ATMOSPHERIC MOTION VECTOR HEIGHT ASSIGNMENT IN THE POLAR REGIONS: ISSUES AND RECOMMENDATIONS

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ABSTRACT

Some unique characteristics of the polar atmosphere affect the height assignment of cloud and water vapor features used in high-latitude wind estimation. In particular, low water vapor amounts, atmospheric temperature inversions, and low, thin clouds on height assignment can significantly impact the infrared window, CO_2-slicing, and H_2O intercept methods. Satellite-derived and modeled cloud and atmospheric properties show that 20-35% of polar clouds are low (greater than 600 hPa) and thin (optical depths less than 5), with associated height assignment errors averaging 75 hPa. Total precipitable water (TPW) is less than 0.5 cm over most of the Arctic and Antarctic in winter and surface contamination in the 6.7 µm water vapor channel is apparent at TPW amounts less than approximately 0.3 cm. To mitigate the effects of low, thin clouds and the relatively dry polar atmosphere on height assignment, it is recommended that atmospheric motion vectors (AMV) based on clear sky water vapor features be flagged and adjusted for surface effects when TPW is less than approximately 0.3 cm, and that AMVs from low, thin water clouds be flagged and adjusted for cloud optical depth in a post-processing step.

1. INTRODUCTION

Satellite-derived wind fields are most valuable over the oceanic regions where few observations exist and numerical weather prediction model forecasts are less accurate as a result. Like the oceans at lower latitudes, the polar regions also suffer from a lack of observational data. We have recently developed a real-time polar winds product using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua polar-orbiting satellites. The procedure is based on geostationary wind retrieval methods, with modifications to address differences in orbital characteristics, temporal frequency, and spatial resolution. The procedure and model impact studies are described in detail in Key et al. (2003).

In spite of the differences in viewing geometry and temporal sampling between polar-orbiting and geostationary imagers, cloud and water vapor feature tracking methods are fundamentally the same for polar and mid-latitude applications. In contrast, the height assignment of MODIS wind vectors is strongly influenced by the unique qualities of the polar atmosphere, such as low atmospheric water vapor amounts, low, thin water (liquid) clouds over bright snow and ice surfaces, clouds that are warmer than the surface, and temperature inversions throughout most of the year. The impact on height assignment is that low water vapor amounts result in a significant radiance contribution from the surface, complicating the conversion of brightness temperature to height, some clouds are too low for CO_2 or water vapor methods to be effective and too thin for simple infrared techniques, and low-level temperature inversions are poorly represented in first guess model fields that are used in CO_2–slicing height assignments. Figure 1 shows temperature and humidity profiles from a variety of standard atmospheres, and clearly illustrates the presence of temperature inversions and low water vapor amounts in the Arctic. The profiles are based on data in Ellingson et al. (1991), with Arctic mean profiles based on Arctic Ocean coastal and drifting station data described by Kahl et al. (1992).

In this paper we examine the relative frequency of these atmospheric features of the high-latitudes, and assess their impact on wind vector height assignments. The analysis is restricted to the infrared window, CO_2-slicing, and H_2O intercept methods. Post-processing quality control and height reassignment are not addressed.

