Seasonal Snow Extent and Snow Mass in South America Using SMMR and SSM/I Passive Microwave Data (1979-2006)

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ABSTRACT

Seasonal snow cover in South America was examined in this study using passive microwave satellite data from the Scanning Multichannel Microwave Radiometer (SMMR) on board the Nimbus-7 satellite and the Special Sensor Microwave Imagers (SSM/I) on board Defense Meteorological Satellite Program (DMSP) satellites. For the period from 1979-2006, both snow cover extent and snow water equivalent (snow mass) were investigated during the coldest months (May-September), primarily in the Patagonia area of Argentina and in the Andes of Chile, Argentina and Bolivia, where most of the seasonal snow is found. Since winter temperatures in this region are often above freezing, the coldest winter month was found to be the month having the most extensive snow cover and usually the month having the deepest snow cover as well. Sharp year-to-year differences were recorded using the passive microwave observations. The average snow cover extent for July, the month with the greatest average extent during the 28-year period of record, is 321,674 km^2. In July of 1984, the average monthly snow cover extent was 701,250 km^2 – the most extensive coverage observed between 1979 and 2006. However, in July of 1989, snow cover extent was only 120,000 km^2. The 28-year period of record shows a sinusoidal like pattern for both snow cover and snow mass, though neither trend is significant at the 95% level.

I INTRODUCTION

In the Southern Hemisphere, seasonal snow cover is essentially confined to southern South America, the South Island of New Zealand and high elevations in eastern Australia. However, South America is the only continent in the Southern Hemisphere (other than Antarctica) where an extensive, winter snow cover may occur. Though snow may fall and even persist on the ground for several days in Africa and Australia, on those continents, its impact on climate and water resources is considerably smaller than is the case for South America. Using data from the Scanning Multichannel Microwave Radiometer (SSMR) instrument on board the Nimbus-7 satellite and from the Special Sensor Microwave/Imager (SSM/I) sensors on board

Defense Meteorological Satellite Platform (DMSP) satellites, seasonal snow extent and snow mass (snow water equivalent [SWE]) have been calculated in South America for the period from 1979-2006.

In the Northern Hemisphere, the land masses are situated much closer to the poles than they are in the Southern Hemisphere (again, excluding Antarctica). The land not only acts as a source area for cold air, but because of its lower thermal inertia compared to water, it does not modify the cold temperatures nearly as much as does water, even cold Antarctic waters. Thus, in the middle latitudes, temperatures during the winter months tend to be colder in the Northern Hemisphere than in the Southern Hemisphere, and snowfall occurs more frequently. Associated with this is the fact that high-pressure systems or anticyclones form less often in the Southern Hemisphere than in the Northern Hemisphere. Because there is less land in the mid latitudes of the Southern Hemisphere, the southern westerlies are stronger than their northern counterpart and large nearly stationary "high" systems such as the "Siberian High" become established less frequently. These large "highs" are important in refrigerating surface air and influencing the strength and tracks of storm systems (Foster et al. 2002). Despite these factors, which act to inhibit snowfall, seasonal snow does occur in the middle latitudes of the Southern Hemisphere and occasionally even in the sub-tropics at elevations below 1,000 m**.** At elevations above about 5,000 m, snow can occur even at the Equator. The objectives of this study are to map the seasonal snow cover in South America (and particularly in Patagonia) during the coldest months of the year (May-September) using passive microwave satellite data and to generate a snow record comparable to the record for North America and Eurasia. Though snow can fall in months other than May-September, especially at higher elevations, snowpacks build only from late fall through early spring, which is the focus of this study.

This paper describes an approach to assemble a consistent 28-year record of seasonal snow covered areas of South America. There are, however, very limited data that can be used to corroborate our findings (station data, satellite data or otherwise), making extensive quantitative validation of the snow estimates extremely challenging. While we are presenting this 28-year dataset as the most reliable yet generated for seasonally snow covered areas of South America, we can not claim that our dataset is in any sense completely validated. When more reliable data become available, we will then be in a better position to perform a more comprehensive validation. In the mean time, in a relative sense at least, this dataset can be used to assess month-to-month and year-to-year differences in a remote region (Patagonia and Andes Mountains) where little is known about variations in the character, coverage and water equivalent of its snow cover. See section VI.

II STUDY AREA

In the Patagonia region of Argentina and the Tierra del Fuego region of Argentina and Chile (Figure 1), a stable snow cover may form as early as May and remain as late as October. Each winter, snow is a regular feature south of about 45 degrees latitude, and in the snowiest years, over 1 million square km of snow has been reported (Dewey and Heim, 1983). However, this is likely an overestimate – see section VI. A single storm may cover the ground with several hundred thousand km^2 of snow. Snow can fall at locations much further north than expected, in northern Argentina or even in southern Brazil, for instance (27 degrees south latitude). Snowfall in these locations is usually confined to elevations greater than 1,000 meters above sea level, however, in July 2007 snow covered the ground in Buenos Aires for the first time since 1918.

Typically, an extensive snow cover in southern South America results from disturbances embedded in the westerly air streams. East winds and heavy precipitation during the winter in southern South America are caused by quasi-stationary high pressure systems at high latitudes over the western South Atlantic Ocean (Kidson, 1988). These anticyclones block the more usual zonal airflow in such a way that normal sea level cyclonic systems are steered around the “high” toward Patagonia (the South American states of Rio Negro, Chubut, Santa Cruz and Tierra Del Fuego). See Figure 1a and 1b. In southeastern Brazil, snow can fall when incursions of polar air originating in the Antarctic (friajes or friagem) push rapidly north-northwestward (east of the Andes), coincident with a weakening of the normally dominant sub- tropical high-pressure belt.

Seasonal snow cover is highly variable from year-to-year in South America. This is to be expected since, typically, accumulations are rather shallow. According to Dewey and Heim (1983), over a 7-year period from 1974-1980, snow cover reached a maximum extent of about 1 x 10^6 million km^2 in 1980, but in 1979, the maximum extent was only about 70% of this amount.

