

**Climate Processes  
over the Oceans**

**An EOS Interdisciplinary Investigation**

**1997-1998 Annual Report**

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## 1. Abstract

Satellite remote sensing data, *in situ* observations, and mathematical models are being used jointly to study climate sensitivity mechanisms involving atmospheric temperature, water vapor, clouds and their interaction with the ocean surface. The goal is to provide a comprehensive understanding of the maintenance of the cloud, humidity and temperature structure of the atmosphere and the tools necessary to incorporate this understanding into global climate models that will be used to predict future climates. The approach involves a strong interaction between observational and modeling studies, and in particular the use of high spatial resolution satellite measurements to test numerical simulations of the phenomena of interest, particularly marine boundary layer clouds and tropical convective clouds systems, and their interaction with large scale circulations and climate. Long records of surface and satellite observations are also being used to investigate past natural variability and trends and what these tell us about the interactions and sensitivity mechanisms of interest.

## 2. Introduction and Background

This is the 1997 progress report and plan for 1998 for an EOS Interdisciplinary Investigation entitled "Climate Processes over the Oceans", which was initiated in 1991 and has increased to the current level of effort. It involves the collaboration of five co-investigators who are faculty in the Department of Atmospheric Sciences at the University of Washington (C.S. Bretherton, R.A. Brown, D.L. Hartmann, R.A. Houze and C.B. Leovy). In the past year Prof. K.B. Katsaros has left the University of Washington to become director of the Atlantic Oceanographic and Meteorological Laboratory(AOML). Her participation in the investigation will become informal and less intense as she takes on added administrative duties associated with her new position. The purpose of this collaboration is to bring together expertise in several areas to make a more comprehensive, coordinated attack on several important climate modeling issues. These issues focus primarily on the maintenance of the cloud and water vapor distribution of the atmosphere above ocean areas, which in turn involves radiative, physical and dynamical processes in the atmosphere and their interactions with the ocean surface, and encompasses spatial and temporal scales that range from those of boundary layer turbulent structures, through mesoscale circulations, to those of the largest scales of planetary motion. A brief description of this investigation with some color graphics of results can also be found on World Wide Web at <http://eos.atmos.washington.edu>. Progress and plans for the future will be outlined here.

### *Milestones in 1997*

We have developed a doubly periodic version of the MM5 mesoscale model, which we have used to study the organization of tropical convection. We have compared a 15 km horizontal resolution version including a convective parameterization with a 5km resolution version in which all cloud processes are explicitly calculated. The results were sufficiently similar that our work to understand the relationship of convection to the large-scale environment can be continued with the 15 km version. Little evidence of self-aggregation was demonstrated in these simulations, suggesting that the organization of super-clusters in the tropics results from synoptic-scale interactions and not from intrinsic mesoscale organization principles.

We have completed a study of methods for estimating surface evaporative energy fluxes over the oceans using remotely sensed data from microwave imagers to estimate low-level humidity fields.

We have completed additional studies of the surface-based record of clouds, with special emphasis on summertime marine cloud in midlatitudes. The relationship of summertime marine boundary layer clouds to the meteorological conditions has been investigated. Both warm and cold advection result in marine boundary layer clouds, but of different types.

We have begun the process of collecting a large volume of data from the visible, IR and water vapor channels on the GMS-5 satellite for studying the relationship of water vapor to convective cloudiness in the western tropical Pacific Ocean and Indonesian area..

We have hired a postdoc to work closely with the co-investigators and with NCAR staff to understand and improve the stratus cloud simulation in the NCAR CSM. This research associate, Dr. Hervé Grenier, will join the project in September. We are running the NCAR CCM3 atmospheric general circulation model on our own local computer in multi-cpu mode.

