Development of the Climatological Database of Atmospheric Rivers

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Abstract

The term "atmospheric river" (AR) was introduced about 25 years ago to characterize the "filamentary" structure of the atmospheric circulation. Since that time considerable research efforts were dedicated to investigate the role of ARs in global transport of precipitable water and latent heat, and in extreme weather conditions caused by their land falling. Principally new opportunities of automated detection of ARs with the use of satellite remote data are discussed as well as the prospects and specific difficulties of developing and routinely populating of a global climatological database of ARs.

1 Introduction

The term "atmospheric river" (AR) originates from the paper [New92] where for the first (and probably the last) time it was used in the form "tropospheric river". This was to emphasize the two main features of these phenomena: their location in lower troposphere (up to the heights of about 3000 meters), and extremely large fluxes of water vapor (and hence of latent heat) within them in comparison with background values. As it was stated in [New92] water transport of a strong AR is comparable to that of the Amazon River.

The later work [Zhu98] allowed to hypothesize that ARs perform more than 90% of meridional water vapor transport in total atmospheric circulation in middle latitudes while occupying less than 10% of the total area. Though the term "AR" itself, as well as the underlying physical nature of the phenomenon along with some preliminary generalizations about its features are still quite questionable [Gim14], these works make it possible to speak of a "filamentary structure" of the global atmospheric circulation resulting from the persistent process of formation, evolution, and disintegration of narrow atmospheric "channels" which "conduct" water vapor from the tropical belt to higher latitudes including polar regions.

The further research was logically developed in the two main directions. The first one concerns AR landfall events that lead to extreme weather conditions like storms, floods, heavy precipitation and snowfalls etc [Det11, Ral11]. As a special case (due to proximity of mainland and significant risks of hazards) such events are often investigated under a complex approach combining satellite, aircraft, weather radar, weather station and other available types of observations [Ral04, Mat12, Mat13].

The second direction is the climatology of ARs: their spatiotemporal distribution, frequency of formation over various basins of the World Ocean in different seasons, their strength in terms of water transport [Zhu98, Wal12, Gim14]. One problematic issue here is the lack of formal definition of an AR. According to early approaches AR should satisfy three limiting conditions: integral water vapor content (IWV) not less than 20 kg m^{-2}; length not less than 2000 km; and width less than 1000 km. This simple approach could be readily applied to detecting ARs in the products of satellite passive microwave observations, namely, IWV fields alternatively called total precipitable water (TPW) fields if not the problems outlined in [Wic13]. An attempt to design an objective automated technique for detecting ARs in TPW fields obtained from satellite radiometry data revealed the fact that the AR dimensions based on threshold algorithm are very sensitive to the TPW threshold, and its optimal value seem to be regionally dependent. Besides the daily satellite TPW fields contain significant regular gaps in tropical regions so that the AR images are usually fragmented. Though a special blending technique was suggested [Wim11] to partly overcome such obstacles, the widely accepted solution is using reanalysis data instead of observational data.

An intension to define an AR more precisely has led to another requirement which sets up the lower limit of the vertically integrated horizontal water vapor transport (IVT) within the AR. A typical threshold value is 250 kg m^{-1} s^{-1} [Gim14]. Such an approach allows for discriminating between AR and other "filamentary" feature of a TPW field that does not provide a significant water vapor transport. However, it has its own disadvantages. Firstly, AR intensity can change in time and space. This means that an AR-like object can both fulfil and not fulfil the IVT requirement being considered at different time moments and places. Intensity limitation makes the definition of AR rather a definition of a particular phase of a process evolution, like a mature stage of a tropical cyclone. In this case new questions arise, e.g. what temporal and spatial intervals should be taken into account when estimating an AR impact into global atmospheric circulation? Secondly, straight-forward calculation of IVT requires knowledge of vertical humidity and wind speed profiles, and hence also is only applicable for reanalysis and model data. Nevertheless an alternative approach mentioned in the next section and applicable to observational data is also possible.