III PASSIVE MICROWAVE OBSERVATIONS

Although a considerable amount of effort has been devoted to developing and refining passive microwave snow algorithms for North America and Eurasia, for example, Chang at al. (1987), Goodison et al. (1993), Pulliainen et al. (1993), Grody and Bassist (1996), Foster et al. (1997), Armstrong and Brodzik, (2001), Kelly et al. (2003) and Foster et al. (2005), very little work has been expended for algorithm development of seasonal snowfields in the Southern Hemisphere. The SMMR instrument operated from November 1978 until August of 1987. The first SSM/I was launched in late 1987, thus there was little overlap between these two sensors and limited opportunity for calibration/validation. For more about this see section V.

While SMMR was fitted with 18 GHz and 37 GHz sensors, 19 GHz and 37 GHz sensors have been employed on the SSM/Is (Table 1). The nominal resolution for the 19 GHz (actually 19.35 GHz) channel is 69 x 43 km^2 and for the 37 GHz channel the resolution is 37x 28 km^2 (Naval Research Laboratory, 1987).

Table 1

Characteristics of the SMMR an SSM/I sensors.

	SMMR	SSM/I	
Platform	Nimbus-7	DMSP F-8, 11, 13	
Period of Operation	1979-87	1987-present	
Data Acquisition	every other day	daily	
Swath Width	780 km	1400 km	
Frequency (GHz)	18.0 37.0	19.35 37.0	
Spatial Resolution (km)	60x40 (18 GHz)	69x43 (19.4 GHz)	
	30x20 (37 GHz)	37x29 (37 GHz)	
Polarization	H & V	H & V	
Orbital Timing (Eq. Crossing for minimum temperature, ascending)	midnight	6:00 a.m.	

SMMR and SSM/I data, available from the National Snow and Ice Data Center (NSIDC), were projected to the Equal Area Scaleable Earth Grid (EASE-grid) for the Southern Hemisphere, at a 25 km x 25 km grid scale (Armstrong et al., 2008). For this investigation, brightness temperature differences between the 18 (19) GHz and 37 GHz channels were multiplied by a coefficient related to the average snow grain size to derive SWE (Chang at al., 1987). The simple SMMR algorithms are then versions of

$$SWE = C\,(T_{18} - T_{37})\ \text{mm} \qquad [\mathbf{1}]$$

For SSM/I the algorithm is

$$SWE = C\,[(T_{18} - T_{37}) - 3.6]\ \text{mm} \qquad \mathbf{[2]}$$

Where SWE is snow water equivalent in mm, C is the grain size coefficient and T_{18} (T_{19}) and T_{37} are the brightness temperatures at the 18 (19) GHz and 37 GHz vertical polarizations, respectively. The density of mid winter snowpacks in this region is assumed to be approximately 200 kgm^{-3}. Snow mass is simply the total SWE for all snow covered pixels. Note that here an offset has been applied to the SSM/I data – see section V.

In the above algorithms, if the 18 (19) GHz vertical frequency is > 252 Tb and the 37 GHz vertical frequency is greater than 245 Tb, SWE is considered to be zero. For prairie or steppe landscapes, C is set at 4.00, whereas for alpine conditions C is set at 4.25. These values are based on results for similar landscapes in North America where previous studies have determined that the average crystal sizes are larger (smaller coefficient) in regions where temperature and vapor gradients are quite large, tundra areas for instance. In contrast, in maritime and alpine areas the crystals sizes are generally smaller (larger coefficient) than those found in prairie or tundra locations. In North America, it was found that based upon the derived coefficient, the over or under estimation for the prairie (steppe) snow class, during mid-winter, was approximately 15%, while in alpine regions, it was approximately 7%. For more on this see Foster et al. (2005). Since the snowpacks in Patagonia and at lower elevations of the Andes are usually rather unstable (snow does not always accumulate throughout the winter months), the coefficients here are static rather than dynamic – they remain constant through the snow accumulation and snowmelt seasons.

It needs to be stressed that no ground data have been collected or field studies conducted that would lend credence to our coefficient assignments. We have only used coefficients measured for similar landscapes – in North America. Thus, we are unable to quantify the bias that exists with these grain size coefficients. East of the Andes in Patagonia, average winter temperatures are higher than on the North American prairies and incursions of moisture laden air occur less frequently. Therefore, even though these different regions are within the same Sturm et al. (1995) snow class, it is expected that snow crystals would metamorphose somewhat differently – coefficients will not exactly mimic those in North America. Furthermore, mountainous snow packs, in the Andes, are characterized by strong east-west as well as vertical precipitation gradients, which again will likely result in snow grains having different dimensions than those examined in the alpine snow class in North America.

Because persistent cloud cover over the Patagonia region, as well as along the spine of the Andes, during the winter season often conceals the underlying snow cover. The brightness temperature contribution for water vapor is nearly the same for both the 19 and 35-37 GHz frequencies. If clouds contain ice crystals (or are not composed of large water drops as is generally the case with warm season precipitation), as they frequently do during the winter months in Patagonia and along the Andes, it is expected that the atmospheric will have a minimal effect on the transmission of microwave energy, and thus atmospheric corrections are not considered here. Therefore, passive microwave remote sensing is particularly suitable in this region.

Clouds and darkness do not preclude snow detection in the microwave frequencies employed on SMMR and SSM/I. Landsat sensors, which have a 16-day repeat period, or even the Moderate Resolution Spectroradiometer (MODIS) on-board the Terra satellite, NOAA/Advance Very High Resolution Radiometer (AVHRR) and GOES satellite data, all available daily, can be rendered nearly useless by persistent cloud cover. However, 8-day composite MODIS data, since February 2000 (Hall and Riggs, 2007), have been employed to map snow cover extent here -- compositing helps eliminate all but the most resolute cloudy areas.

