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TROPOSPHERIC RIVERS? - A PILOT STUDY

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Abstract. Computations of daily global tropospheric water vapor flux values show the presence of a filamentary structure. The filaments, here called rivers, have lengths many times their widths and persist for many days while being translated through the atmosphere. They are present in data analysed for both 1984 and 1991. The water vapor flux maxima coincide quite closely to reflectivity features (averaged from wavelengths of 380 and 360 nm) as revealed by the Total Ozone Mapping Spectrometer (TOMS). It is suggested that the filamentary structure may also be present in other trace constituents.

Introduction

Carbon monoxide has been measured from space as part of the NASA Measurement of Air Pollution by Satellites (MAPS) program [Reichle et al., 1990]. One of the puzzling findings was the presence of high values well removed from potential sources and in regions where neither vertical transport into the free troposphere from the boundary layer or horizontal transport by the prevailing wind provided a straightforward explanation. Water vapor also has a surface source that has large spatial variations and the authors therefore decided to examine daily values of water vapor transport in the troposphere to see if the results would shed some light on the carbon monoxide transport problem.

Data and Computations

The meteorological data which were available at the NASA Langley Research Center to accompany the October 1984 MAPS space shuttle flight included wind velocity, temperature, geopotential and relative humidity as a function of pressure from the analyses every twelve hours by the European Center for Medium-Range Weather Forecasts (ECMWF) for the period September-October 1984. The relative humidity was converted to specific humidity q (the mass of water vapor per unit mass of moist air - usually denoted in g kg^{-1}) and the water vapor flux computation, using the eastwards (u) and northwards (v) components of the wind velocity, proceeded as follows. The eastwards flux is $Q_\lambda = \int_0^\infty u\rho_w dz$ and the northwards flux is $Q_\phi = \int_0^\infty v\rho_w dz$ where ρ_W is the mass of water vapor per unit volume (ρ is the mass of moist air per unit volume and $q = \rho_W/\rho$). From the hydrostatic equation and the definition of specific humidity the flux equations become $Q_\lambda = g^{-1}\int_0^{p_0} uqdp, Q_\phi = g^{-1}\int_0^{p_0} vqdp$ where p_0 is the surface pressure. If $\underline{i}$ and $\underline{j}$ are unit vectors along the wind component directions the total flux may be written

$$\underline{Q} = \underline{i}Q_\lambda + \underline{j}Q_\phi \qquad (1)$$

and it is this vector that we display on maps. The vertical integration uses pressure levels of 1000, 850, 700, 500 and 300 hPa and linear interpolation on both the winds and specific humidity to compute the flux in the four layers so defined. In selected cases maps for the separate layers have also been drawn.

First Results

Reichle et al. [1990] reproduced carbon monoxide data for October 12 and 13, 1984; we examined twice-daily water vapor flux for September and October for 1984 and 1991. Two examples for October 12 and 13, 1991, also based on data from ECMWF, are shown in Figure 1. The maps from both periods show that the water vapor flux is concentrated into filaments in which the along-stream dimension is often up to 5 times the across-stream dimension. When a month's worth of these fluxes computed every 12 hours is laid out it is evident that the filaments, which we refer to as tropospheric rivers, are present at all times and move and develop in a coherent fashion. There is often a flow heading south from Brazil to the east of the Andes which seems to act as a source for filaments flowing south-east into the Atlantic. This transport seems to represent the largest flux between the tropics and southern hemisphere middle latitudes. It was noted by James and Anderson [1984] in a general circulation model run of the Southern Hemisphere and has also been commented on by Zaucker and Broecker [1992] from monthly mean data. Diagnostic studies of the long term mean vertical motion also show rising motion south-east from southern Brazil in the September-November period [Newell et al., 1974]. A typical flow in this South American tropospheric river is very close to that in the Amazon (~165 x 10^6 kg sec^{-1}). There are typically five rivers leading into the middle latitudes of the Southern Hemisphere and four or five leading into the Northern Hemisphere. The rivers persist for 10 days or more while being translated generally eastwards at speeds of about 6 msec^{-1} which corresponds to the mean zonal wind at 850 hPa. The river in the southern Indian Ocean suggests a weak linkage between South Africa and the region to the south-west of Australia at the selected time. This bears on the carbon monoxide results shown in Plate 1f of Reichle et al. [1990] for October 13, 1984; they stress that there was a known source, biomass burning, operating in Africa at the time and our suggestion here is that the material may have been incorporated into a filament.

