A SIMPLE GOES SKIN TEMPERATURE PRODUCT

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Abstract

A skin temperature image product is easy to generate from the split-window bands of the GOES Imager or Sounder. This product can be used to monitor land- and ocean-surface skin temperatures, as estimated by satellite, as well as temporal changes of those temperatures. In addition, other satellite instruments with split-window bands besides GOES are capable of providing this product. Comparisons of the skin temperature product with the Sea-Surface Temperature derived product imagery from the GOES Sounder are very good. However, an advantage of this product is that it can be created using only two bands of the GOES Imager and a simply-applied algorithm. In addition, the Imager version of the product has increased spatial and temporal resolutions over that of the equivalent Sounder product. Real-time skin temperature images using this algorithm are routinely available online for both the GOES Imager and Sounder, and could easily be generated for use by operational meteorologists.

1. Introduction

An image product that is easily generated from the GOES split-window bands can be used to monitor spatial variations and time-changes of the temperature of the earth's surface or skin. This product, a variant of GOES thermal infrared images corrected for low-level atmospheric absorption, is available at the same high (4 km at nadir) spatial and (15 minute minimum) temporal resolution as the images used to generate it. The small transmittance difference between the split-window bands (the infrared window, band-4, 10.7 μm; and the less-transparent "dirty" window, band-5, 12.0 μm, on the GOES-8 through 11 Imager) can be used to correct these bands for the effects of atmospheric absorption, arriving at a skin temperature image product.

First, a bit of terminology: The term "skin temperature" is the temperature of a layer of the earth equal to the penetration depth of the electromagnetic radiation used to measure it (Norman and Becker 1995). The skin temperature in this paper is derived from the radiative (or brightness) temperatures of the GOES split-window infrared bands. The skin temperature should not be confused with the near-surface (2 m instrument-shelter-height, thermodynamic) air temperature. The two temperatures are quite different in meaning and often in magnitude (Jin 2004). However, they can be closely related to each other under conditions of thermodynamic equilibrium (no heat transfer to or from the surface).

The chief use of the skin temperature product is to determine spatial variations or boundaries in the low-level temperature field. Color enhancements are used to quickly quantify the skin temperature and its spatial variations and help track changes over time. This may be especially helpful when near-surface air temperature observations are sparse and higher-spatial-resolution variations in the skin temperature are observed. Many possible applications of this product have been noted by Wan and Dozier (1989) including: spatial variations in surface heating related to differences in surface type and soil moisture [variations which may be used to predict surface wind fields (Fosberg et al. 1980)] and monitoring temporal changes over otherwise uniform surfaces due to changes in the amount of low-level atmospheric moisture. Also, when compared to near-surface air temperatures, the skin temperature can be used as a proxy for temperature lapse rate near the earth's surface, at times indicating the presence of low-level temperature inversions.

The skin temperature product can also be used to estimate daytime sensible heat flux from the heating rates of radiometric temperature (Rabin 2004). The heating rate is obtained by differencing the skin temperature near its peak in the afternoon from that near sunrise. Using the difference in temperature rather than an average daytime temperature reduces some of the possible errors associated with the temperature estimate from satellite. The measured heating rates are also inversely related to surface wetness. The amount of surface heating is reduced over wet surfaces and locations with active vegetation and adequate root