Although the emission from trees can seriously confound the scattering signal of snowpacks (Foster et al., 2005), Patagonia has few forests, and certainly no large tree covered tracks comparable to the boreal forests. However, poleward of about 40 degrees south latitude, portions of the west slope of the Andes are covered by rather dense mid latitude rainforests. In these areas, use of microwave radiometry is impaired, not only because of the presence of forests but also because of the proximity to the Pacific Ocean. Our land mask excludes those pixels within one pixel (25 km) of large bodies of water (see below). Snow beneath those densely forested areas that exist in Patagonia will not be accurately estimated because of their strong emission characteristics. Large lakes, which impose upon the microwave pixels, also reduce the characteristic scattering behavior of snow. Nonetheless, the large inland water bodies and forested tracks cover relatively small areas and do not severely limit our mapping efforts here.

In the Altiplano region of western Bolivia, the ground may be mapped as being snow covered even when no snow is present. In high plateaus areas, a false positive signal can occur with passive microwave observations when and where bare (snow free ground) is quite cold, such as on the Tiber Plateau. Shallow snow can occur on the Altiplano, and the snow mapped here using microwave radiometry is thin, but still, during the course of the snow season, it is likely that the snow extent and mass is overestimated in this region.

Additional disadvantages of using passive microwave radiometry in Patagonia and the Andes are related to the continental shape of southern South America, relative to the large grid cell sizes in this region, and the general shallowness of the snow in this region. Shallow snow, less than about 3 cm in thickness, is often transparent to microwave radiation, and thus snow may not be detected employing the above algorithms when, in fact, a thin veneer of snow is present. Because the southern part of South America is tapered, there is a significant water-land mixed pixel effect on several of the SMMR/SSM/I pixels in the Tierra Del Fuego region (Figure 1). Pixels having more than about 20% surface water (oceans, lakes or bays) cause snow retrieval algorithms to be of little use since the very low brightness temperatures characteristic of open water in the microwave portion of the spectrum are emission-based and not scattering-based.

Melt water in the snowpack also changes the microwave emissivity of snow, causing absorption and emission rather than scattering. This acts to increase the microwave brightness temperature. To minimize this effect, only nighttime passive microwave data were used (approximately local midnight equatorial crossing for SMMR and 6:00 a.m. local node equatorial crossing for SSM/I). This helps to ensure but cannot guarantee that any snow that melted during the course of the day will refreeze.

IV SMMR/SSM/I CALIBRATION

Because of the minimal temporal overlap between SMMR and the first SSM/I instrument, defining a true offset between these two instruments has been problematic. The only time corresponding data from both instruments were available occurred from late July 1987 through mid August 1987, and since SMMR was turned on only on alternate days, there were few opportunities to compare Tbs at the same location and on the same day. Additionally, because the SMMR and SSM/I equatorial crossing is approximately 6 hours different, simultaneous comparisons were not possible. Moreover, the SMMR and SSM/I footprint size is slightly different and the sensor frequencies are not exactly the same. Van der Veen and Jezek (1993) found that a -5 K offset exists between the SMMR and SSM/I observations over Antarctica. This value has been long been cited and may be useful for many regions of the world, however, we chose to derive a value that was more specific to Patagonia and the Andes.

We initially examined ocean Tbs, in the south Atlantic and South Pacific Ocean, and also Tbs over the Amazon Basin and the Argentine Pampas in an attempt to derive a legitimate offset. However, due to the effects of the time difference when the sensors were overhead as well as physical differences in cloud cover and surface roughness (waves and differences in vegetation height, for instance) over large pixel-sized areas, we realized that a more stable surface was required. Therefore, our calibration site was changed to the Antarctic region, where because it was the winter season (winter darkness), the time difference of the overpass had a negligible affect on surface temperature and the difference in surface roughness was minimal.

We examined the area between 70º and 72º degrees south latitude and between 80º and 85º west longitude. We then selected the lowest (coldest) pixels within this area to derive an offset -- 28 pixels were used. This approach resulted in an offset (using both 19 and 37 GHz) of 3.6 degrees (K). This value was then employed to compute snow cover area and SWE (snow mass).

V DATA ANALYSIS AND RESULTS

To ensure that the passive microwave algorithms are sufficiently sensitive to detect snow on the ground, Figure 2 is a plot of the monthly average temperature (departure from normal) during the months of May through August for 1992-1998 versus the number of snow covered SSM/I pixels for these same months. The temperatures are averaged from four meteorological stations; Gobernator Gregores, Rio Gallegos, and Lago Argentino, Argentina and from Punto Arena, Chile (Figure 1a and 1b). It is quite evident that an extensive snow cover exists only when the average daily temperatures are colder than normal, and in this region, when the temperatures are above normal, they are almost always above freezing (0º C), quickly melting the snow.

As previously mentioned, SSMR and SSM/I snow data were acquired from May through September for the years 1979-2006. To construct snow maps, 18 (19) GHz and 35 (37) GHz (vertical polarization) radiances were converted to brightness temperatures. The SMMR/SSM/I data set includes average monthly values, maximum monthly values and weekly values – constructed using daily data (every other day in the case of SMMR). Maps of monthly snow cover extent and SWE (mass) were generated for the 28 year or 140 month period using equations **1** and **2**. Note that much of the snow/ice mass is found in Andean glaciers and ice sheets. Passive microwave approaches, at the frequencies used in this study, are not intended to estimate the mass or volume of glacier ice. Our emphasis is the extent and mass of seasonal snow – that snow which accumulates and melts in a single year.

