Project Atmosphere Canada

MODULE 6

Air-Sea Interaction

Teacher's guide

Canadian Meteorological and Oceanographic Society
La Société Canadienne de Météorologie et d'Océanographie

Environment Canada Environnement Canada

Canada

Project Atmosphere Canada

Project Atmosphere Canada (PAC) is a collaborative initiative of Environment Canada and the Canadian Meteorological and Oceanographic Society (CMOS) directed towards teachers in the primary and secondary schools across Canada. It is designed to promote an interest in meteorology amongst young people, and to encourage and foster the teaching of the atmospheric sciences and related topics in Canada in grades K-12.

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INTRODUCTION

Weather is the current state of the atmosphere at a location. The atmosphere is in constant motion on many scales ranging from the weakest wind gust to the great wind belts that encircle the globe. The energy that sustains these motions comes from the Sun via the surface of the Earth. About 71 % of that surface is ocean water so that it is not surprising that the ocean strongly influences the circulation of the atmosphere and weather everywhere on Earth.

The interface or boundary between the ocean and the atmosphere is dynamic. Matter and energy are continually being transferred across the air-sea interface in both directions. The coupling of the wind with the water surface creates ocean waves and currents. Air either gains heat from or loses heat to the ocean depending on the temperature difference between the sea-surface and the overlying air. Ocean water evaporates into the atmosphere and atmospheric water vapor condenses forming fog, clouds, and possibly precipitation that returns water to the ocean.

Water is a unique substance that has an unusually high specific heat and latent heat. *Specific heat* is the quantity of heat needed to change the temperature of one unit of a substance's mass by one degree. Relatively large amounts of heat are required to change the temperature of water compared to other substances. *Latent heat* is the amount of heat needed to change the phase of a substance, for water to evaporate, for example. These thermal properties of water have important implications for sea- surface temperatures, the temperature of air overlying ocean water, heat transfer between ocean and atmosphere, and the circulation of the atmosphere.

This module deals with one aspect of air-sea interaction, the effect of sea-surface temperature on the weather in coastal regions influenced by wind-driven upwelling and downwelling of ocean water. In some coastal areas, the combination of persistent winds, Earth's rotation, and shoreline orientation can produce vertical circulation of ocean water. At locations where winds transport near-surface water (the surface layer to a depth of about 100 meters) away from the coast, it is replaced by relatively cold water that wells-up from below. This process is called *upwelling. In* other regions, where the winds transport near-surface water toward the coast, water sinks and sea-surface temperatures are higher. This process is called *downwelling*.

The Earth's rotation deflects water and air motions everywhere except at the equator; this deflection is called the *Coriolis effect*. The Coriolis effect combined with the coupling of the wind with water causes a net transport of near-surface water. This transport of water is directed about 90 degrees to the right of the wind direction in the Northern Hemisphere and about 90 degrees to the left of the wind direction in the Southern Hemisphere. Persistent winds blowing along the coast drive near- surface water away from or toward land, resulting in upwelling or downwelling, respectively.

Upwelling and downwelling take place along all three Canadian coasts, the Atlantic, the Pacific and the Arctic. Coastal upwelling occurs because the wind creates a net transport of the water that is to the right of the wind direction. This net transport is shifted to the right of the wind primarily because of the interaction of the wind forcing and the rotation of the earth.

Coastal upwelling and downwelling influence weather and climate by affecting sea-surface temperatures, for example, upwelling cold water contributes to frequent summer fogs as warm tropical air passes over the relatively colder ocean surface. On the other hand cold water inhibits the development of showers and thunderstorms as well as the formation of tropical storms and hurricanes.

Upwelling in the eastern Pacific off the coasts of Ecuador and Peru contributes to the desert conditions in the coastal plains. Weakening of the upwelling associated with atmospheric and oceanic circulations on a three to seven year time span is known as El Nino. Warmer sea surface temperatures lead to enhanced precipitation along the coastal plain.

Regions prone to upwelling and downwelling are of major research interest in the search for global links among wind-driven surface currents, density-driven Deep Ocean circulation, and the atmosphere. It is possible that small changes in upwelling and downwelling may influence not only the ocean, but also weather and climate variability on a planetary scale.

