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Ocean Thermal Structure Monitoring Could Aid in the Intensity Forecast of Tropical Cyclones

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Accurate prediction of the track and intensity of tropical cyclones is highly important for planning the evacuation of densely populated coastal areas and for impact assessment. Though forecasts of Atlantic hurricane tracks have improved greatly during recent years, large errors in intensity forecasts still remain. Dynamical and statistical models are currently being used, with a different range of success, to predict the location of tropical cyclone intensity changes. Statistical prediction models attempt to quantify the relationship between tropical cyclone intensification and variables that can be estimated or observed in real time.

Some examples of these variables, referred to as predictors, are initial maximum wind speed, wind shear, latitude of the tropical cyclones, and sea surface temperature (SST). The subsurface ocean thermal structure is also being considered as a predictor among several other thermodynamic variables that could further enhance our knowledge of the role of the ocean in tropical cyclone intensification.

Results from a methodology for estimating the oceanic tropical cyclone heat potential (TCHP) are now being used to aid in the investigation of intensity changes in tropical cyclones, and to improve current models for operational prediction. Global estimates of this parameter are posted daily at www.aoml.noaa.gov/phod/cyclone/data (Figure 1).

A necessary condition for the genesis of tropical cyclones is that the sea surface temperature be above approximately 26°C. Subsequent intensification involves a combination of different favorable atmospheric conditions such as low vertical wind shear, leading to good outflow aloft and inflow in the near-surface boundary layer. As a result, inflow conditions in the near-surface layer are enhanced. As the tropical cyclone develops and as this process continues over the scale of the tropical cyclone, the upper ocean provides heat to the atmospheric boundary layer. This scenario assumes that the upper ocean thermal structure only plays a marginal role in tropical cyclone intensification. However, after a series of events in which tropical cyclones suddenly intensified when passing over features with a deep upper ocean mixed layer, it is now hypothesized that upper ocean thermal structure may play a more important role.

The thickness of the upper ocean layer from the sea surface to the depth of the 26°C isotherm is only a few tens of meters in most of the tropical regions. A passing tropical cyclone draws energy from these warm waters and mixes them with the cooler waters below. This creates upwelling; the depth of the base of the mixed layer is raised, and the temperature of the surface waters is subsequently lowered. These cooler waters now provide less energy to the tropical cyclones, most likely slowing the rate of intensification. On the other hand, the depth of the 26°C isotherm in the core of warm currents (such as the Loop Current in the Gulf of Mexico) and warm anticyclonic rings may reach more than a hundred meters. This type of condition has values of thermal energy that are usually several times larger than those associated with the genesis and sustainability of a tropical cyclone, and it is found in most regions where tropical cyclones occur.

Understanding the role of these warm features in the intensification of hurricanes in the tropical North Atlantic is an ongoing research topic that is still at an early stage. Preliminary results have shown their importance in the sudden intensification of hurricanes