Table 2 shows the average monthly snow cover and snow mass statistics for the 140 month period. The average snow cover extent for July, the month with the greatest average snow extent during the 28-year period of record, is 320,700 km^2 (Figure 3). In July of 1984, the average monthly snow cover was 701,250 km^2 – the most extensive coverage observed between 1979 and 2006. For the entire 1984 season, the average snow cover was nearly 500,000 km^2. The month having the second greatest average snow cover is August (300,325 km^2). By September, much of the seasonal snow in the higher latitudes and higher elevations is undergoing melt – the average snow extent for September is 240,313 km^2. Of the five cold season months investigated in this study (May-September), the month of May has the smallest average snow cover extent (127,969 km^2). By June, the snow extent expands appreciably (28 year average of 228,400 km^2).

In terms of snow mass (SWE), July is also the month with the greatest average snow mass (0.786 x 10^{13} kg), and August is again the month having the 2nd greatest average snow mass (0.735 x 10^{13} kg). See Figure 3. In July of 1984, the average monthly snow mass was 2.41 x 10^{13} kg – the greatest monthly snow mass observed during the course of this study. Not surprisingly, 1984 was also the year having the greatest average seasonal snow mass (approximately 1.2 x 10^{13} kg). In May, the average snow mass is just 0.170 x 10^{13}.

Snowpacks, though often ephemeral in Patagonia, may continue to build during the winter season. Interestingly, the average snow cover for August is approximately 93% of the average for July, and the average snow mass for August is about 94% of that for July. Similarly, the average snow cover for September is 80% of that of the average August snow extent, and the average September snow mass is 80% of the average August snow mass. The building of the seasonal snow mass seems to correspond closely to the expansion of the snow cover. Still, on seven occasions the average monthly snow mass for July exceeded 1.0 x 10^{13} kg, however, this threshold was surpassed on eight occasions during the month of August.

In some cases, the daily maximum snow extent is hundreds of thousands of km^2 more than the monthly average extent. For instance, in July 2000, the average monthly snow extent totaled 483,125 km^2, whereas the daily maximum extent, on July 13, was 703,125 km^2 (Figure 4). This is not unusual in a climate where temperature extremes are routinely experienced and where snowfall is intermittent. In many years, a storm will deposit a layer of snow that melts before another storm arrives. In July of 2000, the maximum daily snow mass (SWE) occurred on July 27. Note that the date of the maximum daily snow extent for July 2000 and the maximum daily SWE (snow mass) were separated by 14 days.

Figure 5 is a montage of July average snow cover and snow mass as derived from SMMR (1979-1987), and Figure 6 shows the July snow maps for SSM/I from 1979-2006.

VI SNOW COVER VALIDATION

Dewey and Heim (1983) reported that the maximum wintertime snow cover extent in South America, using visible satellite data, ranged from 692,000 km^2 to 1,011,000 km^2 between 1974 and 1980. More recent measurements using the Geostationary Orbiting Environmental Satellites (GOES) and MODIS satellite data indicate that those measurements probably represent an overestimation of the maximum amount of snow cover in South America (Hall and Robinson, in press).

Persistent cloudiness in southern South America precludes the accurate determination of average monthly snow cover using MODIS data. However, maximum monthly snow cover area can be assessed from MODIS observations by considering all pixels covered by snow for even a single day during a given month. Specifically, if there was snow in a 25-km cell for any day during the month, that cell was mapped as being snow covered on the MODIS maximum snow-cover maps. Employing MODIS maps (see Hall and Riggs, 2007) from 2000 to 2006, it was found that the maximum snow-covered area in South America occurred in July 2002 (Table 3) when 656,096 km^2 of snow was measured.

Romanov and Tarpley (2003) mapped snow cover in South America from the GOES satellite at approximately 4-km resolution and found that their measurements also showed lower wintertime snow cover values than were found by Dewey and Heim (1983), although, only 2-years were studied. For the years 2000 and 2001, Romanov and Tarpley (2003) recorded wintertime snow cover values that reached about 620,000 km^2 and 670,000 km^2, respectively. According to Hall and Robinson (in press), the possible discrepancies in maximum snow cover measured using earlier snow measurements might be explained, at least in part, by the poorer spatial resolution of the early NOAA snow charts. Note that both MODIS and passive microwave (SSM/I) maximum measurements show less maximum snow cover in 2001 than in 2000, while the GOES measurements from Romanov and Tarpley (2003) show greater maximum snow cover in 2001 as compared to 2000.

Table 3
Approximate maximum snow-covered area in South America in July as measured using 0.25 MODIS Climate-Modeling Grid (CMG) snow-cover maps (Hall and Robinson, in press) composited for the entire month for all grid cells, snow extent measurements from SSM/I (at 25 km resolution) and snow cover measurements from 4 km resolution GOES data.

Year:	Maximum MODIS snow extent (km^2)	Maximum SSM/I snow extent (km^2)	GOES snow extent
2000	536,011	797,500	620,000
2001	435,255	681,250	670,000
2002	656,096	486,000	
2003	420,899	383,750	
2004	403,828	346,250	
2005	485,724	683,125	
2006	470,658	565,000	

Because MODIS and SSM/I are sensing in different portions of the electromagnetic spectrum, the snow cover values are expected to be somewhat different. For example, as previously mentioned, passive microwave observations often miss very thin snow (<5 cm) because the 35 GHz frequencies may be unimpeded by the shallow snowpacks – too few crystals to induce volume scattering. Furthermore, SMMR and SSM/I pixels along the continental border with the Pacific and Atlantic Oceans are not used in this investigation because pixels containing ocean water produce anomalously cold Tbs. Figure 7 compares a MODIS snow image and SSM/I snow representation for July of 2000.

The differences are also possibly due to MODIS-related problems associated with mapping snow in one of the cloudiest regions in the middle latitudes. Whereas, passive microwave data are minimally affected by clouds composed of ice crystals and thus well suited for mapping in regions where cloud cover is persistent; opportunities to map daily snow cover using visible data can be very limited. In addition, the cloud mask used in the MODIS snow mapping routine, though sophisticated, is overly conservative, thus mapping more clouds than are actually present. Comparison between MODIS and SSM/I will need to be evaluated further. Based on this 7-year comparison, however, the differences (in Table 3) seem more random than systematic.