BASIC UNDERSTANDINGS

Thermal Properties of Water

1. Water is 1000 times denser than air. (The density of water is about 1000 kilograms per cubic meter whereas the density of air is about 1 kilogram per cubic meter.) Hence, there is more matter per volume of water to absorb and emit energy.

2. Compared to other naturally occurring substances, the specific heat of water is exceptionally high. About six times more heat energy is required to raise the temperature of one kilogram of water one Celsius degree than to raise the temperature of one kilogram of air one Celsius degree. Thus for equal volumes of air and water, about 6000 times more heat energy is required to bring about the same temperature change in water as in air.

3. Solar radiation energy that enters the ocean is largely absorbed (converted to heat) in the near-surface water layer. The wind-driven ocean circulation distributes that heat through several hundred metres of ocean-depth. As a result the ocean is a vast reservoir of stored heat.

4. Water changes phase within the Earth-atmosphere system. A change in phase of water is brought about by either an input of heat (that is, for melting, evaporation, and sublimation) or a release of heat to the environment (that is, freezing, condensation, and deposition). Heat involved in phase changes of any substance is known as *latent heat.* Compared to other naturally occurring substances, water has unusually high latent heat values.

5. Evaporation of ocean water followed by condensation within the atmosphere is the major heat-transfer mechanism operating between the ocean and atmosphere. Evaporation of one kilogram of water requires the input of almost 6000 times more heat energy than it takes to warm one kilogram of water by one Celsius degree. Heat required to evaporate water subsequently is released to the atmosphere when water vapour condenses forming clouds.

Implications for Weather and Climate

6. The relatively large specific heat of water compared to land and air is the main reason why the ocean warms more slowly than land or air and also cools more slowly. Compared to adjacent land masses, the ocean surface does not heat up as much during the day and in the summer and cools down less at night and in the winter,

7. The temperature of a mass of air is largely governed by the surfaces over which the air resides and travels. Air over the ocean exhibits less seasonal and day-to-night temperature changes than does air over the continents. Air over the ocean is also more humid.

8. Coastal communities with prevailing winds from the ocean have moderate climates, with cooler summers and

milder winters than might be expected based on their latitude alone.

9. Storms that form over the ocean, such as hurricanes, are powered by the latent heat released to the atmosphere when water vapour condenses. That water vapour is derived mostly from evaporation of ocean water and the rate of evaporation is chiefly governed by sea-surface temperature. The higher the sea-surface temperature, the greater the rate of evaporation, and the more latent heat that is delivered to the atmosphere.

10. In response to differences in temperature over distance (called a *temperature gradient),* heat is transferred from where it is warmer to where it is colder. Hence, warmer air is chilled as it travels over colder ocean water and colder air is heated as it travels over warmer ocean water.

11. Cooling air from below reduces the likelihood of strong vertical motion of air necessary for the development of showers and thunderstorms. Where the sea- surface temperature is lower than the air temperature, showers and thunderstorms are infrequent over the ocean and downwind coastal localities.

12. Heating air from below increases the likelihood of strong vertical motion of air that can lead to the development of showers and thunderstorms. Where the sea-surface temperature is higher than the air temperature, showers and thunderstorms are more frequent over the ocean and downwind coastal localities.

13. The water vapour concentration in the air over the ocean surface is increased by evaporation. Warm humid air moving across a relatively cold ocean surface may be chilled to saturation. Water vapour condenses and sea fog forms. (Fog is a cloud in contact with a water or land surface.) Fog may also form when very cold air passes over relatively warm ocean-water. In that case, evaporation into the cold air produces saturation and fog appears as rising steam-like streamers. That type of fog is common over the North Atlantic in winter and is called steam fog (or *Arctic Sea smoke).*

Role of Wind and Earth's Rotation

14. Friction between wind and the ocean surface helps produce the broad-scale horizontal water movements of the ocean's surface, called surface currents. These currents tend to resemble the patterns of the prevailing surface winds

15. If Earth did not rotate, friction between the wind and the ocean surface would push a thin layer of water in the same direction as the wind, but at a fraction of the wind's speed. This layer, in turn, would drag the layer beneath it and put it into motion. This interaction would continue downward through successive ocean layers, like individual cards in a deck of cards, each moving forward at a slower speed than that of the layer above.

16. Because Earth does rotate, the shallow layer of surface water set in motion by the wind is deflected to the right of the wind direction in the Northern Hemisphere and to the left of the wind direction in the Southern Hemisphere.

