NON-LOCAL, DEEP TRANSPORT IN THE ATMOSPHERE OF MARS

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Introduction:

Non-local, deep transport (NLDT) likely plays an important role in the dynamics, energetics, and chemistry of the atmosphere of Mars, much as it does for Earth. Below, the known impact of NLDT on Earth is discussed, followed by a discussion of how NLDT may operate on Mars.

NLDT is accomplished by transport within coherent and vertically extensive circulations, and provides for both up- and down-gradient transport that, unlike diffusion, does not fundamentally depend on the local gradient. One of the most important aspects of NLDT is its ability to produce local maxima of various quantities in the absence of a local source, and it is this characteristic that makes it "non-local".

While NLDT is recognized as being important within the atmosphere of Earth, it has received little recognition in the atmospheres of other planets, including Mars. This neglect is striking given observations of NLDT processes such as Mars dust storms. and observations of the tell-tale signs of NLDT, such as elevated dust layers..

NLDT on Earth:

The best known example of NLDT is that of "hot towers" first described by [1] to explain the upper tropospheric maximum of moisture and enthalpy (a.k.a. moist static energy) in the Earth's tropical atmosphere and a corresponding moist static energy minimum in the mid-troposphere[2]. The source of moisture and enthalpy is the warm tropical ocean and the adjacent atmospheric boundary layer. Diffusion and large-scale vertical motion cannot explain the local tropopause maximum. It is the rapid and deep transport through updraft cores of tropical thunderstorms—which Riehl and Malkus termed hot towers—that provide the mechanism by which the upper tropospheric maximum is produced and maintained. Importantly, mixing between the cloud cores and the cloud-free environment is limited so that moisture and enthalpy are nearly conserved during the transport.

The Hadley Cell. Atmosphere and ocean circulations are the mechanism by which energy is transferred to counter the radiative imbalance. In the tropical atmosphere, energy is moved vertically before it is transported in the poleward branch of the Hadley Cell[3]. Within the rising branch of the Hadley Cell, latent heat of evaporation originating from the warm oceans is realized as sensible heat within thunderstorms. These storms occupy only a small fraction of the total area of the tropics. In contrast, the non-cloud environment occupies most of the tropics and it is within this broad area where compensating subsidence from convection is found. The compensating subsidence produces adiabatic warming, which is primarily how the sensible heat within the small fractional area of clouds is communicated to the rest of the tropical atmosphere[4].

It is the net difference between the narrow but strong updrafts of convection and the weaker convective downdrafts and compensating subsidence that results in the rising branch of the Hadley Cell. The rising branch of the Hadley Cell, therefore, is a mathematical construct and not a physical circulation. Actual measurements of vertical mass flux in the tropics would reveal either strong upward motion in the clouds or more gentle but widespread downward motion outside of the clouds, but would not reveal anything resembling the mean rising branch of the Hadley Cell. Only once the net motion is considered does the Hadley Cell appear.

It follows then, that vertical advection is performed by actual physical circulations: either within clouds or in the surrounding subsidence. Vertical transport is not performed by the Hadley Cell, since it is not a physical circulation. This has important consequences. Advection by a slow and uniform Hadley cell would produce either a gradient of energy and moisture with a maximum at the surface, or it would produce a well-mixed troposphere of uniform energy and moisture. This is not observed.

What is observed is an atmospheric state that is consistent with transport by physical transport mechanisms. Namely, there is a maximum of moisture near the surface (where the source of water is) and at the top of the tropopause where clouds detrain[5][6]. The middle troposphere is remarkably dry. A similar structure is found for moist static energy: a maximum near the surface and in the upper troposphere and a mid-tropospheric minimum.

The importance of considering the actual circulations as opposed to the mathematically constructed Hadley Cell goes beyond atmospheric structure. Some of the first experiments with general circulation models of the atmosphere investigated the effect of moist convection on dynamics. [7] switched off moist processes and compared the results to a control simulation with moist processes active. While the bulk circulation features were present in all simulations, the strength of the Hadley Cell was greatly reduced in the dry simulations and the trade winds were dramatically reduced. Eddy kinetic energy in the moist simulation compares well with observations in producing a maximum below the tropical tropopause and secondary maxima in the middle latitudes (associated with baroclinic storm systems). Not surprisingly, the tropical maximum in the dry simulation is almost completely absent. Deep convective transport in the tropics has global implications on the mean and eddy kinetic energy.

