Lateral mixing as a source of subtropical tropospheric water vapor

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Abstract

It is hypothesized that the subtropical water vapor distribution results from the interplay of three simple factors: subsidence, which brings down dry air from aloft; lateral mixing, which brings in moistened air from the convective region at various rates; and drying by processing of air through the cold extratropics. A simplified Lagrangian model is formulated, and used to study how this process works during the CEPEX period (March, 1993). A key result is that the Northern subtropics should be viewed as a general background of dry air with mass mixing ratio of 10^{-4} or less on the 330K surface, interrupted by a few coherent moist plumes with mixing ratios on the order of 10^{-3}. It is suggested that the Lagrangian model would also be useful in interpreting satellite water vapor data, and in diagnosing water vapor transport errors in general circulation models.

1. Introduction

The water vapor content of the subtropical atmosphere has a profound affect on climate and on the sensitivity of climate to changes in radiative forcing (Sun and Lindzen 1993a; Pierrehumbert 1995, *interalia*). If unopposed by a moisture source, subsidence through the troposphere in the subtropics would cause the water vapor mixing ratio to relax to the saturation mixing ratio of the tropopause, which is 10^{-5} or less. The subsidence rate can be estimated by radiative cooling calculations, but less is known about the nature and strength of the opposing moisture source. Sun and Lindzen (1993b) proposed that evaporation of precipitation provides the main moisture source for the subtropics. Although this mechanism no doubt plays a role in spreading water vapor beyond the immediate confines of convective towers, its importance in the large scale subsiding regions is uncertain, given the weak rainfall (Spencer, 1993) and rarity of deep convection there as witnessed by the lack of high clouds (e.g. Stephens and Greenwald 1991). An alternate, and more obvious, hypothesis is that lateral mixing by large scale advection from regions directly moistened by deep convection provides the required source (e.g. Emanuel and Pierrehumbert 1996). In order for this mechanism to work, the mixing must be vigorous enough to transport significant quantities of convective-region air into the subtropics before it has a chance to subside too much; air that takes a long time to reach the subtropics originates at a much higher and colder level, and hence will be dry. Significantly, Sherwood (1996) was successful in simulating the major large scale features of the tropical moisture pattern using a model incorporating three dimensional advection based on observations, lateral diffusion, and a suitably tuned moisture source in the convective region. In order to appreciate the general consequences of the advection/subsidence picture, a deeper understanding of the mixing process and of its space and time scales is required.

In this Letter we present results of a calculation documenting the extent and nature of mixing between the convective region and the subtropics during March 1993, which is the period of the Central Equatorial Pacific Experiment (CEPEX, cf. Williams 1993). A novel aspect of the present work is the use of a fully Lagrangian transport scheme, which is entirely free from the spurious transport endemic to commonly employed Eulerian methods, and which can reconstruct theoretical moisture fields at very high resolution. The calculation is described in Section 2, and results on mixing and the implied moisture patterns are given in Section 3. General implications of the work are discussed in Section 4.

2. An idealized advection/subsidence model of subtropical water vapor

Earlier work on isentropic mixing established some general features of the large scale mixing process, and indicated the possibility of extensive mixing within the tropics (Pierrehumbert and Yang 1993, Emanuel and Pierrehumbert 1996). Here and in the following, the word "mixing" refers to rearrangement of air by large scale flow; it is only "mixing" in the coarse-grained sense, as there is no actual exchange of substance amongst air parcels. Isentropic results are suggestive, but a quantitative treatment of subtropical water vapor requires representation of the cross-isentropic transport associated with subsidence. The present analysis relies on a modified isentropic trajectory calculation. Let (λ,φ,θ) be longitude, latitude and potential temperature, and let $(u(\lambda,\varphi,\theta,t),v(\lambda,\varphi,\theta,t))$ be the associated horizontal velocities (in degrees per unit time) on a θ-surface. Given the winds *and given a time series of* $\theta(t)$ *along the trajectory*, we can integrate the trajectory equations $d\lambda/dt = u(\lambda,\varphi,\theta(t),t)$, $d\varphi/dt = v(\lambda,\varphi,\theta(t),t)$. The chief simplification is to specify $\theta(t)$ as a known function of time, with $d\theta/dt <0$, for all trajectories beginning on a given θ-surface. This is certainly incorrect in the convective region, where trajectories are ascending, but this fault is not fatal as we are primarily interested in the fate of air after it leaves the convective region. This simplification eliminates the need for complex diagnosis or computation of the vertical velocity field. It also has the virtue of permitting the subsidence to be characterized by a few simple parameters. Its disadvantage is that it neglects effects due to fluctuation of the cooling rate.

