

Halo of low ice concentration observed over the Maud Rise seamount

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[1] A distinctive halo of low sea ice concentration has been observed above the Maud Rise seamount in the eastern Weddell Sea. The 300-km circular halo is seen most clearly in the monthly mean ice concentration for the months July through November. The mean was computed from satellite-based passive microwave measurements over a 23-year period. The halo is most distinct in October; even then, however, the mean ice concentration in the halo is just 10% less than in the center, where it is very near 100%. The halo may reflect the existence of a Taylor cap circulation over the seamount or other topographically induced mechanisms. **INDEX TERMS:** 4207 Oceanography: General: Arctic and Antarctic oceanography; 4572 Oceanography: Physical: Upper ocean processes; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes. **Citation:** Lindsay, R. W., D. M. Holland, and R. A. Woodgate (2004), Halo of low ice concentration observed over the Maud Rise seamount, *Geophys. Res. Lett.*, 31, L13302, doi:10.1029/2004GL019831.

[2] The Maud Rise seamount in the eastern Weddell Sea rises from the abyssal plain at 5000 m to within 1700 m of the surface. It is located about 500 km north of the Antarctic continent at 65°S, 2.5°E (Figure 1). Here sea ice forms every winter to an extent of about 1500 km north of the coast and usually melts back to near the coast every summer. The region around Maud Rise has attracted research attention because of the very low static stability of the ocean to great depths, the large surface heat fluxes observed in the region, and the likely occurrence of deep convection and ventilation events for the abyssal ocean waters [e.g., *Martinson et al.*, 1981; *McPhee et al.*, 1996; *Muench et al.*, 2001].

[3] It has been hypothesized that the seamount played an important role in the formation of two notable polynyas observed in this region during the satellite era. The first, often called the “Weddell Polynya,” occurred over a 3-year period from 1974 to 1976 [*Carsey*, 1980]. Observations from the first satellite passive microwave sensor, ESMR (Electrically Scanning Microwave Radiometer), indicate the polynya originally formed on the flanks of Maud Rise and then grew to cover over 300,000 km² and migrated west of the seamount into the eastern Weddell Sea. This polynya persisted over several years in spite of the complete melt of the sea ice in the summer and the growth of the ice to near normal northmost extents in the winter. A

second significant polynya, smaller and observed in only one season, developed in August 1994. It was located just to the north and east of the seamount and covered about 30,000 km² in August [*Drinkwater*, 1998].

[4] While it is generally known that small areas of open water frequently form in the region, it has not been clear what their spatial relationship with the seamount is nor just how frequently they form. The 23-year mean ice concentration for the months of July through November (1979–2001) show a distinctive nearly-circular halo of low ice concentration with a diameter of about 300 km (Figure 2). The feature matches in scale the size of the seamount and is located around the flanks of the rise. The monthly change of the halo strength is related to the seasonal cycle of the air temperature. In July, when the mean surface air temperature is about –5°C [*Oort*, 1983], the freezing rates for open water are high and the ice remains well consolidated, although the halo is still evident. The halo is most developed in October when the mean surface air temperature is near 0°C and open water is able to persist for longer periods. In November the ice is melting throughout the region, though the melt is more developed near Maud Rise and a halo is still discernible.

[5] The ice concentration estimates used here are obtained from the archives of SMMR (Scanning Multichannel Microwave Radiometer) and SSM/I (Special Sensor Microwave Imager) data held at the National Snow and Ice Data Center [*NSIDC*, 2003]. The concentration estimates are made at the NSIDC with the Bootstrap algorithm [*Markus and Cavalieri*, 2000] on a 25-km grid. The Bootstrap algorithm is thought to perform better than the NASA Team Algorithm in the southern oceans [*Comiso et al.*, 2003], a region where snow cover is significant and surface flooding often occurs. Passive microwave ice concentration estimates are subject to both random and systematic errors that each may amount to about 7% [*Cavalieri*, 1992; *Kwok*, 2002]. These large errors make detailed quantitative evaluation of our results difficult, but the qualitative spatial patterns presented here are compelling.

[6] The long-term mean ice concentration within the halo is not extremely low. In October the minimum mean concentration estimate is 0.90 in the halo and 0.99 near the summit of the seamount. The uncertainty in the mean is less than 0.01 for unbiased errors. Although the uncertainty in the mean concentration value due to systematic errors is not known, a systematic error would not significantly change the spatial pattern and it is the spatial pattern that is most interesting.

