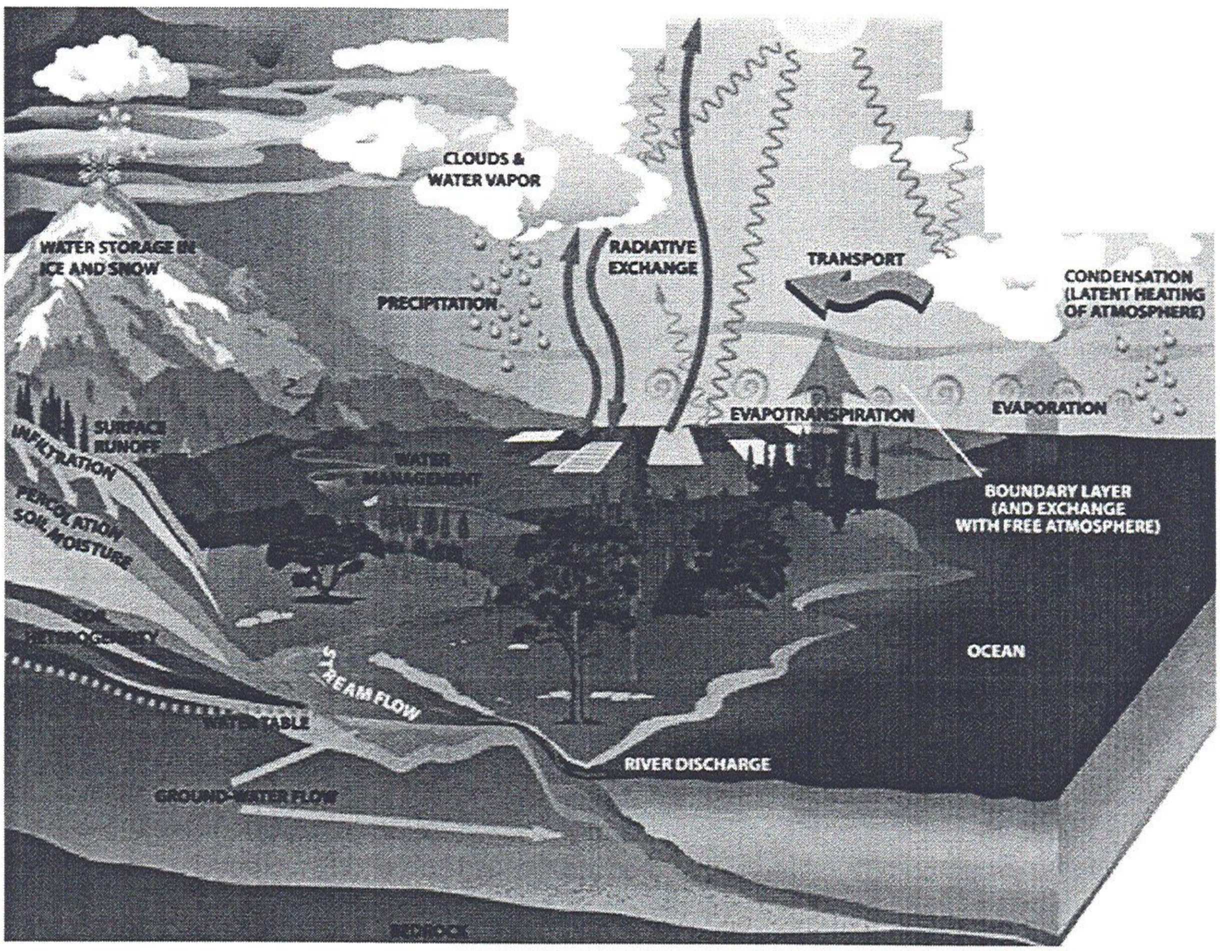
OCEAN IN THE GLOBAL WATER CYCLE

Educational Outcomes: Earth's ocean covers almost 71 % of Earth's surface to an average depth of about 3.8 km (2.4 mi). Earth is truly a water planet, especially when the commanding presence of the ocean is combined with the large expanses of terrestrial ice and snow cover, lakes, groundwater, and the global presence of atmospheric moisture. Central to the functioning of the Earth system is the global water cycle, the ceaseless flow of water, energy, and water-borne materials among the oceanic, terrestrial, and atmospheric reservoirs and their interactions with life on Earth.

A. The Global Water Cycle

In the holistic Earth system perspective, Earth is composed of many interacting subsystems including the ocean, atmosphere, geosphere, cryosphere, and biosphere.

Figure I below schematically illustrates the movements and transformations of water in the Earth system. The figure was developed by the Global Water Cycle program element of the US Global Change Research Program.



