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Offshore Coho Salmon Populations near the Pacific Northwest and Large-Scale Atmospheric Events

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Abstract: Catch of coho salmon off the coast of Washington and Oregon since 1925 appears to be related to large-scale events in the atmosphere, which in turn affect ocean currents and coastal upwelling intensities in the northeastern Pacific. At least two time scales of variation can be identified. The first is that of the El Niño/Southern Oscillation phenomenon giving rise to an irregular cycle of between 3 to 7 years. The occurrence of El Niños is associated with warm water anomalies off the coast and often with depressed salmon catches. The second time scale of variation seems to have a periodicity of about 20 years, although this is based on a limited dataset. This variation has been postulated to be related to the manner in which the subarctic ocean current operates; sometimes directing more nutrient-rich water into the Alaskan current, which moves it northward into the Alaskan gyre, while at other times guiding more nutrient-rich water southward into the Californian current off the shores of Washington and Oregon. During the former times, coho salmon catches tend to be low off the Washington and Oregon coasts, and the opposite also seems to hold true. The difference in these modes of the subarctic current may be related to long-term differences in the mode of operation of the atmospheric currents. The atmospheric currents may be quantitatively described by the use of teleconnective indices, which include: the Southern Oscillation Index and the Central North Pacific and Pacific North American. The values of these indices also have some explanatory power, at least in winter, over temperatures and precipitation values in the Pacific Northwest. This paper endeavors to describe how, if real, these atmospheric/oceanic effects are integrated and might affect the salmon catch. The possibility must also be considered that the atmospheric events are symbiotically related to the oceanic events and, further, that both may be enmeshed in even longer-term variability of climate.

Introduction

The story of salmon in the terrestrial-based freshwater aquatic ecosystems of the northwestern North American continent and the marine ecosystems of the north Pacific Ocean is a fascinating and multi-faceted one. Humans suffer from a lack of knowledge of many of the facets of the tale. One aspects that, until recently, has received little attention is the long chain of events that starts at one end with variations in the atmosphere and ends at the other with variability of population sizes of certain kinds of salmon. Climate is one factor that affects salmon population sizes either directly or indirectly in both the freshwater and marine phases.

This paper reviews some aspects of the effect of climate on salmon. These aspects occur on a variety of time scales. It then outlines a statistical

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relationship that appears to exist on an inter-decadal time scale between the population size of coho salmon as indicated by the catch of these fish off the coast of Washington and Oregon and the air temperature in parts of Oregon. An attempt to explain this relationship requires an examination of the large-scale variability and flow of air currents in the atmosphere of the western part of the Northern Hemisphere and the possibly related variation of ocean currents in the northeastern Pacific Ocean. Suggestions are made for further research that could provide new insight into these longer-term relationships.

Climate/Salmon Interactions in General

A cursory look at the literature reveals several important links between salmon population sizes and climatic variables. These links occur both directly and indirectly and at a variety of time and space scales.

An example of a small time scale link is the small time window of a matter of a few days during which juvenile salmon embark on their journey from the estuary to the sea. Adverse weather conditions, such as severe storms with high onshore winds, during this period could negatively impact survival. Spence and Hall (1994) have shown that the size of this window decreases from low to high latitudes. This fact makes storms and other potentially adverse climatic conditions in the higher latitude estuaries and river mouths particularly critical.

On a monthly time scale, it has been shown that while salmon are young, colder river water temperature slows growth and warmer water accelerates growth (Netboy 1980). However, a temperature increase in rivers generally reduces survival, because it may be associated with an increase in disease and fungal attacks in adults.

On a seasonal and annual time scale, there appear to be many climatic effects on salmon populations. The amount of water in rivers, as controlled by periods of high and low flow, is critical for salmon survival. Sharp (1992) claims that local salmon populations throughout the western continental United States have suffered from drought during 1976 to 1991. The relationship of salmon population size to El Niño conditions, which also occurs on this time scale, is treated more specifically below. Not many studies have been performed concerning the relationship between climate and salmon on decadal and century time scales. On a millennial time scale, there is limited and somewhat tenuous evidence to suggest that the inverse relationship of warmer climate and decreased salmonids, found on the El Niño-type time scale, may persist. Neitzel *et al* (1991) believe that during the Hypsithermal period of the Holocene, salmon were less plentiful in the Pacific Northwest.