To determine the extent to which air from the tropical convective region mixes into the subtropics, air on a given initial θ surface is colored according to whether it is in the convective region. An ensemble of trajectory calculations is carried out to see how the pattern is rearranged by advection as the air subsides to a lower θ-surface. Alternately, the calculation is run as an equilibrium source-sink model, in which we keep track of the evolution of moisture mixing ratio q on each trajectory. In this case, we reset the parcel's mixing ratio to the saturation value corresponding to its current temperature, whenever it enters the convective region. Further, if the parcel wanders into a region cold enough that the local saturation mixing ratio q_{sat} is less than q, then q is reset to q_{sat} (the excess moisture implicitly being rained out). The procedure is similar to that employed in Yang and Pierrehumbert (1994), except that subsidence is allowed for and a more realistic specification of the convective region is employed.

In practice, we carry out this calculation by using a back-trajectory method, which is a variation of the Reverse Domain Filling method developed by Sutton *et al* (1994). To find the mixing ratio at a given $(\lambda,\varphi,\theta,t)$, we run a trajectory *backward* in time from this point until it encounters the convective region; because the mixing ratio is then set to saturation, the air parcel has no memory of earlier times, and further integration is unnecessary. The hypothetical mixing ratio at $(\lambda, \varphi, \theta, t)$ is then simply the minimum q_{sat} encountered along the segment of back-trajectory described. This automatically accounts for both the subsidence effect (i.e. air that has aged a long time since encountering the convection is drier), and the drying due to processing through the cold extratropics.

A calculation of this sort could be run with a variety of idealized or realistic advecting fields and configurations of the convective region. For the results presented below, we have made the following choices. The winds and temperatures (and hence the q_{sat} field) were taken from ECMWF analyses from the operational archive for March 1993. The subsidence of a parcel located at $\theta=\theta_o$ when $t=t_o$ is specified by the formula $\theta(t) = 350. - (350.-\theta_o)\exp((t-t_o)/\tau)$; τ is chosen such that the mean cooling between 320K and 350K is 1K/day, based loosely on dry tropical data by Mapes and Zuidema 1996. We also estimated subsidence rates by running a clear-sky radiation model (Kiehl and Briegleb 1992) to obtain net radiative cooling profiles for four CEPEX soundings taken in the Eastern Pacific subtropics between 11N and 23N. The cooling rate for the 320K-350K layer ranges from .91 to .95 K/day among the soundings, and is consistent with estimates obtained by Mapes and Zuidema (1996) and by Soden (1997) for dry regions. The form of $\theta(t)$ is such that air parcels approach radiative equilbrium as they near the tropical tropopause. Finally, we define the moisture source region as the oceanic area with SST > 300.5K, plus the continental regions within 20^o of the Equator where the ECMWF-analyzed relative humidity is consistently greater than 50% during the month. The latter primarily brings the Amazon and African rain forests into the picture. To simplify the interpretation of the results, we used a *time-independent* convective region, based on March 15 conditions.

3. Results

Figure 1a-d shows the extent to which air from the convective region mixes into the subtropics. The results are presented on an isentropic surface but the drift of air across isentropic surfaces has been taken into account in the calculation. The air arriving at the 330K surface from above on the specified dates has been colored according to its origins 10 days (Fig. 1a-c) or 20 days (Fig. 1d) earlier (see caption for key). In Figure 1a, for example, the pink air was located within the convective region,denoted by the heavy solid contour, on March 1; the Figure shows the disposition of this air on March 10. These results were computed at 1^olongitude by $.5^o$ latitude resolution. The ejection of convective air into the extensive Northern subtropics is highly intermittent and filamentary. The N. Central Pacific subtropics is relatively isolated for March 1-10 and March 20-30, but there is a major Pacific mixing event evident in the March 10-20 period. For March 1-10 there is an Atlantic northern subtropical mixing event, involving a large anticyclonic eddy, which on March 20-30 is replaced by a less contorted plume.

