CRITICAL PROCESSES WITHIN AND ATTRIBUTES OF FRONTAL CLOUDS

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Summary: Extra-tropical layer clouds commonly occur around the Earth. Our understanding of these clouds is briefly reviewed in this article and some uncertainties in our understanding are highlighted. Some of the attributes of the clouds are believed to have an impact on climate. Such attributes include radiational features, microphysical composition, water cycling, and internal dynamics and these features are given special attention in this review.

1. INTRODUCTION

Extra-tropical layer clouds are very common around the globe. Such clouds are typically associated with frontal systems in the mid-latitudes and at high latitudes. They can also be linked with cut-off lows, tropical-extratropical cloud bands, orographic lifting and in the tropics they can be associated with convective systems.

Such layer clouds contribute substantially to the global water and energy cycles. They account for a major fraction of the precipitation in mid-latitudes and they are associated with some of the main avenues for the latitudinal transport of moisture through the atmosphere. Organized vertical motions and latent heat exchanges within such clouds redistribute and alter the vertical profiles of momentum and moisture.

It has recently been inferred that frontal clouds also contribute very substantially to the Earth's global radiation budget. The common occurrence of the clouds, their wide expanse, as well as their highly variable nature contribute to this situation.

The purpose of this article is to briefly summarize our understanding of some of the characteristics of extra-tropical layer clouds, with the focus being on potential climatic implications. A general introduction to the global nature of the phenomenon is first presented. This is followed by a discussion of the various attributes of these systems that can lead to climatic implications. And, in the final section, a brief comment on an international effort aimed at improving the representation of these cloud systems is advanced.

2. GLOBAL DISTRIBUTIONS

As shown in almost any global-scale satellite picture, frontal cloud systems are certainly very common. Generally, there are at least ten organized frontal systems occurring at any one time over the surface of the Earth. The cloud field associated with each of these systems in the mid-latitudes furthermore covers an area of the order of 10^5-10^6 km^2.

The overall attributes of such systems are appreciated in general since they have been the focus of numerous studies. The founding of the Norwegian School of Meteorology some 75 years ago represented a major step in this regard (Bjerknes, 1919; Bjerknes and Solberg, 1922). While the focus of most of the scientific studies of these layer clouds has been the drive for improved prediction, it is becoming appreciated that these weather systems play an important role in the global climate system (see for example Lambert, 1988).

A separate study is underway to better compare the detailed characteristics of the cloud systems in different regions of the world (Ryan, 1994). Many internal features including microphysical components will vary systematically with location and many of these variations will need to be well-handled. Regardless of such detailed features, some critical issues appear to pertain to many systems as will now be described.

3. CRITICAL ISSUES FOR CLIMATE

3.1 Vertical structure

There is a need to provide measurements of cloud layering and thicknesses, liquid/water contents and partitioning between water phases, along with the associated temperature, moisture and wind profiles (including vertical velocity) for a reference set of weather systems. There is also a need to determine the optical properties that influence the radiation budget and the amount of precipitation produced by these systems, particularly over the sea.

Cunningham (1951) wrote one of the first articles stressing this issue (Figure 1). He found that the vertical structure varied greatly within the storms. Quite different profiles of microphysical features occurred within different storm regions. He felt that a critical question affecting the actual vertical profiles was the role played by the initiation of precipitation. He found evidence that such initiation could either be internal to the general cloud field or else external due to the seeding of the cloud field through the settling of particles initiated above.

Cloud top characteristics are critical to the climatic impacts of these systems. It is common for low levels of liquid water to be present within some of these (Rasmussen et al., 1992; Rauber and Tokay, 1991). The cloudscape is also typically very non-uniform due to the presence of small scale convective elements and wave-like structures. It has also been pointed out by Sanders and Bosart (1985) that the tops of these clouds can also experience "pulse-like eruptions" of elevated heights; they attributed these features to the action of symmetric instability.

In fact, the determination of cloud top is not clear-cut in some instances. The upper regions of the clouds are so tenuous and indistinct that even to the unaided eye, one cannot discern cloud top in widespread layer cloud environments. A particular example of this occurred in association with a warm frontal cloud situation during the recent Beaufort and Arctic Storms Experiment (BASE) over northern Canada (Figure 2). The very thin cloud extended from a base of about 1 km to a top of about 6 km, yet one could see the ground from an

