GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 18, PAGES 1999-2002, SEPTEMBER 1, 1994

Atmospheric Rivers and Bombs

Yong Zhu and Reginald E. Newell

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology.

Abstract. Filamentary structure is a common feature of atmospheric water vapor transport; the filaments may be termed "atmospheric rivers" because some carry as much water as the Amazon [*Newell et al.*, 1992]. An extratropical cyclone whose central pressure fall averages at least 1 hPa hr^{-1} for 24 hours is known in meteorology as a "bomb" [*Sanders and Gyakum*, 1980]. We report here an association between rivers and bombs. When a cyclonic system is penetrated by a river, the cyclonic center moves to be close to the position occupied by the leading edge of the river twelve hours previously and the central pressure falls. If the river then moves away from the cyclone, the central pressure rises. Based on a pilot study of pressure fall and water vapor flux convergence for two winter months, the cause of the explosive deepening appears to be latent heat liberation. This is substantiated by composite maps of seven Atlantic and seven Pacific bombs which show that the flux convergence near the bomb center has a comma cloud signature. The observed association may be useful in forecasting 12-hour direction of motion and pressure change of rapidly developing cyclonic systems; the incorporation of better moisture data into numerical forecasting models may be the reason for the reported increase of skill in the prediction of bombs in recent years.

Introduction

Water vapor fluxes have been computed from wind velocity and relative humidity analyses at pressure levels of 1000, 925, 850, 700, 500, 400 and 300 hPa drawn up every 12 hours by the European Center for Medium-Range Weather Forecasts (ECMWF) [*Newell et al.*, 1992]. A climatology of the high-frequency filtered (periods shorter than three days) vapor flux for July 1991 and January 1992 has been presented elsewhere [*Newell and Zhu*, 1994]. Regions of maximum magnitude of the high frequency flux lie over the northern and southern oceans. In an early text on weather forecasting, written at the time when routine analyses of moisture on isentropic charts were made, *Starr* [1942] pointed out that "moisture emanating from the Gulf of Mexico may flow northward usually in the form of a rather narrow tongue situated above a surface cold front so that the forward portion of the moist outbreak is found in the vicinity of a cyclonic disturbance at the ground." The mean positions of the rivers correspond closely to the cold fronts on climatological maps [*Haurwitz and Austin*, 1944] *Harrold* [1973] described a relatively narrow airflow that conveyed large quantities of heat, moisture and westerly momentum poleward and upward as a warm conveyor belt (WCB) and some work (reviewed recently by *Browning*, 1990] has been done on analysis of these features.

We recently applied the rivers concept to the problem of the interpretation of ice core data, arguing that changes in the sources of the rivers, which ranged from the sub-tropical Atlantic to the North Pacific, could be responsible for some of the changes in the observed $\delta^{18}O$ from Greenland cores. We examine here a second possible application, namely that rivers could be a useful phenomenon to monitor in forecasting the motion and development of rapidly deepening cyclones over the ocean. One piece of evidence for a connection between the rivers and cyclonic development is that in the Northern Hemisphere the geographical distribution of rivers we reported previously for the cold season [*Newell and Zhu*, 1994] is similar to that for rapidly developing cyclones found by *Sanders and Gyakum* [1980] which they termed bombs. The purpose of the present note is to explore this association further, to comment on the possible reasons for the association and in the process remark further on the possible origin of the rivers.

