Simulations of Stratus Clouds over Eastern China in CAM5: Sensitivity to Horizontal Resolution

YI ZHANG
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, and University of Chinese Academy of Sciences, Beijing, China

HAOMING CHEN
Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China

RUCONG YU
LASW, Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China

(Manuscript received 2 December 2013, in final form 13 June 2014)

ABSTRACT

This paper evaluates the simulations of stratus clouds over eastern China (EC) in the Community Atmosphere Model, version 5 (CAM5), with an emphasis on the impact of changing horizontal resolutions on the performance. CAM5 in all experiments generally satisfactorily simulates the cloud radiative features over EC, including the spatial distributions of the continental shortwave cloud radiative forcing (SWCF) and stratus regimes, the responses of SWCF to the dynamic and thermodynamic ambient environment, and several relations in the environmental fields that are favorable to the stratus formation. Meanwhile, all experiments suffer from similar biases. Models tend to underestimate the stratus amount because of a corresponding underestimate of stratus occurrence frequency, while the stratus amount when present (AWP) is generally higher than that in the observation. Models also simulate similar errors in the environmental fields. The differences between low- and high-resolution experiments are distinct. An increase of resolution enhances the SWCF in southern China, but the skill deteriorates in the Sichuan basin. Correspondingly, the stratus amount increases in southern China from low- to high-resolution experiments, mainly because of more stratus occurrences, which are found to be related to the better represented environmental fields in the high-resolution experiments, especially the dynamic component. Several relations in the ambient environment are also slightly improved in the high-resolution experiments. Meanwhile, the reason for the decrease of stratus AWP within the Sichuan basin, which is mainly responsible for the decreased stratus amounts and weaker SWCF from low- to high-resolution experiments, is also discussed.

1. Introduction

The uncertainty in modeling clouds and associated feedback is a long-standing problem in the development of atmospheric general circulation models (AGCMs) during the past decades (e.g., Cess et al. 1989, 1996; Williams et al. 2003; Randall et al. 2003; Zhang et al. 2005; Soden and Held 2006; Dufresne and Bony 2008; Lauer and Hamilton 2013; Klein et al. 2013). Particularly, the stratus cloud radiative effect is recognized to cause larger biases than other cloud types (Bony and Dufresne 2005; Vial et al. 2013).

Previous studies suggested a large uncertainty and a common underestimate of the stratus shortwave cloud radiative forcing (SWCF) over eastern China (EC) in models from phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5) (Zhang and Li 2013). The magnitude of errors is comparable to those caused by the marine boundary layer stratocumulus, which has been intensively studied [see Wood (2012) for a review] and regarded as difficult to properly simulate in a GCM (Bretherton et al. 2004) given so many subgrid processes (e.g., Stevens 2002; Wood and Bretherton 2004) that are hard to parameterize.
It has been presented in Zhang and Li (2013) that most CMIP3 and CMIP5 models can reasonably reproduce the ambient environment over marine boundary layer regions but fail to simulate the dependence of SWCF to boundary layer inversion. Over EC, however, most models cannot even simulate a proper ambient environment, which directly affects the representation of the stratus cloud radiative effect. The ambient environment over EC is tightly correlated with the surrounding stratus cloud radiative effect. The ambient environment, which directly affects the representation of the stratus cloud radiative effect. The ambient environment, which directly affects the representation of the stratus cloud radiative effect.

The EC stratus clouds have strong relations with the orography-induced ambient environment (Yu et al. 2004; Li and Gu 2006; Zhang et al. 2013). They usually form under a stable stratification featured with moistening at the middle and low levels. The Tibetan Plateau (TP) leads to a midlevel divergent and low-level convergent flow on its lee side, causing large-scale lifting and favoring the accumulation of water vapor to the middle and low levels. The high stability in the cold season is contributed to by both the near-surface cold advection from northern China and the southwestern warm flow uplifted by the Hengduan Mountain (HDM)—Yungui Plateau (YGP) to middle levels; thus it is also affected by the dynamic circulations. It is expected that if the ambient environment in the model can be improved, a better stratus performance can be achieved.

The contribution of increased resolution to the model performance has long attracted lots of attention (e.g., Boville 1991; Pope and Stratton 2002; Roeckner et al. 2006; Li et al. 2011). A high-resolution GCM is better than its coarse counterpart in simulating the orography-induced climate features (e.g., Gent et al. 2010; Bacmeister et al. 2014), which could lead to a more favorable ambient environment for the simulation of EC stratus clouds. Therefore, it is worthwhile investigating the sensitivity of these stratus clouds in a GCM with different resolution configurations.

This paper will evaluate the performance of the Community Atmosphere Model, version 5 (CAM5) in simulating EC stratus clouds and associated environmental fields under different resolutions. We will document the common strengths, limitations, and changes from low- to high-resolution experiments. We hope this study can help us understand how we can benefit from the increased model resolution in the simulation of EC stratus clouds.

The remainder of this paper is organized as follows: Section 2 describes the model, experiments, datasets, and analysis method. Section 3 compares the cloud radiative properties between model and satellite observations. Section 4 compares the environmental fields between model and reanalysis data. A discussion and a summary will be presented in sections 5 and 6, respectively.