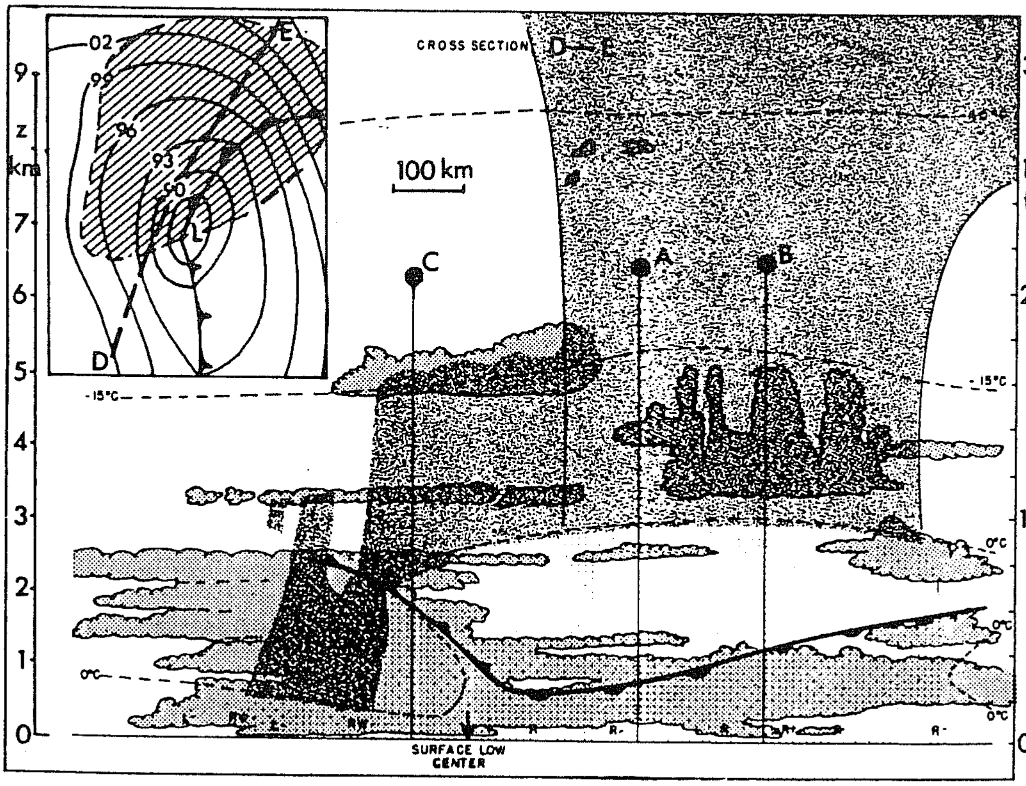

Figure 1: Conceptual model of an extra-tropical cyclone with emphasis on the varying cloud forms. The light shading refers to liquid cloud, heavy shading is mixed-phase cloud, and medium-grey scaling is ice cloud. Adapted from Cunningham (1951).

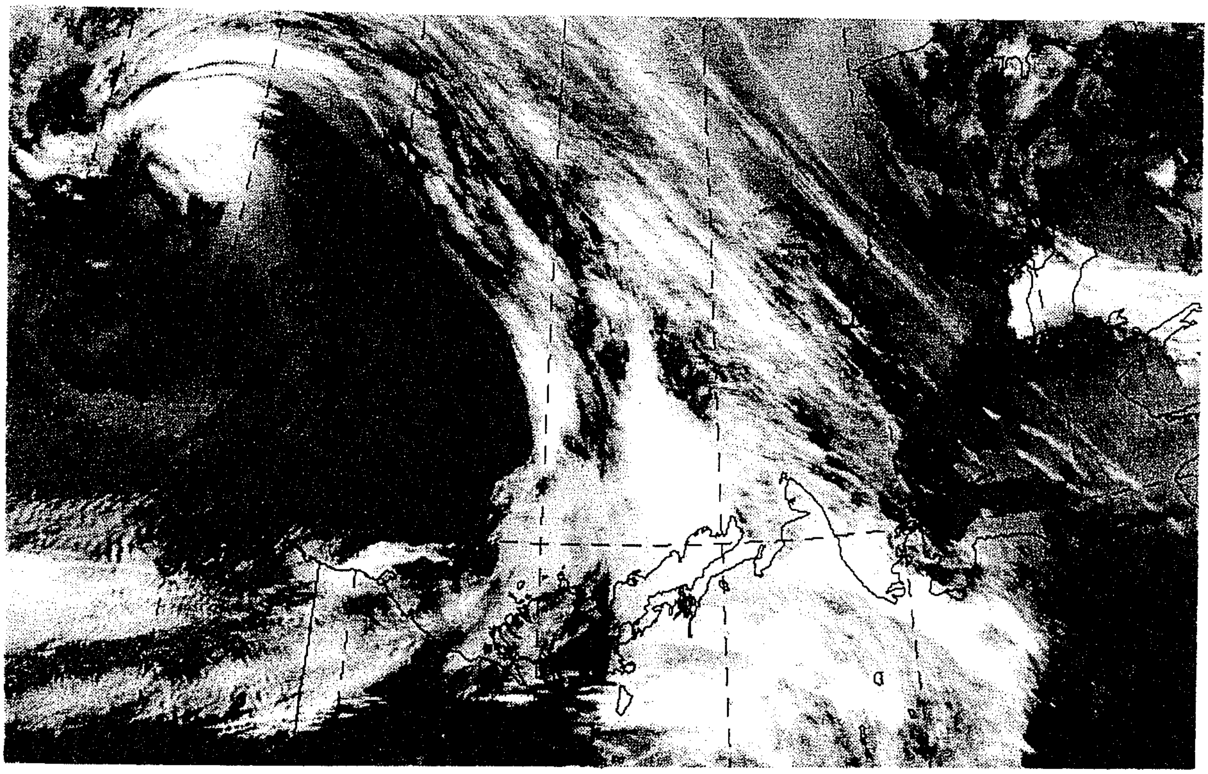

Figure 2: Cloud field infrared temperatures measured in association with a low pressure system over the Beaufort Sea on September 30, 1994. The region in which there was a disagreement between inferred and observed cloud top temperatures is shown by the dot.

overflying aircraft. Furthermore, the deduced cloud top temperature of -10°C, as inferred from an aircraft-based infrared radiometer, was about 20°C too warm.