One important point, which is often neglected, is that the fossil salmon record extends back to the Eocene (Pearcy 1992, p. 5). The implication of this is that at least some species of salmon have survived just about every conceivable extreme climate and type of climate variability the planet can offer or is likely to offer in the next century.

El Niños and Salmon

El Niño occurrences can impact salmon populations in a number of ways. During El Niños, anomalously warmer water is found off the coast of North America, and coastal upwelling and its associated nutrients are suppressed. There is evidence that the 1957-58 El Niño negatively affected salmon, giving rise, in 1960, to the lowest ocean landings off the continental United States coast since 1917 (Pearcy 1992). In addition, the lingering 1991-92 El Niño negatively affected salmon catch (Finley 1993). It has been established that years just following El Niño events generally tend to be years of low coho catches (Miller and Fluharty 1992).

One of the more spectacular and intense El Niño events was in 1982-83. During this event, salmon in the Pacific Northwest appeared to be stalled in estuaries before leaving for the sea because of the warmer water in the ocean. Salmon in the estuaries were subject to disease and predation, which decreased the populations. In addition, reduced primary productivity off the coast impacted both juvenile and adult coho salmon (Pearcy 1992). During this El Niño event, 58% of the adults predicted to return actually died in the ocean. The same El Niño markedly decreased growth and fecundity of the salmon of the year. Warm ocean temperatures off the Oregon coast shifted the center of distribution of juvenile coho northward to the coast of Washington.

Another feature of El Niños that does not seem to have received much attention is that they are often accompanied in the Pacific Northwest by warm, dry winters (Redmond and Koch 1991; Greenland 1994). Whether the lack of precipitation leads to stream discharge values low enough to affect salmon has not been investigated explicitly.

Interdecadal Relationships between Pacific Northwest Air Temperatures and Coho Salmon Catch off the Coast of Washington and Oregon

When temporally smoothed data are used for 1925 to 1985, there is a close inverse statistical relationship between PNW air temperatures and coho salmon catch off the coast of Washington and Oregon. This relationship was discovered by using the following steps.

Frances and Sibley (1991) had reported a close relationship between winter (November to March) air temperature at Sitka, Alaska, surface water temperature at Langara Spit, Queen Charlotte Island, British Columbia, and the catch of pink salmon in the Gulf of Alaska. They had also reported an inverse relationship between the catch of pink salmon in the Gulf of Alaska and the catch of coho salmon off the coast of Washington and Oregon. Both relationships covered the period 1925 to 1985 and were found when the data were normalized and subjected to a 7-year weighted filter (Frances, pers. comm. 1994).

Given these relationships, I reasoned that an inverse relationship between air temperature in the Pacific Northwest and the catch of coho salmon catch off the coast of Washington and Oregon would be likely. I used a 5-year unweighted filter of the annual mean air temperatures at the H.J. Andrews Long-Term Ecological Research site, on the western slope of the Cascades in Oregon (44.2°N, 122.2°W). The filter was applied to values of Andrews temperatures, which were normalized to the long-term mean for 1925-1985. It has been shown elsewhere that Andrews temperatures are well related to those of western Oregon in general (Greenland 1994). Coho salmon catch data were extracted from the graphs of Frances and Sibley and a close inverse relationship was found (Figure 1). This relationship and time series suggest about a 20-year cycle in both PNW air temperature and coho salmon catch off the coast of Washington and Oregon. To attempt to explain this inverse relationship, we must explore the large spatial and long temporal aspects of atmospheric and ocean currents, as well as further thinking of Frances and Sibley and their colleagues.

