Coupled mode of cloud, atmospheric circulation, and sea ice controlled by wave-3 pattern in Antarctic winter

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Abstract
This study examines coupled relationships among clouds, atmospheric circulation, and sea ice in Antarctic winter. We find that the wave-3 pattern dominates the leading covariability mode among cloud, atmospheric circulation, and sea ice. Both horizontal transport and vertical motion contribute to cloud formation, resulting in maximum cloud anomalies spatially between maximum meridional wind and pressure anomalies in the coupled system. The radiative effect of the clouds related to the wave-3 pattern can generate sea ice anomalies up to 12 cm thick in one month in the Amundsen Sea. It also strengthens the sea ice anomalies that are directly induced by low-level atmospheric circulation anomalies. In addition, the radiative forcing of the leading cloud mode in the lower troposphere is suppressed by the dynamic and thermodynamic effects of the circulation anomalies. These discoveries provide a better understanding of Antarctica’s interactive processes, and also offer physical evidence for climate model validations.

1. Introduction
Antarctic sea ice extent (SIE) dropped to a record low in 2017 after a gradual increase over more than three decades (Parkinson 2019). There were also significantly larger fluctuations after 2011 than in earlier decades (Meehl et al 2019). The SIE’s counter-intuitive increase in the warming climate followed by its sudden reduction in recent years has been the subject of many studies. Moreover, CMIP5 models significantly overestimate the natural variability of Antarctic SIE after the long-term trends are removed (Zunz et al 2013), which is due to a lack of in-depth knowledge of this highly interactive climate system in the Antarctic. Sea ice is a highly active component in the polar climate system, contributing to the complexity of simulating the Earth’s system. The variation in SIE is associated with many processes in the ocean and atmosphere (Comiso 2001, Kwok et al 2013, Liu et al 2016, Long and Perrie 2017). Here, we focus on the covariability among clouds, atmospheric circulation, and sea ice in a coupled system.

Clouds play a critical role in the global climate system because they influence the radiation balance (Wang and Key 2005, Li et al 2011, Cox et al 2015, Tricht et al 2016). Clouds force sea ice in two ways: they promote sea ice growth by blocking shortwave radiation and cooling the surface; and they reduce sea ice growth by emitting longwave radiation and warming the surface (Wang and Key 2003, Graversen et al 2008, Lee 2011, Bennartz et al 2013, Lee et al 2017). In polar winter, interference from clouds with shortwave radiation is minimal, so their longwave radiation dominates the clouds’ influence on the surface. The unique Antarctic environment, with extremely low temperature, low moisture, and low aerosol concentration, makes cloud formation different from that in the other regions, including the Arctic (Bromwich et al 2012). Also, the low temperature and bright ice surface limit cloud detection by passive microwave techniques, resulting in a high noise level in satellite observations (Liu et al 2010). Moreover, current state-of-the-art climate models have tremendous inter-model discrepancies in cloud simulations, reflected
by their annual and seasonal means of total cloud fractions (Klein et al 2013, Vignesh et al 2020). The lack of knowledge of cloud processes in the extreme polar environment (Bromwich et al 2012, Scott and Lubin 2016, Scott et al 2017, Dong 2018) introduces errors in simulations of the atmosphere and sea ice interaction in climate models.

Clouds actively engage in the coupled polar climate system. A case study by Wang et al (2019b) suggested that the negative downward longwave radiative forcing (surface heat loss) from clouds alone in winter 2011 was capable of growing an additional 30 cm of sea ice in the Weddell Sea. That is a substantial impact given that winter Antarctic sea ice thickness (SIT) is only about 70–100 cm on average (Worby et al 2008, Zwally et al 2008, Kurtz and Markus 2012). In this study, we focus on the low-to-mid troposphere, and reveal a coupled mode in clouds, atmospheric circulation, and sea ice in Antarctic winter. We also address cloud formation processes associated with the coupled mode. We analyze reanalysis and satellite data during the austral winter (June, July, and August) when the shortwave radiation in the study area is at its annual minimum.

