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Deposition of CO_2 and erosion of the Martian south perennial cap between 1972 and 2004: Implications for current climate change

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[1] We present a comparison of Mariner 9, Viking, Mars Orbiter Camera, and Mars Odyssey Thermal Emission Imaging System visible and infrared images of the south perennial cap taken during the summer between 1972 and 1977 and between 1999 and 2004. Between 1972 and 1977, the lateral expansion and the reduction of the patchiness of the cap indicate that CO_2 ice was deposited. During subsequent years, the distribution of the CO_2 ice has been modified by the erosion and deposition of CO_2 on the cap at the kilometer scale. Because vertical deposition of CO_2 on the cap is only detected when the patchiness decreases as observed between 1972 and 1977, present deposition on the cap would not be detectable and cannot be ruled out. Therefore the current lateral erosion of the walls of the CO_2 cap at the meter scale is not a sufficient observation to conclude that the climate is changing on Mars. The present mass balance of the cap cannot be estimated from available south polar cap images, and it is not possible to determine with the existing data if the climate of Mars is changing.

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1. Introduction

[2] The Mars Global Surveyor (MGS) and the Mars Odyssey missions have provided significant details on the topography, geomorphology, thermal behavior and seasonal evolution of the caps of Mars [e.g., *Albee et al.*, 1998; *Zuber et al.*, 1998; *Hansen*, 1999; *Thomas et al.*, 2000; *Kieffer et al.*, 2000; *Smith et al.*, 2001; *Colaprete and Toon*, 2002; *Titus et al.*, 2003; *Benson and James*, 2005; *Thomas et al.*, 2005, *Kieffer et al.*, 2006]. Among the discoveries was the localized lateral erosion of the south perennial cap at the meter scale [*Malin et al.*, 2001; *Thomas et al.*, 2005] within the so-called "Swiss cheese" features. These features are roughly circular depressions characterized by steep walls ~10 m in height with flat floors [*Thomas et al.*, 2000, 2005]. Thermal models and Thermal Emission Imaging System (THEMIS) temperature measurements show that the upper ~10 m thick CO_2 ice deposit is overlying a layer of water ice [*Byrne and Ingersoll*, 2003]. The total thickness of the CO_2 ice deposit is remarkably uniform over the entire cap (88,000 km^2) suggesting a uniform process of formation and evolution [*Byrne and Ingersoll*, 2003; *Thomas et al.*, 2005].

[3] The observed retreat of the walls of the depressions was interpreted by *Malin et al.* [2001] as a manifestation of the disequilibrium between the CO_2 perennial cap and the atmosphere, and they suggested that Mars is undergoing a climate change as a result. The lateral erosion rates (1–3 m per Martian year [*Malin et al.*, 2001; *Thomas et al.*, 2005]) led to the conclusion that the Martian atmospheric mass increases by 0.08% to 0.008% (6×10^{-3} to 6×10^{-4} mbars) per Martian year. At these rates, all of the layers forming the entire 10 m thick deposit of CO_2 on the water ice cap would sublimate into the atmosphere in a few decades to centuries, with possible implications for the global climate [*Malin et al.*, 2001].

[4] The climate history of Mars is a rich field of study because of the numerous traces left by liquid water on the surface [e.g., *Carr*, 1996; *Baker*, 2001; *Christensen*, 2003; *Malin and Edgett*, 2003]. Under the current atmospheric conditions, liquid water is not stable, which has forced many authors to conclude that warmer conditions prevailed at some point in the past. The influence of astronomical parameters (i.e. obliquity, eccentricity, precession) on the climate has been widely studied, especially with regard to changes of obliquity that would provide conditions (particularly in the polar areas) in which all the CO_2 could be released and create a thicker atmosphere compatible with liquid water [*Murray et al.*, 1973; *Ward*, 1973; *Fanale*, 1976; *Toon et al.*, 1980; *Kieffer and Zent*, 1992; *Jakosky et al.*, 1995; *Laskar et al.*, 2004].

[5] All of these climate models directly or indirectly involve the extent of the cap, i.e., the sequestration of CO_2 from the atmosphere. Therefore a clear understanding of the mass balance history of the cap and the knowledge of the rates at which the cap is growing or contracting at the present time is crucial to any attempt to determine conditions in the past.

[6] In this paper, we focus on the perennial carbon dioxide component of the south polar region and do not treat the water ice reservoir trapped in the subsurface of the

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polar layered deposits. The current models of cap composition, formation and evolution are based on spectroscopic [*Kieffer*, 1970; *Bibring et al.*, 2004], thermal [*Kieffer*, 1979; *Kieffer et al.*, 2000; *Kieffer and Titus*, 2001; *Titus et al.*, 2003], and visible observations at the meter scale repeated over several consecutive summers [*Malin et al.*, 2001; *Thomas et al.*, 2005]. Numerical models have also placed constraints on the nature of the material and the physics involved [*Byrne and Ingersoll*, 2003]. Little input from regional observations over decadal periods of time has been considered, although important work by *James et al.* [1979, 1992] has shown that changes of the ice distribution have been reported in the past. The climatic history of Mars may benefit from data taken over four decades in addition to the high-resolution images obtained by Mars Orbiter Camera (MOC). Ideally, the question of the stability of the current perennial cap should be assessed by comparing the mass of the cap over several years. However, current data do not provide information on mass, volumes or thickness measurements.

2. Method

2.1. Data

[7] Here we present the data sets used to study the size of the south perennial cap between 1972 and 2004. We have selected late summer images (L_s 320 or later) from orbiting spacecraft taken well after the time when the thin seasonal frost has disappeared to expose soil (L_s 305) [*Kieffer et al.*, 2000] in order to minimize confusion with remnants of the seasonal cap. Systematic imaging by MOC and THEMIS has shown that ice that remains through L_s 320 also persists until condensation begins again.

[8] The polar materials consist of ice-free soil, water ice, and CO_2 ice on the basis of their temperature [*Kieffer et al.*, 1976; *Kieffer*, 1979; *Titus et al.*, 2003] and spectral signatures [*Kieffer*, 1970; *Bibring et al.*, 2004]. The southern perennial cap is characterized by a relatively high albedo of about 0.6 [*Titus et al.*, 2003]. Water ice has a lower albedo, around 0.3, probably due to the presence of minor amounts of dust [*Titus et al.*, 2003]. The surrounding fine-grained material composing the south polar layered deposits is also darker than the CO_2 ice (albedo ~0.23 [*Paige and Keegan*, 1994; *Titus et al.*, 2003]). On the basis of these large differences, Mariner 9 and Viking camera images, taken when neither temperature nor spectral observations were acquired to permit more direct observations, are adequate for delineating the edges of the H_2O ice and CO_2 perennial cap versus the surrounding material [*Herkenhoff*, 2001; *Titus et al.*, 2003]. The spatial resolution of the summer polar images is typically low, on the order of 100 to 900 m per pixel on Viking images. To eliminate the bias induced by the comparison of the data from different instruments, we have only considered the changes of more than two pixels during our mapping phase because subpixel mixing between the very bright cap in contact with darker material around can result in relatively high albedo pixels, making the cap appear larger than it truly is. In addition, the different imaging systems were not equally calibrated and a true absolute comparison of the albedo of the different polar units is not feasible. However, an approximate absolute estimation of the albedo and a relative comparison of the different surface units are possible and sufficient as we are mapping changes in the distribution of exposed materials with very strong albedo contrasts.

[9] The different polar materials have remarkably different temperatures despite their close lateral proximity. The ice-free dust can range from 190 K to more than 250 K in the late summer depending on the orientation of local slopes. The exposed water ice is typically 185–210 K depending on the local time in the late summer [*Titus et al.*, 2003]. Finally, the solid CO_2 is at its equilibrium temperature ~150 K, as expected in the presence of a condensable CO_2 atmosphere. As a result, the different polar constituents are easily defined by their temperatures. The Mars Odyssey THEMIS IR imager is well suited for polar studies because of its high spatial resolution (100 m per pixel), frequent repeat coverage and excellent temperature resolution (~1 K at 160 K) [*Christensen et al.*, 2004]. Errors when mapping changes while comparing THEMIS IR images with visible data are unlikely because the albedo and thermal units are homogenous and extremely well correlated near the pole.