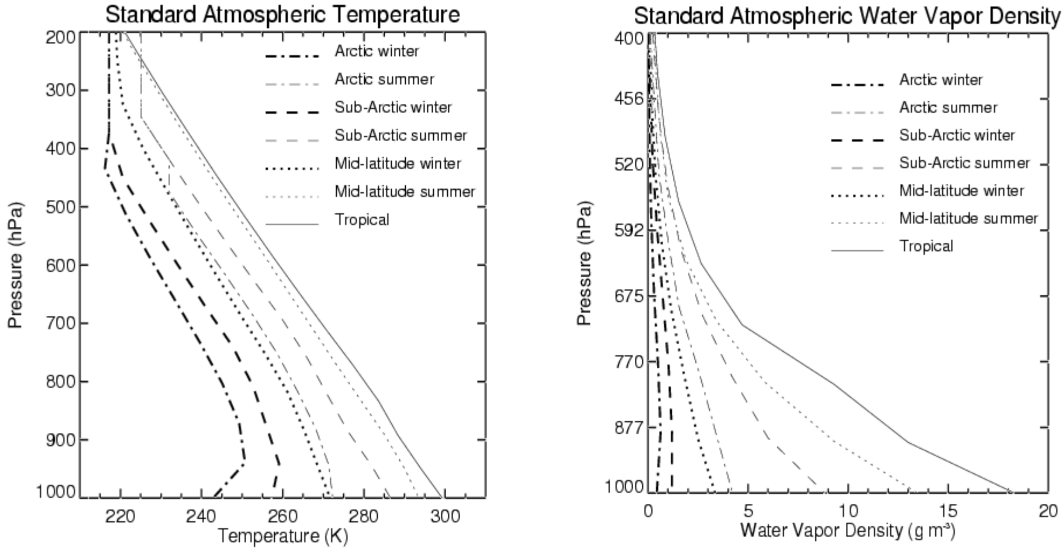

Figure 1. Temperature (left) and humidity (right) profiles for standard atmospheres and for mean Arctic summer and winter conditions.

2. WIND VECTOR HEIGHT ASSIGNMENT METHODS AND ATMOSPHERIC CONSIDERATIONS

Wind vector heights are assigned by one of three methods: CO_2-slicing, infrared (IR) window, and H_2O-intercept. How do characteristics typical of the polar atmosphere, including low temperatures, ubiquitous atmospheric temperature inversions, low water vapor amounts, bright and cold surfaces, extensive cloudiness, and a high frequency of low, thin clouds, affect height assignment?

2.1. CO_2-slicing

The CO_2-slicing method is used to assign a height to a cloud target. It generally works well for both opaque and semitransparent clouds. Cloudy and clear radiance differences in one or more carbon dioxide bands (e.g., 13.3, 13.6, 13.9, or 14.2 µm on MODIS) and infrared window bands are ratioed and compared to the theoretical ratio of the same quantities, calculated for a range of cloud pressures, i.e.,

$$\frac{R(CO_2) - R_{CL}(CO_2)}{R(IRW) - R_{CL}(IRW)} = \frac{nE(CO_2)[R_{BCD}(CO_2, P_c) - R_{CL}(CO_2)]}{nE(IRW)[R_{BCD}(IRW, P_c) - R_{CL}(IRW)]}$$

where CO_2 refers to a carbon dioxide channel, *IRW* is an infrared window channel, *R* is an observed (no subscript) or clear (subscript *CL*) radiance, *nE* is the effective cloud amount, R_{BCD} is the theoretical radiance of an opaque ("black") cloud. The cloud pressure that gives the best match between the observed and theoretical ratios is chosen (Menzel et al., 1983; Frey et al., 1999).

Monthly average cloud amounts over the Arctic and Antarctica range from 50-90%, so cloud targets are numerous. The predominant cloud type in the Arctic is marine stratus, which is relatively low with temperatures within a few degrees of the surface temperature. This is illustrated in Figure 2, which gives the relationship between the surface temperature and cloud temperature on one winter and one summer day over Antarctica. These satellite-derived quantities are from the extended AVHRR Polar Pathfinder (APP-x) project (cf., Maslanik et al., 2001). Small cloud-surface temperature differences, indicated by points along the diagonal lines, are common and are not restricted to low clouds. Note also the frequency of warm clouds (clouds warmer than the surface), especially in winter.