Paper number 94GL01710
0094-8534/94/94GL-01710$03.00

Procedures and Results

A video of the horizontal moisture flux ($\underset{\sim}{Q} = g^{-1} \int_0^{p_0} \underset{\sim}{v} q \, dp$), where $\underset{\sim}{v}$ is wind velocity, q is specific humidity, p_0 is sea level pressure and g the gravitational acceleration) has been produced for each oceanic region separately (North Atlantic and Pacific, South Atlantic, Pacific and Indian Ocean) using daily data at noon and midnight Universal Coordinated Time (UTC) from the analyses of the ECMWF. The videos also contain surface pressure in color. The videos suggest that water vapor is peeled off the tropical belt of high moisture at about 15-20° latitude and often exists in filamentary form for several days before becoming associated directly with a low pressure system. When this association is with a deepening system, as judged from analyzed sea level pressure maps, the deepening accelerates and the low pressure center moves to the position of the leading edge of the river about 12 hours earlier. This sequence is often repeated for several 12 hour periods consecutively. When the river moves away from the cyclone, usually to the east, the central pressure remains constant or rises. Because of this phase lag we display the contemporary pressure field with the moisture flux vectors for 12 hours earlier. During January 1992 there were a total of 14 bombs over the northern hemisphere oceans, 7 in the Pacific region between 140°E and 120°W, and 7 in the Atlantic region between 80°W and 20°E, all of which were associated with rivers. There were five in the Southern Hemisphere, three in the South Pacific, and two in the South Atlantic in July 1991, the corresponding winter month. The definition of a bomb is that given by *Sanders and Gyakum* [1980], which is that pressure fall exceeds one Bergeron, or 24 sin ϕ /sin 60° hPa in 24 hours, where ϕ is latitude; a table appears in a paper by *Sanders* [1987]. An example of a case where the low pressure center moved to be over the leading edge of a river 12 hours earlier is shown in Figure 1a-b. Table 1 contains the positions and pressures of the low pressure center and leading edges of the river for the period prior to and immediately after the first two panels of Figure 1. Figure 1c illustrates a river over the east coast of China and the

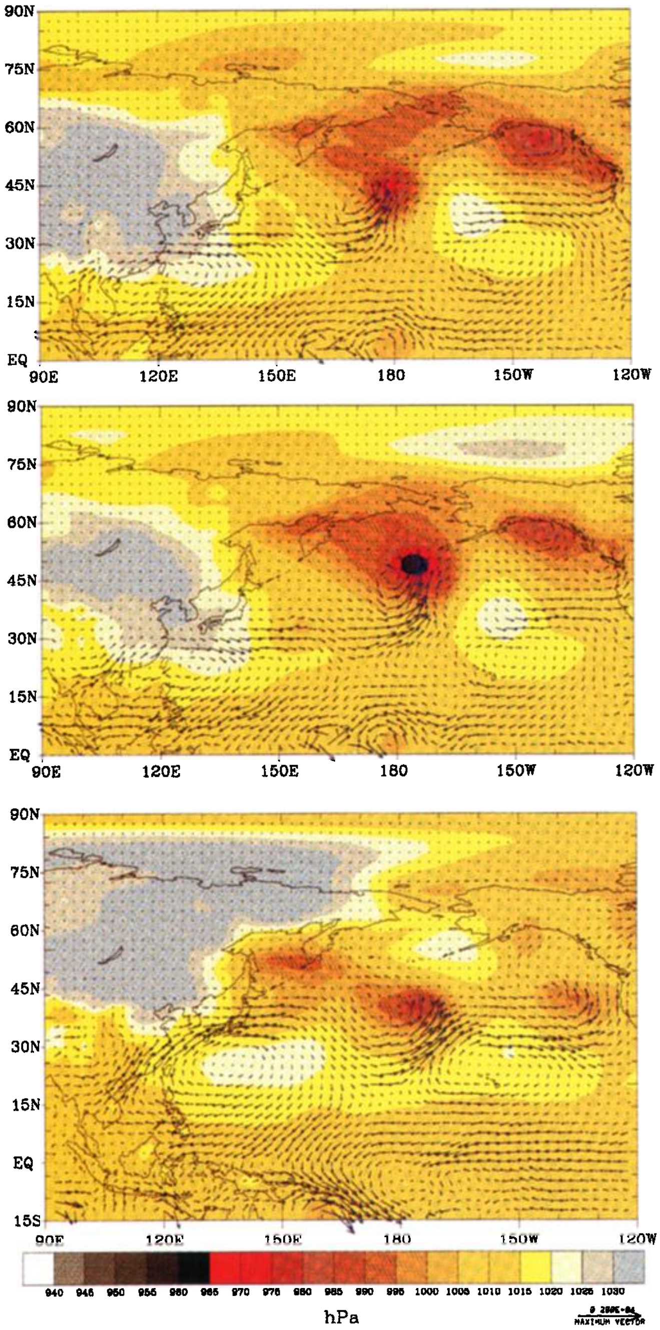

Figure 1. Surface pressure (in hPa) and integrated water vapor flux (in kg m^{-1} sec^{-1}) 12 hours previously. The largest vector near the date line in the upper panel corresponds to 1000 kg m^{-1} sec^{-1}. Upper panel (a): January 4, 1992, 00 UTC; middle (b): January 4, 1992, 12 UTC; lower (c): March 1, 1992, 00 UTC.