### **3. Scientific Accomplishments and Future Plans**

#### **3.1 Boundary Layer Modeling and Surface Fluxes**

Vertical exchanges of heat, moisture, momentum and constituents at the surface and through the planetary boundary layer (PBL) are one of the important uncertainties in climate modeling. Both estimates of observed fluxes and modeling of the planetary boundary layer in climate models are problem areas. We are working in both of these areas. Boundary layer structure and fluxes are also intimately connected to problems of cloud formation and maintenance. Our goals remain:

- To produce the best analysis of surface winds over the oceans using a combination of data available from scatterometry, microwave radiometry, available meteorological analyses, and the best available models.
- To produce the best estimates of surface fluxes of momentum, heat, and moisture, using the same methodology.
- To integrate observation and understanding of boundary layer processes and cloud properties, both for clouds within and above the boundary layer.
- To improve models of the boundary layer and the interaction of the boundary layer with cloudiness and large-scale motions.

#### *Wind Fields*

Over the next few years much effort will focus on utilizing the nine months of NSCAT data to the maximum extent possible, while we wait for ADEOS-II and

SeaWinds data. We have the entire NSCAT data on CD and can very quickly access any time, location. Part of this work will be to correlate NSCAT surface wind convergences over the oceans with cloud properties measured from satellites. It should be possible to study details down to 50km to better understand frontal cloud generation and the surface convergence that may be associated with convective cloud systems.

Use of NSCAT data and our PBL model suggest that GCMs show winds of  $25 \text{ ms}^{-1}$ , where the true winds as measured by NSCAT and the PBL model are  $35 \text{ ms}^{-1}$  (Brown, 1997b). Such errors in analysis and model forecasts are important for hazard warnings and for calculating air-sea fluxes.

#### *Planetary Boundary Layer Modeling*

In the next year graduate student Bart Brashers will finish his Ph.D. thesis. His project is to develop the UWPBL model so that it uses SSMI input to the NSCAT winds on synoptic times and scales to calculate latent heat fluxes, cloud condensation heights, and cloud predictions (Brashers 1997a,b). This will integrate boundary layer fluxes and boundary layer clouds in a way that can be used to integrate satellite observations of several types.

#### *Cloud Interactions and flux Calculations*

The PBL model is being further developed to incorporate cloud processes. Brown and graduate student Brashers are developing and testing theories to determine PBL air temperature, cloud condensation heights, PBL inversion heights and related flux parameters based on EOS-era satellite data. This will allow the PBL model to be extended to incorporate thermodynamics and clouds. The input data can include integrated water and cloud liquid water from microwave imagers such as SSMI, SST from satellite measurements, and scatterometer wind fields. A few assumptions are required to simultaneously determine inversion heights, saturation mixing characteristics, cloud condensation level, air temperature and stability from the PBL model. The validity of these assumptions can be tested against satellite and in situ data.

In the past year Katsaros and Ataktürk have conducted a focused effort to estimate the near surface humidity and the wind speeds from the SSM/I data. This work has been written up for a paper to appear in the PORSEC book (Ataktürk and Katsaros, 1997) and will later be written up for a refereed journal article. In this work they compared surface wind speed and humidity estimates from SSMI with those directly observed from ships during the Structure of the Exchanges in a Marine Atmosphere, Properties of Heterogeneities in the Ocean, Research and Experiment (SEMAPHORE). The wind stress estimates are very good, but the surface humidity is overestimated, which results in inferred evaporation rates that are 20-100% of those inferred from the in situ data.

Our objectives over the next several years for the PBL portion of our research remain:

- To complete the incorporation of thermodynamics and clouds into the PBL model.
- To expand the surface wind assimilation to more cases, a broader area of the Pacific and to the ASTEX regions and period for continued use in boundary layer cloud studies.

- To fully utilize emerging scatterometer wind stress data from ERS, NSCAT and SeaWinds in conjunction with models and to her data sources.
- To provide an adequate parameterization of synoptic-scale surface wind and stress, clouds and air-sea fluxes. This requires a simultaneous analysis of the boundary layer clouds described in the next section and incorporating information from various satellite data sets. We will model the thermodynamic structure of the sub-inversion PBL, and possibly also model cloud coverage and type for comparison with satellite information.