2. Model, experiments, datasets, and analysis method

a. Model, experiments, and datasets

CAM5 is an AGCM developed at the National Center for Atmospheric Research (NCAR) publicly available to the scientific community (http://www2.cesm.ucar.edu/models). The default finite-volume (FV) dynamical core is run at 2.5° × 3.33° (FV3), 1.9° × 2.5° (FV2), 0.9° × 1.25° (FV1), and 0.47° × 0.63° (FV05) resolutions, covering the range of the most common resolution settings among current AGCMs. For convenience, FV3 and FV2 are referred to as the low-resolution runs (LRs), and FV1 and FV05 are referred to as the high-resolution runs (HRs). The hybrid pressure–sigma vertical coordinate (Simmons and Burridge 1981) has 30 levels with a top at 2.255 hPa. The FV dynamical core uses a Lagrangian control-volume discretization (Lin 1997, 2004) with a flux-form semi-Lagrangian transport method for resolving all grid-scale scalar advects (Lin et al. 1994; Lin and Rood 1996). The time step of model dynamics is internally split under different horizontal resolutions within a uniform large physical time step of 1800 s for all experiments.

The major physics parameterization schemes are listed as follows: A deep (Zhang and McFarlane 1995; Richter and Rasch 2008) and a shallow (Bretherton and Park 2008; Park and Bretherton 2009) convection scheme and a moist turbulence scheme (Bretherton and Park 2009) are used for calculating the subgrid vertical transport of heat, moisture, and momentum. A two-moment cloud microphysics scheme (Morrison and Gettelman 2008) with a suite of compatible cloud microphysics schemes that handle the cloud fractions, horizontal and vertical overlapping structures, and the net conversion rates from water vapor to cloud condensates (Neale et al. 2012; Zhang et al. 2003) serves as the cloud parameterizations. A Rapid Radiative Transfer Model for GCMS (RRTMG) package is used as the radiation module (Mlawer et al. 1997). A three-mode modal aerosol module is also implemented in the model (Liu et al. 2012). More details about the dynamical core and model physics can be found in Neale et al. (2012).

In this study, the CAM5.1 version is run as a standalone atmospheric model forced by the prescribed monthly historical Hadley Centre Sea Ice and Sea Surface Temperature dataset. Two groups of experiments are conducted in a long period from January 1979 to December 2009 as well as a short one from January 2000 to April 2004. We only focus on the boreal cold season (from November to the next April).

The long-period experiment generated monthly mean output for analyzing the climatological mean and
interannual correlations in the large-scale environmental fields associated with stratus cloud formation. The first year (1979) is ignored to remove the impact of initial conditions. The short-period experiment (first 10 months ignored) with a Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP; Bodas-Salcedo et al. 2011) enabled generated 3-hourly output for comparing the simulated cloud properties directly with satellite observations. The configuration for COSP in all experiments follows that in Kay et al. (2012). The COSP diagnostic model cloud fields were produced every 3h. The active simulators were run on all columns, while the passive simulators were run on sunlit columns.

The reanalysis and observational data used in this study include the following: (i) European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data for atmospheric state variables (Dee et al. 2011), (ii) Clouds and the Earth’s Radiant Energy System (CERES)-Energy Balanced and Filled (EBAF) data for top of atmosphere (TOA) radiative fluxes (Loeb et al. 2009), and (iii) 3-hourly International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1991) D1 dataset for cloud properties.

b. Cloud classification and stratus statistics

Rossow et al. (1996) divided clouds in the ISCCP classification into nine types in terms of the cloud optical depth (τ) and cloud-top pressure (CTP), including high-topped (CTP < 440 hPa) optically thin (τ ≤ 3.6) cirrus, optically intermediate (3.6 < τ ≤ 23) cirrostratus, and optically thick (τ > 23) deep convective cloud: mid-topped (680 > CTP > 440 hPa) optically thin altocumulus, optically intermediate altostratus, and optically thick nimbostratus; and low-topped (CTP > 680 hPa) optically thin cumulus, optically intermediate stratocumulus, and optically thick stratus. In this paper, we refer to stratus clouds as a combination of nimbostratus, altostratus, stratocumulus, and stratus at middle and low levels. Meanwhile, since the ISCCP D1 data cannot detect specific cloud types during the nighttime, only the data at 0300 and 0600 UTC are used [i.e., 1100 and 1400 Beijing standard time (BST)].

To better figure out the source of model errors, the stratus occurrence frequency and stratus amount when present (AWP) are calculated. The stratus occurrence frequency is defined as a ratio between stratus occurrence times (stratus mount higher than zero) and the total statistical times at a given grid point. The stratus AWP is the composite mean stratus amount when stratus clouds occur. Therefore, the mean stratus amount during a period should be the product of occurrence frequency and AWP. Without counting the leap day of 29 February, there are a total of 1448 statistical time slices (2 data times × 181 days × 4 years) during the cold seasons from November 2000 to April 2004. Meanwhile, we are also interested in the large-scale environmental fields when stratus clouds occur. In this regard, only data at 0600 UTC (1400 BST) are counted because of the limitation of the reanalysis data, which are interpolated to the ISCCP grid using bilinear interpolation.