Sea of Japan that has not yet been incorporated into a cyclonic system. At the same time the river near the date line is seen leaving another low pressure system and moving to the east associated with increasing pressure at the low center.

The water vapor flux divergence was also calculated and mapped for each 12 hour period in January 1992 and July 1991. The maximum value close to each bomb was selected and averages of these maximum values taken for each ocean and each month. For the mid-winter months these averages are (with the number of bombs in parentheses): January, N. Atlantic - 13(7), N. Pacific - 12(7); July, S. Atlantic - 10(2), S. Pacific - 10(3). Units for the flux divergence are 10^{-4} kg H_2O m^{-2} sec^{-1}, which corresponds to a heating rate by the liberation of latent heat of about 2.7K day^{-1} if an atmospheric column 800 hPa is considered. The average of the maximum values for the North Pacific found here is then 32K day^{-1} which compares with a maximum rate of about 26K day^{-1} reported for an explosively deepening North Pacific cyclone for which a detailed heat budget was made, [*Liou and Elsberry*, 1981]; this heating is to a large degree nullified by the adiabatic cooling associated with rising motion, but it is nevertheless an important factor in the rapid deepening. The strong ascent results in strong vortex stretching and a spin-up of the low-level vorticity. The role of latent heat is to make the ascent stronger than it would otherwise be. The smaller number of bombs in the Southern Hemisphere may be an effect of limited sampling and poor spatial resolution; it is noteworthy that local pressure systems in the middle and high latitudes of the Southern Hemisphere generally have lower pressures than those in the Northern Hemisphere; in the cases studied here deepening occurs more slowly and the water vapor convergence is correspondingly lower.

A mean bomb sea level pressure map was drawn up from the data for the seven North Atlantic and the seven North Pacific bombs in January 1992; superimposed on these were the composite water vapor flux vectors and their divergence pattern for a period 12 hours prior to the pressure maps (Figure 2). In these mean maps, the bomb's central sea level pressure was used as a reference point. It is clear from Figure 2 that the regions of maximum water vapor flux convergence show good coincidence with the minimum pressures 12 hours later; their patterns bear a close resemblance to the well-known comma clouds associated with extratropical systems [see, e.g., *Bluestein*, 1993]. The mean convergence magnitude is about 7x10^{-4} kg m^{-2}sec^{-1}, which corresponds to a heating rate of about 19K day^{-1}.

In the original discussion of bombs it was found that they were consistently under-predicted by numerical models used in weather forecasting and inadequate inclusion of the bulk effect of

Table 1. Position of low pressure center (PC) and leading edge of river (LER) 12 hours earlier for cyclone with lowest pressure on 5 January 1992 at 00 UTC, together with maximum water vapor flux convergence (CONQM in 10^{-4} kg m^{-2}sec^{-1}) near low pressure center.

Press. Date 1992	Map Time UTC	Lat. (N) of PC	Long. of PC	MSL Press. hPa	Lat. (N) of LER	Long. of LER	CONQM
01/03	00	37	163E	999	37	163E	5
01/03	12	40	170E	987	40	170E	8
01/04	00	45	180	972	45	177E	13
01/04	12	48	177W	956	48	176W	15
01/05	00	52	171W	946	52	170W	11
01/05	12	54	168W	54	55	166W	3
01/06	00	55	165W	963	55	155W	2

Note that when river's leading edge passes to east of low pressure center the pressure rises.