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.Figure I: Conceptualization of the Water Cycle (Schematic view)

For color version, go to: *http://www.usgcrp.gov/usgcrp/images/ocp2003/ocpfy2003-jig5-I.htm*

Figure I also displays major aspects of the essential reason why water cycles through its reservoirs, namely, energy flow. The mass flow of water as portrayed in the figure is a response to the non-uniform distribution of energy in the Earth system. Note that while Earth is a closed system for cycling mass, as in the case of water, Earth is an open system or "flow-through" system for energy. Energy is not conserved as it comes from space and is

eventually lost back to space. Water's coexistence in all three phases (solid, liquid, vapor) and the relative ease at which it changes phase within the temperature and pressure ranges on Earth makes water the working fluid that absorbs, transports, and releases heat within the Earth system.

Water is the primary mover of energy in the Earth system from where there is relatively more to where there is relatively less. Ocean currents transport enormous quantities of heat energy poleward. The ocean is the primary source of atmospheric moisture, accounting for about 85% of all evaporation worldwide. Winds transport water vapor and the latent heat it absorbed during evaporation to every location on Earth, including the highest peaks. Changing back to liquid or solid within the atmosphere, water begins its gravity-driven return trip to Earth's surface and eventually to the ocean.

1. The depiction of the global water cycle in Figure I shows the ocean to the right. Water substance is provided to the ocean by [(surface runoff) (stream flow) (groundwater) (all three processes)). Precipitation also occurs over the ocean and adds fresh water directly to the ocean surface. Meanwhile, water substance is lost from the ocean as [(evaporation) (/precipitation)). Not clearly shown are oceanic losses by infiltration of salty groundwater and the additions of water to the ocean via volcanic activity.

Components of the energy flow so essential to the water cycle are schematically shown or mentioned in Figure]. Figure 2, below, provides striking evidence of some of these energy flows. It depicts the atmospheric component of the global water by revealing both clouds as bright splotches and water vapor as light gray swirls. The circulation of water (clouds, water vapor) in the atmosphere is the essential heat-driven uphill component of the water cycle that can lift water to great altitudes. Atmospheric water is transported horizontally by the wind, often traveling great distances before precipitating. The rest of the cycle is gravity driven and downhill. Ocean circulation is driven by winds and by variations in water density resulting from temperature and salinity differences.

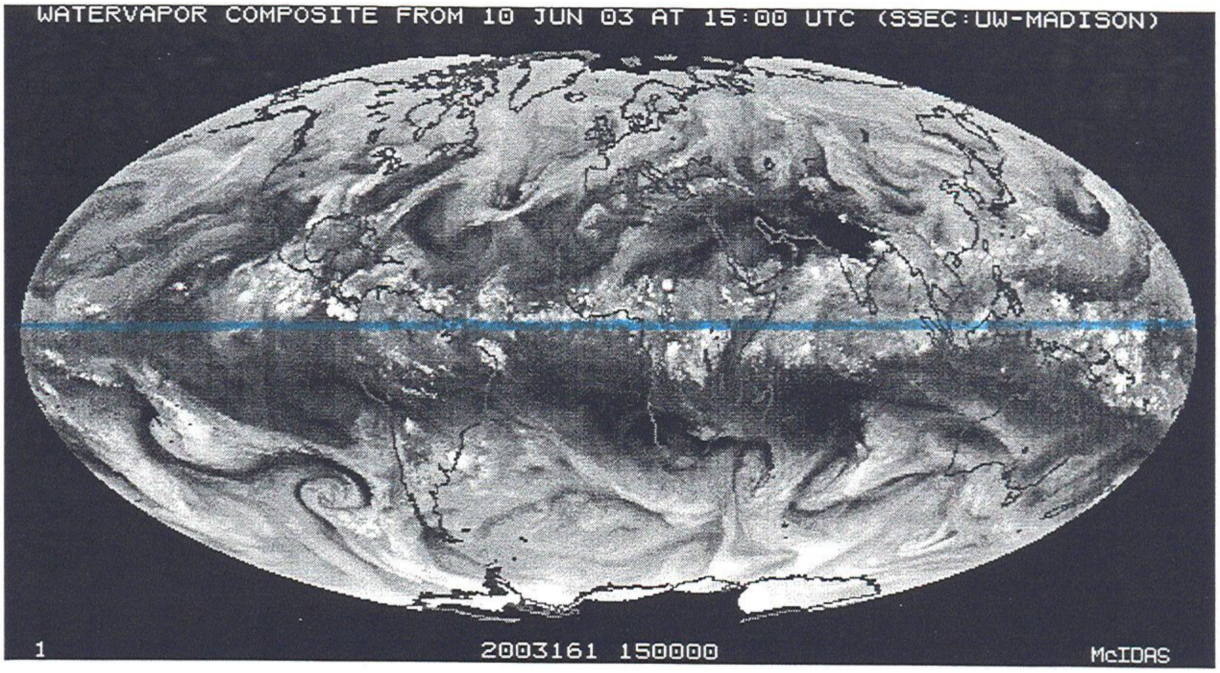

Figure 2. A composite satellite image displaying the distribution of water vapor and clouds in the middle region of the atmosphere.