3. Comparing simulated cloud radiative properties with satellite observations

a. Comparing the shortwave flux at the TOA between models and CERES-EBAF

The EC stratus clouds produce extremely strong SWCF at the TOA, which fundamentally influences the local energy balance and climate. Means of the observed and simulated climatological SWCF are compared in Fig. 1. As shown in the CERES-EBAF (Fig. 1a), the maximum SWCF is located between 24° and 32°N downstream of the TP over mainland China. All experiments (Figs. 1b–e) overall simulate the continental maximums. From LR to HR, the models exhibit slightly improved skill in simulating the spatial pattern. The spatial correlation coefficients (calculated by regridding all data onto a 2° × 2° grid) between four experiments and the CERES-EBAF within 20°–40°N, 100°–120°E slightly enhance from the LR (0.90 for FV3 and 0.89 for FV2) to HR (0.92 for FV1 and 0.93 for FV05).

Two regions are selected to investigate the simulated cloud radiative properties (Fig. 1). A northwest box (region 1) covers the Sichuan basin (27°–32°N, 103°–108°E) and a southeast box (region 2) is over southern China (23°–27°N, 108°–118°E). As revealed in previous studies (Yu et al. 2004; Li et al. 2004), the dominant stratus types over these two regions are different. The Sichuan basin is mainly dominated by midtopped nimbostratus and altostratus, while southern China is primarily covered by low-topped stratocumulus cloud, and nimbostratus also prevails. Therefore, SWCFs are comparably strong in both regions.

Against the observation, CAM5 only reproduces the maximum center in southern China, while it largely underestimates the SWCF over the Sichuan basin. Compared with the LR, the HRs improve the spatial distribution and strength of the maximums in region 2. In LR, the maximum SWCF is mainly located at the border between land and sea, while it moves westward in the HR, closer to the observation. However, the magnitude in some areas within the Sichuan basin decreases from LR to HR, showing a worse performance.

As SWCF measures the difference between total and clear-sky net shortwave flux at the TOA (FSNTOA and...
FIG. 1. The SWCF climatological mean in the boreal cold season from (a) the CERES-EBAF data, (b) FV3, (c) FV2, (d) FV1, and (e) FV05 and the differences of (f)–(i) FSNTOA and (j)–(m) FSNTOAC between model and the observation (W m\(^{-2}\)). White contours on SWCF plots indicate orographic height, and two key regions illustrated in the text are marked by black boxes. Results are from the long-period run.
FSNTOAC), we further illustrate the difference between the simulated and observed FSNTOA/FSNTOAC for each experiment. For this purpose, all data are interpolated onto the same $2^\circ \times 2^\circ$ grid, and only the differences between model and observation (model minus observation) are presented. The maximum positive errors of FSNTOA are located at the Sichuan basin in all experiments (Figs. 1f–i), corresponding to the weaker SWCF in this region. The difference in the FSNTOAC (Figs. 1j–m) is much smaller than that in the FSNTOA over the Sichuan basin, and HRs overall have smaller biases. Results suggest that cloud properties are the major reason for the biased SWCF.

b. Comparing cloud properties between models and ISCCP D1 data

Figure 2 compares the observed and simulated cold-season mean stratus cloud amount (left), stratus occurrence frequency (center), and stratus AWP (right). The maximum stratus amount in the observation (Fig. 2a) can reach above 60% and covers both the Sichuan basin and southern China. The models (Figs. 2b–e) only reproduce the maximum stratus amount over southern China, and cloud amounts increase evidently from LRs to HRs. However, the stratus amounts over the Sichuan basin in all experiments are seriously underestimated, which constitutes a major reason for the underestimated SWCF in this region.

The decomposition of climatological mean stratus amount into stratus occurrence frequency and stratus AWP helps us better understand the source of model errors. As revealed in the observation (Fig. 2f), the maximum stratus occurrence frequencies can reach above 90%, extending from the Sichuan basin to its south. In two LRs (Figs. 2g,h), the occurrence frequencies over the continent are mostly below 70%, primarily located in southern China. Moving from LRs to HRs, the occurrence frequencies in southern China further increase (Figs. 2i,j) but are still less than those in the observation. Meanwhile, although the difference among different experiments over the Sichuan basin is not as significant as it is in southern China, the HRs do show a slight increase of occurrence frequency in some area within the Sichuan basin, especially FV05.

The observed stratus AWP (Fig. 2k) exhibits a similar spatial pattern with the climatological mean amount (Fig. 2a). Generally, the model tends to overestimate the AWP, with values mostly higher than 70% over the continent. Compared with the occurrence frequency, the AWP is relatively insensitive to various resolutions (Figs. 2l–o). The only exception occurs at the Sichuan basin, where two HRs simulate a low AWP value center, which does not exist in the LRs. This constitutes a reason for the weaker SWCF and decreased stratus amount from LRs to HRs in some area within the Sichuan basin (Figs. 2b–e). It is obvious that if there is no such low value center in HRs, they will perform better in simulating the SWCF and stratus amount over the Sichuan basin. The reason for the formation of the low AWP value center will be further discussed in section 5.

