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Northern Adriatic Response to a Wintertime Bora Wind Event

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During winters, the northern Adriatic Sea experiences frequent, intense cold-air outbreaks that drive oceanic heat loss and imprint complex but predictable patterns in the underlying waters. This strong, reliable forcing makes this region an excellent laboratory for observational and numerical investigations of air-sea interaction, sediment and biological transport, and mesoscale wind-driven flow.

Narrow sea surface wind jets, commonly known as "bora," occur when cold, dry air spills through gaps in the Dinaric Alps (the mountain range situated along the Adriatic's eastern shore). Horizontal variations in these winds drive a mosaic of oceanic cyclonic and anticyclonic cells that draw coastal waters far into the middle basin. The winds also drive intense cooling and overturning, producing a sharp front between dense, vertically homogenous waters (North Adriatic Dense Water, or NAdDW) in the north and the lighter (colder, fresher), stratified waters of the Po River plume. Once subducted at the front, the NAdDW flows southward in a narrow vein following the isobaths (contours of constant depth) of the Italian coast. In addition to governing the basin's general circulation, these processes also influence sediment transport and modulate biological and optical variability.

Building on a long history of scientific investigations [*Cushman-Roisin et al.*, 2001], scientists from several countries conducted intensive multi-disciplinary studies of the northern and central Adriatic during 2002 and 2003. The U.S. Office of Naval Research, NATO, the Croatian Ministry of Science and Technology, and the Italian Ministry of the Environment and Ministry of Universities and Research supported large observational and numerical modeling programs.

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The Dynamics of Localized Currents and Eddy Variability in the Adriatic (DOLCEVITA) program investigated the mesoscale and sub-mesocale response to strong atmospheric and riverine forcing within the context of large-scale circulation studies conducted by the Adriatic Circulation, West Istria, and East Adriatic Coastal Experiments (ACE, WISE, EACE). European Margin Strata Formation (EUROSTRATAFORM) investigators worked to understand how sediment transport processes produce observed deposition patterns off the Po and Apennine river systems.

The Mucilage Adriatico-Tirreno (MAT) project conducted monthly physical and biological measurements along three northern Adriatic sections, while other studies focused on bottom-layer hypoxia. The Adriatic Sea Integrated Coastal Area and River Basin Management System (ADRICOSM) pilot project employed measurements and extensive modeling to establish a near-real-time forecast system. High-resolution ocean and atmosphere simulations conducted by the U.S. Naval Research Laboratory supported many of the projects.

The combination of these large, multi-investigator programs and numerous smaller efforts provide a unique, multi-faceted view of the northern Adriatic. Measurements included half-year moored time series at several locations, extensive surface drifter deployments, coastal high-frequency radars, regular hydrographic surveys, high-resolution towed profiler surveys during bora events, microstructure profiles, remote sensing (advanced very high resolution radiometer (AVHRR), ocean color, and synthetic aperture radar) and meteorological sampling conducted from midbasin gas drilling platforms, moorings, and shore stations (Figure 1a).

Most significant, this observational activity documented, with an unprecedented level of detail, the response of the northern Adriatic to a bora event. Many of the projects intentionally focused on the response to bora, and the suite of measurements and numerical simulations provides physical, meteorological, biological, optical, and sediment transport perspectives.

The February Bora

A bora event from 11–19 February 2003 characterizes the scope of these efforts. A synthetic aperture radar (SAR) image taken on 12 February 2003 (Figure 1b) reveals the swift wind bands of the bora (red) interleaved with relatively quiescent areas. Generally, the highest winds were on the eastern side of the Adriatic, although bora jets often maintain their shape and intensity across most of the northern basin. Both SAR and 4-km Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS™) model winds (Figure 1b) depict narrow, sea surface wind jets extending from the eastern boundary at the Gulf of Trieste, Senj, and Sibenik. In contrast, surface winds close to the Italian coast were weaker and less organized.

At Zadar (on the Croatian coast), high-velocity bora flow extended from the surface to 1200 m, with peak speeds of 15 m s^{-1} at 200 m. Wind speed then weakened with height to 2500 m, and increased above this level. Surface winds at Zadar averaged 11 m s^{-1} between 11and 14 February, with -2°C mean air temperature during this period. After a brief slackening, Zadar winds strengthened through 19 February and subsided shortly thereafter. As the strong downslope winds associated with the bora penetrated to the surface, an unstable boundary layer developed due to the approximately 10°C cooler air overlying the relatively warmer sea. This drove strong oceanic heat loss and produced both oceanic and atmospheric convective mixing.