This deflection is called the *Coriolis effect*. The Coriolis effect depends on latitude, being zero at the equator and greatest at the poles.

17. Earth's rotation causes a change in direction of each layer of water that is put into motion by the layer above. Viewed from above, changes in the direction of horizontal water motion (and decreased speed) with increasing depth form a spiral known as the *Ekman spiral*.

18. Although the motion of the surface-water layer can be up to 45 degrees to the right (Northern Hemisphere) or left (Southern Hemisphere) of the wind direction, the Ekman spiral causes the net transport of water in the top 100 metres or so of the ocean to be approximately 90 degrees to the wind direction.

Upwelling

19. Ocean winds can result in the transport of near-surface water away from a coastal area. Colder water then wells up from below to replace it. Upward movement of cold bottom water is called *upwelling*.

20. In coastal regions, upwelling can occur when winds blow more or less parallel to the shoreline. In the Northern Hemisphere, net transport of surface water is to the right of the wind direction. Along the West Coast, upwelling occurs when the wind blows from the north because the net transport of near-surface water is away from shore. Along the East Coast, upwelling occurs when the wind blows from the south.

21. In the Southern Hemisphere, net transport of surface water is to the left of the wind direction. Upwelling occurs along west coasts in the Southern Hemisphere with winds blowing from the south because the net transport of near-surface water is away from shore. Winds from the north cause upwelling along east coasts of the Southern Hemisphere.

22. Upwelling takes place pretty well wherever the wind blows but it does take time for the oceanic response to develop after the upwelling begins. After the wind turns on, it takes a day or so before the ocean will develop its response.

23. Sea-surface temperatures are relatively low in regions of upwelling

Downwelling

24. There are regions of the ocean where winds result in the transport of near - surface water towards a coastal area, causing surface water to pile up. In response, near surface waters sink. This downward movement is called *downwelling*.

25. In coastal regions, downwelling can result from the transport of water towards the coast when winds blow more or less parallel to the shore. In the Northern Hemisphere, net transport of surface water is to the right of the wind direction. Hence, downwelling occurs when winds blow from the south along the West Coast and when winds blow from the north along the East Coast.

26. In the Southern Hemisphere, net transport of near-surface water is to the left of the wind direction. Hence, downwelling occurs when winds blow

from the north along the West Coast and when winds blow from the south along the East Coast.

27. Sea-surface temperatures are relatively high in regions of downwelling

Impacts of Upwelling and Downwelling

28. Upwelling and downwelling are very important in generating large changes in the sea-surface temperature that can persist for several days. Along the Atlantic Coast, these changes can be as large as 10°C and can develop within a day and last for several days. If you know something about upwelling, it may even be helpful to you in selecting a beach to swim as the local temperature along the coastline may depend on this oceanic phenomenon.

29. Large changes due to upwelling in the coastal ocean may also have a substantial influence on fish and other animals that live in the ocean. For example, along the Atlantic coast, fish such as cod and capelin move around from deep to shallow water to avoid the cold water that is brought to the surface by upwelling. Fishermen have discovered this and know enough to place their nets at the best depth to catch the fish.

30. Elsewhere, prevailing summer winds blow from the north along the California coast. This causes coastal upwelling and relatively low sea-surface temperatures. Warm, humid summer air may be cooled to saturation producing frequent fog along the northern and central California coasts. Thunderstorms are also relatively rare along the California coast.

31. Upwelling along portions of the west coasts of the African and American continents leads to colder water in the eastern Atlantic and Pacific Oceans inhibiting development of tropical storms and hurricanes because of relatively low sea-surface temperatures.

32. Surface waters are often exhausted of nutrients (such as nitrate), while deep waters are rich in nutrients. Upwelling of cold, deep, nutrient-rich water is paramount to coastal fishing communities. When the upwelling in the equatorial Pacific stops — causing the onset of El Niño - the anchovy standing stocks in the nearby waters drop drastically because the nutrients which feed the phytoplankton ("sea plants" that are at the bottom of the food chain) are cut off, affecting the entire ecosystem. Off the coast of British Columbia, locations of upwelling are known to be hot spots for fishing, due to the enhanced nutrient supply.

