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NOTE

Deep Convective Entrainment by Downdrafts in Jupiter's Atmosphere

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The Galileo probe into Jupiter's atmosphere entered a "hot spot" composed of dry, less dense air. Despite assertions that hot spots are regions of downwelling, no viable mechanism has been proposed to transport less dense air over a scale height into the deep atmosphere. Here, we present a numerical simulation of convection in Jupiter's atmosphere which indicates that less dense air from above the clouds may be carried into the deep atmosphere by strong convective entrainment. © 1998 Academic Press

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Introduction. Perhaps the most intriguing result from the Galileo entry probe into Jupiter's atmosphere (Young *et al*. 1996) was the low water abundance it measured (Niemann *et al*. 1996). Jupiter most likely has a solar abundance of water or greater (e.g., Pollack and Bodenheimer 1989), but the Galileo probe detected a water vapor concentration of only 3% solar at the 10 bar pressure level (Niemann *et al*. 1996). The probe entered a relatively cloud-free region (a 5-μm "hot spot") (Ragent *et al*. 1996, Orton *et al*. 1996) and thus confirmed earlier Voyager data of low water abundances within hot spots (Drossart and Encrenaz 1982, Bjoraker *et al*. 1986). Furthermore, the temperature lapse rate at the entry site was found to be dry adiabatic down to the 22 bar level (Seiff *et al*. 1996). These data imply that the Galileo probe entered a local region of subsidence with low humidity; i.e., the Galileo hot spot is a dry downdraft (Niemann *et al*. 1996, Atreya *et al*. 1996, Owen *et al*. 1997, Showman and Ingersoll 1998). However, because Jupiter's atmosphere is composed primarily of hydrogen, a dry parcel of air in Jupiter's atmosphere is *less dense* than a moist parcel of air. Evaluation of Galileo probe data indicates that the probe-entry hot spot is indeed less dense than the surroundings below 5 bars and possibly may be less dense than the surroundings from 0.5 to 20 bars (Showman and Ingersoll 1998).

Formation of a dry downdraft on Jupiter poses serious dynamical problems since less dense regions will resist sinking. Mechanical forcing is required to overcome positive buoyancy of relatively less dense air, and this forcing must be quite strong to transport less dense air 1–3 pressure scale heights into the deep atmosphere. Showman and Ingersoll (1998) suggest that radiative cooling may produce a dry downdraft that deeply penetrates the underlying moist atmosphere. However, the timescale associated with radiatively cooled downdrafts is on the order of years, much longer than the observed hot spot timescale of a few weeks (Ortiz *et al*. 1996, Stewart and Orton 1997). Showman and Ingersoll (1998) also propose a scenario in which radiative warming produces a dry, mechanically forced downdraft. The precise source of this mechanical forcing remains unclear. A dynamically viable mechanism for producing deep, less dense downdrafts on Jupiter has yet to be demonstrated.

Strong convective entrainment does offer a possible mechanism for transporting less dense air into the deep jovian atmosphere. As convective downdrafts (composed of more dense air) descend, they may drag or entrain less dense air from above the convection layer into the deep atmosphere. Indeed, cloud-top convective entrainment in the Earth's atmosphere often produces cloud-free regions through mixing of dry air from above with cloudy air. However, the typical scale of entrainment in the Earth's atmosphere is only a few kilometers (Reuter and Yau 1987). Jovian convection must be extremely vigorous to force less dense air over a scale height into the deep atmosphere.

Model and results. We investigate deep convective entrainment in Jupiter's atmosphere with a two-dimensional, nonlinear, fully compressible model of a perfect gas. This finite-difference model previously has been used to investigate convection and gravity waves in Venus' atmosphere (Baker *et al*. 1998). The model does not include jovian cloud microphysics, so the potentially important process of latent heat release (absorption) by condensation (evaporation) is precluded. The purpose here is to demonstrate a mechanism which, under Jupiter-like conditions, will produce less dense downdrafts. In this sense, a dry convection model can be used to assess the possibility of entrainment of less dense air parcels into the deep jovian atmosphere. We also neglect rotation in the model since the Galileo probe sampled the equatorial region.