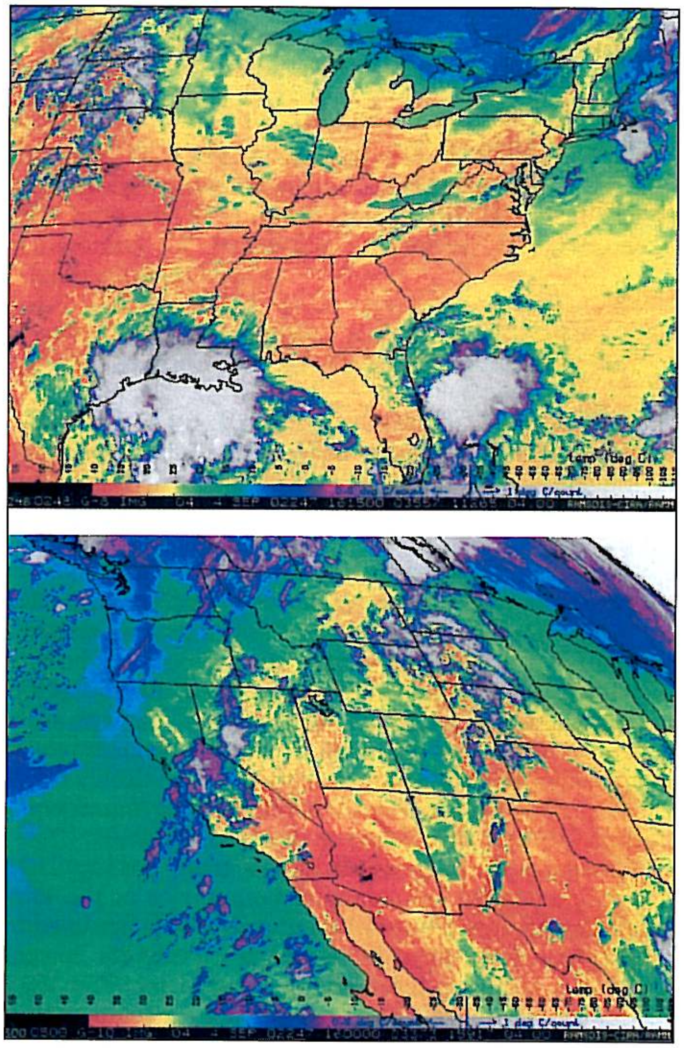

Fig. 1. Skin temperature product images at 4 km resolution from the GOES-8 (top) and GOES-10 (bottom) Imager on 4 September 2002 at 1615 and 1600 UTC respectively. A special "rainbow" color enhancement is applied to emphasize spatial variations in land- and ocean-surface skin temperatures. Gray shades are used for colder cloud tops.

zone moisture; and surface heating increases with drier surfaces where surface evaporation and evapotranspiration from vegetation is limited.

Examples of this product generated from the split-window bands of both the GOES Imager and GOES Sounder have been produced. For the Sounder, a change in the atmospheric correction factor is needed due to spectral differences in the split-window bands. Unfortunately, the split-window difference temporarily disappeared from the GOES-East Imager when GOES-12 became operational in place of GOES-8. The change of the 12.0 μm band to a more opaque 13.3 μm band was intended for better detection of low-level clouds. The new band-6 is too opaque to be used together with the window band-4 to produce a skin temperature product, which is not as easily generated from the larger spectral (and transmittance) separation of those bands. However, the split-window difference remains on the GOES Sounder and will again be available on the imager on the GOES-R series currently under development, the first of which is scheduled for launch in 2012. In the interim, the split-window difference, and thus the skin temperature product, is available through instrumentation on many polar-orbiting satellites. However, polar-orbiting satellites view most areas of the world only twice-a-day, and thus do not allow the skin temperature to be produced at the high temporal resolution possible from geostationary satellites, even with data from two or three polar-orbiting satellites.

2. Analysis of Skin Temperature

Based on the work of McMillin and Crosby (1984), the split-window bands (band-4, 10.7 μm; and band-5, 12.0 μm, on the GOES Imager) can be used together to correct one of them for the effects of atmospheric absorption. The formula is

$$T_{skin} = T_{10.7} + \eta \cdot (T_{10.7} - T_{12.0}) \quad (1)$$

where

$$\eta = \frac{1 - \tau_{10.7}}{\tau_{10.7} - \tau_{12.0}} \quad (2)$$

and τ is atmospheric transmittance (see Kidder and Vonder Haar 1995, 219–225, for details). This derivation is similar to sea-surface temperature algorithms (McClain et al. 1985), but it is simpler. This formulation also assumes the surface emittance (emissivity) to be the same in both bands. Although not strictly true, this is a valid assumption which allows for surface emittances in both bands to be less than one.