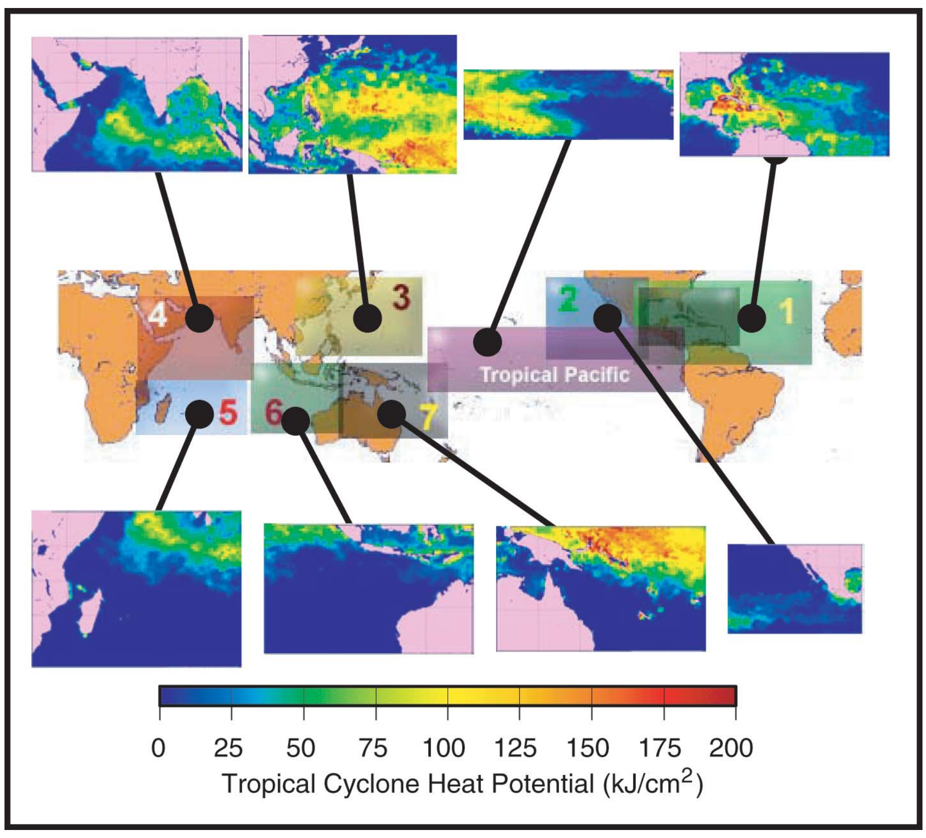

Fig. 1. NOAA's Atlantic Oceanographic and Meteorological Laboratory provides daily estimates of tropical cyclone heat potential (TCHP) for the seven basins where such storms occur and of upper ocean heat content for the tropical Pacific Ocean. The fields for 23 September 2003 are shown here. Areas in yellow and red denote regions with higher values of TCHP.

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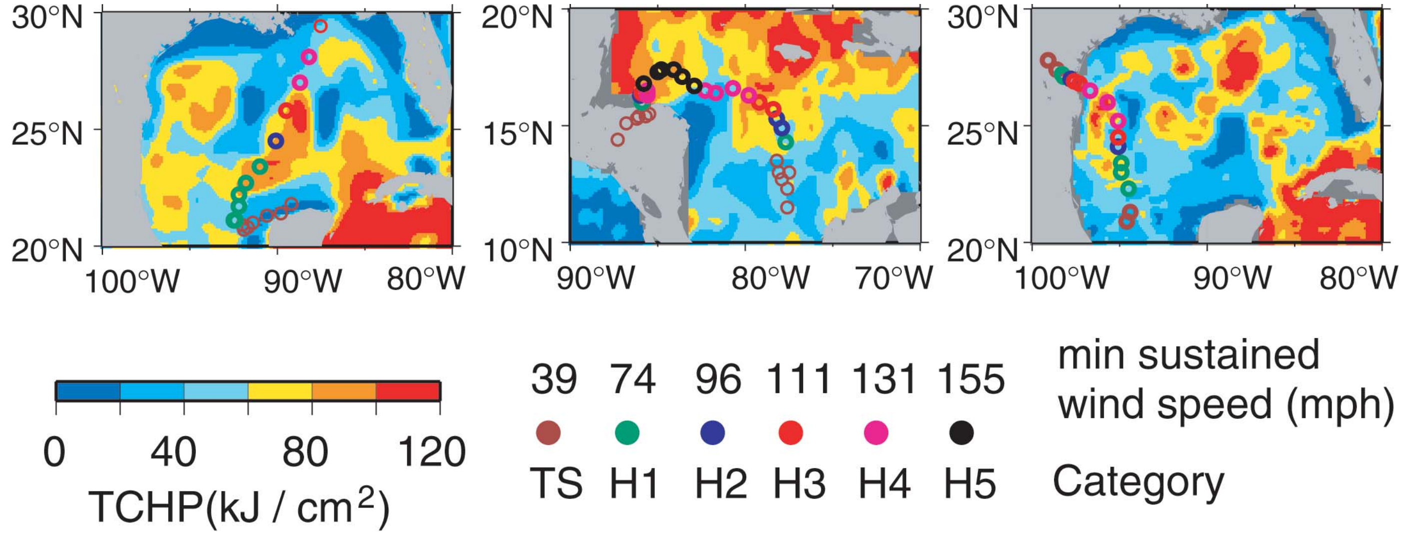

Fig. 2. Tropical cyclone heat potential (TCHP) for three hurricanes: Opal in 1995 (left), Mitch in 1998 (center), and Bret in 1999 (right). The circles on this and Figure 3 correspond to the location of the tropical cyclones at intervals of ~6 hr; the colors denote intensity.

in the Gulf of Mexico [*Shay et al.*, 2000]. For example, in September 1995, Hurricane Opal suddenly intensified when passing over a warm ring that had gone undetected by the sea surface temperature derived from the Advanced Very High Resolution Radiometer (AVHRR) imagery. In August 1999, Hurricane Bret also traveled over two warm features in the Gulf of Mexico, and it intensified each time. Since then, the monitoring of the upper ocean thermal structure has become a key element in understanding and predicting sudden tropical cyclone intensification.