2.2. Cap Ice Distribution

[10] We have compared the areal distribution of the south perennial cap on the basis of late summer images taken by Mariner 9, Viking camera, MOC and THEMIS to study the long-term lateral evolution of the shape of the cap and identify regions of deposition and regions of erosion. We have highlighted and mapped the regions of expansion and the regions of contraction. In this paper, the term "expansion" is used to designate a localized lateral growth of the perennial cap over regions that were previously ice free in the late summer. The word "contraction" is used to refer to any removal of the perennial cap to reveal bare soil. We do not use the terms "progression" and "recession" in order to avoid any confusion with the terminology commonly used to describe the waning and waxing of the seasonal caps, and we do not attempt to characterize an increase or decrease in the thickness of CO_2 ice whose lateral extent remained unchanged. We do, however, consider internal changes in ice thickness that have increased or decreased the pixel to pixel patchiness of the cap. Because we have only mapped the most obvious changes, any contraction (or expansion) that may have occurred in the troughs within the cap has not been mapped. The large majority of those troughs are between −90°N and −87°N where no THEMIS data are available.

[11] Figure 1 displays an example of contraction and one of expansion over the period from Mariner 9 (1972) through Mars Odyssey (2004). In the first case, the change occurs between the Viking era (1977) and the Mars Odyssey era (2004); the expansion might have started between 1972 and 1977. The surface area of typical regions of contraction and expansion varies from around 10 km^2 to 300 km^2. Most are ~15 km^2 and occur near the margin of the perennial cap or next to it. The terrains recently uncovered (contraction) do not show any specific morphology at medium to high spatial resolution. We have generated two maps localizing the regions showing expansion and contraction (Figure 2) using similar comparisons of images over time over the entire south polar perennial cap. The existing data allow three separate time frames to be studied. The first is

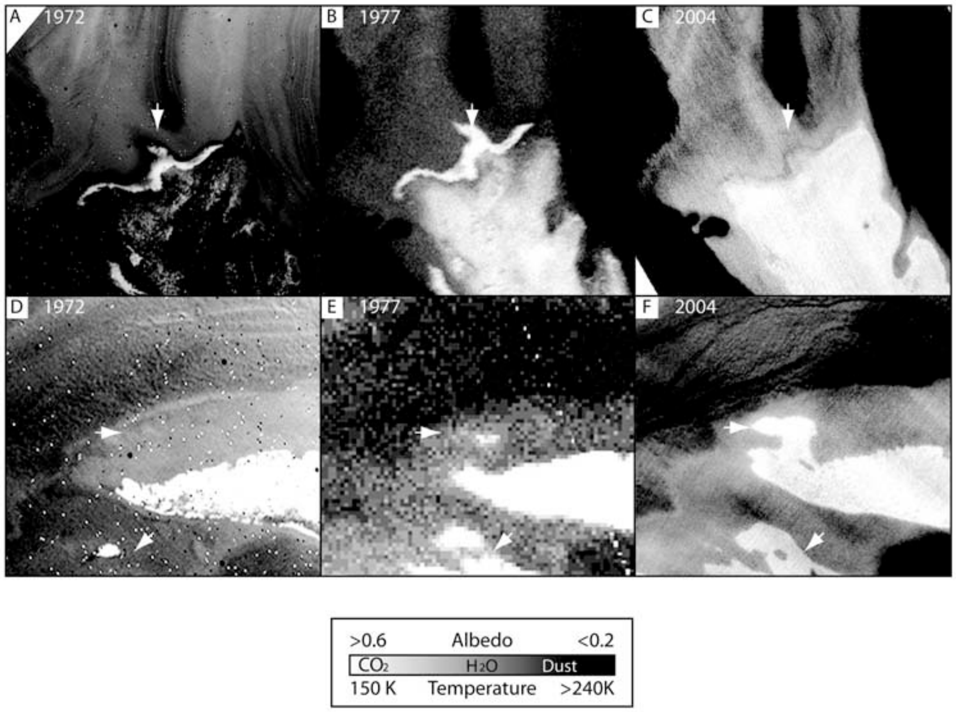

Figure 1. Comparison between Mariner 9, Viking, and THEMIS IR images. Each frame is ~45 × 45 km. (a) Mariner 9 227B05/13 ~L_s 350; (b) Viking 407B57 L_s 342; and (c) THEMIS I09551006, I09451006, and I09039002 L_s 347, 342, and 324 are centered near 346.89°E, −85.49°N. The comparison shows the removal of a 2–4 km large and 25 km long portion of cap from the Mariner 9 and Viking images when compared to the THEMIS images (arrow). (d) Mariner 9 229B01/08 ~L_s 350; (e) Viking 407B57 L_s 342; and (f) THEMIS I09412008, I09549007, I09424009, I09536007, and I09411008 341 < L_s < 347 correspond to net expansion near −86.7°N, 351.5°E. The two arrows point to frosted areas belonging to the perennial cap in 2004 that were frost free in 1972.

between 1972 (Mariner 9) and 1977 (Viking); the second between 1977 and 1999 (MGS) and the last one between 1999 and 2004 (MGS and Mars Odyssey eras). We have listed the images showing changes of ice distribution in Tables 1 and 2.

2.3. Cap Patchiness Mapping

[12] Now we define the patchiness as the relative proportion of dark soil versus bright CO_2 ice at the pixel scale in the perennial cap. Changes of patchiness may indicate the deposition or the removal of a layer of CO_2 frost if bare soil is visible at some point and if the surface turns into CO_2 ice (or vice versa). However, the patchiness is not a direct indication of the thickness of the cap, although thickness and patchiness are likely to be related because of the continuous nature of CO_2 ice condensation and sublimation. Climate modelers on Earth have long been interested in modeling the albedo of snow covers on lands because it has strong implications on circulation and climatic models [*Roesch et al.*, 2001]. An abundant literature treats the relationships between the age of the snow (e.g., the time since precipitation), the depth of the cover (e.g., amount of precipitation, porosity), the albedo (e.g., impurities content, crystal size, porosity) and the snow cover index or fraction which we can compare to the patchiness. Remote sensed data and fieldwork on vegetation free surfaces show that there is a direct relationship between snow cover fraction and snow depth [e.g., *Robinson and Kukla*, 1984; *Baker et al.*, 1991; *Romanov et al.*, 2003]. A smaller snow fraction (or higher patchiness) is observed with thinner snow covers. We are not suggesting that we can extrapolate to Mars the calculations made on Earth with different materials and physical conditions, but it is likely that on Mars, as on the Earth, the patchiness of a terrain decreases when ice is added and increases when frost is removed. The comparison of patchiness is limited by the coverage of the pole provided by Mariner 9 and the extremely variable quality of the data. For this work, we have only used the highest-quality Mariner 9 images, (~45 images) giving ~90% coverage of the cap. The spatial resolution of Viking polar images is also a limiting factor. Global views of the cap are always affected by the very low Sun illumination angle and the variable local slopes, which tend to saturate (both low and high) parts of the images. We have defined three types of surfaces on the basis of their apparent patchiness. The limits are obviously gradational and our ability to distinguish them is only approximate:

[13] 1. Patchy cap surfaces: These terrains are characterized by surfaces where the soil is more abundant than the perennial CO_2 ice. Numerous small mesas of perennial CO_2 ice are present with dark soil visible all around the CO_2 buttes.