Figure 3 summarizes the cold-season mean ISCCP nine-type cloud fraction averaged in the two regions. For model results, only the differences between CAM5 and ISCCP are shown. In region 1, the most dominant cloud types are midtopped nimbostratus and altostratus clouds (Fig. 3a), both of which are largely underestimated in all experiments (Figs. 3b–e), especially the altostratus (except nimbostratus in FV3). All experiments overestimate the high-cloud fraction, primarily cirrus and deep-convective clouds. Therefore, although models underestimate the stratus amount, the contribution from positively biased optically thick high clouds can partly offset the bias in the resultant SWCF. The positive errors of deep-convective cloud amounts in LRs (positive biases 5.7 and 5.3) are reduced in HRs (positive biases 2.1 and 1.4), which also partly explains the weaker SWCF in HRs. Additionally, the models tend to underestimate mid- and low-topped clouds, especially optically thin and intermediate clouds. Meanwhile, aside from FV3, all experiments overestimate low-topped optically thick stratus amounts, and the positive error increases with enhanced resolutions.

In region 2, where the dominant cloud types are stratocumulus, nimbostratus, and altostratus (Fig. 3f), all experiments underestimate optically thin and intermediate clouds at middle and low levels (Figs. 3g–j). The negative error with the greatest absolute value in all experiments comes from the stratocumulus type. Nevertheless, all experiments overestimate mid- and low-topped optically thick clouds, especially the low-topped optically thick stratus, of which the positive error increases with the enhanced resolution, similar to that in region 1. The positively biased optically thick clouds majorly contribute to the increase of stratus cloud amount in southern China, which offsets the bias from the optically intermediate clouds and leads to stronger SWCF than in region 1. Besides, the errors in high cloud amount are small in region 2 overall.

The overestimate of optically thick clouds and underestimate of optically thin and intermediate clouds in region 2 lead to a largely overestimated total cloud optical depth and mean cloud albedo in the model (not shown). These two problems are common systematic errors in current AGCMs (Zhang et al. 2005; Qian et al. 2012). Lin and Zhang (2004) and Kay et al. (2012) compared the simulated clouds in CAM2 and CAM5
FIG. 2. (a)–(e) The cold-season mean stratus amount, (f)–(j) stratus occurrence frequency, and (k)–(o) stratus amount when present in percent for ISCCP D1 and four experiments. Data for both ISCCP D1 and simulator are only taken from 0300 and 0600 UTC. White boxes show the two regions. Results are from the short-period run.
against the satellite data. It is interesting to find that, although both the model dynamics and physics have changed completely in these two generations, the two biases mentioned above hold for both versions. The compensating errors in the biased cloud fraction and optical depth allow the resultant SWCF to have a comparable magnitude with that in the satellite observation.

The analysis above points out that the performance of SWCF with enhanced horizontal resolutions improves in southern China but deteriorates in the Sichuan basin. Both improvement and deterioration partly result from the offsetting of errors. The improvement in southern China results from increased stratus occurrences, primarily more low-topped optically thick clouds. The weakening of SWCF over the Sichuan basin from LRs to HRs is caused by fewer positive errors in the deep convective cloud and the decreased stratus AWP, which exhibits a low AWP value center in the HRs. A striking feature revealed in this section is that an increased horizontal resolution is favorable to more stratus occurrences (Fig. 2). In section 4, we will examine the large-scale environmental fields that are important to the stratus formation.

4. Comparing large-scale environmental fields with reanalysis data

a. Simulated dynamic and thermodynamic environmental conditions and cloud responses

The mid- to low-level divergence difference (or large-scale rising motion that lies between) and the static stability are two primary large-scale dynamic and thermodynamic factors governing EC stratus clouds (Yu et al. 2004; Li and Gu 2006; Zhang et al. 2013). The dynamic component is examined by showing a vertical cross section for the cold-season mean divergence at each layer (Fig. 4). Two solid vertical lines on each plot show the locations at 103°E and 108°E, respectively. Variables in the regions between 100°E–108°E and 108°E–120°E are meridionally averaged in the latitude ranges of the Sichuan basin and southern China, respectively.

As shown in Fig. 4a, the convergent flows dominate at low levels in both regions. The midlevel divergence peaks at 600 hPa on the lee side of the TP. In FV3 (Fig. 4b), the model simulates a convergent flow at middle levels, and the low-level convergence is also weak or nonexistent in two regions. FV2 (Fig. 4c) begins to reproduce the midlevel divergence but still fails to represent the low-level convergence in the Sichuan basin. This bias is largely alleviated by two HRs; both FV1 (Fig. 4d) and FV05 (Fig. 4e) reproduce the low-level convergence and the peak of midlevel divergence at 600 hPa in the Sichuan basin, and...
the representations of low-level convergence in southern China also become closer to the ERA-Interim, especially in FV05. Meanwhile, a small fraction of surface convergence to the west side of 103°E, which is missed by FV3, FV2, and FV1, is also present at FV05. Overall, the simulated dynamical environment is better as the resolution increases.

