For the past decade, cloud feedback on climate sensitivity has been identified as the largest internal source of uncertainty in climate change predictions [1-3]. For instance, current versions of two of the most well-known US climate models, the AM2.7 from GFDL and the NCAR CCSM2, have climate sensitivities of 5 K and 1.5 K, respectively, which are at opposite ends of the spectrum of predictions from climate models. Systematic feedback diagnosis by co-PI M. Zhang has shown that cloud feedbacks are the primary culprit. Fig. 1 shows the change in low cloud cover (within 2 km of the surface) associated with a CO_2 doubling in these two models. The CCSM2 couples the Community Atmosphere Model (CAM2) to a full ocean model while the AM2.7 is coupled to a mixed-layer ocean; this difference is not crucial to climate sensitivity. In the AM2.7, there is a strong decrease in subtropical low cloud (up to 15% at CO_2 doubling) at the edges of the subtropical stratocumulus regions, leading to global albedo decreases and a positive cloud feedback on climate change; the reverse is true in the CCSM2. A newer version of AM2 has somewhat lower climate sensitivity and less subtropical low cloud decrease. The UKMO Hadley Center model exhibits little change in low cloud as CO_2 is increased, and has intermediate climate sensitivity [4]. At present, these important contrasts in behavior and sensitivity are unexplained.

Proposed climate feedback processes involving subtropical boundary layer clouds may be relevant to behaviors seen in Fig. 1. These mainly involve changes in cloud albedo, since longwave cloud forcing by low clouds is comparatively small. Klein and Hartmann [16] showed that regions of persistent stratocumulus cloud show a strong correlation between low cloud cover/albedo and lower tropospheric stability, defined as the difference between 700 hPa temperature and surface temperature (see also [54]). Idealized two-box models of the tropical Hadley/Walker circulation which build in this type of empirical relationship [14, 17, 18] suggest that a warmer climate will be accompanied (due to Clausius-Clapeyron) by a more statically stable moist adiabat in the lower troposphere, increased lower tropospheric stability and more low cloud over the colder parts of the tropical and subtropical oceans. This relation is also built into the CCSM low cloud fraction parameterization, and may partially explain that model's low cloud trends. However, a warmer climate would likely reduce subsidence rates over the low cloud regions, a systematic change that might not follow the Klein-Hartmann empirical relationship. Feedbacks of the changed large-scale environment on low-cloud precipitation and liquid water path (e. g. [19]) may also be relevant.

Climate feedback mechanisms involving middle and high-level cloud may in reality be just as important, even though they do not dominate the CAM2-AM2 differences. A multitude of such potential mechanisms have been proposed. This proposal cannot pretend to many of them justice, but we mention a few that have helped guide our thinking. Early investigations suggested a warmer climate might lead to decreased cloud fraction and increased cloud top height [5, 6]. Hartmann and Larson [7] argued that the interaction of deep convection, water vapor profile, and radiative cooling may produce tropical convective cloud tops whose temperature is independent of climate change. Although tropical convective cloud systems have a near neutral effect on Earth's current top-of-atmosphere (TOA) radiative energy balance, this may not will hold for climate changes. If suspended cloud condensate increased with temperature, the resulting cloud albedo increase would constitute a powerful negative feedback [8-10], though observational studies do not show a signif-

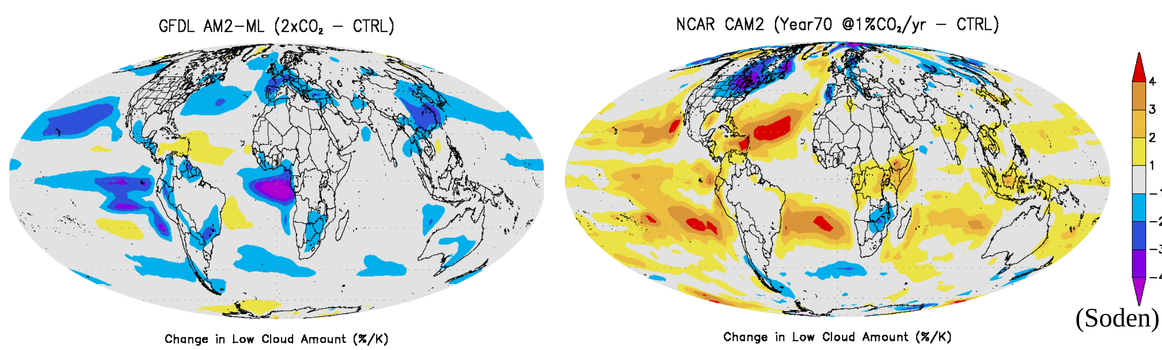


Fig. 1. AM2 and CCSM2 low cloud cover changes in response to CO_2 doubling.

icant increase of cloud water with temperature [11]. The rising height of the ice to water transition can provide a negative feedback to climate warming due to the higher albedo of water vs. ice cloud [12]. Furthermore, changes in area coverage of deep convective clouds might affect the global energy balance through their effect on water vapor [13, 14]. Lindzen et al.'s controversial 'iris effect' [15] was a negative climate feedback process of this type.

One might pessimistically conclude from this abundance of hypotheses that we cannot hope that climate models will soon predict cloud feedbacks more reliably. In a climate model, cloud distribution involves a tight interplay between many parameterizations, all of which have major uncertainties in formulation and possibly major discretization errors. However, (i) the obvious (but not well understood) differences between models, (ii) new research on the physical processes that contribute to cloud feedbacks, (iii) a wealth of new observational data, and (iv) new modelling tools all suggest that a Climate Process Team (CPT) can accelerate progress in improving the representation of cloud feedbacks in leading US climate models.

Our CPT will focus on feedbacks on climate sensitivity from low-latitude clouds (roughly 30S-30N, over both ocean and land), where some of the parameterization problems are most obvious. We hope that in the process, we will also improve the representation of higher-latitude feedbacks. It will involve three modeling centers, NCAR, GFDL, and the NSIPP (NASA Seasonal to Interannual Prediction Project) modeling team from the NASA GMAO (Global Modeling and Assimilation Office (GMAO). NCAR's CCSM is a fully coupled climate model refined over the last decade by combined efforts of NCAR and other US scientists. The CCSM and its atmospheric component, the CAM, support a diverse user community with interests ranging from paleoclimate to prediction to fundamental dynamics. The CCSM is now able to maintain a stable coupled climate for at least a millennium. Over the last five years, GFDL has been intensively developing a new GCM, the AM2 [20] as part of a coupled modeling system with a similar intended range of applications as the CCSM. The GMAO NSIPP has mainly been used for seasonal to interannual prediction; GMAO has ambitious plans to integrate this model with their data-assimilation/forecast model. Table 1 summarizes some salient characteristics of the three models, and emphasizes that their diverse physical parameterizations despite similar vertical and horizontal resolutions.

