Abstract

ABSTRACT

Acknowledgments

Acknowledgements

Publications

Parts of the work presented in the thesis have been published or are in the process of being published.

- Papers (Chapters)

QUOTATION

Reference

Contents

Chapter 1

Marine Boundary Layer Clouds in the Literature

1.1 Introduction

the lists are getting written section by section, highlighted by textbf intros. need to go thru and delete these at some point Basically, we want to set out the background and also what is the reason for asking the questions which we have been asking. looking for around 20 pages, roughly 2 per section. anyting from 15 to 40 is ok though.

1.1.1 setting out hwat the problem is and why we're approaching it in this order.

1.1.2 introducing MBL clouds

Low clouds cover, on average, around 30% of the Earth's surface. Over the ocean, the figure is even higher, with around 35% coverage by Marine Boundary Layer (MBL) clouds on average. There has been much interest in recent years in the processes governing MBL cloud formation and interaction with the imediate environment, in additioin to projects dedicated to improving the model representation of MBL clouds (Fer example part of the Coupled Model Intercomparison Project, CMIP5). As a result of their ubiquity, minor changes in MBL cloud properties and distribution have the potential to cause significant changes to the planetary radiation budget. For example, *find cite?bony?* suggest that an increase in cloud cover over the oceans of 20% *CHECK* would be enough to offset

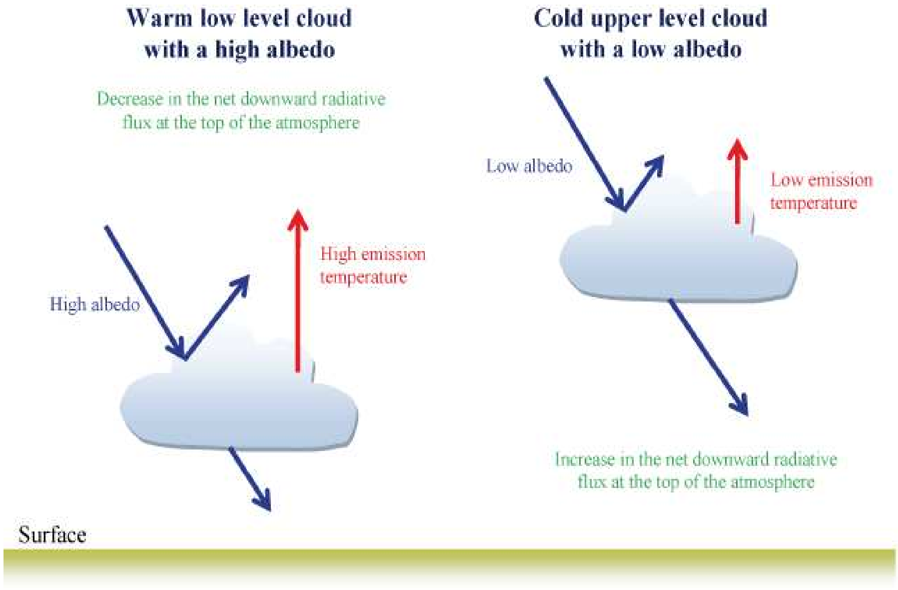

Figure 1.1: Schematic of CRF for MBL clouds..

the currently observed rise in global temperatures of 1-2^{o}C. MBL clouds have a strong net cooling effect on the global energy balance. Their low altitude (1-2km on average) and resulting warm temperature (often not more than 10K cooler than the underlying sea surface) means that they radiate much more heat than equivalent clouds higher in the atmosphere. At the same time, the clouds posess a much higher shortwave albedo than the underlying ocean surface (up to 0.8, as compared with 0.1 for the ocean surface), therefore reflect much of the incident slolar radiation back out to space. A schematic of a single MBL cloud layer is shown in Figure *FIGURE*. Relative to clear sky conditions, the presence of low cloud cools the surface by blocking solar radiation, and, while the emission of thermal radiation to space is slightly less than under clear sky conditions, the large fraction os incident solar radiation that is reflected results in net more energy emmited to space in the presence of cloud relative to thier absence. The relevant equations for cloudy vs clear sky (ignoring absorption/scattering from the atmosphere and the effects of multiple scattering, and assuming that the temperature of the cloud is 10K llower than surface temperature) are as follows:

Clear Sky

$$S = \sigma T_s^4 + 0.1S \tag{1.1}$$

Cloudy (Single Layer) Sky:

From Cloud Top

$$S = 0.8S + 0.1(1-\epsilon)^2 S + \sigma(T_s - 10)^4 \tag{1.2}$$

At the Surface:

$$(1-\epsilon)S + \sigma(T_s - 10)^4 = 0.1(1-\epsilon)S + \sigma(T_s)^4 \tag{1.3}$$

does the σT^4 term in the surface(cloud) eqn need to be (emmision const)$(\sigma)T^4$? rearrange to prove surface cooling.

The effect of clouds on the radiation baudget relative to their absence is known as Cloud Radiative Forcing (CRF) *NOTE this needs filling in , also specify if is per unit cloud or per unit sky - ie is there an Ac term.* Note that cloud longwave forcing is always positive, since clouds are always cooler than the underlying surface, and shortwave forcing is *ALMOST aarctic*always negative, since a higher proportion of Insident solar radiation (ISW) is reflected back to space.

$$CRF_{LW} = \tag{1.4}$$

$$CRF_{SW} = \tag{1.5}$$

$$CRF_{NET} = CRF_{LW} - CRF_{SW} = \tag{1.6}$$

Figure 1.2 (*cite allan*) shows the global mean longwave, shortwave and net CRF from *CERES?* for the years *WHICH years?*. The regions of high negative NCF off the west coast of Peru and California (*FIGURE 1.2C*) are regions that are dominated by Marine Boundary Layer cloud. Their high negative NCF is as a result of a hign negative SWCF (*FIGURE*), combined with negligible LWCF (*FIGURE*)

1.1.3 Types of Stratiform cloud and condtions for their formation.

how do we explain that stratiform is used interchangeably with low and MBL. need a sentence here and/or to change the title of this section.