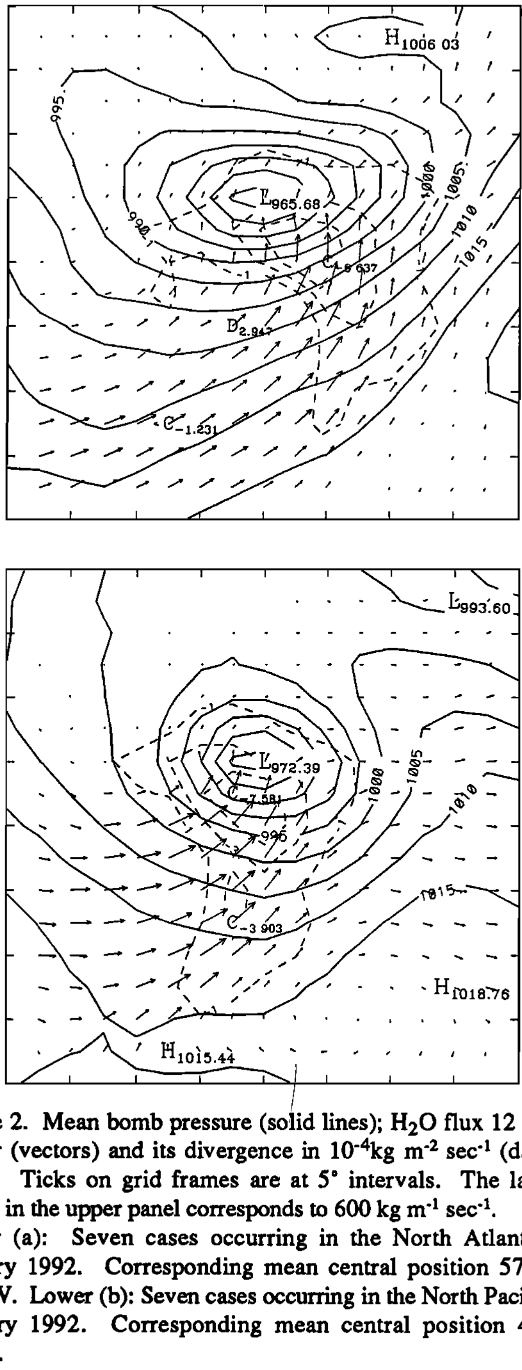

Figure 2. Mean bomb pressure (solid lines); H_2O flux 12 hours earlier (vectors) and its divergence in 10^{-4}kg m^{-2} sec^{-1} (dashed lines). Ticks on grid frames are at 5° intervals. The largest vector in the upper panel corresponds to 600 kg m^{-1} sec^{-1}.
Upper (a): Seven cases occurring in the North Atlantic in January 1992. Corresponding mean central position 57.5°N, 41.5°W. Lower (b): Seven cases occurring in the North Pacific in January 1992. Corresponding mean central position 43°N, 178°E.

cumulus convection was the suggested reason for the discrepancy [*Sanders and Gyakum*, 1980]. Other suggestions were that surface sensible and evaporative fluxes from the ocean were not properly included [*Davis and Emanuel*, 1988] and sea surface temperature gradients were involved [*Sanders*, 1986]. In one case study latent heat release computed from satellite rainfall measurements was found to be important [*Fosdick and Smith*, 1991] The filamentary structure of the water vapor enables large amounts of latent heat to be liberated over a relatively small area. It is noteworthy that the appearance of a cloud head precedes rapid cyclogenesis in the eastern North Atlantic [*Böttger et al.*, 1975]; this may be another way of identifying the leading edge of a river.

In the more recent discussion of the predictability of bombs, it appears that there has been a substantial growth of skill [*Sanders*, 1987; *Sanders and Auciello*, 1989; *Sanders*, 1992], which has been attributed to improved analysis, better model resolution and better treatment of boundary layer fluxes. All these items, plus incorporation of more satellite data on water vapor, could lead to a better definition of tropospheric rivers in the initialized fields on which the forecasts are based.

River Sources

The water vapor contained in the rivers is mostly evaporated from the ocean. One way to estimate the vapor content of rivers is therefore to estimate the surface evaporation using the so-called bulk formula. This requires knowledge of oceanic surface conditions such as wind speed, sea temperature, air temperature and relative humidity, preferably based on daily ships' reports. These estimates give the total water vapor injected over a large area which can then be divided between the convergent boundary regions at the edges of the evaporating air mass by making use of the divergent component of the wind calculated from the velocity potential in the boundary layer. From the divergent wind and specific humidity together the flux into the boundary region between air masses can be computed; this region seems to be favored for river formation. Figure 3 shows an example of the divergent wind patterns; a map of corresponding rivers appears in *Newell et al.* [1992]. Quantitative estimates of the origins of the river flows could be made if daily values of evaporation were available.

