Final Report to the U.S. Department of Energy for studies of

Evaluation of Turbulence Parameterizations for Cloud-Resolving Models

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A. Introduction

The intermediately-prognostic higher-order turbulence closure (IPHOC) introduces a joint double-Gaussian distribution of liquid water potential temperature (θ_l), total water mixing ratio (q_t), and vertical velocity (w) to represent any skewed turbulence circulations .The distribution is inferred from the first-, second-, and third-order moments of the variables given above, and is used to diagnose cloud fraction and grid-mean liquid water mixing ratio, as well as the buoyancy and fourth-order terms in the equations describing the evolution of the second- and third-order moments. Only three third-order moments (those of θ_l, q_t, and w) are predicted in the IPHOC.

IPHOC has been implemented and tested in the super-parameterized Community Atmosphere Model (SPCAM-IPHOC). A greatly improved simulation of low-level clouds over the tropical and subtropical oceans has been achieved. The climatology, seasonal cycle, diurnal cycle, and cloud regime transition simulated by SPCAM-IPHOC are further explored as discussed below.

The improvement in simulation of low-level clouds is sufficient motivation to implement the IPHOC directly into CAM5. A simplified IPHOC was implemented in CAM5 to provide a consistent treatment of subgrid-scale cloud processes except for deep convection. The planetary boundary-layer (PBL) height is prognosticated to better resolve the discontinuity of temperature and moisture above the PBL top. The simplified IPHOC package replaces the boundary-layer dry and moist turbulence parameterizations, the shallow convection parameterization, and the liquid-phase part of the cloud macrophysics parameterization in CAM5. The ability of CAM5-IPHOC on climate simulation will be presented below.

In addition, the CAM5-IPHOC was evaluated in the model intercomparison studies GABLS4 [The Global Energy and Water cycle Experiment (GEWEX) Atmospheric Boundary Layer Study] and CAUSES (The Clouds Above the United States and Errors at the Surface). The LaRC-IPHOC was also evaluated in the CRM (cloud resolving model) intercomparison GASS-WTG (GEWEX Global Atmospheric System Studies-Weak Temperature Gradient) studies.

B. SPCAM-IPHOC evaluation

The output from 10 year and 3 month simulations with SPCAM-IPHOC and several short-term sensitivity experiments was analyzed and documented results in a series of papers (Section G). The SPCAM-IPHOC model can produce a global- and annual-mean low cloud amount that is within 5.3% of observations from the merged CloudSat, CALIPSO, CERES and MODIS data product. The spatial distributions of low clouds are realistic in several ocean basins, with the relationships of low clouds with large-scale variables agreeing with those observed in these ocean basins. The seasonal variations of these low-level clouds in the eastern Pacific are comparable to and in some instances better than those produced by the best regional high-resolution climate models. The spatial distribution and seasonal variation of several variables agree with available satellite observations. SPCAM-IPHOC also produces the most realistic cloud-regime transition among SPCAM-IPHOC, SPCAM and CAM5, compared all of them to observations. Although, some significant differences in the characteristics of stratocumulus-to-cumulus transition and the intensity of overturning circulations were found. The SPCAM-IPHOC simulation can reproduce the spatial pattern of the diurnal variations of low clouds within the SE Pacific region. The maximum cloudiness and

liquid water path occur in the early morning and the minimum in the later afternoon over the open ocean. Two diurnal variation mechanisms were examined in this study.

C. Climate simulation with CAM5-IPHOC

The IPHOC used in the SPCAM is simplified to increase the time step and improved for a realistic coupling with CAM5. A forecasting PBL height approach has been derived and implemented so that the discontinuity above PBL top can be parameterized for relatively coarse vertical grid spacing. On the other hand, the main obstacle limiting the time step of IPHOC is predicting the second-order and third-order moments. Both the diagnosed third-order moment equations and three more second-order moment equations have been derived and implemented for IPHOC.