Clasically, low cloud is split into three main types - Cumulus, stratocumulus and stratus. For the purposes of discussion in the literature, the latter types are referred to collectively as 'stratiform'. Different types of stratiform cloud may appear under different conditions and therefore have different properties and relationships to the atmospheric state. *Klein and Hartmann, find orig cite* describe a simple three-type classification fof stratiform clouds.

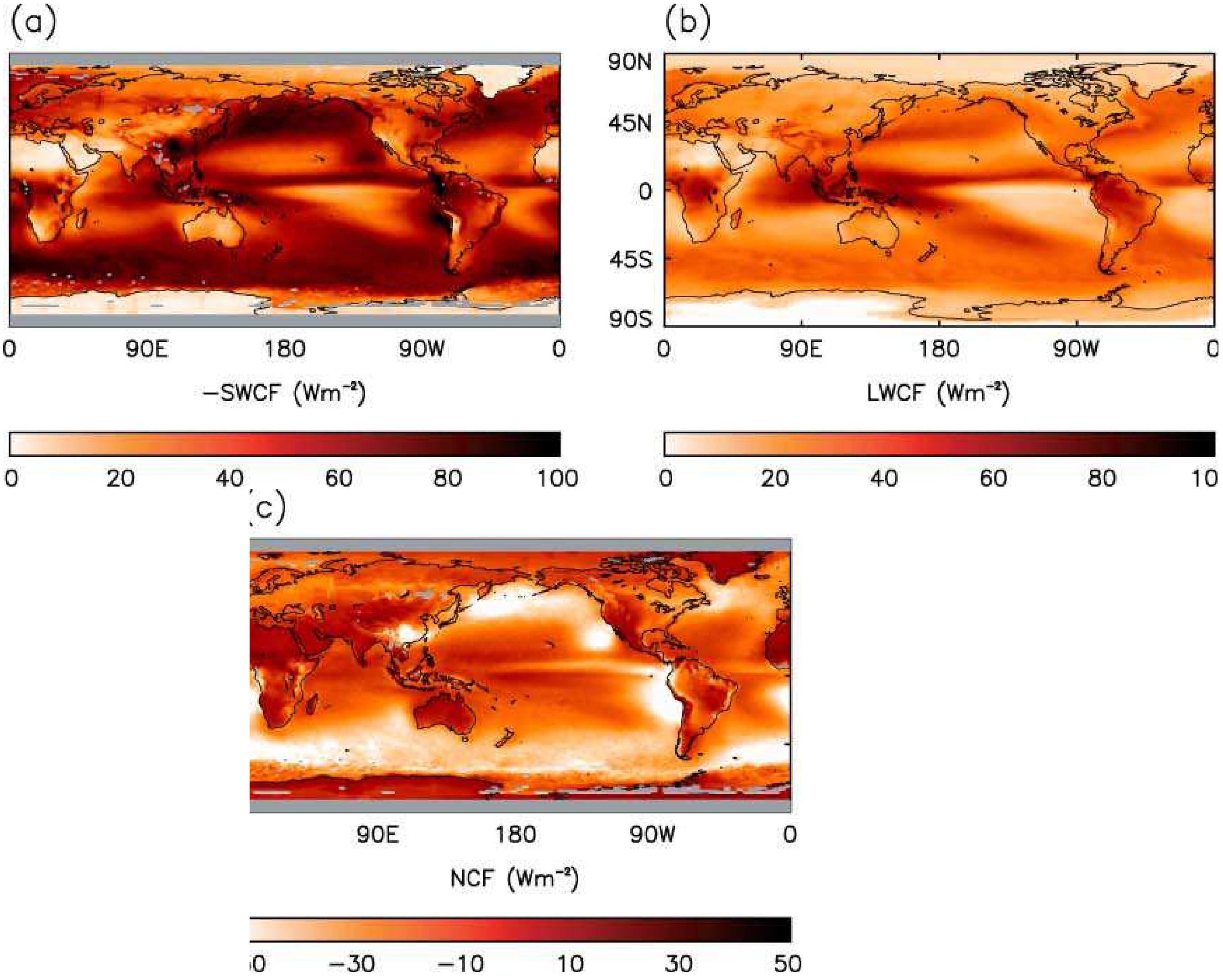

Figure 1.2: Sw, LW and NET CRF at TOA (FROM RPA).

The first, and most extensive type, form in the trade wind regions over the cooler eastern tropical oceans, under a strong temperature inversion assocaited with the descending branch of the Walker circulation. Two of these regions can be seen in *FIGURE 2c*, off the western coaset of Peru and California. A second type of stratiform cloud forms over the ocean currents that transphort warm water from the tropics into the mid latitudes, for example the Gulf Stream off the eastern coast of North America, and the Kuroshio current off the eastern coast of Japan. These can also be seen in *FIGURE 2c* as regions of strongly negative net cloud forcing. *There is a different mechanism for formation of these clouds, which result from cold continental air crossing the warm ocean currents. Fog is more preva-*