This suite of measurements allows a comparison of the February event with a canonical bora. Although the February bora produced only moderate winds, it continued for an extraordinarily long period, exceeding 9 days. Wintertime bora events typically span a single day, although in rare circumstances they may extend as long as 10 days [*Penzar et al.*, 2001]. On 12 February, R/V *Knorr* recorded wind speeds in excess of 20 m s^{-1} off Senj, suggesting that the 11–19 February bora was of moderate intensity relative to the historical maximum (60 m s^{-1} gusts). The statistical quantification of bora characteristics, including characterization of atmospheric boundary layer evolution, is a novel feature of this research.

Ocean Circulation and Mesoscale Response

Strong wind and buoyancy forcing produced by the 11–19 February event drove distinct circu-

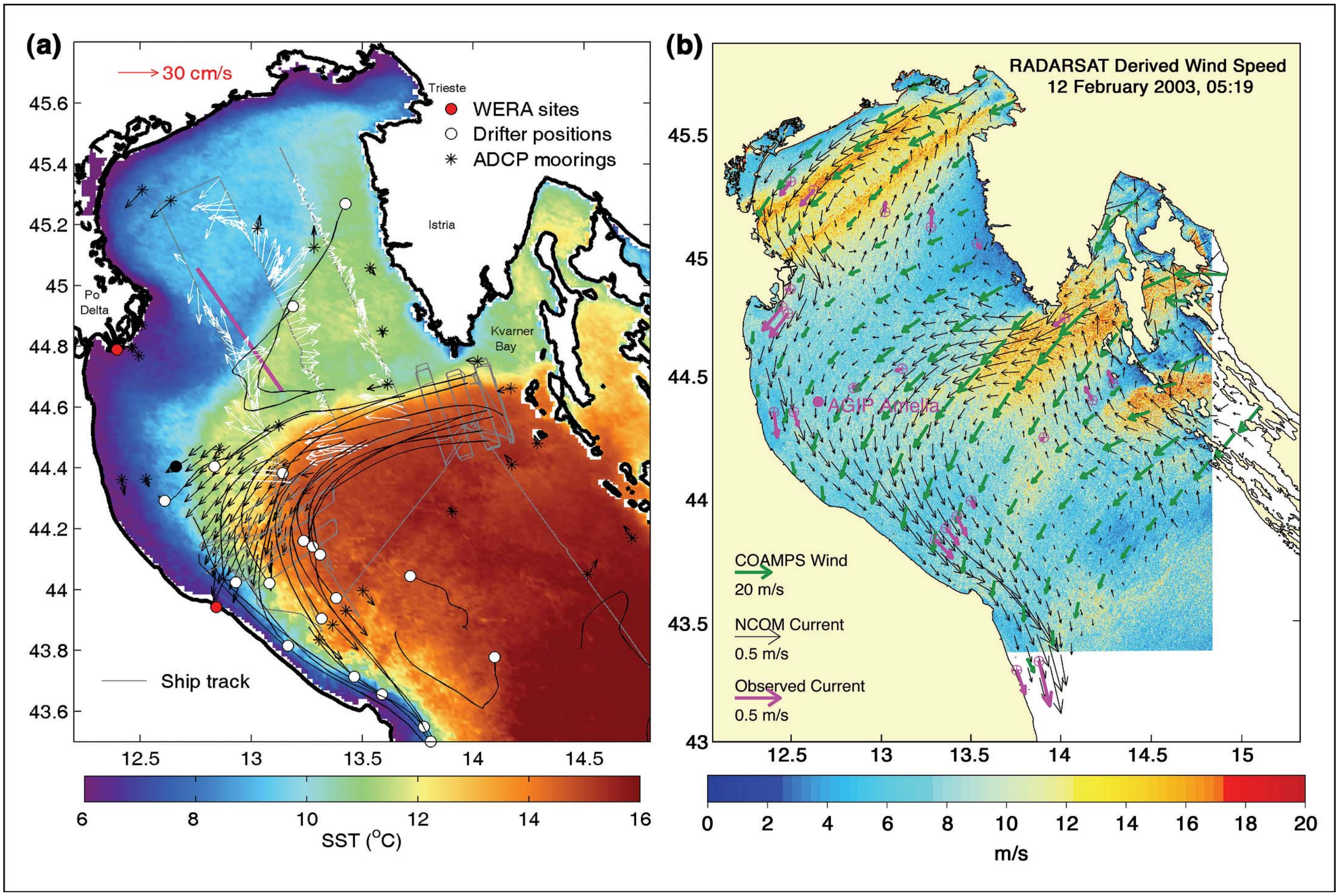

Fig. 1. (a) Nine-day mean AVHRR sea surface temperature with current vectors and drifter tracks illustrating many of the observations collected during the 11–19 February 2003 bora. Gray lines mark part of the R/V Knorr *cruise track, with white arrows showing 12-m velocity measured from the shipboard acoustic Doppler current profiler (ADCP). Black lines trace drifter tracks, with white circles marking locations at the end of this period. Black asterisks and arrows indicate near-surface, 9-day mean velocities measured by bottom-mounted ADCPs and current meter moorings. The field of black arrows between 44°N and 44.4° N depicts the 9-day mean surface velocity field measured by two Wave Radar (WERA) high-frequency coastal radars (located on the Italian coast at the red circles). A black dot marks the AGIP Amelia platform, and a magenta line marks the location of the section shown in Figure 2. All velocity vectors are scaled according to the red vector in the upper left corner. (b) RADARSAT wind speed (color) on 12 February with 48-hour average (12–14 February) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) wind vectors (black), near-surface (5 m) Navy Coastal Ocean Model (NCOM) currents (green), and measured currents (magenta). A magenta circle marks the AGIP Amelia platform. The 4 km (1 km) COAMPS (NCOM) vectors are shown at 16 km (6 km) intervals for clarity. Large-scale bora winds from the northeast are intensified by coastal topographic gaps into sea surface wind jets that can extend across most of the Adriatic.*