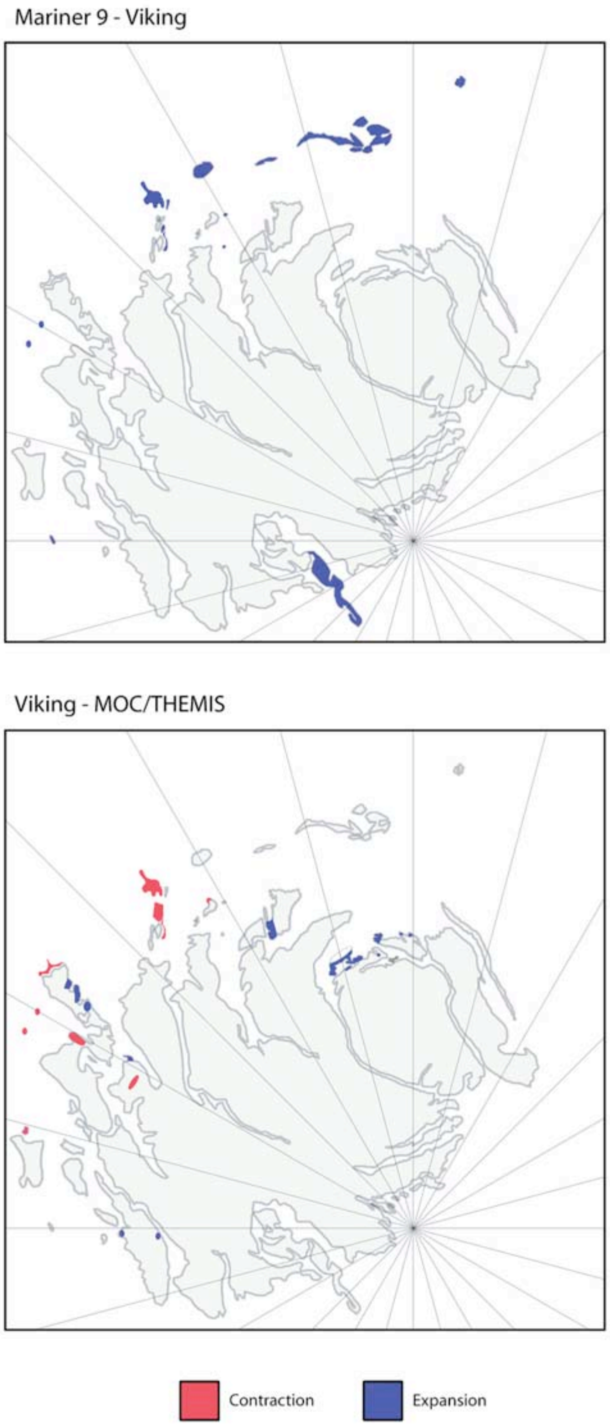

Figure 2. Expansion and contraction of the south perennial cap between (top) 1972 and 1977 and (bottom) 1977 and 2004.

[14] 2. Discontinuous cap surfaces: This type of surface corresponds to terrains that still display dark soil underlying the perennial ice but the CO_2 does not form mesas and buttes but a continuous to subcontinuous unit. The CO_2 ice covers more surface than dark soil.

[15] 3. Continuous cap surfaces: In this case, the CO_2 coverage is nearly complete and the surface is homogeneously bright. Rarely, depressions show the dark underlying material.

[16] Figure 1a is an extreme example of patchy terrain. The high-albedo CO_2 ice covers a very small fraction of the surface of the perennial cap and results in a lower-albedo unit. An example of a continuous surface with a uniform coverage of the cap is shown in Figure 1c. In these regions, the cap is uniformly covered by the CO_2 ice without any window to the underlying material, except near its equator margin.

[17] The intermediate case, where the CO_2 ice continuously covers the cap but displays occasionally the underlying soil in the center of roughly circular regions is what we called discontinuous (Figure 1d). These observations are consistent with a relatively thick ice unit that thins locally to reveal dark soil at the pixel to subpixel scale. On the basis of this definition of the different degrees of patchiness of the perennial cap, we have mapped the distribution of each one from Mariner 9, Viking and MOC wide-angle/THEMIS data. The result is presented in Figure 3.

3. Observations

3.1. Years 1972–1977

[18] The shape of the edges of the cap between 1972 and 1977 underwent significant expansion in 17 locations (Figure 2 and Table 1) with an estimated total surface area of ~600 km^2. The main region of expansion is situated close to the geographic pole where temperatures are lowest for the longest period of time each year and where net accumulation of CO_2 is most likely. The thickness of this layer of CO_2 cannot be determined with the available data. Several smaller patches of CO_2 frost around the equatorial margin of the cap also survived the 1977 summer but were not present in 1972. Most of these patches have continued to survive until the present and they can therefore be considered at parts of the current perennial cap. No region of contraction is identified between 1972 and 1977. Figure 4 is an example of a region of expansion. A large surface becomes covered with CO_2 frost between 1972 and 1977 (between the arrows). This specific patch subsequently

Table 1. Mariner 9 and Viking Data Used to Map the Changes on the Cap

Mariner 9		Viking					
Image ID	L_s	Image ID	L_s	Latitude	Longitude, deg E	Area	Change
215A03/19	306	383B26	328	−83.7	6.2	1	expansion
145B04/32	332	383B42	328	−88.7	216.4	2	expansion
DAS ERT 7612503	336	383B24	328	−83.8	352.5	3	expansion
DAS ERT 7612503	336	383B24	328	−84.0	356.4	4	expansion
DAS ERT 7612503	336	383B24	328	−84.2	353.8	5	expansion
DAS ERT 7612503	336	383B24	328	−84.2	351.0	6	expansion
196B01/27	344	383B24	328	−84.0	346.6	7	expansion
196B01/27	344	390B61	332	−84.0	338.2	8	expansion
196B02/27	344	383B22	328	−84.5	329.2	9	expansion
196B02/27	344	383B22	328	−84.8	325.9	10	expansion
227B02/13	350	390B69	332	−84.0	319.4	11	expansion
227B02/13	350	390B82	332	−83.7	329.9	12	expansion
227B02/13	350	390B69	332	−83.7	323.6	13	expansion
227B02/13	350	390B69	332	−83.9	323.2	14	expansion
215A03/19	350	390B65	332	−83.0	298.8	15	expansion
215A03/19	306	390B65	332	−83.0	297.2	16	expansion
211B03/19	347	390B66	332	−84.6	271.0	17	expansion

Table 2. Viking and THEMIS Data Used to Map the Changes on the Cap

Viking		THEMIS					
Image ID	L_s	Image ID	L_s	Latitude	Longitude, deg E	Area	Change
390B63	332	I17562011	332	−84.3	327.2	A	contraction
390B63	332	I17300009	320	−83.9	321.7	B, C, D	contraction
		I17687018	338				
390B63	332	I17675013	337	−84.0	303.4	E, I, 9, 10, 11, 12	E, I: contraction
		I17488016	329				9, 10, 11, 12: expansion
390B09	332	I17613010	334	−82.1	298.0	F, G	contraction
		I17588009	333				
		I17713014	339				
390B63	332	I17538010	331	−84.3	298.0	H	contraction
		I17588009	333				
		I17613010	334				
390B09	332	I00826006	330	−84.0	284.5	J	contraction
		I17576011	333				
		I17626012	335				
		I17676013	337				
390B09	332	I00826006	330	−86.1	265.0	13, 14	expansion
		I17576011	333				
		I17626012	335				
		I17676013	337				
383B24	332	I17710013	339	−85.9	357.0	1, 2, 3	expansion
		I17735014	340				
		I17785013	342				
		I17835017	344				
		I17573010	333				
383B24	328	I09424009	341	−85.9	345.0	4, 5, 6, 7	expansion
390B09	332	I17711013	339	−85.1	335.1	8	expansion
		I17449009	327				
		I08963009	320				
		I17574010	333				

disappeared between 1977 and 1999, which is rare for regions of expansion. In 1972, the cap was extremely patchy especially along its equatorial margin (Figure 3). By 1977, the situation was very different. As pointed out by *James et al*. [1979], some regions of the cap are much less patchy than in 1972. No patchy units are identified in 1977, although there is still a substantial region mapped as discontinuous, especially close to the geographic pole, and along dark lanes (Figure 3). Some discontinuous regions correlate well with the 1972 patchy terrains, suggesting that those places have experienced detectable CO_2 accumulation since 1972. Similarly, numerous regions mapped as discontinuous in 1972 appear to have increased in ice cover and/or thickness to become continuous in 1977. In summary, the period from 1972 to 1977 saw only expansion and an increase in the inferred ice thickness.

3.2. Years 1977–1999

[19] During the Viking to MGS time period (1977–1999), the cap experienced contraction as well as expansion.