Figure 2 is a composite of images from five geostationary weather satellites sensing water vapor and clouds in the Earth's atmosphere. This image is derived from computer processing of the invisible infrared (heat) radiation emitted by Earth's surface that interacts with water substance in the middle atmosphere and reaches the satellite's sensors. This particular image is from 1500 UTC (I I a.m. EDT) on 10 June 2003.

Bright white patches in the image represent the relatively cold tops of high clouds. Clouds occur where atmospheric motions are upward. Medium gray regions depict mainly water vapor. These regions would probably appear clear on visible and ordinary infrared satellite images. Streaks and curls of gray highlight the generally eastward flow of middle atmospheric water vapor transported by large-scale atmospheric motions. Dark areas are relatively dry middle atmosphere regions where air is sinking.

2. Using a straight edge and pen or colored pencil, draw a line horizontally that divides the image in half and approximates the location of the equator. The bright white cloud patches forming an irregular band roughly along the equator mark areas where huge quantities of water vapor enter the atmosphere from underlying warm ocean surface. These high thunderstorm cloud tops indicate the end product of *[(evaporation) (overland runoff)]* from the ocean surface. If we viewed a sequence of similar water vapor composite satellite images, it would be evident that in the tropics atmospheric water vapor flows more or less steadily from east to west. The flow is embedded in the trade winds of the low latitudes.

3. Over the course of a year, the Atlantic Ocean basin loses more water to the atmosphere by evaporation than it receives by precipitation and other sources. This water loss causes Atlantic surface waters to become saltier, thereby increasing their density. At lower latitudes, there is a net flow of atmospheric water vapor evaporated from the Atlantic Ocean westward across Central America to the Pacific Ocean basin. There, precipitation freshens Pacific surface water and [(increases) (decreases)] salt concentration and water density. We will see later that this atmospheric flow of water vapor enhances the "conveyer belt" thermohaline circulation of the world ocean.

4. Large clusters of thunderstorm clouds mark source regions of water vapor that flows into higher latitudes (shown as broad gray plumes on the satellite image). Darker regions forming two bands located just north and south of the equator indicate [(dry) (humid)] air. These are regions of sinking air that, in combination with the grayer storm swirls at higher latitudes indicating rising air, are evidence of the vertical motions of air that occur in weather systems.

5. The curving swirls of water vapor in the middle latitudes of the Northern and Southern Hemisphere portions of the image imply that the atmospheric motions [(do) (do not)] transport water vapor horizontally north and south as well as east and west within the atmosphere. Midlatitude swirls are storm systems that transport humid warm air poleward to be replaced by colder and drier polar air moving equatorward. Storm motions transfer [(water mass) (heat energy) (both)] within the Earth system.

6. The band of swirls running east and west in the Northern Hemisphere is at higher latitudes than the band of swirls in the Southern Hemisphere. This is because in this June view the [(Northern) (Southern)] Hemisphere is warmer. The sun is higher in the Northern Hemisphere sky providing more incoming solar radiation to fuel evaporation. At comparable latitudes in December, [(Northern) (Southern)] Hemisphere locations receive more incoming solar radiation. This uneven heating of the Earth drives atmospheric circulation to redistribute heat energy in the Earth system. (As we shall see in later investigations, ocean currents also playa role in this heat transfer.)

The actual global-scale transport of atmospheric water vapor and clouds can be observed via image animation by going to the NASA Global Hydrology and Climate Center homepage (www.ghcc.msfc.nasa.l!ov/GOES/ldobalwv.html). Imagery is based on NOAA data.

OCEAN - ATMOSPHERE CONNECTIONS

Educational Outcomes: The interface between the atmosphere and the ocean is dynamic. Solar radiation largely passes through the atmosphere and most of what strikes the sea surface is absorbed (converted to heat) in the upper portion of the ocean (the photic zone). The average albedo (reflectivity) of the ocean surface is only about 8%, meaning that 92% of incident radiation is absorbed by the ocean. Some of the resulting heat at the ocean surface is used to evaporate water. Heat used for this purpose is the latent heat of vaporization. Whereas some water is lost from the ocean to the atmosphere via evaporation, much of it returns to the ocean via precipitation. On an average annual basis, however, more water evaporates from the world ocean than returns to the ocean via direct precipitation. The magnitude and direction of the flux of water between the ocean and atmosphere varies from place to place and over the course of a year.