Multiple layers within clouds represent a particular problem to be overcome in the examination of the vertical structure within these systems. A climatological study of the occurrence of such situations has not yet been accomplished for extra-tropical cyclones. However, the thicknesses of these layers, as revealed by cloud profiling radar measurements, suggests that the most common thickness of layers within cirrus and marine stratus is about 2 km (Uttal, 1994). Data have been obtained within extra-tropical cyclones to be able to allow for a preliminary study of multi-layering and thicknesses but this information has not yet been examined in detail.

There have actually been very few studies of the multi-layering of such cloud systems (Figure 3). It is not currently possible, for example, to even present a detailed depiction of this feature of a single extra-tropical cyclone. As the locations of multi-layering are improved, attention will invariably begin to focus on the mechanisms that lead to the maintenance of separate layers or to their merging.

The impact of multiple layers on the vertical distribution of heating and on radiation and precipitation production will also need to be better appreciated. It may be that multi-layering leads to little difference in some of the radiational consequences since much of the impact is due to processes occurring at the top of the highest and the base of the lowest layer. It is however likely that the phase of the layers can also vary between liquid and solid but that interactions between the layers through, for example, falling precipitation, can alter the phases.

The cloud base characteristics of the layer clouds is a crucial aspect from the point of view of radiation and as an upper bound on sub-saturated conditions below which precipitation will evaporate (or sublimate) before reaching the surface. Cloud base is often strongly influenced by the precipitation produced within the layer. Findeisen (1940) for example showed that such layer clouds often had a cloud base close to the melting layer. This arises through preferential cooling by melting near this level, enhanced updrafts there, strong shears which result in dry air being advected below the melting layer, and the initiation of evaporation rather than sublimation (Clough and Franks, 1991).

Three regions within the precipitating regions of the layer clouds are particularly linked with enhanced liquid water. These regions are cloud top, cloud base, and, where applicable, the melting layer (Hall, 1957). The melting layer is a interesting region where liquid water can be generated and sustained within clouds in which ice-phase production processes are occurring (Stewart et al., 1984; Houze, 1993). The enhanced liquid water near the melting layer occurs through several processes including the direct melting of snow into droplets, the chilling and consequent supersaturation of the air by the melting, the consequences of embedded convection initiated by local instabilities, and maybe even by gravity waves preferentially contained in this region (Robichaud and Lin, 1989). Within the rain region, the amount of liquid water is typically low as the liquid is