lation patterns in the northern Adriatic. Intense wind stress curl associated with the bora jets extending from Trieste and Senj (Figure 1b) drew a cold, fresh plume of Po River water across the northern basin, traversing beneath the wind minimum nearly to the Istrian coast (Figure 1a). The plume separated a northern cyclonic gyre from anticyclonic circulation to the south (Figure 1a).

Another front extended westward from the southern tip of Istria, separating the anticyclonic gyre (cold, fresh waters) from a large cyclonic gyre (warmer, more saline waters) to the south. The West Adriatic Current (WAC) formed the western side of this cyclonic gyre, and its transport was intensified threefold by this bora event. Temperature-salinity contrasts across the Istria front largely compensated, producing only weak density gradients. Nonetheless, strong easterly winds drove downwind (westward) currents along the front. With the exception of those areas influenced by riverine discharge, strong wind-driven mechanical mixing and convective overturning ensured that the northern Adriatic remained vertically homogenous. Lateral variations in winds and net surface heat flux, modulated by the presence of surface-trapped, buoyant river discharge, produced horizontal variations in temperature, salinity, and stratification.

Small-scale variations in atmospheric forcing thus influenced dense water formation by imparting spatial structure through wind mixing and net heat flux and by generating mesoscale and sub-mesoscale features (such as the Po plume extension). Such features, in turn, advectively altered stratification and modulated the effects of atmospheric forcing. The large suite of concurrent physical measurements provides a detailed, four-dimensional (spatial structure and temporal evolution) perspective that will facilitate upcoming dynamical investigations.

Biological and Optical Response

Po River inflow controls wintertime optical variability in the northern basin by influencing circulation and stratification and providing a continuous source of nutrients, suspended particulates, and colored dissolved organic matter (Figure 2). Fresh plume waters exhibit a near-surface nutrient maximum, enhanced phytoplankton activity, and elevated suspended particulate concentrations dominated by small, slowly sinking inorganic material. These biological and optical properties migrated with the plume as bora forcing drew it eastward over the course of the event, with phytoplankton maxima typically occurring near the outer boundaries.