The exchange of water (as water vapor or precipitation) between the atmosphere and ocean involves an exchange of energy. Heat that is used to evaporate water is carried with the vapor and later released to the atmosphere when water vapor condenses (or deposits as ice) into clouds. This heat transfer mechanism is known as latent heating. In addition, where the sea surface temperature (SST) is higher than the air temperature, heat is conducted from the sea surface to the air immediately above and convected into the troposphere. This heat transfer mechanism (combining conduction and convection) is known as sensible heating. On a global annual basis, for the world ocean, latent heating is considerably more important than sensible heating in transferring heat energy to the atmosphere.

The amount of precipitation over the ocean is derived remotely by satellite. Sensors monitor microwaves emitted by the Earth-atmosphere system and the extent and thickness of cloud cover. Estimates of evaporation from the ocean are more difficult to make but are based on satellite-derived values of sea surface temperature and radiation emission along with the few scattered weather observations at sea. Figure I below is the global distribution of the difference between evaporation (E) and precipitation (P) in cm per year over the ocean in the band between 50 degrees N and 50 degrees S for the period 1988- 1 993.

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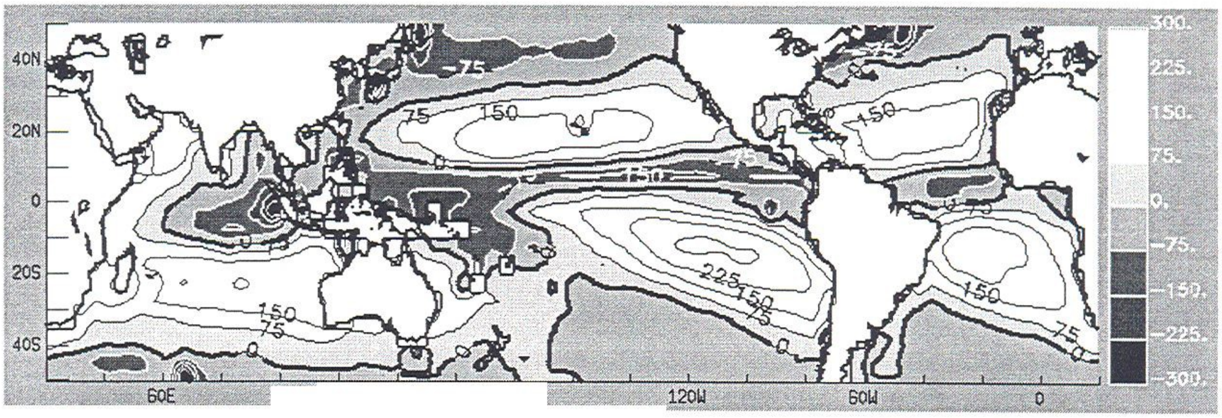

Figure 1. Six-year average of E-P (cm/yr), adapted from Gautier, *et al.,* 1996.

Lighter shadings in Figure 1 signify positive values of E-P, that is, evaporation greater than precipitation. Darker shadings indicate where E-P is negative, that is, precipitation is greater than evaporation. Contour lines are drawn at intervals of 75 cm per year. A bold, heavy line denotes 0 difference, that is, where evaporation equals precipitation. The shading scale is shown to the right. Latitude is along the left and longitude is at the bottom.

I. The region of the ocean where the value of evaporation exceeds precipitation by more than 300 cm per year (lightest shading) is located in the eastern South *[(lndian)(Pacific) (Atlantic»)* Ocean. In this region, more than 3 m of water is lost through evaporation than is gained via precipitation. At the other extreme, the greatest excess of precipitation over evaporation (negative values or darkest shading) occurs along the equator in the *(Atlantic) (western Pacific and eastern Indian Oceans) (eastern Pacific»)* where E-P values exceed 300 cm per year.

2. The greatest positive values of E-P (more evaporation than precipitation) occur in that part of the ocean where the climate is dominated by fair-weather *[(subtropical anticvclones)(subpolar lows)(westerlies)* These massive semi-permanent weather systems are regions where rates of evaporation are relatively *[(high)(low)]* and rates of precipitation are relatively *(high)(low)].*

3. The greatest negative values of E-P (more precipitation than evaporation) occur along and just north of the equator. This excess of precipitation over evaporation *[(does) (does not)]* generally coincide with the location of the Intertropical Convergence lone (ITCZ) where the trade winds of the two hemispheres converge and trigger development of a discontinuous east-west band of showers and thunderstorms.