2. Data and methods

2.1. Data

By comparing with satellite observations, previous studies show that NASA’s Modern-Era Retrospective analysis for Research and Applications reanalysis-2 (MERRA-2, GMAO 2015) is capable of capturing anomaly patterns of cloud-fraction and cloud-radiation physics in polar regions (Hinkelman 2019, Wang et al 2019a, 2019b). The MERRA-2 reanalysis covers the period from 1980 to present at a resolution of 0.5° latitude by 0.625° longitude. The reanalysis uses the updated Goddard Earth Observing System Model (GEOS-5) and a new analysis scheme (Rienecker et al 2011, Molod et al 2015). The 40 years of cloud data from MERRA-2 have advantages over satellite observations since longer time series allow the multivariate empirical orthogonal functions (MEOFs) analysis to capture more reliable modes. Based on the observations at the Barrow and Eureka observation sites in the Arctic and space radar-lidar observations, Liu et al (2017) revealed that clouds are mainly distributed below 400 hPa. Therefore, we calculated cloud fractions at two levels: low-level cloud fraction (CSlow) occurring below 700 hPa, and mid-level cloud fraction (CMid) occurring between 700 and 400 hPa. In addition, we used the monthly surface downward longwave radiative fluxes (SLRFs) for all-sky conditions and cloud-free conditions from the MERRA-2 to calculate the cloud radiative forcing on the Earth’s surface.

To verify the reliability of MERRA-2 cloud modes, we also used multi-level cloud data from the Cloud-Aerosol Lidar and Infrared Pathfinder Observation (CALIPSO) active satellite observations (Winker et al 2003) for the period from 2006 to 2019, and the total cloud cover data from the International Satellite Cloud Climatology Project (ISCCP-H) for the period from 1983 to 2017.

The daily and monthly mean sea ice concentration (SIC), generated using a bootstrap algorithm, is obtained from the National Snow and Ice Data Center (Comiso 2017). The monthly sea-surface temperature (SST) from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) (Rayner et al 2003) are used to show the potential effect of the ocean on sea ice. The SIT is from the Global Ice-Ocean Modeling and Assimilation System (GIOMAS) Data, which is based on the parallel ocean model coupling with a 12-category thickness and enthalpy distribution (TED) ice model (Zhang and Rothrock 2003). The TED model simulates sea-ice ridging processes explicitly following Hibler (1980) and Thorndike et al (1975). The atmospheric variables consist of geopotential height (GPH), wind, and vertical pressure velocity at 850 and 500 hPa, and sensible and latent heat fluxes at the surface. These atmospheric variables are from the latest reanalysis of the European Center for Medium-Range Weather Forecasts, namely, ERA5 (Tetzner et al 2019, Dong et al 2020) with a grid of 0.25° × 0.25° and from the MERRA-2, to represent the low- and mid-level atmospheric circulations.

Since the results from the two datasets are consistent, we only show the results from the ER5 in this paper. Note that the daily data are only used in a lagged correlation and all other results are calculated from the monthly time series.

2.2. Methods

Monthly anomalies are calculated by removing the climatological at each variable’s grid point. Winter time series consist of monthly anomalies in June, July, and August of all years. For SIC, open water, land, and grids with SIC below 15% were masked and excluded from all calculations. All anomaly fields were area-weighted. Here, we use the MEOF analysis (see text S1 in the supporting information available online at stacks.iop.org/ERL/17/044053/mmedia) to identify covariability in the fields of cloud fraction, GPH, wind vector, and SIC. The maximum covariance analysis (MCA, Mo 2003) (see text S1) is also carried out to investigate the correlation between two variable fields. Lagged correlations are further used to assess causality among atmospheric circulation, cloud, and sea ice.

To confirm the relationship between cloud and SIC revealed by the MEOF, we first employ a linear correlation between total cloud and SIC anomaly time series generated by averaging both data sets in a 5° longitude bin and from the coast to the ice edge in latitude. A temporal significance test and a spatial significance test are then used to assess linear correlation results. The methods of temporal and
The Antarctic cloud forcing due to orography does not necessarily contribute to the coupled wave-3 pattern in the leading mode. When the Andes and Antarctic Peninsula obstruct the anomalous easterly wind, uplifted moisture forms more clouds on the mountain ridges’ west side. The lee-side sinking air leads to negative cloud anomalies over the Weddell Sea, which is discouraged by warm advection in the Weddell Sea, the western Ross Sea, and the eastern Indian Ocean. The red and blue arrows in figure 1 schematically illustrate these physical processes. Evidently, atmospheric circulation and sea ice anomalies are highly coupled by the wave-3 pattern, as suggested by early studies (Raphael 2004, Yuan and Li 2008, Renwick et al 2012).

