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Convective storms in planetary atmospheres

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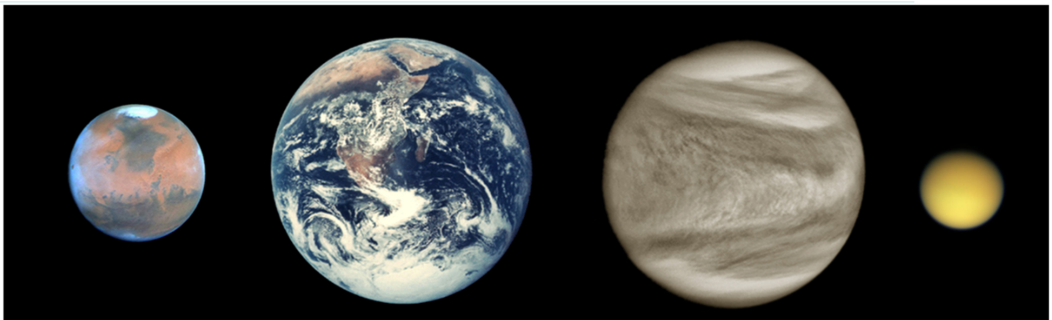
Abstract

The atmospheres of the planets in the Solar System have different physical properties that in some cases can be considered as extreme when compared with our own planet's more familiar atmosphere. From the tenuous and cold atmosphere of Mars to the dense and warm atmosphere of Venus in the case of the terrestrial planets, to the gigantic atmospheres of the outer planets, or the nitrogen and methane atmosphere of Saturn's moon Titan, we can find a large variety of physical environments. The comparative study of these atmospheres provides a better understanding of the physics of a geophysical fluid. In many of these worlds convective storms of different intensity appear. They are analogous to terrestrial atmospheres fed by the release of latent heat when one of the gases in the atmosphere condenses and they are therefore called moist convective storms. In many of these planets they can produce severe meteorological phenomena and by studying them in a comparative way we can aspire to get a further insight in the dynamics of these atmospheres even beyond the scope of moist convection. A classical example is the structure of the complex systems of winds in the giant planets Jupiter and Saturn. These winds are zonal and alternate in latitude but their deep structure is not accessible to direct observation. However the behaviour of large–scale convective storms vertically extending over the "weather layer" allows to study the buried roots of these winds. Another interesting atmosphere with a rather different structure of convection is Titan, a world where methane is close to its triple point in the atmosphere and can condense in bright clouds with large precipitation fluxes that may model part of the orography of the surface making Titan a world with a methane cycle similar to the hydrological cycle of Earth's atmosphere.

1 Atmospheric convection in terrestrial planets

Solar System planets are divided into terrestrial-like planets and giant planets with extended atmospheres and no surface. The terrestrial planets owing atmospheres are Mars, Venus and Earth. In this group we can add Saturn's moon Titan. Figure 1 shows these planets with



Atmospheric composition:			
CO_2 95%	**N_2 78%** **O_2 21%** H_2O, 1% (variable) CO_2 335 ppmv CH_4 1.72 ppmv	**CO_2 96%** **N_2 3%** SO_2 0.015% H_2O < 0.002%	**N_2 95%** CH_4 5%
Surface characteristics:			
P_0=4-9 mb, T_0=-45ºC | Range [-87, -5]ºC	P_0=1013 mb, T_0= 14ºC | Range [-89,+58]ºC	**P_0=92 atm** **T_0= 460ºC**	P_0=1.5 atm T_0= -180ºC (94 K)
Notes:			
Green-house effect: 4-5 ºC	Green-house effect:	***Runaway green-house effect***	Methane triple point Methane atmospheric cycle

Figure 1: Atmospheres of the terrestrial planets. Planets are drawn respecting their relative scale.

relevant characteristics of their atmospheres. Mars is a planet with a variety of clouds made of CO_2 and water and Venus is permanently covered by a vertically extended system of H_2SO_4 clouds. However the absence of a suitable abundant condensible makes moist convection very rare and weak in both planets (although Mars presents its own "rocket-dust" storms powered by solar heating in dust grains lifted by the surface wind [1] and Venus has electric activity [2] and convective cells observed in the top of the uppermost clouds [3]).