4. Areas of excess evaporation (over precipitation) are not symmetric north and south of the equator. Positive E-P patterns generally cover *((larger) (smaller)]* areas in the Southern Hemisphere and their magnitudes are *(greater) (less)]* than in the corresponding ocean basins of the Northern Hemisphere. (The evaporation dominance in the Southern Indian Ocean has no counterpart north of the equator.) This lack of symmetry is based in large part on the greater proportion of water to land that exists in the *[(Northern) (Southern)]* Hemisphere.

5. A secondary region of precipitation dominance (over evaporation) occurs in the ocean to the northeast of the Asian and North American continents from about 40 to 50 degrees N. Heavy precipitation is due to midlatitude storm (cyclone) tracks that exit the continent over the ocean bringing frequent episodes of rain and snow. In addition, surface water temperatures are relatively low thereby *[(reducing)(increasing)]* the evaporation rate. Storminess coupled with the cooler waters of higher latitudes *[(would) (would not)]* favor a negative E-P balance (more precipitation than evaporation).

Evaporation and precipitation have considerable impact on the ocean surface layer, particularly in terms of its salinity. To investigate the effect on salinity, examine Figure 2 for patterns of sea surface salinity on the global scale. (Note: This same figure was delivered in Investigation 3A as Image 2.) Mark each major center of highest salinity with an "H" and survey the map to identify regions of relatively low salinity.

6. Compare Figure 2 depicting mean annual salinity with Figure I displaying average annual E-P values. This comparison shows that, in general, regions of the ocean with higher surface salinities are associated with areas that also experience *[(more)(less)]* evaporation than precipitation. Those regions of the ocean with lower surface salinities are associated with areas that experience *(more)(less)]* evaporation than precipitation.

7. Figure 2 shows that the highest open ocean salinities occur in the *[(Atlantic)(Pacific)(Indian)]* Ocean. Figure I confirms that this is a region where evaporation is *[(lessthan)(mort than)]* precipitation.

8. The region of the ocean identified in Item 7 is a major source of atmospheric water vapor that is transported by the *(trade winds)(westerlies)]* across the isthmus of Central America. This water vapor contributes freshwater precipitation to the southeastern North