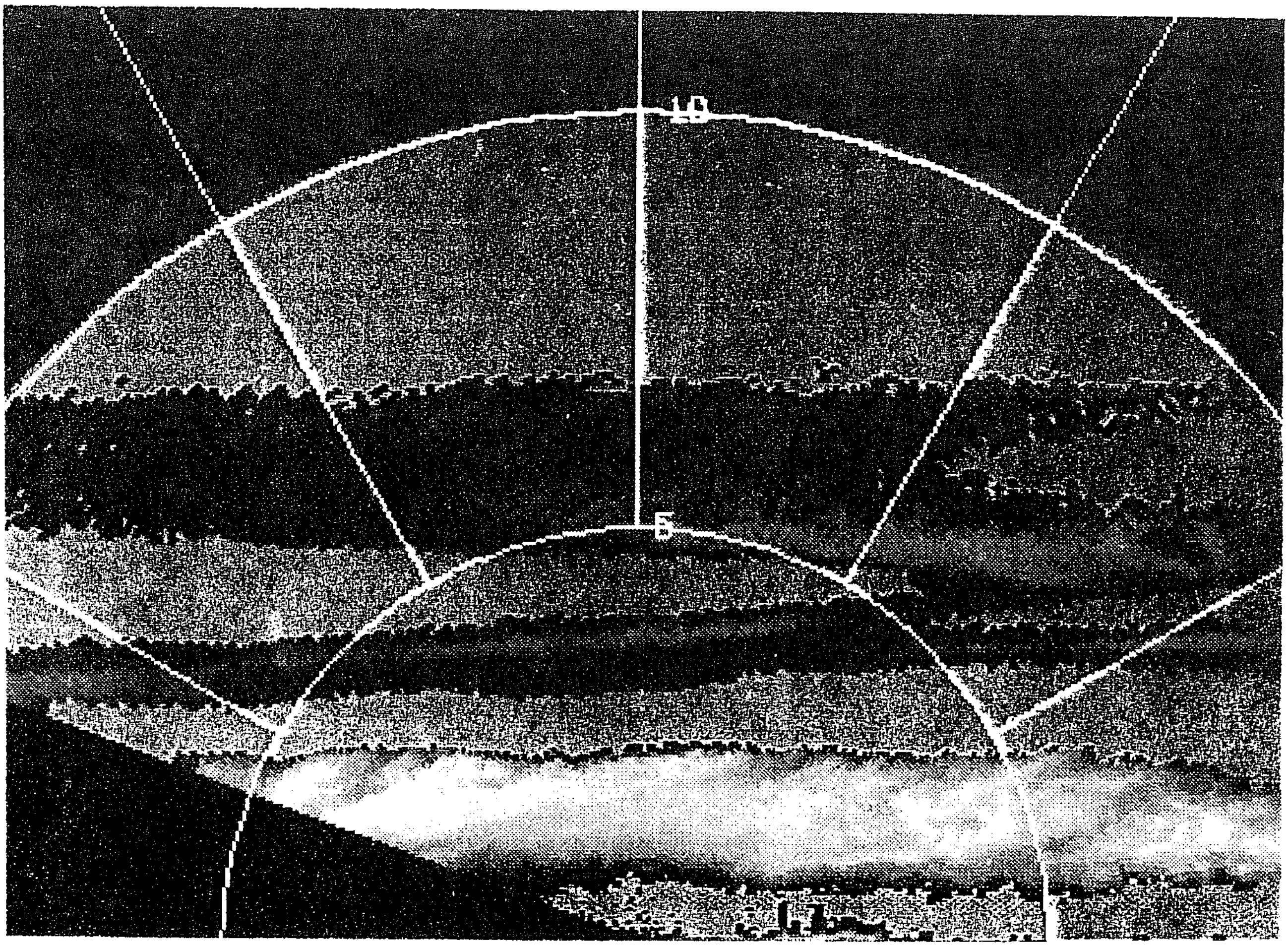

Figure 3: Multi-layering of non-precipitating clouds, as observed by the an 8 mm wavelength radar. The range rings are in units of km. Diagram is couresty of the Environmental Technology Laboratory in Boulder, Colorado.

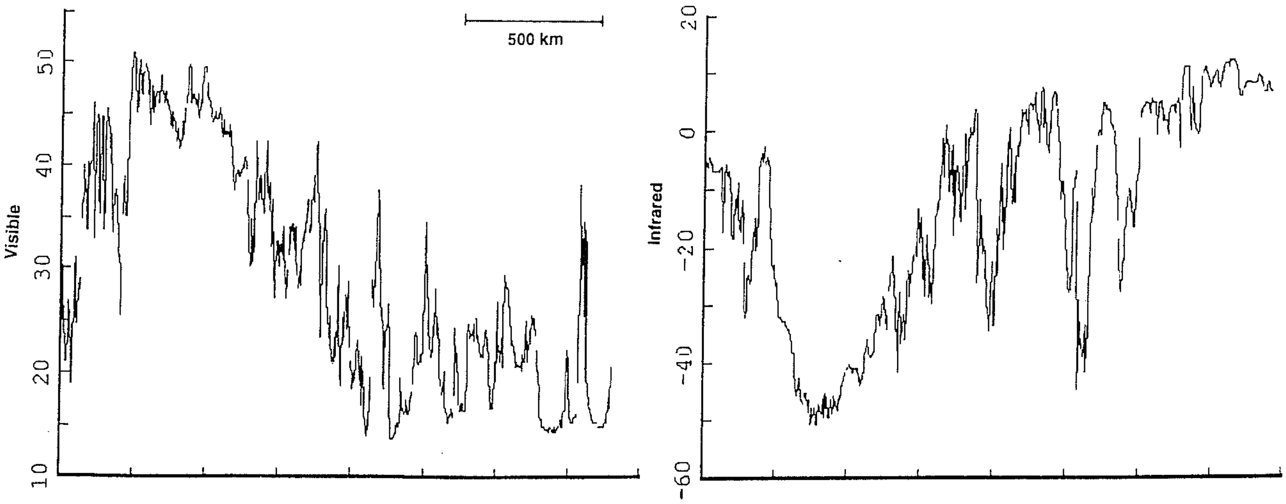

Figure 4: Visible and infrared temperatures observed by polar orbitting satellite along an east-west line through the low centre of an extra-tropical cyclone.

largely confined within the raindrops rather than in small cloud droplets. This region below 0°C is often characterized by descent as a consequence of the diabatic forcing of melting and other factors (see for example Szeto et al., 1988a&b), although other processes such as large scale forcing can still generate uplift and consequent condensation in this region.

Gravity waves may sometimes lead to major alterations in the nature of the layer clouds. In the case of layer clouds affected by orographic barriers, it is believed that such waves are the key phenomenon responsible for the generation of liquid water and precipitation (Reinking, 1993). It is furthermore believed that the presence, location and strength of gravity waves within frontal cloud systems could be significantly affected by the consequences of the precipitation. Both Robichaud and Lin (1989) and Marwitz and Toth (1993a) have shown that the stable layer initiated by melting and the associated strong shear across this region lead to the preference of gravity waves in this region of a storm.

Vertical profiles of latent heating within the precipitating regions of these clouds show typical patterns. Much of the heating aloft is linked with the diffusional growth of ice crystals although this can be augmented lower down by accretion, near the melting layer the process of melting produces a local sink of heating, and below cloud, evaporation (or sublimation if snow) cause another sink. Such results are also seen within the stratiform region of convective systems (Churchill and Houze, 1991). The actual magnitudes of these terms certainly vary with actual situations however. No studies have been conducted of the variation of diabatic heating with environmental conditions however.

3.2 **Dynamic and moisture field evolution**

Since most of the diabatic heating in extra-tropical cyclones is associated with layered cloud and precipitation processes, the study of the cloud is inseparable from the dynamics of the systems. Because of this interlinking it is essential that cloud and precipitation measurements be viewed in terms of measured system dynamical parameters where possible.

The systems exhibit an overall organization in their cloud fields. Often, newly generated systems are characterized by substantial convection, but later on this has evolved into a more stratiform cloud type. Such an evolution is certainly a characteristic of, for example, storms developing over the Gulf Stream (Neiman and Shapiro, 1993). Later in their lifecycle, convection can be completely absent when they move over the much colder north Atlantic Ocean.