The simplified IPHOC package is then implemented in CAM5 to replace the boundary-layer turbulence scheme, the shallow-cumulus and stratocumulus parameterizations, and the liquid cloud macrophysics parameterization. So that all of these sub grid-scale processes are treated in a consistent way. Consistent with the SPCAM-IPHOC MMF, the representation of the low-level clouds is substantially improved in CAM5-IPHOC relative to CAM5 and is similar to SPCAM-IPHOC. The strength and location of the low-cloud maxima-in the northeastern (NE) and southeastern (SE) Pacific, SE Indian Ocean, NE and SE Atlantic Ocean, and Atlantic and Pacific mid-latitudes were well reproduced. The annual global mean low-level cloud fraction is 45.8%, close to the 45.1% derived from SPCAM-IPHOC simulations. There are substantial improvements in cloud radiative forcing, especially shortwave, in the subsidence regime sorted by the pressure velocity at 500 hPa. The relationships among low cloud amount, surface relative humidity, LTS and PBL depth agree well with

observations in five stratocumulus deck regions, although the degree of agreements varies from one region to another with the closest agreements being in the Californian, Peruvian and Canarian regions.

CAM5-IPHOC produces reasonable precipitation patterns except for weak precipitation at the SPCZ and over the southern Indian Ocean. This is opposite to the double ITCZ problem in most global climate models including CAM5. It is likely related to the underestimate of the energy flux into the Southern Hemisphere atmosphere in the CAM5-IPHOC. The additional low-level clouds produced in the ocean basins in the SE Pacific, Atlantic, and the storm track belt located at 60°S in the southern hemisphere, which contribute to decreased incoming TOA radiation and net surface shortwave flux.

D. CAM5-IPHOC evaluation with GABSL4

GABLS4 inter-comparison studies were carried out for boundary layer parameterizations schemes in use by numerical weather prediction and climate models. Under stable stratifications, models still have large biases, which depend on the parameterizations used for the boundary layer and surface. This is a good case to test CAM5-IPHOC. The CLM4 (Community Land Model version 4) driven by observations from 01/12/2009 up to 15/12/2009 at the Antarctic Plateau at DomeC (stage 0) was evaluated. The CLM4 results show an unrealistic penetration of heat in the snowpack. The density profile was prescribed a constant 250 kg/m^3 and snow conductivity is a growing (exponentially) fact of density. So the snow density should be changing with height in future versions of the CLM.

We also participated in the Stage 1 to Stage 3 intercomparisons. Stage 1a used the single column model (SCM) of CAM5-IPHOC. The initial surface and soil conditions are from stage 0. Stage 1b tests the change of the initial condition by using observations. Stage2 prescribes the surface temperature. There was no radiation, humidity, or prescribed surface temperature (same as Stage2), and constant geostrophic wind in Stage3. The results from CAM5-IPHOC are generally comparable to observations and other SCMs. The SAM (Systems for Atmospheric Modeling) -IPHOC was evaluated as a large-eddy simulation (LES) to run Stages 2 and 3.

E. CAM5-IPHOC testing with CAUSES

CAM5-IPHOC participated the CAUSES model intercomparison study to evaluate its ability to simulate the cloud and cloud radiative forcing above the ARM SGP site. A series of 5-day hindcast forecasting are first performed to assess how the surface temperature error and the growth of the surface temperature error are related to the errors in the clouds and errors in precipitation and surface energy budget. Secondly, experiments were performed for a 4-month forecasting period. The results are used to look at the growth of the surface temperature errors on the 5-120 day timescale. Finally, experiments with time scale of ten years are made to look at the surface temperature errors for the 2011warm season and to compare it to the growth of the surface temperature error in other years. The details of the cloud profiles and the cloud regimes over the SGP in the climate model are compared to short-term forecasts to check that the cloud climatology in the model in NWP mode and climate mode are comparable.