Convective storms releasing large amounts of energy into the atmosphere appear in the Earth and Titan. In the first case storms are powered by the release of latent heat when water condenses releasing energy previously deposited by the solar radiation. Most of this activity happens at equatorial latitudes in the Inter Tropical Convergence Zone. The role of water on Earth is taken by methane in Titan's atmosphere. Under its cold temperatures (90 K at the surface) methane is close to its triple point and forms a variety of clouds [4]. Models of convective clouds in Titan show that, just like in the Earth, if favourable conditions are met in terms of high relative humidity and atmospheric thermal profile close to adiabatic, convective clouds can form slightly above the surface ascend to the 35 km altitude producing large precipitation fluxes on the surface in events comparable to flash-floods on Earth [5]. Evidence of recent large events of precipitation on Titan following the development of a giant size storm have been recently found by Cassini ISS observations [6]. Figure 2 shows a comparison of methane and water convective clouds on Titan and Earth. The low gravity of Titan and the low latent heat released by methane are compensated by the large abundance of methane and the vertically extended atmosphere making convection in both planets comparable in terms of maximum precipitation fluxes that can be attained

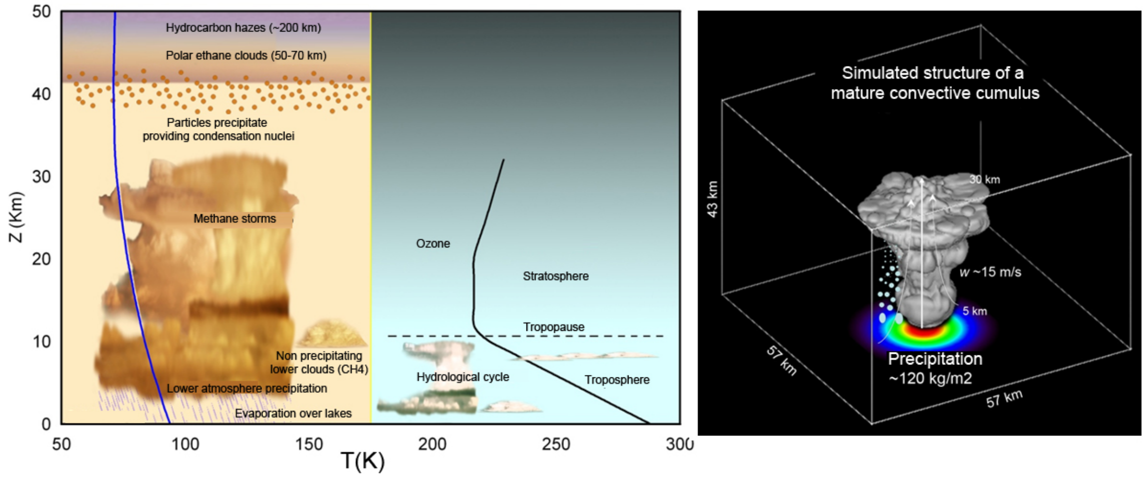


Figure 2: Comparison between convective clouds in Titan and Earth. The right panel shows the morphology of a convective cumulus cloud in Titan from a fully three-dimensional model of Titan's cumulus clouds [5].

in the surface for the most favourable conditions of convection development. However, since Titan is located 10 times further away from the Sun than the Earth the amount of energy stored in the atmosphere as methane vapour able to condense is much lower and convection happen only rarely.

2 Atmospheric convection in the giant planets

The outer planets are divided in two groups: the gas giant planets Jupiter and Saturn; and the ice giants Uranus and Neptune. The four of them have massive atmospheres without a defined surface, internal heat sources comparable to the solar irradiation at their orbit (except for Uranus), condensible gases that are heavier than the dry air of the atmosphere made by Hydrogen with a relevant contribution from Helium. Besides, they are truly large (see Fig. 3) allowing for a different scale of atmospheric phenomena to develop. They are rapid rotators (Jupiter and Saturn turn around their axis in 10 hours while Uranus and Neptune do so in $15 - 17$ hours). The outer layers of these atmospheres are the only part of them that can be observed. Their upper tropospheres and lower stratospheres are cold and condensible gases forming the uppermost clouds are ammonia in Jupiter and Saturn and methane in Uranus and Neptune. Deeper below exotic clouds of ammonia hydrosulfide form in all of them. The base of the weather layer is probably limited by the presence of a deep water cloud layer of paramount importance for convective phenomena in Jupiter and Saturn. The role of water in powering convection is that water is expected to be abundant in the deep troposphere of these planets, it has a large latent heat and is found several scale heights ($100 - 200$ km) below the tropopause which allows a convective storm to accelerate for a long vertical path before stopping when reaching the upper troposphere with high static stability.