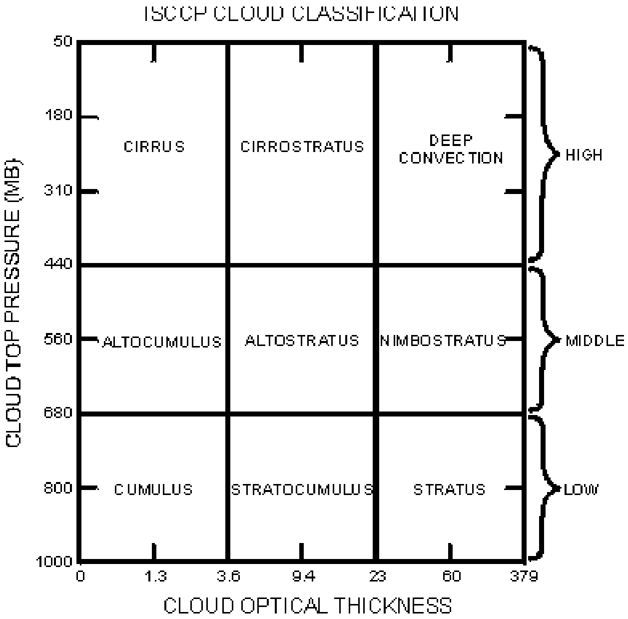

Figure 1.3: Global seasonal Low Cloud Amount from ISCCP. EECRA also available for comparison

lent in these regions. The third major type of stratiform cloud described is Arctic stratus cloud. These clouds form by yet another mechanism, being the result of warmer midlatitude air cooling radiatively and condensing in cold polar conditions. These clouds are often extremely low lying (tens of metres) and may form multiple thin cloud layers *as a result of the characteristic eqtremely shallow arcitc boundary layer.* The reaminder of this thesis is concerned with the first type of stratiform cloud described, the eastern ocean tropical stratiform cloud. These large regions of persistent low cloud (often referred to as 'decks') are the largest coherent regions of boundary layer cloud on the planet, and can extend a thousand or more kilometers from the coast into the free ocean. Further discussion of the mechanisms of formation, maintenance, and dissipation of this type of cloud is provided in section *SECTION*.

1.1.3.1 The influence of the satellite era on the cloud classification system

Clasically, cloud types have a Linnaean-type nomenclature, that is to say, each cloud 'genus' or type may be split into further subtypes, normally characterised by appearance and height. Until the advent of systematic top of atmosphere observations, clouds were observed and recorded according to this system by ground-based observers, for example as in the Comprehensive Ocean-Atmosphere Data Source (COADS) cloud atlas or the

Extended Edited Cloud Record Archive*check these arent the same.* Cloud fraction was recorded in eigths of sky (oktas), and COADS recognises several types of low cloud - cumulonimbus, cumulus and stratus, with (for example) stratus being further subdivided into strats, stratocumulus, fractocumulus, fractostratus, and sky-obscuring fog. These types of observations are obviously not directly applicable to an observing system located some 90km *check* above the earths surface, therefore a direct comaprison between the two observing systems must be made with caution. In the widely used International Satellite Cloud Climatology Project (ISCCP) cloud classification system, low clouds are defined to have air pressure at cloud top not less than 680hPa (relative to MSLP 1013hPa, approximately equivalent to 4km height), and are divided into three types: cumulus, stratocumulus and stratus, accrding to their optical depth, with cumulus cloud being the most optically thin, and stratuse the most optically think. Although this classification system cannot be directly comparable to the surface-based cloud atlases, *look up some of the Joel Norris work, basically the absolute numbers arent the same, but the realtionship etc derived seem to be similar in most cases. add to this the fact that ship obs are basically absent from the 50s*

The ISCCP cloud type histogram is shown in *FIGURE*, and cloud types throughout this thesis refer to this classification system.

1.1.4 Uncertainty in global climate models

the plan was to put the IPCC stuff here - but im going to need to look it up first. also, its not exactly theory, so i'm slightly questioning whether it wants to go here or later.

1.2 Tropical Marine Boundary Layer Cloud

This section discusses tropical eastern ocean MBL cloud in more detail.

1.2.1 schematic of the tropical circulation

Figure *FIGURE* shows a schematic of the tropical circulation *Kelly and Randall2001.* Warm, noist air rises over the tropical warm pool, giving rise to large convective systems. Having risen, air that is now cool and dry is displaced eastward by convective parcels from below. This air descends slowly over the eastern oceans, warming adiabatically as it descends. *NOTE find a better expl(with more science) somewhere* This air is warmer

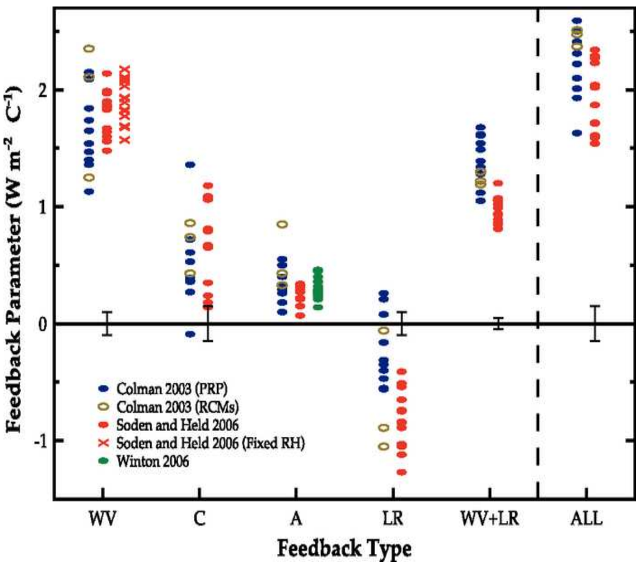

Figure 1.4: Global seasonal Low Cloud Amount from ISCCP. EECRA also available for comparison