The overall cloud fields are produced by broad slantwise ascent within "conveyor belts" that redistribute heat, momentum and moisture over great distances (see for example Browning and Monk, 1992). These "conveyor belts" are synoptic scale in origin but mesoscale ascent may significantly influence their character. Such mesoscale motions certainly alter the local properties of the layered clouds and precipitation through modification of the profiles of moisture and temperature. The measurement of the pattern of mesoscale vertical motion is particularly important to quantitative studies of this issue.

The conveyor belts linked with layer clouds play a major role in establishing the latitudinal heat transport. A key question is what mechanisms are responsible for such flows and how substantial are the flows to small scale processes. Recently, Szeto and Stewart (1994b) examined this question somewhat and they found that indeed the small scale processes occurring in their case in the warm frontal zone were critical to the establishment of the large scale conveyor belt character. The cold conveyor belt is basically the "thermal wind" associated with the strong baroclinicity near the surface front. Any diabatic effect that alters the baroclinicity there can affect the along-front flow (the cold conveyor belt) provided the forcing exists for a sufficient time.

It is also apparent that the phase of the cloud particles within the overall cloud field changes as well. It is expected that many of the clouds occurring within the systems are glaciated but regions of mixed phase and/or all liquid cloud certainly exist (Weinman, personal communication). Azarov et al. (1988) also pointed out that regions of supercooled water exists within all of the frontal systems studied over Russia, including those producing only snow. It may be that some of these traits are an inherent characteristic of the cloud system itself and are a consequence of the processes controlling the overall organization such as the upper lid of the low level cold conveyor belt being at 0°C within storms (see for example Carlson, 1980; Stewart and Macpherson, 1989). There are many articles paying testimony to the occurrence of ice clouds within these systems, but few have examined these other situations.

3.3 **Frontogenesis and embedded circulations**

The forcing of mesoscale circulations is largely associated with dynamically imposed frontogenetic processes driven from larger scales, but two main types of secondary mechanisms result in mesoscale features. These mechanisms are symmetric instability and diabatically-forced circulations. In the case of conditional symmetric instability, latent heat is released during ascent and the second can be triggered through other processes such as the evaporation, sublimation and melting of precipitation. The relative roles of these mechanisms in weather systems is as yet quite unknown.

There are often fine-scale cloud and precipitation structures embedded within the larger scale layer cloud system in mid-latitude depressions. These mesoscale features are typically organized into quasi-two-dimensional structures (rainbands) near the surface fronts (Browning and Harrold, 1970; Hobbs, 1978). Since these sub-structures interact with the larger scales, good physical understanding of these mesoscale features are essential for the accurate representation of the larger scale layer cloud field in global models. If the physical effects of these mesoscale structures are not represented adequately in the global models, spurious heat and momentum transfers from the mesoscale might have great impacts on the predictions of larger scale features.

Several theories have been advocated to explain these banded structure: conditional symmetric instability (CSI) (Bennetts and Hoskins, 1979; Emanuel, 1979), gravity waves, gravity current (Carbone, 1982), and frontal lifting, just to name a few. Parsons and Hobbs (1983) have done some preliminary comparisons of the predictions of the various theories with observations but the results are inconclusive.

The possibility of CSI is of particular interest as some recent studies have shown that it might have great impacts on frontogenesis (Emanuel, 1985) and cyclogenesis (Reuter and Yau, 1993) through latent heat release. Basically, the potential vorticity is reduced in saturated regions due to diabatic effects. Enhanced response to the frontogenetic forcing in these regions of small symmetric stability leads to the formation of banded mesoscale features. Diabatic effects in the enhanced ascents in turn alter frontogenesis.

Numerical models of various degrees of sophistication have been used to study these mesoscale frontal precipitation features. Rutledge and Hobbs (1983) used a diagnostic numerical model with a sophisticated microphysical package to study the feeder-seeder mechanism in the production of enhanced precipitation features embedded in a stratiform cloud. Early dynamical simulations of these phenomena typically employed hydrostatic models with coarse resolutions (for example, Hsie and Anthes, 1984; Knight and Hobbs, 1988). Due to the inherit limitations of these models, the simulations are of limited success.

Recently, some high-resolution non-hydrostatic 2-d simulations of frontal cloud systems have been attempted (Benard et al., 1992a&b; Lafore et al, 1994; Redelsperger and Lafore, 1994; Szeto and Stewart 1994a,b). By using a cloud-resolving non-hydrostatic model, Benard et al. (1992a,b) and Lafore et al. (1994) were able to simulate various cold-frontal rainbands by using both idealistic initial conditions and observed conditions (FRONTS'87). Their analysis showed that various mechanisms (convective instability induced by PBL frictional effects, gravity waves and CSI) were responsible for the different bands in the simulations. Szeto and Stewart (1994a&b) used a non-hydrostatic cloud model including the ice-phase microphysics to simulate warm-frontal cloud systems. Both the larger scale stratiform cloud and precipitation system and enhanced precipitating regions were simulated by the model. Their results show that the diabatic effects associated with these mesoscale precipitation features can have a frontogenetic or frontolytic impact on the parent storm, depending on the locations of these features with respect to the frontal zone. In particular, the cooling induced by the melting of snow particles in the vicinity of the synoptic frontal zone produced fine-scale frontal-structures similar to those observed by Stewart et al. (1994).