Table 4 shows a comparison between MODIS and SSM/I maximum snow extent for 35 months of observations (May-September of 2000-2006). The MODIS values are higher than SSM/I values in May, while SSM/I are higher in August, and the two estimates are comparable in September. The mean bias for all five months is ~ -20,000 km^2 (SSM/I being higher). Students t tests for each month are also shown.

Table 4

May (t, p-value)	3.65*	0.005
June	-0.07	0.25
July	-1.48	0.09
August	-3.55*	0.005
September	1.046	0.16

* significant at the 5% level for a two sided test (p-value <0.05)

This table shows that there is no significant difference between MODIS and SSM/I in June, July and September. MODIS is significantly higher in May and significantly lower in August. The high MODIS value in May could be due to the non-detection of shallow snow by SSM/I. The higher SSM/I estimates observed later in the snow season could be a result of thicker snow depths and a more continuous snow cover and inferior mapping with MODIS due to the above mentioned conservative cloud mask.

Keep in mind that maximum monthly snow cover using SSM/I data, unlike MODIS data, is determined to be the day of the given month having the greatest number of snow covered pixels. For the years 2000-2006, when compared to MODIS maximum monthly snow cover, the SSM/I data show a 5% upward bias. The method of computing the maximum value is likely to affect, to some degree, the differences observed between the MODIS and SSM/I.

A problem with a number of remote sensing approaches in attempting to validate results is the issue of what to use as a standard of reference or a baseline for comparison. While ground truth data often are assumed to be more accurate and reliable than space-borne observations, these data are essentially only representative of points on the ground. Measuring the depth of snow at two points over a km apart could easily result in depths that are different by several cm. Comparing these point data, from meteorological stations, for instance, with satellite pixels that are approximately 25 km on a side in the case of the passive microwave data, is usually not meaningful. In order to adequately compare and validate space-borne microwave estimates of snow depth or SWE, nine or more point measurements across a 1-degree latitude by 1-degree longitude are required (Chang et al. 2005). In densely populated areas such as the US Midwest, it may be possible to use available data from meteorological stations and or local observers to validate the satellite derived snow depths. However, in more remote areas, a sufficient number of point measurements is almost always lacking.

It is worth noting also that snowfall and snow on the ground data from the limited meteorological stations in Patagonia and in the Andes are not always reliable, nor are they always available. Nonetheless, they can be used to “spot check” remotely sensed snow cover and snow depth. For those dates when snow was reported at the stations in Figure 1b (1984 and 2000), snow cover, from SSM/I observations, was observed in their vicinity. On some occasions, SSM/I observed snow but a given station site did not, and on fewer occasions, individual stations recorded snow but SSM/I did not. These peculiarities may result from incomplete station records (the former) as well as the inability of SSM/I to detect shallow snow cover (the latter).

Evaluating snow depth is even more difficult. In some cases, only new snowfall is reported at the selected stations rather than the total snow depth, and of course, even reliable measurements of snow depth made in cities and towns are apt to be quite different from what would be measured in locations outside of population centers and at upland sites. On most occasions, when an increase in snow depth was denoted at those operational meteorological stations in proximity to one another, lower brightness temperatures (increases in SWE) were also observed. The results are shown in Table 5. There is poor correlation between what is observed (station data) and what is estimated (satellite data). However, at Lago Argentino the remotely sensed and station data are in close accord and no systematic errors are evident. Although at Esquel in 2000, the satellite estimates are all higher than the station data. It should be noted that the high agreement at the Lago Argentino site is perhaps due to the presence of dense rainforests along the flanks of the southern Andes in the vicinity of Lago Argentino. Forests and rugged topography act to increase emission, which results in lower passive microwave-derived snow depths than would otherwise be the case if the landscape were more barren and moderate in relief. Moreover, the terrain for both Lago Argentino and Esquel is complex and not necessarily representative of the passive microwave footprint or of the geography found in much of Patagonia

Table 5

Snow depth (in cm) measured from meteorological stations and derived from SMMR observations for the period from July 1-29, 1984

	Lago Argentino		Esquel	
	station	satellite	station	satellite
1			8	13
8			2	10
14			12	10
20			18	15
25			12	17
29	2	8	10	13

Snow depth (in cm) measured from meteorological station data and derived from SSM/I observations for the period July 11-15, 2000.

	Lago Argentino		Esquel	
	station	satellite	station	satellite
11	8	9	8	20
12	8	10	8	28
13	15	11	5	21
14	15	16	10	16
15	13	17	10	18

Thus far, there have been no field campaigns nor airborne overflights to thoroughly evaluate the passive microwave snow extent and snow mass estimates.

VII DISCUSSION

Normally in May, the seasonal snow cover is confined to the higher elevations inland as opposed to coastal areas. Snow cover may be absent in the higher latitudes near sea level, but further to the north, more equatorward, in the highland areas of Boliva, for example, snow may be extensive (see section III). As fall progresses into winter, lowland coastal areas also become snow covered, even as far north as 45° south latitude (in interior areas) in some years. Figure 8 shows the seasonal build up of snow in Patagonia and along the Andes during the fall and winter of 2000, from May through September. Note that 2000 was the 6th largest snow season of the 28-year passive microwave record.

Snow depths are generally less than about 10 cm across most of Patagonia and Tierra del Fuego in mid winter, based on data from available meteorological stations. Since the snow cover is generally shallow, the month having the maximum snow coverage can vary from one year to the next. With few exceptions, however, the coldest month is the month with the greatest snow cover extent. Consequently, July is the month that usually has the greatest snow cover, but in some years August and even September (1979) register the most snow (both snow extent and snow mass). This is the case in North America and Eurasia as well; the greatest snow cover extent occurs during the coldest month (January) or the second coldest month (February). Though, in North America and Eurasia, the greatest snow cover extent for a given year has never occurred in any month other than January or February. Regardless of the month, in many years a storm will deposit a layer of snow that melts before another storm arrives.