MODTRAN (Berk et al. 1989) model calculations for the standard mid-latitude atmosphere, for example, reveal that for the GOES Imager $\tau_{10.7}$ is about 0.68 and $\tau_{12.0}$ is about 0.57. This means that the correction or scale factor η is approximately 2, which is applied to the temperature differential between the two bands and added to the more transparent 10.7 μm band. The resulting product when thus corrected for atmospheric absorption is closer to the actual skin temperature of the earth's surface than either of the input bands. T_{skin} appears quite similar to the usual $T_{10.7}$ image, but with slightly more noise because it is a combination of two bands. Still, most (about 98%) of the variance in the skin temperature product comes from the infrared window (10.7 μm) image, and only a very small amount (about 2%) of the variance comes from the split-window difference added back into the infrared image.

Examples of T_{skin} product images from the GOES-8 (GOES-East) and GOES-10 (GOES-West) Imager are shown in Fig. 1. A "rainbow" color enhancement is used to emphasize spatial variations in temperatures of land and ocean surfaces, whereas gray shades are used for colder cloud tops. The break point between land and ocean skin temperatures, and cloud top temperatures varies by latitude, season, and cloud height, and can be adjusted using the color enhancement applied to the skin temperature product.

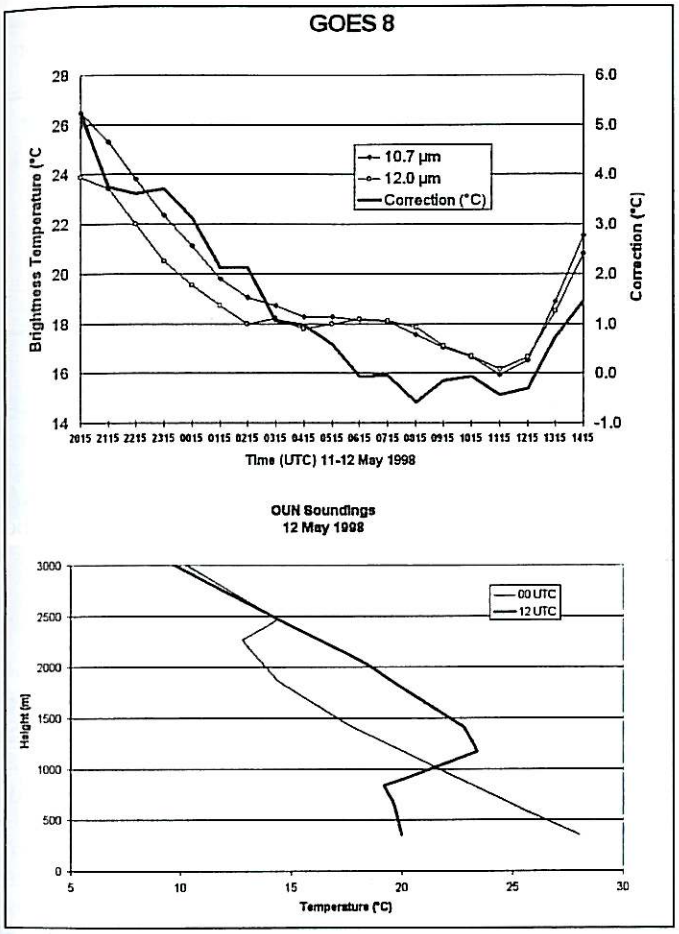

Fig. 2. (Top) Time sequence of GOES-8 $T_{10.7}$, $T_{12.0}$, and the temperature correction used for Norman OK on 11-12 May 1998. (Bottom) 0000 and 1200 UTC temperature soundings at Norman OK on 12 May 1998.

The time evolutions of $T_{10.7}$, $T_{12.0}$, and the temperature correction $[2 \cdot (T_{10.7} - T_{12.0})]$ over Norman, Oklahoma on a mostly cloud-free day (11-12 May 1998) are compared in Fig. 2. The 0000 and 1200 UTC temperature soundings are also shown. GOES Imager band-5 (12.0 µm) is more sensitive to water vapor than is band-4 (10.7 µm); i.e. band-5 is more affected by the atmosphere than band-4. When the atmospheric temperature decreases with height, $T_{12.0}$ is normally cooler than $T_{10.7}$, and the temperature correction is positive. When the atmospheric temperature increases with height (a temperature inversion), the correction can be negative.