The Southern hemisphere results are strongly influenced by the fact that the hypothesized convective region covers almost all of the area between the Equator and 20^{o}S, with the most prominent subsidence occuring in the region W. of South America. Most of the convective region is thus close to the Southern jet stream. The mixing pattern is suggestive of entrainment of convective-region air into the Southern Hemispere storm track, by fairly regular short-wave synoptic wave trains. The same motions import dry air into the Eastern portion of the South Pacific convective region. It is interesting that in all three 10-day periods, air from the Amazon convective region is flushed out by dry subtropical air, with much of the moist Amazon air winding up in the Eastern Pacific cold pool region, near the S. American coast. The Amazon in fact appears to be the main moisture source for the subidence region located there.

It is only over the longer period March 1-20 that subtropical and convective air begin to appear intermixed, though even then considerable large scale inhomogeneity remains. Over shorter time scales, we see only intermittent discrete plumes in the Northern Hemisphere. Air that takes 20 days to reach the subtropics from the convective region has subsided so much that it will be very dry.

It is difficult to infer moisture patterns from the preceding results because the age of the ejected air (and hence the degree to which it has subsided) is not evident. In Figure 1e we show the implied moisture pattern on March 20, taking into account the effects of subsidence and of drying due to passage of air through cold regions. The Northern subtropics consists of a general background of extremely dry air with a mixing ratio of 10^{-4} or less. This background is interrupted by five young, moist plumes with mixing ratios of about 10^{-3}. The plumes appear fatter and less fragmentary than the filaments of convective-source air in Fig. 1c because Fig. 1c represents an initial value problem in which convective air is laid down one time only on March 10, and then redistributed by advection. In contrast, in the equilibrium calculation shown in Fig. 1e, the moisture in the convective region is, in effect, continually replenished. A particularly interesting structure is the moist plume originating in the Western Pacific, which resembles a similar feature noted by Yang and Pierrehumbert (1994) in calculations employing GCM winds for a January simulation, and which is also evident in the isentropic 330K results presented by Emanuel and Pierrehumbert (1996) for the CEPEX period. This moist plume is due to an anticyclonic eddy which pulls moisture out of the Western warm pool region, and simultaneously pulls midlatitude dry air into the Central Pacific subtropics. Isentropic calculations do well at reproducing these plumes, since they are moist precisely because they are ejected rapidly enough that there is little time for much subsidence. Isentropic calculations can reproduce the disposition of dry air rapidly injected from midlatitudes, but they miss the dry air originating from subsidence from aloft.

In the Southern Hemisphere, the ejection of moist air creates a zonally elongated moist region around 25S in the Pacific, due to air entrained into the subtropical jet. It also moistens the Pacific cold-tongue region, and the subsidence region W. of the S. American coast.

Varying the assumed cooling rate between .8ºK/da and 1.2ºK/da had little effect on the results. For example, at .8ºK/da the mean and standard deviation of $\log_{10}(q)$ along 23N are (-3.752,.636), whereas at 1.2ºK/da they are (-3.780,.633). We also repeated the calculations using NCEP winds and temperatures (Kalnay *et al* 1996), and found identical large-scale features, though the fine-grained structure changed somewhat.

We have compared the calculation to the ECMWF-analyzed moisture field for the same date (Figure 1f). Because the ECMWF analysis is influenced by the model used for data assimilation, this is not an ideal check of the simplified simulation. However, a check of Figure 1f against TOVS satellite data available for the same day (R. Engelen, personal communication) indicates that the picture given by the figure is not badly wrong.

In the Northern subtropics, the configuration of the moist plumes agrees well between the simulation and the ECMWF analysis, though the ECMWF analysis fails to resolve the finer scale features produced by the Lagrangian calculation. The effect of coarse resolution in the analysis is most evident in the Central Pacific, where there is insufficient penetration of the midlatitude dry plume into the subtropics. In the Southern hemisphere, the boundary of the moist plume ejected into the Southern Hemisphere jet is also well reproduced. Overall, the gravest differences are to be found within the hypothesized convective region, which is maintained at saturation in the simulation, but which has considerable embedded dry air in the ECMWF analysis. This discrepancy is especially evident in the Eastern portion of the Southern Pacific convective region, which, as discussed earlier, is a major site of dry air import. Evidently the convection here cannot moisten the air rapidly enough to keep up with the rate at which dry air is bring brought in. Another discrepancy is that the cold pool subsiding region W. of the S. American coast is too moist in the simulation, which may be a result of the over-estimated moisture source in the adjacent oceanic convective region.