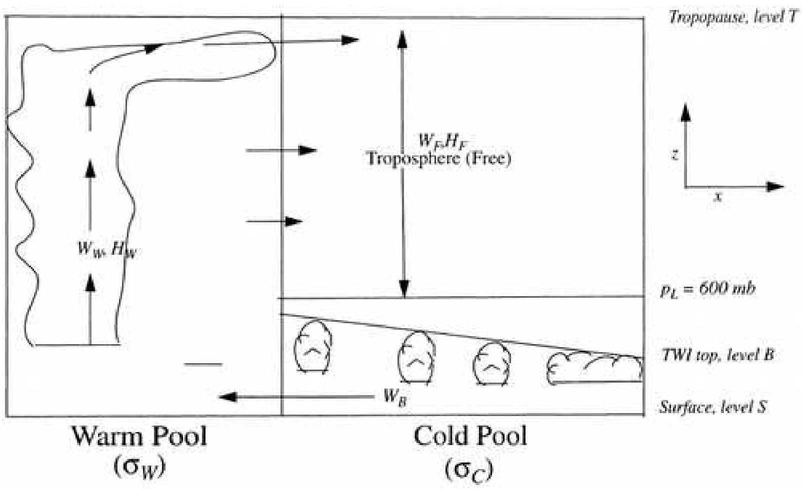

Figure 1.5: Global seasonal Low Cloud Amount from ISCCP. EECRA also available for comparison

than the rising air at the top of the boundary layer over the tropical cold pool, which results in a temperature inversion at the top of the boundary layer. *FIGURE* shows a typical temperature profile through the eastern ocean boundary layer, together with the temperature and humidity profiles of a typical air parcel. *CHANGE FIGURE, describe figure*

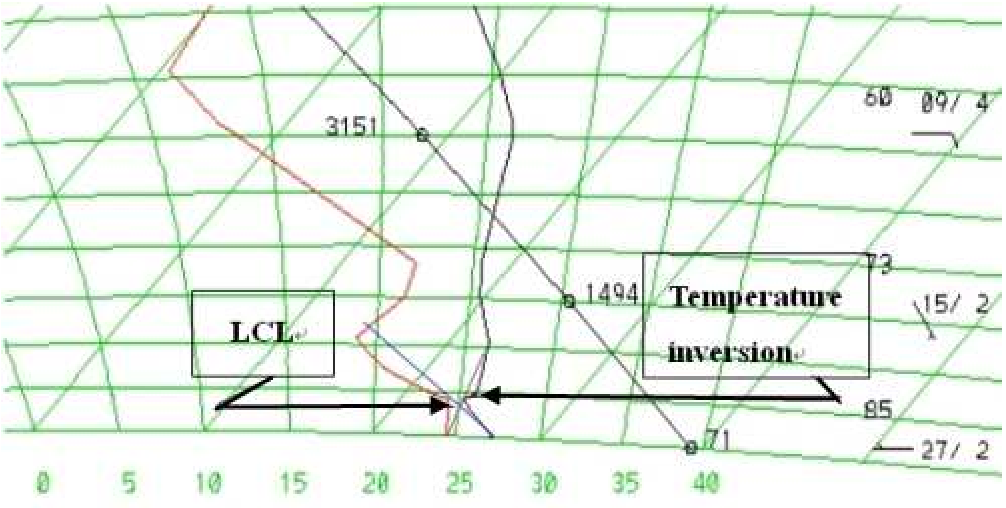

Figure 1.6: Global seasonal Low Cloud Amount from ISCCP. EECRA also available for comparison

1.2.2 Formation, and maintenance

rve cooling from cloud top supports convection(backwards, borrow janet barlow conv pic Air from the descending branch of the Walker circulation warms adiabatilcally as it descends. At the point at which this free tropspheric air meets the boundary layer (around 1-2km), it can be as much as 15-20K (*check*) warmer than the boundary layer. This results in a strong temperature inversion at the interface, effectively decoupling the free tropopsphere from the boundary layer. Below this 'capping inversion', a layer of cloud may form, which is unable to prnetrate the inversion layer, and therefore spreads out at the level of the inversion. The cloud layer may initially form when turbulently mixed moist surface air rises above the lifting condensation level (LCL), but cannot penetrate the inversion layer. Once the cloud layer has formed, it is maintined primarily by radiative cooling from the cloud top. which causes relatively dry air to descend in strong, narrow downdrafts, which displace moist surface air upwards, helping to maintain the cloud layer. This is in contrast to standard convective cloud systems, which are formed when surface or near surface heating of moist air causes it to become buoyant, resulting in strong convective updrafts, with associated slower, wider downdrafts of dry air. FIGURE shows a schematic of a typical well-mixed boundary layer cloud system under a capping inversion.

processes within the cloud including the bretherton theory(from lect notes) on the increase of LWP from cloud base to cloud top. Also that turbulence is present throughout

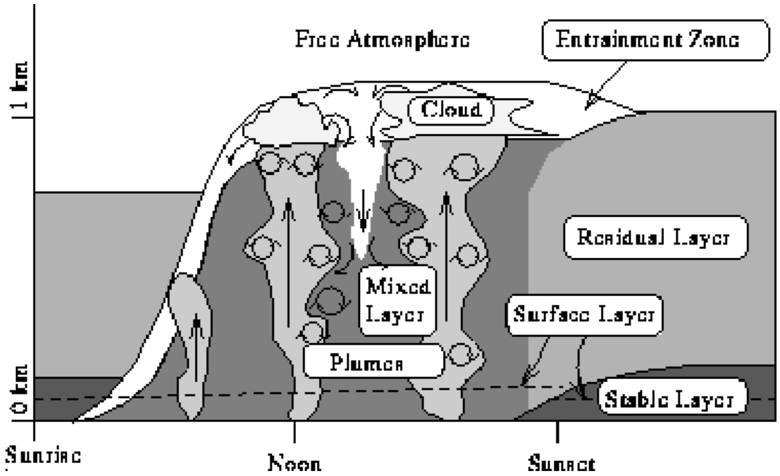

Figure 1.7: Sw, LW and NET CRF at TOA (FROM RPA).

the boundary layer. Could probably do with adding some maths in near here somewhere.

turbulence

moisture fluxes Because the capping inversion inhibits mixing of air at the cloud top, the SC MBL can be modelled as a closed sytem, at least for theoretical/instructional purposes. FIGURE shows typical vertical profiles of sensiblle and latent heat, and moisture.

heat fluxes and profiles

1.2.3 decoupling and dissipation

- focus on mechanisms eg entrainment
- entrainment/radiative dissipation in stu. The rate of entrainment can be influenced by the strength of the capping inversion, see breth notes
- decoupling

focus on mechanisms eg entrainment Turbulence generated at the cloud top by cloud radiative cooling results in entrainment of warm, dry air from the inversion layer. This tends to dissipate the cloud from the cloud top.