The low level divergence patterns provide one approach to the classification of boundary layer air into "air masses." Notice that the boundaries are continuous over substantial distances. In the example of Figure 3, a boundary which originates over the Central Pacific north of the equator extends eastward to South America, crosses the continent to the South Atlantic, heads southeastwards and apparently ends near Antarctica - a total distance of ~20,000 km. The low level map corresponds to a pressure level of 1000 hPa. Where the land surface is high so that the surface pressure is lower than 1000 hPa, wind and relative humidity are set to the lowest model level values in the ECMWF analysis procedure. These are liable to be different from 1000 hPa values nearby so that discontinuities may appear in the 1000 hPa field. This may be the reason for the discontinuity along the Andes west of Brazil. The scale of this division could be termed "atmospheric plate tectonics". One would anticipate that the chemical constituents in the separate plates would be different as a consequence of their differing photochemical histories. At the boundary there is local convergence, rising motion, and sometimes movement of the moisture parallel to the boundary -- to the east in the South Atlantic case considered. Other constituents originating near the surface could be transported likewise.

Concluding Comments

As a final observational point, we note that satellite-measured reflectivity at 0.36 and 0.38 μm was found to give a good description of rivers in motion [*Newell et al.*, 1992]. Just as satellite data on moisture is useful in identifying dry tongues [*Appenzeller and Davies*, 1992] so total moisture content data may be used for moist tongues [*Katsaros et al.*, 1989] and indeed has been shown to have a beneficial impact on ECMWF forecasts [*Illari*, 1989].

As a possible practical application we suggest the following procedure: use computed water vapor flux vectors and ultraviolet or other satellite images (with looping) to identify moving rivers; use the leading edges of the rivers to predict cyclonic center movement and the flux convergence to predict possible intensity

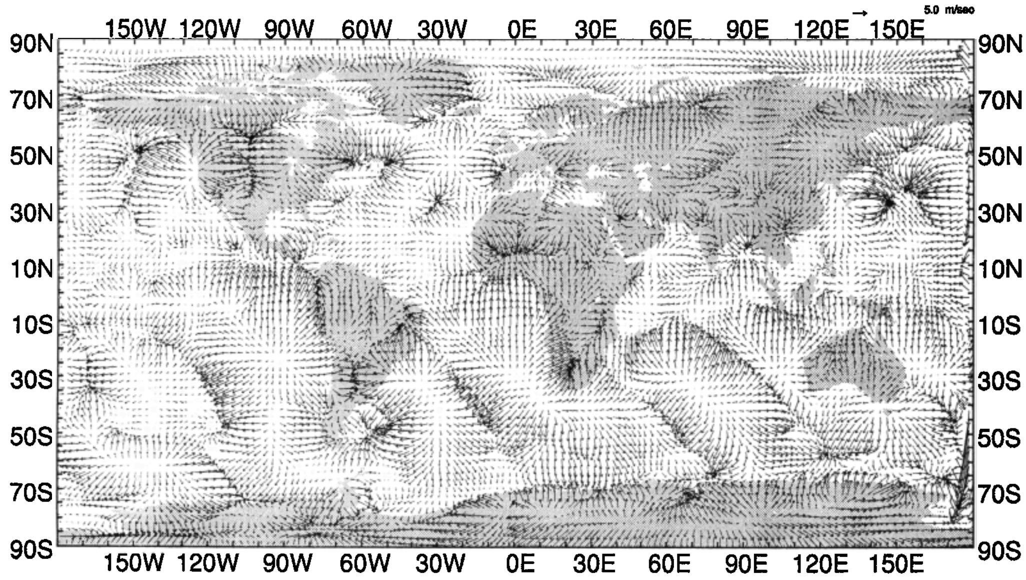

Figure 3. Example of surface divergent component for October 13, 1991.

changes 12 hours later; carry out for one winter set of data to see how much of the variability between the traditional forecast and this type of forecast could be due to the specific use of the rivers concept. The basic importance of studies of water vapor transport have been widely acknowledged [*Chahine*, 1992]; their practical use would be valuable.