Table 1: Characteristics of participating GCMs

AGCM	CAM2	AM2.11	NSIPP (v2)
Center	NCAR	GFDL	GMAO
Coupled?	Yes	Coming	Yes
OML-capable?	Yes	Yes	Yes
Purpose	General community use. Long coupled runs. IPCC.	Climate research, coupled predictability/IPCC	S-I prediction
Advection	Spectral or finite volume	Hor:Finite diff., Vert:FV	4th order FD
Vert. levels	26	18	40
PBL scheme	Surf.-forced nonlocal	Dry thermo, prog. TKE	1st order K
Shallow Cu	Hack 3-layer plume	None	None
Deep Cu	Constrained-spectrum A-S	Relaxed A-S	Relaxed A-S
Cloud	Prog. condensate/diag. fraction Max. random overlap	Prog. condensate/frac. Random overlap	Prog. cond,/ hybrid frac.
Ice	T-dep. phase+Lin et al microph.	T-dep. phase, fallspeed	T-dep. phase

We will focus our CPT efforts at model diagnosis and improvement of the NCAR and GFDL models, which have greater scope and diagnostic infrastructure. However, the smaller GMAO group will also actively participate, providing the valuable perspective of a third cutting-edge GCM with different physical parameterizations. The main goals of our CPT will be:

(1) (a) To fully understand the difference in the low-cloud trends in the NCAR and GFDL models when CO_2 is doubled,

(b) To use observations and recent advances in understanding the component physical processes to improve both models,

(c) To thereby reduce, or at least better estimate, our uncertainty about the sensitivity of climate to low-latitude marine boundary layer clouds.

(2) (a) To compare in detail the representation of tropical deep convective clouds and their radiative effects in both models with observations, and suggest improvements.

(b) To bound (with more certainty than at present) the likely feedbacks of these clouds on climate sensitivity.

Our initial focus will be on the first goal, and we will consider the CPT a success if it makes substantial progress toward this goal alone. The second goal is more ambitious, but again new tools put the CPT in a good position to accelerate modeling progress on deep convective cloud systems.

A central CPT strategy will be to use **column-oriented** diagnostic and modeling strategies for model-data comparison, model improvement, and diagnosis of cloud feedbacks on climate sensitivity. We recognize that the climate system and hence cloud feedbacks on climate are dramatically affected by coupling through large scale circulations, and ocean and land feedback on the atmosphere. But modelled cloud distributions depend mainly on **atmospheric physical parameterizations** and **vertical resolution**. An instantaneous parameterization change will (i) immediately impact the simulated clouds, even before (ii) the cloud changes impact the large-scale circulation and climate. Since step (i) is the driver for step (ii), it is useful to explore (i) in isolation, for which column methods are ideal. Our methods for doing this are articulated in the sections on ‘integrating concepts’ and on individual PI tasks.

CPT organization and management

The CPT will be organized as a *core group* of scientists funded to carry out with the help of the modeling centers a specific set of interlocking tasks (Table 2), along with an expert *advisory panel* of scientists (Table 3) who will attend one CPT-wide meeting per year, and in some cases a smaller focus meeting. The advisory panel will discuss modeling issues and parameterization details with the core group, and will provide strategic advice, criticism and access to datasets. Lastly, there will be *modeling center leads* responsible for coordinating the CPT activities at the three centers. The *project PI* (Bretherton) will supervise the overall CPT activity to maintain its scientific focus, and report on its progress toward achieving its specific milestones.

The core group all have current interest and skill in one or more of parameterization, model/observational comparison and process modeling relevant to low-latitude cloud formation. They span a remarkable range of expertise and ideas. Each can also leverage the knowledge from other related projects within their research group. In addition, they all can commit the effort required to make the CPT succeed as a group effort, while at the same time distilling publishable contributions of scientific value from their individual tasksThe advisory panel is yet broader. It brings in leading scientists in several other GCM groups who have made important contribution to the modeling of low-latitude clouds (Mechoso, Randall, Suarez), experts in cloud-related parameterization for numerical weather prediction models (Pan, Teixeira), experts on ice microphysics (McFarquhar), cloud-microphysical-aerosol parameterization (del Genio, Ghan), in-situ observations of tropical deep convection (Raymond), air-sea fluxes (Weller), and land-surface/PBL/cloud interactions (Betts). All of these scientists have agreed to the lead PI to serve on the advisory panel, knowing that they will be asked to critique the detailed formulation of parameterization schemes and their physical basis, suggest appropriate tests, and help the core group procure relevant datasets if necessary. They will be funded for travel to CPT meetings only, and are considered co-investigators for the purpose of this proposal..

Table 2: Core group members (outside modeling centers)

Name	Affiliation	K$/yr	Task Summary
Chris Bretherton (+CPT meeting budget)	U. Washington	150 (+60)	CPT coordination, ShCu/microphys. param, Column diagnosis/SCM.
Marat Khairoutdinov Cara-lyn Lappen	Colo. St. U	150	CF diagnosis using superparam., CRM SCM diagnosis; turb./shal. Cu param
Brian Mapes	NOAA/CDC	100	ShCu-deep Cu-cloud-rad. feedbacks
Joel Norris	Scripps	travel	Historical cloud variability vs. models
Robert Pincus	NOAA/CDC	80	Subgrid microphys./rad. obs./param.
Bjorn Stevens	UCLA	90	Bulk turb./ShCu/cloud param.
Kuan-Man Xu	NASA Langley	100	CERES/MODIS. CRM modeling.
Minghua Zhang	SUNY Stony Bk	100	ISCCP/CERES comparison

Table 3: CPT advisory panel

Name	Affiliation	CPT-relevant expertise
Bruce Albrecht	U. Miami	Shallow cu obs and bulk models
Alan Betts	Atmos. Res.	Land surface/cloud/PBL/convection interaction
Chris Fairall	NOAA/ETL	Shipboard cloud/PBL/surface flux measurements
Tony del Genio	GISS	microphysical param.; GISS GCM
Steve Ghan	PNL	Cloud/aerosol param, ARM contact
Greg McFarquhar	U. Illinois	Ice microphysical measurement, parameterization
Roberto Mechoso	UCLA	GCM climate/low cloud feedbacks; UCLA GCM
Hua-lu Pan	NCEP	NCEP model physical parameterizations
David Randall	Colo. St. U.	CSU model physical parameterizations
Max Suarez	NASA/GSFC	Coupled modeling; GSFC GCM
Joao Teixeira	NRL Monterey	PBL, low cloud parameterization;Navy models
Robert Weller	WHOI	Surface flux observation/ocean feedbacks

Table 4: Modeling center participation

Center	Lead co-PI	Other participating scientists	$/yr 1	CPT staff
GFDL	Klein	Soden, Held, Ramaswamy, Donner	travel	Liaison
NCAR	Kiehl	Collins, Hack, Rasch	206	Liaison
GMAO	Bacmeister	Suarez	0	

The modeling centers are at the heart of the CPT effort. Significant improvement of a cutting -edge model requires not only computer resources, but a substantial dedication of scientist and support staff time to the CPT project at a modeling center. The development of new parameterizations is helped by a subtle knowledge of the existing model architecture and of how its current parameterizations interact; thus active involvement of scientists and software engineers at the modeling center will greatly expedite such development efforts. Software tools such as single-column models permit comparison of parameterization approaches in controlled situations, allowing the broad group of scientists in our CPT to effectively contribute. CPT scientists must also have easy, flexible access to model output in the form that they need, be it exotic output variables or high time-resolution output for a particular model column. Lastly, a modeling center's staff forms the institutional memory for the physical parameterizations in that model, so must thoroughly understand the code and its scientific bases.