On occasion, the average snow mass may be greater in a month when its corresponding snow extent is less than it is for another month having a greater area of snow cover. In May of 1982, for example, the snow extent was 176,250 km^2 and the corresponding mass was 0.24 x 10^{13} kg, whereas in May of 1983 the snow extent measured 185,000 km^2 but the mass was 0.21 x10^{13} kg. See Table 2.

For the 28 years studied, the average maximum snow depth per SSMR or SSM/I pixel was approximately 11.0 cm (July, 2000). During months when the snow cover area exceeds 500,000 km^2, approximately 3% of South America is snow covered. In contrast, for the month of maximum snow extent in North America (January) and Eurasia (February), the maximum snow extent encompasses approximately 62% and 53% of the land area, respectively (NOAA, Northern Hemisphere Snow Cover Charts). Of course, the land mass configurations are very different in the Northern and Southern Hemisphere.

In the Northern Hemisphere, by the mid 1990s, it became clear that the snow cover extent changes were trending downward (Robinson et al., 1995; Robinson and Frei, 2000). Annual averages of snow cover extent since the mid 1980s have remained approximately 2 million square kilometers (approximately 8%) lower than averages in the first 20 years of the satellite era. Similar trends are not yet apparent for South American snow cover; however, a small downward trend in snow cover area can be discerned. Figure 9 shows the average May-September snow cover values plotted for all 28 years (1979-2006). The regression line equation is y= -1962x +4E06. Here -1962 is the slope and 4E06 is the intercept of the regression. The slope is not significantly different from zero at the 95% level, with a p-value of 0.36. In regards to snow mass, the trend is slightly upward (Figure 10). The equation (for all months, May-September) is y = 0.0023x – 3.9481. Again, the trend is insignificant at the 95% level -- p value for May-Sept snow mass is 0.76. When there is so little change over a relatively long time period, it is not unusual for one variable to be show a slight positive trend even when a complimentary variable is slightly negative.

Though there seems to be a cyclic wave pattern of snow upturns and downturns over the period of record, overall there is very little change in regards to gains or loses of snow cover extent and SWE (mass) between 1979 and 2006. Data from Comiso (2003) and Comiso and Parkinson, 2004) shows similar results for Antarctic sea ice trends (Figure 11).

Snow cover extent and snow mass data (daily, weekly and monthly data) for South America will soon be available for the years 1979-2006 (for the months May-September) at the following url
http://neptune.gsfc.nasa.gov/southamericasnowcover/
More information concerning how data was acquired, maps constructed, snow classes, etc., is located here as well.

VIII CONCLUSIONS AND FUTURE WORK

Exclusive of Antarctica, seasonal snow in the Southern Hemisphere is, for the most part, confined to South America. This study demonstrates that passive microwave radiometry is useful in estimating the snow cover extent and snow mass in the Patagonia region and Andes Mountains of South America where clouds are a major problem for snow mapping using visible/infrared data and where the snow is often ephemeral in nature. The passive microwave observations show that there are sharp year-to-year differences that exist in the seasonal snow extent over the study area. Snow cover extent in the month of July, the month typically having the greatest snow cover, varied during the 25-year period from a high of 701,250 km^2 (about the size of Chile or Texas) in 1984 to a low of 120,000 km^2 in 1989. The greatest monthly snow mass varied from x 2.41×10^{13} kg also in 1984 to 0.23×10^{13} kg in both 1989 and 1990. The building of the seasonal snow mass seems to correspond closely to the expansion of the snow cover. The average snow cover for August is approximately 93% of the average for July, and the average snow mass for August is 94% of that for July. Similarly, the average snow cover for September is 80% of that of the average August snow extent, and the average September snow mass is 80% of the average August snow mass. The 28-year period of record shows a sinusoidal-like pattern for both snow cover and snow mass, though neither trend was found to be significantly different from 0 (at the 95% level).

Shallow snow, wet snow, snow beneath forests, as well as snow along coastal areas all may confound interpretation using passive microwave approaches. In this long term climatology, even if only in a relative sense, snow mass and snow cover extent are shown to vary considerably from month to month and season to season. Still, more work needs to be done to reduce the uncertainties in the data and hence, increase the confidence of the interpretation. This is indeed a challenging task. Nevertheless, this analysis presents a consistent approach to mapping and measuring snow in South America utilizing an appropriate and readily available long term snow satellite dataset. This is the optimal dataset available, thus far, for deriving seasonal snow cover and snow mass in this region.

Future work will focus on lengthening the period of record. Thirty years of data will be available at the end of 2008 for comparison with data from North America and Eurasia. We will also compare and contrast snow cover in South America with that of a similar latitude and longitude in North America in order to assess whether or not an association exists when examining regional data. In addition, we will determine if a relationship exists between the South American seasonal snow extent (and mass) and climate indicators including the Southern Oscillation Index (El Nino and La Nina) and the Antarctic Circumpolar Wave (White and Cherry, 1998).

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REFERENCES

Armstrong, R. L., K. W. Knowles, M. J. Brodzik and M. A. Hardman, “DMSP SSM/I Pathfinder daily EASE-Grid brightness temperatures,” Boulder, Colorado USA: National Snow and Ice Data Center. Digital media, 2008.

R. .L. Armstrong and M.J. Brodzik, “Recent northern hemisphere snow extent: a comparison of data derived from visible and microwave satellite sensors” Geophysical Research Letters, Vol. 28, No. 19, pp. 3673-3676, 2001.

Chang, A. T. C., J. L. Foster and D. K. Hall, “Nimbus-7 derived global snow cover parameters”, Annals of Glaciology, Vol. 9, 39-44, 1987.

Chang, A. T. C., J. Foster, D. Hall, H. Powell, and Y. Chien, “Product description and user’s guide for the Nimbus-7 SMMR-derived global snow cover and snow depth data set” The Pilot Land Data System, 1990.

