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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Trajectory analysis on the origin of air mass and moisture associated with Atmospheric Rivers over the west coast of the United States" *by* J.-M. Ryoo et al.

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Thank you for the helpful comments that are valuable to improve the manuscript. Here we repeat the reviewer's comments and respond to them. Figures will be presented in the attached supplement.

Major issues:

1. The scope of the paper is not clearly defined. While the motivation focuses on atmospheric rivers, part of the manuscript is written as sort of a comparison of the influence of different reanalysis datasets, and a test of the last saturation approach for identifying moisture sources. However, the manuscript discusses none of the three

topics in sufficient detail. In a revised manuscript, the main focus should be clearly on only one of these aspects.

- The primary goal of this study is to find the transport pathways of air masses and moisture associated with atmospheric rivers (AR). In order to do that, first we test the sensitivity of the trajectories to the different datasets, which use different model physics and parameterizations. This helps increase the credibility of the trajectories and reduce the concern that different reanalysis data may result in different trajectory results. We conclude that the trajectory paths are not large between different dataset. This allows us to use one set of reanalysis data for results (i.e. MERRA for reconstruction of water vapor in the revised paper). Our second goal is to characterize the trajectories and where moisture and air masses originate. We no longer use a last saturation approach. Instead, we let the model internal physics determine how moisture is conserved along the trajectories, including changes with local condensation and evaporation from model water vapor sources and sinks. By doing that, the reconstruction of moisture from 5-7 day trajectory (we make short the trajectory simulation period according to the referee's suggestion) has improved. We show this in the revised paper.

We compare of trajectories using three different reanalysis during several AR events, and show that transport pathway and moisture source are closely linked to each other. In this paper we focus on the trajectory pathways and moisture sources on these atmospheric river case events.

2. Quasi-isentropic trajectories are calculated from 3 different reanalysis data sets. From the approximate agreement between trajectories calculated from the three data sets in just one case, the authors conclude that the trajectories are realistic. There are several problems with this.

2. 1) First, diabatic heating rates are calculated differently for each data set, and contain different terms. These differences need to be investigated and discussed in much more detail, for example by directly comparing diabatic heating rate fields.

- In the revised manuscript, we have followed the referee's suggestion to compare the different diabatic heating rates used to the trajectory calculations. Figure 1a, 1b compare of maps of diabatic heating during 5 days for 30th December, 2005. As seen in the right panels of Fig. 1, 5 days time mean maps of diabatic heating rate at 700 hPa from NCEP, MERRA, and ECMWF-interim data are all similar. The height-latitude cross section averaged over 120-250oE (spanning an average horizontal pathways that trajectories may cross in 5-7 days previous to landfall) shows that the diabatic heating rates are also similar, though with some difference in detail. Over the tropics (5-10oN) and lower troposphere, MERRA and ECMWF diabatic heating is more similar than those in NCEP. All three reanalysis heating fields are robust over the subtropics (15-25oN). Over the mid-latitude in the upper troposphere those in NCEP and MERRA are similar, but in the mid troposphere, those in NCEP and ECMWF are more consistent. We also compare the diabatic heating rate for other AR cases, and in general they are all similar in overall shape and mean magnitude.

2. 2) Second, the correlation between trajectories is just evaluated for one specific day. The finding that correlation is good up to day -7 and becomes much lower thereafter may just be a coincidence for that example, because some atmospheric process caused large differences in diabatic heating at that location and point in time. It could be investigated what process is taking place at that time that causes the divergence of the trajectories.

- To investigate how trajectories diverge during backward integration, we calculated the correlation and RMSE of locations among different datasets for the various cases shown in Fig. 2. Although the timing of the divergence of trajectories differs case by case, some cases diverge very quickly and other cases diverge slowly, the correlation of different data set for the most of cases is higher than 0.7 (0.6) during 5 (7) days back trajectory and decreases as the simulation time gets longer. However, for some particular cases, the correlations of longitudes and altitudes begin to decrease even after day = -3 for some cases, (e.g., the cases on 26th March, 2005 and 4th December,

2007). We looked at the trajectories among reanalysis data at these particular events, and found that the variability of trajectories is large over the mid-latitude storm track regions for those cases, which results in a large spatial variation among reanalysis dataset.

Difference in trajectory calculations using different reanalyses also results from the different spatial and temporal resolutions of the reanalysis data. In general, the difference between trajectories calculated using NCEP and MERRA or using NCEP and ECMWF-interim is larger than the difference between those using MERRA and ECMWF-interim. Other causes of divergence of trajectories include different parameterization schemes and model microphysics. However, comparing those details from different reanalysis data is beyond the scope of our current study and will be the object of future work.

