

A Standard Atmosphere of the Antarctic Plateau

Ashwin Mahesh

Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County

and

NASA Goddard Space Flight Center, Greenbelt MD

Dan Lubin

Scripps Institution of Oceanography, University of California, San Diego, La Jolla CA

Submitted to the *Journal of Climate*, August 2004

Corresponding Author Address:

Dr. Ashwin Mahesh
Code 912, NASA GSFC
Greenbelt MD 20771
Mahesh@agnes.gsfc.nasa.gov

Abstract

Climate models often rely on standard atmospheres to represent various regions; these broadly capture the important physical and radiative characteristics of regional atmospheres, and become benchmarks for simulations by researchers. The high Antarctic plateau is a significant region of the earth for which such standard atmospheres are as yet unavailable. Moreover, representative profiles from atmospheres over other regions of the planet, including from the northern high latitudes, are not comparable to the atmosphere over the Antarctic plateau, and are therefore only of limited value as substitutes in climate models. Using data from radiosondes, ozonesondes and satellites along with other observations from South Pole station, typical seasonal atmospheric profiles for the high plateau are compiled. Proper representations of rapidly changing ozone concentrations (during the ozone hole) and the effect of surface elevation on tropospheric temperatures are discussed. The differences between standard profiles developed here and the most similar standard atmosphere that already exists – namely, the Arctic winter profile – suggest that these new profiles will be extremely useful to make accurate representations of the atmosphere over the high plateau.

Introduction

Since the 1970s representative atmospheres have been available for several regions (the tropics, mid-latitudes, the sub-Arctic and the Arctic) and within these, for the seasons (McClatchey et al., 1972). Together, these standard profiles represent the majority of the planet's atmospheric conditions, and modelers of regional as well as global climate have routinely included them in their calculations. Significantly, however, this suite of model atmospheres does not include representations for the Antarctic coast and the vast continent. The lack of such profiles is significant, especially because the atmosphere over the high plateau of the continent is significantly different even from those of the coldest regions for which standard atmospheres are now available (Schwerdtfeger, 1970). Figure 1 shows the spectrum of downward longwave emission from existing standard profiles compared with observations made at South Pole station; the near-total lack of water vapor and the extreme cold over Antarctica produce a radiance regime that is noticeably different even from conditions in the Arctic. Accurate representations of the atmosphere over Antarctica, therefore, must derive from observations made on the continent itself.

The development of an Antarctic standard atmosphere was greatly inhibited by the extreme conditions of the continent, as also by its remoteness. Whereas routine weather observation programs in the more accessible and inhabited places often date back more than a century, it was only in the International Geophysical Year (1957) that monitoring programs over the Antarctic continent began (King and Turner, 1997). Although these greatly added to our understanding of the continent, nearly all the stations

were – and are, even today - from the coastal Antarctic, and only a few stations were ever operational on the high plateau. Of these, Amundsen-Scott station at South Pole provides the longest time series of data, with continuous observations dating back to the IGY itself.

Fortunately, despite the isolated nature of South Pole station, observations from this location may reasonably represent average conditions over much of the continent. The surface elevation at the geographic pole is comparable to the average elevation over the high plateau (see figure 2). Also, the high visible reflectance and infrared emissivity of the snow surface makes representations of other contributions to the energy balance far easier; conditions at the surface are largely determined by the longwave downward radiance alone. The surface-based temperature inversion maintained by the radiative balance exceeds 20 degrees over a few hundred meters of the lowest atmosphere for a large portion of the plateau (Jeff Key, personal communication, 2003; Philpot and Zillman, 1970). Recently, using a time series of annual mean temperatures for each pixel in the 18-year satellite record over Antarctica, King (personal communication, 2003) developed a method to determine the degree to which any given location is representative of other locations in the continent. The correlation coefficient between the time series for the South Pole and the time series at every other point (figure 3) shows that annual mean temperature fluctuation at 90 S is representative of surface conditions over much of plateau, with the exception of the highest elevations.