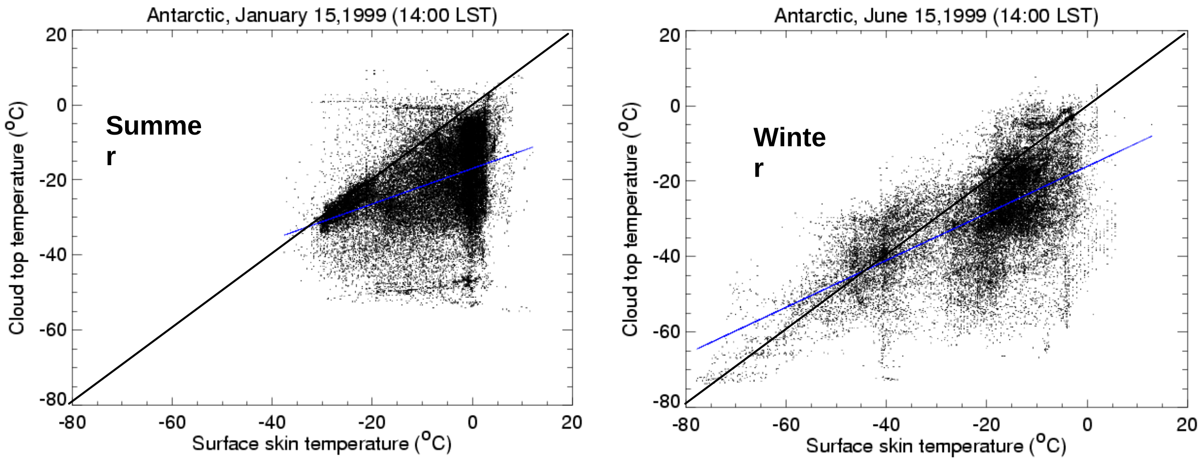

Figure 2. The relationship between the surface temperature and cloud temperature on one winter and one summer day over Antarctica based on satellite data. Results are similar for the Arctic.

The CO_2-slicing method is very sensitive to the clear-cloudy radiance difference, and no height retrievals can be done if that difference is very small. The clear-cloudy radiance differences approach zero as the cloud temperature approaches the surface temperature, as is commonly the case for low clouds. Figure 1 demonstrates that CO_2-slicing height assignment "failures" will be relatively common for polar clouds.

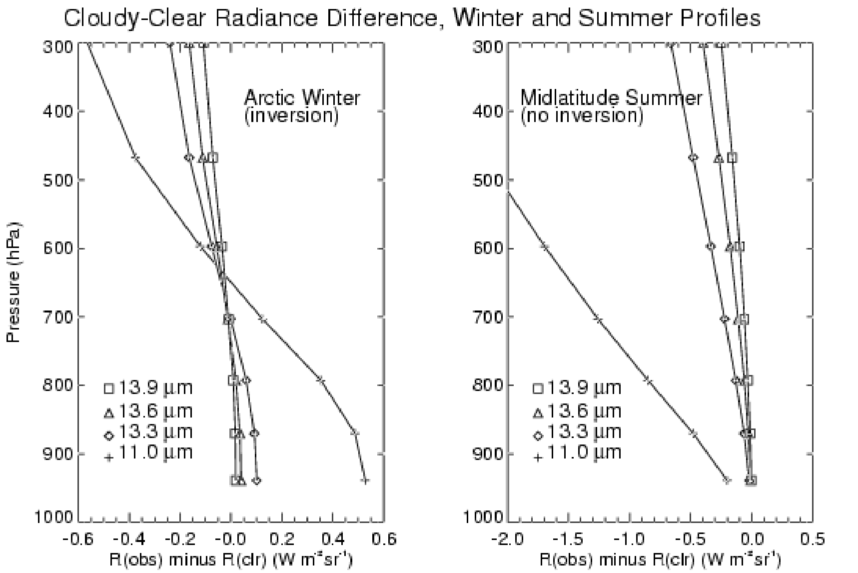

Figure 3. The difference between simulated cloudy and clear radiances for an Arctic winter profile that has a low-level temperature inversion (left) and for a mid-latitude summer (right), as a function of height for three carbon dioxide channels and one infrared window channel.

It also raises the question of how temperature inversions affect height assignments. Figure 3 shows the difference between a modeled cloudy radiance and the modeled clear radiance for an Arctic winter profile that has a low-level temperature inversion and for a mid-latitude summer profile without an inversion. A radiative transfer model was used to simulate the radiances. The radiance difference is shown as a function of height for three carbon dioxide channels and one infrared window channel. The radiance difference in the CO_2 channels is near zero at 700 hPa in the winter profile and near zero at 950 hPa in the summer profile. The effect of the inversion is, not surprisingly, to raise the level where the radiance difference is near zero. For these particular profiles, the CO_2-slicing method could be expected to "fail" for clouds between approximately 600 and 800 hPa in the presence of an inversion and below (in altitude) approximately 800 hPa when no inversion is present. Based on these results, CO_2-slicing should not used for cloud pressures greater (cloud altitudes lower) than about 700 hPa, although it may be possible to apply it for clouds within low-level temperature inversions.