F. LaRC CRM testing with RCE multi-equilibrium

LaRC CRM is run months to equilibrium state for more than 50 experiments using the weak temperature gradient (WTG) method and the damped gravity wave (DGW) method. The implementation of the WTG or DGW methods assumes a simulated column. It is coupled to a reference state, which is from the LaRC CRM's radiative convective equilibrium (RCE). The simulated column has the same surface conditions as the RCE reference state and is initialized with profiles from their RCE reference state. The LaRC CRM does not reproduce its RCE reference state for all values of SST and for both WTG and DGW methods, consistent with 6 of the 8 models participating in the intercomparison study. The LaRC CRM shows a fairly linear relationship between precipitation and circulation. When initialized dry, DGW simulations always result in a precipitating equilibrium state. Multiple equilibria are more likely to exist at higher SST for LaRC CRM.

G. Paper published and conference presentations

The following two sections present the peer-reviewed papers published and conference presentations, which were partially (0.25 only) supported by DE-SC0008779.

Peer-reviewed publications

Neggers, R. A. J., **A. Cheng**, and Coauthors, 2015: Single-column model simulations of subtropical marine boundary-layer cloud transitions under weakening inversions. In preparation *J. Adv. Model. Earth Syst*.

Cheng A., K.-M. Xu, 2015: Impact of subgrid-scale turbulence mixing on diurnal cycle simulation of middle latitude cloud systems. In preparation for *J. Geophys. Res.*

Cheng A., K.-M. Xu, 2015: Cloud feedbacks on greenhouse warming from an upgraded multiscale modeling framework. In preparation *J. Adv. Model. Earth Syst*.

Norman, G. L., Wang H., **A. Cheng**, S. Kato, J. T. Fasullo, K.-M. Xu, and R. P. Allan: Observational constraints on atmospheric and oceanic equatorial heat transports: resvisiting the precipitation asymmetry problem in climate models. submitted *Climate Dyn.*

Daleu, C. L., **A. Cheng**, and Coauthors, 2015: Intercomparison of methods of coupling between convection and large-scale circulation. Part I: comparison over uniform surface conditions. Submitted *J. Adv. Model. Earth Syst.*

Cheng A., K.-M. Xu, 2015: Improved low-cloud simulation from the Community Atmosphere Model with an advanced third-order turbulence closure. In press, *J. Climate*.

Painemal D., K-M Xu, **A. Cheng**, P. Minnis, and R. Palikonda, 2015: Mean structure and diurnal cycle of Southeast Atlantic boundary layer clouds: Insights from satellite observations and multiscale modeling framework simulations, *J. Clim.*, **28**, 324-341.

Cheng A., K.-M. Xu, 2014: An explicit representation of vertical momentum transport in a multiscale modeling framework model through its 2D cloud-resolving component. *J. Geophys. Res.*, **119**, *doi:10.1002/2013JD021078*.

Ovchinninkov, M., M., **A. Cheng,** and Coauthors, 2014: Intercomparison of large-eddy simulation of Arctic mixed-phase clouds. *J. Adv. Model. Earth Syst.*, **6**, *doi:*10.1002/2013MS000282.

Zhang, M., **A. Cheng,** and Coauthors, 2013: CGILS: First results from an international project to understand the physical mechanisms of low cloud feedbacks in general circulation models. *J. Adv. Model. Earth Syst.*, **5**, doi:10.1002/2013MS000246.

Cheng, A., and Xu, K.-M., 2013: Diurnal variability of low clouds in the southeast Pacific simulated by an upgraded multiscale modeling framework model. *J. Geophys. Res.*, **118,** 9191-9208, doi:10.1002/jgrd.50683).

Blossey, P., **A. Cheng,** and Coauthors, 2013: Marine low cloud sensitivity to an idealized climate change: The CGILS LES intercomparison. *J. Adv. Model. Earth Syst.* **5**, 234–258, doi:10.1002/jame.20025.

Xu, K.-M., and **A. Cheng**, 2013: Improving low-cloud simulation from an upgraded multiscale modeling framework model. Part I: Sensitivity to spatial resolution and climatology. *J. Clim.*, **26**, 5717-5740.

Xu, K.-M., and **A. Cheng**, 2013: Improving low-cloud simulation from an upgraded multiscale modeling framework model. Part II: Seasonal variations over the eastern Pacific. *J. Clim.*, **26**, 5741-5760.