1.2.4 warming-deepening

- warming-deepening longitude dependence

- formation of cumulus under Sc
- heightening of Sc, change in properties
- warming-deepening(beth,hart,klein grp somewhere, lin, by analogy useful for climate change.
- this thinning difficult to measure - cloud epth etc much more difficult that cloud properties
- problems with extending this to a climate changed environment

This very general picture is fine on global, seasonal scales. the old research tends to focus either on horizontal cloud extent or radiative impact as a measure of overall cloud impact. with the advent of resltively long term, high resolution datasets (for example aqua), there is a new swath of studies looking at more detailed aspects of the MBL cloud systems. Current research has focused in on more detailed aspects of the stratiform cloud system.For example, there has been work on the sc-cu transition (im sure there has, somewhere). The klein and jensen groups are loking at horizontal inhomogeneity.

It is now possible to emprirically test the decomposition of the radiative impact/optical depth of clouds in to droplet size and liquid water or layer depth (note that these do not necessarily correspond, see eg linea) . the advent of cloudsat means that drizzle studies are everywhere, and often these are tied in with aerosol studies, which can focus on very small, idealised studies or field campaigns.

recent liquid water path studies include the lovely li paper that compares lots of models and lots of measuring systems, the lin paper that uses the rubbish isccp data, the statistical teixeira paper that purports to find an lts like metric for lwp, the jensen inhomgeneit papers

1.3 Raditative transfer and impact

1.4 Cloud Variability as related to the Large-scale atmospheric state

Lots of studies on seasonal variablity.

- use the slingo/norris as a where are we

- use the stevesbook as a setting out of the problem

1.4.1 Cloud Fraction

Cloud fraction is the major fator that geoverns cloud radiative impact at TOA. For example, do a back of the envelope calculation illustrating that the daily cycle (assuming a fixed optical depth) has a much greater impact htan e.g. doubling the LWP or halving the droplet raduis. However, changes in cloud fraction may be either enhanced or mitigated by accompanying changes in LWP, therefore its useul to know not only how the overall cloud optical depth changes, but also how the contributing componenets(LWP and re) are affected by factors that may change cloud fraction and distribution.*NOTE that thsi is also currently the closing paragraph to the chapter.*

Cloud fraction has been known to be affected by the large scale atmospheric circulation for a long time (can we find a nice study here?hartmann and michelsen 92?)

- Separation of dynamic and thermodynamic changes. the Bony study.
- LTS including more recent studies in the satellite era
- EIS

Lower Tropopspheric Stability Section *SECTION* above described the processes involven in the maintenance and dissipation of a typical Sc cloud layer below a capping inversion. Two of the major factors affecting cloud dissipation are the entrainment of dry air t the cloud top, and the decoupling of the surface layer from the Sc cloud layer itself, and thus the supply of moisture into the cloud. Klein and Hartmann (1993) (hereafter KH93) proposed a simple, physically based metric for relating cloud fraction to atmospheric properties, which takes the difference of the potential temperature above and below the inversion to form the 'Lower Tropospheric Stability', LTS. LTS is measured as

$$LTS = \theta_{p=700hPa} - \theta_{p=1000hPa} \tag{1.7}$$

Using surface-based observations of cloud fraction from the COADS archive, KH93 were able to explain around 80% of the observed variability in LCA on seasonal timescales (that is, the r^2 value for LCA-LTS correlation was in excess of 0.80). The observe an increase of around 6 percentage points cloud cover pes degree increase in LTS. Subsequent studies have updated and expanded this realtionship. (studies that do kh93-make table, dataset, region size, slope, mean ac if avail)Studies such as *LIN, ?jensen, others* have recalculated the realtionship between LCA and LTS using satellite observations. TABLE shows the different slopes for each study. It should be noted, however, that the realtionship also depends on the size of the region under study, and that larger regions (which may include some areas that are not Sc-dominated, for example) will tend to reduce the slope of the relationship. (change of slope, satellite data, valid range). The ongoing use of LTS in a number of studies has also resulted in a refinement of the range of temperatures over which it is valid. *Hartmann in stevens book* note that 14K seems to be the lower temperature at which LTS can be used to prodict cloud fraction (and separate the tropics into 2 regimes using this as a dividing line. LOOKUP)

1.4.2 Metrics including other variables

more recent studies have also assesed the impact of the chosen metric on other cloud properties

- LTS and the LIN study. possibly the chapman poster too
- eLTS
- LTS has remained the most popular and enduring of these metrics as its really vey good, and very easy to work out.

1.4.3 Cloud Inhomogeneity and Subseasonal timescales

With the advent of high resolution data, subseasonal studies have become more comon. Those using data from polar orbiting satellites are necessaily limited to one or at most two times of day , which should be borne in mind. Daily or subseasonal variability is not often considered explicitly however, there are an increasing number of studies that exploit this data to build statistical pictues of cloud inhomogeneity