All three participating modeling centers have formally agreed to provide sufficient resources for active participation in the CPT, both human and computational. NCAR and GFDL will both maintain single-column models. They will also provide 3D model diagnostics requested by the CPT, adequate computational resources and human assistance for CPT members to run their GCM for development or diagnostic purposes, and an easily-accessible archive of output from standard model runs. GMAO will also implement similar model diagnostics and provide model output for CPT use, although those capabilities are currently less well developed. At both NCAR and GFDL, several scientists in addition to the modeling center PI will participate in CPT activities. GFDL and GMAO will provide their resources at no expense to the CPT, while NCAR proposes hiring a support scientist who will act as a liaison and assistant for CPT scientists working with the CCSM. Table 4 lists participating scientists and other staff to be committed to the CPT at the three modeling centers. GFDL and GMAO are separately submitting a letter of commitment to Jay Fein detailing their participation. NCAR's funding proposal serves as its commitment letter.

Starting in late 2003, we plan a two-day pan-CPT meeting per year to guide strategy and assess overall progress. All core PIs and the three modeling centers will present their progress and issues to eachother and the advisory panel for discussion. During each summer, we will also convene one 'focus group' meeting, e. g. on shallow cumulus convective parameterization, comparison with field observations, or issues in GCM simulation of deep convective cloud fields, involving a self-selected subset of the team. This second meeting could be coordinated with the CCSM annual meeting. Core PIs are budgeting for 2.5 trips per CPT participant per year, 1.5 per year for these meetings and one more for presenting their work in AMS meetings. The U. Washington budget includes travel funds for 1.5 trips per year for the 12 advisory panelists, 2 trips per year for unfunded core members Norris and Bacmeister (GMAO), and for 5 GFDL scientists, funds for meeting logistics, and 10% of a fiscal specialist to handle travel reimbursement, accounting, and meeting organization. This is a placeholder; per conversations with Jay Fein (NSF) the intent is to transfer travel funding/logistics to UCAR/JOSS if awkward procedural hurdles can be overcome.

Our CPT will make good use of leveraging. Most of the core group and advisory panel members are also engaged in related research in process modeling, observations and their analysis, or global modeling and parameterization. In some cases, this research already involves related investigations of cloud feedbacks on climate sensitivity. One core group member (Norris) already receives NSF support so closely related to the CPT goals that he requires no additional non-travel funding to participate. The CPT thus not only leverages off the existing expertise of its members, but also their other current research interests; in fact we hope that many CPT members may ultimately be attracted to shape those related external research interests in ways beneficial to the CPT effort . Where appropriate, we indicate how particular CPT tasks interleave with related ongoing research by the CPT members.

The CPT also leverages off current modeling center efforts. A year ago, the large-scale atmospheric modeling groups at NCAR and GFDL set up a collaboration involving annual joint meetings, diagnostic comparisons, and discussions about model physics. Three of the CPT core group (Bretherton, Norris, Zhang) have participated in one or more of these meetings. Diagnostic tools developed at NCAR and GFDL in support of this collaboration (e.g. ISCCP diagnostics, model output comparisons) will accelerate CPT progress, and conversely the CPT should maintain the momentum behind this collaboration. In addition, the CPT will have very close ties to the CCSM Atmospheric Model Working Group (AMWG), the community-run CAM developer/user group. All core group and participating modeling group members have attended at least one AMWG meeting, and most attend regularly. Lead PI Bretherton will ensure that CPT research is reported and discussed at AMWG meetings. We view the CPT as a chance to enhance the AMWG by dedicating resources to one of its highest priorities, namely improving the representation of cloud, turbulence, and moist convective processes in the CAM.

Core Group Research Tasks - Integrating concepts

At present, we do not know how to predict a given GCM's cloud feedbacks to climate sensitivity without running the full model either in an ocean-coupled or 'Cess-style' mode (with specified SST perturbations, e.g. 2K everywhere). One tactic the CPT will collectively exploit is to use **single-column methods** to better understand these cloud feedbacks and facilitate model-observation comparisons. Long time series of high-frequency **GCM single-column output** will be extracted at select locations at which we have unique long-term observations (e. g. the ARM Southern Great Plains and Nauru sites, Amazonia, and flux-reference buoys in the SE Pacific stratocumulus and subtropical Atlantic trade cumulus regimes). This can be done for both control and 2xCO_2 simulations for all the participating GCMs, and the differences in cloud response can be examined in detail, as well as biases of the control run vs. observations. This column output can also be used to force **single-column model** (SCM) versions of the different GCMs, and **cloud resolving models** (CRMs, which resolve and predict the turbulent circulations that create the clouds) of the cloud fields at that location. These allow quick diagnosis of the likely effect and realism of changing individual parameterizations on the simulated clouds and their radiative effects in a given column in control and 2xCO_2 worlds. SCMs also allow us to easily experiment with new parameterization approaches and test the sensitivity of physical parameterization packages to **vertical resolution**. This is a more ambitious way to use column data and SCMs than typically employed in past at NCAR, GFDL and GMAO. Bretherton, Mapes, Zhang, and others will work with the modeling centers to fully exploit this approach.

A second theme is effective use of newly emerging **global cloud and radiation datasets** to help develop and test parameterizations, e.g. from new NASA satellites or new syntheses of historical data. Here the issue is diagnostic analyses or retrieval methodologies that convincingly connect the model output with the observables, and allow us to make best use of the limited long-term record of systematic cloud observations . Bretherton, Klein, Norris, Pincus, Xu, and Zhang will all bring expertise in this area.

Another theme is that boundary layer, shallow convection, deep convection and microphysical schemes, even though they are usually separate model components, need to be thought of as an **integrated package. Consistent assumptions about subgrid variability** and its microphysical and radiative consequences need to be made across these schemes. Both the NCAR and GFDL modeling groups are committed to overhauling all of these components of their model. Members of this CPT (Bretherton, Lappen, Pincus, Stevens and collaborators at all the modeling centers) will scrutinize these components and their interactions in the context of present cloud climatology and climate sensitivity implications, and collaborate with others working both inside and outside the modeling centers in targeted efforts to improve them. In this spirit, we will also employ the perspective of **'superparameterization'**, in which all of these components are replaced by a small cloud-resolving model. This is attractive both as a direct prediction of cloud feedbacks on climate sensitivity and indirectly as a way to understand the subgridscale cloud-process variability issues across a full range of low-latitude climate regimes (Khairoutdinov). We will also make traditional comparisons of GCM column output with suitably forced CRMs (Bretherton, Khairoutdinov, Xu).