The moisture transported poleward would condense into clouds when encountering the cold polar environment, as positive cloud anomalies appear over the Indian Ocean. On the other hand, negative cloud anomalies associated with the equatorward flow of cold and dry Antarctic air occur in the western Pacific. However, the cloud anomalies in the other regions of the Antarctic do not correspond well with the moisture transport process associated with the wave-3 pattern. Other processes must play a dominant role in the cloud distribution of the lower atmosphere. For example, the cloud formation due to orography does respond to the circulation change but does not necessarily contribute to the coupled wave-3 pattern in the leading mode. When the Andes and Antarctic Peninsula obstruct the anomalous easterly wind, uplifted moisture forms more clouds on the mountain ridges’ west side. The lee-side sinking air leads to negative cloud anomalies over the Weddell Sea, which may overcome the poleward moisture transport, as marked by the red arrow in figure 1(a). Other complex processes may also be involved in determining the low-atmosphere’s cloud distribution, which is not the focus of this study. Thus, the low-level atmospheric circulation anomalies likely drive the sea ice anomalies, suppressing the radiative effect of the leading C_{low} mode.
3.2. The coupled mode of mid-level clouds and atmospheric circulation

The MEOF analysis of $C_{\text{mid}}$, SIC, and 500 hPa atmospheric variables, including GPH, wind, and vertical velocity, shows that the wave-3 pattern dominates the anomalous circulation in the first mode (figure 2). It is worth noting that the $C_{\text{mid}}$ and SIC patterns are almost unchanged after reducing the circulation weight in the MEOF analysis by removing the wind vector from the MEOF (not shown). The consistent circulation patterns in figures 1 and 2 suggest the barotropic nature of the wave-3 mode in Antarctic winter. So, the SIC patterns associated with pressure anomalies at the low- and mid-levels are similar.

Unlike $C_{\text{low}}$, the $C_{\text{mid}}$ leading mode shows a more intuitive relationship with sea ice. The positive (negative) $C_{\text{mid}}$ anomalies correspond well to the negative (positive) SIC anomalies around the Antarctic (figures 2(a) and (d)). The positive cloud anomalies emit more longwave radiation to the surface, increase surface net radiation flux, and hinder sea ice growth, resulting in negative sea ice anomaly. The negative cloud anomalies decrease surface net radiation flux in winter, and lead to more heat loss from the surface, promoting the sea ice formation in the Amundsen Sea, western Pacific, and the Indian Ocean. Simple linear regression between $C_{\text{mid}}$ and SIC, which represents full anomalous fields instead of the leading MEOF mode, also shows the same result in these areas: more clouds correspond to less sea ice (figure S2).

In addition, the maximum cloud anomalies do not occur in the areas of maximum northerly wind anomalies, where moisture is transported into the polar region. Instead, cloud anomalies are shifted to the west by 5°–15° longitude relative to northerly maxima, especially in the area north of 65° S. This indicates other processes must be involved in addition to horizontal moisture transport. Furthermore, the maximum cloud anomalies also do not occur in the areas of low-pressure centers where the clouds can form due to convection. On average, cloud anomaly centers shift eastward by 15°–25° relative to the low-pressure centers.

To illustrate the relationships among clouds, anomalous vertical and horizontal air motions, we superimpose the results of circulation and clouds to form a 3D schematic circulation (figure 2(f)). It shows that maximum cloud anomalies are formed between the low-pressure centers and maximum northerly wind, as a result of both cloud formation mechanisms: uplifted air and horizontal moisture transport. Similarly, the minimum cloud anomalies occur between the high-pressure center and maximum southerly wind. We conclude that both horizontal transport and vertical motion induced cloud formation processes contribute to the wave-3 $C_{\text{mid}}$ distribution, resulting in maximum mid-level cloud anomalies between meridional wind and pressure anomalies. Vertical motion mainly represents a local moisture source for clouds, while horizontal transport represents a remote moisture source from middle latitudes. Thus, the discovery provides a better understanding of the winter cloud distribution and moisture source in the Antarctic.