### 3.2 Boundary Layer Clouds

The cloud type that makes the largest contribution to top-of-the-atmosphere (TOA) cloud radiative forcing is marine boundary layer cloud, particularly stratiform cloud (Klein and Hartmann, 1993). This part of our research focuses on the behavior and properties of these clouds. Our long term objectives are:

- To document the climatology of marine boundary layer clouds and their relationships to other geophysical variables on diurnal, synoptic, seasonal, interannual, and interdecadal time scales,
- To use this information to improve our understanding of the properties of these clouds to contribute to accurate boundary layer cloud simulation in coupled climate models, and to apply and test new cloud parameterizations in GCMs,
- To use the information on cloud climatology and variability to refine our knowledge of cloud radiative forcing and its long term changes,
- To incorporate improved treatment of boundary layer clouds into estimations of latent and sensible heat fluxes over oceans.

In our previous work, we have documented interannual and interdecadal variations of low clouds by cloud type over the mid-latitude Pacific and the tropical Pacific and Indian Oceans, as well as the relationships between these variations and variations of sea surface temperature, surface pressure, and surface winds (Norris, 1997a,b,c; Norris et al., 1997; Bajuk and Leovy, 1997a,b). The deduced cloud variations are large in some cases, and significant and continuing interdecadal trends were revealed over large areas of the mid-latitude and subtropical Pacific Oceans. These results suggest two avenues of follow-on research: (1) application of the results of these studies to improvement of the representation of stratiform cloudiness in climate simulation models, (2) estimation of the corresponding variations in cloud radiative forcing at the surface and at the top of the atmosphere for the summer mid-latitude Pacific.

In the coming year we will begin to merge our understanding of observed marine boundary layer cloud behavior with efforts to simulate boundary layer clouds in GCMs. Our new post doctoral research associate, Dr. Hervé Grenier will collaborate with the PIs in the development and testing of parameterized models of marine boundary layer clouds that will be suitable for use with NCAR CCM3. Such models should reproduce the sensitivities to ocean and atmosphere properties revealed by the observational studies of

Klein (1994, 1997), Klein et al. (1995), Norris (1997a,b,c), and Bajuk and Leovy (1997). We will attempt to derive and apply sensitivities to key parameters such as subsidence velocity, free air humidity, and sea surface temperature that are separated in the sense of partial derivatives.

Further observational work will focus on relating the surface-based observations of clouds to satellite-based observations such as those from ISCCP. A by product of this effort will be improved estimates of cloud radiative forcing at the surface and top of atmosphere, especially over mid latitude oceans during summer, when this forcing is most important. This effort will require the use of ISCCP D2 and DX data sets, and active collaboration with Bill Rossow's group at GISS.

### 3.3 Tropical Convective Clouds

Deep convective clouds of the tropical atmosphere are one of the most important and interesting components of the climate system. They are the primary means whereby water vapor is removed from the tropical atmosphere, and in doing so they warm the air through the release of latent heat and associated subsidence. In this way they move solar energy collected in the ocean to the atmosphere. They also have significant radiative effects, which also tend to heat the atmosphere and cool the surface. They interact strongly with the large-scale wind systems of the tropics, the Hadley and Walker Circulations, in determining the climate of the tropics, and play a central role in ENSO variability.

We are studying the interactions of tropical convection with the tropical climate by using a combination of data from field studies, meteorological analyses, and satellites, together with modeling studies. The goals of the study are:

- To define the structure of the tropical convection using high resolution satellite data and supporting *in situ* data,
- To relate these structural properties to the large-scale dynamic and thermodynamic conditions,
- To quantify the role of tropical deep convection in moistening the upper tropical troposphere
- To successfully model the mesoscale structure of observed tropical convection in a regional mesoscale model,
- To verify that a regional mesoscale model can reproduce the observed relationships between the structure and properties of mesoscale convective complexes and the large-scale environment in which they are embedded,
- To use a nested model to investigate the equilibration between tropical mesoscale convection and the large-scale environment, including the effects of large-scale circulations.
- To utilize the information gained from the coordinated modeling and observational studies to suggest improvements in convective cloud parameterizations that will be useful in global climate models.