Temperature

Twice daily in summer (November-February) the South Pole Weather Office (SPWO) conducts routine radiosonde launches; in winter the sondes are launched only once each day. The temperature profiles obtained by these radiosondes include errors due to the thermal lag of the thermistors; this problem is especially significant in atmospheric layers where the lapse rate is very high – as in the surface based temperature inversion over the Antarctic plateau. The values reported by the thermistor were corrected for this lag thermal lag of thermistors on the radiosondes according to the method of Mahesh et al. (1997). Using a 10-year period (1993-2002) of observations, monthly average profiles were constructed from radiosonde reports during each month, and multi-year averages of such monthly profiles were created. Averages were obtained as follows: temperatures from each sounding were first interpolated on to a 50-m grid. Following this, temperature values at each height were averaged using all available soundings that reached that height. The heights that soundings reach in the atmosphere vary considerably; at stratospheric heights, therefore, fewer radiosondes are included in the average values than at tropospheric elevations. For temperatures above 30 km (i.e. at atmospheric pressures below 10 mb) we used monthly-average temperatures obtained by the Upper Atmosphere Research Satellite (UARS) (Walden 1995). There is typically some overlap, as the highest elevations reached by the sondes are often some kilometers higher than the lowest elevation of UARS sounding. Mahesh (1999) observed that observations of atmospheric radiance at the surface were better matched with calculations when UARS data from the upper atmosphere was also included, but the radiances calculated were not particularly

sensitive to the temperatures at those elevations. Continuity between the soundings and the UARS observations was therefore established by using the radiosonde data at the overlapping elevations, and the UARS observations at higher levels.

Figure 4 shows the monthly average atmospheric profiles of temperature obtained in this manner. The key features of Antarctic temperatures - the strong surface-based inversion in the winter months, the extreme cold stratospheric temperatures at which Polar Stratospheric Clouds form in the spring, the core-less minimum in surface temperature throughout the winter – are all evident. There is also considerable variability in upper-air temperature, but as noted earlier the contribution to the energy balance at the surface from this portion of the atmosphere is small. The surface temperature, inversion strength, stratospheric temperatures also suggest a basis for classification of the year-round observations into seasonal profiles: Mar-April-May, June-July-August, September-October-November, and December-January-February, as fall, winter, spring and summer respectively. Temperature values for the individual months, as well as for these seasons, are included in Tables 1 and 2; these may also be downloaded from <http://www.url-to-be-decided/antkprofiles.htm>.

Ozone

Current research on high latitude climate change has emphasized the importance of radiative and dynamic coupling between the troposphere and stratosphere, and the impact of these interactions on the polarity of the Northern or Southern Annular Mode (NAM or SAM; Shindell et al., 1999). Over Antarctica in particular, the springtime ozone

decrease in the stratosphere has been linked to a gradual strengthening of the SAM, which may have driven a cooling of the continental interior and a warming of the Antarctic Peninsula over the past two decades (Comiso, 2000; Thompson and Solomon, 2002; Gillett and Thompson, 2003). A complete standard atmosphere of the Antarctic Plateau must therefore account for stratospheric ozone variability in order to be fully applicable to climate studies.

The most important, and extreme, ozone variability is related to the anthropogenic ozone decrease in the lower stratosphere from heterogeneous chemistry, that begins during late winter and in recent years has lasted well into summer (Solomon, 1999). We have therefore constructed model ozone profiles, from the surface through 50 km, as a function of total column ozone amount in Dobson units (DU), for each of four seasons. In contrast to the monthly variability in temperature and pressure profiles, the climatological (pre-industrial) monthly variability in total column ozone is much smaller than the variability due to the ozone "hole" and related dynamics of the stratospheric polar vortex. However, there is enough seasonal variability in climatological ozone over Antarctica that these variations should also be considered (Brasseur and Solomon, 1984). Our objective is to provide a set of ozone profiles that allow the researcher to construct a realistic horizontal and vertical distribution in ozone abundance using readily available satellite data from instruments such as the Total Ozone Mapping Spectrometer (TOMS). Given a satellite measurement of total column ozone, the researcher can interpolate between these standard ozone profiles at each altitude. In this way a climate model

simulation can be accurately initialized to account for the large anthropogenic changes to the ozone column over Antarctica.

The model ozone profiles are based primarily on five years of electrochemical concentration cell (ECC) ozonesonde data from the South Pole, collected by the NOAA Climate Modeling and Diagnostics Laboratory (CMDL), kindly provided by Dr. J. Hoffman. We analyzed 325 ozone profiles collected between January 1998 and January 2003. For each season, all ozone soundings that reached above 25 km were sorted into total ozone column bins 10 DU wide. When there were fewer than three soundings in a bin, adjacent bins were combined, resulting in some bins as wide as 30 DU. In each bin, the soundings were averaged at each altitude grid point (0.25 km increments) and this average was then smoothed from the surface to 30 km with a moving average over a 1 km altitude range. For the remaining ~10-15% of the ozone column above 30 km, Solar Backscatter Ultraviolet (SBUV) satellite ozone profiles were binned and averaged in a similar fashion. Ten years of SBUV data were kindly provided by Dr. R. D. McPeters (NASA Goddard Space Flight Center, personal communication, 2003). These matching higher altitude profiles, for the closest season and total ozone column bins, were joined to the tops of the appropriate sounding profile averages. Discontinuities between the two profiles at 30-34 km were removed by smoothing if smaller than $2 \times 10^{11} \text{ cm}^{-3}$, and by scaling the SBUV profile to the sounding end point if larger than $2 \times 10^{11} \text{ cm}^{-3}$. After joining the sonde and SBUV profiles, the combined profile was smoothed a second time with a moving 2 km average. This procedure for combining SBUV and sounding data is adequate for constructing model ozone profiles whose primary applications include