The effects of banded frontal precipitation structures on the larger scale have been studied by Redelsperger and Lafore (1994) by analyzing the model heat, moisture and momentum budgets in their simulations. Their analysis indicates that these mesoscale features have significant effects on the larger scale and these effects are similar to those found in squall line systems.

As implied by the potential importance of the latter category, the presence of the precipitation itself is critical. Due to the initiation of precipitation and its consequent melting, Taylor et al. (1993) and Marwitz and Toth (1993b) showed that some of the surface fronts observed within large scale systems is impacted greatly by precipitation phase changes. As well, Heymsfield (1979) showed that some warm frontal circulations were affected by melting, and Gedzelman and Arnold (1993) showed that diabatic effects such as melting can influence wide regions of the lower atmosphere within precipitating clouds. Huang and Emanuel (1991) showed that the evaporation of rain within downdraft regions enhances frontogenesis, and Thorpe and Clough (1991) showed that the sublimation of snow can enhance descent near frontal surfaces. These and other examples clearly demonstrate that the presence of the precipitation leads to very significant effects on the structure and characteristics of the parent clouds.

Processes tending to push the atmosphere to neutrality may be associated with small scale processes but end up affecting large scale uplift and the nature of ensuing clouds. Clough and Franks (1991) have in particular shown that the descent of air within precipitation can be maintained in saturation by the sublimation of the falling snow particles.

Numerous individual case studies and models of particular processes are being made, but the emergence of a consensus view depends upon an integration of the diverse approaches used and a much wider study than has yet been possible. This is not simple, however: both types of mechanisms are complex to measure or model, and are influenced by many mesoscale environmental factors not available from routine measurements. Because the horizontal scales of these circulations are below those likely in currently foreseeable general circulation models, there is a need to investigate whether they can be adequately parameterized within coarser resolution models.

3.4 **Radiational impacts**

Viewed from space, the most obvious impact of these weather systems is their alteration of the top-of-the-Earth radiation. While long recognized, the impact of this radiation perturbation is not fully understood.

The results of recent studies of the Earth's radiation balance have furthermore implied that anomalies exist in the mid-latitude cyclonic storm tracks and in particular over the north Atlantic (see for example Ramanathan et al., 1989). As presently believed, it appears that the cloud fields in this region are responsible for net heating aloft and cooling in the lower troposphere. At the top of the atmosphere there is a net positive forcing due to the dominance of the long wave cloud forcing. It needs to be demonstrated to what extent these features are directly related to the presence of the large organized systems themselves and, if so, what critical aspects are responsible.

A substantial degree of variation exists in the top-of-the-atmosphere radiation, even over the apparent deep cloud shield to the north and east of a low centre (Figure 4). One can see that considerable structure exists in both the infrared and solar radiation on scales of the order of 100 km. Such variations may be due to effects of embedded mesoscale structures existing within the overall system or they may result from processes and wave-like instabilities occurring near the cloud top.

The vertical radiational heating profiles within these layer clouds need to be better related to the actual nature of the systems. As already mentioned, the common presence of multiple layers and highly variable microphysical attributes mean that these profiles are very complicated.

Completely understanding the radiational properties and impacts of these cloud fields will therefore not be an easy task. The types of clouds vary (between, for example, low level convective, deep precipitating or non-precipitating as well as shallow layers) across each cloud system. Within each cloud type, the microphysical properties also vary enormously and it is believed that some of the upper level cirrus canopies can even contain regions of liquid water down to about -40°C (Sassen et al., 1985).

3.5 **Precipitation**

Precipitation represents a major transport mechanism for water. In addition, the phase changes linked with this process produce dramatic impacts on the thermal structure of the atmosphere. Consequently, this feature needs to be well-handled in models depicting these cloud systems.

Present numerical weather prediction models appear to often have reasonable accuracy in the prediction of rainfall but snowfall and orographically-affected situations may be less well simulated even though they have major hydrologic implications.

Precipitation formation within precipitating layer clouds can occur through several mechanisms (see for example Cunningham, 1951). Much of the precipitation is produced through ice-based processes requiring ice nuclei. Subsequent growth is through diffusional ice growth and through aggregation until the particles reach the melting layer. Drop interactions and condensational growth then dominate the subsequent development of precipitation.

Much of the precipitation is in the form of rain but snow and freezing precipitation are common in some regions. There is often an organization to the occurrence of these forms of precipitation and it is often found that some of the heaviest precipitation rates within the storms occur in the region where all types occur (Stewart, 1992).

Model resolution is an important factor to consider in regards to precipitation because these layer clouds may be only a few tens or hundreds of meters deep and because precipitation can sublimate, evaporate, melt or freeze within a few hundred meters. This issue is furthermore critical since the seeder-feeder process typically requires the sustaining of embryonic crystals through a fall from higher level to lower level clouds.

3.6 Moisture budgets and precipitation efficiency

There is a need to carefully quantify the overall moisture and other budgets of these systems and reconcile them with the smaller scale models and observations. Since mesoscale vertical velocities can greatly exceed those on the synoptic scale the transport properties of weather systems must be substantially influenced by these embedded circulations which, although they are mesoscale in extent across a frontal discontinuity, may extend for hundreds of kilometers along the front.