### 3.3.1 Observational studies of Convective - Large-Scale Interactions.

Houze and Chen will continue their analysis of TOGA COARE convective systems using both satellite and airborne as well as shipborne radar data. The continuous ship radar coverage over about three months (with several days break at times) during TOGA COARE provides a unique opportunity to examine the three-dimensional structure of cloud systems. These observations will explore and, to a large degree, determine the uncertainty in satellite observation of tropical convection. We will also compare the radar observations with MM5 simulations.

Chen and Houze (1997a) further analyzed TOGA COARE satellite data. They examined the open-ocean diurnal cycle of convection and showed that the diurnal cycle has an important relation to the 2-day variability at a given location. The diurnal cycle is dominated by the broadest (mesoscale) convective cloud systems, which last for a day or more. They also studied interannual variability (Chen and Houze, 1997b).

#### *Tropical Convective Cloud Systems and Relative Humidity*

Tropical convective clouds are believed to have a powerful effect on upper tropospheric humidity in the tropics, both through moistening by delivering water vapor and ice directly via detrainment, and through drying they cause by driving subsidence in the surrounding atmosphere. The manner in which these two competing effects will change in an altered climate is not understood and could have a substantial influence on the magnitude of the temperature change, because upper tropospheric water vapor has a strong influence on outgoing longwave radiation in the tropics, particularly in those cloudless regions from which much of the OLR escapes.

Salathé and Hartmann (1997) analyzed the distribution of upper-tropospheric water vapor in the tropical eastern Pacific using moisture data retrieved from GOES 6.7 $\mu\text{m}$  observations and wind data from ECMWF analyses. The motions and processes that control tropical moisture are isolated, transient and embedded in the tropical wind pattern. Previous studies of tropical moisture have relied on averaging methods that mix dynamically disparate regions. By computing trajectories of air motions, we can associate air masses with their convective source and analyze the moisture variations in coordinates established by the actual air motion. We have used this trajectory method to analyze a one-month set of satellite moisture data and examine the effects of subsidence and horizontal transport on the distribution of tropical moisture. In Salathé and Hartmann(1997) we have shown that the distribution of upper-tropospheric humidity (UTH) in the cloud-free tropics can be simulated with a simple model in which air expelled from moist convective regions is dried by subsidence along its trajectory. The distribution of UTH is analyzed in the tropical eastern Pacific using moisture data retrieved from GOES 6.7 micron observations during September 1992. The analysis examines the variation in moisture along horizontal trajectories derived from ECMWF wind analyses. Trajectory analysis is used to trace the convective sources of subtropical air. For the eastern subtropical Pacific, convective sources lie entirely outside the dry region, and are predominately in the ITCZ and over South America, with some air tracing to midlatitudes. The analysis also shows that, over large parts of the eastern subtropical Pacific, air has advected horizontally for five or more days since exiting convection. Composites of many trajectories from specific source

regions show that radiatively driven subsidence appears to control the decrease in relative humidity away from convection.

The observed UTH distribution along trajectories is then simulated with a simple model of horizontal advection and subsidence of an initial convective moisture profile. Finally, the monthly mean horizontal distribution of water vapor is related to the distribution of the mean time since air at any location was in a convectively active region. We are currently applying the results of this study to analyze atmospheric model results to evaluate the moisture dynamics in the models. A mesoscale model, MM5, and a global model, CCM3, will be used for this study. The analysis of MM5 will look more closely at the dynamics in the vicinity of convection, and the CCM3 study will test the models ability over a large region and time period. The comparisons to the models, especially MM5, should also help clarify some aspects of the problem that are difficult to resolve using the satellite data. In particular, the MM5 should illustrate the relationship between air motions and moisture profile in the vicinity of convection and the large-scale flow and moisture transport. To extend this analysis, we plan to examine micro-wave limb sounding (MLS, Read, et al., 1995) data, which will reveal the moisture dynamics at the highest levels of the troposphere, where deep cumulus towers detrain. The data used in the initial work indicates the mean humidity over a broad layer of the upper troposphere. Thus, important issues regarding the vertical variations in moisture dynamics have been left unanswered. The earlier study also only examined moisture sources in the tropical region, but there is strong evidence that midlatitude processes play an important role in the subtropical moisture distribution. We also plan to make a longer term global trajectory analysis of the sources and mean time from source of tropical air in order to examine the relative roles of tropical and extra-tropical processes.

