Environmental Modelling in Industry Study Group,
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**Organisers:** The EPSRC *Living with Environmental Change - Maths Foresees* Network and the NERC Probability, Uncertainty and Risk in the Environment (PURE) Network.

**Problem Statement to be Presented by JBA Trust**
**Identification of Coherent Weather Features in Three Dimensions**

# 1 Background Information

Most of us are familiar with the depiction of fronts on weather charts [Figure. 1]; they are a common tool used in everyday life, allowing us to quickly assess the current or a future weather situation with only a basic understanding of the symbols and their interpretation. While these features have long been subjectively hand-analysed on weather charts, recently there has been a push to use computer algorithms to objectively identify the location of weather features. The UK Met Office now uses such techniques to draw the various types of fronts (cold, warm, occluded) and surface pressure troughs on their surface pressure charts. In the research community, the use of computer algorithms to objectively identify weather features in global atmospheric reanalysis datasets (i.e. three dimensional representations of the atmosphere produced using numerical weather prediction models and global climate models) allows the long-term climatology of weather features to be assessed for the first time. Traditionally, the temporal and spatial variability of weather features, such as fronts and surface pressure troughs, on seasonal and interannual timescales was deduced from just a few years of data on regional scales due to vast amounts of hand-analysis required. With the aid of objective, computer-based analysis, global climatologies of weather features based on decades of data are now possible; for example, the first global climatology of fronts was published in 2011.

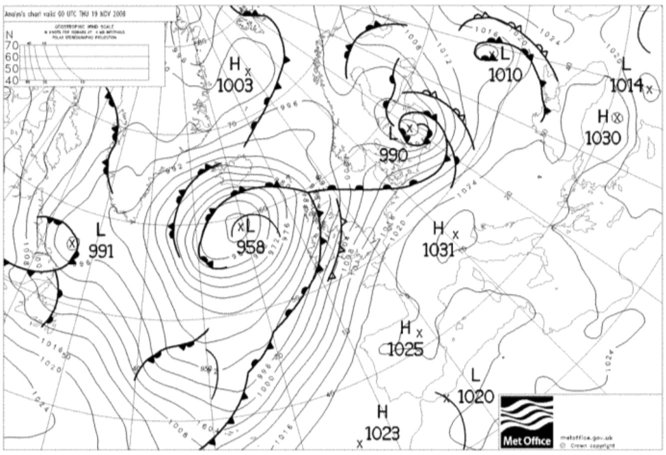


*Figure 1 - Surface pressure chart for 00 UTC 19 November 2009, produced by the UK Met Office. Obtained from http://www.wetterzentrale.de/topkarten/tkfaxbraar.htm.*

Identification of weather features is crucial to both understanding the atmospheric processes occurring and predicting how the atmosphere may evolve. Two examples of weather features that have been objectively identified and how that information is used are presented below.

## 1.1 African Easterly Waves

During summer months over tropical regions of North Africa, large clusters of thunderstorms develop over eastern Africa near the Ethiopian Highlands with a periodicity of about 3-5 days. These weather systems move west towards the West African coast and then across the Atlantic to the Caribbean [Figure 2]. Occasionally, these storms, referred to as African easterly waves, form into tropical cyclones, possibly becoming strong enough to be referred to as hurricanes. While the thunderstorms within each cluster are relatively transient, existing for several hours, the atmospheric disturbance responsible for the existence of the cluster of thunderstorms is longer-lived. This atmospheric disturbance can be identified as coherent, quasi-linear wind shift feature at about 700 hPa; i.e., a change from a southwestward directed wind on the western side of the thunderstorm cluster to a northwestward directed wind on the eastern side at around 2.5 km (~7500 feet) altitude, with this wind direction change present as a coherent feature from south to north across the thunderstorm cluster.