An example of the utility of the high-spatial-resolution skin temperature product is the following situation. The top image in Fig. 3 is the GOES-10 Imager skin temperature product over the western U.S. at 2000 UTC 3 December 2004. The white contour lines are surface air temperatures plotted over the colored skin temperatures. In this case, high pressure over the western intermountain region allows a clear view for analysis of the skin temperature. Surface air temperatures are in the 0°C to -5°C range over most of the region. However, they are generally sparse and do not reflect the detail available in the skin temperatures. Although the skin temperatures are also in the 0°C to -5°C range (magenta in color), much more detail is available. Both warmer (blue) and colder (gray) areas are detected in the image. The warmer areas, which are more common, are valleys in western Colorado, Utah, and Nevada where skin temperatures are warmer than surrounding mountains. The colder skin temperatures are limited to a couple of small valleys in western Colorado and a large area around Reno, Nevada. Those areas have skin temperatures of about -15°C, much colder than adjacent areas. By examining the visible image for this case (Fig. 3, bottom), the difference can be attributed to the fact that the colder valleys have snow-covered surfaces, whereas the warmer valleys are snow-free. The snow reflects solar heating and slows the heating of the earth's surface, keeping those areas colder than snow-free valleys. In this case, high-spatial-resolution variations in the skin temperature product can be detected and used to help predict air temperatures for those areas.

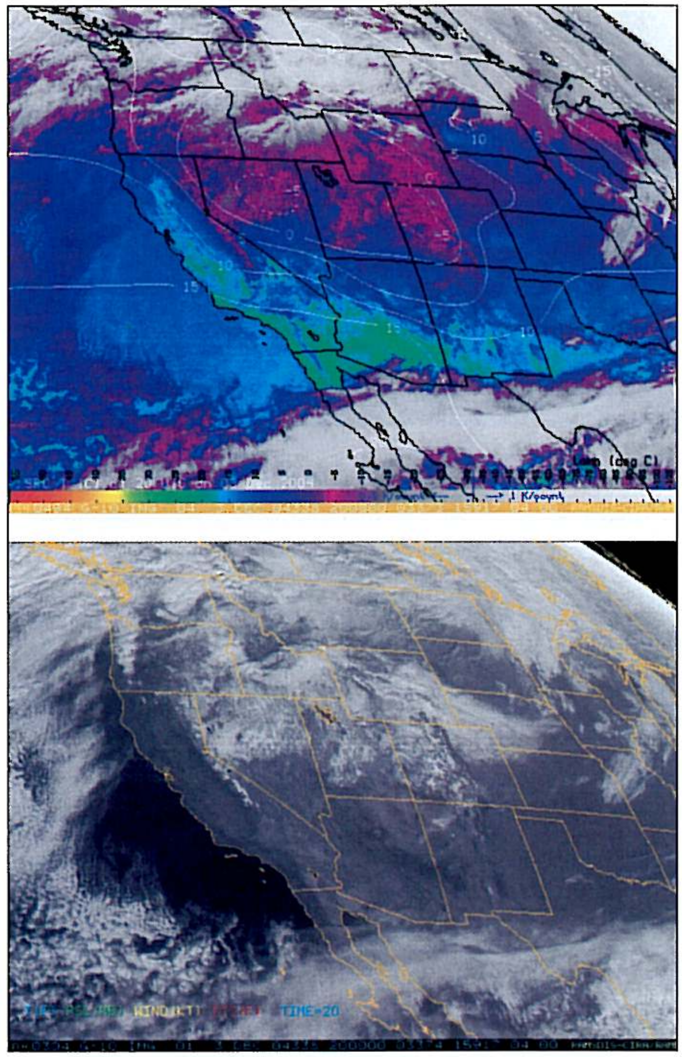

Fig. 3. (Top) Skin temperature product image at 4 km resolution from GOES-10 (GOES-West) on 3 December 2004 at 2000 UTC. Color enhancement and gray shades are as in Fig. 1. White contours show analysis of near-surface air temperatures. (Bottom) Visible image at the same time reveals that high-spatial-resolution variations in the skin temperature are related to mountain valleys being either snow-covered or snow-free.