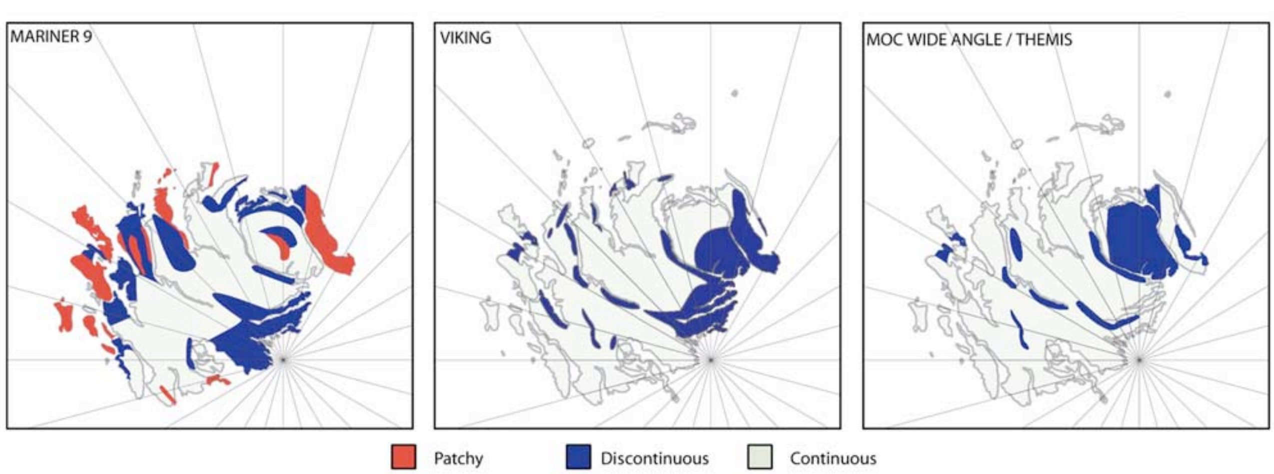

Figure 3. Maps of the apparent dark soil to bright perennial CO_2 ice ratio (patchiness) within the perennial cap in 1972, 1977, and 1999–2004. We define three types of surfaces: patchy, discontinuous, and continuous.

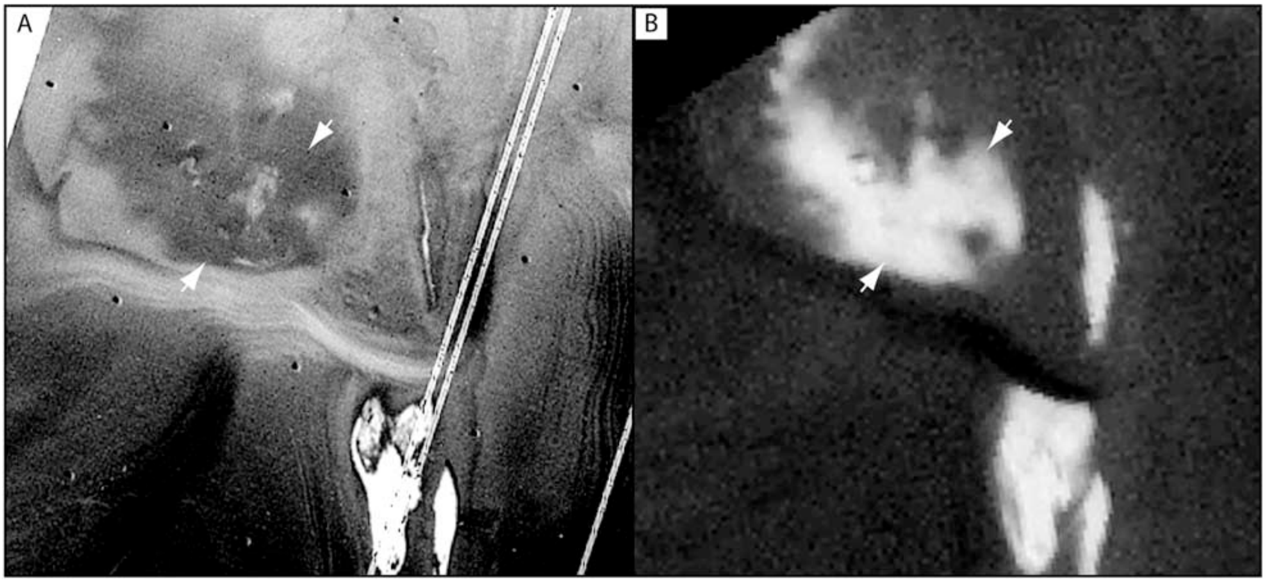

Figure 4. Example of expansion between 1972 (Mariner 9 227B03/13 L_s 350) and 1977 (Viking 390B63 L_s 332) where a large patch of CO_2 appears (white arrows). The frames are 55 km × 55 km.

Nine places where the cap has contracted (i.e. transitioned from a CO_2 covered terrain in 1977 to a water ice covered or bare soil terrain in 1999) are identified. They represent a total surface of ~300 km^2. The largest single area is situated at -83.59°N, 322.22°E and corresponds to a ~120 km^2 contraction of the CO_2 ice cap (Figures 1b and 1c). Contraction generally occurs at the edge of the cap, but not always; for example, at -85.22°N, 296.97°E, there is contraction of the cap in a depression in the middle of the perennial CO_2. Finally, it seems that the ice within the few troughs equatorward of -87°N has contracted.

[20] Twelve major places show noticeable expansion of the area occupied by CO_2 in the late summer between 1977 and 1999. Collectively, these regions represent a surface of ~320 km^2. The largest single area of expansion is ~80 km^2 and is located at –85.90°N, 342.48°E. Like contraction, expansion primarily occurs at the edge of the cap, not inside the thin dark lanes surrounded by CO_2 in the heart of the cap, although this may be an observational artifact.

[21] The expansion is mostly concentrated at -85.9°N, 342°E where around ten new patches are identified. The thickness of a patch of cap that appeared between 1977 and 1999 has been tentatively evaluated using Mars Observer Laser Altimeter (MOLA) data (Figure 5). The MOLA cross sections suggests that the top of the CO_2 layer might be up to 4 m above the surrounding terrains, which may indicate that the patch is 4 m thick. Data are variable, the uncertainty is on the order of 2 m, and the elevation of the terrain underneath the CO_2 ice is unknown. Unfortunately, no overlapping MOC narrow angle images are available in these regions of interest to conduct a detailed comparison of those areas between 1999 and the present.

[22] The cap's patchiness appears nearly identical from 1977 through the MGS era. It is mostly mapped as continuous. The patchier parts are associated with the edges of dark lanes inside the cap. The largest unit mapped as discontinuous, around 0°E, correlates with a region already mapped as such in 1977.

3.3. Years 1999–2004

[23] Between 1999 and 2004, the southern Martian summer cap has been observed repeatedly by MOC wide angle and THEMIS. Over this period of time, no contraction or expansion has been observed at the multikilometer scale at the margin of the cap. However, *Winfree and Titus* [2007] have reported that the area of the cap seems to have increased during the Mars Odyssey era because of the deposition of CO_2 ice within the troughs of the cap. No significant change of patchiness of the cap is observed between 1977 and 1999 or later.

4. Interpretation

4.1. Size of the Cap

[24] Changes of the cap area are identified because they result in expansion or contraction. There is no data in the vertical dimension indicating the volumes of ice involved, so expansion and contraction can only be interpreted in terms of lateral erosion or deposition of CO_2 at the periphery of the cap. Net expansion of the cap is observed between 1972 and 1977. Net expansion means that the overall surface covered by CO_2 frost has increased over time and a new layer of CO_2 condenses from the atmosphere on bare soil. It cannot be determined if the cap gains mass when expansion is observed because the volumes are unknown. Localized expansion is also observed between 1977 and 1999 but the total surface area of the regions of contraction is similar. As a result the overall surface area of the cap was the same in 1977 and 1999. The observation of two large events of expansion (net expansion in 1972–1977 and expansion and contraction in 1977–1999) shows that the lateral deposition of CO_2 ice is possible.