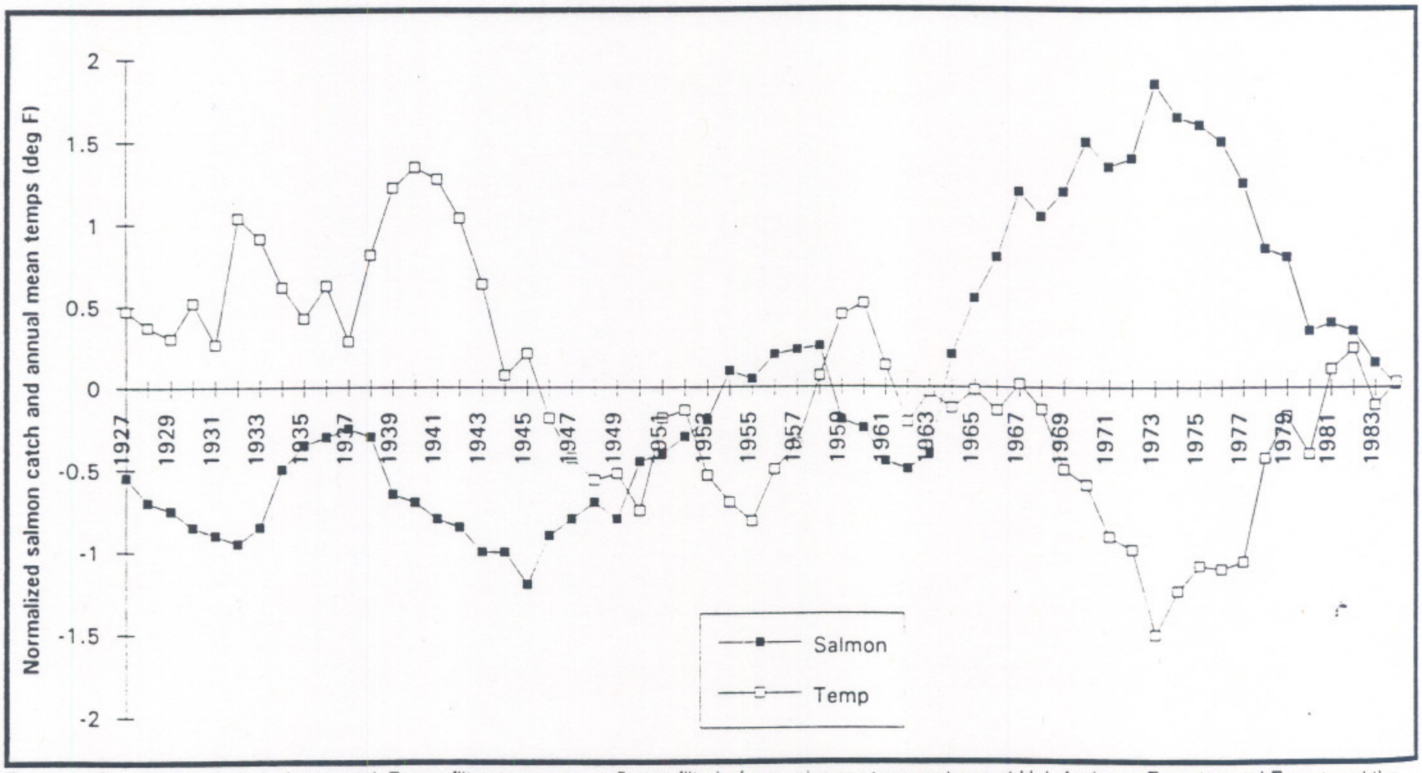

Figure 1. Smoothed values (salmon catch 7-year filter, temperature 5-year filter) of annual mean temperatures at H.J. Andrews Experimental Forest and the catch of coho salmon off the coast of Washington and Oregon, 1927-1983.

arge Spatial and Long Temporal Aspects of .tmospheric and Ocean Currents

It is well known that the currents of the atmosphere and ocean are related. Airflow over the surface of the ocean is one of the major driving forces of the ocean currents. Ocean flow in the eastern North Pacific is dominated by the Subarctic current and West Wind Drift, to its south, which together transport water eastward approximately between latitudes 40° and 50°N. This flow is driven by the westerly atmospheric flow at these latitudes. Toward the east of the ocean, the flow of these currents bifurcates. Part of it flows northward, as the Alaskan current, along the coast of British Columbia, and then westward along the southern coast of Alaska to form the Alaskan Gyre. Another part flows southward, forming the California current, part of which flows eastward, under the influence of the Trade Winds when it reaches about 20°N. The West Wind Drift, California current, and return westward flow of the North Equatorial current form part of the Central Pacific Gyre.