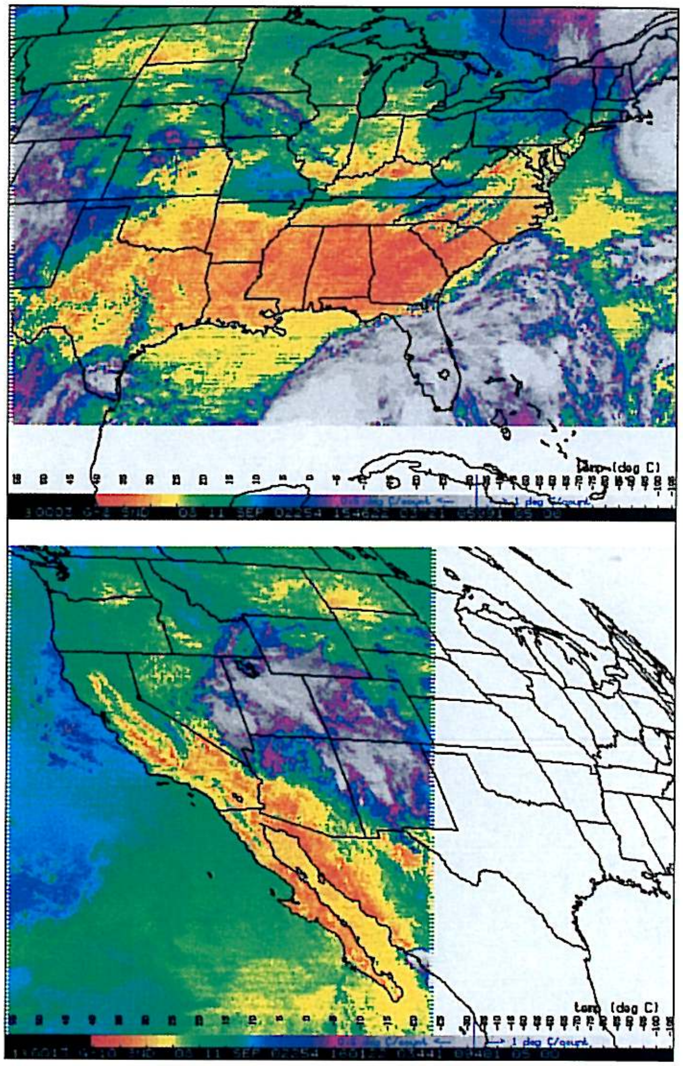

Fig. 4. Skin temperature product images at 10 km resolution from the GOES-8 (top) and GOES-10 (bottom) Sounder on 11 September 2002 at 1546 and 1601 UTC respectively. The same "rainbow" color enhancement applied to the Imager-derived product is applied to the Sounder-derived product to emphasize spatial variations in both land- and ocean-surface skin temperatures. Gray shades are used for colder cloud tops.

3. GOES Sounder and Other Instruments

Split-window spectral bands are present on the 19-band GOES Sounder, on the Advanced Very High Resolution Radiometer (AVHRR) on polar-orbiting NOAA satellites, and on the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM/Terra and EOS-PM/Aqua. Because the bands are spectrally different, a recomputed correction factor is necessary: such as $\eta \sim 3$ for AVHRR (Price 1984). Table 1 lists the wavelengths, transmittances, and scale factors computed for each of these instruments (based on a standard mid-latitude atmosphere) in addition to the GOES Imager. Because the spectral bands are closer spectrally and in transmittance, the resulting scale factor more than doubles for the GOES Sounder and MODIS than for the GOES Imager.

Table 1. Wavelengths, transmittances and scale factors for various satellite instruments with split-window bands.

Satellite Instrument	Wavelength(μm) γ_1	γ_2	Transmittance τ_1	τ_2	Scale Factor η
GOES-8/11 Imager	10.7	12.0	0.71	0.57	2.1
GOES Sounder	11.0	12.0	0.65	0.57	4.4
NOAA AVHRR	10.8	12.0	0.68	0.57	2.9
EOS MODIS	11.0	12.0	0.65	0.57	4.4

Examples of T_{skin} product images from the GOES-8 (GOES-East) and GOES-10 (GOES-West) Sounder are shown in Fig. 4. In this case, the scale factor is much larger (4.4) than that for the GOES Imager or for the NOAA AVHRR instrument, but about the same as would be used for the MODIS split-window bands.