In collaboration with Dr. Udelhofen at CRC/Monash University, Australia, we will continue to collect and process hourly GMS-5 water vapor data for the time period of Nov 1996 - Feb 97 which contains two intraseasonal oscillation events. We will analyze the water vapor channel data to examine the multi-scale variability of upper level water vapor variability associated with deep convective activity on intraseasonal and synoptic (2-3 days) as well as mesoscale (a few hours to 1 day) time scales. The results will be used to compare and validate mesoscale model (MM5) simulated water vapor field over the western Pacific. These data can also be subjected to the trajectory analysis described above. This analysis will also be used in planning aircraft field experiments to see how air is process as it leaves the convective region and heats north toward Guam or Hawaii during each of the winter and summer seasons.

### *Box Modeling of Tropical Climate*

Hartmann and graduate student Kristin Larson have developed a simple two box model which incorporates the Cloud-Detrainment-Subsidence explanation for the clear-sky moisture balance into an interactive model of the tropical climate. This model is giving very interesting insights into tropical climate sensitivity. In this simplified model one can study the interplay among circulation, humidity, radiation and both convective and boundary layer clouds. It is easy to show that in the tropics the radiative effects of deep convective clouds are most important at the top of the atmosphere. The redistribution of

heat between the surface and that atmosphere that is produced by convective clouds is only of second order importance, because the convective fluxes of energy easily compensate for these radiative effects in an atmosphere that adjusts to a convective balance. The model suggests ideas that can be tested with data or more complicated models. A paper for the *Journal of Climate* describing these results is in the latter stages of preparation (Larson, Hartmann and Klein, 1997).

### 3.3.2 Mesoscale Modeling

#### *Modeling of Observed Cloud Populations in the Tropics*

In our cloud modeling research we use the TOGA COARE data set as calibration of MM5 model simulations of equatorial deep convection over the Pacific. We aim to use the model in a climatological mode. That is, we run the model for periods of several weeks and determine statistics of the convection that occurs and the relationship between the model convective population and the large-scale fields of water vapor and radiative and latent heating. To test the model we have analyzed the TOGA COARE satellite, ship, and aircraft data in such a way as to characterize the ensemble behavior of the convection and its environment. This work has been conducted by post-doctoral research associate Shuyi Chen and graduate student Hui Su together with several of the PIs.

During the past year, we have made simulations with the MM5 of the circulation and cloud patterns over the COARE region. One simulation covered several days during a convectively active phase of the ISO. Another simulation has been made for several days during a convectively suppressed phase of the ISO. A third simulation has been made to represent conditions in the eastern Pacific Intertropical Convergence Zone (ITCZ), in order to compare and contrast the cloud ensembles that occur over the relatively uniform sea surface temperature (SST) of the western tropical Pacific and the strong north-south SST gradient of the eastern tropical Pacific. All of these model runs have been successful, and we have verified the results of the first two runs statistically against TOGA COARE satellite and aircraft data.

These successful tests of the MM5 simulations against the TOGA COARE aircraft data give us considerable confidence that the cloud and precipitation fields computed with the MM5 are adequate to determine the water vapor and radiative budgets over the tropical Pacific on monthly, seasonal, and annual time scales. We will be devoting some of our future EOS research to these efforts.

Under the direction of co-PI Bretherton, graduate student Hui Su has been using the PSU/NCAR MM5 nonhydrostatic mesoscale model to study fundamental features of tropical convective organization. Our focus has been on examining 'self-organization'--a hypothesized tendency for deep convection to develop synoptic scale organization even when all external boundary conditions such as sea-surface temperature and insolation are spatially uniform. Sub-synoptic scale features such as superclusters and tropical cyclones, synoptic scale easterly waves, and global patterns such as the intraseasonal oscillation have all been attributed by many theoretical studies to convective self-organization. From the climate perspective, these phenomena are collectively responsible for much of the transience in tropical convection. This transience in turn feeds back on the mean climate by

affecting the spatial and temporal distribution of latent heating, cirrus cloud, and detrained water vapor, and contributing to such features as double ITCZ's in the mean Hadley circulation.