Further Exploration

Filamentary structure is also evident in reflectivity data obtained from the Total Ozone Mapping Spectrometer (TOMS). The data represent the mean reflectivity of solar radiation over two channels centered at 360 and 380 nanometers (where ozone absorption is very small) each about 0.1 nm in width. The reflectivity data is contained in a 2 dimensional array termed GRID-T where one dimension is latitude in 1 degree increments, and the other is longitude in 1.25 degree increments. The reflectivity is used to estimate cloudiness which in turn is included in the procedure to

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estimate total ozone amount. Cloudiness is determined by assuming clear skies for reflectivities less than 20%, cloudy skies for reflectivities greater than 60%, and partially cloudy skies for reflectivities from 20%-60%. A linear approximation is performed to determine the "cloudiness" of the partial cloud pixel. TOMS has no way to determine the height or the type of cloud. Thus, a general climatology, based on latitude, is used to specify cloud height so that a tropospheric ozone correction can be estimated. Discussion between the fourth and first author resulted in the GRID-T maps being made available for the September-October 1991 NASA Global Tropospheric Experiment Pacific Exploratory Mission-West (GTE/PEM-West). The two GRID-T maps corresponding to Figure 1 are shown in Figure 2. It is clear that the two sets of maps obtained by completely different means exhibit the same phenomenon of filamentary structure. The moisture flux filaments in middle latitudes of the Southern Hemisphere agree almost exactly with the images. One can also note that the general magnitudes of the tropospheric rivers are related to the percentage of the reflectivity in the TOMS data. Some circular H_2O flux patterns also appear in the TOMS data. We have also calculated the total mass flux in the 1000-300 hPa layer, which can be written as $g^{-1}\int_{300}^{1000}\underline{v}\,dp$, to try to differentiate the two components that make up the water vapor flux field, namely the specific humidity and the flow. Examples drawn from October 1991 show that poleward mass flux, including that in large-scale waves, is generally accompanied by substantial water vapor flux whereas equatorward flow is not.

Discussion

Vertical integrals of water vapor transport are dominated by events in the lower atmosphere because of the decrease of specific humidity with altitude and yet there is good agreement with near ultraviolet images which in several cases here appear to be related to cloud in the middle and upper troposphere. Why does this occur? We have examined the contribution of wind and specific humidity patterns to the computed transports by looking at the two fields separately and by examining the contributions to the transport by separate pressure levels. Many of these specific humidity maps show filamentary structure. The structure is a little sharper if the equivalent potential temperature, derived from specific humidity and temperature at 850 hPa, is examined. Examination of the water vapor flux computed for the separate maps shows, as expected, that most of the contribution occurs below 500 hPa.

The reflectivity measured by TOMS is presumably cloud except over ice surfaces such as Antarctica and Greenland. The cloud association is borne out by examination of a video of the Japanese Geostationary Meteorological Satellite (GMS) for the PEM-West period. The filament to the west of Australia seen by TOMS corresponds to a cloud street from what appears to be middle or high cloud on GMS. The pre-requisite for clouds is moisture and rising motion and the problem then becomes one of reconciling these two variables with the horizontal transport of water vapor in the lower atmosphere. There is a possible linkage through the vertical motion at 500 hPa and we have found several good examples in the ECMWF data which show rising motion in conjunction with a filament. Another possible reason for the relationship between the Q vector filamentary structure and the upper level clouds may be that the clouds interfere in some way with that part of the water vapor structure in the analysis contributed by satellites. However water vapor specification techniques have changed considerably between 1984 and 1991 yet the filamentary structure evident in Figure 1 is also present in 1984. Additionally, TOMS reflectivity measures the irradiance of the earth with ultraviolet wavelengths, thus TOMS is not measuring water vapor directly.

The association of water vapor flux with polewards mass flux as described above is expected because the equatorwards components are generally dry air while the polewards components have picked up moisture in the tropics or subtropics. The boundary layer has been stripped off the surface in these regions and carried to higher altitudes and latitudes. Green et al. [1966] studied a case of this sequence of events in detail and found the cloud filament concomitant with a cold front but this does not always appear to be the case. The cloud images persist essentially unaltered as the filament moves over a continent in some cases. In the large-scale waves it is known that polewards-moving parcels are rising, moisture-rich and warmer than the average for their latitudes, with opposite circumstances for equatorward-moving parcels. The addition of this entrainment of the boundary layer in a limited region would account for the jet like structure of the water vapor flux.