In two parts of these flows, nutrient-rich water can be brought from lower levels of the ocean by upwelling. Along the coast of the conterminous United States, this is achieved by application of the Coriolis force to coastal airflow (with a northerly component in summer) and coastal ocean current flow. The Coriolis force tends to deflect objects to the right of their path of motion in the Northern Hemisphere. This leads to offshore and divergent surface ocean flow which, in turn, draws the nutrient-rich water up from below. There is also upwelling on the northern side of the Subarctic current in the southern part of the Alaskan gyre. This upwelling is due to a process called Ekman pumping, which is caused by the change of flow direction of the faster velocity water near the surface compared to the slower velocity water at increasing depths in the ocean.

Winds in the atmosphere above the ocean are responsible for both the velocity of the ocean currents and their precise location from year to year and from decade to decade. They may also be responsible for the precise location of the bifurcation of the Subarctic current and the way in which quantities of nutrient-rich water are partitioned into the Alaskan and California currents.

The atmospheric currents of importance here are the winter flow of the mid-latitude westerly winds and, to a lesser extent, the flow of the easterly Trade Winds. At the surface of the Earth, the westerlies in winter are manifested by geostrophic air flow at the southern part of the Aleutian Low pressure system. In the upper air, at about 18,000-20,000 feet above the Earth's surface, the flow takes the form of long waves (parallel to the Earth's surface). The position and strength of the air flow in the waves is variable but on the average is characterized by a ridge of high pressure over the eastern Pacific sandwiched between a trough of low pressure in the western Pacific, off the coast of Asia, and another trough over eastern North America and the western Atlantic Ocean (Barry and Chorley 1987. p. 136). The actual position and strength of the Aleutian Low and the position, degree of sinuosity (or amplitude of the waves), and strength of the flow in the upper air westerlies from year to year and from decade to decade is critical to controlling the flow and location of the ocean currents.

Climatologists have developed some simple indices to collapse a large amount of this atmospheric flow into a few numbers. The indices are sometimes called "teleconnective indices" since they help explain how pressure variations in one part of the hemisphere are related (teleconnected) to those in another part. The indices of use in this discussion are the Central North Pacific index (CNP), the Pacific North American index (PNA) and the Southern Oscillation Index (SOI). It should also be remembered that the strength of the teleconnective patterns is not necessarily stable over time.

The SOI is commonly used to measure the strength of the El Niño and the opposite La Niña phenomena. The SOI is measured as the mean sea level pressure difference between Tahiti and Darwin, Australia. Due partly to difficulty in terminology, it is becoming increasingly common to refer to "warm events" (which include El Niño) and "cold events" (which include La Niña). In the newer terminology "warm" and "cold" refer to the SSTs of the central Pacific Ocean.

Wallace and Gutzler (1981) were the first to introduce the PNA index. They characterized a strong winter PNA pattern as one associated with higher-than-normal temperature in the Pacific Northwest, resulting from a strong ridge of high pressure in the 700-millibar height field extending from the Pacific Northwest to Canada and Alaska. Wallace and Gutzler use a PNA index comprised of the pressure at four points on the latitude-longitude grid. The PNA index designed by Leathers *et al* (1991) and Leathers and Palecki (1992) following Yarnal and Diaz (1986) is the one used in this study. It uses a linear combination of standardized 700-mb geopotential height anomalies (Z*) at the grid points nearest the anomaly field centers. It is constructed as follows:

$$PNA = 1/3\{-Z^*(47.9°N, 170.0°W) + Z^*(49.0°N, 111.0°W) - Z^*(29.7°N, 86.3°W)\}$$

The PNA index describes the amplitude of the 700-mb flow pattern over the United States, which has a basic pattern of troughs of low pressure in the eastern Pacific and the eastern United States and a ridge of high pressure over the Rocky Mountain cordillera (see Leathers *et al* 1991, Figure 1). The meridional extreme of the pattern produces positive PNA values (and potentially more southwest winds over the Pacific Northwest), while the zonal extreme produces negative PNA values (and potentially more west winds over the Pacific Northwest). Yarnal and Diaz (1986) demonstrated how strongly positive PNA and negative (reverse) PNA patterns are associated, respectively, with warm and cold El Niño/Southern Oscillation events and, in turn, with precipitation and temperature anomalies on the west coast of North America.