climate and radiation budget studies in the troposphere and stratosphere. For applications involving dynamics or chemistry of the upper stratosphere and mesosphere, the researcher is advised to use SBUV data directly, which extend downward to 100 mb (approximately 15 km over Antarctica). For climate studies, our ozone profiles are more relevant than SBUV data alone, because the sounding averages realistically specify ozone abundances at the tropopause and in the lower stratosphere. The model ozone profiles are tabulated online at <http://www.url-to-be-decided/antkprofiles.htm> as a function of their total ozone column abundance in DU.

Examples of the model profiles from each season are shown in Figure 5. During spring, we were fortunate to have CMDL sondes during the weak ozone "hole" of 2002, and several of these showed climatologically normal ozone profiles with column abundances greater than 330 DU. Thus our standard atmosphere is applicable to pre-industrial climate modeling simulations. Most springtime ozone soundings, however, showed some degree of anthropogenic ozone depletion, and the severest examples (column abundances ~100 DU) show a near total ozone loss between 15-20 km. During the 1990s, the anthropogenic ozone decrease began to last into December, and the suite of ozone profiles for summer includes one with total column abundance 154 DU. The ozone profiles for autumn and winter show total column abundance variations that are mainly climatological (e.g., Brasseur and Solomon, 1984), and the major differences here are slightly larger ozone abundances (~30 DU) and a slightly thicker and higher stratospheric ozone layer during autumn.

Water vapor

The measurement of water vapor over the high plateau has been severely impeded by the lack of sensitivity of hygriators typically attached to radiosondes at the low temperatures prevalent in the Antarctic atmosphere. This is made further difficult by the fact that water vapor exists in such low quantities here; over much of the high plateau, precipitable water vapor amounts are below 2 mm throughout the year. The spectral signature from such low water vapor amounts (see infrared window between 8 and 12 microns in figure 1) is extremely small, even in comparison to that from high latitudes in the Arctic. Nonetheless, comparisons between measured downwelling longwave radiance and calculations (Walden 1995) using theoretical profiles show that while minimal, water vapor amounts cannot be set to zero, i.e., anecdotal knowledge of conditions on the plateau can be used to provide reasonable representations of water vapor in standard profiles, and these are adequate to mimic the gas's measured radiative impact.

Even in clear-sky conditions it is common to find suspended ice-particles – known as ‘diamond dust’ in the inversion layer just above the surface; this suggests that this portion of the atmosphere is likely saturated with respect to ice. UARS data provide some measurements of atmospheric water vapor in the middle and upper troposphere. Radiosonde observations during and after cloudiness in the free troposphere (above the inversion layer) suggest much greater variability of saturation levels here. And UARS observations indicate only a few parts per million by volume (ppmv) of water vapor in the upper troposphere. Following Walden (1995) we recommend setting relative humidity with respect to ice at 90% in the surface-based inversion layer, and at 75% at elevations above the inversion but below 7 km. There is no sensitivity in radiative

calculations to values above this height; an efficient representation is to simply set water vapor values to 5 ppmv at all heights above the tropopause.

Adjusting temperature for surface elevation

Several attributes of Antarctica – snow and ice cover, high elevation, latitude, etc. – together allow representations of radiative conditions over the continent to be made more easily than elsewhere. However, there is one key attribute that impacts atmospheric conditions, especially temperature, significantly – namely, the surface elevation. In figure 2, we observed that South Pole is most unlike the locations where surface elevation is either substantially higher or lower, and much more representative of locations at similar surface elevation. Observations of radiosonde data from the few stations where these are available suggest that whereas lower tropospheric temperatures are markedly different depending on surface elevation, upper troposphere temperatures are more comparable. In particular in the lower troposphere, the inversion strength – the difference between surface temperature and the warmest point of the lower troposphere - is much smaller on the coast, and correspondingly the inversion height - the elevation of the warmest location - is much greater. This variation is expected; when the surface elevation is at a lower pressure, downward longwave emission from the atmosphere is radiatively balanced by upward infrared emission by a colder surface, although surface conditions themselves may be comparable in the two cases. This increases the inversion strength with altitude, and correspondingly reduces the thickness of the layer over which the radiative balance is established (this latter quantity is the inversion height).

