for studying climate change. By considering configurations of climate models that could not be adapted to prior knowledge of the 'correct answer' (through tuning), idealizations like the aqua-planets shown in this figure helped highlight both short comings and robustness in our understanding of the climate system.

In Figure 13, aqua planets (simulations of an earth with only a water covered surface whose temperature is prescribed) are evaluated. Two simulations, which differ only in the prescribed surface temperature are compared to assess the response of the circulation to warming. Shown in the upper panel are changes in cloud radiative affects accompanying warming. In the lower panel changes in precipitation are shown.

The models agree well in the changes in the extra tropics, but are striking for the very large differences are apparent in the change in the tropical climate. These aqua planet simulations helped show how uncertainty in the response of clouds and convection leads to differences in atmospheric circulation, with some models showing a narrowing of the tropical circulation and more precipitation on the ITCZ in the highly idealized world (i.e., the MPI-EMS), and others showing a broadening of the tropical precipitation belt (MIROC). Although the correct answer is not known research by EUCLIPSE investigators has shown that differences in the simulated aqua planets capture differences in more Earth like planets, and that a poor understanding of how water (clouds and convection) couples to circulation is the major source of uncertainty in future predictions of climate change. These findings are helping to launch new efforts which focus on large-scale circulation changes as a basis for understanding changes in regional climate.

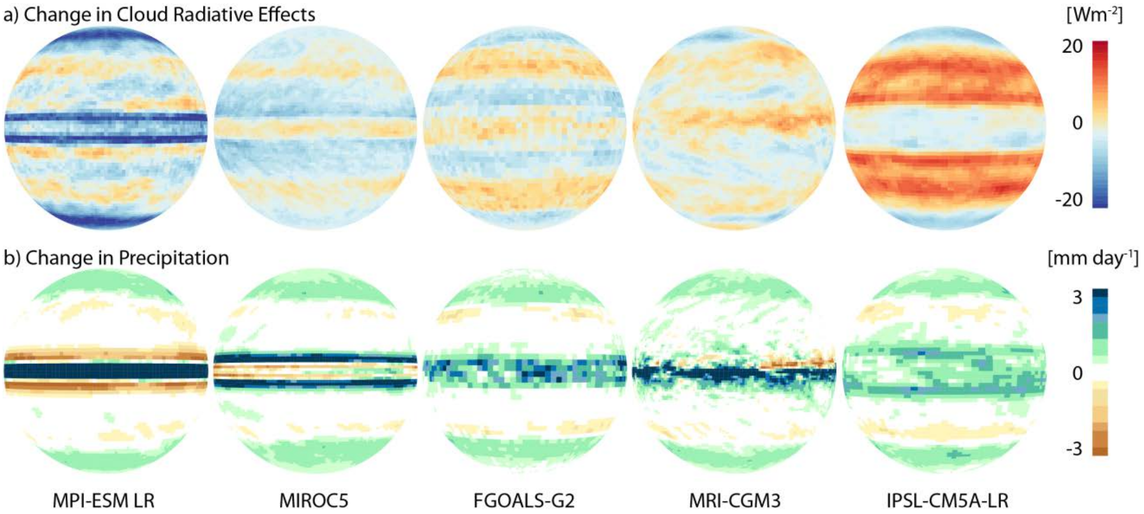

Figure 13: Wide variation. The response patterns of clouds and precipitation to warming vary dramatically depending on the climate model, even in the simplest model configuration. Shown are changes in the radiative effects of clouds and in precipitation accompanying a uniform warming (4°C) predicted by four models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a water planet with prescribed surface temperatures (Taken from Stevens and Bony 2013 Nature)

5.3 New Cloud Process evaluation techniques

EUCLIPSE advanced the use of new diagnostic techniques to better link observations to modelling, both through the development of simulators that are now routinely imbedded in climate models, but also through the development of high frequency grid-point output for comparison with ground stations. As an example, Figure 14 shows a comparison of the observed (from CALIPSO lidar satellite data) and predicted (from CMIP5 models using satellite simulator outputs) frequency of occurrence of cloud layers of a given fraction at a given altitude in the lowest 4 km of atmosphere under non-overlapped low-level cloud conditions in shallow cumulus regimes. Maps show the frequency of occurrence of these regimes derived from CALIPSO observations and ERA-Interim reanalysis. This comparison shows that many climate models underestimate the vertical extent of cloud layers and tend to produce low-cloud layers which are too extensive and too close to the surface (Nam et al., GRL, 2012).