The thermal structure measured by the Galileo entry probe is implemented. A dry adiabatic layer exists roughly from 2 to 22 bars with a stable layer located above (Seiff *et al*. 1996). Convection is driven in our model by the flux of heat from the planet's interior (5.4 W m^{-2})

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(Chamberlain and Hunten 1987). Jovian values of the gravitational constant (23.3 m sec^{-2}), specific heat at constant pressure (1.13 × 10^4 J kg^{-1} K^{-1}), and gas constant (3616 J kg^{-1} K^{-1}) are used. Small-scale turbulence is parameterized by constant eddy diffusivity. Values of eddy diffusivity in Jupiter's atmosphere remain largely unconstrained. Terrestrial values of eddy diffusivity have magnitudes of order ~1—1000 m^2 sec^{-1} (Houghton 1986, Xu and Gal-Chen 1993); we use a value of eddy diffusivity ~315 m^2 sec^{-1}. We believe that Jupiter's atmosphere most likely has smaller values of eddy diffusivity, but we are unable to produce simulations with smaller values given present computational resources. It will be important to carry out further studies to test the sensitivity of these results to eddy diffusivity. Nevertheless, the above parameter values give a Rayleigh number (a measure of convective vigor) of $Ra = 2 \times 10^9$, indicative of highly turbulent convection Krishnamurti 1970, Heslot *et al.* 1987). The computational domain spans 0.1–22 bars vertically (−135–45 km altitude) and 520 km horizontally. The horizontal domain is large enough to allow for multiple convective downdrafts and to prevent the solution from being adversely affected by the lateral boundaries (Hurlburt *et al.* 1984). The vertical grid resolution is 0.50 km and the horizontal grid resolution is 0.61 km. The horizontal domain is smaller than the typical scale of hot spots in Jupiter's atmosphere (10^3–10^4 km) (Carlson *et al.* 1993), but is necessitated by the fine resolution required to resolve convective structures associated with highly vigorous convection. The lower boundary is stress-free with fixed heat flux, the upper boundary is stress-free and isothermal, and the lateral boundaries are periodic. The simulation is initialized with a lower Rayleigh number (higher eddy diffusivity) solution and is integrated for 49.2 hr (roughly 5 convective overturns).

The model spontaneously produces strong convective downdrafts with a horizontal spacing ~250 km. Figure 1 focuses on a single downdraft region at three instances in time separated by roughly 1.5 hr. A strong, negatively buoyant downdraft composed of more dense air occurs at horizontal location $x \approx 80$ km. At time $t = 18.1$ hr (Fig. 1a), the downdraft region consists of numerous downwellings beginning to merge into a stronger downdraft. Even though the downdraft region is morphologically complex, coherent downflows exist from roughly 2 to 22 bars. The merging downwellings later form a single downdraft structure (Fig. 1b). Within three hr, the strong downdraft extends roughly three pressure scale heights (2–22 bars) into the deep atmosphere (Fig. 1c). Typical downdraft velocities are roughly 10 m sec^{-1} with gusts of up to 15 m sec^{-1}. These velocities are consistent with horizontal winds ~10–30 m sec^{-1} observed converging into a jovian hot spot (Vasavada *et al.* 1997). The process of complex downwellings merging to form strong downdrafts happens repeatedly. The downwelling region remains in roughly the same location throughout the simulation, but the morphology of the downwelling vacillates with a characteristic timescale of a few hours.

Strong convective entrainment occurs in the downdraft region. A less dense pocket of air exists near the top of the convection layer ($x \approx 140$ km, $p \approx 2$ bars) at $t = 18.1$ hr (Fig. 1a). Ninety minutes later, this less dense air, now located at $x \approx 100$ km, $p \approx 6$ bars, has been dragged down roughly one pressure scale height into the deep atmosphere by the strong downdraft (Fig. 1b). As the downdraft becomes more focused, entrained air reaches the 10–14 bar level (Fig. 1c). Such strong entrainment is produced by pressure gradients which form in response to the strong downdraft. For example, at $t = 19.6$ hr, the downdraft region from 4 to 14 bars is characterized by negative pressure perturbations (Fig. 2). Indeed, the smallest (most negative) values of pressure perturbation occur at the leading edge of the strong downdraft. These pressure fluctuations induce pressure gradients that mechanically force less dense air downward. The net result is that less dense air is entrained roughly two pressure scale heights into the deep atmosphere.