This observation, while it is evident from the radiosonde data, is inadequate to make strong correlations between surface elevations and inversion properties, because nearly all of the radiosonde data is from coastal locations and the only long-period observations other than these are from a single source (South Pole). Recently, however, Liu and Key (2002, see figures 12 and 13) have developed a method of determining inversion strengths and heights from clear-sky observations made by MODIS. Climate modelers desirous of making more spatially detailed representations of lower tropospheric temperatures can apply corrections based on relationships made from such findings.

Conclusions

The need for standard atmospheric profiles of Antarctica that can be used in climate models has been long-standing. It has especially been prompted by the knowledge that not only is the atmosphere over the Antarctic plateau extreme, but additionally, even in comparison to the Arctic winter atmospheres it is significantly different. The extreme transparency of the infrared atmospheric window in Antarctica also makes downward radiances in particular wavelength intervals highly sensitive to the temperature profile. Mahesh et al. (1997) showed that temperature differences of only a few degrees in the atmosphere below the inversion could produce a half percent change in the downward longwave flux for clear sky in winter at the South Pole; this is comparable to the effect caused by changes in carbon dioxide concentrations from pre-industrial times to the present. Such sensitivity confirms that radiative transfer

calculations for the Antarctic atmosphere cannot be approximated by even the coldest conditions elsewhere.

Clear sky fluxes at the top of the atmosphere as well as at the ground elevation of South Pole (2835 meters) were calculated by the radiative transfer program STREAMER (Key and Schweiger, 1998), using the standard Arctic winter profile, and again using a typical Antarctic profile from this research. Fluxes at the top of the atmosphere and at the surface differed by as much as 5-10 percent. These values are significantly greater than the magnitude of changes in fluxes expected from global warming over the next century; to attempt to model Antarctic conditions using profiles taken elsewhere, therefore, would significantly undermine our ability to model the expected changes.

The standard profiles presented here primarily offer representations of temperature and ozone concentrations in the atmosphere over the Antarctic plateau, whose understanding has been limited by the historical paucity of detailed observations. Because the great majority of the area of the plateau is at a significant elevation, the temperature correction for surface elevation is only significant near the edge of the ice sheets. Ozone concentrations of different columnar amounts are shown for each season, to account for the fact that the vertical distribution of ozone varies with season, even when total column amounts are comparable. While water vapor amounts are extremely low across much of the continent, clearly this is not the case near the coasts; fortunately a number of coastal stations are available from which routine observations can be obtained wherever it is deemed that coastal values are more appropriate.

Acknowledgments

Contributions from both authors were supported by the Goddard Earth Science and Technology program. We thank Prof. J. Hoffman for providing the ozonesonde data and Dr. R. D. McPeters for providing the SBUV data.

References

- Brasseur, G., and S. Solomon, 1984: *Aeronomy of the Middle Atmosphere*. D. Reidel, Boston, 441 pp.
- Comiso, J. C., 2000: Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements, *J. Clim.*, **13**, 1674-1696.
- Gillett, N., and D. F. W. Thompson, 2003: Simulation of recent Southern Hemisphere Climate Change. *Science*, **302**, 273-275.
- Key, J., and A. J. Schweiger, 1998: Tools for atmospheric radiative transfer: Streamer and FluxNet. *Computers and Geosciences*, **24(5)**, 443-451.
- King, J. C., and J. Turner, 1997: *Antarctic Meteorology and Climatology*. Cambridge University Press, 40 West 20th Street, New York, NY 10011-4211, USA
- Liu, Y. and J. Key, 2003: Detection and analysis of clear sky, low-level atmospheric temperature inversions with MODIS, *J. Atmos. Ocean. Tech.*, **20**, 1727-1737.
- Mahesh, A., 1999: *Ground-based infrared remote sensing of cloud properties over the Antarctic plateau*, Ph.D. thesis, University of Washington, Seattle WA 98195.
- Mahesh, A., V. P. Walden, and S. G. Warren, 1997: Radiosonde temperature measurements in strong inversions: Correction for thermal lag based on an experiment at the South Pole. *J. Atmos. and Oceanic Tech.*, **14**: 45-53
- McClatchey, R. A., R. W. Fenn, J. E. A. Selby, F. E. Volz, and J. S. Garing, 1972: *Optical Properties of the atmosphere*. Rep. AFCRL-72-0497, 108 pp. Available from Geophysics Laboratory, Hanscom AFB, Bedford MA 01731.
- Phillpot, H. R., and J. W. Zillman, 1970: The surface temperature inversion over the Antarctic continent. *J. Geophys. Res.*, **75**, 4161-69.