[7] A partial halo is evident in each of the monthly-averaged ice concentration maps for individual years, but its shape, location, and strength are highly variable. The low ice concentration appears on all sides of the seamount, but in all individual months there is a large degree of asymmetry in its configuration. In particular, the daily ice

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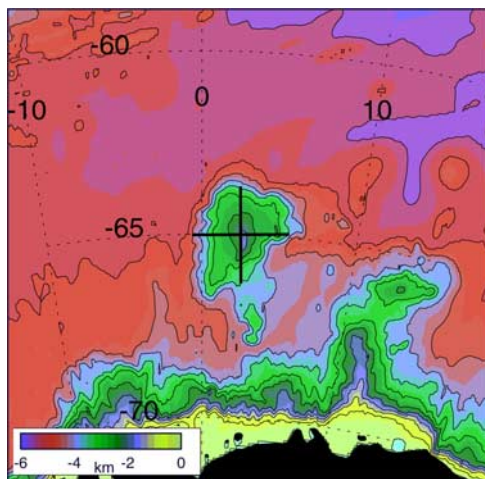


Figure 1. Topography of the Maud Rise region with a 300–km cross centred on the summit of the seamount (also seen in Figures 2, 3, and 4). The Antarctic continent is near the bottom of the figure, shaded in black.

concentration never shows a complete halo shape, although isolated areas of reduced ice concentration near the location of the halo are often observed. The feature is not easily seen in the annual monthly average ice concentration maps (1979–1986) in the atlas of *Gloersen et al.* [1992] because the color scale for ice concentration in those maps is not sufficiently stretched.

[8] Large expanses of open water are not common in the halo during the winter. Considering the daily observations rather than the 23–year mean, Figure 3 shows the fraction of occurrence of daily ice concentration less than 0.75 for the 25–km satellite pixels during October. In the most developed parts of the halo, in the northeast quadrant, about 10% of the time the ice concentration is less than 0.75. Low ice concentrations are much less frequent earlier in the winter.

[9] The daily ice concentration maps occasionally show a dipole structure with low concentrations on two sides of the seamount, often, but not always, on the southwest and

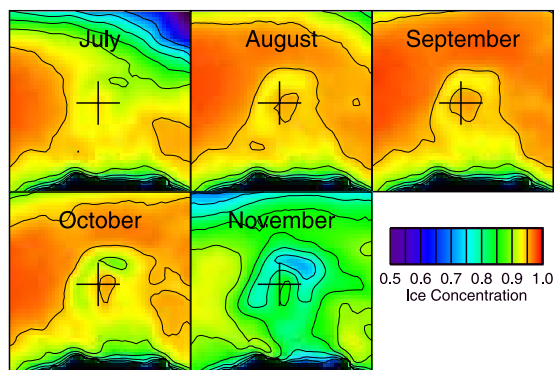


Figure 2. Monthly-mean ice concentration around Maud Rise from 23 years of observations (1979–2001) from the satellite-based passive microwave sensors SMMR and SSMI. The 300–km cross marks the location of Maud Rise. The black shading at the figure bottom indicates the Antarctic continent.

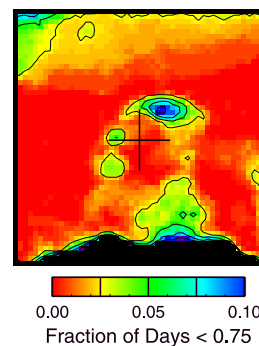


Figure 3. The frequency of occurrence of daily ice concentrations less than 0.75 for October, computed for 1979–2001.

northeast quadrants as seen in Figure 3. They also sometimes occur closer together, even within the same quadrant, but commonly within the ring defined by the halo.

[10] What might be the causes of this distinctive feature of the ice cover? Ice concentration can be reduced by ice divergence (with slow formation of new ice) and/or by ice melt (caused by a heat source either from the ocean or the atmosphere). Ice divergence might be observable in the mean ice velocity. Satellite passive microwave data were used by R. Kwok to track Antarctic ice using a maximal correlation technique [*Kwok et al.*, 1998; ice motion data are at www-radar.jpl.nasa.gov/rgps/ice_motion.html]. Figure 4 shows that the mean ice movement in the region is a cyclonic rotation with a mean drift velocity to the north over Maud Rise. There appears to be a slight slowing in the mean drift on the north side of the seamount.

[11] The ocean-based origins of the ice halo are suggested by the correspondence between the size and location of the halo and the size and location of the seamount (Figures 1 and 2). The 300–km crosses depicted in the figures coincide very nearly with the size of the seamount rising above the abyssal plain and with the diameter of the low ice concentration halo.

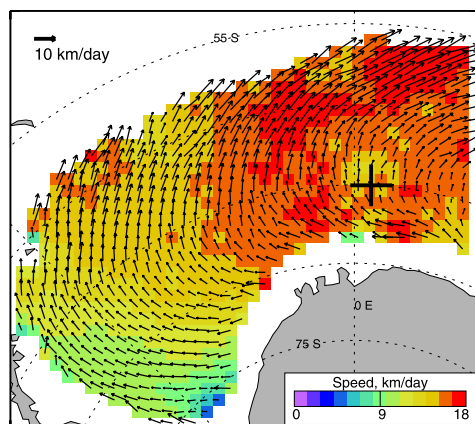


Figure 4. Mean ice velocity and speed from tracking brightness temperatures of the ice measured with passive microwave [*Kwok et al.*, 1998] for the months of July through October 1979–1997. The Weddell Sea and the Antarctic Peninsula are to the west and the Antarctic Continent is to the south.