There are few articles addressing the water budgets associated with individual weather systems. However, Houze et al. (1976) and McBean and Stewart (1991) estimated these budgets within storms over the west coast of North America and over the north Pacific Ocean respectively. They both found that the main source of moisture was from the low levels east of the storms with net inflow rates less than or of the order of 100 $kg^{-1}s^{-1}$. At levels above 50 kPa, there was net divergence.

It has been shown by Lau et al. (1993) however the water budget of tropical convective systems is very dependent upon detailed microphysical processes. Complex interactions involving all forms of water substance phase changes are critical to understanding features such as moistening and drying. Due to contrasting effects, the local rates of condensation and evaporation occurring within the storms can be 2-3 times larger than the overall values of moisture convergence.

Such an examination of the sensitivity of extra-tropical cyclone budgets to microphysical processes is certainly needed. It is quite probable that the water budget of such systems will be at least as complicated. Smith (1992) for example has asserted that the moistening of the upper atmosphere within these systems is assisted substantially through the direct lofting of ice crystals, as opposed to just the vertical ascent of water vapour. As well, Lau et al. (1993) pointed out how critical the melting level was to the overall water budget of tropical systems; within extra-tropical cyclones this level can be present everywhere, it can occur in some sectors, or it can be completely absent.

There do not appear to be any articles in the literature that directly discuss the precipitation efficiency of the systems. However, the results of McBean and Stewart (1991) implied that the precipitation efficiency in their case over the north Pacific Ocean was close to one, but they acknowledged that their dataset was not definitive. The question of precipitation efficiency is certainly a critical one however. Precipitation efficiency will depend on many aspects of the cloud structure. It will particularly be critical to the processes that can initiate precipitation with the systems and will furthermore be very sensitive to conditions below cloud base. In the high Arctic for example where dry sub-cloud conditions commonly prevail during the winter, it is expected that there will be a great loss due to sub-cloud sublimational processes. Because of these critical dependencies, it is expected that the efficiency will be very dependent upon the proper parameterization of the detailed microphysics.

The dependence of precipitation efficiency can easily be seen in some warm frontal precipitation system simulations of typical conditions found in different regions. The simulations were carried out using a cloud model described by Szeto and Stewart (1994a&b). Initially, a sounding in the warm sector of a storm was used to initialize the model and a simple 1°C per 100 km temperature gradient was assumed, as well as near neutral conditions aloft. As shown in Figure 5, the moisture flux in the calculated warm frontal cloud field varied greatly. The very moist north Atlantic case showed very high precipitation efficiencies whereas a case with very dry sub-cloud conditions over Australia showed very low efficiencies. Furthermore, the Australian case was characterized by an order of magnitude more moisture input than the Arctic case with temperatures everywhere below 0°C, but the flux of precipitation at the surface was the same.

It should be added that in a very recent article, Tinsley (1994) assumes a precipitation efficiency of 0.1 in connection with extra-tropical cyclones over the north Atlantic. He suggests that even small alterations in this quantity could furthermore be linked with significant changes in the diabatic heating within the systems. If precipitation efficiency is not handled well, neither will latent heat exchanges.

3.7 Microphysical level of detail

As previously shown, microphysics has a strong control over the conversion of moisture into condensate and on the radiational properties of the clouds. A critical issue to pursue is to somehow assess what level of detail in connection with the microphysics is needed to be handled within larger scale models.

The ice/water/water vapour system is complex, and uncertainties exist in a number of the processes, as well as variations in morphology because of the complex temperature/humidity dependence of ice growth. These processes and microphysical properties are likely to influence the observed onset and dissipation of some of the clouds, and hence the extent and influence of these clouds both on precipitation and radiation.

It has also been recently demonstrated that understanding the radiational attributes of mixed phase clouds will need very detailed treatments of the constituent particles. Sun and Shine (1994) showed that the classic approach of separating the particles into the two different phases and then adding the results together is not sufficient. One must do the calculation collectively. If such regions within the clouds account for a significant contribution to the overall radiation budget, this imposes a severe restriction on the degree to which simplifications can be made.

In summary, there is a clear need to evaluate the sensitivity of model results to the rates of processes such as sublimation and melting and the dependence of these rates upon both uncertainties in laboratory measurements and atmospheric variability in microphysical properties such as particle size or density.