2.3) Finally, the relative agreement between three quasi-isentropic trajectory models does not allow to conclude that the calculation is reliable by itself, a comparison against fully 3-dimensional kinematic trajectories that are commonly used in the troposphere would have to be carried out to prove that point.

- We test the reliability of this model by comparing with the results from the NOAA Air Resources Laboratory (ARL) HYSPLIT model, shown in accompanying Fig. 3a-3b (Draxler and Rolph, 2011). We use trajectory ensembles, which start multiple trajectories from the first selected starting location.

In general, there is good agreement between trajectories from our model and HYSPLIT. The HYSPLIT model result also in Fig. 3 shows two branches of the airstream in the extreme precipitation events (16th February, 2004; 30th December, 2005). However, HYSPLIT model seem to yield smoother patterns of air parcels because it utilizes the coarse resolution reanalysis dataset (2.5o x 2.5o) and uses pressure as a vertical coordinate. In cloud parameterizations, only a small portion of a grid is assumed to be covered by clouds (Arakawa et al., 1974), resulting in unrealistic vertical motion under the developing synoptic motion. Therefore, using vertical velocities from the coarse resolution reanalysis data (for example, 2.5o x 2.5o horizontal resolution) may not resolve the convection or cloud.

Isentropic surfaces are more indicative of parcel trajectories, but they only include the adiabatic component of vertical motion, so the diabatic component needs to be considered in the heavy precipitation events. We use the quasi-isentropic surface as the vertical coordinate, and this allows the diabatic heating to drive vertical motion across isentropes. Other studies using moist theta for calculating moist ascent within synoptic waves and consider the vertical component by the latent heating release to be most important (Parazoo et al. 2011). However, although latent heating is the most important component of the diabatic heating for synoptic motions, there are other terms in the diabatic heating such as radiative cooling, sensible heating, etc. The quasi-isentropic model takes into account not only latent heating but also other terms contributing to the diabatic heating. This supports the reliability of the trajectory model we use for describing the mass and moisture transport under developing synoptic motions such as ARs. We also compare our results to the result of Bao et al. (2006) using MM5 simulation, and agree well, as shown in Fig. 3c.

3.1) Water vapour sources are identified from an identification of the regions of last saturation. This approach has commonly used in the relatively dry regions of the subtropical and tropical upper troposphere. An application to cases of heavy precipitation seems beyond the scope of the method, as the results shown in the manuscript actually demonstrate (in contrast to the interpretation of the authors). In the case of a heavy precipitation event such as studied here, most of the air masses causing rainfall will be saturated at the start point or close to the target area. The last saturation is then very close to or at the start location. The trajectories where last saturation occurs at some distance from the arrival region are then necessarily the ones that are relatively unsaturated, but consequently also drier and thus not relevant for the heavy precipitation event. This is seen in Fig. 4a,b where the target domain occurs in intense red shading in all panels. It may also be the reason why Fig. 4 appears so spotty, be-

cause the moistest trajectories are locally saturated and don't contribute to the humidity reconstruction.

- Our original assumption has a shortcoming that trajectories lose water vapor without adding moisture during strong convective events. Therefore we do not use the last saturation mechanism but instead considering water vapor sources and sinks, as determined by the model physics, along the trajectories.

We reconstruct the water vapor assuming that it is conserved except for local condensation and evaporation from the reanalyses (Yanai et al. 1973, Wong et al. 2011). In this way, the reconstruction of trajectory simulated water vapor shows good agreement with the reanalysis specific humidity (q). Our reconstruction shows that although the saturation occurs at some distance from the arrival region, the parcel exchange moisture through local balance (by condensation and evaporation) at each time step during the trajectory simulation. We found that saturated air becomes relatively dry (due to removal of condensed water) so parcels could bring dry air to the target area. However, parcels also could provide moisture to the target area even after local saturation and rainout, via remoistening through evaporation processes

By substituting the local condensation and evaporation from the apparent water vapor source and sink instead of last saturation concept, reconstructed water vapor is much better matched with the reanalysis q. Therefore, while our original assumption that moisture is quasi-conserved along the trajectory still holds, we can improve the water vapor reconstruction and find where moisture originates by considering local hydrological balance. We find large moisture sources in the Pacific Ocean for North America precipitation not only from our back trajectory model simulation, but also from the other largrangian trajectory model study (Gimeno et al. 2010). We show this more in detail in a future paper.