2.2. H_2O-intercept

The H_2O-intercept method of height determination can be used as an additional or in the absence of a CO_2 band. This method examines the linear trend between clusters of clear and cloudy pixel values in water vapor-infrared window brightness temperature space, predicated on the fact that radiances from a single cloud deck for two spectral bands vary linearly with cloud fraction within a pixel. The line connecting the clusters is compared to theoretical calculations of the radiances for different cloud pressures. The intersection of the two gives the cloud height (Szejwach, 1982; Schmetz et al., 1993).

The H_2O-intercept method is generally not useful for clouds lower in the atmosphere than about 600 hPa because upwelling radiation comes primarily from the atmosphere above the cloud. In the relatively dry polar atmospheres, where total precipitable water is often less than 0.5 cm in the winter and 1-2 cm in summer, lower clouds can be detected. Nevertheless, very low clouds cannot be detected with the commonly-used water vapor channels centered near 6.7 µm. However, the MODIS 7.2 micron channel sees lower into the atmosphere, as illustrated in Figure 4. The figure shows modeled brightness temperatures in two water vapor channels (6.7 and 7.2 µm) for clouds at two different heights. The slope of the theoretical curve becomes nearly asymptotic for low clouds at 6.7 µm, but is less so for the 7.2 micron channel. The lower-peaking channel may therefore permit tracking and height assignment of lower cloud layers than the 6.7 micron channel. Figure 4 also illustrates the effect of temperature inversions on the H2O-intercept method. In theory the method should also work in the presence of an inversion, as long as the inversion is present in the model field used to generate the theoretical radiances.

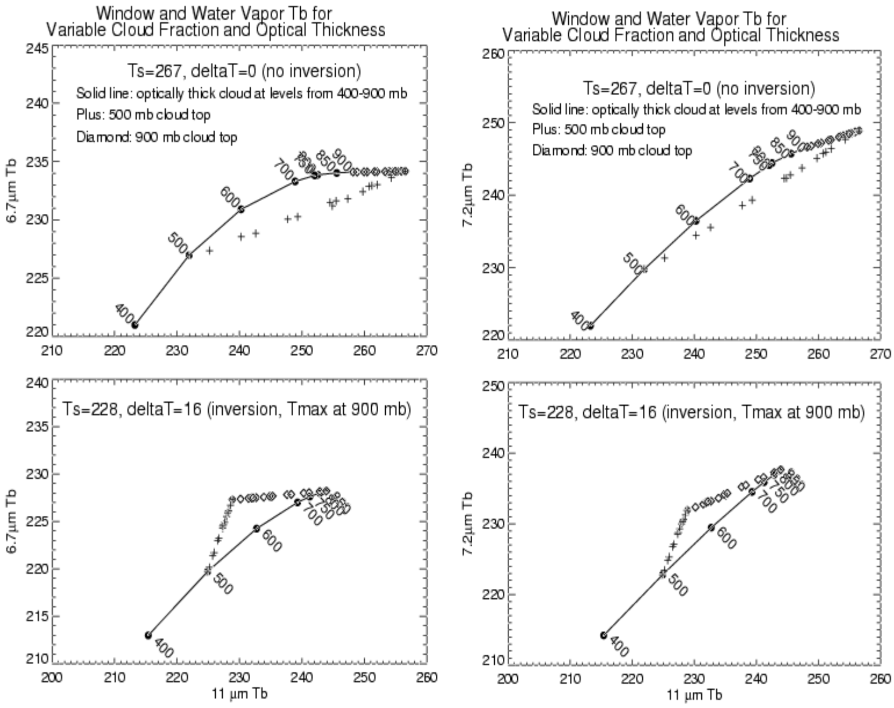

Figure 4. The H_2O-intercept method for two water vapor channels (6.7 µm at left; 7.2 µm at right), for conditions without and with a temperature inversion (top and bottom), and for two different cloud heights. Results are based on radiative transfer calculations. The strength of the temperature inversion is given as "deltaT". Ts is the surface temperature.

Due to the low water vapor amounts, brightness temperature gradients in the 6.7 µm band are small, and surface emission can sometimes contaminate the radiances in clear sky areas. This is illustrated in Figure 5, where the range in simulated brightness temperatures for a 15 C range in surface temperature is plotted as a function of total precipitable water. The calculations are based on a variety of Arctic and Antarctic temperature and humidity profiles. At 6.7 µm, changing the surface temperature by 15 C has little effect on the upwelling 6.7 micron radiance for TPW values greater than approximately 0.5. As TPW decreases, the effect of surface emission on the brightness temperature increases. At 7.2 µm, there is always a surface effect so it is not recommended for use in clear sky water vapor height assignments.