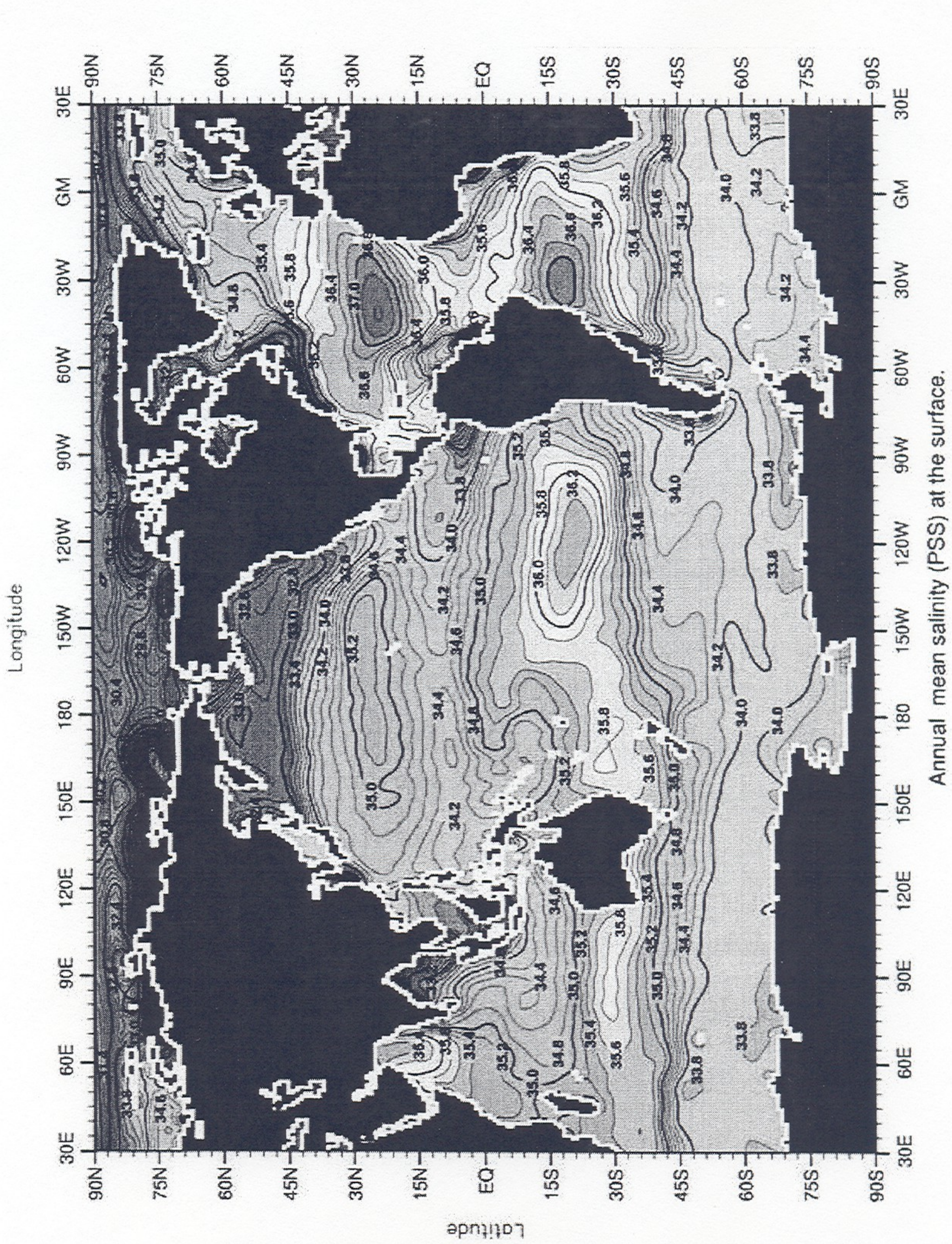

Figure 2. Annual mean salinity at the ocean surface (from *World Ocean Atlas 2001*, (*http://www.nodc.noaa.gov/OC5/WOA01F.ssearch.html*)

Pacific. The east-to-west transport of water substance is accompanied by a(n) [(west-too east)(east-to-west)] transport of latent heat. This transport of water out of the Atlantic into the Pacific is important to the dynamics of the ocean conveyer belt.

Acknowledgement: Figure is adapted from Gautier, c., P. Peterson and C. Jones, J 996. "Global Estimation of Freshwater Fluxes and Freshwater Oceanic Transport from Satellite Data", World Water Resources, 8 (4), 505-514. (available from hllp://www.icess.ucsb.edu/esrg/Publicalions/World- Water _Resources_96/ World- Waler _Resources.hlml)
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OCEAN - ATMOSPHERE CONNECTIONS

In the first part of this investigation, we examined the variation in evaporation versus precipitation over the world ocean. We also saw how this variability related to patterns of sea surface salinity and large-scale atmospheric circulation systems. In this part of the investigation, we relate the pattern of precipitation over the ocean to seasonal changes in incoming solar radiation and sea surface temperatures.