#### *Model intercomparison work*

We have used the PSU/NCAR mesoscale model MM5 to simulate the tropical convective system over the IFA(Intensive Flux Array) during TOGA COARE (Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment) from 19-26 December 1992. Two simulations with two horizontal grid spacing, 15 km and 2 km are conducted. With 15km resolution, cumulus convection is parameterized, while mesoscale convective organization is explicitly resolved over a 600 km x 600 km domain. For 2 km simulation, convection is fully resolved over a 210 km x 210 km domain.

We compared the model results against a variety of TOGA COARE observations and found that the MM5 reproduced many ensemble properties of the convection in response to evolving large-scale conditions. The domain averaged cloud amount and precipitation agree with the observed data. Over the eight-day period, the model produced mean temperature drifts about 2 K colder than observed. Histograms of cloud top temperature and radar reflectivity are qualitatively similar to their observed counterparts.

The two model simulations with different horizontal resolution and different treatment of moist convection produced very similar temporal variability in domain-averaged temperature and relative humidity profiles. They also closely resemble each other in various statistical properties of the convection. This study suggests that large-domain simulations using the MM5 with 15 km resolution will be useful for further study of tropical convection and its interaction with large-scale circulation (Su, et al., 1997a).

We also participated in GCSS Work Group 4 Model Intercomparison project which involved a six-day simulation of TOGA COARE convective systems during 20-26 December 1992 using the same model framework with a slightly different initial sounding and 'IFA mean forcing' profiles. Results of the intercomparison can be found in the 22nd tropical meteorology and hurricane conference preprints(Krueger, 1997). A formal journal paper is in preparation by Steve Krueger.

#### *'Self-aggregation' and large-scale control of tropical deep convection*

In the past year, a primary topic we have been working on is the mechanism responsible for the grouping or superclustering of tropical deep convection. Particularly, we have been investigating whether the superclustering is a spontaneous self-aggregation of convection or it requires preexisting large-scale circulation and/or horizontal boundary inhomogeneity by idealized modeling study using the MM5. We conducted a set of experiments with different initial conditions and reference wind profiles. Our modeling results suggest self-aggregation of convection could not explain the superclustering of tropical convection. Random distributed convection does not evolve into organized cloud clusters of dimension greater than 300 km when uniform 'large-scale forcing' is imposed. Strong surface fluxes along with strong vertical wind shear help form linear convective organization but does not seem to help form superclusters. Results of this work can be

found in the 22nd tropical meteorology and hurricane conference preprints(Su et al., 1997b). A formal journal paper is in preparation.

One of our future plans is a sensitivity study of the long-time MM5 simulations to different surface flux algorithms, such as Blackadar and TOGA COARE algorithms. This work is in progress and the results will be reported in an upcoming paper. Surface fluxes are one of the most important boundary forcing of the atmospheric mesoscale model. A recent study by Wang et al. (1996) have indicated that convective systems are very sensitive to various flux calculations in their model over a 12 h period and relatively small model domain. However, the effects of surface fluxes over a large model domain which includes both convective systems and the environment for a longer time period (several days) which includes multiple lifecycles of convective systems is unknown. Su and Chen have recently implemented a new surface flux algorithm from TOGA COARE (Fairall et al. 1996) in MM5. We will test the sensitivity of our current MM5 simulations described in Chen (1996, 1997) and Su et al. (1997) to different surface fluxes calculations in MM5.

Another major issue we are going to explore next year is the interaction of large-scale wave and convection, particularly, the 'Wave-CISK' theory. By using the similar framework of the MM5 with a large horizontal domain and rigid-wall boundary conditions, we will impose a large-scale wave pattern in the initial velocity and temperature fields. Then we will look at the wave propagation and the phase relationship between wave perturbation and convection. This can be used to verify or refute the 'Wave-CISK' theory.