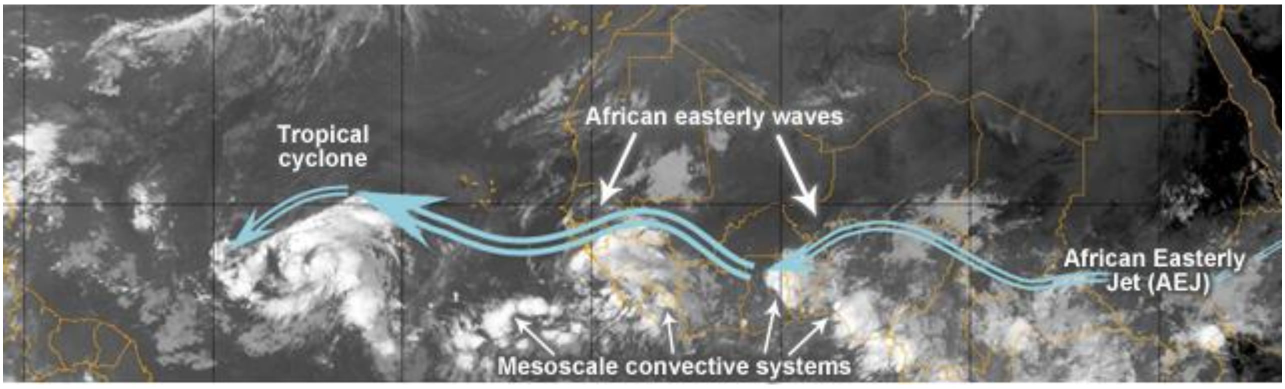


*Figure 2 - Exemplary visible satellite image showing thunderstorm clusters over Africa and a tropical cyclone in the Atlantic. The thunderstorm complexes exhibit southward and northward winds on their west and east sides, respectively; as instability "waves" along a jet. Image obtained from https://www.meted.ucar.edu.*

The presence of this wind shift provides one means by which these African easterly waves can be identified in global gridded reanalysis datasets. By locating grid points at the 700 hPa pressure level where the northward component of the wind changes sign, and then joining together similar near-by grid points, the coherent "wave" is identified. Climatologies of the frequency of occurrence of these "waves" at each grid point can then be compiled, allowing hot-spots of activity to be identified. Studies have focussed on these hot-spot locations to understand the dynamical processes occurring in the atmosphere that are responsible for making a particular location favourable or preferential for easterly wave activity. Further studies have extended the identification algorithms to develop tracking routines that allowed the evolution of individual waves to be investigated and composites of common wave evolution to be proposed.

## 1.2 Atmospheric Rivers

Many of the major wintertime flooding events that have occurred in the UK and Europe, and those on the west coast of the US, have been attributed to atmospheric rivers. While this term may seem euphemistic at first, it is actually a very accurate description of this weather phenomenon. We are familiar with the schematic depiction of extratropical cyclones (low pressure systems that occur within the middle latitudes (i.e., neither tropical or polar regions)), with the warm front as the leading "leg" on a weather map with the cold front as the trailing "leg" [Figure 3]. The area between the warm and cold fronts is referred to as the "warm sector", due to winds in this region generally blowing warmer and moister air (warm air holds more water) from lower, tropical latitudes polewards, ahead of the trailing cold front. While this configuration is present in all extratropical cyclones to some extent, for some, the current of lower latitude air that gets carried into the warm sector is exceptionally moist and exceptionally long-lived. Essentially, in some cases, the current of lower latitude air "taps into" to the reservoir of warm moist air that exists in the tropics. Such cases give rise to extensive and exceptional flooding, as there is essentially a river of moisture leading back to the reservoir in the tropics.

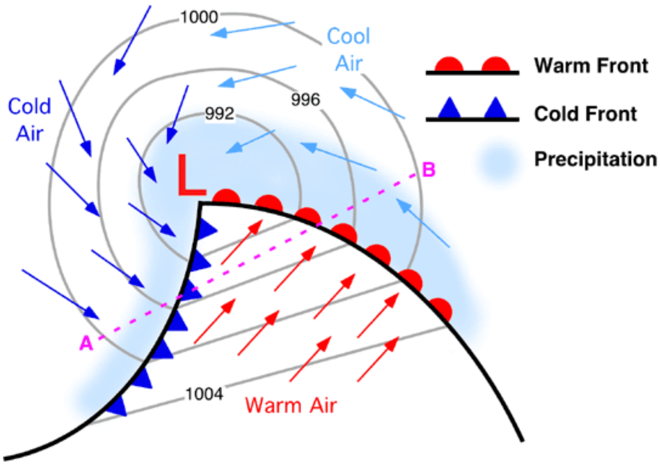


*Figure 3 - Schematic showing the surface structure of an extratropical cyclone. Obtained from http://www.physicalgeography.net.*