The 1ºx.5º simulation of Fig. 1e does not resolve all the structure in the moisture field. In Fig. 2 we use the back-trajectory method to reconstruct 330K water vapor in the domain 0-30N latitude, 210-240E longitude at .075º (about 7.5km) resolution on March 26 and 27. This calculation is similar in spirit to that carried out by Waugh *et al* (1994) for reconstruction of filamentary structures in the stratosphere. Since the large scale advection problem has a positive Lyapunov exponent (Pierrehumbert and Yang 1993), a tracer will develop exponentially small scales as time passes. In the present case, moist plumes cannot have arbitrarily small scales, since only the "young" air has subsided little enough to remain moist relative to the ambient air. Figure 2 shows that the strain is nonetheless strong enough to create some moist filaments with scales of 10km. or less, though the dominant moist structure has a thickness of approximately 100km. The results also reveal the sharp boundaries between moist and dry air. Radiosonde data is available in this region, and the sonde locations are plotted in the figure. Both sondes are located in predicted dry regions; consistently with this, the March 26 sonde reports a mixing ratio of 2×10^{-4} at 330K, and the March 27 sonde reports 7×10^{-5}. At these low values, the accuracy of the sondes is dubious, but the observations at least confirm the general dryness predicted by the advection/subsidence model for this region.

4. Discussion

Insofar as the CEPEX period is representative of general equinoctial conditions, we can conclude that the moisture leaking into the Northern subtropics takes the form of a small number of coherent plumes with a time scale of 5-10 days and a meridional scale reaching across the entire subtropics. On the 330K surface they have mixing ratios of around 10^{-3}, whereas the background subtropical mixing ratio is at least an order of magnitude less. It is likely that at any given time, most of the Northern subtropical moisture is contained in such structures. These structures are the counterparts of the dry-tongues appearing in the convective region, as analyzed by Mapes and Zuidema (1996). The homogenization process discussed by Pierrehumbert and Yang (1993) occurs on too slow a time scale in the Tropics to be of much significance for the water vapor distribution, and so one sees fairly large scale moisture inhomogeneities, rather than a uniform admixture of convective air into the subtropics.

The Southern Hemisphere mixing is rather different, owing to the disposition of the convective region relative to the midlatitude storm track, and to differences in the character of Southern Hemisphere transient eddies. Probably, the most important aspect of this mixing is the massive importation of dry air into the convective region of the Southern tropical Pacific. We believe this North-South asymmetry in the mixing, as well as the location of the major Northern subtropics moist plumes, to be real features. They are largely unchanged if ECMWF winds are replaced by those from the NCEP analysis. They also check out against the ECMWF operational moisture analysis, which in turn resembles TOVS data in a coarse-grained sense.

Recently Soden (1997) has analyzed water vapor transport in the GOES-E region using a pattern-tracking method that requires no data besides satellite radiances. His results on the import of dry air into the subtropics, the export of moisture from the Amazon, and the control of moisture outside the convective region by simple advection and subsidence, are all broadly consistent with the picture we have presented.

The major moist plumes have embedded fine-scale structure, as shown in Figures 1e and 2. A pressing question is whether this structure is real. The calculations were done without parameterized small scale mixing of any type, and thus air parcels do not exchange moisture with their neighbors no matter how close they may lie. The real atmosphere may have vertical or horizontal exchange mechanisms that smear out sufficiently thin filaments. Mixing of this type is poorly understood. Comparison between the Lagrangian predictions and aircraft or satellite moisture observations may prove to be the best way to get a handle on the extent of unresolved small scale transport.

Our calculations provide hints (though at the present stage they are *only* hints) as to the type of motions that must be modelled accurately if a GCM is to faithfully reproduce the water vapor distribution, and the type of motions that must be parameterized in idealized theories of the tropical climate. For example, the moistening of the Southern subtropics depends on the position of the subtropical jet relative to the convective region. In general, simplified models based on mean advection plus intermittent large displacements of coherent patches of convective-region air appear to be called for. The obvious influence of transient motions also shows that changes in the character of tropical transient activity can affect the subtropical moisture, and thus provide a pathway to climate change. The mixing diagnostics in any event underscore that there is no particular barrier to interchange of air between the convective and nonconvective regions of the tropics, and that the interchange is rapid enough for large scale advective mixing to be viable as a source of subtropical water vapor.