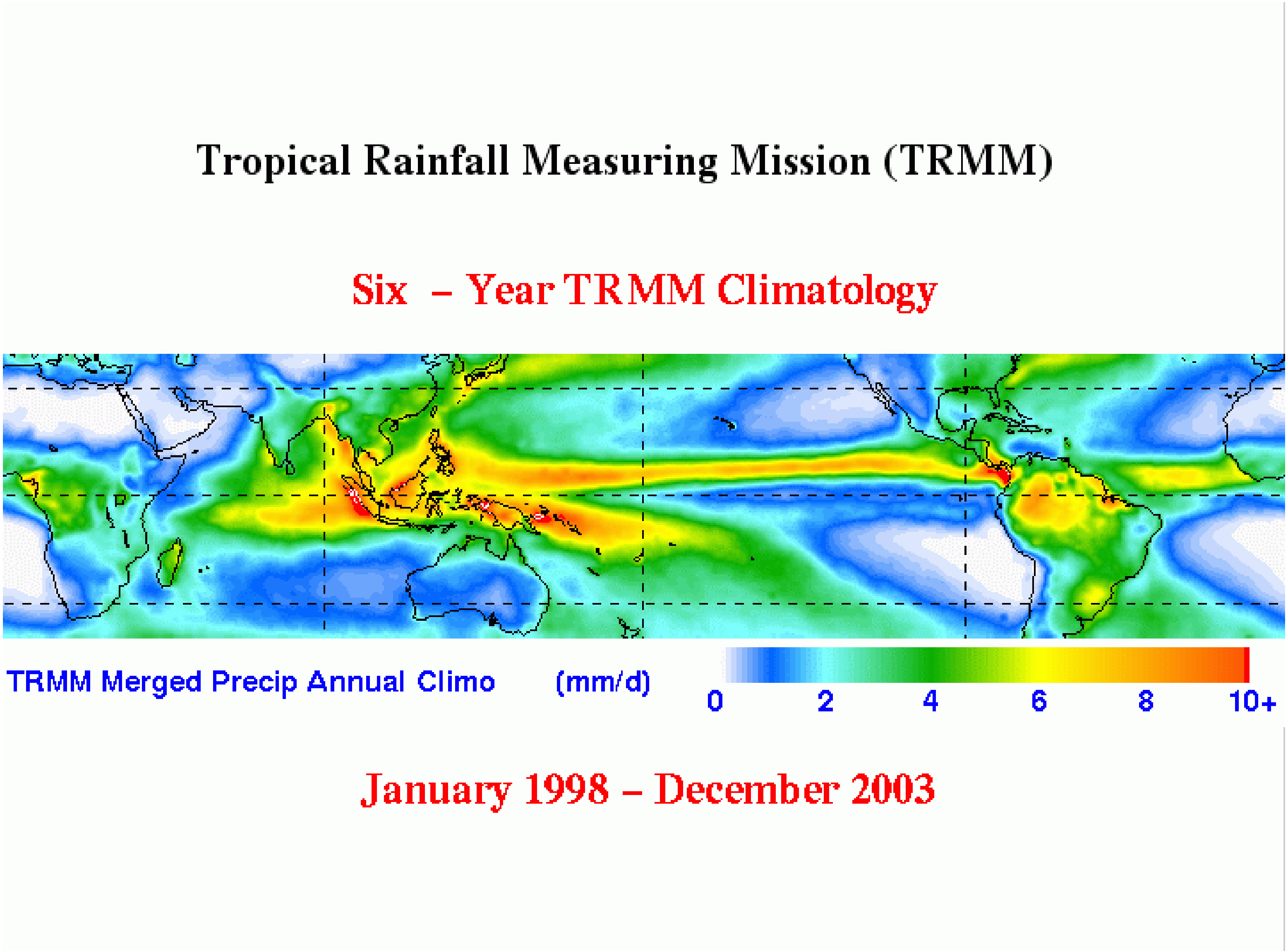

Image 1

9. Figure 1 in the first part of this investigation summarizes the global pattern of evaporation versus precipitation (E-P). Image 1 in this part of the Investigation displays precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM) satellite in millimeters per day (mm/d) averaged over a six-year period, January 1998 through December 2003. (*This image is best viewed in color or colors noted from screen view.*) The precipitation pattern shown in Image 1 **[(*is*) (*is not*)]** generally in alignment with the E-P pattern in Figure 1 (e.g., regions of greatest net evaporation coincide with regions of least precipitation).
10. Image 1 shows that across the central and eastern tropical Pacific Ocean, precipitation is highest primarily **[(*north of*) (*at*) (*south of*)]** the equator.
11. In the western tropical Pacific, the highest precipitation occurs **[(*on either side*) (*well to the north*)]** of the equator. This precipitation pattern is associated with the active-weather of the intertropical convergence zone (ITCZ), which closely corresponds to the latitude of Earth's highest mean surface temperature, the *heat equator*. Across the tropical Pacific, the heat equator varies in location from just south of the geographic equator in the

west to north of the geographic equator to the east. Averaged for the globe as a whole, the heat equator is located about 10 degrees latitude north of the geographic equator. Its location north of the geographical equator arises from the unequal distribution of land and ocean in the Northern and Southern Hemispheres.