Remote Monitoring of the Upper Ocean Thermal Structure

Two key problems need to be addressed: the location of these warm features and an estimate of their vertical thermal structure. These warm features, such as rings and eddies, have warmer waters than their surrounding waters, and their isotherms deepen toward their centers. This translates into a large horizontal temperature gradient at or near the surface, and large sea-height anomaly values toward their centers.

Unfortunately, sea surface temperature is not always a good proxy for identifying these warm features, since the thermal contrast at the surface is sometimes weak or does not always exist, particularly during the summer months. This situation severely limits the value of remote sensing procedures for identifying warm rings from sea surface temperature in certain regions, which is already constrained by the cloud coverage (as for AVHRR data), or lower spatial resolution (as in the case of the Tropical Rainfall Measuring Mission Microwave Imager (TMI) data). On the other hand, satellite altimetry provides global observations of the sea surface height anomaly, a parameter that allows identification of the location and estimation of the vertical thermal structure of these warm features.

Depending on many factors, such as the vertical stratification and the dynamic processes involved, the relationship between selected isotherms (such as the depth of the 20°C isotherm, which usually lies within the thermocline waters in most tropical regions) and the sea surface height can be readily estimated from the altimeter-derived sea height anomalies, in combination with in situ and climatological hydrographic observations. In many regions, these estimates were confirmed to be adequate for the purpose of describing the main temperature features of the upper ocean.

In general, and as a first approximation, variations in the depth of the main thermocline can be associated with variations in the sea height anomaly field, where the sea height anomaly is the value of the sea surface height at a fixed location with respect to a mean value in that same location. Given the strong relationship that exists between the depth of the upper ocean mixed layer (with water temperatures generally above 26°C) and tropical cyclone genesis, it is therefore rational to address the issue of tropical cyclone intensification by estimating the thermal (heat) content in the upper ocean from the sea surface to the depth of the 26°C isotherm. Within this reasoning, the term hurricane heat potential was introduced to estimate the field of integrated vertical temperature from the sea surface to the depth of the 26°C isotherm, in an area of the Gulf of Mexico using expendable bathythermographs (XBT) temperature profiles [*Leipper and Volgenau*, 1972].

The methodology used here combines near-real time observations of sea height anomalies from blended altimetry and sea surface temperature satellite data with climatological temperature and density fields within a two-layer, reduced-gravity scheme [*Goni et al.*, 1996]. The synthetic temperature profiles are then estimated using the values obtained from the fields of sea surface temperature and the altimeter-derived depth of the 20°C layer, along with historical information on the shape of the profiles in the region. The TCHP is then estimated by integrating the temperature profile from the sea surface to the depth of the 26°C isotherm. These estimates are being carried globally and in near-real time (1-day delay) to cover all seven oceanic basins where tropical cyclones occur, as well as in the tropical Pacific Ocean.

Tropical Cyclone Heat Potential and Intensification

Four examples of intensification of three Atlantic hurricanes and one western Pacific typhoon that passed over areas with very high values of TCHP are shown here: Hurricanes Opal, Mitch, and Bret (Figure 2) and Typhoon Imbudo (Figure 3).

Hurricane Opal, which occurred in the Gulf of Mexico in September and October 1995, is shown in Figure 2 (left). This tropical cyclone intensified from a category 1 hurricane (74 to 95 mph sustained winds) to a category 4 hurricane (131 to 155 mph sustained winds) on the Saffir-Simpson scale while traveling over a number of warm features in the Gulf of Mexico. In particular, this tropical cyclone suddenly intensified from a category 2 hurricane (96–110 mph sustained winds) to a category 4 hurricane in a period of 10 hours when its track went over a very well-defined warm ring with a mean radius of 150 km that had been shed by the Loop Current. Altimeter-derived fields indicate that the increase in TCHP associated with this warm ring was approximately 30 kJ/cm². The most striking information about the ocean conditions during the time span of this hurricane was that this warm ring was not detected using the AVHRR-derived sea surface temperature fields.