- Jensen cloud diameter
- wielicki ceres cloud objects if relevant
- POCs

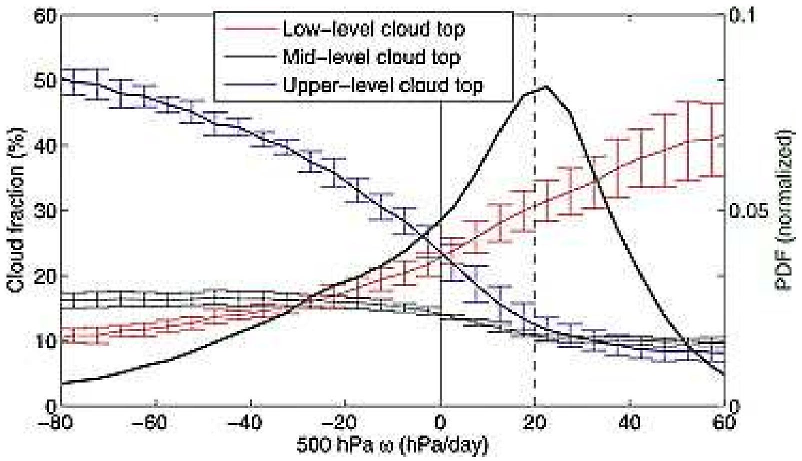

Figure 1.8: Sw, LW and NET CRF at TOA (FROM RPA).

- field campaigns (briefly)

1.4.4 subdaily timescales

we do not consider subdaily timescales in this thesis, however, since we use instantaneous 13:30 measurements, here is a brief section on the diurnal cycle

- brief theory, compare to first section
- so at 1pm we might expect the folowing
- geostationary studies are very few and far between, the teixiera LWP study is one such, can we find any other examples?

1.5 Aerosols and Drizzle

There is a huge body of work , however, much of this work requires high qulity data and therefore relies on field campaigns and very short-term, localized studies. For marine boundary layer clouds, probably the most relevant sets are the fire and astex peruvian group of field campaigns.

- theory - twomey effect and albrecht effect

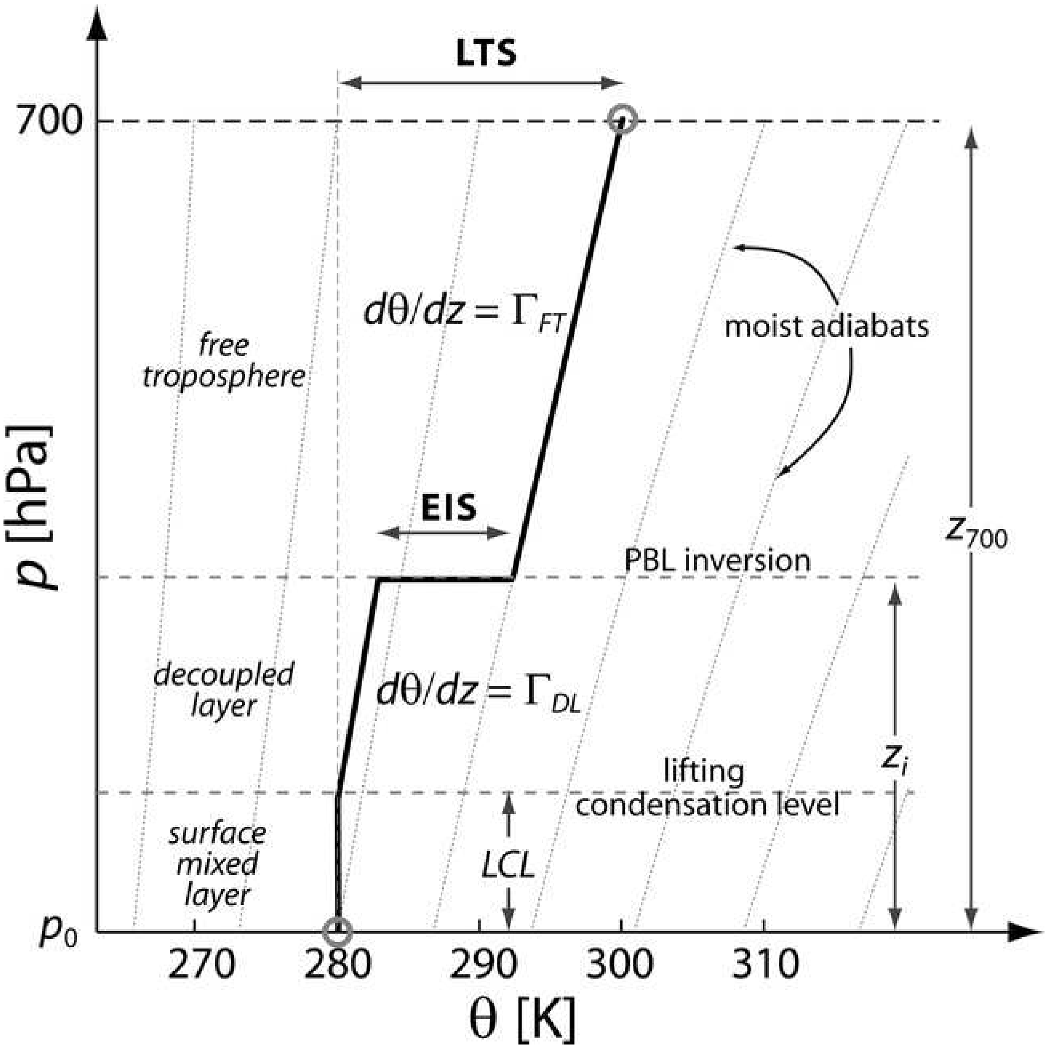

Figure 1.9: Global seasonal Low Cloud Amount from ISCCP. EECRA also available for comparison

- its really difficult to speparate these two. also cloud spreading means that it is not inconceivable that changes in cloud depth may in fact manifest themselves as a change in cloud fraction
- its also improtant for us to recognise that a change in e.g. ccn may in fact be initialted by eg a change in local wind speed, which may be realted to the atmospheric state
- LWP variability sits somewhere between these two study techniques, being neither quite a macro nor a icrophysical variable (look at the stephens paper where it talks about the separation of temporal and spatial scales.

Figure 1.10: Sw, LW and NET CRF at TOA (FROM RPA).