The method we have used is a straightforward extension of the RDF method (Sutton *et al* 1994), in which we allow for cross-isentropic drift and keep track of the minimum temperature encountered along the trajectory. It is potentially useful for diagnosing water vapor transport errors in general circulation models, since the method can reconstruct what the water vapor would have been in the absence of numerical diffusion and other errors due to inadequate resolution. It could also be used to aid in the interpretation of satellite moisture data, since it permits one to distinguish between changes due to fluctuation in the wind patterns, and changes due to fluctuation in the configuration of the convective region. It could also be used to determine the time scale over which dry air picks up moisture as it enters the convective region— a parameter of key climatic interest.

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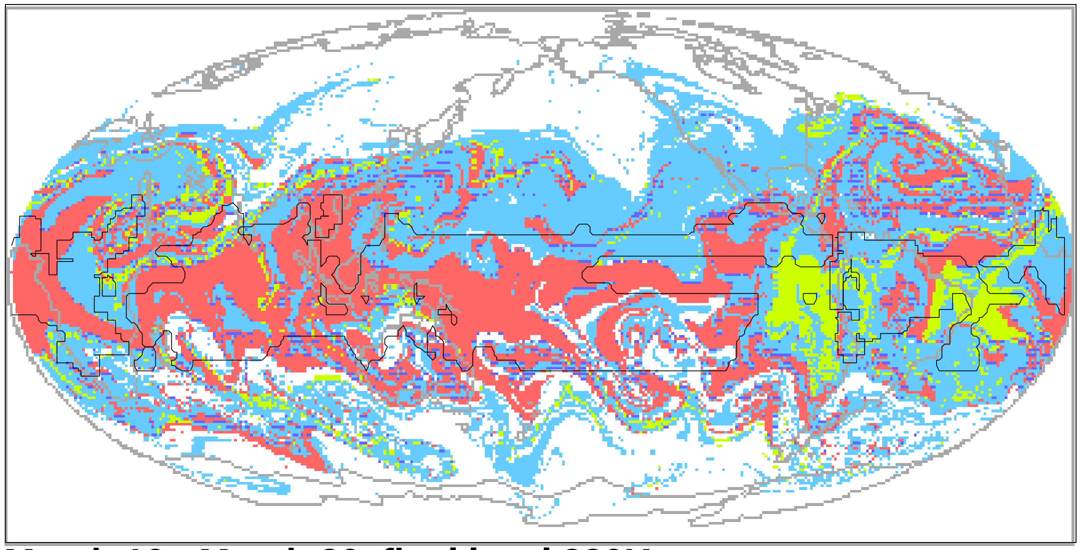
Figure Captions

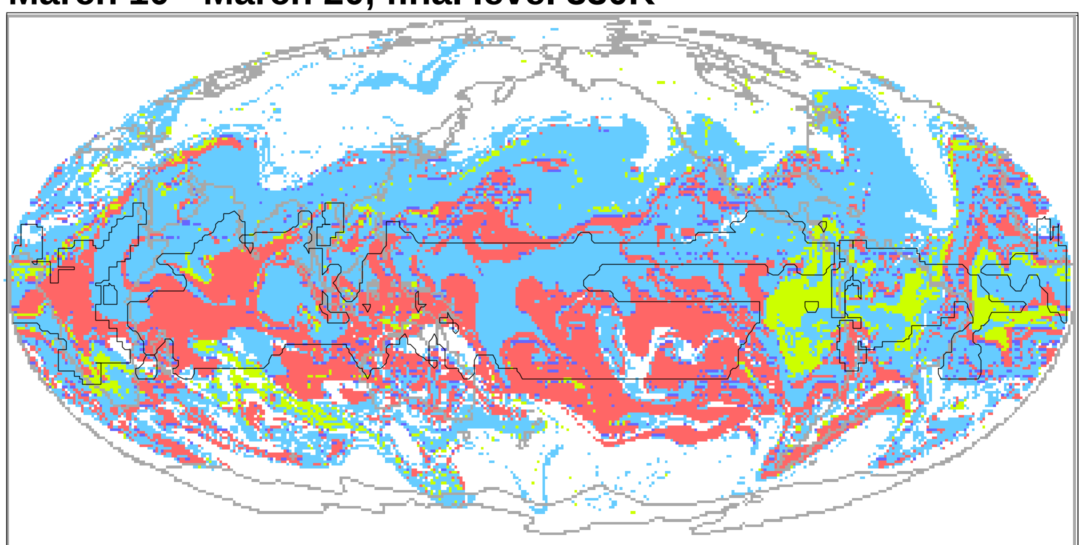
Figure 1 ....Panels (a-d): Maps showing where air landing on the 330K surface on the specified final date was located on the specified initial date. Air originating in the oceanic convective region is colored pink, air from the Amazon and African moist regions is colored yellow, and the rest of the air originally located between 30N and 30S is colored blue. Air of extratropical origin is white. The heavy contour shows the outline of the assumed convective region. Panel (e) Theoretical moisture mixing ratio for March 20, 1993, reconstructed using the advection/subsidence model. Panel (f) ECMWF-analysis of mixing ratio for March 20, 1993.