The moisture held in the air within these "atmospheric rivers" is present over a relatively large depth of the lower atmosphere (the troposphere). At any given location, the amount of water that could precipitate out as rain is essentially an integral of the moisture content of the air over the depth of the troposphere. To account for the fact that this air is continually moving, it is more accurate to consider the flux of water vapour throughout the depth of the troposphere, i.e., the water vapour content multiplied by the wind speed, summed over the depth of the troposphere. This gives rise to an “integrated water vapour transport” which can be used to identify atmospheric rivers in global gridded reanalysis datasets. As with the African easterly waves, objective computer-aided identification of these weather features allows climatologies of the spatial and temporal variability of the features to be compiled. And again, identification of activity hot-spots helps us to better understand the dynamical processes involved in moderating the variability of this type of weather feature.

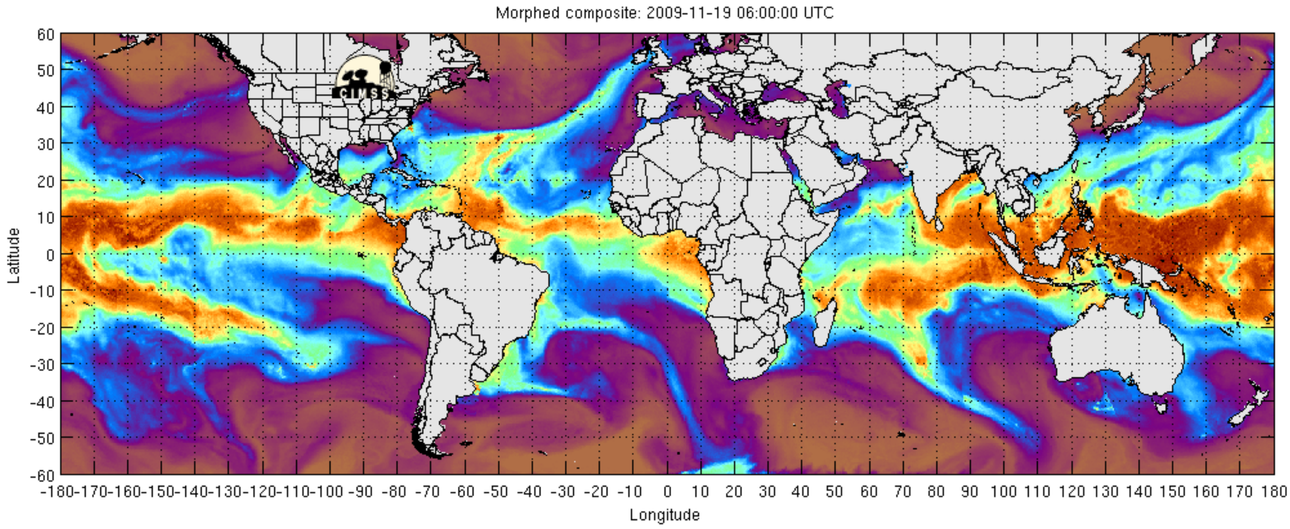


*Figure 4 - Global composite mosaic of total precipitable water from SSMI/SSMIS/AMSR2-derived satellite platforms for 06 UTC 19 November 2009. Purples and blues indicate small water amounts while greens, yellows and browns indicate large water amounts. Obtained from [http://tropic.ssec.wisc.edu/real-time/mimic-tpw/global/main.html](http://tropic.ssec.wisc.edu/real-time/mimic-tpw/global/main.html).*

The examples above have described two different weather features and how their objective identification has led to advancements in the understanding of atmospheric processes. In both examples however, a clear limitation is that the features were identified in two dimensions only: at a single level for easterly waves and through integrating over a depth for atmospheric rivers. Both weather features do exhibit three-dimensional structure, and at least in the case of the African easterly waves, changes in the vertical structure of the “wave” throughout an individual wave’s lifecycle can be indicative of intensification or dissipation of the wave. This information is lost when the feature is identified in two dimensions only unless the feature identification is performed at multiple vertical levels and some association between similarly located features at different levels is made. Such a process is performed for the identification of tropical and extratropical cyclones in vortex identification and tracking schemes, however it has not (yet?) been employed for other types of weather features. For atmospheric rivers, their three-dimensional structure has received little, to no, attention; the usefulness to weather prediction is entirely unexplored.