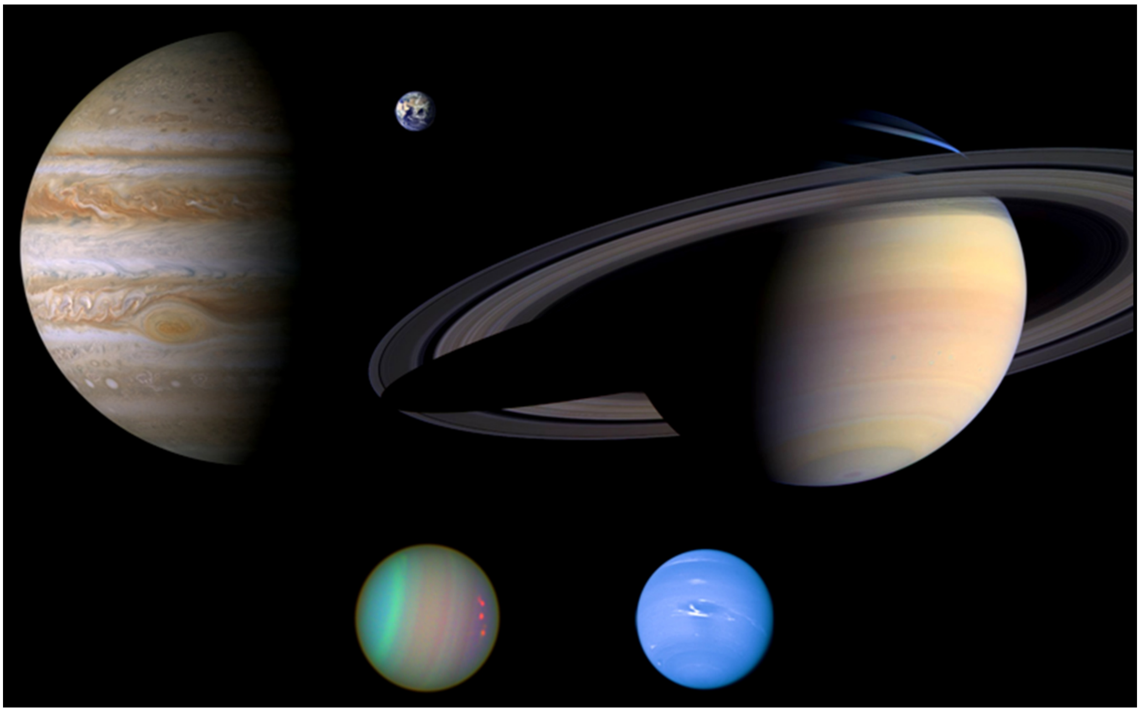


Figure 3: Atmospheres of the giant planets. Figure is drawn respecting the scale of the different planets. The Earth has been added as a reference for sizes. Mid-scale storms of 3,000 km are visible north-west of the Great Red Spot in Jupiter and in the North Temperate Belt, Saturn appears bland and with no storms in most observations, Uranus shows some spring-time convective features and Neptune shows a variety of clouds with some of them probably of convective origin.