Figure 2 ....330K mixing ratio reconstructed by the advection/subsidencemodel on a 400x400 regional grid covering 0^{o}-30^{o}N, 210^{o}-240^{o}E. Left panel is for 00Z March 26, 1993, and right panel is for 00Z March 27, 1993. Sonde positions on respective days are marked.

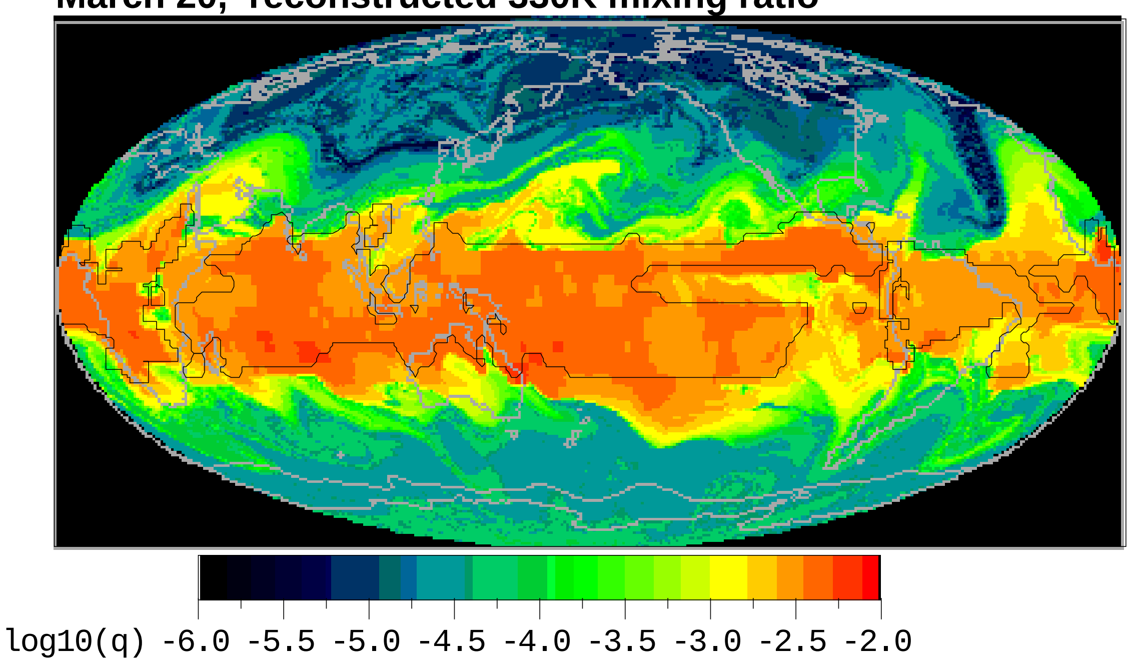
March 1 - March 10, final level 330K



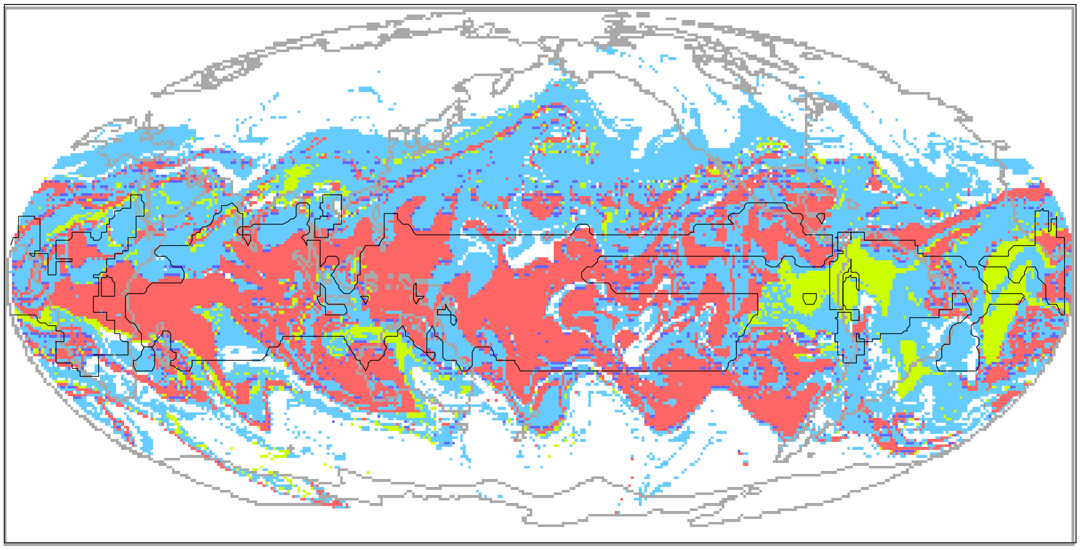
March 10 - March 20, final level 330K



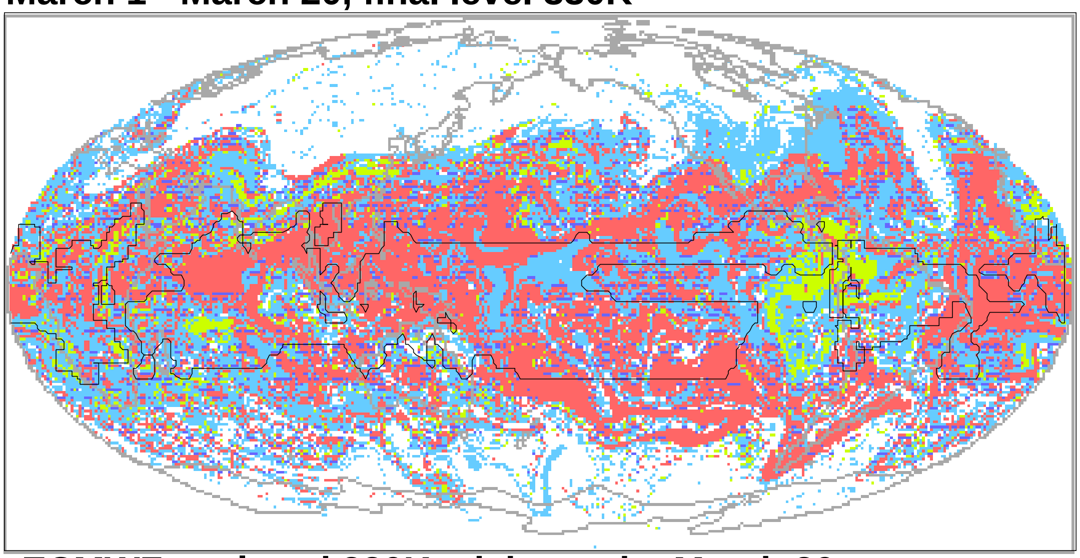
March 20, reconstructed 330K mixing ratio