Cheng, A., and Xu, K.-M., 2013: Improving low-cloud simulation from an upgraded multiscale modeling framework model. Part III: Tropical and subtropical cloud transitions over the northern Pacific. *J. Clim.*, **26**, 5761-5781.

Liu, Z., **A. Cheng,** and Coauthors, 2012: The CALIPSO LIDAR dust measurement: transpacific transport of Asian dust. *J. Quant. Spectr. Rad*. **116**, 24-33.

Cheng A., K.-M. Xu, Y. Hu, and S. Kato, 2012: Climate simulation with a liquid and ice mixed-phase parameterization based on CALIPSO observations. *J. Geophys. Res.*, **117**, D09103, doi:10.1029/2011JD017263.

Conference Presentations

Zhu L., K.-M. Xu, and **A. Cheng**, 2015: The response of simulated Arctic low clouds to sea ice cover variation under constant large-scale forcing. *CFMIP Meeting on Cloud Processes and Climate Feedbacks*, Monterey, California, June 8-11.

Cheng A., and K.-M. Xu, 2015: Cloud feedbacks on greenhouse warming in an MMF with a higher-order turbulence closure. *2015 ASR Science Team Meeting.* Vienna Virginia, March 16-19.

Cheng A., and K.-M. Xu, 2015: Role of grey zone on diurnal cycle simulation in MC3E. *2015 ASR Science Team Meeting.* Vienna Virginia, March 16-19.

Cheng A., and K.-M. Xu, 2015: Cloud feedbacks on greenhouse warming in an MMF with a higher-order turbulence closure. *The eighteenth CMMAP Science Team Meeting*, San Diego, CA, January 13-15.

Norman, G. L., Wang H., Cheng A., and K.-M. Xu, 2014: Exploration of hemispheric asymmetry in the surface energy budget using CERES and Reanalysis data. *CERES Science Team Meeting.* Toulose, France. October 6-10.

Blossey, P., **A. Cheng,** and Coauthors, 2014: The response of marine boundary layer clouds to idealized climate perturbations. *AGU fall meeting*, San Francisco, CA, December 15-19.

Xu, K.-M., and **A. Cheng**, 2014: Composite Madden-Julian oscillation cloud structures from satellite observations and a multiscale modeling framework simulation. *11th AOGS Annual Meeting.* Sapporo, Japan. July 28 – August 1.

Xu, K.-M., **A. Cheng**, and Y. Hu, 2014: Southern ocean low-level clouds and the causes of radiative biases: a multiscale modeling framework perspective. *11th AOGS Annual Meeting.* Sapporo, Japan. July 28 – August 1.

Cheng A., and K.-M. Xu, 2014: Preliminary results and challenges for using a third-order turbulence closure to parameterize deep convection. *11th AOGS Annual Meeting.* Sapporo, Japan. July 28 – August 1.

Painemal D., K-M Xu, and **A. Cheng**, 2014: Mean structure and diurnal cycle of Southeast Atlantic boundary layer clouds: Insights from satellite observations and multiscale modeling framework simulations. *14th Conference on Atmospheric Radiation*. Boston, MA. July 7-11.

Xu, K.-M., **A. Cheng**, and Y. Hu, 2014: Composite Madden-Julian oscillation cloud structures from satellite observations and a multiscale modeling framework simulation. *31st Conference on Hurricanes and Tropical Meteorology.* San Diego, CA. March 31- April 4.

Ovchinnikov, M., **A. Cheng,** and Coauthors, 2014: Intercomparison of large-eddy simulations of Arctic mixed-phase clouds: Importance of ice size distribution assumptions. *2014 ASR Science Team Meeting*. Rockville, Maryland, March 10-13.

Cheng A., and K.-M. Xu, 2014: Impact of turbulence in free troposphere on cloud system simulation of MC3E. *2014 ASR Science Team Meeting.* Rockville, Maryland, March 10-13.