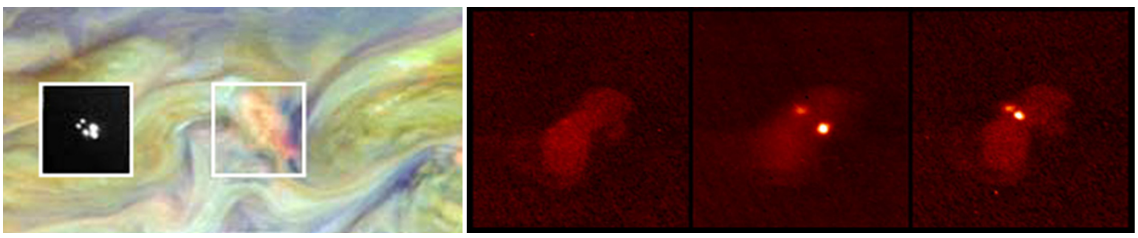


Figure 4: *Left panel:* Night-side lightning observed in Jupiter and related convective system observed in the day-side of the planet. Images acquired by the Galileo spacecraft [9]. *Right panel:* Night-side images of Saturn illuminated by the rings show a convective cloud in Saturn's storm alley with intense lightning activity in several long-exposure images. Images from the Cassini spacecraft [11].

These systems of vertically differentiated clouds form a complex "weather" layer which is prompt to the development of moist convective storms powered by latent heat release that plays an important role in the large-scale dynamics of these atmospheres. Large [7, 8, 15] and mid-scale storms [9] have been observed in both planets with lightning discharges [11, 13] and intense releases of energy [12] that point to a deep source in the unobserved water cloud layer (see Fig. 4). Jupiter maps of lightning activity based on night-side observations of the planet from spacecraft [10] have resulted in statistics of convective activity and maps of the latitudinal distribution of these storms. Saturn lightning activity is more difficult to observe visually because of the light reflected by the rings but electrostatic discharges produced by the lightning are routinely registered by Cassini's RPWS instrument [13] allowing to monitor the overall moist convection activity in the planet.

The large distance to Uranus and Neptune does not allow a regular monitoring of both planets but images obtained from ground-based large-scale telescopes and the Hubble Space Telescope show also the apparition of several middle size convective systems probably based on methane moist convection.

3 Planetary-scale disturbances in Jupiter and Saturn

Ocassional outbursts of convective storms can result in large changes in the visual appearance of Jupiter that can endure a few years (see for instance [14]). Recent advances in understanding these storms came from the onset of large-scale storms in Jupiter's North Temperate Belt in 2007 [7] and in Saturn's northern mid-latitudes in December 2010 [8, 15] (see Fig. 5) accompanied by strong lightning [16]. Numerical simulations of these storms provided strong evidences that they are powered by water convection lying at depth at least at the 5 and 9 bar levels respectively [7, 8]. Their vertical extension allowed to use the storms as probes of the first $100 - 150$ km in the planet tropospheres and served to demonstrate that the complex system of winds in both planets have deep roots at least to the water cloud levels.

4 Models of moist convection for the Giant Planets

The scale size ($1,000 - 10,000$ km), long temporal evolution of the storms (from a few days to several months), and the lack of information from the lower water cloud have made difficult to progress in the development of numerical models able to reproduce the observations and their spatial scales. However, a battery of models exist to address different questions. For instance, models that attempt to reproduce the cumulus formation process range in complexity from one-dimensional models [19] to two-dimensional (axysimmetric) [20, 21] and three-dimensional models [17, 18] (see Fig. 6). These models simulate a small portion of the atmosphere for a few hours and they predict the maximum height of the clouds depending on the thermodynamical state of the atmosphere at the lower levels, updraft velocities and divergence of cloud material at the cloud tops. Except for the height of the cloud material the rest of the predictions are difficult to confirm even from spacecraft observations. The height of the clouds produced which is linked to the energy released points towards water