Schwerdtfeger, W. 1970: The Climate of the Antarctic. *World Survey of Climatology* **14**, 253-355.

Shindell, D. T., R. L. Miller, G. A. Schmidt, and L. Pandolfo, 1999: Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Nature*, **399**, 452-455.

Solomon, S., 1999: Stratospheric ozone depletion: a review of concepts and history. *Rev. Geophys.*, **37**, 275-319.

Thompson, D. W. J., and S. Solomon, 2002: Interpretation of recent Southern Hemisphere climate change. *Science*, **296**, 895-899. Walden, V. P., 1995: *The downward longwave radiation spectrum over the Antarctic plateau*. Ph.D. Thesis, University of Washington, Seattle, 267 pp.

List of figures

Figure 1: Infrared spectra from tropical, arctic and antarctic atmospheres show considerable variability due to temperature and atmospheric composition. The Antarctic plateau marks an endpoint in terrestrial climate, and is too dry and cold to be represented by conditions at similar latitudes in the northern hemisphere. [Reproduced from Mahesh, 1999].

Figure 2: Histogram of surface elevations on the Antarctic plateau, for values greater than 500 meters. Each grid-point included in the distribution spans one degree of latitude and longitude.

Figure 3: Representative-ness of surface locations on the Antarctic plateau. Numbers show the correlation coefficient of the time series for surface temperatures at South Pole with the time series at every other location.

Figure 4: Monthly average profiles of atmospheric temperature, from radiosonde observations and UARS.

Figure 5: The vertical distribution of ozone in the atmosphere varies significantly during the year. A total column ozone amount of 170 Dobson Units, in this example, corresponds to very different vertical profiles.