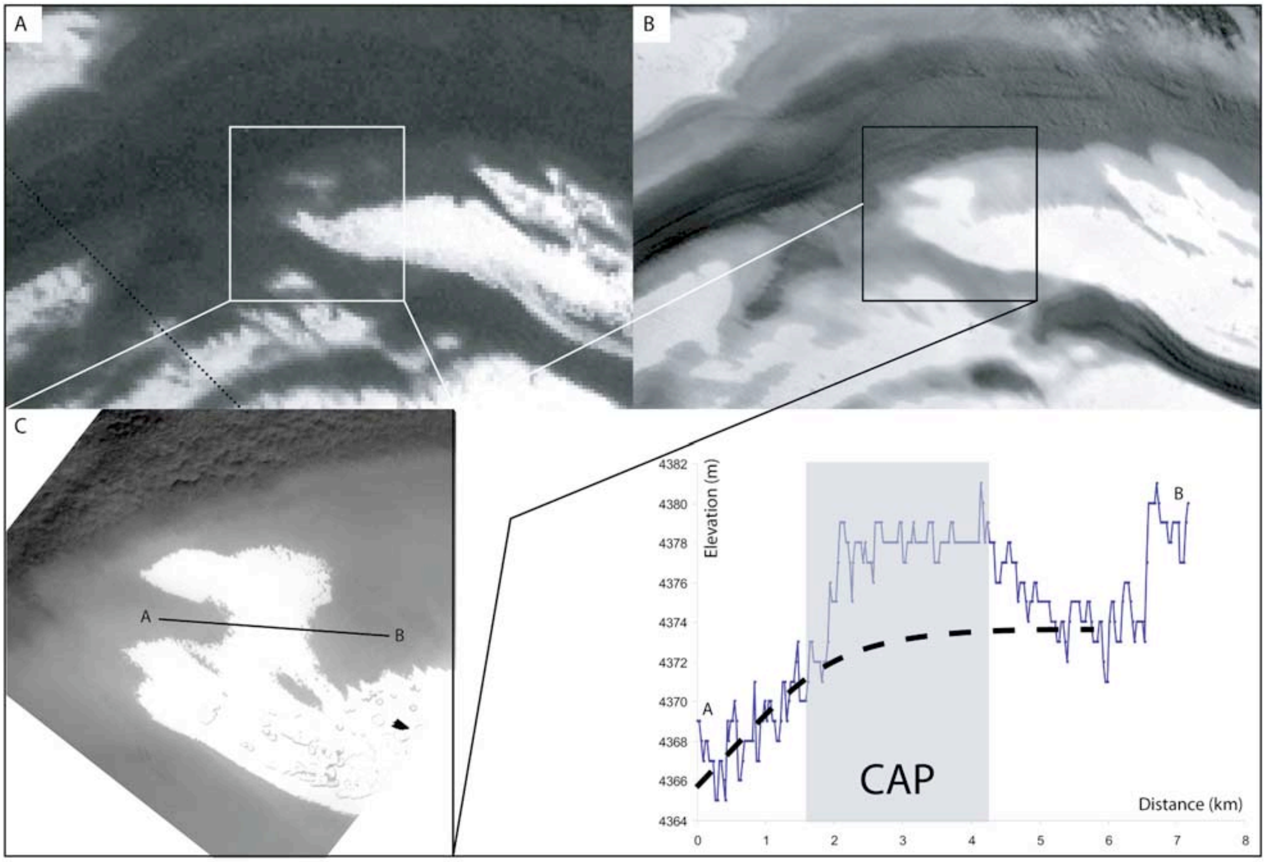

Figure 5. Example of expansion between (a) Viking 390B61 L_s 332 in 1977 and (b) THEMIS IR in 2004. A patch of CO_2 appears during this time period. The frames are 80 × 50 km. Also shown is (c) a portion of THEMIS V17935011 L_s 349 with the position of a MOLA cross section suggesting that the ice deposit could possibly be up to ~4 m thick.

[25] The contraction of several regions of the cap is observed between 1977 and 1999. Contraction means that the surface covered by CO_2 frost has decreased over time. Wherever contraction is observed, the local mass budget of the CO_2 ice is negative. Again, because the volumes of the units removed are unknown, at the cap scale, the mass budget cannot be evaluated. However, the observation of contracting regions in the recent past confirms that lateral erosion over large surfaces (tens of square kilometers) does happen.

4.2. Patchiness

[26] The patchiness is the ratio of bright CO_2 ice versus dark soil. A change of patchiness is an indicator of the deposition or removal of a veneer of CO_2 in the interior of the cap. Changes in patchiness are different from contraction and expansion because they concern the interior of the cap, not the periphery, and they indicate vertical variations of carbon dioxide ice distribution. The absence of change of patchiness cannot be interpreted: vertical deposition and erosion might occur on thick CO_2 layers without reaching bare soil and be undetected. However, when the cap evolves from patchy to continuous, a layer of CO_2 is deposited and covers more bare soil. The thickness of the layer cannot be determined, only a new vertical layer can be detected. Between 1972 and 1977, the patchiness decreases significantly, indicating the deposition of a layer of CO_2 on most of the cap. After 1977, the patchiness does not appear to evolve. Whether the veneer has thickened, thinned, or remained the same cannot be directly determined. An important point here is that the vertical deposition of CO_2 frost did occur at the regional scale between 1972 and 1977.

4.3. Recent Cap History

[27] The patchiness evolution, contraction and expansion of the cap show that several episodes of lateral and vertical erosion and deposition of CO_2 happened since 1972. We now propose to reconstruct the history of the changes of the cap from the late 1960s to 2004.

4.3.1. Before 1969

[28] The best Mariner 9 images of the polar cap acquired in 1972 have a resolution high enough to display the large circular depressions shown in detail by MOC and THEMIS. These features are formed by the retreat of the walls as modeled by *Byrne and Ingersoll* [2003] and observed by *Malin et al.* [2001]. Their current size indicates that these features take many years to form, maybe ~100 Martian years [*Thomas et al.*, 2005]. Therefore their presence in 1972 proves that a similar lateral erosion of the cap walls was active at some point before 1972 and lasted long enough to

form large depressions. More than a Martian year before, e.g., before 1969, the walls of the cap were retreating in a similar fashion as they do today [*Thomas et al.*, 2005].

4.3.2. Year 1969

[29] *Jakosky and Barker* [1984] proposed that the entire CO_2 cap disappeared in 1969, explaining the spike of water vapor in the atmosphere that specific year [*Barker et al.*, 1970]. They concluded explicitly that all the southern CO_2 ice had to be removed to expose enough water ice under the CO_2 veneer to explain the magnitude of the increase of the atmospheric water vapor content. As explained above, the Mariner 9 images do not support this hypothesis because they display large circular depressions (probably on the surface type A [*Thomas et al.*, 2005]) identical to those observed today. If the retreat of the scarp was similar to what it is today or even orders of magnitude larger, these features could not have formed between 1969 and 1972. We propose that an event did occur in 1969, resulting in the exposition of more water ice to the atmosphere, but the entire CO_2 cap was not removed. Additionally, water ice could have been exposed if a regional layer of the cap sublimed or if the millimeter to centimeter thin layer of dust on the water ice table in the polar layered deposits had been removed by strong winds [*Piqueux et al.*, 2006]. In 1972, the cap had the smallest surface area of any other year and its patchy appearance suggests that a layer had been removed regionally but the entire cap could not have disappeared.

4.3.3. Year 1972

[30] *James et al.* [1979, 1992] compared the aspect and changes of the cap between Mariner 9 and Viking images. They noted that the perennial cap was locally patchier in 1972 giving the unusual aspect depicted in Figure 1a or Figure 1d. Our regional observations confirm the findings of *James et al.* [1979, 1992] regarding the eroded aspect of the cap, which may have been caused in part by the erosive event of 1969 and the meter scale lateral erosion of the cap [*Thomas et al.*, 2005]. Figure 2 also demonstrates that the 1972 cap had the smallest surface area of any other year.

4.3.4. Years 1972–1977

[31] In 1977, the retreat of the seasonal cap was significantly delayed compared to other years [*James et al.*, 1979]. The cap also experienced expansion during this period (Figure 2) and we have interpreted the reduction of the patchiness as the result of the deposition of a regional layer of CO_2. At the regional scale, there is no indication of mass loss of the cap but high-resolution data are not available so the mass balance of the cap during this period is not known. However, an important observation during this time period is that vertical deposition of CO_2 ice on the cap did occur.

4.3.5. Years 1977–1999

[32] Between 1977 and 1999, some CO_2 ice has been deposited to the periphery (expansion) and some has been removed (contraction). The areal expansion and contraction are balanced but it is not known if the same volumes of CO_2 were involved. In addition, the patchiness did not change. Again, there is no data at the meter scale and in the vertical dimension.