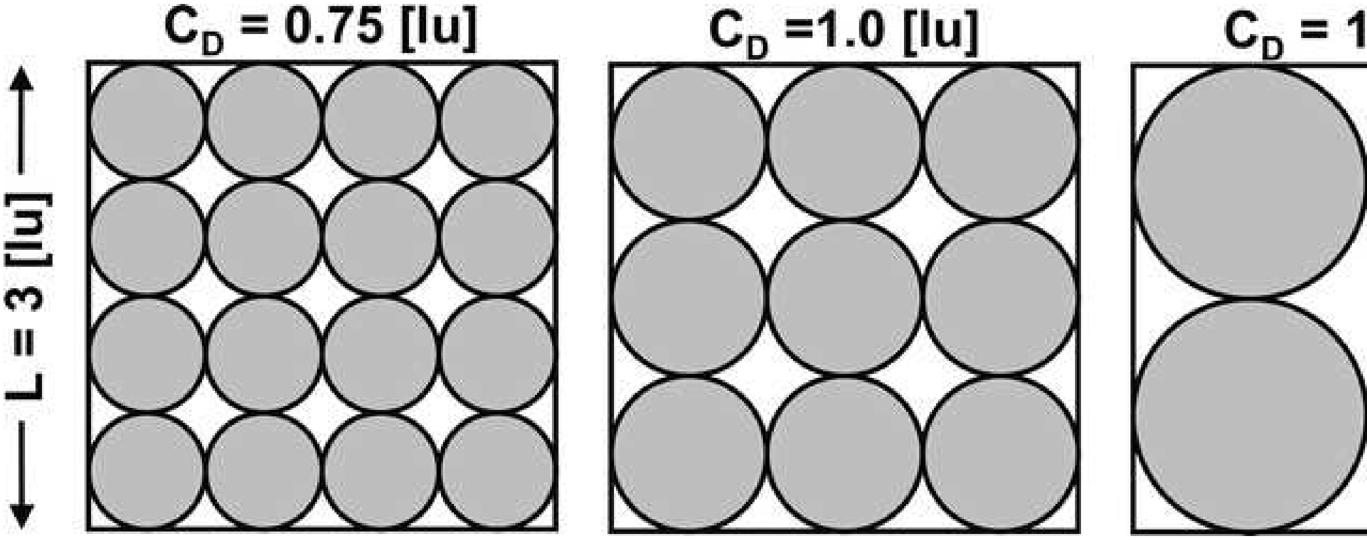

Figure 1.11: Sw, LW and NET CRF at TOA (FROM RPA).

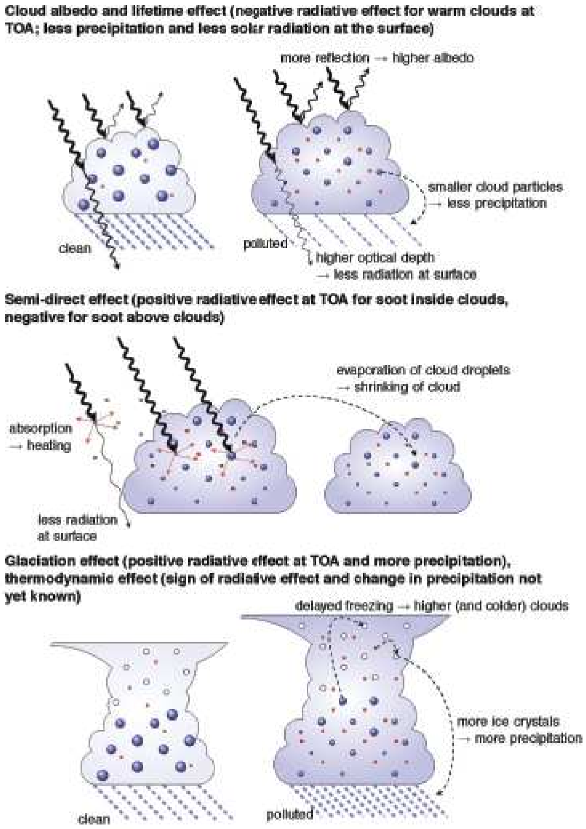

Figure 1.12: Global seasonal Low Cloud Amount from ISCCP. EECRA also available for comparison

1.6 L:iquid water path

so for the moment this is just a collection of papers. I guess we want to get across that a lot of the LWP stuff is as part of larger studies. Can we use the wielicki series of papers - which satrts off with aditaion and ends up with cloud amount - as a sort of template for structuring our argument?

- Li paper where they look at lots of different datasets
- teixiera paper where they invent their statistical metric
- jensen papers have some LWP stuff
- so do the lin papers
- the MCC hartmann paper is apparently about LWP

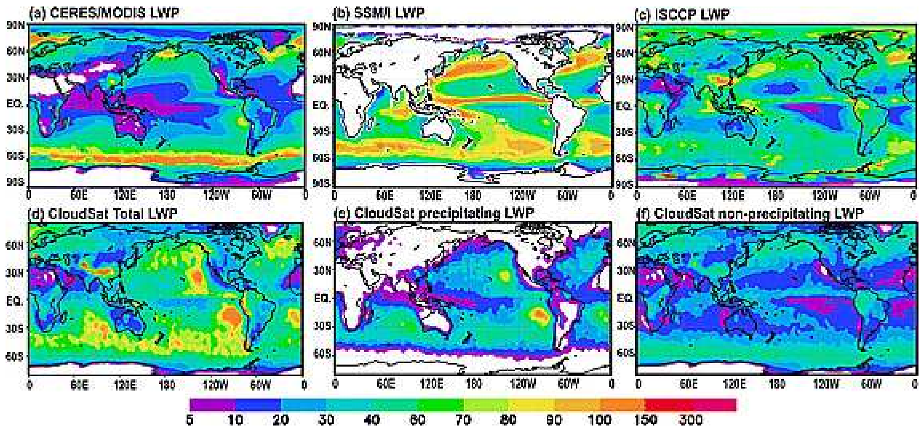

Figure 1.13: LWP data from Li GRL

- possibly the AIRS paper, if not here then somewhere else.
- possibly the CERES papers

1.7 Models anfd feedbacks

Need to have a coherent paragraph here about what the essential problem is. Its somethign along the lines of the feedback is very uncertain. Then we need wo seguay into well this is because the representation is fairly poor in climate models and this might be for a number of reasons. try going through some of richards papers. also good for this is the stephens review paper, and possibly the bony papers.