Viewing the terrestrial general circulation holistically to include cloud circulations rather than just a

Hadley cell alone leads to very different interpretations of water and energy transport. For example, neglecting the rapid and deep transport of mass, momentum, and energy by tropical thunderstorms and relying only on the mean meridional circulation for such transport leads to a grossly inaccurate representation of the hydrologic cycle[8][9] and the Hadley cell itself. Similar effects were found by [10]. [11] showed that deep convection strongly influences the El Niño Southern Oscillation (ENSO), which is a dominant climate signal. In a comprehensive study of the effects of deep cumulus convection, [9] found statistically significant effects on the circulation and on boundary layer and upper-level moisture structure, zonal winds, and moisture and heat flux transports.

Chemistry and Aerosols. [12] recently compiled balloon and aircraft observations from a variety of field experiments to determine that deep cloud transport has a major impact on upper tropospheric and stratospheric chemistry. This result is consistent with observations obtained by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission [13] all of which show that deep convective clouds have a substantial and important impact on the chemical composition of the upper troposphere and lower stratosphere. Ozone has been found to be a particularly good tracer of deep convective transport within clouds (e.g., [14])

There is also a chemical-dynamical interaction within clouds such that the ventilation of boundary layer pollutants modifies chemistry within the clouds and has a strong influence on the concentration of species that are vented at higher altitudes. For example, [15] found almost a 50% increase on O_3 production rates due to the rapid transport of NO_x within clouds. [16] found not only large increases in NO_x concentration due to clouds, but numerous other chemical species with reservoirs in the planetary boundary layer: e.g., H_2O_2, O_3, and SO_2. Numerous other studies (e.g., [17], [18], [19]. [20]) all point to the importance of cloud transport in determining the distribution and concentration of chemical species.

Aerosols, including those generated through forest fires, have been observed to undergo significant transport through deep convective clouds. [21] observed the transport of smoke from Brazilian rainforest fires into the upper troposphere and out over the Pacific Ocean. Numerous chemical species (CO, CO_2, acetonitrile, methyl chloride, hydrocarbons, NO, O_3) were also found within the smoke layer. During the INDOEX field campaign aerosol concentrations of up to 600 cm^{-3} were observed, which rivals the background marine aerosol load[22], leaving little doubt that NLDT is an important mechanism in the global aerosol budget. The earlier mentioned CALIPSO mission provides further support for the important role of NLDT of aerosols within clouds[13].

NLDT on Mars:

Elevated and detached haze layers were recognized in the Mariner television images[23], Viking orbiter limb images[24], and images obtained by the Mars Orbiter Camera on the Mars Global Surveyor (MGS). Thermal Emission Spectrometer limb dust retrievals, also show elevated dust layers or "layers of altitude increasing dust"[25]. It should not be surprising that similar and persistent elevated dust layers have now been observed by the Mars Climate Sounder on the Mars Reconnaissance Orbiter[26].

Despite the elevated layers of dust and water on Mars, the transport of these quantities has, with few exceptions, been credited to the Hadley Cell (e.g., [27], [28], [29]). The most widely used dust prescription for models—the Conrath-ν vertical distribution—rests on the notion of a balance between upward diffusion of dust and gravitational sedimentation[30]. As noted for Earth, the mean meridional circulation (or diffusion) cannot produce elevated layers of water and dust, leading [26] to state "the existence of this maximum suggests that current understanding of the mechanisms by which dust enters and leaves the atmosphere is incomplete." But, this is not entirely accurate.

