

ties to emphasize those measurements of our local astrophysical laboratory that will best illuminate how these fundamental cosmic entities operate. Moreover, observations to date already indicate that the Saturn system is literally changing before our eyes. We anticipate that even more dramatic transformations in our neighborhood's astrophysical laboratory will be monitored by Cassini's instruments over the next several years.

References and Notes

1. Special Issue on Cassini at Saturn, *Science* **307** (25 February 2005).
2. J. J. Lissauer, J. N. Cuzzi, in *Protostars and Planets II*, D. C. Black, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1985), pp. 920–958.
3. Special Issue on Disks in Space, *Science* **307** (7 January 2005).
4. M. S. Tiscareno *et al.*, paper presented at the American Geophysical Union fall meeting, 5 to 9 December 2005, San Francisco (abstract FM-P33B0245T2005).
5. J. E. Colwell, personal communication.
6. J. E. Colwell, L. W. Esposito, M. Sremcevic, *Geophys. Res. Lett.* **33**, L07201 (2006).
7. M. M. Hedman, P. D. Nicholson, B. D. Wallis, paper presented at the American Geophysical Union fall meeting, 5 to 9 December 2005, San Francisco (abstract FM-P31D02H2005).
8. H. Salo, *Icarus* **117**, 287 (1995).
9. A. W. Harris, in *Planetary Rings*, R. J. Greenberg, A. Brahic, Eds. (Univ. of Arizona Press, Tucson, AZ, 1984), pp. 641–658.
10. M. S. Tiscareno *et al.*, *Nature* **440**, 648 (2006).
11. P. Kalas, J. R. Graham, M. Clampin, *Nature* **435**, 1067 (2005).
12. Support from the Cassini project is gratefully acknowledged. We thank M. Tiscareno, M. Hedman, and P. Nicholson for comments.

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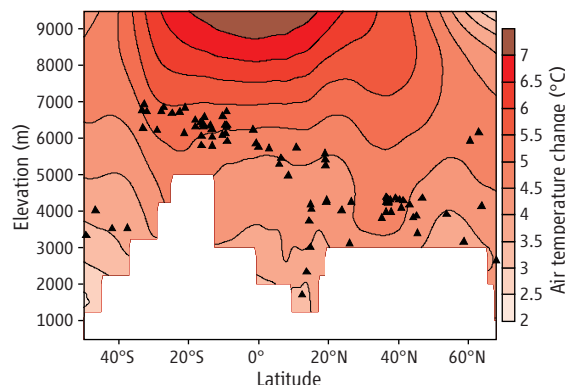
CLIMATE CHANGE

Threats to Water Supplies in the Tropical Andes

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According to general circulation models of future climate in a world with double the preindustrial carbon dioxide (CO₂) concentrations, the rate of warming in the lower troposphere will increase with altitude. Thus, temperatures will rise more in the high mountains than at lower elevations (see the figure) (1). Maximum temperature increases are predicted to occur in the high mountains of Ecuador, Peru, Bolivia, and northern Chile. If the models are correct, the changes will have important consequences for mountain glaciers and for communities that rely on glacier-fed water supplies.

Is there evidence that temperatures are changing more at higher than at lower elevations? Although surface temperatures may not be the same as in the free air, in high mountain regions the differences are small (2), and changes in temperature should thus be similar at the surface and in the adjacent free air. Unfortunately, few instrumental observations are available above ~4000 m. The magnitude of recent temperature change in the highest mountains is therefore poorly documented. An analysis of 268 mountain station records between 1°N and



Global warming in the American Cordillera. Projected changes in mean annual free-air temperatures between (1990 to 1999) and (2090 to 2099) along a transect from Alaska (68°N) to southern Chile (50°S), following the axis of the American Cordillera mountain chain. Results are the mean of eight different general circulation models used in the 4th assessment of the Intergovernmental Panel on Climate Change (IPCC) (15), using CO₂ levels from scenario A2 in (16). Black triangles denote the highest mountains at each latitude; areas blocked in white have no data (surface or below in the models). Data from (15).

23°S along the tropical Andes indicates a temperature increase of 0.11°C/decade (compared with the global average of 0.06°C/decade) between 1939 and 1998; 8 of the 12 warmest years were recorded in the last 16 years of this period (3). Further insight can be obtained from glaciers and ice caps in the very highest mountain regions, which are strongly affected by rising temperatures. In these high-altitude areas, ice masses are declining rapidly (4–6). Indeed, glacier retreat is under way in all Andean countries, from Columbia and Venezuela to Chile (7).

A convergence of factors contribute to these changes. Rising freezing levels (the level where temperatures fall to 0°C in the atmosphere) (8, 9)

Climate models predict that greenhouse warming will cause temperatures to rise faster at higher than at lower altitudes. In the tropical Andes, glaciers may soon disappear, with potentially grave consequences for water supplies.

lead to increased melting and to increased exposure of the glacier margins to rain rather than snow (10). Higher near-surface humidity leads to more of the available energy going into melting snow and ice, rather than sublimation, which requires more energy to remove the same mass of ice. Therefore, during humid, cloudy conditions, there is often more ablation than during drier, cloud-free periods (6). In some areas, changes in the amount of cloud cover and the timing of precipitation may have contributed to glacier mass loss through their impact on albedo (surface reflectivity) and the net radiation balance (11). As these processes continue and snow is removed, more of the less reflective ice is exposed and absorption of the intense high-elevation radiation increases, thus accelerating the changes under way through positive feedbacks.

The processes involved in mass-balance changes at any one location are complex, but temperature is a good proxy (12) for all these processes, and most of the observed changes are linked to the rise in temperature over recent decades (5). Further warming of the magnitude shown in the figure will thus have a strong negative impact on glaciers throughout the Cordillera of North and South America. Many glaciers may completely disappear in the next few decades, with important consequences for people living in the region (7).

Although an increase in glacier melting initially increases runoff, the disappearance of glaciers will cause very abrupt changes in streamflow, because of the lack of a glacial buffer during the dry season. This will affect the availability of drinking water, and of water for agriculture and hydropower production.

In the High Andes, the potential impact of such changes on water supplies for human con-

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