Individual PI and modeling center tasks: Chris Bretherton

Lead PI Bretherton will coordinate overall project management, including scheduling of CPT meetings, arranging for interactions with the AMWG, CLIVAR, and the sponsors, and trying to optimize coordination between the co-PI tasks. In addition, Bretherton's specific goals are (1) to demonstrate the utility of single column and cross-section methods for understanding cloud process biases and cloud feedbacks on climate sensitivity, and (2) to intensively work on improving low cloud-relevant physical parameterizations in the NCAR model. Goal (2) will involve close collaboration with Hack, Kiehl, and Rasch (NCAR), Bacmeister (GMAO), Khairoutdinov (CSU), and

Stevens (UCLA); goal (1) will also involve Klein (GFDL).

Bretherton will use the single-column CAM (a.k.a. SCAM) to test the following approach to understanding cloud feedback on climate sensitivity. High time-resolution output from the CAM2 at selected columns will be used to create column 'forcings' (SST, hor. advective tendencies, vertical motion) to drive the SCAM. The SCAM has been designed so that using these forcings, we should be able to exactly replicate the column evolution from the 3D model. For these same columns he will also calculate monthly-mean climatological differences between the column 'forcings' in a 2xCO_2 or Cess run and the control run. These represent the 'large-scale' feedback of the changed climate on the low clouds. These differences are added to the original SCAM forcings, and the SCAM is rerun to look for systematic changes in the column cloud and thermodynamical structure. Our hypothesis is that these systematic changes will be similar to those in the corresponding column of the full 3D model. If so, we have a powerful single-column tool for understanding doubled-CO_2 changes in cloudiness. We can use this same SCM approach for assessing cloud feedbacks for other parameterization choices or CRM simulations of the column. We will compare the 2xCO_2 forcing perturbations derived from all three GCMs for the same grid column; this might help to elucidate the dynamical feedbacks of the intermodel cloud differences.

Bretherton will make a detailed comparison of high time-resolution output at selected columns from versions of the CAM2, AM2, and NSIPP models (and CAM superparameterization- see Khairoutdinov task) with data from the TOGA-COARE, EPIC and ARM field projects. He will also intercompare selected climatological cross-sections (e.g. San Francisco to Hawaii, central Pacific ITCZ) between models and with ECMWF thermodynamic analyses and satellite cloud products. This should illuminate differences between the mean structure in the different models that relate to differences in their cloud fields.

He will work with the NCAR group (and in consultation with Bacmeister, Lappen, Mapes, and Ghan) on the development of a shallow cumulus scheme for CAM. Our approach is inspired by a mesoscale model buoyancy-sorting entraining-detraining plume parameterization of Bretherton and McCaa [55, 56]. He will also work with Rasch (NCAR) and Pincus on the development of improved representation of subgridscale (SGS) microphysical variability in the CAM, using a pdf approach with specified distribution, diagnosed variance, and predicted mean to specify the SGS distribution of humidity and microphysical variables.

A full time research scientist, Dr. Matthew Wyant, will assist Bretherton. Bretherton is committing two months of academic-year time to CPT project management and to the above scientific objectives. He leverages heavily off a pending NASA IDS proposal with D. Hartmann and R. Wood (U. Washington) to study low-latitude cloud feedbacks on climate sensitivity using NASA satellite products and idealized mesoscale modeling, and to refine a new moist-entraining boundary layer scheme developed for the CAM. Bretherton is also head of the GEWEX Cloud System Study (GCSS) boundary-layer cloud working group, and (with Lappen and Klein) will entrain the NCAR and GFDL SCMs into GCSS intercomparisons, providing a broad international benchmark for the physical parameterizations relevant to low cloud feedbacks.

Marat Khairoutdinov

Kharoutdinov will use 'superparameterization' (SP) along with some limited supplementary CRM simulations as a perspective on cloud feedbacks. In SP, the physical parameterizations describing turbulence, convection, and cloud processes are replaced in each grid column of a host GCM by a 2D CRM with periodic boundary conditions [45]. At each GCM timestep, each CRM is forced with advective tendencies and lower boundary conditions for the corresponding column derived from that GCM; the CRM is marched forward a GCM timestep, and the GCM prognostic variables are updated using the horizontally averaged tendencies from the CRM instead of conventional physical parameterizations. A strength of this approach is in regions of persistent deep cumulus convection, where it circumvents notoriously unreliable subgridscale modeling assumptions inherent in the parameterization of both convection and associated cloud processes. However, it is 50-100 times as computationally intensive as a conventional GCM simulation with the same host model resolution.

The first non-idealized SP was pioneered by Khairoutdinov and Randall [46], who used the CAM as the host GCM for a two-dimensional version of the Colorado State University CRM. Recently, they have performed a series of 500-day long runs with this 'SP-CAM' configuration using T42 horizontal resolution. The SP-CAM produces seasonal climatologies of precipitation, precipitable water, cloud-radiative forcing and high-cloud fraction that are quite competitive (though different) than the conventional CAM2, but has dramatically improved Madden-Julian Oscillation (MJO) and diurnal variability of precipitation frequency over the standard CAM. The SP-CAM has a more realistic representation of cloud and microphysical feedbacks in tropical deep convection regions than any conventional GCM; the CRMs running in its individual columns also sample the entire spectrum of low-latitude climate regimes. Our goal is to translate this into useful improvements in our understanding of climate sensitivity to deep tropical convective clouds. In addition, we would like to compare to what extent the climate sensitivity of the SP-CAM can be understood simply by looking with a 3D version of the same CRM at simulations of radiative-convective equilibrium at different SSTs.

In years 1-2, cloud-feedback simulations will be performed with the SP-CAM in collaboration with NCAR. Cloud feedback will be assessed by running a simulation of at least five years using prescribed SSTs obtained from the last 10 years of a quadruple-CO2 run of the conventional CCSM2. This run will be compared with to a similar control run with present climatological SST distributions and CO_2 run with prescribed climatological SSTs. The computations (on NCAR's bluesky computer) will take several months of computation time, but the result is perhaps as close as we can come to deep convective cloud feedback estimates that shortcut conventional parameterization uncertainties in favor of the more physically grounded microphysical parameterizations in CRMs.

In the meanwhile, in collaboration with Collins and Hack (NCAR), detailed analysis of the 500-day SP runs will be performed, including high-frequency column output over selected columns in regions of deep convection (including over Amazonia and the ARM SGP site), comparison of microphysical and thermodynamic profiles with the CAM, AM2 and NSIPP models, comparison of subgrid horizontal cloud and condensate variability with the overlap assumptions in the CAM and AM2 radiation schemes. The 'ISCCP simulator' (see Zhang task) approach will be used for validating the SP-CAM vertical cloud structure.

In years 2-3, the cloud feedbacks in the SP-CAM climate-sensitivity simulation pair will be diagnosed and analysed with Collins, Hack and Kiehl of NCAR. Khairoutdinov will propose changes to the NCAR CAM shallow and deep cumulus, cloud microphysical, and radiation parameterizations based on these results. We will compare SP-CAM cloud feedback with that implied by 3D simulations of radiative-convective equilibrium at different SSTs, and if time permits, with 3D simulations of a strip, long in the N-S direction, with 'swamp' lower boundary conditions and latitude-varying insolation that induces a meridional overturning circulation. Three months of salary per year of CPT funding plus travel are requested.