Despite the improvements in HRs, several systematic biases still remain. First, the depth of low-level convergence in southern China is shallower than in ERA-Interim. Furthermore, it seems the model simulates an erroneous orographic effect in the Sichuan basin when resolution enhances. As the orography is resolved more finely in the HRs, the divergence clinging to the orography at the near-surface level in the Sichuan basin is much stronger compared with that in ERA-Interim, especially in FV05. The overly strong divergence at the near-surface level dissipates the moisture and may also induce compensating subsidence, both of which are unfavorable to the water vapor lifting. The formation of this problem in the HRs currently remains unknown, but we will discuss its consequence further in section 5.

The thermodynamic environment is checked by showing the stability field, defined as the potential temperature difference between 500 and 850 hPa, as shown in Fig. 5. The four experiments all reproduce the high-stability belt centered over 22°–32°N, 103°–118°E over mainland China but underestimate the magnitude of the maximum
FIG. 5. The cold-season mean stability (K) from (a) ERA-Interim, (b) FV3, (c) FV2, (d) FV1, and (e) FV05. Results are from the long-period run.
stability that can reach 27 K above in ERA-Interim. The stability in FV1 is the strongest among all experiments. Meanwhile, although the stability in FV05 seems to be inferior to its low-resolution counterpart (FV1), this does not suppress the stratus occurrences (Fig. 2), indicating the more important role of the dynamic component in determining stratus formation, which is better represented in FV05.

Because both the large-scale lifting and stable stratification contribute to the formation of stratus clouds, the observed SWCF and stratus amount downstream of the TP respond to both factors (Zhang et al. 2013). This metric is used to investigate whether such a relation exists in the model (Fig. 6). The monthly anomalous SWCF (within 27°–32°N, 103°–118°E) is binned to a regime sorted by the stability (the abscissa) and vertical pressure velocity at 700-hPa ($\omega_{700}$; the vertical axis) anomalies. The occurrence frequencies are given by the percentages in four quadrants. As illustrated by ERA-Interim and CERES (Fig. 6a), when two factors are simultaneously favorable (fourth quadrant) or unfavorable (second quadrant) to the stratus increase/formation, the SWCF tends to strengthen or weaken; while when only one favorable condition (first and third quadrants) is present, the variation of SWCF becomes a competing result of two factors.

All the experiments satisfactorily reproduce the uniform strengthening and weakening of SWCF in the fourth and second quadrants. The relative weights of the occurrence frequencies in all quadrants are also similar with those in the ERA-Interim. All the experiments indicate that the second quadrant has the largest frequency, the third quadrant has the smallest one, and the other two quadrants have close occurrence frequencies. The common discrepancy in all experiments mainly lies in the larger range of the rising motion anomalies than that in ERA-Interim.

The differences between LRs and HRs are also evident. In the LRs, it seems SWCF (Figs. 6b,c) is mainly dominated by the anomalous $\omega_{700}$, yet the stability shows a weak effect. The competing results in first and third quadrants become clearer in two HRs (Figs. 6d,e), indicating a more evident importance of the stability when the resolution increases.

Findings in section 4a demonstrate that HRs overall improve the simulated dynamic and thermodynamic (except stability in FV05) environmental conditions and simulate a more reasonable interannual response of SWCF to the large-scale controls. Besides these two basic dynamic and thermodynamic conditions, the next section will examine several key relations in the simulated environmental fields associated with stratus formation.

b. The simulations of physical mechanisms associated with stratus formation

During the cold season, a branch of low-level southwestern warm and moist flow is uplifted by the orography at the southwestern flank of the HDM–YGP to the middle levels. The midlevel westerly further advects this flow to the lee side of the TP, warming and moistening the midtropospheric atmosphere. Accompanied by the surface cold advection from the Siberian high that reduces the low-level temperature, the circulation directly leads to a moist and stable environment over EC. Meanwhile, the northerly winds from northern China and the southerly winds from the South China Sea increase the local convergence that is also favorable to the increase of moisture lifting by enhancing the large-scale lifting, and the latter one (southerly winds) also transports water vapor. Therefore, the accumulated moisture over EC is strongly influenced by the wind fields at the middle and low levels, as well as the large-scale lifting that lies between.

The above mechanisms result in a negative correlation between 500- and 700-hPa vertically integrated specific humidity (TMQ) and $\omega_{700}$ averaged over 27°–32°N, 103°–118°E (−0.6), a positive correlation between TMQ and the zonal wind component at 600 hPa (U600) downstream of the TP (Fig. 7a), positive correlations between TMQ and meridional wind component at 850 hPa (V850) at the east Bay of Bengal and at the southeastern flank of HDM–YGP (Fig. 7f), and a negative correlation between TMQ and V850 in the Sichuan basin (Fig. 7f).