4.3.6. Year 1999 to Present

[33] The CO_2 cap seems to be losing mass because of the retreat of the walls of the circular depressions [*Malin et al.*, 2001] and because no large (e.g., multikilometer scale) regions of expansion or change of patchiness are visible (this work). The mass lost to the atmosphere is evaluated by *Malin et al.* [2001] at $2-10 \times 10^9$ m^3 per year or $6-30 \times 10^9$ m^3 in three Martian years and at 0.04% of the mass of the atmosphere by *Thomas et al.* [2005]. The surface area of the cap is 88,000 km^2. If the CO_2 removed from the wall was redeposited vertically on the cap, the equivalent thickness of the layer would be $\sim$8–34 cm (17 cm calculated from *Thomas et al.* [2005]) which could not be detected by any available imaging system.

[34] Yet, recent THEMIS observations [*Winfree and Titus*, 2007] suggest that localized expansion may be presently occurring in the troughs of the cap, increasing the area of the cap. Because volumes are not known, it is not possible to evaluate if this deposition balances the lateral erosion of the wall of the perennial cap.

5. Model of Polar Cap Evolution

5.1. Perennial Cap Evolution

[35] From the energy budget of the CO_2 ice deposits point of view, there is a continuum between the seasonal and perennial cap, and the perennial cap continues to lose ice throughout the summer. The perennial cap is simply those locations where the ice is thick and dense enough to persist until condensation begins again in the fall (e.g., where the total latent heat of sublimation budget of the CO_2 ice deposits exceeds the solar energy input). The persistence of most of the new patches that we identified in the regions of expansion originates from the incomplete sublimation of the seasonal cap and survived one summer. Except for a few limited cases, each new patch always survives the next few summers (Figure 2) and therefore has become a part of the perennial cap. The perennial cap is made of a series of stratigraphic layers of CO_2 [*Thomas et al.*, 2005] being on the order of 1–2 m thick, which may correspond to different events of deposition. Occasionally, regional events of erosion may remove one or several layers of seasonal CO_2 as might have happened in 1969.

[36] A similar process may have occurred at earlier times. Percival Lowell reported a series of observations of the retreat of the seasonal cap in 1894 [*Lowell*, 1896] remarkably consistent with Thermal Emission Spectrometer (TES) data (Figure 6a). The comparison of the original drawing and TES maps [*Kieffer et al.*, 2000] indicates that the absolute position of the cap was slightly offset on Lowell's drawing by 2°–5° which may be due to an error in the absolute determination of the latitudes and longitudes. The surface and shape of the cap are remarkably similar in 1894 and 1999 at Ls 215 and 225 (Figure 6b). At Ls 235 and after, Lowell's drawings suggest that the recession of the cap was faster than in 1999. He and his assistant noticed that at Ls 300, the cap became faint, shrunk to a size of $\sim$390 km^2 (compared to 88,000 km^2 presently) and finally disappeared [*Lowell*, 1896]. A regional dust storm may have reduced the visibility of the cap but Lowell did not report significant changes or loss of contrast on the Martian disk during this period. It might be possible that the cap experienced an extreme event of erosion shortly followed by the redeposition of a new series of layers, free of erosive features. If the lateral erosion rates of the cap have not significantly changed over time, the age of Unit A (at least

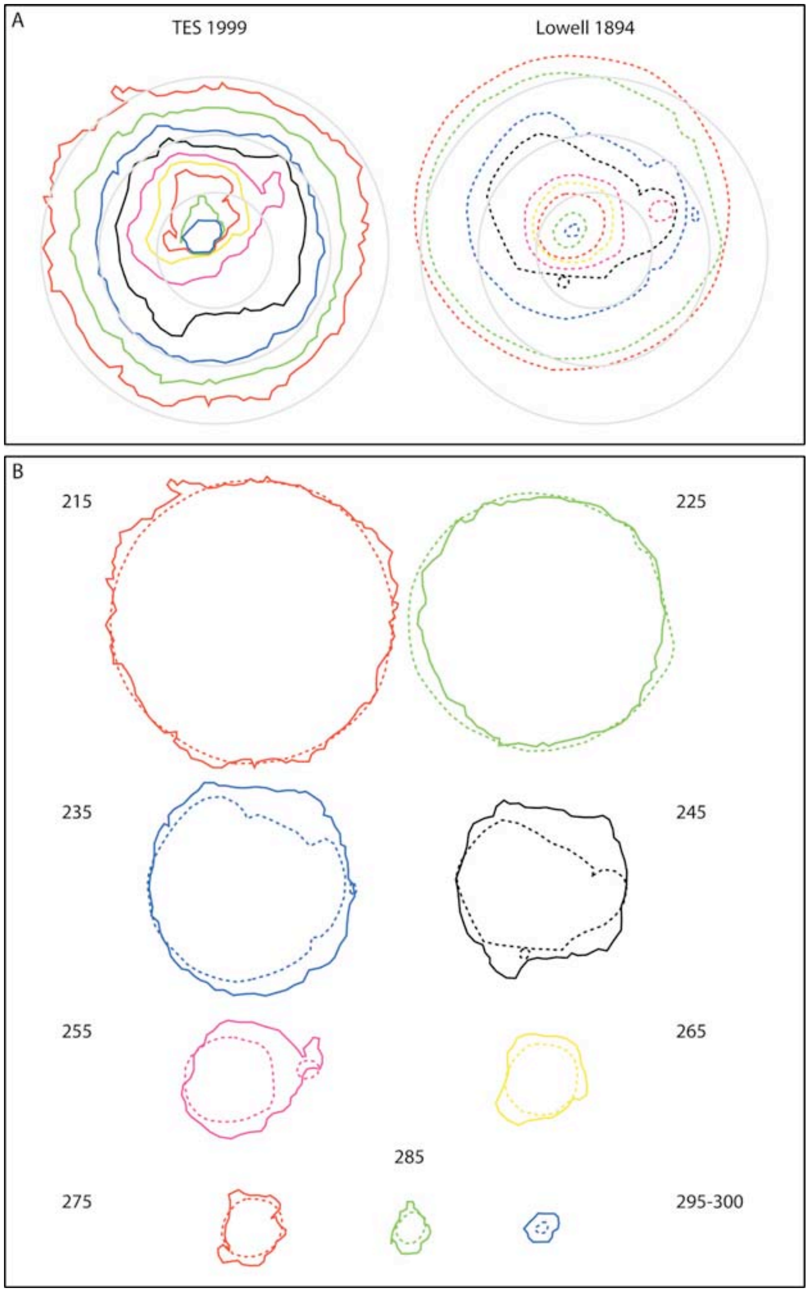

Figure 6. Comparison of the extent of the seasonal and perennial cap in 1894 from Percival Lowell's drawings [*Lowell*, 1896, chapter 3, plate 2] and TES data from 1999 [*Kieffer et al.*, 2000, Figure 9] between L_s 215 and 300. Latitude lines are −80°N, −70°N, and −60°N.

~150 Martian years old) calculated by *Thomas et al.* [2005] necessitates that it was deposited in the early 18th century and has survived since then. The age of Unit B (~45 Martian years) is consistent with the putative 1894 event (there are 58 Martian years between 1894 and 2004) leaving open the possibility that this event eroded all of the cap except for Unit A, making the cap difficult to observe. The deposition of a series of layers (Unit B) followed this erosive event.

[37] During the opposition of 1956, visual observations from several astronomers suggest that the seasonal and perennial cap disappeared at ~Ls 256 [*Kuiper*, 1957; *Křivskỳ et al.*, 1965, and references therein] and reformed a few days later but dust storms, large clouds and hazes have been reported all over the planet during the spring and the summer and may have hidden the polar surface for some days. In addition, photographs from several observatories clearly show the cap during this period [*Slipher*, 1962].

[38] In 1969, one or several layers of CO_2 may have been removed regionally resulting in the sublimation of unusually high amounts of water ice into the atmosphere. The comparison between Mariner 9 (1972) and Viking (1977) images suggests that after such an event, the cap recovers part or all of its lost mass by lateral deposition at its periphery (net expansion) and vertical deposition of CO_2 (patchiness decrease).

[39] Lateral erosion at the meter scale also occurs, as first reported by *Malin et al.* [2001] and at a larger scale between 1977 and 1999. The absence of large changes between 1999 and 2004 may indicate that the perennial cap is back to a steady state in which its mass is roughly stable. Migration of CO_2 within the cap might be possible and hardly detectable.