4. Comparison to Sea-Surface Temperature Derived Product Images

The GOES Imager skin temperature product can be compared to other similar products, such as the GOES Sea-Surface Temperature (SST) product, which is a Derived Product Image (DPI) generated operationally from the GOES Sounder. The SST DPI is an image product that is derived from a temperature and moisture retrieval at each image pixel (Hayden et al. 1996). Since this product is produced over both ocean and land, it is not strictly a sea-surface temperature product, but a land-surface temperature product as well. But, the SST terminology used by the developers will be used here to distinguish it from the skin temperature product featured in this article.

Figure 5 contains a comparison of the Imager skin temperature product with the Sounder SST for approximately the same time (1445 and 1446 UTC respectively) on 15 January 2003. The same "rainbow" color enhancement used on the skin temperature product in previous figures is used here as well. However, the Sounder SST product employs a similar, but shifted, color enhancement that cannot easily be matched to that of the skin temperature product due to the different scaling of the SST as an image product. Nonetheless, it can be noted that some of the warmer (yellow in color) features of the sea-surface in the Gulf of Mexico and off the east coast of Florida in the Imager product are not detected as well in the lower (10 km) resolution Sounder SST product. In both images colder cloud tops are shaded gray.

Also plotted in Fig. 5 are white contour lines for the near-surface air temperatures. At the near-local-noon time of the images, the air temperatures are much cooler over land than the skin temperatures, whereas they are much more in equilibrium over water. The large difference over land is a reflection of the non-equilibrium of the land and the air, with a large implied sensible heat flux from the earth's surface. However, it is more important to note that high-spatial-resolution variations exist in the skin temperatures that are not reflected in the much