Cara-lyn Lappen

Lappen's expertise is in unified parameterization of turbulence in convective boundary layers and cumulus clouds. If successful, such an approach could avoid some of the representational problems in current GCMs, where deep cumulus, shallow cumulus and boundary layer turbulence parameterizations often compete with unintended results.

Her first CPT goal will be to help implement in the single-column CAM a new unified parameterization that she and Dave Randall of CSU have been developing. If this is promising, the parameterization will be tried in the full 3D CAM. Her second major task (in collaboration with Bretherton and Hack) will be to prepare the forcing datasets for the single-column CAM for salient past and upcoming GCSS WG1 (boundary layer cloud) and WG4 (deep convective cloud system) case studies, and compare the impacts of alternative parameterizations of turbulence and shallow convection on these case studies. For upcoming GCSS cases, she will also prepare the model output for inclusion in the GCSS intercomparison, providing an important link between the CPT and the international GCSS effort.

At present, the most elaborate one-dimensional models of the PBL are higher-order closure (HOC) models, which prognose some statistical characteristics of the turbulence field. Some GCMs use the simplest HOC approach, a prognostic equation for turbulent kinetic energy. None prognose more turbulent moments despite the potential for better accuracy and flexibility, because of unacceptable constraints on timestep and/or vertical resolution. Without regime-specific tuning, HOC has proven unable to represent the variety of PBLs encountered in the global atmosphere, especially shallow cumulus layers and their interaction with the subcloud layer [21, 22].

In Lappen and Randall's unified scheme (called 'assumed distribution' HOC or ADHOC), in turbulent layers, the fractional area of the domain covered at any level by updraft (related to the cloud fraction in a cumulus cloud field) is predicted. This contrasts with typical GCM PBL models, which assume this fraction is near to 1/2, or cumulus schemes, which assume it is small. A prognostic equation for the third moment of vertical velocity is used, closed using assumptions about the joint pdf of vertical velocity, temperature, and water vapor based on modified bimodal distributions [23-26]. ADHOC can combine ideas from convective mass-flux parameterizations and from HOC into a unified model for cloudy and non-cloudy turbulent processes. Technical problems still to be resolved include stability restrictions on the timestep, performance on a coarse vertical grid when there is a sharp inversion, and achieving sufficiently small updraft/cloud fractions in shallow cumulus regimes. However, the idea is promising enough to entrain into the CAM development stream and may cross-fertilize other PBL/shallow cumulus/pdf-based microphysical parameterization work in the CPT by Bretherton, Klein, Pincus, Stevens and others. Under separate funding, Lappen is implementing ADHOC in the Colorado State University GCM (which has a different PBL parameterization architecture, including a model level that tracks the PBL top, and provides a somewhat different set of technical challenges for ADHOC). Lappen's CPT effort, for which she requests three months of salary per year plus travel, leverages heavily off her CSU GCM work.

Brian Mapes

Mapes intends to undertake a detailed diagnosis of convection and cloud parameterizations in time-height GCM column data sets from several low-latitude regions, including trade cumulus and marginal and core regions of deep convection. One focus region will be the south-central equatorial Pacific, where both the CAM and AM2 models produce an excessively persistent second ITCZ. The goal is to understand the couplings within each model that link cumulus convection, precipitation, clouds and radiation (and hence the cloud feedback) on a time step-by-time step basis. This approach is suggested by developer experience that all these processes together create a complex nonlinear system that may have a lot of internal 'chaos' as well as externally forced variability, and this can have unintended but climatically important consequences for the processes regulating cloud at all levels in regions of cumulus convection.

The diagnosis will employ the corresponding CSMs forced by column forcings extracted every timestep from the GCM columns. Mapes will carefully examine of how the local profile of large-scale state variables is processed by the physical process subroutines (especially convection and cloud) to produce the final tendencies of those state variables. Of particular interest is a comprehensive diagnosis of the decision variables which are used to decide the amounts of shallow and/or deep convection, and the associated cloud-radiative tendencies. Sensitivity studies will explore the importance of possible nonlinearities (such as thresholds). If quasi-linearity is found to hold, then subsequent diagnosis may use more standard daily- or monthly-mean model state-variable data sets.

To do this may require some modification of the SCM corresponding to each GCM, e.g. to output its internal decision variables (such as parcel buoyancies, cloud work functions, mass fluxes, etc.), as well as its final tendencies. Center liaisons may expedite any such modifications. Model developers will help Mapes parse the code structure. A suite of plots will be devised to depict the whole chain of model physics processes as simply and clearly as possible.

Because the diagnosis will be expressed in the conceptual language of each parameterization scheme, results will not be standard or common to models or model versions. Some diagnosed quantities may be amenable to observational comparisons. Others will not, and will simply be judged by the standard of reasonable behavior. Initially Mapes will work on the GFDL model, then the slightly more complex (two convection scheme) NCAR model . He may also look at the NSIPP model if suitable column modeling tools are developed for it. Thereafter, he will use this methodology to understand the impacts of new parameterizations with new conceptual underpinnings (and hence new diagnosis language).

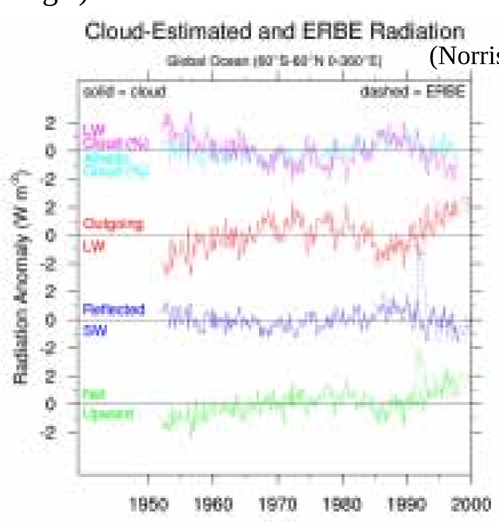
Throughout this work, Mapes will be watching in particular for opportunities to optimize convection scheme closures, trying to improve the competition or interaction between shallow and deep convection. He will try to infer how shallow and deep convection processes (and the associated cloud-radiative forcing) interact across space, e. g. through perhaps simple and foreseeable effects on Hadley and Walker circulations. Such inferences about the large-scale interactions of convection across regions will be tested in collaboration with modeling center liasons or other CPT members, using experimental GCM runs in which closure (decision) processes are adjusted in the convection schemes.

Mapes is requesting 6 months CPT salary funding per year plus incidentals. This work seeks to leverage Mapes' other NSF work on cumulus parameterization, which is aimed at comprehensive closure for the interplay between shallow and deep convection.