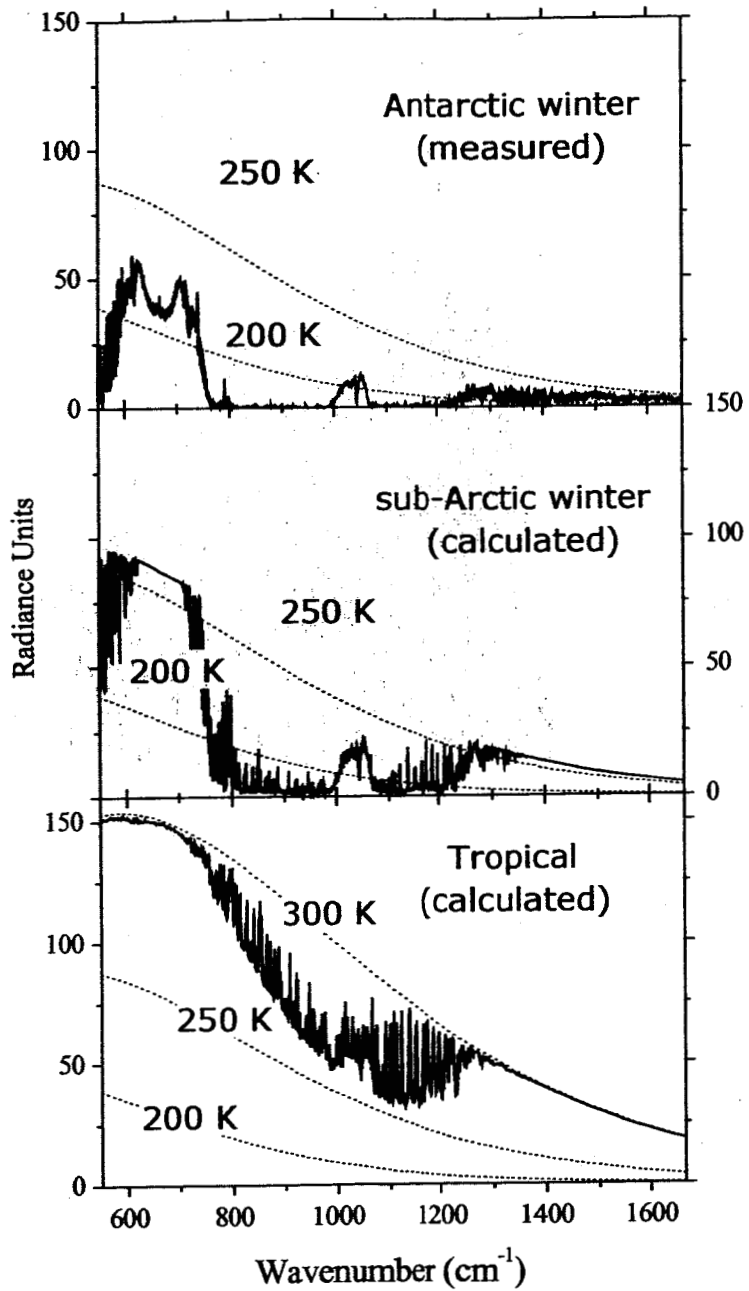


Figure 1

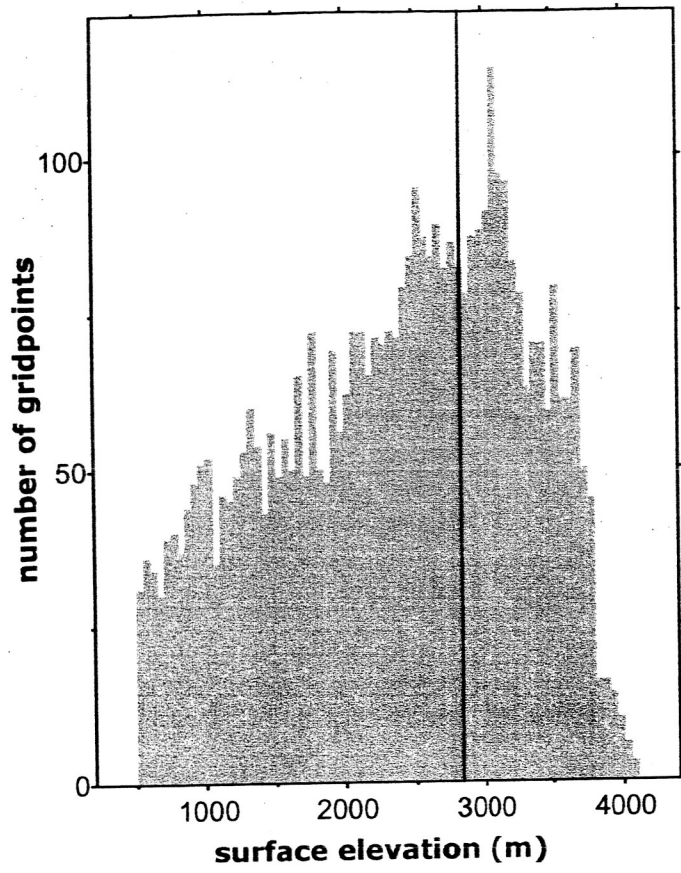