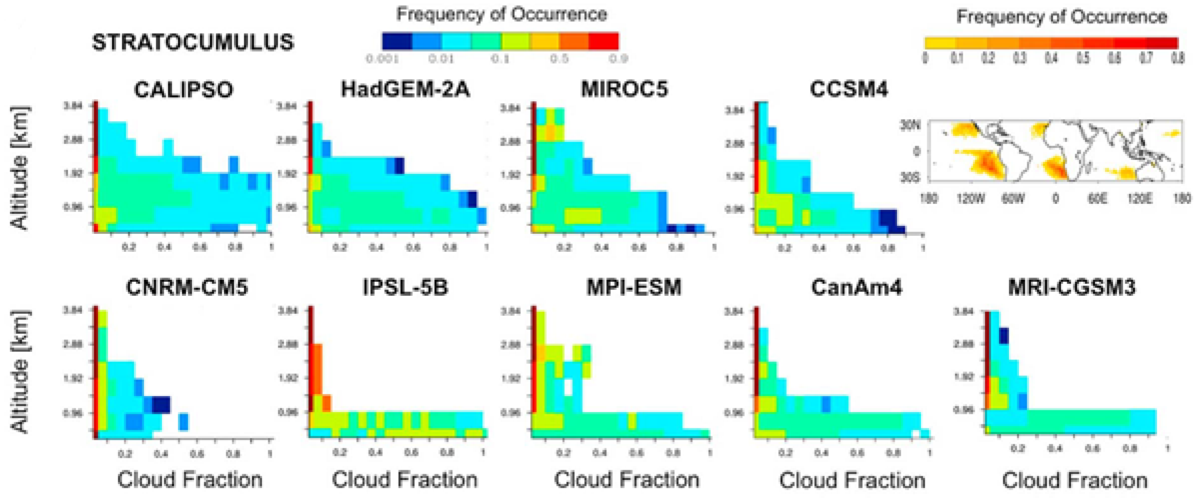

Figure 14: Comparison of the observed (from CALIPSO) and predicted (from CMIP5 models) frequency of occurrence of cloud layers of a given fraction at a given altitude in the lowest 4 km of atmosphere under non-overlapped low-level cloud conditions for the stratocumulus regime (taken from Nam et al., GRL, 2012).

5.4 Training of a new generation of climate scientists

In addition to training a new generation of scientists, EUCLIPSE has helped advance the question of the role of clouds, circulation and climate more broadly - both through a book, and through a summer school. The book, entitled Clouds and Climate will be published by Cambridge University Press in 2015, consists of thirteen chapters authored by EUCLIPSE investigators, and will help define the background and challenges for the next generation of climate scientists. The summerschool was designed to help develop the chapters within the book and attracted fifty-five advanced PhD students and young postdocs for a two week period in the French Alps in the summer of 2013. Through these activities, and through its contribution to Chapter Seven in the AR5, EUCLIPSE has helped define a new, and increasingly recognized, sub-discipline within climate science more broadly.

Figure 15: Participants and Lecturers of the EUCLIPSE Les Houches Summerschool on "Clouds & Climate".

5.5 Contribution to the IPCC Fifth Assessment Report (AR5)

EUCLIPSE PIs and science featured very prominently in the latest IPCC report. The EUCLIPSE community was fundamental in establishing clouds and aerosols as one of the new process chapters to be included in the AR5. EUCLIPSE contributions featured prominently in this report, with figures developed through EUCLIPSE projects featuring directly in the report (see Figure 16) , and some of the major findings, i.e., mechanisms for positive low cloud feedbacks which supported the IPCC assessment of a likely positive cloud feedback, or the effect of CO2 on regional patterns of precipitation change, arising directly from research within EUCLIPSE. More than 10 papers from EUCLIPSE were cited in the AR5 IPCC report.

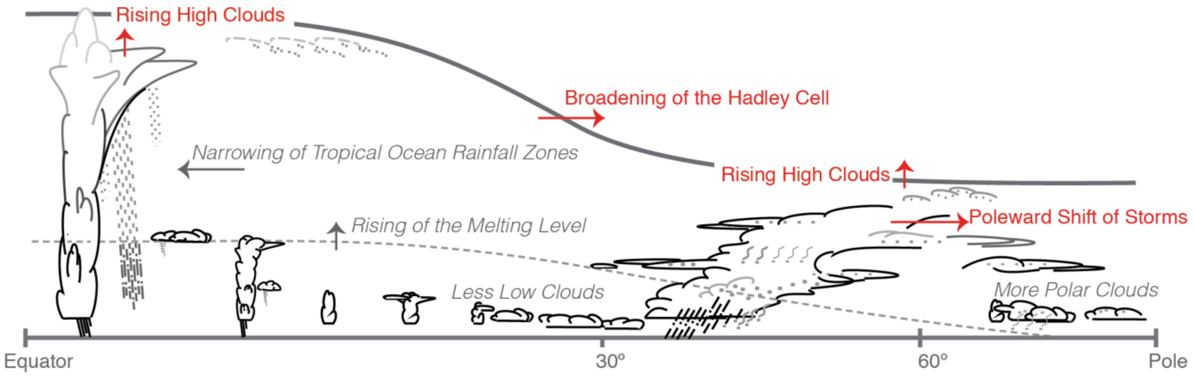

Figure 16: Schematic summary of the major cloud regimes involved in determining cloud feedbacks.

EUCLIPSE research and EUCLIPSE authors (B. Stevens was a lead author for the chapter, and S. Bony was a contributing author) played an important role in contributing to the first ever IPCC chapter on clouds and aerosols. The figure above, which was drafted by Bjorn Stevens (a EUCLIPSE Work Package leader), of the WG1 report of AR5, summarizes the major cloud regimes involved in determining cloud feedbacks. Prior to EUCLIPSE there was an appreciation that cloud feedbacks were important for determining the climate sensitivity, and that an inability to predict their magnitude was a leading source of uncertainty in model based estimates of climate sensitivity, so much so that the sign of the net cloud feedback was not known. EUCLIPSE authors contributed greatly to a physical understanding of how and why clouds might change as the climate warms. Particularly for the case of low clouds, which were responsible for most of the uncertainty in climate model based predictions of cloud feedbacks, EUCLIPSE research identified several new robust mechanisms were identified as to why low-level cloudiness over the tropical oceans might be expected to decrease, leading to the expectation of 'Less Low Clouds', a statement which underlined the first assessment of a likely positive net cloud feedback in the AR5.

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