Joel Norris

Norris recently received an NSF CAREER award to reliably document observed cloud and related radiation trends over the past fifty years and compare with corresponding GCM output to evaluate GCM cloud simulations and climate sensitivity. Norris uses interannual and longer cloud variability obtained from the EECRA dataset (50 years of routine shipboard synoptic observations of cloud type and amount) to assess possible associated trends in TOA and surface radiative fluxes. This is done by matching cloud data with ERBE wide field-of-view radiance measurements over the last 13 years to empirical correlation cloud type/amount with longwave and shortwave cloud forcing (Fig. 2). Both trends and interannual to decadal variability appear. Since this activity is already a natural part of the CPT project, Norris will be considered part of the CPT core group, but will not request CPT funding (except travel to CPT meetings.)

The CPT question is to what extent AMIP-style integrations of the participating GCMs using 50 years of specified historical SST data match these variations, and if so, on what timescales . Both the CCSM2 and AM2 appear to have different predicted trends in TOA cloud forcing in rising CO_2 scenarios than the historical observations. The regional structure of low-frequency cloud and radiation variations is also an important test of models -ENSO has been studied a bit but there is much more to learn. Norris will dig into these issues using standard model monthly average cloud diagnostics for AMIP runs of all three models, and try to understand any discrepancies. Possible issues include regional cloud indirect effects from aerosols, biases from observation practices, interannual variability that is not driven by boundary conditions (this can be investigated using AMIP ensembles, which GFDL and NCAR are both planning to create in any case), and making the definitions of radiatively-important cloud as congruent as possible between models and observations. These may require some special model outputs, e.g. overlapped high+mid-level cloud amount which exceeds a specified optical depth threshold.



(Norris)

Fig. 2. TOA radiative fluxes inferred from ship cloud reports calibrated to ERBE.

Robert Pincus

Pincus brings expertise in microphysical and radiative biases produced by unresolved subgrid-scale variability, low cloud-radiative-microphysical interactions, and experience with MODIS (multispectral high spatial resolution) observations from the NASA Terra satellite. He will contribute to MODIS data analysis, GCM model diagnosis, and parameterization development.

His first role will be to decide how best to compare processed MODIS data, which includes retrievals of cloud fraction, optical depth, cloud-top temperature, and cloud particle phase and size, at spatial resolutions down to 1 km, with the GCM output, in a manner coordinating with the International Satellite Cloud Climatology Project (ISCCP) data being used by Zhang. One particular task will be to generate cloud distribution statistics for some of the columns selected for high time-resolution GCM analyses, and assess GCM biases in the statistical distributions of cloud e. g. cloud-top temperature pdf's), and look at what biases in the radiative and microphysical properties of the clouds we might be anticipate to be associated with sub-250 km scale 'subgrid' variability in the cloud properties.

Pincus will also be collaborating with Zhang, Bretherton, and NCAR's Rasch and Kiehl to define and implement efficient subgrid assumptions for a new microphysical scheme to be developed for the CAM, including a treatment of vertical overlap consistent between radiation and microphysics schemes. Under separate funding, Pincus will be working with Klein on the development of a sophisticated pdf-based microphysical scheme for the GFDL model; that scheme would likely be more complex than any CAM scheme though there might be some conceptual overlap.

Lastly, Pincus will collaborate with Khairoutdinov on analysis of aspects of the SP-CAM superparameterization runs. In particular, he will examine how much the cloud radiative forcings in the deep convective regime in the CAM-SP run and the local cloud feedbacks on radiation associated with CO_2 doubling would be affected by aggregation of the SCM columns into one or two categories (e.g. horizontal mean, 'clear' and 'cloudy') before the radiative transfer calculation. In association with this Pincus will work with Collins (NCAR) and Ramaswamy (GFDL) on how to more efficiently do radiative transfer and microphysics/precipitation through a set of subgrid columns with differing cloud water/ice profiles but similar water vapor/temperature profiles (such as one might get out of superparameterization output for a single large-scale grid column and time.)

Pincus is requesting four months salary for himself and a programmer per year.

Bjorn Stevens

Diagnostic studies (e. g. [28-30]) suggest that suitable bulk models can adequately represent boundary layer cloud climatology in particular regimes, e.g. stratocumulus-capped mixed layers or trade-cumulus capped boundary layers. bordered by regime transition rules [31, 32]. These results suggest that one of the shortcomings of current approaches to modeling stratocumulus is not our theoretical deficiency, but rather the challenge of implementing our theories as general-purpose parameterizations within a model of coarse vertical resolution. This also suggests that within their regimes of applicability, bulk models of cloud-topped boundary layers may also provide both a useful comparison with the parameterization suite of a similarly forced GCM run at various vertical resolutions and may also provide useful insights about cloud feedbacks on climate sensitivity (see also Bretherton's section for a column-oriented strategy for doing this)

Stevens will focus on subtropical stratocumulus-capped mixed layer regimes. Using column forcing datasets in regions that approximate stratocumulus-capped mixed layers, e. g. in the SE Pacific [33] he proposes in year 1 in collaboration with Bretherton to compare a mixed layer model with simple microphysics with a SCM run at varying vertical resolutions employing existing and proposed (e.g. Grenier-Bretherton [34]) PBL parameterization schemes coupled to the GCM microphysical, radiation and vertical advection schemes. The cloud feedbacks to $2xCO_2$ perturbations to the column forcing in the two approaches could also be compared. Moist PBL parameterizations are designed to approximate mixed-layer convection under appropriate conditions if vertical resolution is sufficient, so this is a good test of whether parameterization implementation/discretization errors may be significantly affecting low cloud feedback on climate sensitivity. In addition, mixed layer model solutions are readily interpreted in a semi-analytic sense, thereby promoting theoretical understanding where they are applicable.

In year 2, he will experiment with implementing in the CAM an adjustment-type stratocumulus boundary layer parameterization which consists of a relaxation to steady state cloud-topped mixed layer solutions on a dynamically determined timescale, in regimes where such states exist. A challenge of this approach is smoothly evolving the cloud top inversion across a coarse vertical grid - a 'level set' method will be tested for this purpose. In years 2-3, he also plans to explore the effects of drizzle, the diurnal cycle of insolation and subsidence on mixed-layer driven cloud feedbacks to climate variations, and hope to work with S. Park (currently an NCAR ASP/MMM postdoc) to use a more broadly applicable but also more empirically tuned bulk model of cloud-topped boundary layers that also incorporates a stratified cumulus layer for climate sensitivity tests [30].

Funding is requested for 11 months per year of a postdoc to work with Stevens, plus travel. The CPT effort leverages off Stevens' separately-funded implementation of a simpler variant of the mixed-layer adjustment model in the QTCM one-vertical-mode atmospheric model [35], his leadership of the 2001 DYCOMS-II stratocumulus experiment, which collected a wealth of data on entrainment and microphysical processes in nocturnal stratocumulus [36], and his collaboration with colleagues at NCAR/MMM.

Kuan-Man Xu and Takmeng Wong

Xu's group (co-PI Takmeng Wong) will provide a tight link to cutting-edge NASA cloud products, and will perform CRM of boundary-layer cloud systems at selected grid columns for comparison with parameterizations and assessment of local CO_2-doubling induced cloud feedbacks.