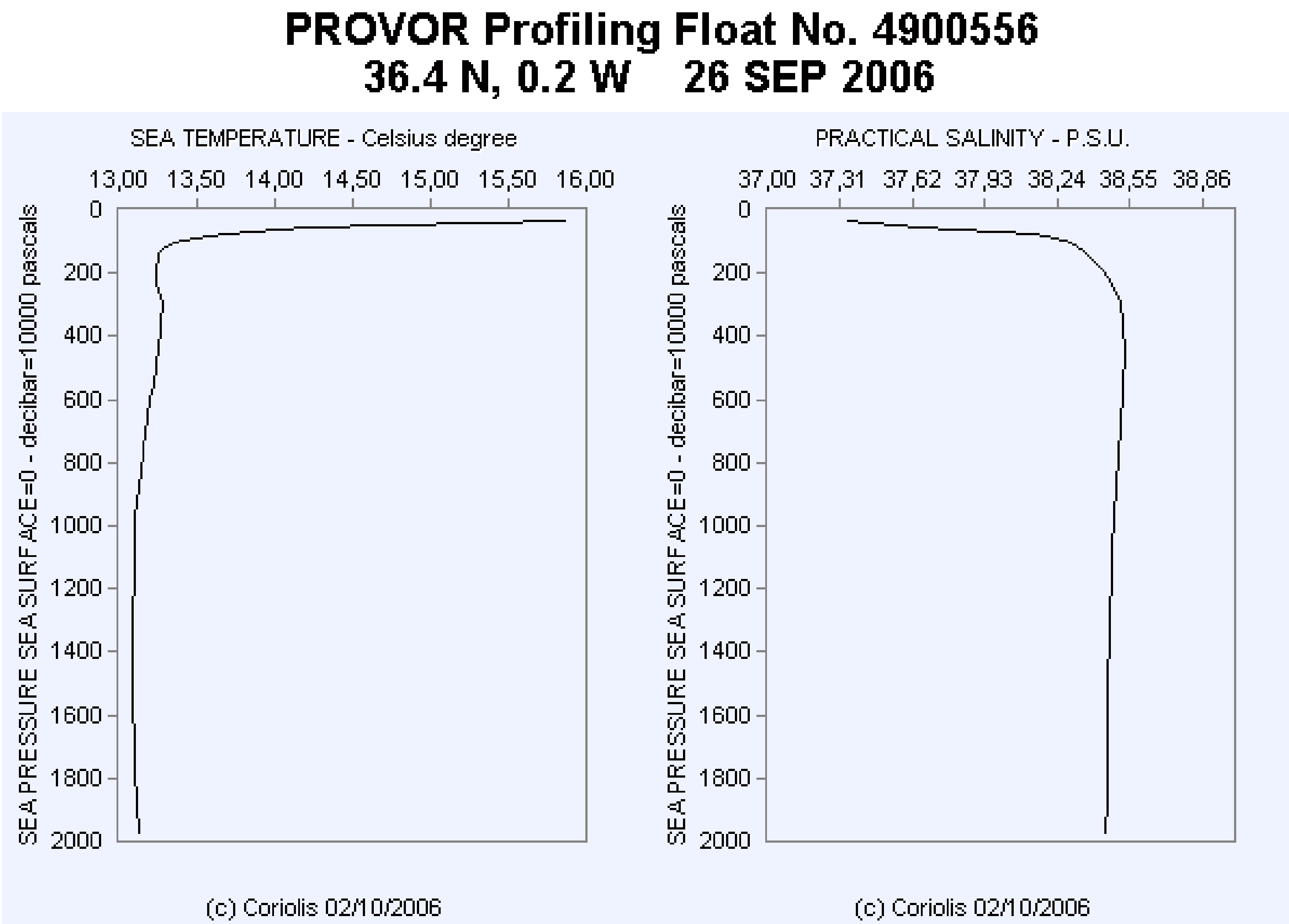

Image 3

The relationship between evaporation and precipitation can have profound effects on ocean structure and circulation. The Mediterranean Sea, a semi-enclosed basin, is subject to greater evaporation than precipitation (plus river discharge) throughout the year. But it is not drying up! Its level is maintained by the influx of surface currents of Atlantic Ocean water through the Strait of Gibraltar. Image 3 provides temperature and salinity profiles acquired by a PROVOR profiling float (WMO No. 4900556). The float was located in the western Mediterranean Sea basin near the Strait of Gibraltar at 36.359 degrees N and 0.155 degree W on 26 September 2006 during its 110th cycle ascent and surfacing from a depth of almost 2000 m.

12.The temperature profile shows that at depths below about 100 m there is a nearly uniform water temperature of approximately **[(*12*) (*13.2*) (*14.1*) (*16*)]** °C. This is substantially warmer than Atlantic open-ocean temperature values at the same latitude and depths.

13.Throughout most of the plotted profile below 300 m, salinity values are approximately **[(*36.5*) (*37.5*) (*38.5*)]**. These values are considerably higher than Atlantic open-ocean salinities at the same latitude and depths.

14.Compared to values at greater depths, the upper 50 m of seawater is characterized by **[(*lower*) (*higher*)]** temperatures and lower salinities.

15. Hence, compared to values at greater depths, the upper 50 m of seawater is characterized by **[(*lower*) (*higher*)]** densities. The temperature and salinity profiles displayed in Image 3 are in alignment with the influx of Atlantic surface water into Mediterranean basin and the outflow of Mediterranean seawater to the Atlantic Ocean at depth through the Strait of Gibraltar.

The greater evaporation than precipitation plus runoff across the Mediterranean basin produces seawater having a combination of relatively high temperatures and high salinities.