Cheng A., and K.-M. Xu, 2014: Improved low-cloud simulation from the Community Atmosphere Model with a third-order turbulence closure. *2014 ASR Science Team Meeting.* Rockville, Maryland, March 10-13.

Xu, K.-M., and **A. Cheng**, 2014: Climate simulation from super-parameterized and conventional general circulation models with a third-order turbulence closure. *European Geosciences Union General Assembly.* Vienna, Austria, April 27-May 2.

Xu, K.-M., and **A. Cheng**, 2014: Implementing a higher-order turbulence closure in CAM5 and SPCAM: issues, successes and remaining challenges. The sixteenth *CMMAP Science Team Meeting*, Newport Beach, CA, January 7-9.

Cheng A., and K.-M. Xu, 2013: Improved low-cloud simulation from the Community Atmosphere Model with an advanced third-order turbulence closure. *AGU fall meeting*, San Francisco, CA, December 9-13.

Cheng A., and K.-M. Xu, 2013: Cloud regime transition along GPCI line in CAM5 with a higher-order turbulence closure. *2013 ASR Working Group Meeting.* Rockville, Maryland, November 4-8.

Cheng A., and K.-M. Xu, 2013: Effects of orientation of the mesoscale convective system on climate simulation with a multiscale modeling framework. *2013 ASR Working Group Meeting.* Rockville, Maryland, November 4-8.

Cheng A., K.-M. Xu, 2013: An explicit representation of vertical momentum transport in an multiscale modeling framework model through its 2D cloud-resolving model. The fifteenth *CMMAP Science Team Meeting*, Ft. Collins, CO, 5-8 August.

Cheng A., K.-M. Xu, 2013: Sensitivity of global summer precipitation on the resolution and dynamical core of MMF. The fifteenth *CMMAP Science Team Meeting*, Ft. Collins, CO, 5-8 August.

Xu, K.-M., and **A. Cheng**, 2013: The statistics of the transition from stratocumulus clouds to shallow cumulus clouds simulated from SPCAM-IPHOC and CAM5 along the MAGIC line. *2013 ASR Science Team Meeting.* Rockville, Maryland, March 18-22.

Cheng A., and K.-M. Xu, 2013: The statistics of the transition from shallow cumuli to deep convective clouds simulated from SPCAM-IPHOC and CAM5 along the GPCI line. *2013 ASR Science Team Meeting.* Rockville, Maryland, March 18-22.

Cheng A., and K.-M. Xu, 2013: Preliminary results on implementing a third-order turbulence closure in the Community Atmosphere Model. *2013 ASR Science Team Meeting.* Rockville, Maryland, March 18-22.

Cheng A., and K.-M. Xu, 2013: Comparison of low-order and third-order turbulence closures in the cloud resolving simulation of MC3E. *2013 ASR Science Team Meeting.* Rockville, Maryland, March 18-22.

Xu, K.-M., and **A. Cheng**, 2013: Performance of SPCAM and SPCAM-IPHOC at high vertical resolution in the low troposphere. The fourteenth *CMMAP Science Team Meeting*, Boulder, CO, 22-24 January.

Cheng A., and K.-M. Xu, 2012: Preliminary results from the testing of a third-order turbulence closure in the Community Atmosphere Model. *AGU fall meeting*, San Francisco, CA, December 3-8.

Blossey, P., **A. Cheng,** and Coauthors, 2012: CGILS LES intercomparison. *AGU fall meeting*, San Francisco, CA, December 3-8.

Cheng A., K.-M. Xu, 2012: The sources of uncertainties in simulating shallow cumulus-to-stratus cloud transitions in MMF and CAM5. *2012 ASR Working Group Meeting.* Rockville, Maryland, October 29-November 2.

Zhang, M., **A. Cheng,** and Coauthors, 2012: CGILS SCM intercomparison. *First Pan-GASS meeting*. Boulder, Colorado, September 10-14.

Blossey, P., **A. Cheng,** and Coauthors, 2012: CGILS LES intercomparison. *First Pan-GASS meeting*. Boulder, Colorado, September 10-14.