2 Methodologies

The principal idea of the work is to create a climatological database of ARs based strictly on observational data (more precisely – on a long series of global TPW fields retrieved from satellite passive microwave observations). As it was mentioned in previous section a systematic approach to investigation of ARs climatology requires answering several crucial questions: what is an AR (as an object of interest and as a storage unit); how to detect ARs in fragmented satellite-derived TPW fields; how to estimate their intensity?

For the sake of objectiveness it was decided not to discriminate AR-like processes by their IVT values. Instead, on the first step of processing all filamentary features of the global TPW field structure considered objects of interest. To this end TPW fields were searched for local “crests” of TPW values in middle and high latitudes, and every continuous crest longer than 2000 km considered the axis of a potential AR. Every crest defines an AR which is represented as a two-dimensional mask on the geographic grid consisted of all nodes close enough to the detected crest. The threshold distance accounts for both inaccuracy of the detection algorithm and maximum AR width. The processing technique is briefly outlined below.

2.1 Satellite radiothermovision of atmospheric processes

A blending technique mentioned above [Wim11] allows constructing TPW fields without gaps by combining observational data (retrieved TPW values) with model data (wind fields at several horizons). However an alternative approach based strictly on observational data is possible [Erm18a]. This approach is aimed at investigation of two-dimensional dynamic of observed TPW fields. It complements the classical formulation of the inverse problem of satellite radiometry with a simple kinematic model describing atmospheric advection (horizontal motion).

In the most general form, obtaining the estimates $\tilde{x}_j$ of a set of geophysical parameters x_j from multichannel radiometric measurements T_{bi} is a minimization problem of some functional:

$$F\left(T_{b1},...,T_{bm},\tilde{x}_1,...,\tilde{x}_n\right)\to \min . \quad (1)$$

Solving (1) means finding such estimates $\tilde{x}_j$ which provide the optimal (in some sense) description of the observed media characterized with particular (measured) radiometric properties (brightness spectra, polarization contrasts etc). Commonly the measurements are treated as independent, point and instant, i.e.:

$$T_{bi}\left(t,\vec{r}\right)= f_i\left(x_1\left(t,\vec{r}\right),...,x_n\left(t,\vec{r}\right)\right)+e_i\left(t,\vec{r}\right), \quad (2)$$

where t and $\vec{r}$ represent moment of time and point in space correspondingly; f_i model relationships between geophysical and radiometric properties of the media; and e_i account for both measurements errors and model inaccuracy.

However when studying dynamic processes (like ARs) it makes sense to consider spatiotemporal correlation in geophysical fields. One of the simplest ways to do so is introducing a linear kinematic model:

$$x_j\left(t,\vec{r}\right)=x_j\left(t+\delta t,\vec{r}+\vec{v}_j\delta t\right)+\varepsilon_j\left(t,\vec{r},\delta t\right), \quad (3)$$

explaining the change of x_j within a small time interval δt as a result of motion with velocity $\vec{v}_j$, where errors ε_j are supposed to be relatively small and account for both nonlinearity and non-conservatism of x_j (e.g. phase transitions of atmospheric water). Then (1) takes the form:

$$F\left(T_{b1}\left(t,\vec{r}\right),...,T_{bm}\left(t,\vec{r}\right),x_1\left(t+\delta t,\vec{r}+\vec{v}_1\delta t\right),...,x_n\left(t+\delta t,\vec{r}+\vec{v}_n\delta t\right),\vec{v}_1,...,\vec{v}_n\right)\to \min . \quad (4)$$

This task can be solved under some additional assumptions as shown in [Erm18a] and the works cited therein. This provides simultaneous reconstructing geophysical fields in some outer neighborhood of regions of observation and two-dimensional effective velocity of advection in these fields. The latter is the key point for estimation of water vapor transport and latent heat fluxes directly from observational data, e.g. [Erm15, Erm17].

