Satellite microwave measurements in the arctic and antarctic

Abstract

Satellite microwave measurements can penetrate through clouds and therefore provide unique information of surface and near-surface temperatures and surface emissivity. In this study, the brightness temperatures from NOAA-15 Advanced Microwave Sounding Unit (AMSU-A) are used to analyze the surface temperature variation in the Arctic and Antarctic regions during the past 13 years of period from 1998 to 2010. The data from four AMSU-A channels sensitive to surface are analyzed with wavelet and Fourier spectrum techniques. A very pronounced maximum is noticed in the period range centered around four months. Application of a statistical significance test confirms that it is a dominant mode of variability over polar regions besides the annual and semi-annual oscillations. No evidence of this feature could be found in middle and low latitudes. The four-month oscillation is 90o out of phase at Arctic and Antarctic, with the Arctic four-month oscillation reaching its maximum in the beginning of March, July and November and the Antarctic four-month oscillation in the middle of April, August and December. The intensity of the four-month oscillation varies inter-annually. The years with pronounced four-month oscillation were 2002-2003, 2005-2006 and 2008-2009. The strongest year for the Arctic and Antarctic four-month oscillations occurred in 2005-2006 and 2008-2009, respectively. The sign of four-month oscillation is also found in the surface-skin temperatures and two-meter air temperatures from ERA-Interim reanalysis. It is hypothesized that the Arctic and Antarctic four-month oscillations are a combined result of unique features of solar radiative forcing andsnow/sea ice formation andmetamorphosis.

Introduction

The spectrum analysis of wind time series revealed a 40-50 day Madden and Julian oscillation (MJO) in the zonal wind in the tropical Pacific (Madden and Julian 1971). In the course of an investigation of Advanced Microwave Sounding Unit-A (AMSU-A) for globalclimate changeandglobal warming, we stumbled upon an apparent four-month oscillation in the surface-sensitive channels in the Arctic and Antarctic. It is not a " periodicity" in the sense of tidally induced oscillation, but certainly a broadband phenomenon. It passes a statistical significance test with more than 95% confidence. A spectral analysis of both surface skin temperature and two meter air temperature from ERA-Interim reanalysis also confirms the existence of a four-month oscillation in the Arctic and Antarctic. It is our understanding that the AMSU-A observations can be strongly influenced by variable surface emissivity in polarenvironmentand have not been effectively utilized through the ERA data assimilation. Thus, the confirmation of a four-month oscillation signal from ERA-Interim reanalysis is significant and believed to be mostly associated with the physical process.

Satellite Brightness Temperature Data

NOAA-15 AMSU-A has 15 channels and is a cross-track scanning radiometer, providing 30 field of views (FOVs) along each scan line. Near the nadir of satellite observations, the FOV size is at best of 48 km. There are a total of four AMSU-A surface-sensitive channels: channel 1 (23. 8 GHz), channel 2 (31. 4 GHz), channel 3 (50. 3) and channel 15 (89 GHz) (Mo 1999; Goodrum et al. 2009). Over land where the surface emissivity is high, the measurements from these surface-sensitive channels are primarily affected by surface emissivity and surface temperature. Over oceans where the emissivity is relatively low, the channels are also a function of temperature, water vapor and liquid water in the lower troposphere. Channels 1, 2 and 15 are located at frequencies away from the major oxygen gaseous absorption lines and can thus see through the atmosphere. The radiation at these channels mainly comes from the earth's surface, which is proportional to the product of surface emissivity and surface temperature. For a cloudy atmosphere, a portion of surface emission at these channels can be attenuated by cloud and the rest transmitted through the cloud. The cloud also emits additional radiation. Channel 3 is near an oxygen absorption line and contains the upwelling microwave radiation from both the earth's surface and the near surface atmosphere.

Satellite measurements and their retrieval products were used for studying climate variability and decadal trends (Christy et al. 1998, 2000, 2003; Izaguirre et al. 2010; Johannessen et al. 1995, 1999; Mears et al. 2003, Mears and Wentz 2009; Schneider et al. 2004; Vinnikov and Grody 2003; Zou et al. 2009). In these study, the AMSU-A brightness temperatures onboard NOAA-15 from October 26, 1998 to August 7, 2010 are analyzed for various applications including climate trend and global change.