3.2) In fact, Fig. 4 and 5 demonstrate that the approach does not work, the agreement is too poor to be of practical use. If you calculated the difference in % between panels a-c and b-c in Fig. 4 it would become clearer how severe the problems are. A much simpler and more appropriate approach would be to trace specific humidity along the trajectories, as previous studies have shown.

- We have improved the reconstruction by (1) shortening the backward integration to 5-7 days, and (2) implementing the apparent water vapor source/sink estimated from the reanalysis. Please see our response to issue 3.1) above, and Fig. 6 and Fig. 7 in the revised manuscript.

4. Many figures, in particular ones containing maps, are poorly drafted. World maps become almost unreadable if the latitude-longitude aspect ratio is heavily distorted, such as in Fig. 2, 3, 6, 7, 8. The writing needs copy-editing. The last paragraph of the Conclusions section discussing further research topics is not relevant to what is presented in the paper and should be completely removed.

- We replaced most of figures in the revised paper to address these issues. We also worked on the writing to make it more clear and concise. We have rewritten the discussion of future studies in the revised manuscript. The future study should be more focused on the relation between the moisture transport pathways and precipitation. We agreed that some conclusions in the previous manuscript are not relevant to the current work, so we removed them.

5. The target region appears far too large for the analysis. It is not clearly described at what spatial and horizontal interval trajectories are started. It would seem necessary to consider only a subset of the trajectories in that large domain for each case, otherwise the analysis is dominated by trajectories without relevance for the actual heavy precipitation event.

- The reasons to take the target regions (235-245oE and 34-50oN) are as follows. First, the AR cases that we investigate are not confined to certain regions but spread over the west coast of the U.S. Some big AR events (such as 30th December, 2005) occur over the entire western regions (34-52oN) and some ARs (e.g. for 3rd - 4th

December, 2007) affect the northern west coast (41-52oN) first (3rd December, 2007), then encounter the southern west coast (32-41oN) on the next day (4th December, 2007). Furthermore, as seen in Fig. 6 in the revised paper, the area covered by moisture in AR events includes the entire west coast of the U.S.

Second, our trajectories are calculated and stored at resolution of the corresponding reanalysis data being used. For example, trajectory using MERRA is saved on 1.25o x 1.25o grids, using NCEP is on 2.5o x 2.5o grids, and using ECMWF-interim is on 1.5o x1.5o grids. Therefore, the number of samples is much smaller if we choose smaller regions. By covering the entire west coast of U.S., we include more data.

Third, according to the referee's suggestion, we performed the sensitivity test by changing the reference regions. Slight changes in target region (for example, shifting the region (235-245oE and 34-50oN) to the narrower region (235-240oE and 37-43oN)) do not significantly change the main result we try to convey, but reduction in target area may eliminate the primary region containing trajectories which may contribute most to the precipitation over the west coast of the U.S.

6. The conclusion that high-altitude trajectories contribute to heavy precipitation is unsubstantiated, if not wrong. How large is the specific humidity of the cluster 2 trajectories compared to cluster 1? If anything, I would assume that due to the descending motion of air parcels, cluster 2 contributes dryness, but not humidity to the meteorological situation during heavy precipitation events.

- The attached Fig. 4 shows horizontal pathways and temporal variation of vertical coordinate of the median locations of the trajectories in clusters 1 and 2 for the AR event on 26th March, 2005. In general, the air from cluster 1 contains substantially more moist than cluster 2 with an average mixing ratio of about 1$\sim$15 g/kg and about 0.1$\sim$5 g/kg in cluster 2. This is because most air trajectories corresponding to cluster 1 come from the tropical lower troposphere ($\sim$1km) where the air is moist compared to other contributing regions. In contrast, most air associated with cluster 2 comes from the high altitudes mid latitudes, resulting in either moist or dry air transport to the west coast of the U.S.

To summarize, although those two clusters having the different origins, both of them are associated with precipitation events. In general, cluster 1 trajectories originate at low levels and undergo ascending motion near the west coast of U.S., bringing heavy rainfall. Cluster 2 trajectories exhibit more variability and subsequently undergo either ascending or descending motion near the coastal region of western U.S., causing either rainfall or drying. As noted, descending air may bring dry air, so not provide moisture to the target area and playing a small role in heavy precipitation. The 16th February, 2004 AR case in the previous manuscript belongs to the descending case, similar to 26th March, 2005 AR case presented in attached Fig. 4. These preliminary finding will need further research.

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Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/11/C8180/2011/acpd-11-C8180-2011-supplement.pdf

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