Streakiness in atmospheric features is not unusual (e.g. see Kuettner, 1959). A pertinent study is by Welander [1955] in which he showed the two dimensional distortion of an initial block of grid squares as a function of time as they were moved by a shearing flow. They soon developed into streaks like those shown here. Ludlam [1980], developing further the earlier joint work with Green et al. [1966], carried the investigation into the third dimension, and applied it to account for extensive cloud streets quite similar to the patterns found here. Significant evaporation from the ocean surface certainly does not act over a uniform set of grid squares as in Welander's model so another source of inhomogeneity is present in reality yet still the atmosphere manages to create order in the final patterns. It is noteworthy that some numerical simulations of turbulence show similar tube-like structure [She et al., 1990]. The TOMS images show a spread at the southern limit of the filament similar to that in the numerical simulations. Air entering the troposphere from the stratosphere also has a filamentary structure as has been demonstrated from aircraft observation and computations of potential vorticity on isentropic surfaces (see for example, the pioneering work of Danielsen, 1968 and a recent contribution by Appenzeller and Davies, 1992); in contrast to the present studies those filaments show up by their dryness. Filamentary structure evidenced by clouds has been noted previously (e.g. Anderson and Oliver, 1970). Bands of high or middle clouds extending polewards and eastwards from the tropics, termed moisture bursts (McGuirk et al., 1987) or tropical-extratropical cloud bands (Kuhnel, 1989), have also been discussed although associated moisture fluxes were not calculated. The seasonal cycle of the occurrence of these features was examined; they had to cross 15° latitude in one case, or originate equatorward of 20° latitude in the other, to qualify for inclusion. Many of the filaments that we see occur at higher latitudes than these limits. This point, and the fact that our water vapor fluxes have a bias towards the lower troposphere suggest that the phenomenon we see is not identical to the subject of these previous studies.

This is by nature a pilot study. There are other months to be explored and Ludlam's ideas and analyses

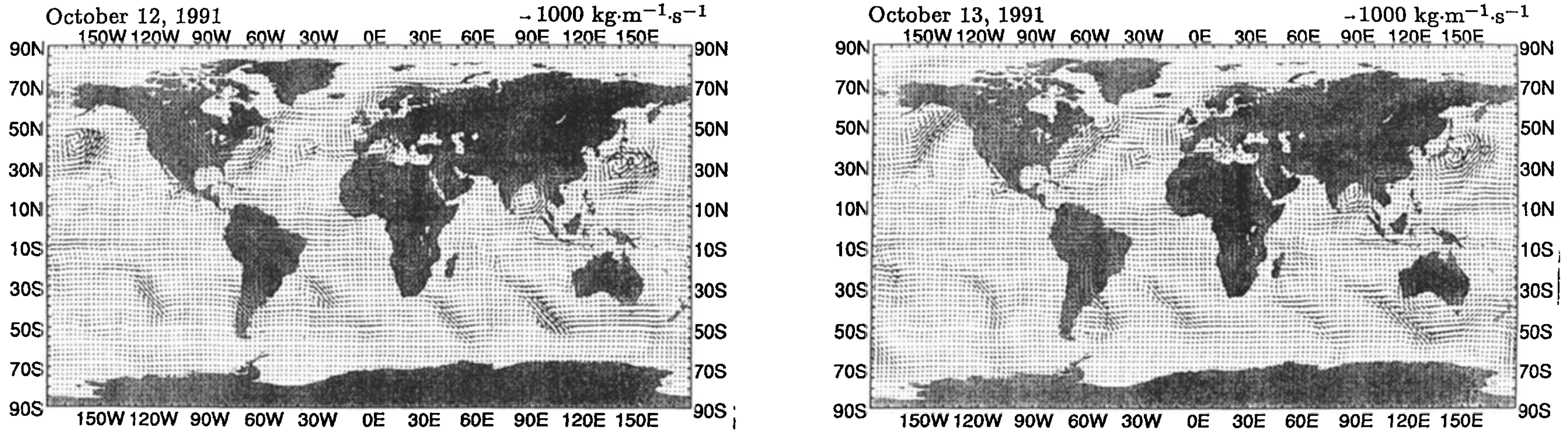

Fig. 1. Vertically integrated water vapor flux vectors for October 12 and 13, 1991. Units: kg $m^{-1}sec^{-1}$.