While the details of mechanisms by which dust enters the atmosphere is incomplete, [31] specifically identified NLDT as a likely mechanism by which elevated dust layers could be created, including the following statements: "*The flow becomes horizontally divergent near the top of the circulation, where the outflow branches of the circulation transport dust laterally up to a thousand or more kilometres on either side of the volcano…A dust particle of less than 1 μm in diameter falling at 1 cm/s would require in excess of 20 Martian days to fall 20 km in altitude in the absence of vertical motion in the atmosphere. Such a particle could travel significant horizontal distances within this timeframe. Dust less than 1 μm in diameter would remain aloft for even longer periods, and could easily circle the planet given only the moderate wind speeds predicted by Mars GCMs.*"

The paper concludes with the following statement: "*Mars is dotted with numerous topographic features that are too small in horizontal extent to be captured by GCMs, but which may produce large-scale thermal circulations that could perturb the general circulation. Our results suggest that mesoscale thermal circulations may collectively be important in the atmospheric dust budget, and individually can produce strong regional perturbations in the background large-scale flow.*"

The importance of NLDT for Mars was further emphasized in [33] with specific reference to the hot towers of [1] and the unambiguous claim that "The existence of deep thermal circulations forced by topography is almost certain on Mars." This claim was not referring only to the thermal circulations of the massive Tharsis volcanoes, but to thermal circulations associated with lesser topography such as crater rims and hills as further emphasized in the statement, "*Smaller orography produces similar [to the Tharsis volcanes] but smaller transport. The net large-scale vertical transport need not (and in fact, may not) be accomplished principally by the Hadley cell circulation.*"

Figure 1 shows one example of such lesser topography that produces deep, vertical transport. Strong, narrow and coherent updrafts of several m/s in strength are not unlike terrestrial thunderstorms. These are penetrative circulations that "punch" into the stable atmosphere above to heights substantially above the top of the convective planetary boundary layer. This is a different phenomena than the vertically extended boundary layers observed over some regions by [33]. Regions of the atmosphere outside the updrafts are weakly subsiding. Therefore, the actual transport of dust, volatiles and other substances is different than what would be accomplished by the mean circulation. Detrainment of dust, water and other volatiles or chemical species above the top of the boundary layer will result in elevated concentration layers.

NLDT on Mars should not be limited to dust. The transport of water was specifically targeted in [34]. In this paper, it was shown that, like dust, the thermal circulations of the Tharsis volcanoes provided substantial deep, vertical transport of water. Quantitative analysis of model output showed that the vertical flux was roughly one third of the total water flux that would be provided by the Hadley Cell. Thus, the localized upward motion associated with Tharsis and other topographic circulations may very well constitute almost entirely the mean upward motion that results in the mathematically constructed Hadley Cell, just as upward motion in clouds is entirely responsible for the upward rising branch of the terrestrial Hadley Cell. Or, as stated by [34], "*Such mountain-induced circulations are thus an important facet of the global water cycle, and possibly the dust cycle as well. This indicates that one longitudinal asymmetry in the MGCM Hadley cell water transport (dominant/enhanced rising branch over the Tharsis region) may in reality be substantially due to these volcano induced circulations.*"

Thermal circulations may be the dominant NLDT mechanism on Mars, but the observational evidence for NLDT in dust storms cannot be ignored. Local dust storms occur on Mars on almost a daily basis and larger, regional dust storms are also relatively frequent. Orbital imagery of these disturbances clearly show coherent, convective circulations that rapidly transport dust from the surface into the free troposphere. The veils of dust that linger for days attest to this transport. In simulating idealized dust storms, [35] showed that the convective circulations in some dust storms behave like the thunderstorms within terrestrial tropical storms; the updrafts in dust storms are then analogous to the hot towers of [1]. In a paper from this workshop, [36] shows the production of elevated dust layers in realistic simulations of dust storms.

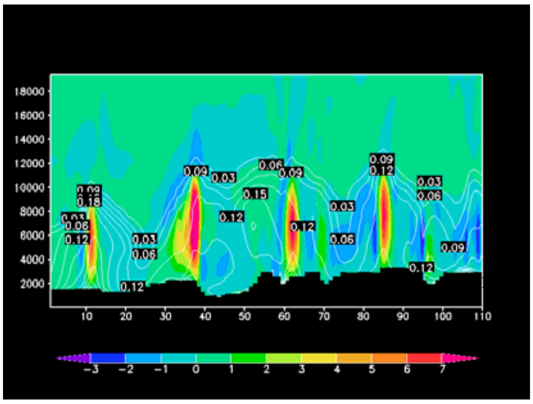

Figure 1. A typical example of NLDT associated with small scale topography as simulated by the MRAMS (Rafkin et al. 2001), in this case for the proposed MSL landing site of Mawrth Valles. Vertical velocity (m/s) is shaded, dust mixing ratio (g/kg) is contoured. Grid spacing is ~9 km.