Hurricane Mitch occurred in the Caribbean Sea in October 1998 (Figure 2, center). This cyclone intensified from a category 2 hurricane to a category 5 hurricane (sustained winds above 155 mph) when its track traveled over a region of warm surface waters; and intensifying from a category 3 hurricane (111–130 mph sustained winds) to a category 5 with an increase in values of TCHP under the track of this tropical cyclone of ~80 kJ/cm² in 22 hours.

Hurricane Bret occurred in the Gulf of Mexico in August 1999 (Figure 2, right). This hurricane intensified several times in the southwestern Gulf in a period of ~36 hours while traveling over two warm feature remnants of a warm ring that had been shed by the Loop Current several months earlier. The increase in TCHP under the track of the tropical cyclones during this period was approximately 80 kJ/cm².

Typhoon Imbudo occurred in the western Pacific in July 2003 (Figure 3). As a western Pacific example, the upper ocean conditions are shown prior to (19 July) and after (23 July) the passage of Typhoon Imbudo through the northern Philippines. This typhoon intensified from category 1 (65 mph sustained winds) to category 4 (130 mph sustained winds) during a period of only 12 hours on 20 July, when its track crossed a region that increased its oceanic TCHP by almost 100 kJ/cm². The sea height anomaly fields (SHA) are evidence of the change in the upper ocean dynamics and thermal conditions due to the passage of the tropical cyclones. The upper ocean exhibits a cooling (decrease of TCHP values) of 60–100 kJ/cm², with the sea surface temperature decreasing by 3–4°C, along the track of the tropical cyclones. Similarly, the depth of the 26°C isotherm (d26) decreased by 25–100 m due to the mixing and upwelling of waters, as well as to the uptake of thermal energy by the tropical cyclones.

In these four cases, an association was observed between the increase in tropical cyclone intensity and a rise in the value of TCHP under the track of each of the tropical cyclones. Preliminary evaluation of the upper ocean thermal conditions during the intensification of 32 of the 36 strongest tropical cyclones in the tropical Atlantic, from 1993 to 2000, indicates that their intensification can be associated with the passage of their tracks over regions with increased TCHP of at least 20 kJ/cm² along the storm track.

Real-Time Monitoring of the Tropical Cyclone Heat Potential

The sea height anomaly fields used here are a blended altimeter product that combines data from several altimeters; these data are distributed by the U.S. Naval Oceanographic Office (NAVOCEANO). The sea surface temperature is obtained from the TMI fields, and the historical hydrographic data are from the *World Ocean Atlas* (2001). Near-real-time fields of TCHP are posted on the National Oceanographic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory Web page (www.aoml. noaa.gov/phod/cyclone/data), along with other parameters