Chang, A.T.C., Kelly, R.E.J., Josberger, E.G., Armstrong, R.L., and Foster J.L., “Analysis of Gauge-measured and Passive Microwave Derived Snow Depth Variations of Snowfields,” Journal of Hydrometeorology Vol. 6, 20-33, 2005

Colton, C. and G. Poe, “Intersensor calibration of DMSP SSM/I’s: F-8 to F-14, 1987-1997” IEEE Transactions on Geoscience and Remote Sensing, Vol. 37, No.1, pp. 418-439, 1999.

Comiso, J. C.: Warming trends in the Arctic from clear sky satellite observations. J. Climate., 16 (21), 3498-3510, 2003.

Comiso, J. C., and C.L. Parkinson: Satellite-observed changes in the Arctic. Physics Today, 57 (8): 38-43, 2004.

Dewey, K. and R. Heim, Jr., "Satellite observations of Southern Hemisphere snow cover" NOAA Technical Report NESDIS 1, Washington, D. C., 1983.

Foster, J. L., A. T. C. Chang, and D. K. Hall, "Comparison of snow mass estimates from a prototype passive microwave algorithm and a snow depth climatology" Remote Sensing of the Environment, Vol. 62, 132-142, 1997.

Foster, J. L., A. T. C. Chang, and D. K. Hall, and R. Kelly, "Passive microwave measurements of seasonal snow in South America," Proceedings of the 2001 International Geophysical and Remotes Sensing Symposium, Sydney, Australia, July, 2001.

Foster, J. L., A. T. C. Chang, D. K. Hall, and R. J. Kelly, "Seasonal snow extent and snow mass in South America using SSM/I data" Proceedings of the 29th International Conference on Remote Sensing of Environment, Buenos Aires, Argentina, April, 2002.

Foster, J., A. Chang, D. Hall, and R. Kelly, "Seasonal snow extent and snow mass in South America using passive microwave data" Polar Geography, Vol. 25, N0. 1, pp. 41-53, 2002.

Foster, J. L., A. T. C. Chang, D. K. Hall, and R. J. Kelly, "An examination of South American snow cover and snow mass from 1979-2003 using passive microwave satellite data" Proceedings of the 7th International Conference on Southern Hemisphere Meteorology and Oceanography, Wellington, New Zealand, 2003.

Foster, J., C. Sun, J. Walker, R. Kelly, A. Chang, and J. Dong, "Quantifying the uncertainty in passive microwave snow water equivalent observations," Remote Sensing of Environment Vol. 94, 187-203, 2005.

Goodison, B., H. Rott and R. Armstrong, “Snow Group Workshop Report” in Proceedings of ESA/NASA International Workshop on Passive Microwave Passive Microwave Sensing Research Related to Land Atmosphere interaction, St. Lary, France, 1993.

Grody, N. C. and A. N. Bassist, “Global identification of snow cover using SSM/I measurements” IEEE Transactions on Geosciences and Remote Sensing, Vol. 34, 237 –249, 1996.

Hall, D. K. and G. A. Riggs, “Accuracy and assessment of the MODIS snow products” Hydrological Processes, 21, 1534-1547, 2007.

Hall, D. K. and D. R. Robinson, “Global snow cover” in R. S. Williams, Jr. and J. Ferrigno (eds.) Satellite Image Atlas of Glaciers of the World – Introduction, U.S.G.S. Professional Paper 1386, US6PO, Washington, D.C., in press.

Kelly, R., and A. Chang, L.Tsang, and J. Foster (2003), A prototype AMSR-E global snow area and snow depth algorithm. IEEE Transactions on Geoscience and Remote Sensing, 41 (2), 230-242.

Kidson, J. W., “Interannual variations in the Southern Hemisphere circulation” Journal of Climate, Vol. 1, 1177- 1198, 1988.

Naval Research Laboratory, “Special Sensor Microwave/Imager User’s Guide” Wash., D. C., 120 pp, 1987.

NOAA, “Monthly Snow Cover Data for the Northern Hemisphere, 2006.

Njoku, E. G., B. Rague, and K. Fleming, “Nimbus-7 SMMR Pathfinder brightness temperature data” Jet Propulsion Laboratory Publication 98(4), 1998.

Prohaska, F., "The climate of Argentina, Paraguay and Uruguay" Climates of Central and South America, edited by W. Schwerdtfeger, Elsevier Scientific Publishing Co., Amsterdam, 1976.

Pulliainen, J., Karna, J. P., and Hallikainen, M.,"Developing of geophysical retrieval algorithms for MIMR" IEEE Transactions on Geosciences and Remote Sensing, Vol. 31, 268 -277, 1993.

Ramsey, B. H., "The interactive multisensor snow and ice mapping system" Hydrological Processes, Vol. 12, 1537-1546, 1998.

Robinson, D.A., A. Frei and M. Serreze: Recent variations and regional relationships in Northern Hemisphere snow cover. Annals of Glaciology, 21, 71-76, 1995.

Robinson, D.A., and A. Frei: Seasonal variability of Northern Hemisphere snow extent using visible satellite data. Professional Geographer, 52 (2), 307-314, 2000.

.

Romanov, P., and Tarpley, D., 2003, Automated monitoring of snow cover over South America using GOES Imager data: International Journal of Remote Sensing, v. 24, no. 5, p. 1,119–1,125.

Steffan, W, C. Otto and K. Jezek, "Comparison of brightness temperatures from SSM/I instruments on the DMSP F 08 and F 11 satellites for Antarctica and the Greenland ice sheet" International Journal of Remote Sensing, Vol. 16, pp. 1223-1229, 1995.

Sturm, M., J. Holmgren and G. E. Liston (1995), A seasonal snow cover classification system for local to regional applications. Journal of Climate, 8, 1261-1283.