## 2 Problem Outline

The identification of weather features in three dimensions presents an interesting problem. The nature of weather features and the representation of the atmosphere using gridded three-dimensional datasets means the form of the features to be identified can be complex and highly variable. In addition to simply locating each feature, it is also necessary to include information about the state of the atmosphere associated with the feature, and often perform calculations relating to the feature itself, such as calculating gradients. Therefore, information

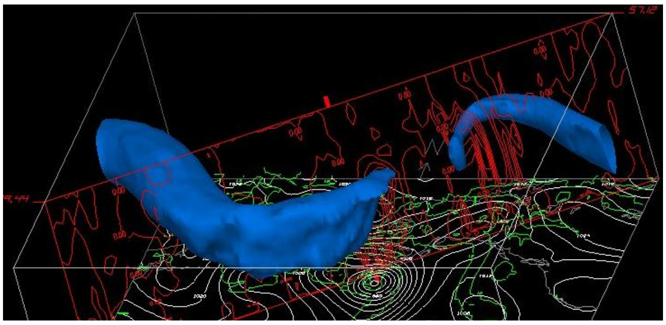

*Figure 5 - Example of 3D rendering of meteorological variables: Blue isosurface is 50 kt wind speed overlain on surface pressure in white contours with cross section showing vertical motion. Obtained from [http://www.aos.wisc.edu/~rlyuen/](http://www.aos.wisc.edu/~rlyuen/).*

regarding the orientation and length scale of the feature may also need to be included. A first attempt to identify coherent three-dimensional objects would likely require a simplification of the problem to known structures such as plane surfaces at various orientations or simple shapes such as cylinders.

## 2.1 Objectives

- Develop a generic computer-based tool or algorithm to identify coherent three-dimensional structures.
- Include in the method a way of associating properties describing the shape and orientation of the coherent structure, and also a way of including other properties associated with that feature.
- Test the methodology on the more complex problem of three-dimensional weather features, such as African easterly waves and atmospheric rivers, using gridded atmospheric datasets.

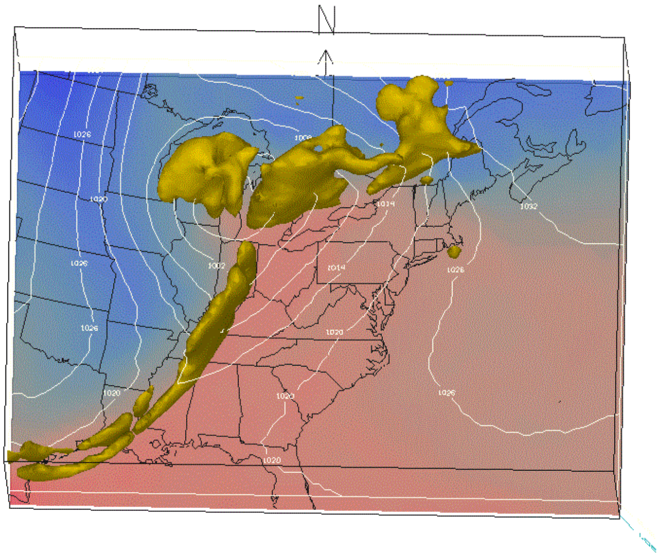


*Figure 6 - Example of 3D rendering of meteorological variables: Gold isosurface is 0.13 m s-1 upward motion, overlain on surface pressure in white contours and lower troposphere temperature in shading; obtained from http://www.aos.wisc.edu/~acwinters/lab11.htm.*

## 2.2 Data Format

The most common format for atmospheric datasets is NetCDF (http://www.unidata.ucar.edu/software/netcdf/), which allows for the storage of the data in four dimensional arrays (latitude, longitude, pressure or height, and time).
These data are typically interrogated, analysed and visualised using utilities such as Python (https://www.python.org/), Matlab (http://uk.mathworks.com/products/matlab/), NCAR Command Language (http://www.ncl.ucar.edu/), IDL (http://www.exelisvis.co.uk/ProductsServices/IDL.aspx), CDO (https://code.zmaw.de/projects/cdo), NCO (http://nco.sourceforge.net/), Panoply (http://www.giss.nasa.gov/tools/panoply/) and Fortran (http://www.fortran.com/).
Many other tools are also available.