Figure 2

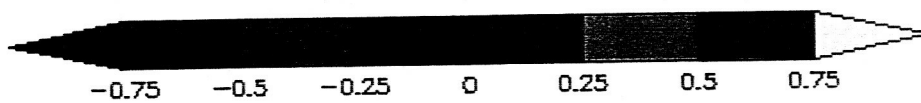
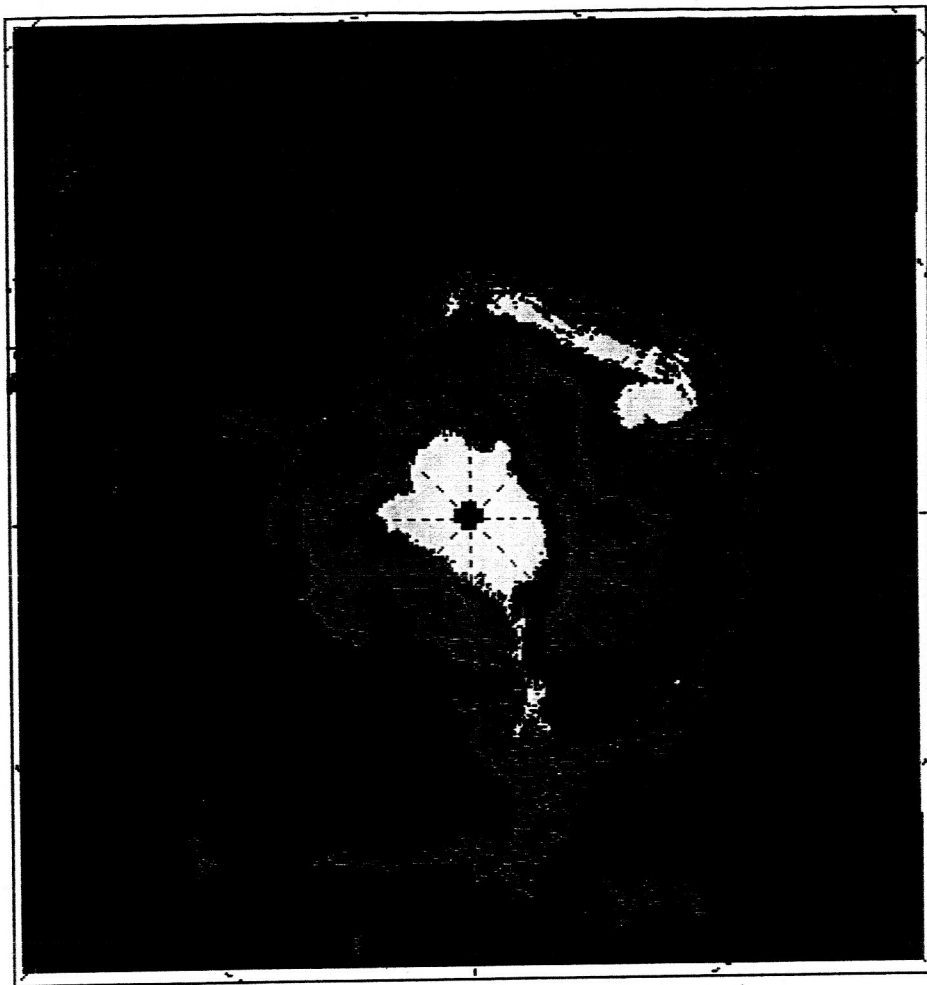