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#### 4. Management of this Investigation

##### *Personnel*

In the past year we have had several major changes in personnel. In the summer of 1997 Prof. Kristina Katsaros became director of NOAA's Atlantic Oceanographic and Meteorological Laboratory and resigned her position at the University of Washington. Her collaboration with our group has been reduced to an informal basis and her associate, Dr. Serhad Ataktürk, will no longer be supported under this grant. Also this summer, Dr. Shuyi Chen took a position at the University of Miami. She was supported 30% under this grant to help with satellite observations and mesoscale modeling of tropical convective cloudiness. She will continue to collaborate with the group, but as an independent scientist rather than a research associate. Eric Salathé who is doing our tropical water vapor work with GOES and GMS will continue to do the same work, will collaborate with the EOS mesoscale modeling projects, but will begin to work on a separately funded field project.

Graduate student Joel Norris received his Ph.D. degree and will move to NCAR. We expect to continue some collaboration, however.

We have no plans to add a co-investigator to replace Katsaros at this time, since we added Bretherton a couple years ago without a corresponding increase in budget. We have added a new research associate to work with global climate models, Dr. Hervé Grenier, who joined the project in September of 1997. Dr. Grenier came to us from Paris, where he worked with a French/Belgian consortium to develop a coupled climate model. We plan to add another postdoc in the near future.

##### *Co-I's*

- C.S. Bretherton: Is leading part of effort in tropical convective cloud modeling. Also provides strong theory component for the boundary layer cloud studies. Joined the team as a Co-I in early 1995. Provides a link to ASTEX, FIRE and SHEBA experiments.
- R.A. Brown: Is in charge of the UWPBL modeling effort, and provides a link with the scatterometry experiments at ESA and NASA/NASDA. He also has been a WetNet PI and so provides us with good access to SSMI data.
- D. L. Hartmann: Provides coordination within the group and with the project, and leads effort in upper tropospheric water vapor study and uses of radiation budget data. Responsible for large-scale diagnostics effort, including new efforts to use NCAR CCM3 and collaborate with J. Kiehl and others at NCAR in model improvement. Collaborates in mesoscale modeling project.
- R.A. Houze: Provides leadership for the cloud cluster climatology project and for the modeling effort in tropical convection and its relationship to the large-scale environment. He provides a link to the TOGA COARE project, TRMM project and future east Pacific project (PACS).

C.B. Leovy: Leads the effort in using conventional data to understand variations and trends in stratocumulus clouds. He also leads an effort to use high resolution satellite images to better understand PBL fluxes of heat and moisture, particularly in stratocumulus regimes. Is developing simplified models to compare with observations. He will also collaborate in developing and testing new GCM parameterizations for marine boundary layer clouds.

*Post Docs:*

Dr. Hervé Grenier: Will join project after completing degree with André Berger working on the development of a coupled climate model in France and Belgium. Will have primary responsibility for link between our observational and simple model studies of marine boundary layer clouds and the NCAR Climate System Modeling Project (CSMP). (100%) Working with Hartmann, Bretherton, and Leovy.

Unnamed research associate: To be added in cloud modeling or analysis of satellite observations of clouds and water vapor.

*Graduate Students:*

Joel Norris: Ph.D. student has graduated and will move to NCAR postdoc.

Bart Brashers: Ph.D. student working on UWPBL model development with Brown as supervisor.

Su Hui: Ph.D. student who is working on the mesoscale modeling project with Bretherton and Hartmann as supervisors.

Kristin Larson: Ph.D. student supported under NASA GC Fellowship. Working with Hartmann on simple, but comprehensive model of tropical climate.

New Student: Will enter in the fall of 1997.

*Staff:*

Marc Michelsen: Software Engineer: responsible for development and maintenance of our Science Computing Facility. (50%)

Candace Gudmundson: Editor: Assists with preparation of documents describing the research results and develops web pages for the investigation and for the SatView Manual. (25%)

Shirley Joaquin: Fiscal Specialist: Provides program management, fiscal report production, does purchasing and provides other services necessary to meet the objectives of this project.