March 20 - March 30, final level 330K



March 1 - March 20, final level 330K



ECMWF analyzed 330K mixing ratio, March 20

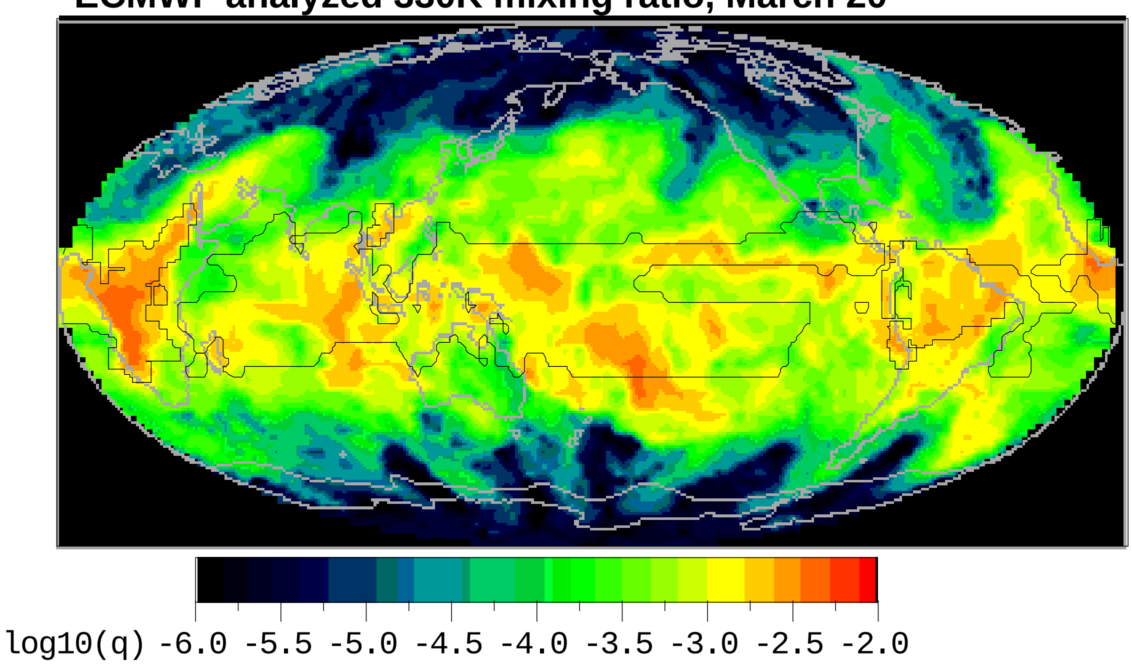
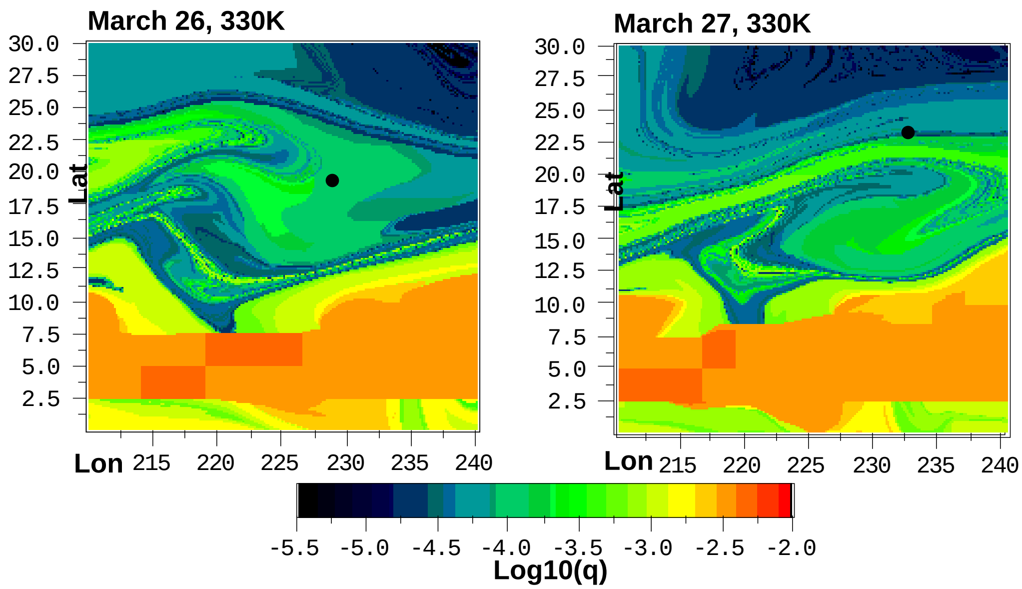


Figure 2



March 26, 330K
March 27, 330K
30.0
27.5
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
Lat
Lon
215
220
225
230
235
240
-5.5
-5.0
-4.5
-4.0
-3.5
-3.0
-2.5
-2.0
Log10(q)