Discussion. This simulation shows that, under Jupiter-like conditions, less dense air can be forced multiple scale heights into the deep atmosphere by strong downdrafts. Such strong convective entrainment is unprecedented in planetary atmospheres; terrestrial entrainment spans less than a scale height (Reuter and Yau 1987). Indeed, convective entrainment on Jupiter may help explain the reduced water abundance within hot spots. Strong downdrafts may entrain dry, less dense air from above the clouds into the deep atmosphere. At the least, this dry air will mix

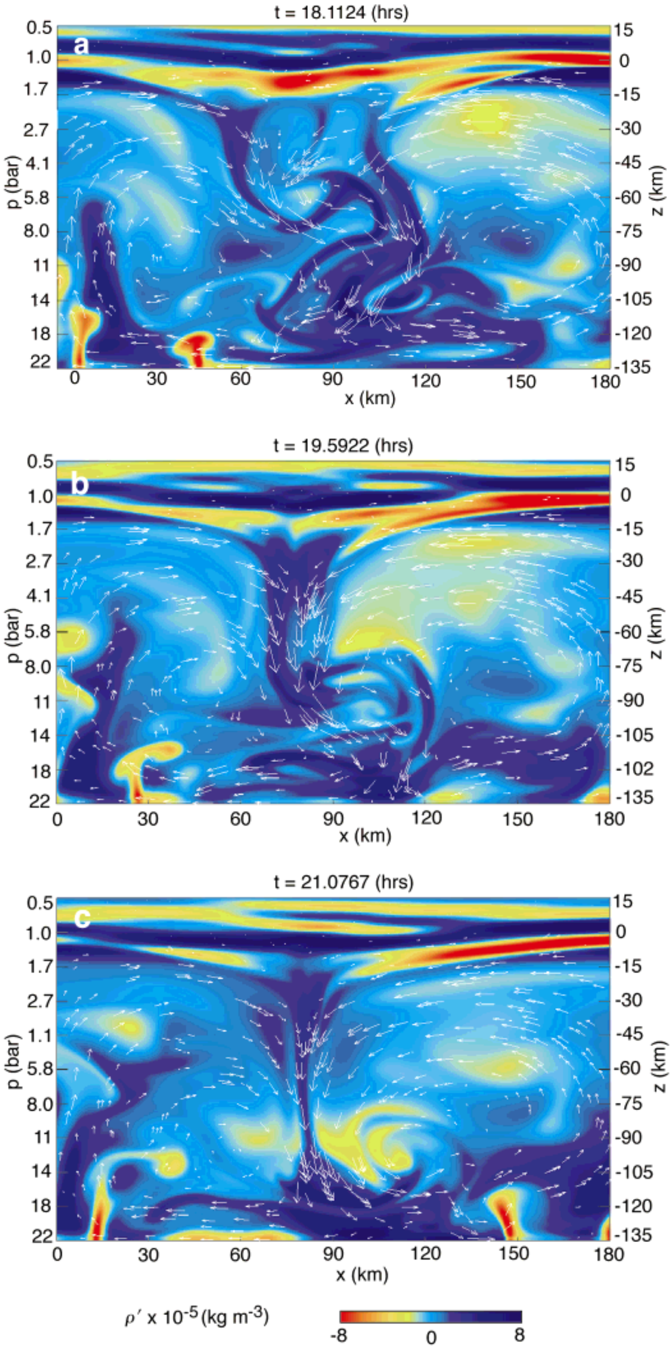

FIG. 1. Density perturbations near a convective downdraft as a function of horizontal distance x, pressure p, and altitude z at time (a) $t = 18.1$ hr, (b) $t = 19.6$ hr, and (c) $t = 21.1$ hr. Red indicates less dense air and blue indicates more dense air. Arrows indicate wind direction and magnitude. The largest wind velocity is 15.1 m sec^{-1}.