3.3. Impacts of cloud radiative forcing related to wave-3 on sea ice

We calculate the surface radiation budget controlled by cloud to isolate its radiative effect on sea ice in the coupled mode. We decompose the SLRF and $C_{\text{mid}}$ by MCA to isolate the SLRF pattern associated with $C_{\text{mid}}$ anomalies. The result shows that the first SLRF mode (figure S3) has a similar spatial distribution as the first $C_{\text{mid}}$ mode (figure S3), with a high temporal correlation of 0.9. So, the SLRF mode is considered the signal of dominant variability from cloud related to wave-3. In other words, the cloud radiative forcing associated with the wave-3 pattern, best represented in the leading mode of $C_{\text{mid}}$, exists in the total cloud and is reflected in SLRF. Although the leading mode in figure 2 only accounts for 11%
Figure 2. The first MEOF mode of winter $C_{mid}$, SIC, and 500 hPa atmospheric circulation. (a) Spatial pattern of $C_{mid}$; (b) 500 hPa GPH and wind vector; (c) meridional wind; (d) SIC; (e) vertical pressure velocity. This mode accounts for 11% of the total variance. (f) A schematic circulation that combines the processes in (a)–(c), and (e) to illustrate the cloud formation. Meridional wind (shading) is superimposed by the vector wind. Blue (red) shading represents southward (northward) wind. The blue (red) circle represents the center of negative (positive) pressure anomaly and is marked with L (H). The blue (red) dashed line indicates upward (downward) air motion associated with convergence (divergence). Columnar shadows represent the centers of maximum cloud anomalies and are marked with ‘less cloud’ and ‘more cloud’, respectively.
of the total covariability in the coupled system, the SLRF related to wave-3 cloud pattern can account for 20%–30% of radiation variance in some key regions such as the Ross Sea and Bellingshausen Sea (figure S3(c)). We combine the eigenvector of the first SLRF mode and its principal component to reconstruct the associated cloud forcing anomalies for the period of 1980–2019. To highlight the potential influence of the SLRF mode on sea ice, we choose a strong sea ice anomaly case in August 2018 to show the contribution of cloud radiative forcing related to wave-3 pattern. Figure 3(a) shows that the cloud forcing anomaly is approximately $-15$ W m$^{-2}$ over the Amundsen Sea, $12$ W m$^{-2}$ over the northern Ross Sea, and $9$ W m$^{-2}$ over the northern Weddell Sea. Overall, the magnitude of cloud forcing corresponding to the wave-3 pattern is approximately 25% of that of turbulent heat flux, which is mainly related to surface air
temperature and wind and represents the thermodynamic forcing of the low-level atmospheric circulation (figures 3(a) and (d)).

Negative anomalies of surface cloud forcing (the ocean losing heat) favor sea ice growth. Here, we use equation (2) to estimate the change in SIT due to cloud radiative flux associated with the wave-3 pattern. The results show that the cloud radiative effect could generate sizable SIT anomalies in the Weddell Sea (−10 cm), in the Amundsen Sea (12 cm), and the northern Ross Sea (−12 cm). This radiative effect is relatively weak in the other areas but still creates 3–6 cm sea ice anomalies. The magnitude of sea ice growth resulting from cloud forcing is approximately 20% of that of SIT total anomaly (figures 3(b) and (e)). Furthermore, we calculated SIT anomalies due to the cloud forcing within the black box in the Amundsen Sea (shown in figure 3(c)) using the entire time series. The areal mean of SIT anomalies shows that the wave-3 associated cloud anomalies produce −12 to 12 cm of SIT anomalies in the winter months.

The above results suggest that the winter cloud controlled by the wave-3 pattern has an indispensable radiative influence on SIC. The radiative effect would reinforce the sea ice variability forced by low-level atmospheric circulation since the sea ice growth is in accordance with the sea ice pattern in the coupled mode shown in figures 1(c) and 2(d).

3.4. Discussion

Although cloud in the coupled mode has a substantial influence on SIC, distinctions between the sea ice growth pattern controlled by cloud forcing and leading SIC pattern also exist in some areas, such as in the eastern Atlantic (0°–45°E) (figures 2(d) and 3(b)). The correlation between total $C_{\text{mid}}$ and SIC anomalies is also not significant. A possible explanation is that the sea ice variability might be dominated by other factors, especially by interactions with the ocean in these regions. These sea ice variability drivers include SST (Kusahara et al., 2017, Blanchard-Wrigglesworth et al., 2021, Zhang et al. 2021) and polynyas (Tamura et al., 2008, 2016). Figure S4 shows that SIC and SST are well correlated in the eastern Atlantic ($r = −0.81$) and SIC lags SST by about half a day. Statistically, this means SST can account for more than 66% of the total SIC variance in the area, playing a critical role in SIC variability. Besides, large amounts of sea ice are produced at Mertz Glacier Polynya (172 km$^2$ a$^{-1}$) (Tamura et al., 2016), which is also an indispensable factor in sea ice variability. Despite the above-mentioned processes, the clouds’ radiative forcing on sea ice stands out significantly in the ADP regions and the Ross Sea. Moreover, sea ice anomalies could feed back positively to cloud anomalies through modifying evaporation, which needs to be addressed in future studies.