Forced by much weaker riverine sources, the eastern basin exhibits reduced nutrient, particulate, and phytoplankton concentrations. Biological and optical properties trace the origins of the waters to either side of the Istria front. Low chlorophyll concentrations and elevated, vertically uniform suspended particulate concentrations characterize the cold, fresh waters of the front's north side.

The absence of a near-bottom suspended particulate maximum suggests that these high concentrations were not produced by local resuspension, but may instead have been advected from the region surrounding the coastal islands to the east and southeast. The physical and bio-optical variables were highly correlated on either side of the front, indicating that the physical processes dominated the distributions of the bio-optical properties.

Sediment Transport

Bora winds affect sediment distribution by enhancing waves and strengthening currents. The Po River in the north and small, episodically flooding rivers that drain the Apennine Mountains to the Adriatic central basin are the major sources of sediment. Though most Po River sediment appears to settle on the bed within hours of reaching the coastal sea, much is redistributed before ultimately being buried. Transport within the bottom boundary layer (~10 m thick) usually dominates sediment flux. Although sediment flux variability is high, on average bora events drive sediment southward along the shelf with little across-shelf transport.

The 11–19 February bora produced sediment transport patterns consistent with larger bora events on record. Elevated sediment concentrations measured at sites along the Italian coast are associated with waves generated during bora events (Figure 3). Wave heights on the Po delta reached approximately 1.1 m, with peak suspended-sediment concentrations approaching 0.5 g/L at 30 cm above bottom (Figure 3).

Between 15 and 19 February, net sediment flux on the Po delta was dominated by a 22-hour period when the currents were consistently southward, along the bathymetry. Although sediment concentrations were equally high during the rest of the bora period, fluctuating current direction produced little net flux.

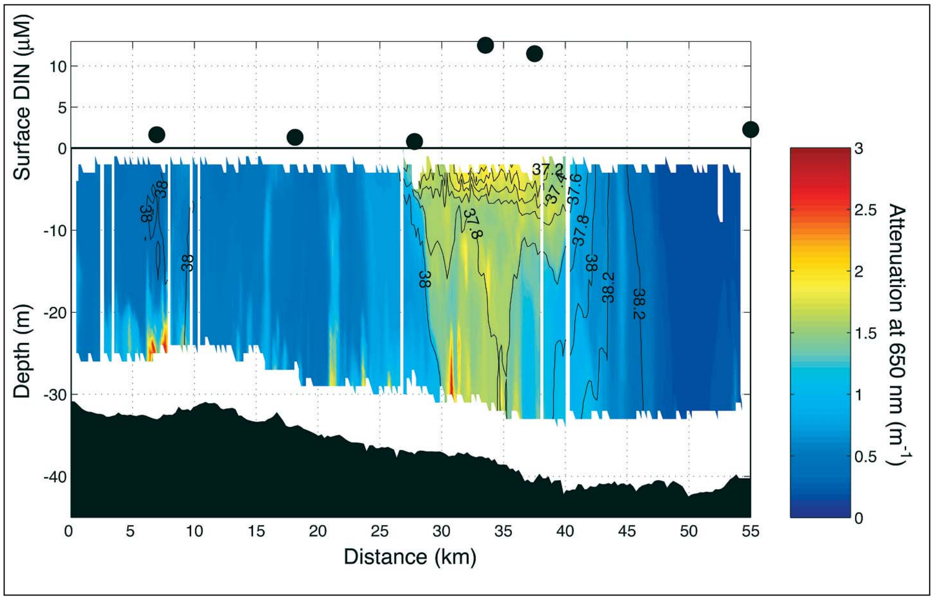

Fig. 2. Salinity (contours) and 650-nm beam attenuation (color) from a high-resolution towed profiler section across the Po plume (20 February 2003, magenta line in Figure 1a). Black dots (top panel) mark surface dissolved inorganic nitrogen (DIN; nitrate + nitrite + ammonium) measured from bucket samples along the survey track.