Ovchinnikov, M., **A. Cheng,** and Coauthors, 2012: Unraveling interactions among microphysical, dynamical and radiative processes in persistent mixed-phase Arctic clouds: Results from ISDAC LES intercomparison. *First Pan-GASS meeting*. Boulder, Colorado, September 10-14.

Ovchinnikov, M., **A. Cheng,** and Coauthors, 2012: ISDAC LES intercomparison: Overview and preliminary results. *First Pan-GASS meeting*. Boulder, Colorado, September 10-14.

Cheng A., 2012: Ice-phase microphysics option for UCLA-LES. *First Pan-GASS meeting*. Boulder, Colorado, September 10-14.

Xu, K.-M., and **A. Cheng**, 2012: GPCI tropical cloud and subtropical cloud transitions simulated from CAM5 , SPCAM and SPCAM-IPHOC. *First Pan-GASS meeting*. Boulder, Colorado, September 10-14.

Cheng A., and K.-M. Xu, 2012: GPCI tropical cloud and subtropical cloud transitions simulated from CAM5 , SPCAM and SPCAM-IPHOC. *First Pan-GASS meeting*. Boulder, Colorado, September 10-14.

Xu, K.-M., **A. Cheng**, 2012: GPCI tropical cloud and subtropical cloud transitions simulated from CAM5, SPCAM, and SPCAM-IPHOC. The thirteenth *CMMAP Science Team Meeting*, Ft. Collins, CO, August 7-9.

Peter N. Blossey, C. S. Bretherton, C. R. Jones, M. Zhang, **A. Cheng**, S. R. de Roode, S. Endo, T. Heus, Y. Liu, A. Lock, and K. M. Xu, 2012: Clouds to idealized climate perturbations: the CGILS LES intercomparison. The thirteenth *CMMAP Science Team Meeting*, Ft. Collins, CO, August 7-9.

Peter N. Blossey, C. S. Bretherton, C. R. Jones, M. Zhang, **A. Cheng**, S. R. de Roode, S. Endo, T. Heus, Y. Liu, A. Lock, and K. M. Xu, 2012: Sensitivity of marine boundary layer clouds to idealized climate perturbations: The CGILS LES Intercomparison. *20th Symposium on Boundary Layers and Turbulence/ 18th Conference on Air-Sea Interaction.* Boston, Massachusetts, July 9-13.

Cheng A., K.-M. Xu, 2012: A higher-order turbulence closure incorporated with prognostic planetary boundary-layer height for use in climate models. *20th Symposium on Boundary Layers and Turbulence/ 18th Conference on Air-Sea Interaction.* Boston, Massachusetts, July 9-13.

Cheng A., K.-M. Xu, 2012: Comparison of TOA and surface radiation between multiscale modeling frameworks simulation and CERES EBAF. *CERES Science Team Meeting.* Newport News, Virginia, May 1-3.

Xu, K.-M., **A. Cheng**, 2012: Improved simulation of boundary-layer clouds from an upgraded multiscale modeling framework model. *2012 ASR Science Team Meeting.* Crystal City, Virginia, March 12-16.

Xu, K.-M., **A. Cheng**, 2012: Global climatology simulated from an upgraded multiscale modeling framework model. *2012 ASR Science Team Meeting.* Crystal City, Virginia, March 12-16.

Cheng A., K.-M. Xu, 2012: Improving boundary-layer turbulence and cloud processes in CAM with a simplified higher-order turbulence closure scheme. *2012 ASR Science Team Meeting.* Crystal City, Virginia, March 12-16.

Hu, Y., K.-M. Xu, **A. Cheng**, 2012: CALIPSO water cloud phase statistics and comparisons with model. *CESM Atmosphere Model Working Group Meeting*. Boulder, CO, 1-3 February.

Xu, K.-M., **A. Cheng**, 2012: Improving low-cloud simulation with an upgraded multiscale modeling framework. The twelfth *CMMAP Science Team Meeting*, Ft. Lauderdale, FL, January 10-12.