We also conducted an MCA between $C_{\text{mid}}$ and SIC, 850 hPa GPH and SIC, and 500 hPa GPH and $C_{\text{mid}}$ to show the direct connections between these paired fields. The results show that the spatial patterns of the leading MCA mode are similar to those of MEOF (figures 2 and S5). For example, the positive (negative) $C_{\text{mid}}$ anomalies correspond well to the negative (positive) SIC anomalies around the Antarctic (figures S5(a) and (d)). This mode can account for 24% of the total squared covariance between SIC and $C_{\text{mid}}$. Heterogeneous correlations between the $C_{\text{mid}}$ time series of the first MCA mode and total SIC anomalies range −0.3 to −0.5 in the Amundsen Sea, eastern Weddell Gyre, and western Pacific. Thus these analyses support MEOF results and suggest that the method used here is reliable.

For the cloud data used in this paper, we admit that the MERRA-2 cloud has its own limitations. Previous studies showed that the MERRA-2 under-estimates near-surface clouds (Rozenhaimer et al., 2018) and its mean bias is −2.73% over the Arctic compared with NASA CERES-MODIS (Huang et al., 2017). To verify whether the cloud pattern in the coupled mode derived from the MERRA-2 data (figure 2(a)) represents a real pattern in observations, we use the MCA to analyze the similarities between the clouds from MERRA-2 and satellite observations from CALIPSO (figure S6). The results show that the wave-3 pattern appears in the leading modes of both cloud products, although the anomalies are weaker in CALIPSO compared to MERRA-2. The leading patterns of $C_{\text{low}}$, $C_{\text{mid}}$, and $C_{\text{high}}$ from MCA between two cloud datasets accounted for 24%, 19%, and 32% of the total squared covariance respectively, and the associated time series were correlated at 0.84, 0.94, and 0.97 respectively. $C_{\text{high}}$ shows the highest consistency between the two data sets. $C_{\text{high}}$ here is just for the verification of the MERRA-2 cloud because the high-level clouds are thin and have a limited impact on sea ice (Liu et al., 2017). It indicates that the leading cloud modes calculated from MERRA-2 at different levels are the real patterns in satellite observations.

We also use the total cloud fraction of satellite data ISCCP to extract the cloud fraction modes coupled with 500 hPa meridional wind using the MEOF analysis. The result shows that the MERRA-2 $C_{\text{mid}}$ anomaly pattern (figure 2(a)) mostly resembles the ISCCP second mode of the MEOF (figure S7), although there are some regional differences. Considering significant differences in cloud data sets from different sources (Bromwich et al., 2012), the consistent cloud patterns between MERRA-2 and two satellite data sets suggest that the wave-3 pattern in $C_{\text{mid}}$ is a predominant mode in the total cloud and $C_{\text{mid}}$ and the MERRA-2 is capable of capturing it.

To examine possible causality relationships among investigated parameters, daily SIC anomalies, $C_{\text{mid}}$ anomalies, and the PC of the first 850 hPa GPH EOF mode are used in the lagged correlation. The PC represents the low-level atmospheric circulation variability associated with the wave-3 pattern. Although
Figure 4. Correlations as a function of lead and lag days between daily SIC total anomalies and the principal component (PC) of the first 850 hPa GPH EOF mode (black), SIC and $C_{\text{mid}}$ total anomalies (red), and $C_{\text{mid}}$ and the PC of the first 850 hPa GPH EOF mode (green). The circles represent confidence levels above 95%. Negative lags represent the first variable of each pair marked in figure lagging. Here we consider the time series of the first 850 hPa GPH EOF mode as the low-level atmospheric circulation daily variabilities that are associated with the wave-3 pattern.

the circulation and cloud anomalies occur simultaneously, the circulation leads SIC by 3 d while the cloud leads SIC by only 1 d, suggested by the maximum correlations (figure 4). It suggests that circulation and clouds drove sea ice anomalies independently, and cloud radiative forcing related to wave-3 has its contributions to SIC variabilities.

4. Summary and conclusions

We found a well-defined coupled mode associated with the wave-3 pattern in winter Antarctic atmospheric circulation, cloud, and sea ice. In the coupled mode, both horizontal and vertical moisture transports contribute to the cloud’s wave-3 distribution at the troposphere mid-level, indicating that the moisture sources of cloud come from both local and remote regions. The sea ice variability in winter is driven by both low-level atmospheric circulation and cloud radiative forcing related to the wave-3 pattern. The atmospheric circulation controls $C_{\text{mid}}$ distribution. In turn, cloud radiative forcing further strengthens the sea ice anomalies generated by the low-level atmospheric circulation. However, the leading $C_{\text{low}}$ mode dominated by orography effects and atmospheric circulation anomalies does not match the wave-3 pattern, of which the radiative forcing on sea ice is suppressed by the direct dynamic and thermodynamic forcing of the circulation.