2.2 Characteristics of the remote data used

The satellite radiothermovision analysis was performed over the TPW fields retrieved from satellite radiometric observations by SSM/I, SSMIS, WindSat, AMSR-E and AMSR-2 instruments within continues interval of years 2003 – 2018. As a result, the full-coverage TWP fields over the World Ocean were reconstructed on a regular geographic grid with the cell size of 0.25 geographic degrees and with the time step of 3 hours. All TPW fields are available for browsing and downloading at the geoportal of satellite radiothermovision (https://fireras.su/tpw/) along with additional information on the source data and processing details.

2.3 A concept of AR detection procedure

The AR automated detection procedure was composed of several steps ideologically similar to those described in [Wic13], but with the two main differences. Firstly, the procedure was designed for and applied to the TPW fields resulting from satellite radiothermovision analysis. Though formally applicable as well to original satellite-derived TPW fields with gaps, the procedure make use of full-coverage fields both for estimating some statistics (as briefly explained further) and spatial properties of ARs. Secondly, the procedure does not use any fixed or manually-tuned thresholds to rectify the detection results at any processing steps. It is tested and proved to be universally applicable over all main basins of the World Ocean.

The first processing step is to exclude the intertropical convergence zone from the analysis, see [Wic13]. This step is performed by analysis of histograms of TPW values over the considered basin. The histograms are approximated with four Gaussian modes from which one with the biggest mean TPW corresponds to tropical air masses, the one with the smallest mean TPW corresponds to polar air masses and the two others correspond to mixture of air masses over middle latitudes [Erm18b]. The approximation algorithm is designed as a minimization problem solved with the use of Levenberg-Marquardt method and is completely automatic. The regions of the TPW field corresponding to tropical and polar air masses are then excluded from further analysis.

The next processing steps are aimed at detecting the crest (lines of local maxima) in TPW fields associated with axes of ARs. These steps are based on image analysis techniques (gradient analysis, skeletonization, morphology analysis) very similar to those described in [Wic13]. However due to no strict limitation of TPW values the algorithm appears to detect more filamentary features in TPW fields. Some of them which are shorter than 2000 km are then filtered out. Some others however connect to the "main" crests and must be filtered out using a special technique of "cutting branches".

Some preliminary results of the data processing are discussed in the next section.

3 Discussion of results

An example of ARs detection is demonstrated in figure 1.

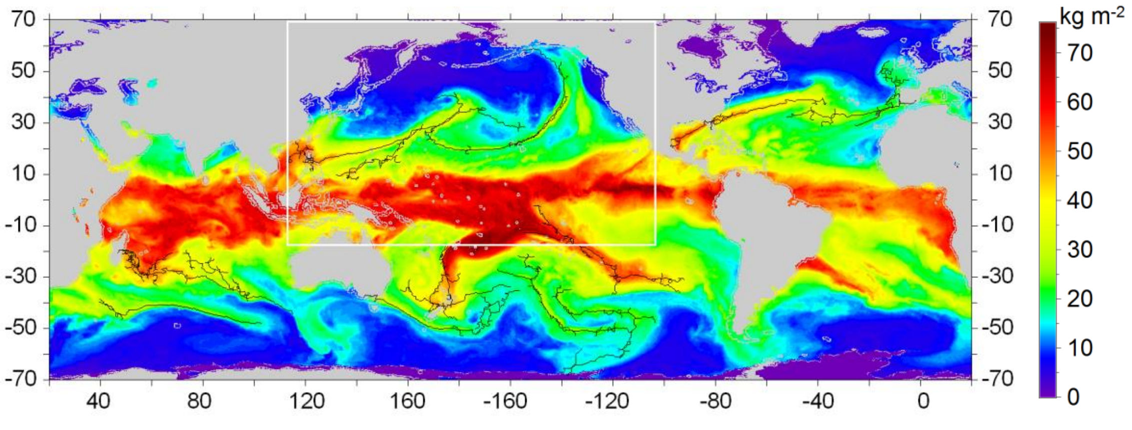

Figure 1: detected axes of ARs (black lines) in the TPW field (color scale to the right) for January 01, 2016 over South Indian, North Atlantic and Pacific oceans; landmasses masked with grey