Cayan and Peterson (1989) designed the CNP index as being the mean sea level pressure over the region 35-55°N and 170°E-150°W. They show that streamflow in the west has correlations in the range 0.3-0.6 SLP with anomalies in the North Pacific. During times of a weak CNP, streamflows are high in Washington and Oregon. During times of a strong CNP, the polar front jet stream flows north of the Pacific Northwest, and below-average streamflow is observed. This is also often seen during El Niño events (see Cayan and Peterson 1989, Figure 9).

Interrelationships between the values of the SOI, PNA, and CNP indices have also been shown (Cayan and Peterson 1989). Significant correlations appear between the SOI and PNA during winter and spring; the SOI and CNP during winter; and the PNA and CNP during winter, spring, and fall. All of the synoptic studies indicate quite clearly the linkages between SSTs and particular pressure and teleconnective patterns in the Pacific Ocean and various aspects of climate on the West Coast and in the Pacific Northwest.

The HWFS Model and its Relationship to Atmospheric Flow

To explain the relationships between catches of Alaskan pink salmon and northern sea and air temperatures and the inverse relationship between catches of Gulf of Alaskan pink salmon and Washington/Oregon coho salmon, Frances and Sibley (1991) and Frances (1993) use a model suggested by Hollowed and Wooster (1991). For convenience, I call this the HWFS model, after the initials of all four investigators. According to this model, the inverse relationship in catch in the two ocean areas might be explained by the north or south movement of the divergence, or bifurcation, zone between the Alaskan and California current and the greater or lesser effect of the currents related to that north-south movement. The model is bimodal and postulates two states or modes of operation of the ocean currents. When the bifurcation zone is more to the north (HWFS Type A-West Coast), more cold, Subarctic current water is taken into the California current, and upwelling of nutrient-rich water off the Oregon and Washington coasts is enhanced. When the bifurcation zone is farther south (HWFS Type B-Alaska), more cold, Subarctic current water is taken into the Alaskan current, and water off the Oregon and Washington coasts is warmer.

Synthesis of Teleconnective Indices with the HWFS Model

The HWFS model may be placed in a larger atmospheric context by noting its relationship to the teleconnective index values discussed earlier (Figure 2). HWFS Type A-West Coast flow is associated with a high CNP value. This describes a weak Aleutian Low pressure, with winds coming more directly from the west across the Pacific at the latitudes of Washington and Oregon. This is consistent with a negative value of the PNA. The more northerly bifurcation of the Subarctic current pushes more water into the California current and gives rise to negative sea surface temperature anomalies. These conditions are not generally consistent with intense El Niño conditions. HWFS Type B-Alaska flow is associated with a low CNP value. This describes a strong Aleutian low pressure and enhanced southwesterly winds in the northeast Pacific. It is associated with meridional upper air flow and a positive PNA value. The more southerly Subarctic current bifurcation enhances northward ocean flow into the Alaskan current, giving rise to positive SST anomalies in the eastern part of the northeast Pacific. These conditions are consistent with results of El Niño events.