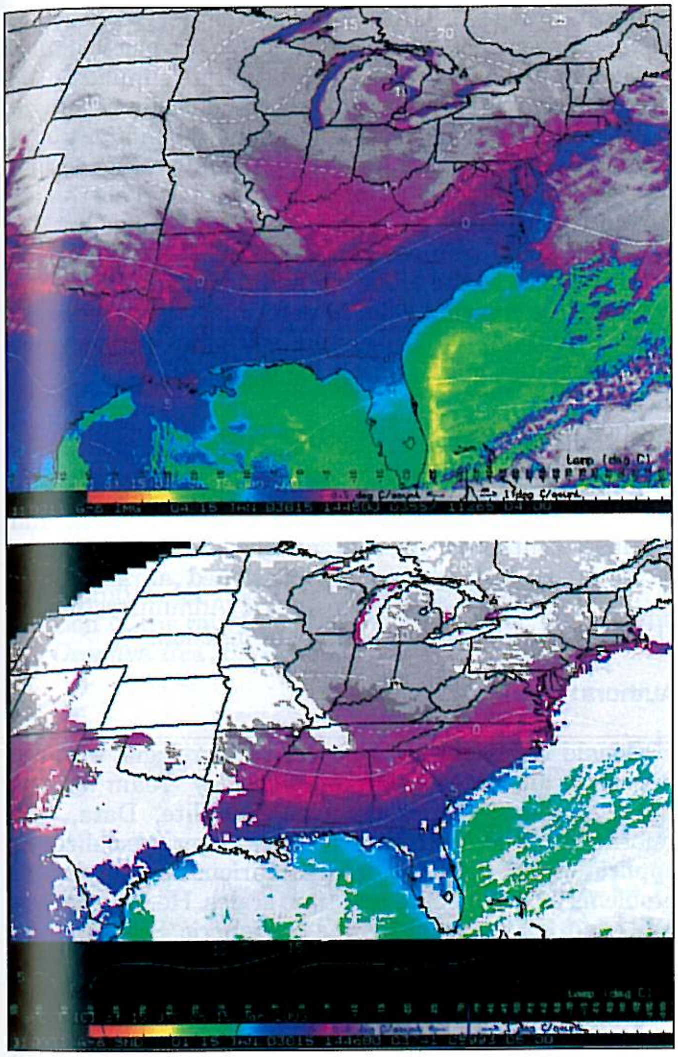

Fig. 5. Imager skin temperature product vs. Sounder (land and ocean) SST product for 1445 and 1446 UTC respectively on 15 January 2003. The color enhancement applied to the Imager-derived product is same enhancement used in previous figures. A similar but slightly-shifted color enhancement has been applied to the Sounder SST product. Gray shades are used for colder cloud tops in both images. White contours on the images are near-surface air temperatures.

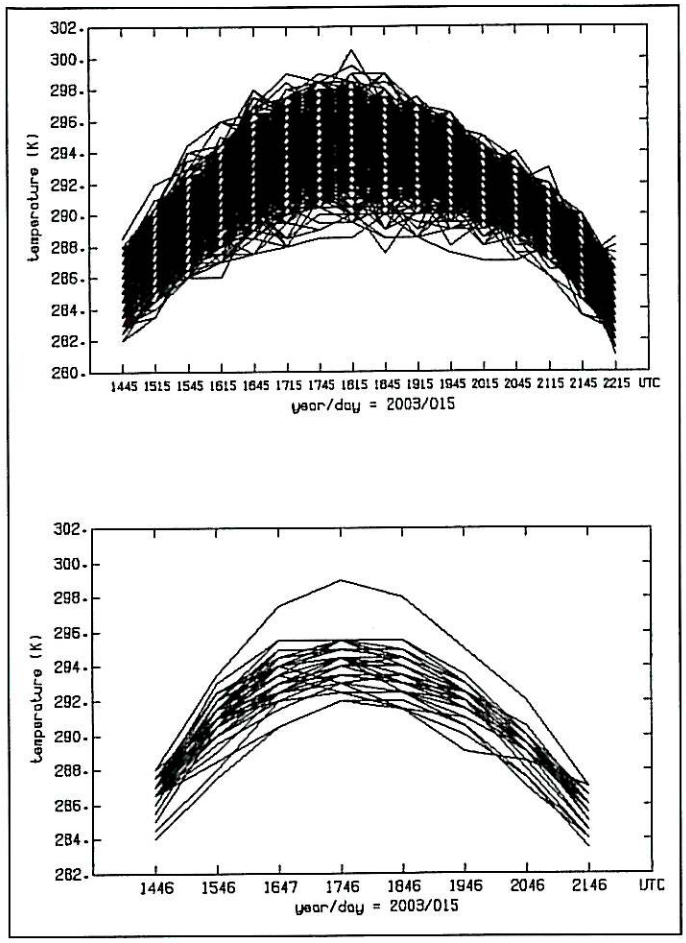

Fig. 6. Time series of Imager skin temperatures (top) and Sounder (land) SSTs (bottom) for 7.5 and 7 hours respectively on 15 January 2003. Lines are time series of temperature for land-surface only pixels over Florida, showing warming and then cooling as the day progresses.

smoother near-surface air temperature contours. These local variations can be used for local or mesoscale analysis at a scale much higher than that of near-surface air temperatures.

The images in Fig. 5 are only one of several times that the two image products were compared on that day. Figure 6 is a time series of values from both the skin temperature product (top) and SST product (bottom). The vertical axes display the temperatures for each product. The product times range from morning through evening and illustrate the diurnal temperature rise and fall. Each line in the figure represents the time series for a single land-surface pixel over Florida, with many more pixels for the higher (4 km) resolution Imager product compared to the lower (10 km) resolution Sounder product. Land-surface pixels alone were chosen for this figure because they exhibit a significant rise and fall in skin temperature throughout the day (heating and then cooling), unlike ocean-surface pixels. The range of temperatures in the two products is similar, but some of the difference between the two products is due to both space and time resolution differences. The Imager product has been generated at 4 km resolution every half hour, while the Sounder product has been generated at 10 km resolution every hour, the minimum interval between Sounder sectors available over the same geographic area.