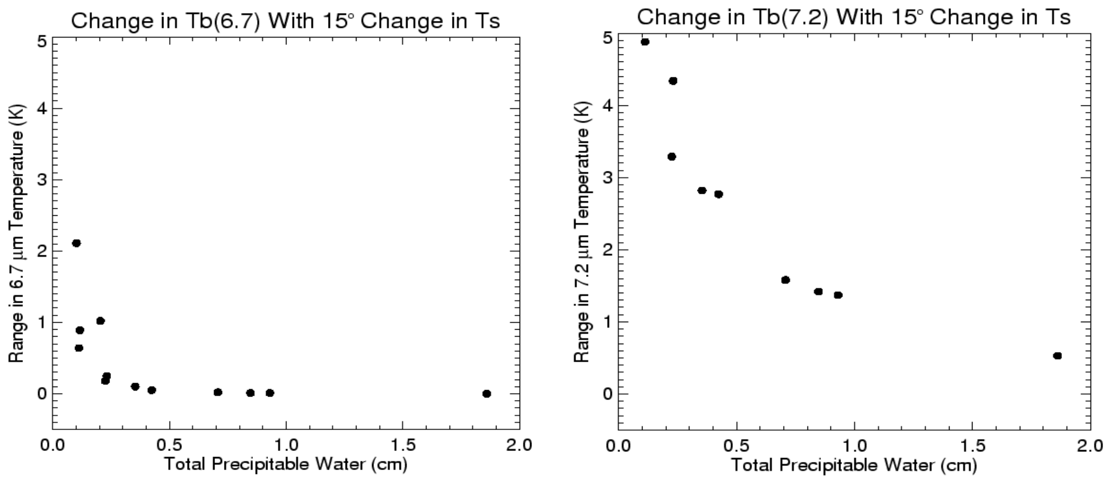

Figure 5. The modeled change in the 6.7 µm (left) and 7.2 µm (right) brightness temperatures as a function of total precipitable water (TPW) when the surface temperature is varied by 15 degrees. For a given temperature/humidity profile, TPW is held constant while the surface temperature is varied.

This issue of the satellite "seeing" the surface in a water vapor band is further exemplified in Figure 6, which shows MODIS data at 11 and 6.7 µm covering the coast of Greenland and adjacent sea ice in March. The ice floes are clearly seen in the window channel, but are also evident in the water vapor channel. While such surface contribution to the water vapor radiance should be captured to some degree in the radiative transfer calculations of the H_2O-intercept method, uncertainties in the surface temperature and emissivity become significant as TPW decreases.

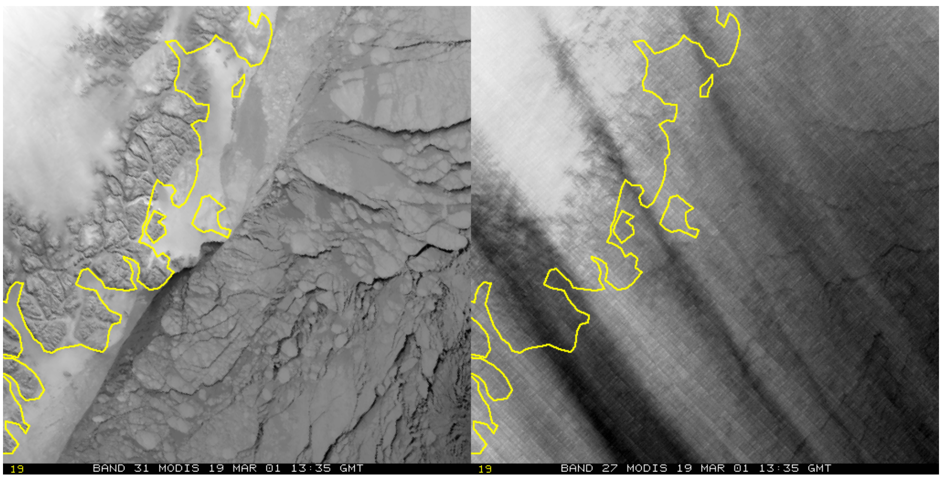

Figure 6. MODIS images covering part of southeastern Greenland (left of each image) and sea ice on 19 March 2001. The left image is the 11 micron infrared window channel; the right is the 6.7 micron water vapor channel.