Two types of satellite cloud and radiation data products will be provided. These are (1) monthly mean gridded 1°x1° CERES broadband radiance data, and (2) 'cloud object' data generated from the instantaneous CERES Single Scanner Footprint (SSF) data. The broadband radiance data, the successor to the ERBE broadband dataset, is a benchmark for validating cloud forcing and TOA radiative fluxes in GCMs. Initially, eight months of TRMM CERES data, stratified by hour of day, and sun-synchronous (10:30 am) Terra monthly means up through 2000 will be available for GCM comparison. In years 2-3, monthly-mean data from Terra will also be obtained for 2001, 2002

The cloud object data can be used to statistically characterize subgrid characteristics of distinct types of cloud systems and the frequencies of occurrence of distinct types of cloud systems in different locations. The cloud object data for three types of boundary-layer clouds (solid stratus, transition stratocumulus and cumulus) are stratified according to the sea surface temperature, the inversion strength, and the divergence strengths above and below the cloud tops deduced from ECMWF analyses. This rich data stratification allows for discerning comparison with GCM-simulated boundary-layer cloud fields, to be carried out in collaboration with Pincus and Zhang. Samples of cloud object data for some months of 1998 and March 2000 will be available in Year 1, followed in years 2-3 by much more from 2000 and 2001 Terra observations.

The CRM work will employ a 2D model with third-order turbulence closure, run for simulated periods of weeks to months using spatial resolution and domain size appropriate to the cloud system (i.e. small for stratocumulus, large for deep cumulus). In collaboration with Bretherton and others, simulations will be performed for selected columns, using (a) ECMWF forcings, (b) GCM forcings derived each timestep to assess the impact of model subsidence/advection biases, and (c) adding the doubled-CO_2 monthly-mean forcing perturbations to assess local cloud feedbacks.

Funding is requested for a half-time data analyst, 1.5 month per year for a modeler, and 1/2 month per year for Drs. Xu (modeling supervisor) and Wong (data analysis supervisor). The CPT contribution leverages off Xu and Wong's leadership of a large NASA project to produce the cloud object data, and Wong's participation in the international CERES Science Team.

Minghua Zhang

Zhang will initially focus on diagnosing the different response of subtropical boundary layer cloud in the NCAR and GFDL models to CO2 doubling using two approaches, (1) the evaluation of simulated cloud and radiation fields in the two models, and (2) preparation and analysis of column datasets (including corresponding SCM forcings) for relevant field campaigns.

CPT member Klein pioneered a powerful GCM diagnostic tool, the 'ISCCP simulator', for comparing the vertical structure of simulated clouds with the ISCCP dataset. The concept is to derive at each model gridpoint, the cloud optical depth and infrared brightness temperature, and then use these as input to ISCCP algorithm for cloud classification. This removes semantic problems with comparing 'low' or 'thick' cloud between models and observations. Klein has implemented an ISCCP simulator for the GFDL model; Zhang has recently carried this over to the CAM2. Figure 3 shows an example cloud frequency histogram, stratified against cloud top pressure and cloud optical properties, using ISCCP data for the entire tropics (30^oN to 30^oS) from 1981 to 2001, and an ISCCP simulator applied to a CAM2.0 model simulation. Fig. 3 shows several CAM2 cloud biases - excessive thick low and middle clouds and too much optically thin high cloud.

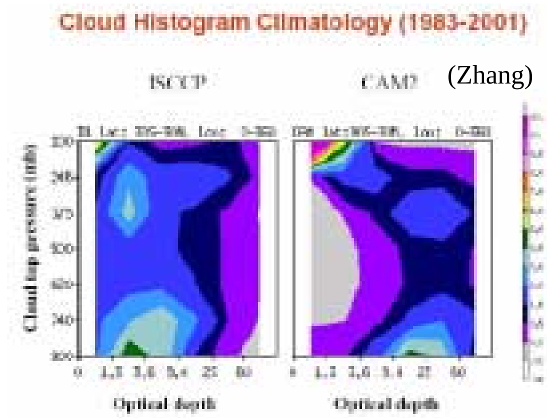


Fig. 3. ISCCP cloud frequency vs. CAM2.

Zhang and Norris propose to use this methodology to compare AMIP runs of the CAM2 and AM2 models with ISCCP data in low latitudes stratified regionally, diurnally, seasonally, and interannually, by SST, and by 500 hPa vertical motion. ERBE/CERES data will be used to evaluate the impact of cloud variations on the TOA radiation. The cloud effects of simulated CO_2 doubling in the two GCMs will also be diagnosed in this way, and we will relate these to the cloud-radiative forcing. This will help us assess the realism of the mean cloud properties and the cloud feedbacks to climate sensitivity in the two models.

Column-oriented analysis is a major strategy of this CPT. In other DOE, NASA, and NSF-funded research, Zhang is synthesizing field observations from several field projects (e. g. ARM, TOGA-COARE, some TRMM field campaigns) using a variational integration method to provide SCM forcing datasets [38, 39]. This approach allows blending of multiple datasets and enforcement of internal consistency constraints in the objective analysis of the necessary upper-air fields, but the forcings are still imperfect. By using some of these locations as foci for GCM and SCM column analysis, the CPT can both benefit from this major source of data and contribute to its refinement through an iterative process between data analysis and model evaluations. Zhang will work with other members on the CPT team (e.g. Bretherton, Hack, Mapes, Klein) using the CAM and GFDL SCMs to evaluate parameterization components. This work also has a strong connection to past and future GCSS case studies.

NASA/GMAO (CPT Lead: Julio Bacmeister)

The NASA/GMAO modelling effort provides a valuable third opinion on the behavior of moist parameterization in GCMs; however the NSIPP model cloud and radiation characteristics have not been studied as extensively as in the other two models. GMAO will do much of its own diagnostic work, paralleling where possible the NCAR/GFDL model comparisons. By year 2, GMAO expects to have an ESMF-based unified model framework that should facilitate exchange of modeling components. GMAO will start by comparing existing NSIPP monthly/seasonal mean cloud/convection output with NCAR and GFDL, including selected cross- sections such as San Francisco-Hawaii. Capability for high frequency column output streams will be implemented and analyzed in collaboration with other CPT members. Simple sensitivity studies will test the low cloud impact from modifying microphysical, cloud, turbulence or radiation parameters in the currently configured model. Later, more "aggressive" sensitivity studies (e.g. swapping of parameterizations between models) may be tried if indicated by model intercomparisons. A Cess-style climate sensitivity experiment will performed and analyzed in comparison with the other two GCMs. In Year 3, we may turn to "longer term" issues of CPT, i.e. diagnosis of midlevel, high-level and deep convective moist processes, and experiment with modification of the RAS convection scheme as the CPT effort uncovers weaknesses, e. g. in vertical cloud distribution or shallow convection.

This effort meshes with a GMAO plan during Year 1 to evaluate GCM/NWP physical parameterization packages in an effort to develop a unified model for weather, seasonal forecasting and data assimilation applications. This will involve Bacmeister and many distinguished colleagues from GMAO and GSFC. GMAO could also contribute to the CPT by quickly assessing the impacts of modified cloud/convection/turbulence parameterizations on data assimilation in the tropics, ultimately leading to improved low-latitude upper-air analyses.