Figure 3

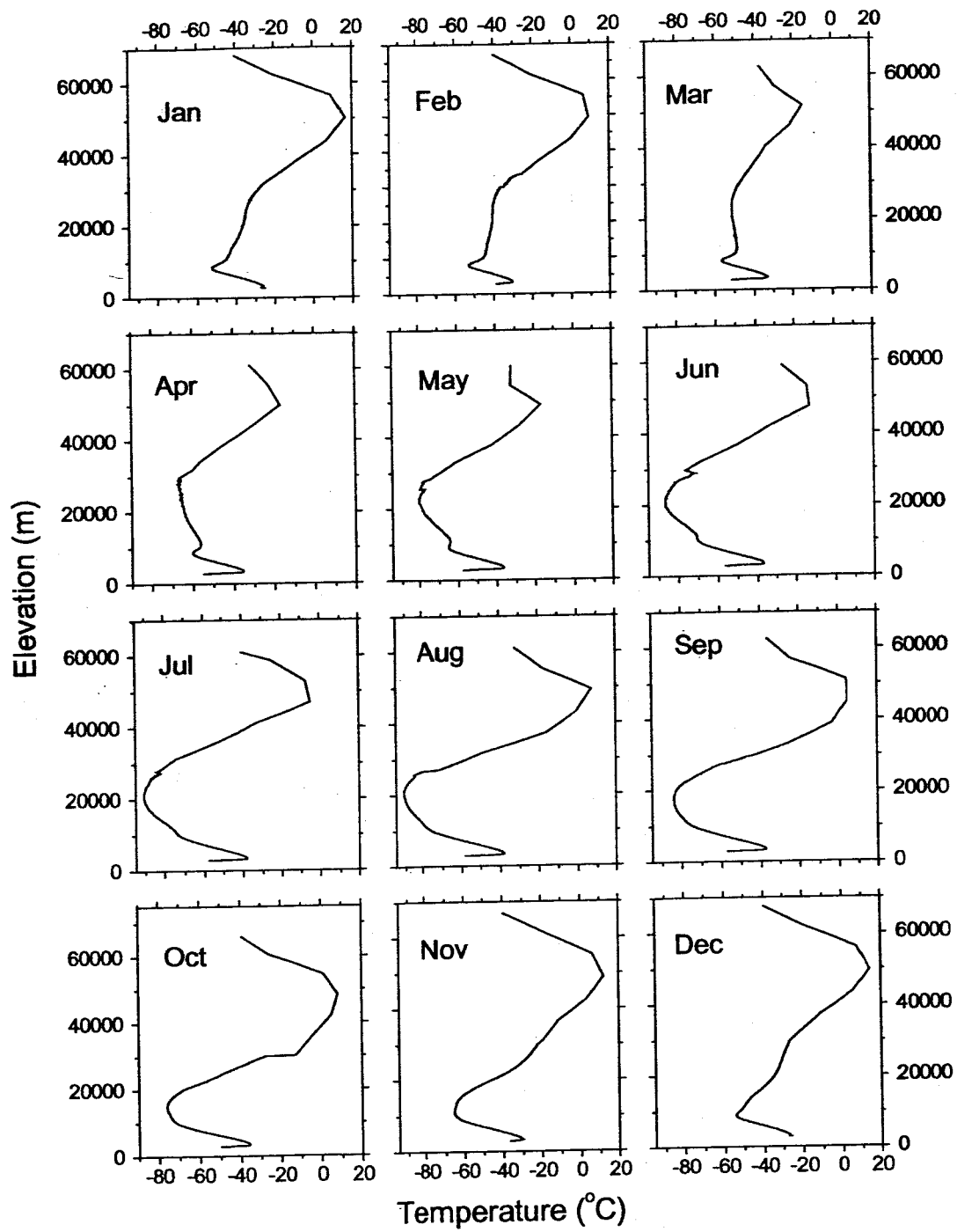


Figure 4

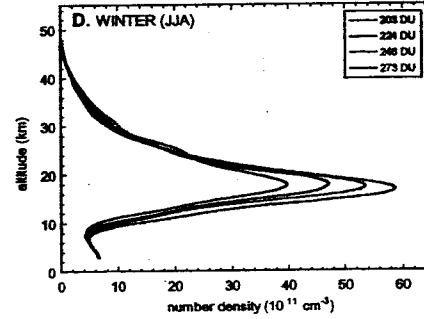
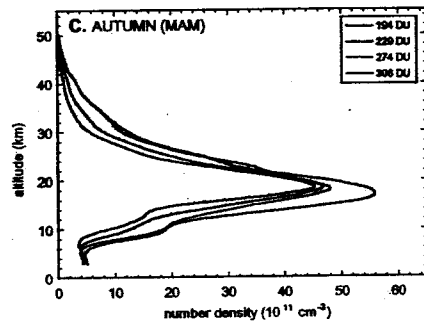
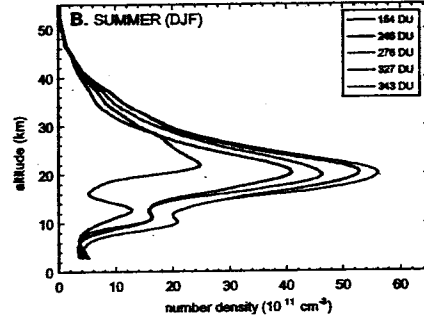
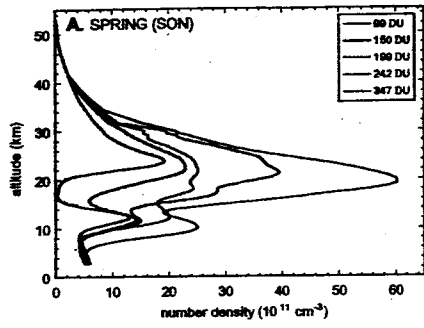


Figure 5

POPULAR SUMMARY

A Standard Atmosphere of the Antarctic Plateau

Ashwin Mahesh and Dan Lubin

Submitted to the *Journal of Climate*, August 2004

Climate models often rely on standard atmospheres to represent various regions because it is often computationally too difficult to include local representations from every location in the model. These standard profiles broadly capture the important physical and radiative characteristics of regional atmospheres, and become benchmarks for simulations by researchers. Such standards were made in the 1970s for most regions of the planet, but not for Antarctica. This is a significant omission, because Antarctica occupies a significant area (comparable to the United States) and is also very different from any place on Earth. The standard profiles of other regions made for use in climate models are not representative of Antarctica, and are therefore only of limited value as substitutes in climate models. This research is an effort fill the void in the scientific community's library of standard atmospheres, so that future representations of the region in climate models can be more accurate.

Using data from radiosondes, ozonesondes and satellite along with other observations from South Pole station, typical seasonal atmospheric profiles for the high plateau are compiled. Temperature profiles had to be corrected for measurement errors caused by the slow response of the recording thermistors. Proper representations of rapidly changing ozone concentrations (during the ozone hole) were also necessary, because the same total column amounts of ozone in the atmosphere correspond to

different vertical distributions in different seasons. The effect of surface elevation on tropospheric temperatures is also discussed; this is necessary because much of the high plateau is at a very high elevation, and lower atmospheric temperatures are sharply dependent on these heights. The differences between standard profiles developed here and the most similar standard atmosphere that already exists – namely, the Arctic winter profile – are calculated. These differences suggest that these new profiles will be extremely useful to make accurate representations of the atmosphere over the high plateau.

The standard atmospheres developed here will be maintained online at both NASA Goddard Space Flight Center and at the University of California, and freely available to the global community of climate modelers and researchers.