The cloud radiative forcing associated with the wave-3 pattern, best represented in the leading mode of $C_{\text{mid}}$, exists in the total cloud and is reflected in SLRF. Despite the fact that the leading MEOF mode only accounts for 11% of the total variance in the coupled system of mid-level circulation, cloud, and sea ice, the total cloud radiative forcing related to the wave-3 pattern can account for 20%–30% of radiation variance in some key regions such as the Ross Sea and Bellingshausen Sea. This cloud radiative forcing can contribute $-15 \, \text{W m}^{-2}$ to the surface radiation budget in the Amundsen Sea, $12 \, \text{W m}^{-2}$ in the northern Ross Sea, and $9 \, \text{W m}^{-2}$ in the northern Weddell Sea in August 2018, producing up to $-12$, $12$, and $10 \, \text{cm SIT}$ anomalies, respectively, in these regions, which accounts for approximately 20% of the SIT total anomaly. This study suggests that the cloud radiative effect on sea ice is not an isolated event as presented in the case study by Wang et al. (2019b), but plays a nonnegligible role in sea ice variability consistently.

In addition to the wave-3 pattern, SIC variability can be attributed to other climate modes, such as SAM, ENSO, and ASL, and many factors, such as ocean temperature, ocean currents, ice drift, and polynyas. Here, we only focused on the coupled mode associated with the wave-3 pattern, which yields a better understanding of clouds’ roles in the Antarctic climate system and provides evidence for climate
model validation. The study also reveals the importance of understanding cloud processes in the polar environment for improving Earth system models in the future.

**Data availability statement**

No new data were created or analyzed in this study.

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**References**

Bennartz R, Shupe M D, Turner D D, Walden V P, Steffen K, Cox C J, Kulie M S, Miller N B and Petterssen C 2013 July 2012 Greenland melt extent enhanced by low-level liquid clouds Nature 496 83–86

Blanchard-Wrigglesworth E, Roach I A, Donohoe A and Ding Q 2021 Impact of winds and Southern Ocean SSTs on Antarctic sea ice trends and variability J. Clim. 34 1–47

Bromwich D H, Nicolas J P, Hines K M, Kay J E, Key E L, Lazzara M A, Lubin D, McFarquhar G M, Gorodetskaya I V and Grovesen D P 2012 Tropospheric clouds in Antarctica Rev. Geophys. 50 RG1004

Clem K R, Renwick J A and McGregor J 2017 Large-scale forcing of the Amundsen Sea low and its influence on sea ice and West Antarctic temperature J. Clim. 30 8403–24

Comiso J C 2001 Correlation and trend studies of the sea-ice cover and surface temperatures in the Arctic Ann. Glaciol. 34 420–8

Comiso J C 2017 Bootstrap sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, version 3 ( Boulder, CO: NASA National Snow and Ice Data Center Distributed Active Archive Center)

Cox C J, Walden V P, Rowe P M and Shupe M D 2015 Humidity trends imply increased sensitivity to clouds in a warming Arctic Nat. Commun. 6 10117

Dong X 2018 Preface to the special issue: aerosols, clouds, radiation, precipitation, and their interactions AdAtS 35 133–4

Dong X, Wang Y, Hou S, Ding M, Yin B and Zhang Y 2020 Robustness of the recent global atmospheric reanalyses for Antarctic near-surface wind speed climatology J. Clim. 33 4027–43

Eayrs C, Li X, Raphael M N and Holland D M 2021 Rapid decline in Antarctic sea ice in recent years hints at future change Nat. Geosci. 14 460–4

Eisenman I 2012 Factors controlling the bifurcation structure of sea ice retreat J. Geophys. Res. Atmos. 117 D01111

England M R, Polvani L M, Smith K L, Landrum L and Holland M M 2016 Robust response of the Amundsen Sea low to stratospheric ozone depletion Geophys. Res. Lett. 43 8207–13

Graversen R G, Mauritsen T, Tjernström M, Källén E and Svensson G 2008 Vertical structure of recent Arctic warming Nature 451 53

Hibler W D 1980 Modeling a variable thickness sea ice cover MWRV 108 1943–73

Hinkelmann L M 2019 The global radiative energy budget in MERRA and MERRA-2: evaluation with respect to CERES EBAF data J. Clim. 32 1973–94