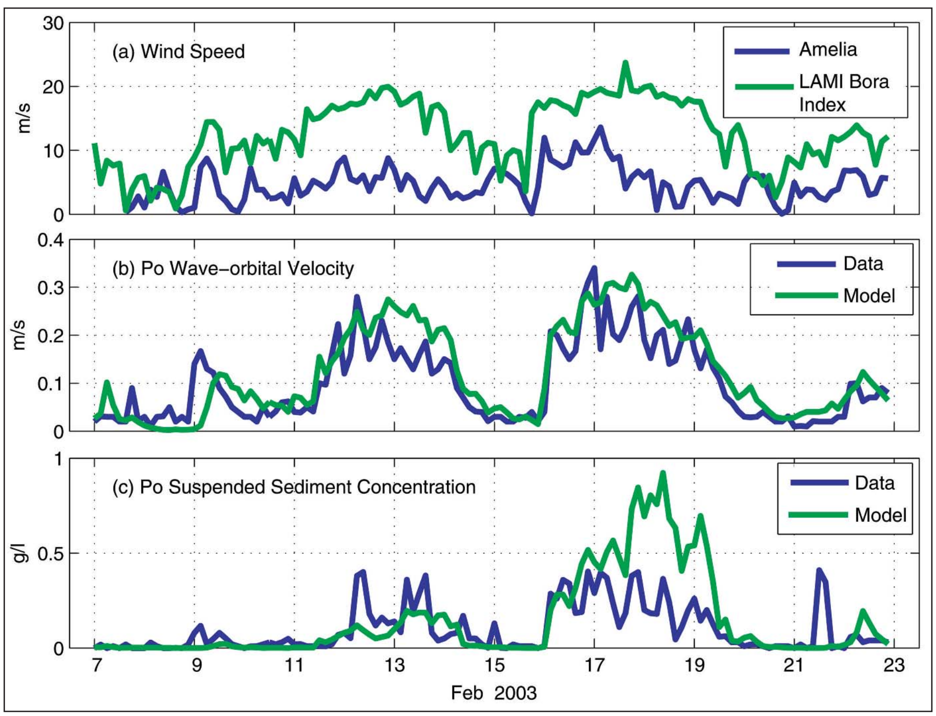

Fig. 3. (a) Maximum wind speed in the bora jet of Kvarner Bay (modeled) and maximum observed wind speed at the AGIP platform Amelia (see Figure 1a for location). (b) Wave orbital velocity from the Po 12-m tripod data and from the Simulating Waves Nearshore (SWAN) wave model. (c) Suspended sediment concentrations from the Po 12-m tripod data and from the Regional Ocean Modeling System (ROMS) sediment transport model.

Synthesis Provided by Numerical Results

Several groups conducted high-resolution ocean (2 km), atmosphere (4 km), and sediment transport simulations that provide critical tools for assessing Adriatic dynamics. Counter-rotating gyres, cyclonic in the far north and anticyclonic nestled against the Istrian peninsula, are a generic response to bora forcing that strongly affects the biology and sediment (Figure 1b). The gyres help maintain frontal boundaries and drive cross-basin transport. The WAC acts as a conduit for riverine waters and sediment. A paucity of observations impedes the understanding of small-scale circulation along the Croatian coast, although these features may participate in wintertime dense water formation. The cyclonic gyre located off the Po mouth transports a small, but noticeable fraction of sediment to the northeast (not shown).

Modeled wave orbital velocities and sediment concentrations capture the dynamics of bora-induced transport (Figures 3b and 3c). Model results for the 9-month winter period show that several mechanisms contribute to southward alongshore sediment transport in a narrow coastal band in the western Adriatic. These include buoyancy-induced coastal flow associated with river-derived sediments, wind-enhanced coastal flow coupled with wave-resuspended sediments under both strong winds, and persistent counter-clockwise flow driven by basin-scale estuarine circulation and mean wind stresses. In these simulations, these mechanisms produced depositional patterns similar to the observed late Holocene deposits, suggesting that event scale models can provide insight about sedimentation on geologic timescales.

The unprecedented suite of research activities that focused on the Adriatic in winter 2003 provided a multi-faceted view of bora events and the resulting oceanic response. Observational and numerical efforts spanned a broad range of temporal and spatial scales, providing a "four-dimensional" (space and time) depiction of bora response that will facilitate detailed dynamical investigations of response to small-scale wind forcing, dense water formation, and Adriatic general circulation. Likewise, multi-disciplinary measurements and modeling promise to characterize the biological and sediment response to bora-induced dynamics.