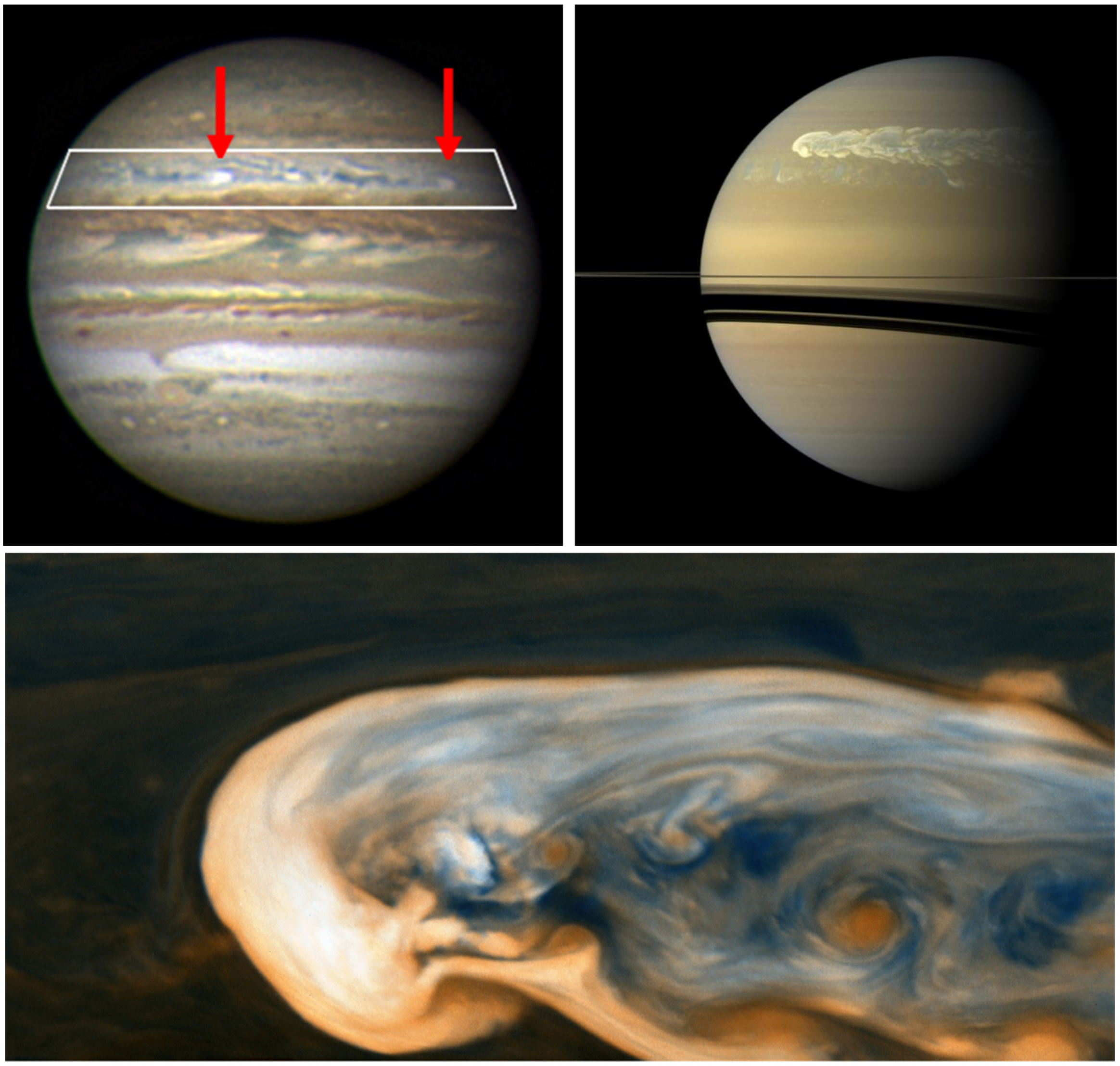


Figure 5: *Upper panels:* recent large scale convective disturbances in Jupiter and Saturn atmospheres. *Lower panel:* High-resolution observation of Saturn's 2010 − 2011 Great White Spot as observed in February 26, 2011. The convective head extends 6,000 km in latitude and produces an extended tail of vortices and bright cloud material that fully encircled the planet. Both large scale storms in Jupiter and Saturn ended when the head of the storms encountered their tail.

