Large-Scale Variability in Marine Low Stratiform Cloud Amount and Its Relationship to Lower-Tropospheric Static Stability in Terms of Cloud Types(Digest_要約)

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1. Introduction

Low stratiform clouds (LSCs) strongly affect the Earth's climate by influencing the radiation budget because they are often horizontally extensive over the ocean and have large radiative cooling effects due to their relatively high albedos and cloud-top temperatures. These vertically thin clouds are formed and maintained by a subtle balance of various marine boundary layer (MBL) processes. Therefore, LSCs are particularly difficult to simulate in global climate models (GCMs) with coarse horizontal and vertical resolutions. In the past decade, it has been recognized that it is important to improve the reproducibility of the marine LSC amount in GCMs, since previous studies have shown that uncertainties in future temperature increases in global warming simulations can be mainly attributed to uncertainties in these cloud amount in a warming climate. Meanwhile, the climatological marine LSC amount is well correlated with the static stability in the lower troposphere resulting from various MBL processes; there is a strong linear relationship between the LSC amount and the estimated inversion strength (EIS), an empirical index based on the difference between the potential temperatures at the 700-hPa level and the surface, over the subtropical and midlatitude oceans. In this thesis, temporal and spatial variabilities in the relationship between the marine LSC amount and EIS are observationally demonstrated more in detail by decomposing LSCs into three types: stratocumulus (Sc), stratus (St), and sky-obscuring fog (FOG). Moreover, the relationships between the marine LSC amount and EIS simulated in state-of-the-art GCMs are evaluated in terms of the LSC types.

2. Seasonal variations over the global ocean

Using long-term ship-based observations, climatological seasonal relationships between the amounts of three LSC types and EIS are investigated over the global ocean. The relationships are clearly divided into two regimes at a sea surface temperature (SST) of approximately 16°C. The Sc amount is strongly correlated with EIS in the warm SST regime, whereas FOG amount significantly increases with EIS in the cold SST regime. The St amount increases with EIS in both regimes, with higher sensitivity in the cold SST regime. Because this suggests that the inferred inversion contributing to EIS exists at a different level for each SST regime, layered EISs are newly introduced to quantitatively capture its variability. An analysis using the layered EISs reveals that an increase in the inferred inversion strength between the 850- and 925-hPa levels corresponds to increases in the Sc amount and EIS in the warm SST regime, where cold advection generally occurs. In the cold SST regime, as EIS increases, relatively high values of inferred inversion strength between the 700- and 850-hPa levels change to a rapid increase in that between the 925-hPa level and the surface, which coincides with the transitions from Sc to FOG and from cold to warm advection.

3. Interannual variations over the summertime North Pacific

Interannual variability in the LSC amount and its relation to EIS, which have not been demonstrated yet, are investigated over the summertime North Pacific, where and when the ship-based observations are abundant and all the three LSC types are often observed. The interannual relationships between the LSC amount and EIS show the regional contrast: the correlations are stronger in the southeastern North Pacific (SE NP) and weaker in the northwestern North Pacific (NW NP), although variations in EIS are large in both regions. The LSC types and layered EISs make it possible to explain this contrast. Over the SE NP, variations in Sc amount are large and correlated with the inferred capping inversion strength. Over the NW NP, variations in FOG amount are large and correlated with the inferred surface-based inversion strength. The compensating variations between the Sc and FOG amounts result in an apparent small variation in the total LSC amount in this region. Variations in St amount are small over the whole North Pacific. Local SST anomalies are essential to the variation in the Sc amount over the SE NP, whereas basinwide sea level pressure (SLP) anomalies are essential to the variation in the FOG amount over the NW NP.

The possibilities of links between these variations and El Niño–Southern Oscillation (ENSO) are also discussed.

4. LSC Amount–EIS relationships over the subtropical oceans in GCMs

Following these observational facts, climatological linear relationships between the LSC amount and EIS simulated in 12 GCMs participating in the Coupled Model Intercomparison Project phase 5 (CMIP5) are examined. Over the subtropical oceans, where higher clouds are much less common and Sc is the only dominant LSC type, the relationships are robustly and quantitatively evaluated for the first time by directly comparing the LSC amounts derived from the International Satellite Cloud Climatology Project (ISCCP) observations with those from the ISCCP simulator implemented in each model. Although EISs are well-simulated in all the models, more than half of the models show weaker responses of the LSC amount to EIS (2%–3% K^{-1}) than the observations (~4.5% K^{-1}), and some models even show negative responses. Furthermore, layered EISs and layered cloud amounts from the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) simulator make it possible to diagnose the simulated LSC type. From this analysis, the models with poor representation of the subtropical marine LSC amount–EIS relationship show inversion levels lower than observed and fail to simulate the vertical structure of Sc. The results reveal practical implications for improving the treatments of MBL processes in these models.

5. Conclusions

The most important achievement of the research described in this thesis is that by dividing the total LSC amount–bulk EIS relationship into the relationships between the amounts of three LSC types (i.e., Sc, St, and FOG) and the inferred inversion strengths at the different vertical levels measured by layered EISs, meteorological factors related to the large-scale variations in LSCs have been observationally revealed for the first time, for both their seasonal climatologies and interannual variabilities. It is difficult to elucidate the physical association of the total LSC amount with meteorological factors; the variation in the total LSC amount is the superposition of those in each LSC-type amount closely linked with distinctly different meteorological fields. Furthermore, by directly comparing the LSC amounts derived from satellite observations and the corresponding satellite simulator outputs, the LSC amount–EIS relationships simulated in a dozen of state-of-the-art GCMs have been robustly and quantitatively evaluated for the first time. In addition, the problems for the treatments of MBL processes in these models have been revealed by diagnosing the simulated LSC type from the layered EISs. The layered EISs newly proposed in this thesis properly represent the height and strength of the temperature inversion in the lower troposphere. They are extremely useful in identifying the inferred inversion strength related to each LSC type not only for reanalysis data but for GCM simulations. Therefore, the research conducted in this thesis significantly advances the understanding of the mechanisms involved in the large-scale variability in the LSC amount and provides useful information for improving the reproducibility of the LSC amount in GCMs.