ERA-Interim Reanalysis Data

The ERA-Interim reanalysis is produced by European Center for Medium-Range Forecast (ECMWF) (Simmons et al. 2007). By employing an advanced four-dimensional variational data assimilation (4D-Var) approach with improved data quality control, satellite bias correction, and fast radiative transfer model, conventional surface and upper air observations and satellite brightness temperatures and cloud motion winds from Television InfraRed Observational Satellite (TIROS) Operational Vertical Sounder (TOVS), Special Sensor Microwave/Imager (SSM/I), ESA Remote-Sensing Satellites (ERS-1 and ERS-2), and Advanced TOVS (ATOVS) are optimally combined with model forecasts in ERA-Interim reanalysis. The ERA-Interim reanalysis products are thus suitable for use in studies of climate variability and decadal trends (Agudelo and Curry 2004; Chelliah et al. 2004; Frauenfeld et al. 2005).

The ERA-Interim analyses consist of a high quality set of global analyses of the state of the atmosphere, land, and ocean-wave conditions from 1989 to present time. The surface-skin temperatures and two-meter air temperatures from ERA-Interim are used in this study. These data has 1. 5° resolution and 37 pressure levels and is publicly available on the ECMWF Data Server.

Arctic Four-Month Oscillation

A wavelet analysis is applied to global daily mean, nadir only, surface-sensitive brightness temperatures observed by the NOAA-15 AMSU-A over the time period from October 26, 1998 to August 7, 2010, as well as daily mean surface skin and surface air (two-meter) temperatures from ERA-Interim reanalysis. Specifically, the brightness temperature measurements at the surface-sensitive channel 1 (, 23. 8 GHz), channel 2 (, 31. 4 GHz), channel 3 (, 50. 3 GHz) and channel 15 (, 89 GHz) near the nadir direction (FOVs 15 and 16), at both descending and ascending nodes, and north of 75oN and south of 70oS are averaged to provide eight daily time series from October 26, 1998 to August 7, 2010. Surface skin temperatures () and two-meter surface air temperature () from ERA-Interim north of 75oN and south of 70oS are also averaged to provide four more time series in the same time period. Using the Morlet wavelet analysis with statistical significant testing, each time series is decomposed into time-frequency space, from which the dominant modes of variability and their temporal evolution can be determined with great confidence (Torrence and Compo 1998). The wavelet transform is chosen for this study as it can be used to analyze time series that contain non-stationary power at many different frequencies.

Figure 1 shows the wavelet power spectrum (shaded) of daily mean nadir only brightness temperatures from NOAA-15 AMSU-A surface-sensitive channel two in the Arctic and Antarctic, and the surface skin and 2-m air temperature of ERA-Interim from October 26, 1998 to August 13, 2010. To show the significance of a peak in the wavelet power spectra, regions of greater than 95% confidence is indicated (line). For period less than semi-annual oscillation, most of the power is concentrated around the four-month period within the 95% confidence level. The existence of the four-month oscillation is also confirmed using the Fourier spectrum analysis technique and is shown in Fig. 2. However, with wavelet analysis, one can see variations in the frequency occurrence and amplitude of the Arctic/Antarctic four-month oscillations shown in Fig. 1. Large amplitude four-month oscillation events occurred at a period about 3 years. The strongest years were 2002-2003, 2005-2006 and 2008-2009. Similar wavelet power spectra are seen in other AMSU-A surface-sensitive channels in the Northern Hemisphere and AMSU-A channel 1 in the Southern Hemisphere (Figure omitted). Due to the fact the Antarctic is covered mostly by land, the Antarctic four-month oscillation is very weak in channels 15 and 3.

A four-month oscillation is also found in daily mean surface skin temperatures and surface air temperatures from ERA-Interim reanalysis in the Arctic (Fig. 1c-d), but not in the Antarctic (figure omitted). The reduced power of surface and near-surface temperatures (Fig. 1c-d) compared to satellite observations (Fig. 1a-b) is possibly due to the fact that most of surface channels observations are excluded from data assimilation in high latitudes owing to large impacts of surface emissivity uncertainty on radiance simulations. From Fig. 1, it is seen that the ERA-Interim captures the four-month surface oscillation better during 2005-2006 and 2008-2009 than earlier years.

Figure 3 presents the temporal evolution of Arctic (75oN-90oN) and Antarctic (70oS-90oS) daily mean brightness temperatures in 2005 (black line), in which mean values, annual and semi-annual components are removed, as well as the corresponding four-month oscillation (red curve). The four-month oscillation of AMSU-A channel 2 has the largest amplitude at the beginning of March, July and November. No significant phase difference is found between this and other three surface sensitive channels (Figures omitted). The Antarctic four-month oscillation is 90o out of phase with the Arctic oscillation. It peaks in the middle of April, August and December.