[40] Recent work by *Winfree and Titus* [2007] suggests that some lateral expansion may be occurring. Therefore the retreat of the walls of the circular depressions is not a sufficient observation to conclude that the cap is losing mass. The current estimations of the sublimation rates suggest that the cap is losing mass and will be entirely removed in a few Martian decades or more [*Malin et al.*, 2001; *Thomas et al.*, 2005]. However, the Mariner 9 images (1972) show a cap that was much more eroded than now (Figures 1–4), and even if we cannot measure the mass balance, the data suggest an important mass gain between 1972 and 1977.

[41] Figure 7 illustrates the complex behavior of the CO_2 ice between 1972, 1977, and 2004. Three representative regions are shown during three different summers. In the first series (Figures 7a, 7b, and 7c), a portion of the cap is being permanently removed. The contraction in this area is suggestive of mass loss by the cap and rapid, but minor, climate change. Alternatively, the CO_2 ice could have been redeposited somewhere else with no net change in mass. The second series (Figures 7d, 7e, and 7f) shows a region where some CO_2 is being eroded locally and some is being deposited. From this specific region alone, one may conclude that the CO_2 is mobile. The amount eroded near the upper arrow may redeposit somewhere else, near the second arrow for example. Without knowledge of the volumes, the mass balance cannot be determined but this series shows

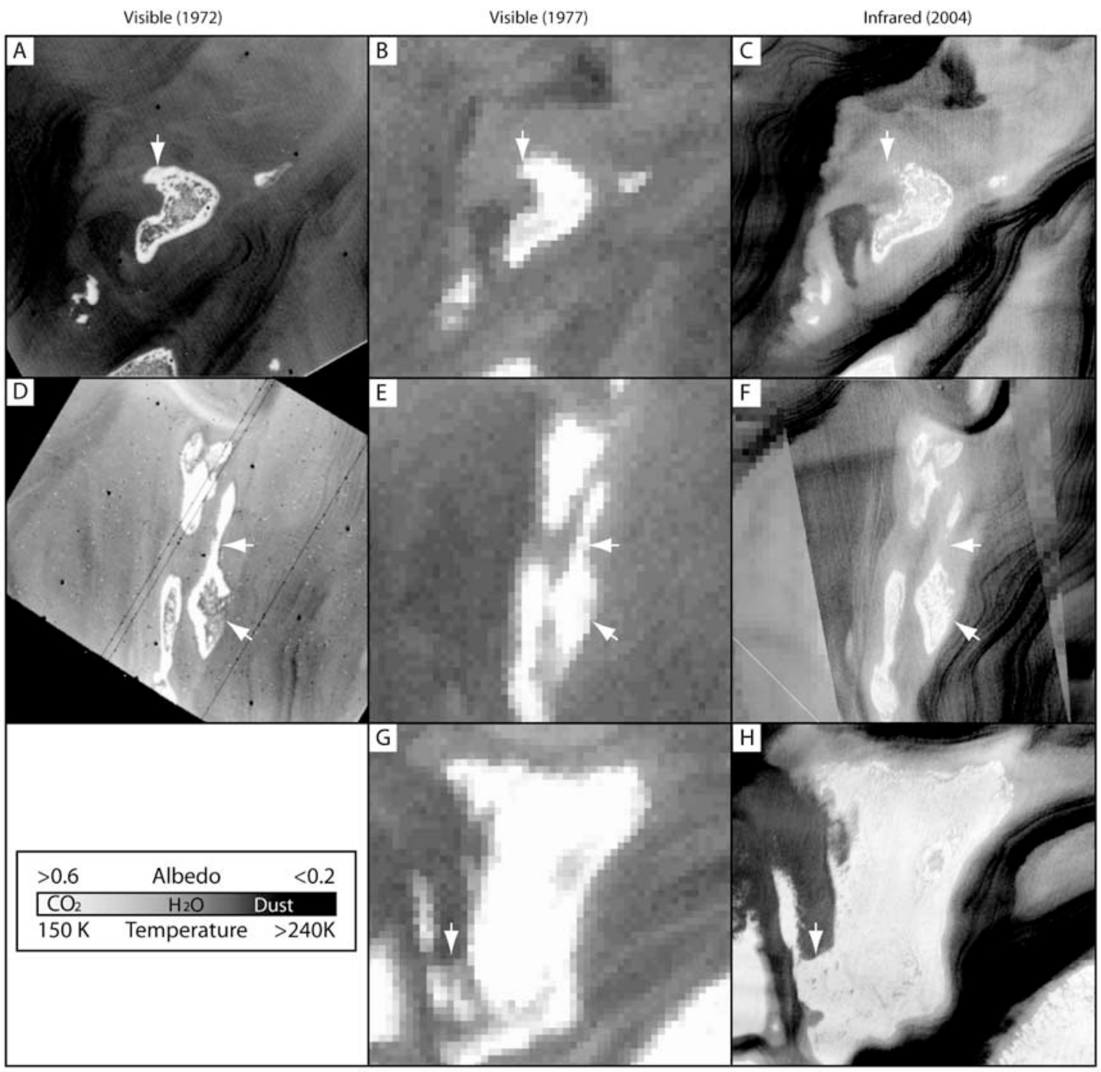

Figure 7. Three areas (−84.4°N, 327.1°E; −84.1°N, 319.4°N; and −85.0°N, 336.6°E) with different evolution. (a) Mariner 9 196B02/27 L_s 343; (b) Viking 390B61 L_s 332; and (c) THEMIS I17562001 L_s 332 are examples of contraction. (d) Mariner 9 227B03/13 L_s 350; (e) Viking 390B63 L_s 332; and (f) THEMIS I17787014, I17762012, and I17712014 L_s 342, 341, and 339) are examples of local migration of ice. (g) Viking 390B61 L_s 332 and (h) THEMIS I17861013, I17786014, I17736016, and I17624010 L_s 345, 342, 340, and 335 are examples of expansion.