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The Earth Sciences, Human Well-Being, and the Reduction of Global Poverty

PAGES 157, 164–165

Poverty is not solely a social or political matter, nor is it caused simply by population pressures as Thomas Malthus postulated in 1798. A new understanding of poverty is emerging in which natural and environmental drivers, together with social, political, and demographic causes, underpin livelihoods. The Earth sciences, therefore, play a critical role in identifying the deep causes of human suffering and in identifying solutions.

The State of the Planet: Why Are So Many So Poor?

For far too many, the state of human well-being is bleak. Around one in six human beings—1 billion people—live in extreme poverty, struggling to survive on less than $1 a day; another one sixth of humanity ekes out existence on $2 per day (U.N. Development Programme (UNDP) Human Development Report, 2004; http://hdr.undp.org/2004/). The extreme poor lack all normal attributes of a decent, dignified life: adequate food, housing, sanitation, health care, education, and employment. Some 800 million people lack sufficient nourishment almost every day. It stunts their mental and physical development and shortens their lives, making them susceptible to common illnesses that attack their hunger-weakened bodies. Poor nutrition in mothers and infants is the leading cause of reduced disability-adjusted life years in poor countries [*Economist,* 2004].

By J. C. Mutter

Poverty worldwide claims 30,000 lives every day—one life lost about every 3 seconds—and in places like Sub-Saharan Africa, the situation worsens daily.

How can our world be this way? Population pressures, as Malthus described, surely make a difference. In areas of high rural population density, farm households tend to be extremely poor, and landless rural peasants are even poorer. Yet some places, like Japan, also have low land areas per person and are rich, while other places, like Bolivia, have large land areas per rural household and are extremely poor.

Governance and political institutions matter a lot, as seen in the striking differences between North and South Korea, but countries in extreme poverty lack the resources to combat basic causes of hunger and illness and cannot simply "govern" themselves out of poverty.

The root causes of poverty are complex, involving a suite of time-variable determinants, contingent influences, and internal feedbacks, many of which are location-specific. Economists and other social scientists have sought to understand the basic causes of, and solutions

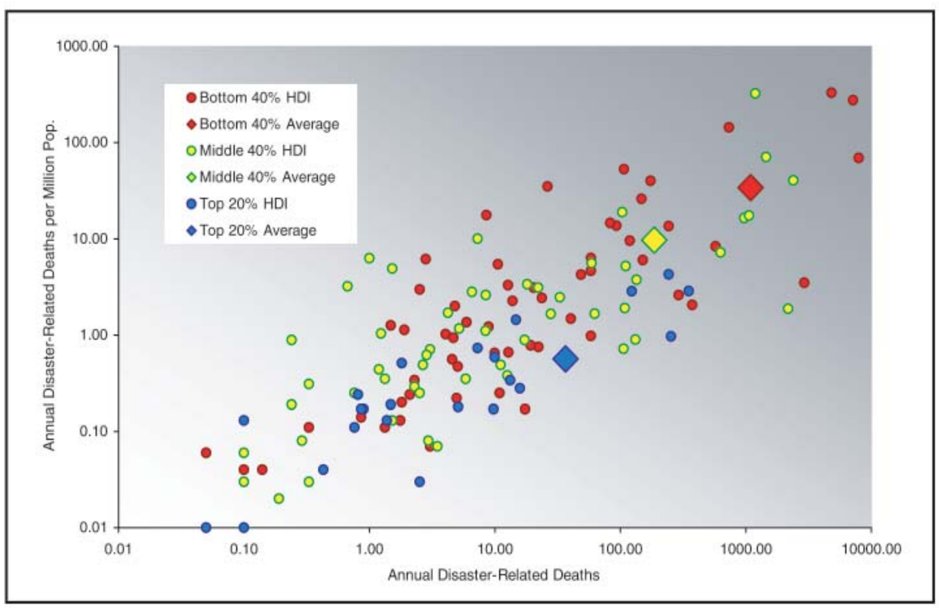

Fig. 1. Average annual death toll for all hazards against the death toll relative to population, 1980–2000. Highly impacted countries are in the upper right where many deaths occur, and those deaths are in high proportion to population. Countries are colored with the Human Development Index (HDI) that combines indexes of per capital income with health status (longevity) plus a measure of educational opportunities. A simple average is included. While there is a great deal of spread indicating that a variety of influences are important, there is a clear relationship between human development and mortality risk from natural hazards.