Van der Veen, C. J. and K. C. Jezek, "Seasonal variations in brightness temperature for central Antarctica" Annals of Glaciology, Vol. 17, 300-306, 1993.

White, W.B. and N.J. Cherry, 1998: Influence of the Antarctic Circumpolar Wave on New Zealand temperature and precipitation during autumn-winter. J. of Climate, **12**, 960-976.

Williams, R. S. Jr. and J. G. Ferrigno, Satellite Image Atlas of Glaciers of the World – South America, USGS Professional Paper 1386-1, US Government Printing Office, Washington, D. C., 1998.

Zuerendorfer, A. and A. England, 1992: Radiobrightness decision criteria for freeze-thaw boundaries, IEEE Transactions of Geophysical Remote Sensing, Vol. 30, No 1.

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Figure 10. Plot showing average monthly snow mass for all months (May-September) from 1979-2006.

Figure 11: Figure showing Southern Hemisphere sea ice coverage: from Comiso and Parkinson, 2004.

Table 2

SMMR and SSM/I monthly snow cover extent and snow mass (SWE) statistics

for the period 1979-2006

Mon	Date	Extent (km**2)	Mass (kg)*10**13
5	1979	152,500	0.16
5	1980	209,375	0.35
5	1981	195,000	0.24
5	1982	176,250	0.24
5	1983	185,000	0.21
5	1984	184,375	0.23
5	1985	151,250	0.18
5	1986	0	0.00
5	1987	185,000	0.18
5	1988	20,625	0.03
5	1989	33,750	0.05
5	1990	31,250	0.04
5	1991	25,625	0.05
5	1992	119,375	0.16
5	1993	125,625	0.19
5	1994	130,000	0.17
5	1995	127,500	0.20
5	1996	128,750	0.17
5	1997	124,375	0.20
5	1998	158,750	0.24
5	1999	138,125	0.17
5	2000	127,500	0.16
5	2001	131,250	0.19
5	2002	111,875	0.16
5	2003	98,125	0.13
5	2004	174,375	0.25
5	2005	125,000	0.21
5	2006	131,875	0.20

Average		**129,722**	**0.18**
6	1979	201,250	0.23
6	1980	260,625	0.42
6	1981	321,250	0.50
6	1982	323,750	0.42
6	1983	398,125	0.54
6	1984	516,250	1.00
6	1985	206,875	0.31
6	1986	311,250	0.85
6	1987	259,375	0.39
6	1988	90,625	0.12
6	1989	86,875	0.14
6	1990	66,250	0.09
6	1991	100,000	0.21
6	1992	218,125	0.42
6	1993	200,000	0.32
6	1994	301,875	1.07
6	1995	213,125	0.43
6	1996	168,125	0.22
6	1997	140,000	0.20
6	1998	175,625	0.25
6	1999	183,125	0.22
6	2000	185,625	0.24
6	2001	210,000	0.36
6	2002	373,750	1.08
6	2003	198,125	0.34
6	2004	180,625	0.24
6	2005	223,125	0.47
6	2006	161,250	0.23
Average		**224,107**	**0.40**
7	1979	201,875	0.25
7	1980	306,875	0.52
7	1981	322,500	0.48
7	1982	595,000	1.43
7	1983	399,375	0.69
7	1984	701,250	2.41
7	1985	328,750	0.49
7	1986	372,500	0.94
7	1987	231,875	0.34
7	1988	145,625	0.28
7	1989	120,000	0.23
7	1990	121,875	0.23
7	1991	178,125	0.41
7	1992	551,875	2.07
7	1993	306,875	0.62
7	1994	333,750	1.07
7	1995	358,750	0.85

7	1996	233,750	0.39
7	1997	318,750	1.02
7	1998	193,125	0.30
7	1999	262,500	0.58
7	2000	483,125	1.75
7	2001	363,125	0.84
7	2002	331,875	0.97
7	2003	254,375	0.51
7	2004	228,125	0.38
7	2005	493,125	1.68
7	2006	268,125	0.53
Average		**321,674**	**0.79**
8	1979	278,750	0.40
8	1980	330,625	0.68
8	1981	278,125	0.48
8	1982	406,875	0.95
8	1983	402,500	0.94
8	1984	541,250	1.55
8	1985	299,375	0.49
8	1986	336,250	0.69
8	1987	501,875	1.03
8	1988	104,375	0.18
8	1989	90,625	0.18
8	1990	100,625	0.21
8	1991	103,125	0.24
8	1992	373,125	1.27
8	1993	208,750	0.50
8	1994	359,375	1.21
8	1995	425,000	1.27
8	1996	209,375	0.35
8	1997	230,000	0.57
8	1998	251,250	0.44
8	1999	263,750	0.52
8	2000	411,250	1.38
8	2001	343,750	1.03
8	2002	362,500	1.21
8	2003	295,625	0.63
8	2004	181,250	0.44
8	2005	366,875	0.93
8	2006	337,500	0.86
Average		**299,777**	**0.74**
9	1979	294,375	0.49
9	1980	284,375	0.60
9	1981	280,000	0.46
9	1982	298,750	0.70
9	1983	375,000	0.90
9	1984	378,125	0.77

9	1985	234,375	0.36	
9	1986	307,500	0.96	
9	1988	55,000	0.08	
9	1989	59,375	0.13	
9	1990	29,375	0.06	
9	1991	31,250	0.08	
9	1992	321,875	0.98	
9	1993	246,875	0.62	
9	1994	251,250	0.63	
9	1995	286,250	0.99	
9	1996	200,625	0.40	
9	1997	188,125	0.60	
9	1998	244,375	0.44	
9	1999	253,750	0.60	
9	2000	361,250	1.08	
9	2001	271,250	0.73	
9	2002	278,125	0.84	
9	2003	236,250	0.53	
9	2004	191,250	0.41	
9	2005	275,000	0.91	
9	2006	223,125	0.57	
Average		**239,144**	**0.59**	note: 1987 data is missing