THE COMPLEXITY OF AIR-SEA INTERACTION

As already stated in the previous section "the interface between the ocean and the atmosphere is dynamic". The introduction to the thermal properties of water and the discussion on the impacts of upwelling and downwelling brings one significant dimension to this dynamic relationship. However, the real world of air-sea interaction is much more complex and less likely to fit a standard model.

When one listens to radio and TV news reports about an intensifying ocean storm approaching the coast, the image of upwelling and downwelling water doesn't immediately enter the visual picture. One must appreciate the significance of those factors, but, also must see the other relationships and interactions taking place to appreciate the complexity of this process and challenge in forecasting the weather associated with that storm.

The following identifies and explains in a limited fashion several other aspects of air-sea interaction process and the phenomenon commonly associated with each of them:

1. **Marine Boundary Layer**:
   Winds increase with height in the atmosphere. At the top of the boundary layer, wind speed and direction are determined by the atmospheric pressure patterns. Wind speeds in the boundary layer are reduced by the friction induced by the land or ocean surface. The rate of change in the near surface layer depends on the roughness of the surface, which varies depending on the terrain. Over the ocean, the surface is relatively smooth, except when large waves are present. Over the ocean, in neutral conditions (either stable or unstable), the increase in winds with height in the near surface part of the boundary layer (typically the lowest 60m) is described by a logarithmic profile. It can also be approximated by a power law formula. The rate of change depends upon atmospheric stability. More unstable conditions means the winds are mixed more uniformly in the vertical, so there is less change from one level to another. In stable conditions, there is less transport of momentum from one level to another, so winds decrease more rapidly toward the surface.

2. **Marine Inversion**:
   In a persistent flow of warm air from the south over colder water, a stable situation will result. If this persistent flow continues for a long enough period of time, a marine inversion will form wherever there is little transport of moisture or momentum across the inversion. Winds can be much lighter below the inversion, than above. Moisture picked up from the ocean by the winds near the surface remains in the marine inversion, so that the air becomes saturated and fog will form.

3. **Sea Fog (also called Advection Fog)**:
   Sea fog is especially prevalent along the east coast particularly in springtime and early summer when ocean water temperatures are still cool over the continental shelf (the Labrador current bringing cool water southwestward) and warmer air from the south moves over this cooler water. This process forms fog banks that can remain over the water for days at a

time, sometimes moving inland at night then retreating to the coast in the daytime as the land warms up.

4. **Circulation Cloud, Drizzle and Fog**:
   In a similar process as the formation of sea fog, air flowing over cool water picks up moisture and is cooled. If this happens for a long enough period of time, low cloud and fog will form. For example, winds blowing over the cold waters east of Newfoundland, particularly in springtime, pick up moisture and are cooled. If a northeasterly flow persists for some time, these conditions can bring low cloud, fog, and drizzle or freezing drizzle onto the northeast coast of Newfoundland, for hours or days at a stretch, until the prevailing flow changes.

5. **Waterspouts**:
   These form occasionally over warm ocean water, particularly in the early fall when sea surface temperatures are still fairly warm, and colder air begins moving over marine waters. Fishermen working in the Gulf of St. Lawrence, for example, often report waterspouts in the early-mid fall. Colder air aloft is necessary to make conditions unstable enough for waterspouts to form.

6. **Cloud Streaks, Snow Streamers and Squalls**:
   All of these can occur when cold wintertime northwesterly winds blow over the relatively warmer waters of the ocean, including the Gulf of St. Lawrence when it is not covered in ice. The dry cold air picks up warmth and moisture from the ocean surface. This makes the air unstable at low levels, so it begins to rise. As it does the moisture condenses and forms clouds. Sometimes these form in long lines interspersed with clear bands of subsiding air. These are clearly seen on satellite photos as long lines of cloud running northwest to southeast, over the Maritime waters and over the Labrador Sea, during what are called "cold outbreaks". These frequently form in the wake of a strong low pressure centre, in advance of an area of high pressure. If the convection in these clouds is strong enough, they can produce heavy snow.