In addition, the regionally averaged (27°–32°N, 103°–118°E) temperature at 500 hPa (T500) over EC exhibits a Γ-shaped positive correlation pattern with the temperature field at a diagonal cross section (line on Fig. 7a), extending from the southwestern flank of the HDM–YGP in the surface to the lee side of the TP in the middle level (Fig. 8a). This diagonal cross section is selected because it includes all key regions where the environmental fields are tightly associated with stratus formation, including the east Bay of Bengal, the southwestern and northeastern flanks of the HDM–YGP, and EC downstream of the TP. The latitudes and longitudes of each point on this line are scattered from 16° to 32°N by 0.8° and from 80° to 120°E by 2° (21 points in total). The variables on the line are determined from those on the CAM5/ERA-Interim grids by an inverse distance–weight interpolation. The regionally averaged (27°–32°N, 103°–118°E) temperature at 850 hPa (T850) is also positively correlated with the low-level temperature field, suggesting the influencing range of surface cold air.

CAM5 in all experiments can reproduce the negative correlation coefficients between TMQ and $\omega_{700}$, which
FIG. 6. The responses of anomalous SWCF (W m$^{-2}$) to the stability (abscissa; K) and $\omega$700 (ordinate; hPa day$^{-1}$) anomalies over 27°–32°N, 103°–118°E for (a) ERA-Interim/CERES, (b) FV3, (c) FV2, (d) FV1, and (e) FV05. The occurrence frequencies of environmental fields in four quadrants are given by percentages. Results are from the long-period run.
Fig. 7. The correlation coefficients between the midlevel (500–700 hPa) accumulated moisture (regionally averaged over 27°–32°N, 103°–118°E) and (left) U600 and (right) V850 fields for (a),(f) ERA-Interim, (b),(g) FV3, (c),(h) FV2, (d),(i) FV1, and (e),(j) FV05. The black shadings denote the orography, and the hatched shadings denote areas that are significant at a confidence level of 0.1 according to Student’s t test. The black line in (a) shows a diagonal section used in the next three figures. Results are from the long-period run.
FIG. 8. The correlation coefficients between regionally averaged (27°–32°N, 103°–118°E) temperature at (left) 500 and (right) 850 hPa and the temperature fields at the diagonal cross section denoted in Fig. 7a for (a),(f) ERA-Interim, (b),(g) FV3, (c),(h) FV2, (d),(i) FV1, and (e),(j) FV05. The hatched shadings denote areas that are significant at a confidence level of 0.1 according to Student's t test. Results are from the long-period run.
are $-0.57$ (FV3), $-0.77$ (FV2), $-0.41$ (FV1), and $-0.63$ (FV05). The correlation between TMOQ and U600 is not well simulated in FV3 (Fig. 7b), while the other three experiments can reproduce this pattern (Figs. 7c–e). The two LRs also have difficulty in simulating the correlations between TMOQ and V850 (Figs. 7g–h). FV1 begins to simulate the role of southerly winds at the southeastern flank of the HDM–YGP and a weak correlation between the moisture and northerly winds over the Sichuan basin (Fig. 7i). In FV05 (Fig. 7j), besides the similar patterns at the southeastern flank of the HDM–YGP and the Sichuan basin, CAM5 begins to show a positive correlation at the east Bay of Bengal, although the strength is weak overall. For the temperature fields (Fig. 8), it seems all experiments can simulate the $\Gamma$-shaped positive correlation between T500 and the temperature fields and the influencing range of the surface cold air to the low-level atmosphere on the lee side of the TP, although the ranges that pass the significance test differ from each other.

Results in Figs. 7 and 8 have shown that CAM5, especially in its high-resolution configuration, is capable of simulating the interannual correlations that are associated with stratus formation to a certain extent. Figure 9 further shows the differences between several composite mean fields in months with the negative anomalous regionally averaged ($27^\circ$–$32^\circ$N, $103^\circ$–$118^\circ$E) SWCF (as an agent of positive stratus anomaly) and the cold-season mean at the diagonal cross section. The reanalysis results are taken from 2001 to 2010 because of the limitation of CERES data. These anomalies summarize the key variations of large-scale environmental fields that favor the stratus increase/formation.

Figure 9a shows the anomalies in the circulation fields for the ERA-Interim. To the east of $105^\circ$E, anomalous westerly and southerly components above 900 hPa are accompanied by anomalous rising motion, while the near-surface level is dominated by the anomalous northerly winds. These signals suggest that the strengthening of the low-level northerly, the rising motion downstream of the TP, and the westerly and southerly components all lead to the increase of stratus clouds. All experiments (Figs. 9b–e) overall reproduce these patterns on the diagonal section. Nonetheless, FV3, FV2, and FV1 simulate a very shallow vertical extent of the near-surface northerly anomalies, which becomes more evident in FV05.

The anomalies in the temperature field are associated with the anomalous circulation fields (Fig. 9f), exhibiting warming variations above 800 hPa, especially at the middle levels ($500$–$600$ hPa). Together with the anomalous cooling at the near-surface levels (below $800$ hPa), they jointly enhance the local stability. Model results (Figs. 9g–j) also show the corresponding anomalous variations induced by the circulation fields. Nevertheless, the vertical extents of low-level negative anomaly values are also shallower in FV3, FV2, and FV1 than those in ERA-Interim. This problem, similar to that in the circulation fields, is also alleviated in FV05, although it tends to simulate weaker warming anomalies at the middle levels. This suggests FV05 is better in representing the low-level environmental fields that are favorable to more stratus occurrences.