Hobbs W R, Massom R, Stammerjohn S, Reid P, Williams G and Meier W 2016 A review of recent changes in Southern Ocean sea ice, their drivers and forcings Glob. Planet. Change 143 228–50

Huang Y, Dong X, Xi B, Dolinar E K, Stanfield R E and Qiu S 2017 Quantifying the uncertainties of reanalyzed Arctic cloud and radiation properties using satellite surface observations J. Clim. 30 8007–29

Klein S A, Zhang Y, Zelinka M D, Pincus R, Boyle J and Gleckler P J 2013 Are climate model simulations of clouds improving? An evaluation using the ISCCP simulator J. Geophys. Res. Atmos. 118 1329–42

Kurtz N and Markus T 2012 Satellite observations of Antarctic sea ice thickness and volume J. Geophys. Res. Oceans 117 C08025

Kusahara K, Williams G D, Massom R, Reid P and Hasumi H 2017 Roles of wind stress and thermodynamic forcing in recent trends in Antarctic sea ice and Southern Ocean SST: an ocean-sea ice model study Glob. Planet. Change 158 103–18

Kwok R, Spreen G and Pang S 2013 Arctic sea ice circulation and drift speed: decadal trends and ocean currents J. Geophys. Res. Oceans 118 2408–25

Lee S-S 2011 Atmospheric science: aerosols, clouds and climate Nat. Geosci. 4 826

Lee S, Gong T, Feldstein S B, Screen J A and Simmons I 2017 Revisiting the cause of the 1989–2009 Arctic surface warming using the surface energy budget: downward infrared radiation dominates the surface fluxes Geophys. Res. Lett. 44 10654–61

Li X et al 2021 Tropical teleconnection impacts on Antarctic climate changes Nat. Rev. Earth Environ. 2 680–98

Li Z, Niu F, Fan J, Liu Y, Rosenfeld D and Ding Y 2011 Long-term impacts of aerosols on the vertical development of clouds and precipitation Nat. Geosci. 4 888

Liu N, Lin L, Wang Y, Kong B, Zhang Z and Chen H 2016 Arctic autumn sea ice decline and Asian winter temperature anomaly Acta Oceanol. Sin. 35 36–41

Liu Y H, Ackerman S A, Maddux B C, Key J R and Frey R A 2010 Errors in cloud detection over the Arctic using a satellite imager and implications for observing feedback mechanisms J. Clim. 23 1899–907

Liu Y, Shupe M D, Wang Z and Maze G 2017 Cloud vertical distribution from combined surface and space radar–lidar observations at two Arctic atmospheric observatories Atmos. Chem. Phys. 17 5973–89

Long Z and Perrie W 2017 Changes in ocean temperature in the Barents Sea in the 21st century J. Clim. 30 5901–21

Meehl G A, Arbaster J M, Chung C T, Holland M M, DuVivier A, Thompson L, Yang D and Bitz C M 2019 Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016 Nat. Commun. 10 14

Mo R P 2003 Efficient algorithms for maximum covariance analysis of datasets with many variables and fewer realizations: a revisit JATOT 20 1804–9