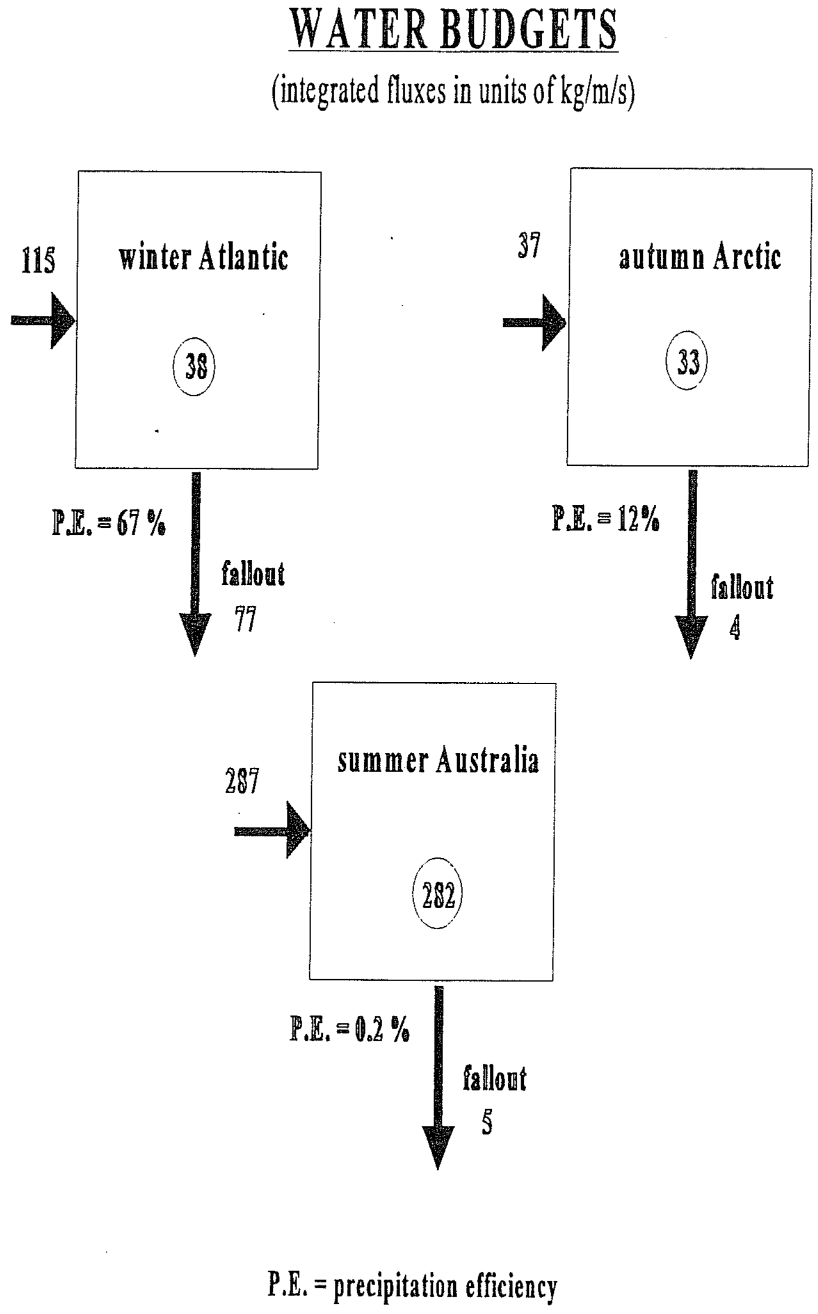

Figure 5: Schematic diagram illustrating some aspects of the water fluxes within three situations, as discussed in the text.

It does need to be appreciated however that some of these fundamental microphysical processes have not been adequately understood. An example is the sublimation of ice crystals. This is a critical issue in the entire feeder-seeder process and can produce a major impact on surface snowfall amounts. There has not been a single observational study conducted in order to validate the parameterizations of this process. The variable ice particle characteristics and the difficulties of accurately measuring ice particle mass are major impediments to such a study.

3.8 **Cloud fields and surface effects**

The locations of storm tracks are thought principally to depend upon large-scale dynamical factors outside the scope of this study. However, a number of smaller scale factors at the surface such as sea surface temperature gradients, sea ice cover and topographic features have been shown to sometimes modify the locations of either the entire cloud systems or some of their layered cloud regions. Such effects may need to be well simulated in climate models.

Numerous studies have documented the dependence of cloud field to the underlying surface. This interaction is often the result of forced baroclinicity at the surface or alterations in surface roughness, as imposed by numerous situations. Some of these include gradients in sea surface temperature that leads to the positioning of low centres to the north wall of the Gulf Stream (Neiman and Shapiro, 1993). Other examples include the sea ice edge, snow cover edge, and coastlines.

It is critical to precisely determine the large scale conditions that allow the alteration of positioning by surface processes to occur. It is likely that a spectrum of situations can occur in which surface effects such as mentioned above vary from being critical to positioning to those instances in which it is marginal. If surface processes such as coastlines impose a significant impact on positioning, they can be thought of as resisting any tendency for changes in cloud patterns induced by climate change. However, some of these surface factors, such as the sea ice edge and the snow edge, can be altered by climatic change and this may lead to important and complicated feedback mechanisms.

These layer cloud systems can be extensively modified through interactions with orography. This modification affects many attributes of these clouds including their precipitation and cloud layering characteristics. In terms of the proper incorporation of these systems within climate models, what level of detail is needed?

4. CONCLUDING REMARKS

Layer clouds occur in many regions of the Earth. The ubiquitous presence of these clouds and their associated dynamic, thermodynamic, radiational and precipitation features means that they must be carefully handled within realistic simulations of climate. Physical processes governing the character of these clouds are extremely complex with many interactions involving precipitation for example being only discovered in the last few years.

The GEWEX Cloud System Study has been developed in order to better incorporate the effects of these clouds within climate prediction models has been established and is currently underway. Because of the complex nature of these clouds, the challenge is daunting and can only be successfully accomplished through the collective resources between many institutes and countries around the world. The approach of GCSS will rely upon the validated simulation of these clouds with cloud and mesoscale models. It should be noted though that the non-hydrostatic prognostic simulation of frontal clouds appears to have been a missing field of study. The first such 2D simulations of a case were not published until very recently (Benard et al., 1992a&b, Redelsperger and Lafore, 1994) and no such studies exist for warm fronts.

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