Acknowledgments. We thank the National Science Foundation Climate Dynamics Program for their support under Grant ATM 9106902. The views expressed herein are those of the authors and do not necessarily reflect the views of NSF. We also thank ECMWF for use of their gridpoint data. We thank William Heres, Dorothy Frank, and Susan Midlarsky for their assistance. We appreciate the constructive remarks of the anonymous reviewers.

References

Appenzeller, C. and H. C. Davies, Structure of stratospheric intrusion into the troposphere, *Nature*, *358*, 570-572, 1992.

Bluestein, H. B., *Synoptic-Dynamic Meteorology in Midlatitudes: Volume II. Observations and Theory of Weather Systems*, Oxford University Press, New York, 148-155, 1993.

Böttger, H., M. Eckardt, and U. Katergiannakis, Forecasting extratropical storms with hurricane intensity using satellite information, *J. Appl. Meteor.*, *14*, 1259-1265, 1975.

Browning, K. A., Organization of clouds and precipitation in extratropical cyclones, in *Extratropical Cyclones - The Erik Palmén Memorial Volume* (eds. Newton, C. and Holopainen, E.O.) Amer. Meteor. Soc., Boston, 129-153, 1990.

Chahine, M. T., The hydrological cycle and its influence on climate, *Nature*, 359, 373-380, 1992.

Davis, C. A. and K. A. Emanuel, Observational evidence for the influence of surface heat fluxes on rapid maritime cyclogenesis, *Mon. Wea. Rev. 116*, 2649-2659, 1988.

Fosdick, E. K. and P. J. Smith, Latent heat release in an extratropical cyclone that developed explosively over the southeastern United States, *Mon. Wea. Rev.*, *119*, 193-207, 1991.

Harrold, T. W., Mechanisms influencing the distribution of precipitation within baroclinic disturbances, *Q. J. Roy. Met. Soc.*, *99*, 232-251, 1973.

Haurwitz, B. and J. M. Austin, *Climatology*, McGraw-Hill, N.Y., 410 pp., 1944.

Illari, L., The quality of satellite precipitable water content data and their impact on analyzed moisture fields, *Tellus*, *41A*, 319-337, 1989.

Katsaros, K. B., I. Bhatti, L. A. McMurdie, and G. W. Petty, Identification of atmospheric fronts over the ocean with microwave measurements of water vapor and rain, *Weather and Forecasting*, *4*, 449-460, 1989.

Liou, C.-S. and R. L. Elsberry, Heat budgets of analyses and forecasts of an explosively deepening maritime cyclone, *Mon. Wea. Rev.*, *115*, 1809-1824, 1987.

Newell, R.E. and Y. Zhu, Tropospheric rivers: a one-year record and a possible application to ice core data, *Geophys. Res. Lett.*, *21*, 113-116. 1994.

Newell, R. E., N. E. Newell, Y. Zhu, and C. Scott, Tropospheric rivers? - A pilot study, *Geophys. Res. Lett.*, *19*, 2401-2404, 1992.

Sanders, F., Explosive cyclogenesis in the west-central North Atlantic ocean, 1981-84. Part 1: Composite structure and mean behavior, *Mon. Wea. Rev.*, *114*, 1781-1794, 1986.

Sanders, F., Skill of NMC operational dynamical models in prediction of explosive cyclogenesis, *Weather and Forecasting*, *2*, 322-336, 1987.

Sanders, F., Skill of operational dynamical models in cyclone prediction out to five-days range during ERICA, *Weather and Forecasting*, *7*, 3-25, 1992.

Sanders, F. and J. R. Gyakum, Synoptic-dynamic climatology of the "bomb", *Mon. Wea. Rev.*, *108*, 1589-1606, 1980.

Sanders, F. and E. P. Auciello, Skill in prediction of explosive cyclogenesis over the Western North Atlantic Ocean, 1987/88: A forecast checklist and NMC dynamical models, *Weather and Forecasting*, *4*, 157-172, 1989.

Starr, V. P. *Basic Principles of Weather Forecasting*, Harper and Bros. Publ., N.Y., p. 55, 1942.

Y. Zhu and R.E. Newell, Department of Earth, Atmospheric and Planetary Sciences, Room 54-1824, Massachusetts Institute of Technology, Cambridge, MA 02139. (e-mail: newell@newell1.mit.edu)

(Received: February 21, 1994; Revised: May 18, 1994; Accepted: June 27, 1994)