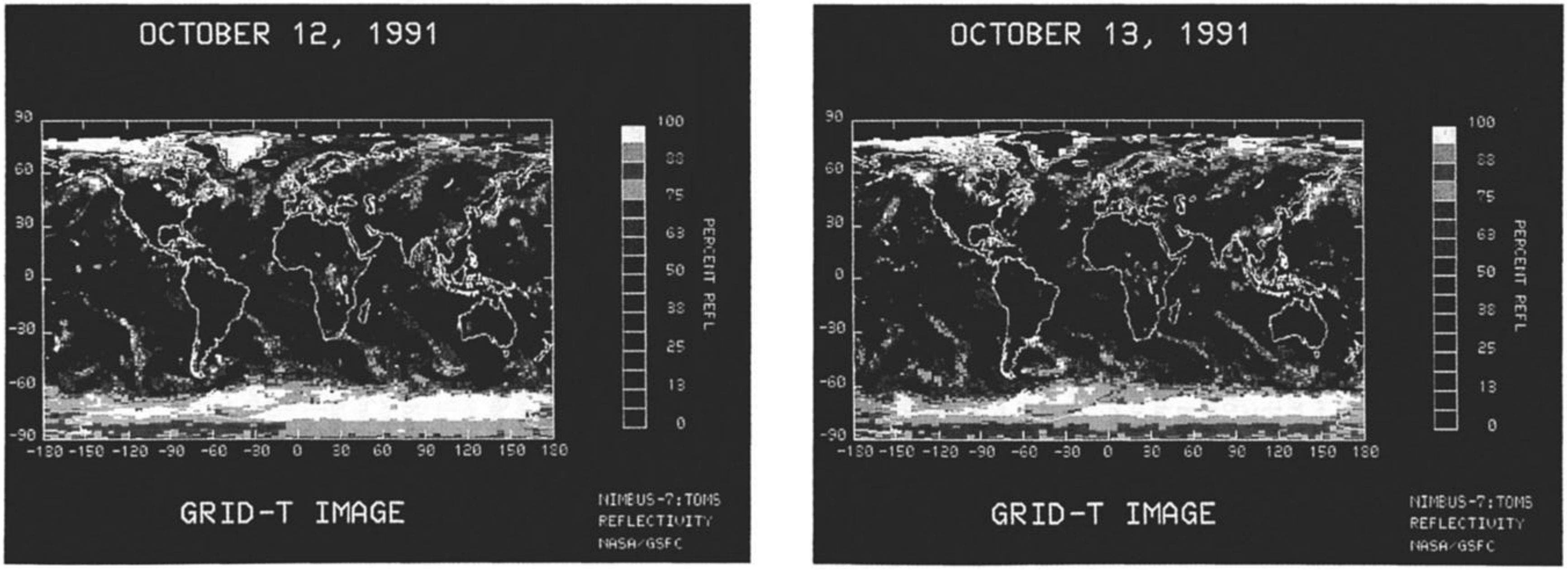

Fig. 2. Reflectivity from Total Ozone Mapping Spectrometer (TOMS) for October 12 and 13, 1991.

to be developed further. The association between filaments and other meteorological features can be investigated from a larger sample of data. The annual cycle of the source regions of the rivers can be examined. There are other ways of performing the vertical integration which need to be tried out and assessed. Furthermore in some cases the source fields can be examined from surface marine data and application of the bulk equations while the convergence fields, generally at higher latitudes, may be related to precipitation regions. Some of the high latitude sinks may be related to passage through cold upper troposphere polar regions as suggested by Kelly et al. [1991]. These features of atmospheric flow patterns clearly have to be taken into account for all trace constituents and not just water vapor. For example extension of the filaments further south to 70°S (without water vapor) could possibly account for the surface ozone fluctuations observed in Antarctica [Winkler et al., 1992]. Several other atmospheric constituents could be examined for traces of this structure. The question of interference between the specification of water vapor in the lower troposphere and the presence of cloud in the middle and upper troposphere needs to be examined further. Finally can any practical use be made of the apparent relation, revealed through serendipity, between TOMS images and lower atmosphere water vapor flux?

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