Numerous studies on the Mars dust cycle have been published, all of which rely on maintaining the background dust load through a combination of dust devil and mean wind lifting followed by transport via resolved motion and turbulent (and numerical) diffusion (e.g., [28], [29], [37]). Dust devils are known to lift dust, but these circulations are confined to the planetary boundary layer and are therefore unlikely to contribute directly to dust in the free atmosphere above. Dust devils likely do play an important role in maintaining the boundary layer dust load upon which NLDT mechanisms can feed. Only then to the extent that the models capture NLDT circulations will the modeled dust cycle match reality. This is exactly analogous to the moist and dry Hadley Cell studies described for Earth [7]. At present, general circulation models may only partially capture NLDT from the large Tharsis volcanoes and capture none of the NLDT from smaller-scale topographic features or the convective updrafts present within dust storms. Therefore, it is very likely that these models are under-representing the flux of dust from the boundary layer into the free atmosphere.

There is nothing special about water or dust. Any quantity that can be advected should respond in a similar manner. This includes other chemical species such as CH_4. The concentration and distribution of CH_4 is presently an area of strong interest, but no attention has been given to whether chemical species can be rapidly vented and transported from the boundary layer. Likewise, no attention has been given to how NLDT may impact chemical processes as they do in terrestrial clouds. Photochemical models still rely solely on diffusion and Hadley Cell-like motion to transport chemical species (e.g., [38], [39],

[40]).

Summary:

NLDT is an important transport mechanism for Earth and it plays a key role in regional and global energy, hydrologic, aerosol and chemical cycles. NLDT is necessary to produce elevated layers (local maxima) of energy, aerosols, and chemical species that are physically separated from their source. Observations of energy, momentum, water, aerosols and other chemical species cannot be reproduced without incorporating NLDT.

Deep convective clouds are the most important and best understood NLDT mechanism, and the primary manifestation is in providing the upward branch of the Hadley Cell. The rising branch of the Hadley Cell is a mathematical construct that plays no physical role in vertical transport within the tropics. Instead, transport is accomplished through the updrafts in the clouds and the compensating subsidence forced by the clouds. NLDT processes must be included to properly characterize many global and regional atmospheric cycles on Earth.

There is observational evidence, in the form of elevated dust layers, of NLDT on Mars; It is almost inescapable that NLDT is playing an important role. On Mars, NLDT of dust is the most likely mechanism by which elevated dust layers are produced. If so, the NLDT hypothesis forwarded by [31], [32], and [36] should be included as part of a complete theory of the Mars dust cycle. In particular, while dust devils and mean wind lifting provide a source of dust to the boundary layer, the NLDT mechanism transports this dust out of the boundary layer and into the free atmosphere. The upward branches of these thermal circulations and within dust storms are the physical circulations that actually produce transport, while the upward branch of the Hadley Cell is a mathematical construct just as it is on Earth. NLDT is a reasonable explanation for the observations of elevated layers of dust.

With respect to water and other species, NLDT on Mars will influence transport in a manner similar to dust; water, CH_4, O_3, etc. can all be vented from the boundary layer via NDLT processes, as described by [34]. It should, however, be recognized that water and dust cycles can interact, since dust may serve as condensation nuclei. The rapid transport of species such as CH_4 could have a dramatic impact on the highly controversial and still poorly understood distribution of CH_4, which for now, has been modeled via general circulation models that can only crudely resolve NLDT associated with the largest topographic features (e.g., [40]).

If NLDT is an important process on Mars, there are tell-tale signs and predictions that could be tested. Some of this evidence has already been obtained (e.g., elevated dust layers). Other direct evidence for Mars would include observations of enhanced plumes over topographic features, elevated layers and a mid-tropospheric minimum of water in regions of active NLDT, and compensating subsidence in regions of the rising branch of the Hadley Cell.

Numerical models can also play an important role in supporting the NLDT hypothesis. For Earth, inclusion of NLDT processes via parameterizations has led to an improvement of model results when compared with observations. Parameterization of NLDT processes for Mars might provide similar improvements. Further study on the importance of NLDT in atmospheres other than Earth is warranted.

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