2.3. Infrared window

The infrared window method assumes that the mean of the lowest (coldest) brightness temperature values in the target sample is the temperature at the cloud top. This temperature is compared to a numerical forecast of the vertical temperature profile to determine the cloud height. With optically thick (opaque) clouds, the IR brightness temperature is a reasonable proxy for the cloud temperature. For thin clouds, the surface and atmosphere below the cloud may contribute significantly to the upwelling radiance. Therefore, the method is reasonably accurate for opaque clouds, but inaccurate for semi-transparent clouds.

How common are low, thin clouds in the polar regions? Figure 7 shows the relative frequency of cloud pressure and visible cloud optical depth over the Arctic in January and June from the APP-x dataset. Clouds are thin during winter and summer, with the relative frequency of low clouds increasing during the summer. For the Antarctic (not shown) there is also a high frequency of low clouds (low relative to the surface elevation). An optical depth of 4.5 corresponds to a transmittance of approximately 1%; an optical depth of 1 corresponds to a transmittance of 37%. So the IR radiance for clouds with optical depths less than 4 contains a significant contribution from below the cloud.

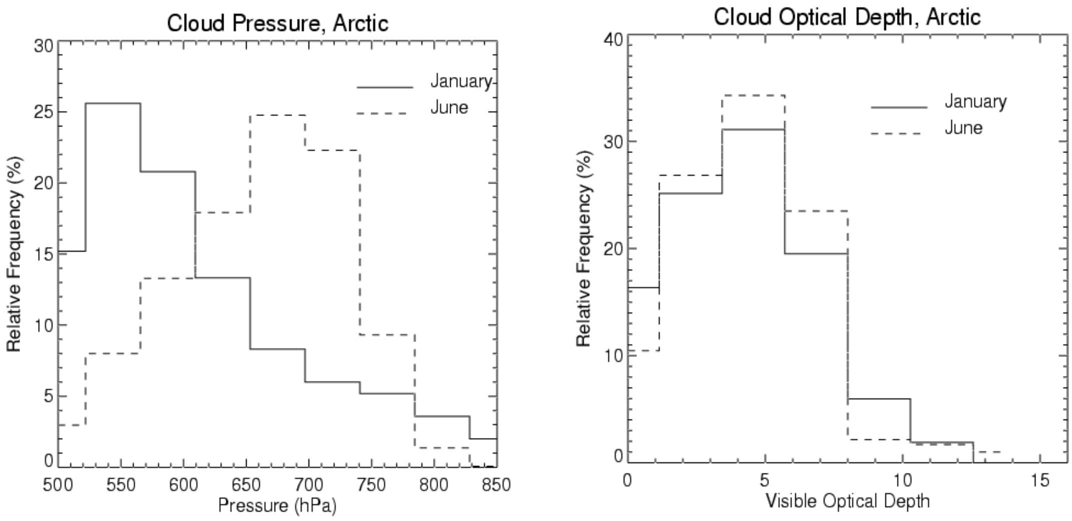

Figure 7. Relative frequency of satellite-derived cloud top pressure (left) and visible optical depth (right) for January and June in the Arctic. Data are from the extended AVHRR Polar Pathfinder project.

The impact of this transmission on height assignment is illustrated in Figure 8. Cloud heights were estimated with and without adjusting for cloud optical depth using APP-x data for the Arctic summer. Converting the cloud temperature to a cloud pressure with a temperature profile, the adjustment in summer will generally increase the cloud altitude. The adjustment can be large, even as high as 500 hPa. In winter, and to a limited extent in summer, the direction of change may be reversed due to inversions. The implications of these results for wind retrievals are that low cloud wind tracers need to be treated with caution, and cloud height assignment with the IR window method should include a correction for optical depth when clouds are thin.