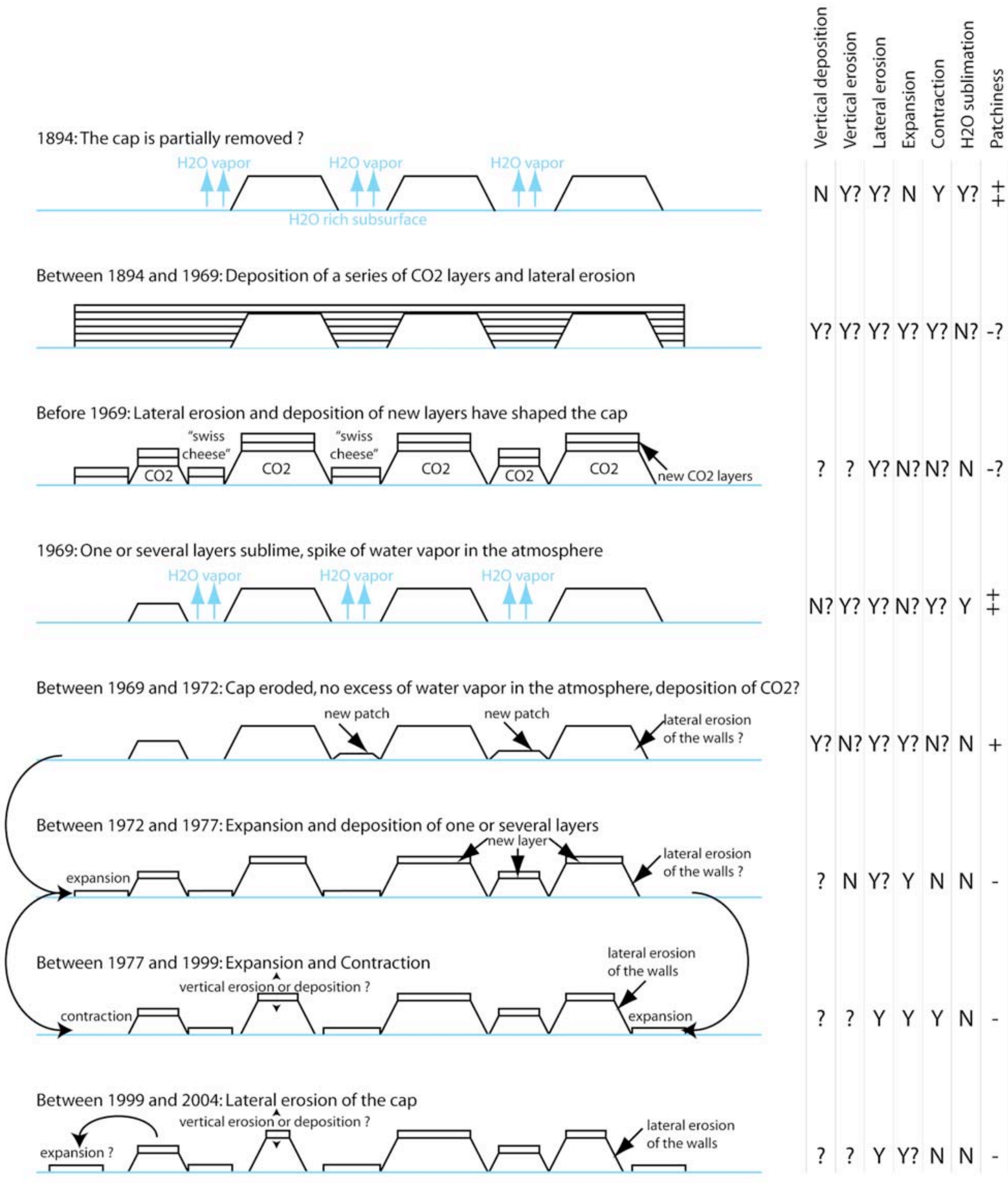

Figure 8. Summary of the model of evolution of the cap between 1894 and 2004. Y and N stand for yes and no. The degree of patchiness is relative (two pluses indicate a very patchy surface, and a minus indicates a continuous surface). "H_2O sublimation" refers to spikes of water vapor in the atmosphere similar to the one observed in 1969.

that migration of CO_2 ice occurs at a short spatial scale. Finally, the last series (Figures 7g and 7f) shows a portion of the cap expanding. The observation of this region may lead to the conclusion that the cap is gaining mass and/or that CO_2 ice is coming from a place experiencing erosion at the same time (similar to the region shown in Figures 7a, 7b, and 7c). The observation of each region is suggestive of a different and opposite evolution, involving deposition, erosion and redistribution of CO_2 ice. One cannot conclude that the cap is losing mass by looking at the cap without accurate mass balance estimates.

[42] The variability of the seasonal and perennial caps characteristics (timing of the recession, albedo, and changes of the edges of the residual cap) is not attributed to a specific identified process. Dust storms have been proposed to contribute to this variability because they have a regional and global influence on the energy budget of the surface and the atmosphere, on the albedo of the regions where dust is deposited, and on the concentration of suspended dust from which frost crystals nucleate in the fall [*Kahn et al.*, 1992]. Atmospheric and surface dust deposition should enhance the sublimation rate of the caps [*Paige and Wood*, 1992; *Bonev et al.*, 2006, 2008]. Dust storms of all magnitudes occurring over a wide range of locations and seasons have been documented [*Kahn et al.*, 1992] and their influence on the polar environment has not been shown to be determinant [*James et al.*, 1987; *Benson and James*, 2005]. However, *Titus and Kieffer* [2002] and *Bonev et al.* [2002] observed a faster recession of the seasonal cap in the region of the Mountains of Mitchel in 2001, the year of a major dust storm. During the three years of pressure measurements by the Viking landers, little variability was observed, whereas the storm activity varied significantly, indicating that the CO_2 cycle is not strongly linked to the occurrence of dust storms [*James et al.*, 1987]. The phases of deposition and erosion of CO_2 near the south pole of Mars since 1972 have been characterized during time periods of several Martian years (1972 to 1977; 1977 to 1999), and not individual years so the exact timing is not known and cannot be compared with dust storms. The localized erosion and deposition may be associated with local weather conditions whose unpredictable variability cannot be linked with global or regional climatic patterns.

[43] The south perennial cap can provide information on climatic change only if mass or volume balances can be determined. This is not the case with present data sets. Figure 7 illustrates the local mass loss and gain in specific regions, and shows that a representative behavior of the entire cap cannot be determined from a few small regions alone. Figure 8 summarizes the different steps of the model of polar cap evolution that we have presented here.

5.2. Climate Change

[44] The last decades of observations show that the southern cap is not a static geological unit but has undergone numerous changes. The actual volume of the CO_2 perennial cap can be evaluated knowing its surface (88,000 km^2) and thickness (<10 m) [*Thomas et al.*, 2005]. Even if the cap were to be entirely eroded and transferred to the atmosphere through a global sublimation process, the net increase of the atmospheric pressure would only be on the order of 0.36 mbar [*Byrne and Ingersoll*, 2003]. The mean pressure of Mars is 5.2 mbar [*Smith and Zuber*, 1998] so the polar reservoir of carbon dioxide represents only 7% of the actual atmospheric pressure, and does not even correspond to the seasonal variation measured by the Viking landers.

[45] No massive carbonate body has been discovered [*Christensen et al.*, 2001], although disseminated carbonate does occur in minor amounts in the Martian dust [*Bandfield et al.*, 2003; *Christensen et al.*, 2004]. These mineral reservoirs cannot, however, easily exchange with the atmosphere.

[46] The adsorption and desorption of atmospheric CO_2 by the regolith is the subject of an abundant literature [*Fanale and Cannon*, 1971, 1974, 1978, 1979; *Fanale et al.*, 1982]. Laboratory measurements indicate that crushed basalt and clays easily adsorb and desorb CO_2 [*Fanale and Cannon*, 1971]. As the atmospheric pressure increases, the regolith can adsorb larger amounts of CO_2 and, with the polar caps, acts as a buffer to the atmospheric pressure. At low obliquity, the polar caps act as a CO_2 sink and the regolith as a CO_2 source and at high obliquity the system reverses [*Fanale et al.*, 1982]. When the perennial cap is losing mass, a fraction of the CO_2 is transferred to the regolith and does not participate to any enhanced green house effect [*Fanale et al.*, 1982] attenuating the climatic impact of the reduction of the mass of the perennial cap.

[47] The only near-surface solid carbon dioxide reservoirs available on Mars are the seasonal and perennial caps. This has a fundamental application for the investigation of the past climate of Mars. During high-obliquity periods, when the perennial polar caps are likely to have entirely sublimed away [*François et al.*, 1990], the maximum partial pressure of CO_2 in the atmosphere was not fundamentally different from what it is now. Therefore gaseous carbon dioxide cannot account for a hypothetical enhanced greenhouse effect in Mars recent history. Water vapor is the only other common gas whose concentration can significantly change over time in the Martian atmosphere.

6. Conclusion

[48] The south perennial cap of Mars is an active geological unit that responds dynamically to its environment. These adjustments correspond to (1) the erosion of the perennial cap where the CO_2 latent heat of sublimation budget of the seasonal and perennial caps is lower than the solar energy budget and (2) deposition in the opposite case. When changes occur on the edges of the cap, they result in the apparent expansion or contraction of the cap. When they happen vertically, within the cap, they affect the CO_2 ice patchiness.

[49] Several observations suggest that the cap has experienced major changes and local adjustments within its history. In 1894 and 1969, one or several layers of CO_2 may have been removed from the cap. Between 1972 and 1977, only expansion and vertical ice deposition was observed, indicating that CO_2 ice was deposited. Following these events, the local distribution of CO_2 has been modified by the local erosion and deposition of the cap. Because mass budgets cannot be presently calculated, the meter-scale retreat of the walls of the erosional features in the cap is not a sufficient observation to conclude that the cap is losing mass in the long term and that Mars is experiencing climate change. Carbon dioxide may redeposit elsewhere on the cap as observed between 1972 and 1977. Vertical changes of the thickness of the cap compensating the wall retreat would be under the resolution of MOC or HiRISE.

[50] Regional and local changes seem to have occurred regularly in the last century. The continuous monitoring of Mars may help to identify and better characterize future events and the present complex balance or imbalance of the cap. Future surface pressure measurements will quantify changes of mass of the atmosphere and help to determine if

the cap is losing mass and if Mars is experiencing climate change.

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