Figures 9k–o portray the anomalous specific humidity in ERA-Interim (Fig. 9k) and the four experiments (Figs. 9l–o). In ERA-Interim, an evident moistening effect over EC above the surface can be observed. In all experiments, the moistening over EC can be well reproduced. Aside from FV05, the other three experiments show stronger moisture increase than in ERA-Interim, suggesting the models may need more moisture for stratus increase/formation. Figures 9p–t show the relative humidity (RH) anomalies. The patterns are, overall, similar to those in the specific humidity field.

The differences of the cold-season mean environmental fields between each experiment and the ERA-Interim along this cross section are summarized in Fig. 10. The panels in Figs. 10a–d depict the biases in the circulation fields. All simulations simulate subsiding motion biases between $105^\circ$ and $110^\circ$E and rising motion biases to the east of $110^\circ$E. To the east of $105^\circ$E, common southerly and northerly biases are located at the low and middle levels, respectively. Given that both ERA-Interim and models are dominated by rising motion (anomalies) between $105^\circ$ and $110^\circ$E, low-level northerly winds (anomalies), and midlevel southerly and westerly winds (anomalies), these errors suggest weaker circulation magnitude in models that are unfavorable to the stratus increase/formation. Particularly, an easterly bias between $100^\circ$ and $110^\circ$E at the middle levels exist in the LRs, indicating weaker midlevel westerly winds. This problem is alleviated in the HRs, which might explain why HRs are better in reproducing the westerly-induced midlevel divergence (Fig. 4) and the interannual correlations in Fig. 7.

For the temperature fields (Figs. 10e–h), the whole layer between $700$ and $500$ hPa in all experiments is colder than the one in the ERA-Interim. Between $105^\circ$ and $115^\circ$E, models have positive biases extending from the surface to the lower troposphere. Generally, the low levels tend to be warmer while the middle levels are colder over EC, which is unfavorable to the increase of the local stability. Since the surface cooling is contributed by the low-level northerly winds, and the midlevel warming is caused by mid- to low-level westerly and southerly components, the biased temperature fields can be attributed to discrepancies in the circulation fields.
Figures 10i–l show the specific humidity biases for the four experiments. Common negative biases can be found between the surface and 700 hPa from about 95°E to 110°E and below 900 hPa from 110°E to 120°E. Yet the rest of the panels over EC (to the east of 105°E) show positive biases corresponding to the bias of simulated relative humidity fields (Figs. 10m–p), which reveals an insufficient moisture supply near the northwestern flank of the HDM–YGP that is unfavorable to the stratus increase/formation.

5. Discussion of the model biases

In section 3, it has been shown that the largely underestimated stratus occurrence frequency (Fig. 2) is a major reason for the underestimated EC stratus amounts (Fig. 2) and weaker SWCF (Fig. 1) in all experiments, especially in the Sichuan basin. Although HRs enhance the simulation of stratus occurrences, which may be contributed to by the generally improved dynamic and
thermodynamic conditions (Figs. 4 and 5) and interannual variability in the environmental fields (e.g., Figs. 6 and 7), the systematic underestimation still remains because of the common biases in the large-scale environmental fields (Fig. 10), which are of great importance to the stratus formation downstream of the TP.

To directly investigate the sensitivity of the simulated stratus clouds to the large-scale environmental fields, the authors conducted a group of numerical weather prediction (NWP) integrations (e.g., Phillips et al. 2004; Rodwell and Palmer 2007; Xie et al. 2012). An ensemble of many short-period experiments in this approach makes the model climate more realistic. Results suggest that the NWP experiments successfully raise the climatological mean stratus occurrences as well as the stratus amounts (Zhang et al. 2014). A high-resolution GCM is helpful in simulating EC stratus clouds because it also improves the ambient environment, especially the dynamic component (Fig. 4) because of the finely resolved orography.

On the other hand, CAM5 exhibits a systematic overestimate of stratus AWP. The cloud fraction tends to be higher than that in the observation when stratus clouds occur. Meanwhile, two HRs produce a low AWP value center in the Sichuan basin not observed in the LRs. To better understand these two biases, the composite environmental fields when stratus clouds occur are shown in Fig. 11. As mentioned in section 2b, this is the only result from 0600 UTC.

Figures 11a–e show the mean specific humidity averaged between 500 and 700 hPa for the ERA-Interim and the four experiments, respectively. The results confirm that the model requires more water vapor than the observation (ERA-Interim/ISCCP) when stratus clouds...
Fig. 11. Composite environmental fields (ERA-Interim/ISCCP and the four experiments) for (a)–(e) 500–700-hPa averaged specific humidity (kg kg$^{-1}$), (f)–(j) 500–700-hPa averaged relative humidity (%), and (k)–(o) $\omega$700 (hPa day$^{-1}$) when stratus clouds occur. Results are from the short-period run.
occur, as first inferred from Fig. 9. Meanwhile, two HRs show a low value area over the Sichuan basin (especially FV05), corresponding to the low AWP value center. Thus, the relative humidity fields (Figs. 11f–j) also exhibit a similar low value area in the Sichuan basin.