3. CONCLUSIONS AND RECOMMENDATIONS

Wind vector height assignment methods examined here include CO_2-slicing, H_2O intercept, and IR window. Each method is intended for use under a specific set of conditions, and therefore each has its limitations. For example, the CO_2-slicing method requires that there be a significant difference between clear and cloudy radiances, the H_2O intercept method works best on scenes with broken cloud cover, and the IR window method requires that clouds are optically thick. Some of the assumptions and limitations of these methods are put to the test in the polar regions, where cloud temperatures are often within a degree or two of the surface temperature and low thin clouds occur far more frequently than at lower latitudes.

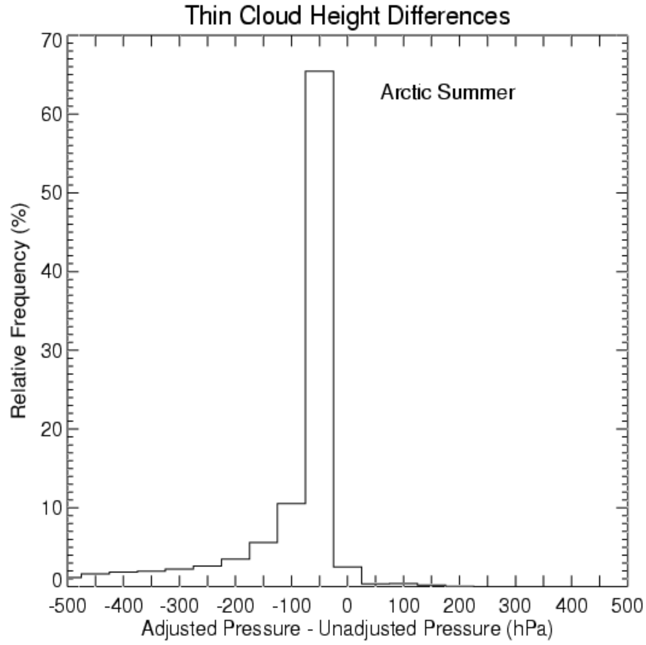

Figure 8. The relative frequency of the differences in cloud pressure with and without a correction for transmission of radiation through the cloud.

We make the following recommendations regarding height assignment:

- CO_2-slicing should not be used for clouds below (in altitude) 700 hPa. However, the possibility of using CO_2-slicing for clouds within temperature inversions should be investigated. Additionally, because of larger uncertainties in model surface temperatures, radiance biases in radiative transfer calculations may be large. Model surface temperatures need to be carefully evaluated.
- With the H_2O intercept method, surface emission in the dry polar atmosphere complicates height assignment in clear sky conditions. A simple solution is to use an estimate of total precipitable water, or an empirical relationship between surface temperature and TPW, to avoid situations where this is a problem. For example, radiative transfer calculations show that surface emission is a significant contribution to the upwelling radiance at 6.7 µm when TPW is below about 0.3 cm. A more complex solution is to remove surface emission from the measured radiance. In any case, a level-of-best-fit procedure should be used to determine biases that result from inaccurate surface temperature and emissivity in model calculations. For cloudy conditions, the use of the 6.7 µm channel below 600 hPa is discouraged. A 7.2 µm channel can improve the height assignment of low clouds. A two-channel approach may be useful for high clouds and would eliminate the need for opaque cloud calculations.
- For the IR window method, cloud optical depth should be estimated and the cloud temperature should be adjusted for the transmission of radiation from below the cloud. This is more important at high latitudes because of the relatively high frequency of low, thin clouds. Some implementations of the IR window method assume that clouds are colder than the surface, i.e., that the coldest pixel is a cloud. This assumption is invalid for much of the year in the polar regions.

Regarding MODIS polar winds, the use of additional spectral channels should prove beneficial not only for height assignment, but also for cloud-clear labeling and the identification of thin clouds. For example, 1.6 or 3.7 µm channels would greatly improve snow-cloud discrimination during the sunlit portions of the day/year, and could also improve height assignment by providing the information needed to estimate cloud optical depth. Channel differences such as 3.7-11 µm and 11-12 µm will better distinguish thin clouds, while 7.2-11 µm is extremely important for low cloud detection at night.

4. ACKNOWLEDGMENTS

This work was supported by NOAA grant NA07EC0676 and the NASA EOS program. The views, opinions, and findings contained in this report are those of the author(s) and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

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