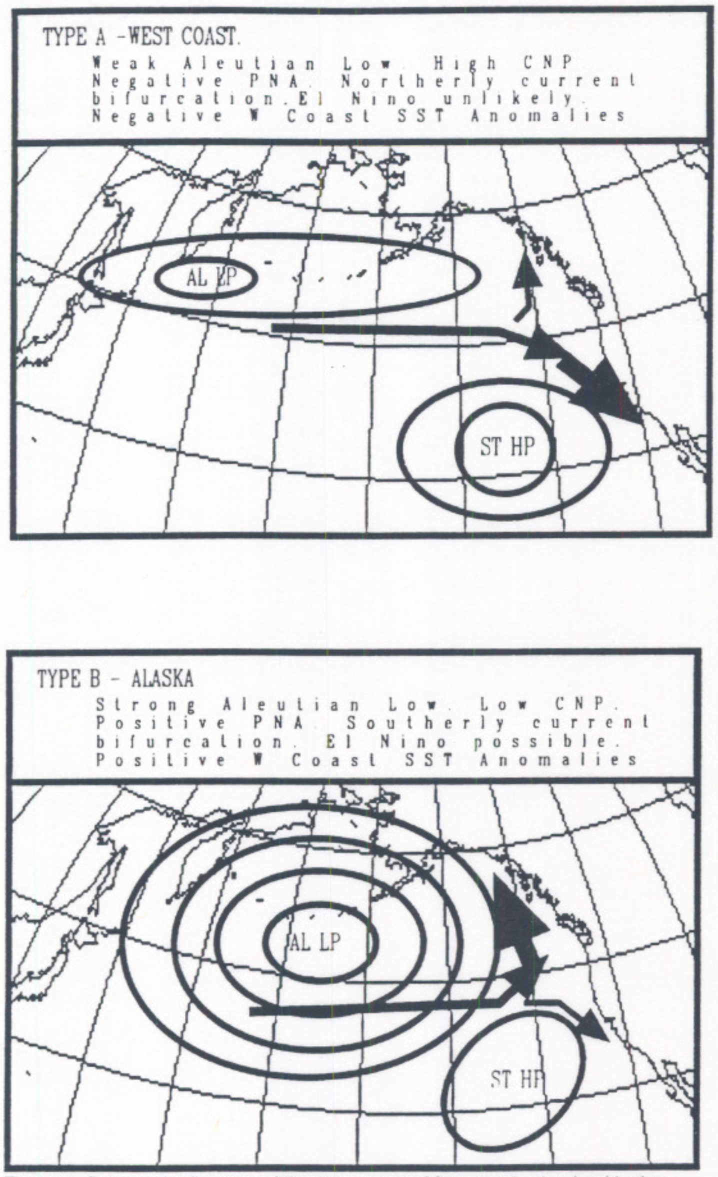

Figure 2. Schematic diagram of the two types of flow hypthothesized in the HWFS model and its associated atmospheric and oceanic events. Thick black lines schematically represent isobars of surface atmospheric pressure. Shaded arrows schematically represent the flow of the subarctic current and its partitioning into either the Alaskan current or the California current.

Hollowed and Wooster (1991) and Frances (1993) have suggested that El Niños are related to the change of state between Type A and Type B flow. They suggest that over the last 60 years, the switch from Type A mode to Type B mode has always occurred at the time of significant El Niño events (*eg*, 1925/26, 1940/41). This relationship, if true, is worthy of further investigation.

Further Research and Concluding Comments

There is a large amount of research to be completed before the ideas discussed here can be finalized and confirmed by observational data. Some of the more important research tasks include:

- Examine individual El Niños and salmon catch off Washington and Oregon with respect to the entire available salmon catch record and the intensity values of individual El Niños.
- Examine in more detail the exact biophysical processes leading to the decrease of salmon population size during El Niño years.
- Further identify the variability of the bifurcation of ocean water flow from the central north Pacific into the Alaskan and California currents. Possible tools for doing this include: an examination of ocean temperature, salinity, and other flow-identifying data from ocean weather ship P; and use of remote sensing imagery.
- Recalculate the PNW air temperature/coho salmon catch using the more representative climate divisional air temperature records of the National Weather Service and a temporally coherent salmon catch data series updated into the mid-1990s.
- Extended these analyses to look for relationships between salmon catch and the teleconnective indices. Jamir *et al* (1994) have started work on this.
- Test the hypothesis that intense El Niño conditions occur more often under HWFS Type B mode than under Type A mode.
- Study the flip-over between the HWFS Type A to Type B mode and vice versa. In particular, investigate the role, if any, of El Niño events in this and the relationship of the mode change to known major step functions in atmospheric flow, such as occurred in 1976 (Trenberth 1990).

If the HWFS model is confirmed, we need to ask:

- How is it effected by long-term climate change at scales longer than the interdecadal scale?
- What feedbacks are there from the ocean to the atmosphere and vice versa, and how do they operate?

With respect to the second question, Namias has pointed out, in a whole series of papers (*eg*, Namias 1969), the importance of the two-way interaction between the Pacific Ocean and the atmosphere above it. This needs to be taken into account in a more time-specific framework with respect to the HWFS model.

If the results of these and other investigations confirm the existence of interdecadal cycles related to the atmospheric and ocean current operation, such confirmation will have important management implications for the salmon resource. Not the least, it will be important to cast any management plans within a framework of interdecadal natural variability, which may also have some predictability. Possibly more important is to further examine the historical and paleo record to further establish the strength of the variability and possibility of forecasting it in the future.

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