## **5. Conclusion**

A viable scientific collaboration has been established between the five co-investigators on this project, and we are undertaking a broad approach to a difficult and important problem that must be solved in order to provide credible forecasts of climate change. Currently available satellite measurements, in situ measurements, and models are being used in a coordinated way to attack the cloud-climate interaction problem, especially for marine boundary layer clouds and tropical convective clouds and their mutual interaction with the atmospheric climate and ocean surface. The investigation is poised to take advantage of the EOS satellite data when they become available, and the co-investigators are contributing to the development of the larger EOS enterprise. We have moved more toward cloud, boundary layer and climate modeling, and have established a strong working relationship with a major climate modeling center, as well as increasing our ability to do climate modeling locally on our own hardware.

## 6. Publications supported in whole or in part by this grant

*Refereed Publications: Recent ones are marked with a \**

\*Ataktürk, S. S. and K. B. Katsaros, 1997: Estimates of the surface humidity and wind speed obtained from satellite data in the stratocumulus regime in the Azores region. *PORSEC '97*. Eds., in press.

\*Bajuk, L.J., and C.B. Leovy, 1997a: Marine clouds from surface observations, Part I: Seasonal and interannual variations in tropical low cloud type. *J. Climate*, submitted.

\*Bajuk, L.J., and C.B. Leovy, 1997b: Marine clouds from surface observations, Part II: Interdecadal variations. *J. Climate*, submitted.

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\*Brown, R.A., 1997a : *PORSEC Book II*, Pacific Ocean Remote Sensing Congress publication, Ed. R.A. Brown, Seven chapters, 36 articles, about 300 pp. (in press).

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\*Chen, S. S., and R. A. Houze, Jr., 1997a: Diurnal variation and lifecycle of deep convective systems over the tropical Pacific warm pool. *Quart. J. Roy. Meteor. Soc.*, **123**, 357-388.

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#### *Theses:*

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Miletta, J., 1993: "Meteorological Applications of Coincident Visible, Infrared, and Microwave Observations from the Defense Meteorological Satellite Program", M.S. Thesis, University of Washington, 155pp.

Norris, J.R., 1997: Interannual variability in cloudiness, sea surface temperature, and atmospheric circulation over the midlatitude North Pacific during summer. Ph.D. dissertation, Department of Atmospheric Sciences, University of Washington.

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*World Wide Web Pages:*

SatView Manual: Find with software manuals under; <http://www.atmos.washington.edu>,  
or directly to <http://www.atmos.washington.edu/gcg/SV.man/SVmanual.html>.

Climate Processes over the Ocean, <http://eos.atmos.washington.edu>.

TOGA-COARE Summaries: Find under <http://www.atmos.washington.edu>.

## **7. One-page summary of most important findings in 1997**

Satellite observations and other data have been used to better understand tropical convective complexes and their relationship to other phenomena and scales in the tropics (Chen and Houze, 1997a,b)

Satellite observations of clouds and water vapor have been combined with meteorological analyses of wind to show that a simple model of horizontal advection and diabatic subsidence can be used to explain the observed variations of upper tropospheric water vapor in the tropics. (Salathé and Hartmann, 1997). Further analysis of observations and models is planned that will use this paradigm to estimate the role of upper tropospheric water vapor in feedback mechanisms determining the sensitivity of climate to forcings such as a human-induced increase in atmospheric greenhouse gases.

Tropical convection has been simulated in a mesoscale model, and these simulations have been compared successfully with observations (Su et al., 1997a). The mesoscale model thus provides a new tool with which to study the relationship of clouds and water vapor to the mean climate of the tropics. This investigation will help in understanding this relationship and in developing parameterizations for critical climate feedback processes in global climate models.

Relationships between marine boundary layer cloud properties and the vertical structure of the boundary layer have been determined from observations (Norris, 1997a,b). These observations provide insight into the mechanisms that maintain marine boundary layer clouds, which have a large influence on the radiative energy balance of the planet and a potentially large role in climate sensitivity. These relationships can be used to test climate model performance and to develop improved parameterizations for boundary layer clouds, which are currently not well simulated in global climate models.