NCAR (PI: Jeff Kiehl)

Over the next five years, a high NCAR priority is improvement of cloud, convection, and turbulence processes in CAM, as all of these parameterizations have significant known deficiencies in their physical assumptions and numerical implementation. The CPT should add focus and community attention to this priority, supporting ongoing cloud, radiation, and aerosol parameterization development efforts by the NCAR modeling group. In addition to climate sensitivity, tropical precipitation errors (e.g. double ITCZ biases, lack of MJO, poor diurnal cycle) and eastern/central Pacific ocean-atmosphere coupling are leading concerns. Kiehl, Hack and Collins, in collaboration with CPT PIs Zhang and Norris, will lead the assessment of climate feedbacks in the CAM/CCSM, using (i) AMIP-style atmospheric simulations with special focus on ENSO and decadal response, (ii) Cess-style simulations with prescribed SST and/or CO_2, (iii) simulations coupled to a mixed layer ocean, and (iv) fully coupled simulations. With Khairoutdinov, they plan extensive analysis of the SP-CAM runs, especially CRM-scale statistics such as moments and pdfs of condensate, vertical motions, etc. and their implications for improved subgrid process parameterizations. In addition, Kiehl and Collins will coordinate standardized input control and climate-perturbation SST datasets to be used by all modeling centers for Cess-style climate sensitivity simulations. Hack will work with Bretherton on comparison of single-column diagnostics from CAM with field experiment data, streamlining the process for generating forcings derived from the full CAM suitable for driving the single column SCAM, and improving the SCAM.

NCAR requests resources to hire an Associate Scientists III as a liaison to assist CPT members working with the CAM/CCSM. This person will facilitate 3D and single-column model simulations, distribution of CAM output to various team members and archiving of datasets, and interface of new parameterizations with the CAM software framework. Kiehl and Collins will lead a CPT request for NCAR Climate System Laboratory computational resources, including Khairoutdinov's superparameterization climate sensitivity simulations.

GFDL (CPT Lead: Steve Klein)

The GFDL modeling group has similar priorities to NCAR's, and will work with the CPT PIs in a manner similar to that described above with NCAR. The AM2 has comparable shortcomings in individual parameterizations and overall tropical biases, even though the parameterizations are all quite different than in the CAM. Soden will carry out climate sensitivity analyses with different version of the GFDL model that parallel to the NCAR effort , with the same CPT collaborators. Klein will try to improve the AM2 simulation of shallow cumuli, and be the GFDL lead for SCM simulations. Held is leading an effort to use idealized GCM configurations (e.g. 2D nonrotating Walker cell, AGCM and coupled aqua-planet) to gain insight into the overall low-latitude circulation and its sensitivity to changes in model physics through cloud and water vapor feedbacks. Ramaswamy will work with the Xu CERES group, Norris, Zhang, Pincus, and on comprehensive comparison of the AM2 TOA and surface radiation budgets on seasonal and longer timescales with CERES, ISCCP, and MODIS datasets.

GFDL will internally fund a liaison person to work with the CPT core members, and requests only travel funding for its CPT participants (the liaison person plus 4 scientists). An important leveraging activity is a planned collaboration between Klein and Pincus to design a statistical cloud scheme with higher order prognostic moments to incorporate into the GFDL model over the next few years. CPT diagnostics should prove useful in assessing the effects of this new cloud scheme.

Project milestones

By the end of each of the three years of funding, we would like to have achieved the following:

Year 1: Diagnose in detail the reasons for different behavior of NCAR vs. GFDL low cloud distribution with 2xCO2 and be able to present a convincing explanation of this difference

Year 2: Constrain the relevant low cloud feedbacks using current and historical data from both global observations and local process studies, and use this to critique both model simulations. Begin implementing and testing physically-based improvements in those parameterizations the NCAR and GFDL models that the CPT deems most likely to be contributing to errors in low-latitude low cloud feedback on climate sensitivity.

Year 3: Improve relevant GCM parameterizations using best available physics, focussing esp. on cloud microphysics, shallow and deep cumulus convection, and cloud-topped PBLs.

Results from Prior NSF Support (only one award per NSF-funded PI during prior 5 years)

Under ATM-0082384 to **Bretherton** [33, 40, 41], radar and radiosonde data was gathered, analyzed and synthesized during the Oct. 2001 EPIC SE Pacific stratocumulus cruise, documenting a surprisingly well-mixed stratocumulus-capped boundary layer in this region with a diurnal cycle strengthened even over 1000 km offshore by interactions with the Andes. A major accomplishment was assessing the importance of precipitation in regulating cloud thickness. Periods of substantial night-time drizzle with cellular organization were observed; most drizzle evaporated above the surface. Work is ongoing.

Under ATM-0073206 to **Mapes** [42, 43], properties of the water vapor field in the tropical atmosphere are being explored. Complex variability was found, with fluctuations on many space and time scales, and non-Gaussian (bimodal) distributions. Undersampling of fields with multiple scales (wind as well as humidity) contributes substantial random errors to water budgets, errors which decrease with space/time averaging.

Under ATM-9812384 to **Randall**, our recent work has focused on bringing parameterizations of cumulus convection, stratiform clouds, and the planetary boundary layer (PBL) into a common framework, so that the interactions among these processes can be represented more realistically. A new PBL parameterization has been developed that can represent a wide variety of regimes including shallow cumuli [24-26], and we have developed a parameterization of deep convection that includes an improved representation of cloud microphysics, so that the stratiform clouds produced by cumulus detrainment can be more realistically simulated [44]. Finally, we explored the use of cloud-resolving models as "super-parameterizations" inside general circulation models [46, 47].

Under ATM-9985413 to **Stevens**, we investigated the ability of bulk models to represent the statistics of tropical shallow convection and surface wind [48]. Our results illustrate the ability of mixed layer models to diagnostically represent the basic climatology of marine stratocumulus [29], and clarify regime rules which delineate the domain of validity of this approach [32]. Ongoing research explores the use of a level set method to better represent the marine inversion in stratocumulus regions. Large-eddy simulation studies [49-51] have also been used to lay the groundwork for similar investigations of trade cumulus.

Under ATM-97195 to **Zhang**, a constrained variational analysis approach was developed for creating single-column datasets and forcings from multi-platform observations from major field experiments, for comparison with GCM parameterizations and cloud-resolving models. The method ensures physically consistent column budgets of mass, water vapor, and energy. We have evaluated the advantages and disadvantages of various objective analysis methods, and carried out observing system simulation experiments to assess the approach [38, 39]. Several integrated datasets that we have developed have been used in GCSS, ARM and other modeling studies. In collaboration with Bretherton and NCAR colleagues, we developed a fractional condensation rate scheme for the NCAR CAM2 [52], and revealed convective triggering problems in the CCM [53].

PIs **Pincus** and **Xu** have not received NSF funding during the past five years.