[12] That the ocean circulation of the region is affected by the presence of the seamount is indisputable in the hydrographic data (see e.g., *Muench et al.* [2001], for an overview). The generic temperature profile in the region consists of a surface (ca. 0–100 m) layer of cooler, fresher water, underlain by a warmer saltier layer (ca. 100–500 m), which in turn lies above a much thicker, cooler layer. In the region of Maud Rise, anomalously warm waters are found over the flanks of the rise, with a colder cap of water lying over the top of the rise, [e.g., *Gordon*, 1978; *Bersch et al.*, 1992; *Muench et al.*, 2001]. This warm “halo” layer [*Muench et al.*, 2001] is an obvious candidate heat source for thinning of the ice cover and several authors [e.g., *Martinson et al.*, 1981; *McPhee et al.*, 1999; *Muench et al.*, 2001] consider strong vertical heat fluxes near the surface.

[13] The effects of a seamount on the ocean flow are addressed by many authors. Theoretical considerations [e.g., *Ou*, 1991] indicate that, given the physical parameters of the system (the dimensions of Maud Rise, the ambient ocean stratification, and the measured speeds of flow), Taylor cap dynamics are important, i.e., the ocean flow intensifies around the flanks of the seamount; a quasi-trapped, anticyclonic circulation (with associated doming of isopycnals) is found in the region; and a relatively stagnant cap of water forms directly above the seamount. This hypothesis is supported by the known hydrography. However, numerous other processes also apply, e.g., trapped waves, lee waves, resonance, tidal interactions, and eddies [e.g., *Chapman and Haidvogel*, 1992; *Haidvogel et al.*, 1993; see *Beckmann et al.*, 2001, for a discussion]. These complex dynamics also include the spawning of cyclonic eddies from a seamount [*Huppert and Bryan*, 1976], again a phenomenon consistent with the observations [e.g., *Muench et al.*, 2001].

[14] Several authors go further and hypothesize how these environmental features may interact to cause ice thinning and polynya formation. *Holland* [2001a, 2001b] uses an isopycnal model to demonstrate how Ekman effects, induced by ocean circulation (in particular, cyclonic eddy shedding) can lead to ice thinning and polynya formation around an idealized seamount. He shows that transients in the mean oceanic flow toward the seamount produce a polynya positioned on the flank of the seamount and located about 90 degrees to the left of the direction of the oncoming flow transient. *Beckmann et al.* [2001] use an s-coordinate model to simulate the response to steady and tidal flows around a realistic simulation of Maud Rise to demonstrate substantial tidal amplification around the seamount. They predict polynya formation in the NW quadrant of the rise driven dominantly by rectified tidal effects, the non-tidal mean-flow being required only to separate the polynya from the rise. The potential for tidal flows to enhance vertical motion and mixing is also investigated more idealistically by *Goldner and Chapman* [1997]. In addition, *McPhee* [2003] shows how thermobaricity — the pressure dependence of the thermal expansion coefficient for seawater — can be an important mechanism in stimulating or enhancing convective mixing under the conditions found near Maud Rise. Despite these many studies, consensus has not yet been reached concerning either the dominant mechanism causing ice thinning or the region relative to the seamount most favored for thinning.

[15] We stress that, during those infrequent times that a transient polynya does appear near the Maud Rise, it does not exist in the shape of a halo of low ice concentration completely circumscribing the flanks of the seamount. The emergence of the halo feature in the time-averaged satellite record demonstrates, in fact, that localized, individual polynya occur *sporadically* in time and space around the flanks of the seamount. An example of an individual, transient polynya, covering the northeast flank of the seamount, is given by *Drinkwater* [1998]. We hypothesize that such individual polynya are the result of seamount, ocean, and sea ice interaction, as suggested by the theoretical and modeling studies mentioned above, and that the variability in the positioning of individual polynya around the flanks of the seamount could result from the variability of the direction of the mean oceanic flow toward the seamount [*Holland*, 2001a, 2001b]. Such variability in ocean flow has been documented by current meters placed along the flanks of the seamount [*Bersch et al.*, 1992]. The average through time of such individual polynya gives rise to the halo shape we describe.

[16] These satellite observations show the existence of the halo of low mean ice concentration around the Maud Rise seamount but they cannot demonstrate its cause. While modeling studies indicate Taylor column circulations, trapped and lee waves, resonance and shedding, tidal currents, and other topography-induced effects in the vicinity of the seamount, little consensus is reached on the relative importance of these processes on ice divergence, ocean heat flux, and the physical mechanisms important in deep ocean convection. Indeed this cannot be determined from remote observations alone. Further theoretical studies and field work are required to help unwrap the mysteries of the variability in ocean circulation and heat exchanges in the vicinity of the Maud Rise ice halo.

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