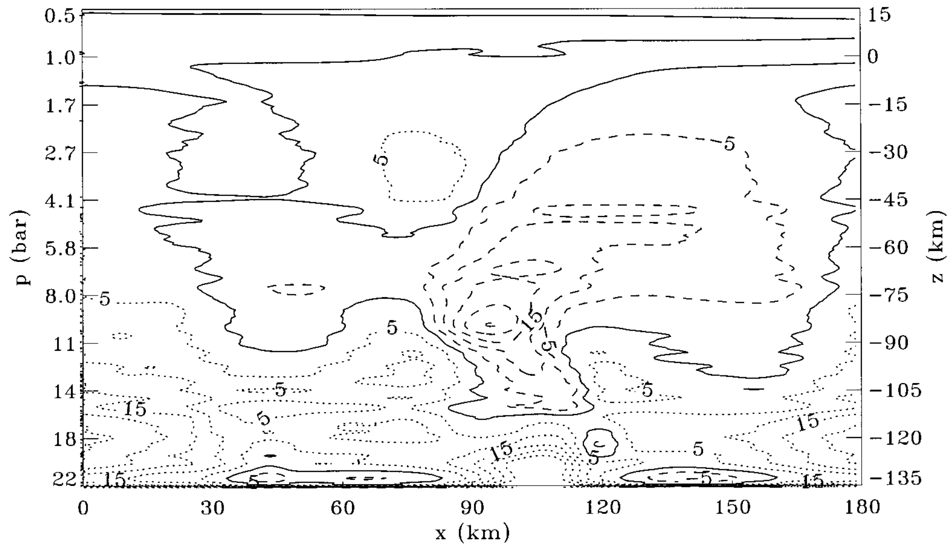

FIG. 2. Pressure perturbations near a convective downdraft as a function of horizontal distance x, pressure p, and altitude z at time t = 19.6 hr. The solid contour indicates a zero value of pressure perturbation, dashed contours indicate negative pressure perturbations, and dotted contours represent positive pressure perturbations in units of Pa.

with moist air from below and effectively reduce the water vapor mixing ratio in the downdraft region. At most, hot spots could consist entirely of entrained dry air with a water abundance similar to that found above the clouds. The second scenario agrees better with observations of water abundance ~100 times greater in regions adjacent to hot spots than in hot spots themselves (Roos-Serote *et al.* 1997). Entrainment of this magnitude is plausible considering that convection in Jupiter's atmosphere is likely more vigorous than simulated here (the actual value of eddy diffusivity is probably less than the value used in our model and thus the Rayleigh number is potentially larger). Although higher Rayleigh number convection could produce small-scale turbulent convection without coherent downdrafts, laboratory experiments with Rayleigh numbers of 10^{14} exhibit large-scale coherent circulations embedded within a field of turbulence (Siggia 1994). If this is true for higher Rayleigh number jovian convection, both downdraft velocities and pressure gradients would be larger, convective entrainment would be stronger, and long-lived conduits of less dense air could possibly extend into the deep atmosphere.

Rotation has been neglected in this calculation since rotational effects are minimized near the equator and for small horizontal scales. However, rotation could affect convective entrainment on scales comparable to the size of hot spots. Rotation acts as a stabilizing influence on convection aligned perpendicular to the axis of rotation (Chandrasekhar 1961) and thus would potentially reduce convective downdraft velocities. Nevertheless, theoretical and laboratory studies of oceanic downwelling on Earth indicate that the extent of convective entrainment is independent of rotation (Visbeck *et al.* 1996; Whitehead *et al.* 1996). Alternatively, upward penetration by deep convection aligned *parallel* to the axis of rotation can be quite strong in a rapidly rotating system (Zhang and Schubert 1997). Upward penetration by convective plumes could displace stable air downward and thus enhance downward forcing of less dense air. Large-scale hot spots could be associated with this deep "slanted" penetrative convection.

Convective downdrafts and strong convective entrainment may account for the regular spacing of hot spots in the equatorial region (Ortiz *et al.* 1996). Although convection in our simulation is highly turbulent, downdrafts remain as coherent structures ~250 km apart at approximately the same locations throughout the simulation. Hot spots in Jupiter's atmosphere have both larger horizontal scales and larger horizontal spacings between them than downdrafts in our simulation. Still, the process of convective entrainment will likely be important on these larger scales if the convection is vigorous. Moreover, inclusion of moist processes and the presence of a thicker convection layer may eliminate the discrepancy in scale. Latent heat release (absorption) by a solar amount of water produces temperature fluctuations of roughly 0.5 K, nearly an order of magnitude larger than the temperature perturbations present in our simulation. At the cloud tops, the larger thermal perturbation produced by latent heating will take a longer time to cool (by radiation or turbulent diffusion), and therefore a parcel of air at the cloud tops will travel a larger horizontal distance before sinking. In addition, the convection layer may extend to much greater depths than the 22 bar level where Galileo data terminate. A thicker convection layer would likely produce both wider downdrafts and broader convection cells. Indeed, atmospheric dynamics in the deep jovian atmosphere may dramatically influence the development and evolution of features near the cloud tops.

The current two-dimensional simulation may produce stronger entrainment than may possibly occur in three dimensions. Convective downdrafts in a fully compressible system have been shown to more deeply penetrate an underlying stable layer in 2-D simulations than in 3-D simulations (Muthsam *et al.* 1995). It therefore seems likely that entrainment by convective downdrafts would be weaker in 3-D simulations, and even more vigorous convection would be required to entrain less dense air into the deep atmosphere. Further work is necessary to determine the scale and extent of jovian convection and entrainment in three dimensions.

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