A weak four-month oscillation is also found in the daily mean surface-skin temperatures and two-meter air temperatures from ERA-Interim reanalysis. However, a significant phase difference is found between the AMSU-A surface-sensitive channels and the ERA-Interim surface skin temperature and surface air temperatures. The four-month oscillation of both surface skin temperature and surface air temperatures peaks in late June, about one and half months earlier than satellite observations. Given the fact that the brightness temperatures at the four surface-sensitive channels approximately equal to the product of surface emissivity and surface skin temperature, with a small contribution from the atmosphere in a shallow layer above the Earth's surface, the phase differences between the ERA-Interim surface variables and AMSU-A surface channel brightness temperatures suggest that the brightness temperature change is delayed by surface emissivity change. It is worth mentioning that the four-month oscillation is not found in the brightness temperature measurements of the other 11 AMSU-A channels, which approximately represent the air temperature in a broad layer centered in the troposphere or stratosphere.

Figure 4 provides the percentage of explained variances by annual (black), semi-annual (red) and four-month (yellow) oscillations in middle and high latitudes for NOAA-15 AMSU-A channel 2. It is seen that the annual variation increases toward high latitudes from 20oN to 70oN or from 20oS to 70oS. The annual oscillation becomes a dominant feature with 50oN-70oN and 50oS-70oS. The sum of annual and semi-annual oscillations explains more than 80% of the total variances within the latitudinal band 60oN-70oN or 60oS-70oS, which reduces to below 60% in higher latitudes 70oN-90oN and 70oS-80oS. The four-month oscillation explains about 10% of the total variance in the Arctic and Antarctic.

Figure 5 presents the annual cycles of Arctic four-month oscillation in three selected years (1999, 2003 and 2009) from all the six time series (, , , , , and). The four-month oscillations of all four surface-sensitive channels have the largest amplitude at the beginning of March, July and November. No significant phase difference is found among these four channels. However, a significant phase difference is found between the AMSU-A surface-sensitive channels and the ERA-Interim surface skin temperature and surface air temperatures. The four-month oscillation of both surface skin temperature and surface air temperatures peaks in late June, about one and half months earlier than satellite observations. Given the fact that the brightness temperatures at the four surface-sensitive channels is a sum of the surface term (approximately equals to surface emissivity times surface skin temperature) and the atmosphere term (about equal to the air temperature in a shallow layer (~1 km) above the Earth’s surface), the phase differences between the ERA-Interim surface variables and AMSU-A surface channel brightness temperatures suggest that the four-month oscillation started from the surface. In fact, the four-month oscillation is not found in the brightness temperature measurements of the other 11 AMSU-A channels, which approximately represent the air temperature in a broad layer centered in the troposphere or stratosphere.

Wave structures with periods between 60 days and 150 days are shown in Fig. 6 based on the daily mean brightness temperatures in 75oN-90oN latitudes at nadir of NOAA-15 AMSU-A channel one, two, three, fifteen, skin and 2-m surface air temperature of ERA-Interim from January 1, 2004 to January 1, 2007. The four-month oscillation is a dominant feature in all years. A weak 90-day oscillation is also found in satellite measurements. The intensity of the Arctic four-month oscillation varies inter-annually.

Discussions of the oscillation

A four-month oscillation is found in the satellite microwave measurements in the Arctic and Antarctic for the first time. The ERA-Interim reanalysis data confirms the existence of such an oscillation. Such oscillation is not found in other regions over the globe and nor in other AMSU-A atmospheric sounding channels.

The surface temperature in polar regions is determined by surface heat budget equation, which relates changes in surface upward long-wave radiations to changes in (i) the surface downward short-wave radiation, (ii) surface downward long-wave radiations, (iii) heat storage for both land surface and ocean, (iv) surface sensible heat flux, and (v) surface latent heat flux. The presence of polar day/night is a unique feature that makes the annual variation of solar radiative forcing within the frigid zone[1] substantially different from middle and low latitudes. Since solar radiation is a major source of energy for the snow/ice melting in polar regions, the unique annual variation of solar radiation can modulate microwave surface emissivity and thermodynamic and dynamic processes near the surface boundary. The responses of surface-sensitive brightness temperature to solar radiation can also be delayed due to the time for the snow and ice metamorphosis process to occur. The combined effect of polar day and night during the year and snow/ice metamorphosis process probably gives birth to a four-month oscillation in the Arctic and Antarctic. The fact that the four-month oscillation is stronger in higher latitudes is consistent with the increase of the length of the time when the sun is below the horizon from the Arctic Circle (20 hours) to North Pole (179 days).

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