As documented in Fig. 4, two HRs simulate overly strong divergent flows at the near-surface levels (e.g., 850 hPa) around the orography. This erroneous orographic effect may cause the compensating subsiding motions in the Sichuan basin, thus suppressing the moisture lifting. To confirm this assertion, Figs. 11k–o show the composite $\omega$700 field when stratus clouds occur. In ERA-Interim (Fig. 11k), a large area is occupied with rising motion downstream of the TP. All experiments can reproduce the dominant large-scale lifting over the continent, and the rising motion in southern China is stronger in the HRs. However, both HRs simulate strong and evident subsiding motions from the Sichuan basin to its south. This subsidence will suppress the water vapor supply over the Sichuan basin to the upper level and therefore lead to lower relative humidity and less stratus AWP in this region. To fundamentally alleviate this problem, the reason for the presence of overly strong low-level divergent flows near the orography in HRs should be further explored.

6. Summary and concluding remarks

In this paper, the performance of the NCAR CAM5 in simulating EC stratus clouds at four resolution configurations is assessed to investigate the sensitivity of such simulations to the horizontal resolution. The cloud radiative properties and large-scale environmental fields are compared with the satellite observations and reanalysis data. The common strengths, weaknesses, and changes from LRs to HRs are summarized as follows.

The models generally satisfactorily simulate the cloud radiative features over EC in the cold season. All experiments reproduce the spatial distributions of the continental SWCF and stratus regime. The large-scale dynamic and thermodynamic environmental conditions and the responses of SWCF to large-scale controls are reproduced, and the correlations between the midlevel accumulated moisture and large-scale lifting are also represented. Meanwhile, the models simulate several processes that are important to the formation of stratus clouds on a diagonal cross section, including the anomalous rising motion downstream of the TP, the cooling and northerly anomalies at the near-surface levels, the warming variations and anomalous westerly and southerly winds at the middle levels, and the anomalous changes in the moisture fields.

Several common biases in all experiments are also exposed. The models underestimate the SWCF over the Sichuan basin, where the stratus cloud amounts are also seriously underestimated. Models tend to underestimate stratus cloud occurrence frequency and overestimate stratus AWP, underestimate optically thin and intermediate clouds, and overestimate optically thick clouds. Meanwhile, the model climate tends to be colder at the middle levels with weaker southerly winds, be warmer at the low levels with weaker northerly winds, and show an insufficient moisture supply near the northwestern flank of the HDM–YGP with weaker rising motion. The vertical extents of surface cooling anomalies associated with the stratus increase/formation are shallower in several experiments, resulting from the similar shallower low-level northerly anomalies and limiting the development of the midtopped stratus clouds.

A comparison between LRs and HRs suggests an increase of the horizontal resolution can change the model performance from the following aspects: The SWCF increases and becomes closer to the observation in southern China as a result of a large increase of optically thick low-topped cloud. The SWCF weakens and deteriorates in the Sichuan basin because of decreases of deep convective cloud and stratus clouds. The stratus occurrence frequency increases with enhanced resolution and becomes closer to the observation in the HRs, primarily over southern China. Meanwhile, although the stratus AWP is relatively insensitive to the horizontal resolution, a low AWP value center is produced in the Sichuan basin by two HRs, resulting from the increased subsiding motion magnitude when stratus clouds occur and causing less moisture and lower relative humidity. For the environmental fields, HRs simulate better dynamic and thermodynamic environments (except the stability in FV05) as well as more reasonable responses of SWCF to large-scale controls. The correlations between the midlevel moisture and horizontal circulation fields are also slightly improved. At the same time, the HRs correct easterly biases at the middle levels and exhibit a deeper vertical extent (FV05) of the near-surface northerly and cooling anomalies over EC.

The findings of this study help us to understand what we can benefit from the increase of horizontal resolution in terms of simulating EC stratus clouds. It suggests that a finer model grid is helpful in reproducing more favorable ambient environments that lead to more stratus occurrences. However, the contribution is still limited, and the model shows systematic errors, requiring further improvement in the orography-induced environment fields. This requires eliminating the errors arising from the dynamical core and subgrid-scale parameterizations. A previous study suggested that horizontal and vertical
resolution ought to be chosen consistently (Roedeker et al. 2006). Although the horizontal resolution used in this study can reach approximately 50 km, the 30 vertical levels are coarse compared with the horizontal resolution. The impact of higher vertical resolution on the cloud simulation will be investigated in the future. The erroneous orographic effect that leads to a low AWP value center in HRs should also be explored.

Acknowledgments. The authors are grateful to the editor and reviewers for their constructive comments that helped largely improve the original manuscript and to Dr. Tony Jun Huang for helping polish the English. This research was supported by the Major National Basic Research Program of China (973 Program) on Global Change under Grant 2010CB951902; the National Natural Science Foundation of China under Grants 41221064, 41205078; the Basic Scientific Research and Operation Foundation of CAMS under Grant 2013Z004; and the China R&D Special Fund for Public Welfare Industry (meteorology, GYHY201306068). Computing resources were provided by National Super Computer Center in Tianjin as well as the National Meteorological Information Center. This paper constitutes a part of the first author’s doctoral dissertation. All data used in this study are available from the first author upon request (zhangyi@lasg.iap.ac.cn).

REFERENCES