The figure illustrates the TPW field for January 01, 2016 in a color scale showed at the right side of the image. The detected axes of ARs are indicated with black lines. Notice that the processing was performed separately for South Indian, North Atlantic, North Pacific, and South Pacific basins. The results were then combined in a single image. Hence the same automated procedure is able to detect AR axes throughout the World Ocean basins.

However the procedure has particular malfunctions among which one of the most noticeable is the strong bifurcation of the branches due to sensitivity of the algorithm to relatively small local perturbations of TPW field. Due to special “cutting” procedure the remaining branches are usually quite short and lie totally within AR width. Besides some of them reflect actual ambiguity of the AR flow direction, and handling them will require a more thorough approach probably based on analysis of fluxes. Still, this extreme “branching” is subject to further investigation and algorithm refinement.

An even worse problem is looping which takes place when to branches cross each other several times. In this case it is problematic even to determine the correct position of the main axis of the AR. Again, the analysis of fluxes and of AR dynamics can be of potential use here.

Some sample problematic cases are illustrated in figure 2.

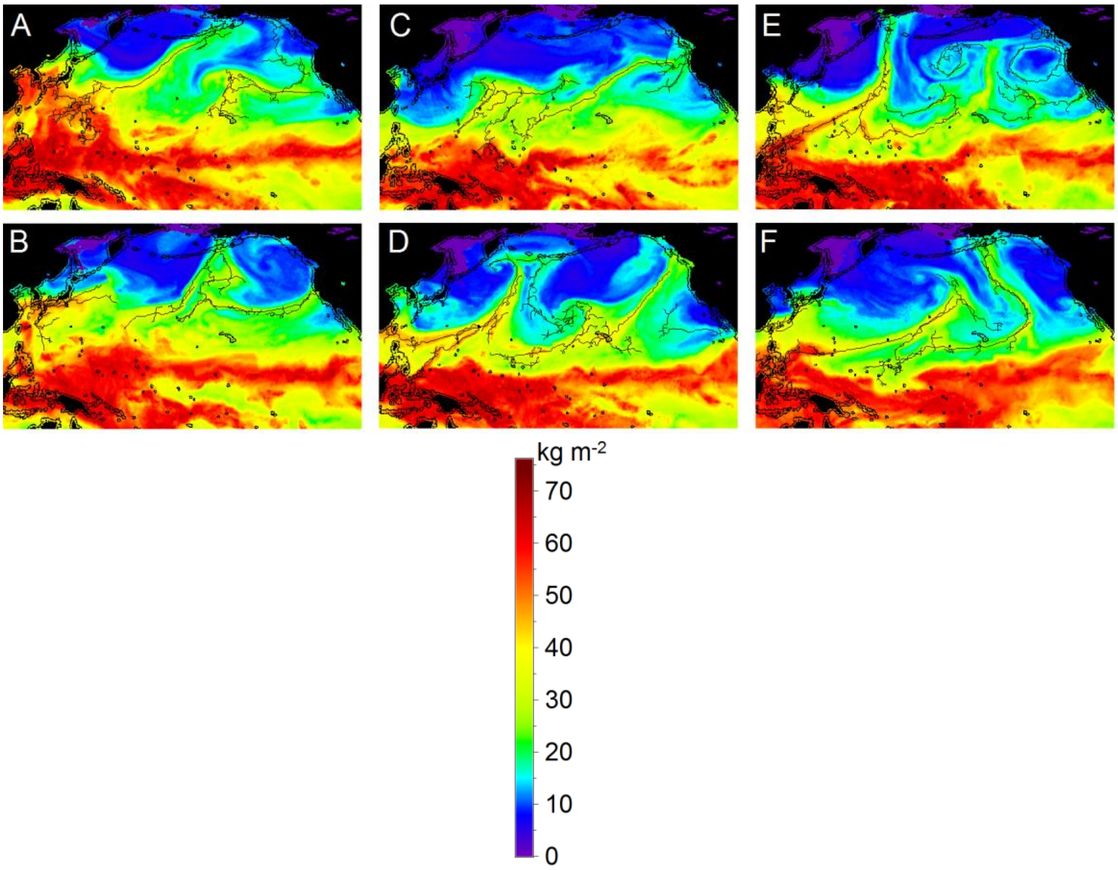

Figure 2: some problematic cases of detection AR axes over North Pacific, see comments in text

The figure illustrates the case of analysis over North Pacific. The outer boundary of the region was indicated with the thick white frame in figure 1. The problems to be emphasized (and addressed in future research) are as follows:

A) The beginnings of ARs are sometimes subject to significant branching due to proximity of humid tropical air masses resulting in complicated structure of local “crests” and “ravines”; a more sophisticated algorithm is then required to estimating AR lengths;

B) Individual ARs sometimes make a “bridge” and virtually become one AR; an algorithm is required to adequately separate them;

C) A lot of short “filamentary features” can combine to create a overall long-enough structure; sometimes its an origin of a new AR, but these cases also require more thorough analysis perhaps with the use of information on velocity directions;

D) Sometimes an AR-like features appear in the TPW fields which apparently have different nature (and opposite direction of water vapor transport) like a jet of warm humid air inflowing the tropical cyclone in figure 2-D to the east of the west-most AR; a detailed analysis of fluxes can be helpful;

E) Loop-like structures of different sizes are sometimes a case; they obviously reflect the actual features of TPW field and fulfill the formal algorithm requirements, but definitely are not ARs; further algorithm refinements are needed;