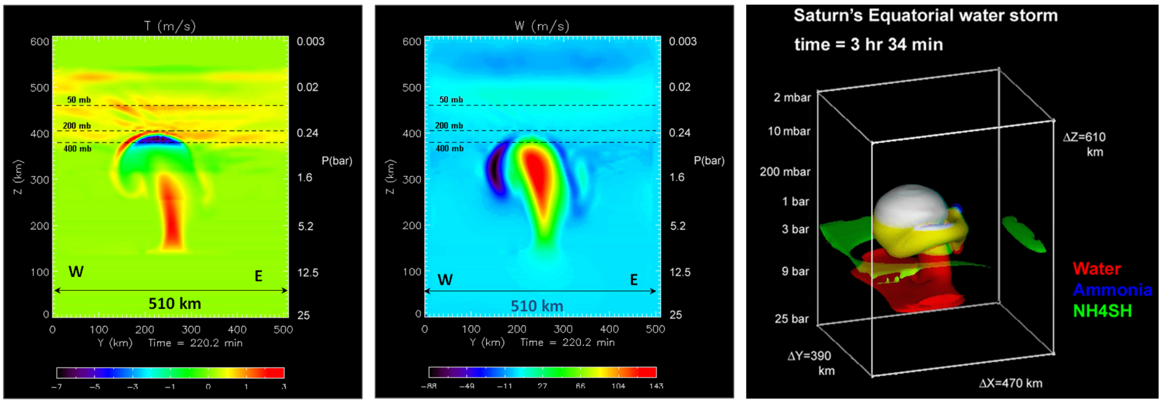


Figure 6: Snapshots of a three-dimensional simulation of a convective storm in Saturn. Left panel shows the thermal perturbation imposed by the storm in the environment, the center panel shows vertical velocities that peak at 150 m s^{-1}. The right panel displays the morphology of a convective cumulus clouds from the simulation. The three condensible gases: water, ammonia hydrosulfide and ammonia condense, but it is the release of latent heat at the water condensation level the most important source of energy heating the storm and accelerating its vertical ascent.

as responsible of the largest scale storms. Another families of moist convection models try to study the global impact of moist convection in the planet atmospheres, whether in its vertical structure [22, 23] or in the role of transporting the inner heat of the planet to the upper troposphere and their implications for powering the atmospheric wind jets [24].

5 Concluding remarks

Despite much modeling efforts and several spacecraft observations there are fundamental questions still unanswered. Some of them are here summarized:

- What is the amount of water in the inner tropospheres of the giant planets powering their storms?
- What settles the periodicities of convective phenomena in these planets and the frequency of convection in Titan?
- What settles the latitudes where moist convections occur?
- How is it possible that seasonal effects in Saturn propagate downwards to the deep water cloud level at 9 bar?
- What is the overall moist convective activity on any of the two giants over a full year and how does it affect moist convection to the vertical transport of energy? Are moist convective storms responsible for the multi zonal jets weather system in these planets?

Acknowledgments

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References

[1] Spiga, A., et al. 2012, Geophys. Res. Lett., 39, 2201

[2] Russell, C. T., et al. 2007, Nature, 450, 661

[3] Titov, D., et al. 2012, Icarus, 217, 682

[4] Lellouch, E. 2006, Science, 311, 186

[5] Hueso, R. & Sánchez-Lavega, A. 2006, Nature, 442, 428

[6] Turtle, E. P., et al. 2011, Science, 331, 1414

[7] Sánchez-Lavega, A., et al. 2008, Nature, 451, 437

[8] Sánchez-Lavega, A., et al. 2011, Nature, 475, 71

[9] Gierasch, P., et al. 2000, Nature, 403, 628

[10] Little et al., 1999, Icarus, 142, 306

[11] Dyudina, U., et al. 2010, Geophys. Res. Lett., 37, L09205

[12] Ingersoll, A. P., et al. 2000, Nature, 403, 630

[13] Fischer, G. P., et al. 2007, Icarus, 190, 528

[14] Sánchez-Lavega, A., et al. 1996, Icarus, 121, 1

[15] Sánchez-Lavega, A., et al. 2012, Icarus, 220, 561

[16] Fischer, G. P., et al. 2011, Nature, 475, 75

[17] Hueso, R. & Sánchez-Lavega, A. 2001, Icarus, 151, 257

[18] Hueso, R. & Sánchez-Lavega, A. 2004, Icarus, 172, 255

[19] Stoker, C. 1986, Icarus, 67, 106

[20] Yair, Y., et al. 1992, Icarus, 98, 72

[21] Yair, Y., et al. 1995, Icarus, 114, 278

[22] Nakajima, K., et al. 2000, Geophys. Res. Lett. 27, 3129

[23] Sugiyama, K., et al. 2011, Geophys. Res. Lett. 38, L13201

[24] Showman, A. P. 2007, J. Atmos. Sci., 64, 3132