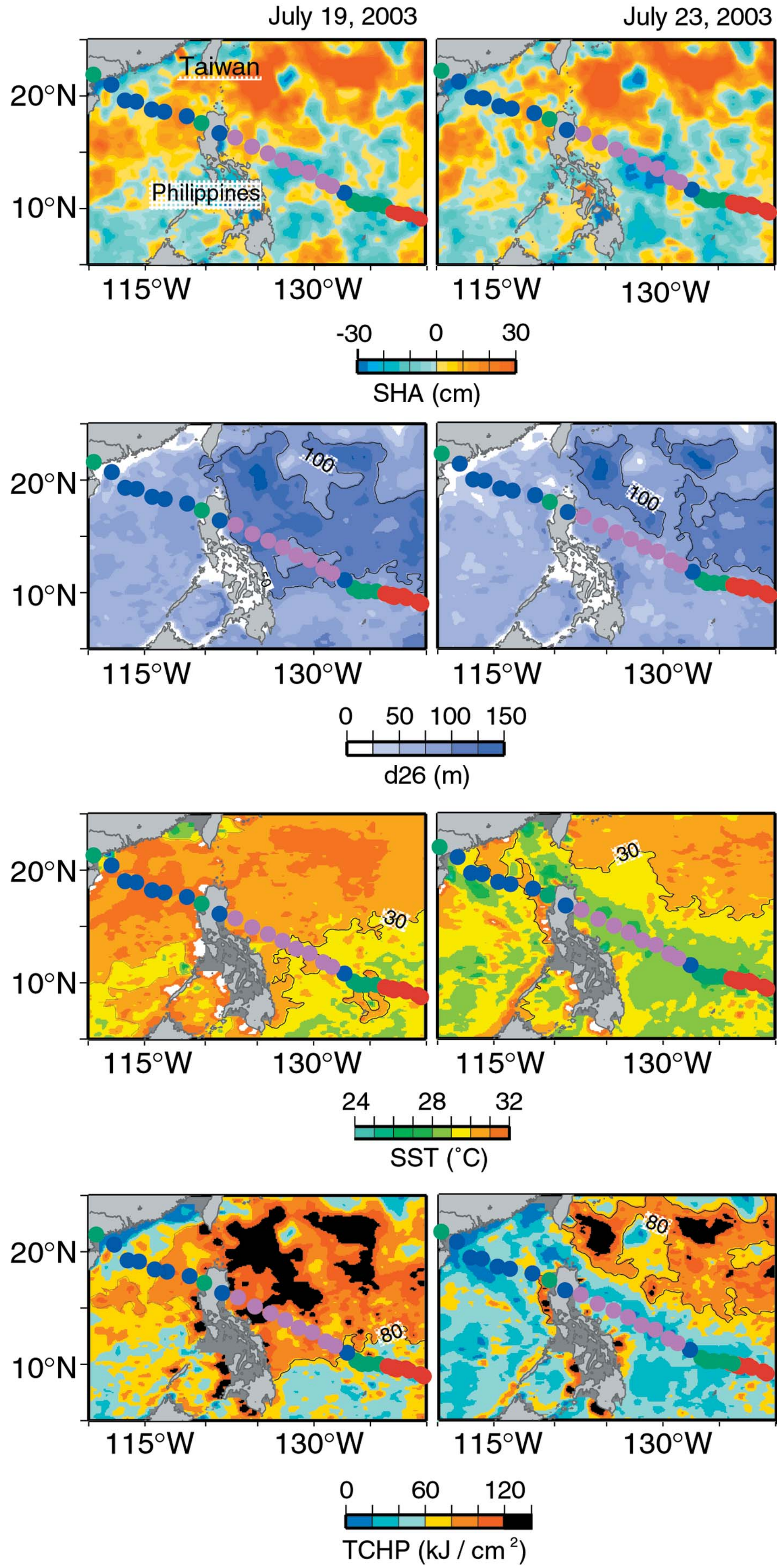

Fig. 3. Ocean conditions before (left panels; 19 July 2003) and after (right panels; 23 July 2003) the passage of Typhoon Imbudo through the northern Philippines. From top to bottom, the fields are: sea height anomaly, depth of the 26°C isotherm, sea surface temperature, and tropical cyclone heat potential (TCHP). The colors of the circles denote the track of storm and go from red (tropical cyclone) to magenta (category 4 Typhoon).

such as sea height anomaly, sea surface temperature, and altimeter-derived depth of the 20°C and 26°C isotherms.

The examples here provide an indication that the ocean may play a role in tropical cyclone intensification. It is also suggested that the TCHP in itself may not necessarily be the dominant ocean parameter linked to intensification, but rather a derived quantity, such as its gradient along the track of the tropical cyclones above some threshold value of TCHP and also related to the velocity of translation and radius of maximum winds of the tropical cyclones.

In addition, the thermal conditions below the tropical cyclones may affect its intensity, but with a delay in time. Nevertheless, the TCHP appears to be a better predictor than sea surface temperature alone for intensification purposes. We hope that our TCHP fields will contribute to the understanding of the role that these warm features play in rapid tropical cyclones intensification, and that this knowledge will improve tropical cyclone intensity forecasts.

Acknowledgments

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Mesoplates: Resolving A Decades-Old Controversy

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A new concept unifies several diverse lines of evidence regarding the kinematics of lithospheric plates ("lithoplates") and the underlying mesosphere. Three "mesoplates"—shallow, kinematically rigid regions of the upper mesosphere of the Earth—are inferred to be the habitat of most hot spots, as well as the source region for the sea floor spreading. The recognition of mesoplates, which range in depth from perhaps 100–300 km+, provides a framework for resolving part of the ongoing hot spot-plume debate.