F) T-shaped junctions and other abrupt changes of AR axes directions are often a case; perhaps a more thorough definition of objects of interest is necessary which includes some requirements of spatial smoothness.

Notice that most of these problems are rather of “conceptual” nature. They don’t prevent the algorithm from successful detection of “filamentary features” in TPW fields and most of them will not be so distinct after transition from AR axes to two-dimensional masks representing regions covered by each AR (due to smoothing effects). It is also worthy noting that such AR masks are considered in this work as a preferable representation of AR as a storage object in the designed climatologic database. On one hand, they bare enough information to calculate statistics on formation of ARs over various basins (average frequency, average lifetime, “hot spots” – the areas most frequently crossed by ARs etc). This already provides a useful instrument to investigate the interrelations of “fine structure” of atmospheric circulation with climate variations, because most of the estimates will not change crucially due to further algorithm refinements. On the other hand, the estimates of some over features of a detected AR (like exact local position of its axis, local velocity and IVT, latent heat flux within the AR) can be calculated online by a user’s request, i.e. they will be automatically refined each time when some changes take place in processing algorithms.

This is the main architectural idea behind the AR database being developed.

4 Conclusions

The work considers some principally new opportunities of automated detection of ARs with the use of satellite remote data as well as the prospects and specific difficulties of developing and routinely populating of a global climatological database of ARs.

The basic concept of the new database design are as follows:

1) Performing the investigation with exclusive use of observational data (no reanalysis data, no results of numeric weather modeling);

2) Implementing satellite radiothermovision approach in order to obtain global TPW fields over ocean of full coverage along with the vector fields of velocity of advection;

3) Implementing completely automated algorithms of TPW field analysis in order to design an objective technique of AR detection;

4) Restrict the actually stored information with the masks of the detected ARs; this will make some results of further analysis more robust with respect to ongoing algorithm refinements while preserve an opportunity to perform a deeper investigation of AR feature in online mode.

The database interfaces are planned to be integrated into the geoportal of satellite radiothermovision (https://fireras.su/tpw/) and will be made publically available on the successful completion of database population and testing.

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