- smithcld
- aquaplanets
- too far from coast
- cloud fraction rather tahn cloud layer depth

1.8 remote sensing of low clouds

what properties can and cant be retrieved with various instr. why do we think our question is worth asking. This may well become the data chapter at some point.

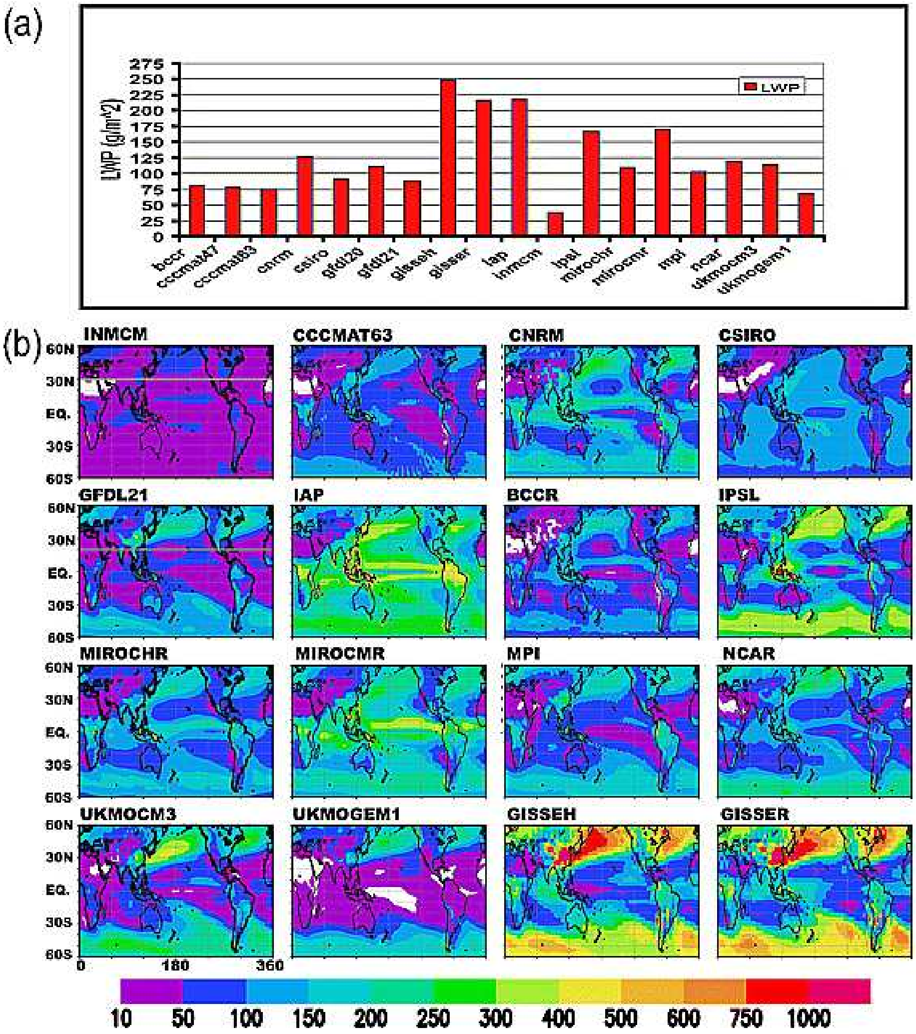

Figure 1.14: Global seasonal Low Cloud Amount from ISCCP. EECRA also available for comparison

SET OUT that the first section of the thesis deals with long term, monthly mean datasets. For this reason, for example, we do not use the MODIS clw product, as it is not comparable with the model, and at monthly mean resolution (L3), it is not possible to convert in-cloud to scene average sufficiently accurately to allow analysis, especially for such a short data run(8 years last count).

1.8.1 Cloud Fraction, height and optical properties

1.8.2 ISCCP

1.8.3 EECRA

1.8.4 SSM/I

1.8.5 MODIS

ctp-co2 slicing see stePHensbookpp375

1.8.6 ERA Interim

1.8.7 TOA radiation

geostationary vs sun-synchronous for making monthly mean data.

1.8.8 CERES

1.8.9 ERBS

1.8.10 ISCCP-FD

1.8.11 Reanalyses and other data

1.8.12 ERA Interim

1.8.13 NCEP/NCAR

1.8.14 HadISST

1.8.15 Daily data

This section introduces the datasets, the detailed discussion of biases etc is elsewhere, as is the version number etc of the specific dataset we used. check ruths thesis for a template.

1.8.16 AMSR-E

1.8.17 CERES-SSF

1.9 the rest of the thesis

*Note this sentence is also in the cloud fraction lts section. be sure it is only used once!*Cloud fraction is the major fator that geoverns cloud radiative impact at TOA. For example, do a back of the envelope calculation illustrating that the daily cycle (assuming a fixed optical depth) has a much greater impact htan e.g. doubling the LWP or halving the droplet raduis. However, changes in cloud fraction may be either enhanced or mitigated by accompanying changes in LWP, therefore its useul to know not only how the overall cloud optical depth changes, but also how the contributing componenets(LWP and re) are affected by factors that may change cloud fraction and distribution.

chapter 3 does some things. chapters 4 5 and 6 contain vaguely real science etc etc

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