It has been 40 years since J. Tuzo Wilson suggested that oceanic chains—for example, the Hawaiian Islands—record motion of oceanic floor over hot spots, and 30-plus years since W. J. Morgan postulated that hot spots form a fixed reference frame and manifest deep mantle plumes. Subsequently, the hot spot-plume debate has separately focused on the two parts of Morgan's proposal. Geodynamic modelers and petrologists have attempted to infer the nature of mantle plumes, while seismologists have attempted to establish their existence. Kinematic modelers have attempted to verify the hot spot global reference frame. An implicit rationale for the combined hot spot-plume hypothesis is the apparent existence of a contemporary hot spot reference frame (see references in *Pilger* [2000]); mass movement constraints require that the reference frame be located deeper than the deepest subduction zones. However, physical and numerical models suggested progressive displacement of plume heads from their tails, and plumes from one another [see examples and references in *Richards et al.*, 1989]. (Some workers may prefer the term "melting spot" to "hot spot;" for the purposes of this discussion, the more compact term is used, but without genetic significance.)

From plate reconstructions, progressively improved models of the Atlantic and Indian Ocean hot spot traces began to emerge. *Müller et al.* [1993] produced a model that closely fits the trends of virtually all of the traces (except for Iceland) in the two oceans, especially over the past 100 m.y. Similarly, models of the Pacific Ocean hot spot traces have advanced (e.g., *Harada and Hamano, Norton*, and *Raymond et al.* in *Richards et al.* [2000]).

Despite progress in kinematic modeling, a glaring problem persists, as first identified by Peter Molnar and co-workers. The models of the Pacific Ocean and those of the Atlantic/Indian Ocean are incompatible. The long-recognized discrepancy between east and west hot spot sets has been conventionally attributed to internal deformation of the Antarctic plate. *Cande et al.* [2000] constrained the amount of internal deformation for much of the Cenozoic from magnetic isochrons in the Australian-Antarctic-Pacific triple junction area; even when this deformation is taken into account, the misfit remains [*Raymond et al.*, in *Richards et al.* [2000]). Further, discrepancies with the paleomagnetic frame exist, as recognized for the Atlantic by Morgan and more recently demonstrated for the Hawaiian-Emperor chain [*Tarduno and Cottrell*, 1997].

The new proposal attempts to resolve part of the hot spot-plume controversy. The proposed model [*Pilger*, 2003] includes the following. The two recognized hot spot reference frames are real and distinct (*Gaina et al.* in *Richards et al.* [2000]), named "Hawaiian" after the principal hot spot of the Pacific, and "Tristan" after Tristan da Cunha. A third, the "Icelandic" reference frame, is inferred beneath Eurasia and Greenland [e.g., *Norton* in *Richards et al.* [2000]). All three frames are independent of the paleomagnetic frame. The reference frames are shallow and manifest the three mesoplates (Figures 1 and 2). The upper surface of mesoplates corresponds with the mesosphere-asthenosphere boundary. Finally, boundaries between mesoplates largely correspond with deep subduction zones that extend below 200 km. The remaining boundaries beyond the subduction zones are determined by the relative kinematics of the mesoplates.

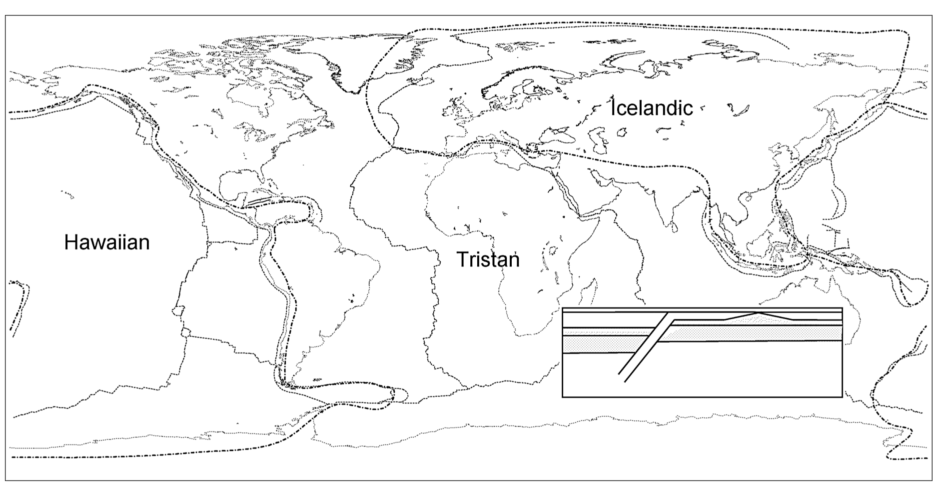

Fig. 1. This global map (equatorial equidistant) shows approximate boundaries of the Hawaiian, Tristan, and Icelandic mesoplates. Inset: Cartoon section of lithoplates, asthenosphere, and mesoplates.

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