A comparison between the two products is shown in Fig. 7, which is a scatter plot of 8835 matched pairs of land- and ocean-surface pixels between the two products given in Fig. 5 (1445 and 1446 UTC on 15 January 2003). Both land-surface pixels over Florida and ocean-surface pixels surrounding Florida are shown in this figure, to include a large range in skin temperatures. The Imager skin temperatures are on the horizontal axis, and the Sounder SSTs are on the vertical axis. Because of spatial resolution differences between the products (4 km vs. 10 km for the Imager and Sounder, respectively) several Imager pixels will match up with each Sounder pixel.

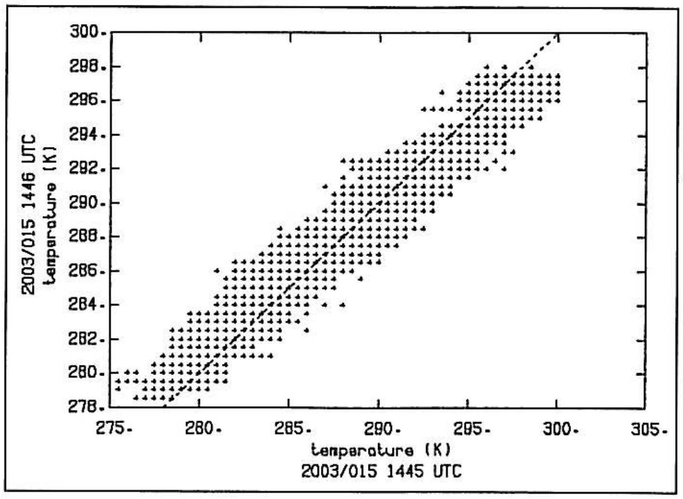

Fig. 7. Comparison of the Imager skin temperatures (horizontal axis) and Sounder (land and ocean) SSTs (vertical axis) for matched pairs of pixels (over Florida and the surrounding ocean) at 1445/1446 UTC respectively on 15 January 2003. The dashed line is a one-to-one equal-temperature relationship. The two products have a high correlation of 0.98 and a low RMS difference of 0.11 K.

This is one of the reasons for the broad scatter between the two products, as well as the fact that many pixels with similar temperatures are being compared. A dashed one-to-one line is the equal-temperature relationship. Scatter plot values seem to be somewhat equally distributed around the equal-temperature line, with slightly cooler values for the Imager product at the cool end, and slightly warmer values at the warm end compared to the Sounder product. The two products correlate at the 98% level, or an RMS difference of 0.11 K.

5. Summary and Conclusions

A simple skin temperature image product for the earth-air boundary, that can be constructed from GOES Imager or Sounder data (or polar-orbiting AVHRR or MODIS data), has been presented as an aid for weather analysis and forecasting by monitoring high-resolution variations and temporal changes in land- and ocean-surface skin temperatures. This may be especially helpful when near-surface air temperature observations are sparse and higher-spatial-resolution variations in the skin temperature are observed.

This type of product is simple, easily-produced, comparable to similar products, and physically based (Kidder et al. 2000). The skin temperature is generated on a continuing real-time basis from both GOES Imager and Sounder data on operational systems at CIRA and is frequently consulted in daily weather discussions. This product is also made available on RAMSDIS (Regional and Mesoscale Meteorology Team Advanced Meteorological Satellite Demonstration and Interpretation System) (Molenar et al. 2000) on-line for experimental testing at: http://www.cira.colostate.edu/RAMM/rmsdsol/ROLEX.html.

The GOES Sounder SST DPI is currently available on AWIPS (Advanced Weather Interactive Processing System) for use by NOAA/National Weather Service forecasters. However, it is believed that this product is underutilized in its current form. Because of its simplicity, the Imager skin temperature product could easily be substituted or added (while the split-window bands are still available on the GOES Imager), providing a higher-spatial-resolution product at more-frequent intervals than is currently available to users. Feedback from SatMet (COMET 2000) trainees suggests that the product has potential uses in the following additional situations: the potential for freezing rain, to determine the extent of a freeze situation, to discriminate soil types versus snow and fog/stratus, and to assess fog potential.

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