7. **Sea Breezes**:
   Sea breezes can affect the weather along most coastal zones as the air above the land rises and air flows in from the ocean to replace it. The sea breeze is enhanced when the prevailing synoptic pattern is for light to moderate offshore winds, so that there is a return flow aloft bringing air back out over the ocean, forming a circulation cell. The boundary between the warm land air and the incoming cooler air from the ocean is called the *sea breeze front*. The sea breeze front can reach several kilometres inland over the course of the day, and can help to trigger showers and thundershowers that remain over the land, in a line, not moving off as they might ordinarily do. The reverse of the sea breeze can occur at night, when the temperature contrast reverses with the land cooling relative to the ocean, usually under clear skies. This is called a *land breeze* that brings a breeze from off the land out over the ocean.

8. **Ocean Surface Waves**:
   This is a result of air-sea interaction that is familiar to everyone. Near-surface winds act as a stress on the ocean surface, which causes waves to form. The waves build in

height and length as the fetch (the distance over which the winds have been blowing) and duration of the winds increase. In an offshore wind, waves will build higher further out from shore. Waves can grow to 10 to 15 m in height in winter storms or in hurricanes. Individual waves may be twice that. Wave heights describe the distance from peak to the trough of the wave.

9. **Freezing Spray**:
This is an serious hazard to mariners in the wintertime, usually associated with the strong winds around or in the wake of a winter storm that moves out over the ocean. When sea surface temperatures are low, and strong cold winds are blowing over the water, forming waves and spray, the spray droplets can become super-cooled and freeze on contact with the hulls or superstructure of ships. If this continues for long enough the ice from the freezing spray can accumulate enough to make the ship unstable. Freezing spray can be a contributing factor in the sinking of ocean-going vessels. Ships experiencing freezing spray try to avoid the problem by sailing to warmer water, such as near the Gulf Stream, or into the lee of the land or pack ice, where the waves are much smaller.

10. **The North Atlantic Oscillation (NAO)**:
This is an example of air-sea interaction on the seasonal or inter-annual scales, where the atmosphere affects the ocean. The Atlantic equivalent to the well known Pacific ENSO cycle (La Niña -El Niño cycle), the North Atlantic Oscillation (NAO) refers to patterns of long term atmospheric circulation with two phases. In the positive phase, the low pressure centres over the Iceland area are deeper, and the high pressure centres over the Azores area are higher, and the pressure gradient between these areas is stronger. This causes the prevailing westerly winds over the North Atlantic to be stronger. It also brings more storms and warmer winters to Western Europe. In the Northwest Atlantic, the positive phase corresponds to strong northwesterlies blowing over the Labrador Sea, bringing cold air from the Arctic. Winter temperatures tend to be colder especially over Newfoundland during winters where the NAO is mainly in a positive phase. This causes colder water temperatures, and more sea ice. Colder conditions resulting from several years of winters with a positive phase of the NAO is thought to have contributed to the decline of the cod stocks in the early 90's. Water temperatures over the Grand Banks reached low enough values to affect the survivability of cod eggs. The opposite phase corresponds to more frequent "blocking" episodes, where weather patterns move more slowly, and there may be more frequent easterly winds and warmer conditions over the Northwest Atlantic. In the past, when there were several years of winters with a negative phase NAO, the fishery has been more productive. The NAO varies monthly, seasonally, and inter-annually, in an unpredictable way. There is still debate among researchers on the contribution that ocean temperatures make to this long-term atmospheric circulation pattern. In that way, the NAO is quite different from the El Niño and Southern Oscillation (ENSO) where changes in the atmosphere are clearly linked, and predicted by, observed changes in the tropical ocean.

11. **Deep Convection in the Labrador Sea**:
It is clear that the atmospheric circulation described by the NAO does affect ocean temperatures and circulation. Positive phases of the NAO correspond to strong cold flows of northwesterly air over the Labrador Sea that causes the surface of the Labrador Sea to lose significant amounts of heat. This cools the surface water and causes it to sink. In winters with a lot of cooling this can trigger considerable "deep convection" where cold, lower salinity, water sinks down to lower and lower depths. This deep convection is thought to be one of the main sources of North Atlantic deep water that drives the deep ocean circulation

12. **Fluxes of Momentum, Heat, and Moisture between the Atmosphere and Ocean**:
The transfer between the atmosphere and the ocean of momentum, moisture, and heat occurs through air-sea interaction. Wind stress is used as the driving parameter for ocean circulation models. The latest global atmospheric climate models are coupled with ocean circulation models to predict long term changes to global climate. The coupling occurs at the ocean surface and the fluxes depend on the temperatures and the strength of the wind stress on the surface.