Molod A, Takacs L, Suarez M and Bamberjeet J 2015 Development of the GEOS-5 atmospheric general circulation model:
evolution from MERRA to MERRA2 Geosci. Model Dev. 8 1339–56
Parkinson C L 2019 From the covering article: a 40-year record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic Proc. Natl. Acad. Sci. USA 116 14414–23
Raphael M N 2004 A zonal wave 3 index for the Southern Hemisphere Geophys. Res. Lett. 31 L23212
Raphael M N, Marshall G J, Turner J, Fogt R L, Schneider D, Dixon D A, Hosking J S, Jones J M and Hobbs W R 2016 The Amundsen Sea low: variability, change, and impact on Antarctic climate Bull. Am. Meteorol. Soc. 97 197–210
Rayner N A, Parker D E, Horton E B, Folland C K, Alexander L V, Rowell D P, Kent E C and Kaplan A 2003 Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J. Geophys. Res. Atmos. 108 1063–82
Renwick J A, Kohout A and Dean S 2012 Atmospheric forcing of Antarctic sea ice on intraseasonal time scales J. Clim. 25 5962–75
Rienecker M M, Suarez M J, Gelaro R, Todling R, Bacmeister J, Liu E, Bosilovich M G, Schubert S D, Takacs L and Kim G-K 2011 MERRA: NASA’s modern-era retrospective analysis for research and applications J. Clim. 24 3624–48
Rozenhaimer M S et al 2018 Bias and sensitivity of boundary layer clouds and surface radiative fluxes in MERRA-2 and airborne observations over the Beaufort Sea during the ARISE campaign J. Geophys. Res. Atmos. 123 6565–80
Scott R C and Lubin D 2016 Unique manifestations of mixed-phase cloud microphysics over Ross Island and the Ross Ice Shelf, Antarticca Geophys. Res. Lett. 43 2936–45
Scott R C, Lubin D, Vogelmann A M and Kato S 2017 West Antarctic ice sheet cloud cover and surface radiation budget from NASA A-train satellites J. Clim. 30 6151–70
Tamura T, Ohshima K I, Fraser D A and Williams G D 2016 Sea ice production variability in Antarctic coastal polynyas J. Geophys. Res. Oceans 121 2967–79
Tamura T, Ohshima K I and Nihashi S 2008 Mapping of sea ice and Niboshi S 2008 Mapping of sea ice production for Antarctic coastal polynyas Geophys. Res. Lett. 35 284–98
Tetzner D, Thomas E and Allen C 2019 A validation of ERA5 reanalysis data in the Southern Antarctic Peninsula—Ellsworth Land region, and its implications for ice core studies Geosciences 9 289
Thompson D W and Wallace J M 2000 Annual modes in the extratropical circulation. Part I: month-to-month variability J. Clim. 13 1000–16
Thorndike A S 1992 A toy model linking atmospheric thermal radiation and sea ice growth J. Geophys. Res. Oceans 97 9401–10
Thorndike A S, Rothrock D A, Maykut G A and Colony R 1975 Thickness distribution of sea ice J. Geophys. Res. 80 4501–13
Tricht K V, Lhermitte S, Lenaerts J T M, Gorodetskaya I V, L’Ecuyer T S, Noël B, Broeke M R V D, Turner D D and Lipzig N P M V 2016 Clouds enhance Greenland ice sheet meltwater runoff Nat. Commun. 7 10266
Vignesh P P, Jang J H, Pangaluru K, Su H, Smay T, Brighton N and Velicogna I 2020 Assessment of CMIP6 cloud fraction and comparison with satellite observations Earth Space Sci. 7 e2019EA000975
Wang W, Zender C S, van As D and Miller N B 2019a Spatial distribution of melt season cloud radiative effects over Greenland: evaluating satellite observations, reanalyses, and model simulations against in situ measurements J. Geophys. Res. Atmos. 124 57–71
Wang X and Key J R 2003 Recent trends in Arctic surface, cloud, and radiation properties from space Science 299 1725–8
Wang X and Key J R 2005 Arctic surface, cloud, and radiation properties based on the AVHRR polar pathfinder dataset. Part i: spatial and temporal characteristics J. Clim. 18 2558–74
Wang Y, Yuan X, Bi H, Liang Y, Huang H, Zhang Z and Liu Y 2019b The contributions of winter cloud anomalies in 2011 to the summer sea-ice rebound in 2012 in the Antarctic J. Geophys. Res. 124 3435–47
Winker D M, Pelon J and McCormick M P 2003 The CALIPSO mission: spaceborne lidar for observation of aerosols and clouds Proc. SPIE 4903 1211–29
Worby A P, Geiger C A, Paget M J, van Woert M L, Ackley S F and DeLiberty T L 2008 Thickness distribution of Antarctic sea ice J. Geophys. Res. Oceans 113 C05S92
Yuan X 2004 ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms Antarct. Sci. 16 415–25
Yuan X, Kaplan M R and Cane M A 2018 The interconnected global climate system–a review of tropical–polar teleconnections J. Clim. 31 5765–92
Yuan X and Li C 2008 Climate modes in southern high latitudes and their impacts on Antarctic sea ice J. Geophys. Res. Oceans 113 C06S91
Yuan X and Martinson D G 2000 Antarctic sea ice extent variability and its global connectivity J. Climate 13 1697–717
Zhang J I and Rothrock D A 2003 Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates MWR 131 845–61
Zhang X, Deser C and Sun L 2021 Is there a tropical response to recent observed Southern Ocean cooling? Geophys. Res. Lett. 48 e2020GL091235
Zunan V, Goosse H and Massonnet F 2013 How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? Cryosphere 7 451–68
Zwally H J, Yi D, Kwok R and Zhao Y 2008 ICESat measurements of sea ice freeboard and estimates of sea ice thickness in the Weddell Sea J. Geophys. Res. Oceans 113 C02S15