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# Variability of the Columbia River plume observed in visible and infrared satellite imagery

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**Abstract.** Variability of the Columbia River plume in coastal waters off the northwestern United States, 1979–1985, was observed in sea surface temperature and phytoplankton pigment images derived from Advanced Very High Resolution Radiometer and Coastal Zone Colour Scanner data. The orientation, shape, intensity and relative temperature of the plume vary in response to coastal winds and wind-driven surface currents. From October to April, plume water is oriented northward along the coast. Following the spring transition in April or May, the plume is oriented southward, either adjacent to the coast or offshore. Transition between the winter and summer forms can be observed in the satellite imagery. Brief reversals of the prevailing seasonal winds cause rapid changes in the orientation and shape of the plume. Remote sensing of the Columbia River plume offers valuable information for oceanographic studies and fisheries management in the region. Derivation of an appropriate visible–infrared signature for plume waters and tracking of tidal pulses in the plume is suggested as a promising direction for future research.

## 1. Introduction

The Columbia River, with a mean flow of $7300\,m^3\,s^{-1}$, is the largest point source of freshwater flow into the eastern Pacific Ocean. Columbia River water forms a low-salinity plume extending outward from the river mouth above a shallow ($<20$ m) halocline. Seawater is entrained into this plume by wind-generated turbulence and by frontal mixing and secondary lateral flow induced by potential energy within the plume (McClimans 1979). River flow and turbulent mixing rates are such that anomalously low surface salinities ($<32{\cdot}5$ psu) may be detected over the entire shelf and slope and out to 400 km from the coast of Washington and Oregon (figure 1).

The Columbia River estuary is partially mixed, meaning that seawater intrudes beneath the freshwater outflow, except at very high or low stages of river flow (Neal 1972). A recent model study of such estuaries (Zhang *et al.* 1987) has shown that the basic tendency of a river plume to turn to the right, facing downstream in the northern hemisphere, is modified and even reversed by the steepness of the continental shelf and by longshore surface current velocity. The Columbia River plume flows out over a relatively narrow and steep shelf, accentuating the Coriolis deflection, but is subject to strong seasonal variation in longshore flow of coastal waters.

Coastal surface currents in this region are primarily wind-driven (Huyer *et al.* 1975, Huyer 1979, Hickey 1979 a). Seasonal variability is very strong: large-scale changes in atmospheric pressure systems over the North Pacific drive spring and fall transitions in prevailing winds, sea level, currents, and temperature on the continental

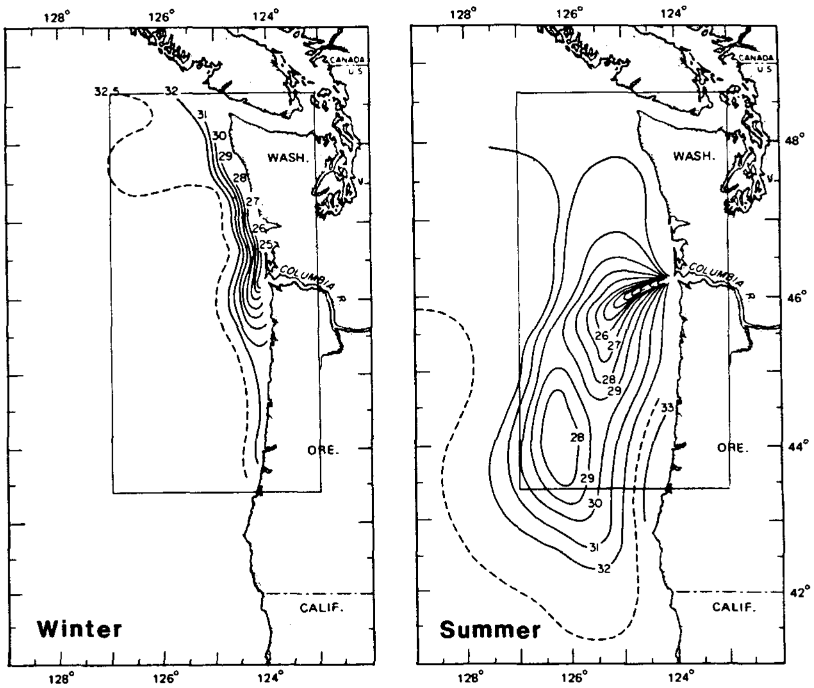


Figure 1. Generalized winter and summer surface salinity distributions in the Columbia River plume region (Barnes *et al.* 1979, figure 3.12). Box indicates coverage of satellite imagery in figures 4, 5, and 6.

shelf (Strub *et al.* 1987 a,b). In winter, southerly winds cause onshore Ekman transport of surface water, high sea level and downwelling of isopycnal surfaces towards the coast. These conditions are balanced by northward geostrophic flow. As prevailing winds shift from southerly to northerly in April–May, offshore Ekman transport begins, sea level drops, and upwelling causes isopycnal surfaces to slope upwards towards the coast. The resulting geostrophic flow is then southward. Surface temperatures decline as summer upwelling intensifies. The fall transition back to winter downwelling, high sea level and northward surface currents occurs in September–October.

Seasonal variability in the distribution of plume water is known from conventional hydrographic surveys (Barnes *et al.* 1972). In general, the plume is oriented northward in winter and southward in summer, transported by alongshore surface currents. Repetitive point sampling from ships has indicated that the plume responds quickly to high-frequency (days) changes in local winds (Hickey 1979 b). The size of the plume may be affected by Columbia River flow, which varies by a factor of five or more over the year, with a maximum in May–June from snowmelt and a minimum in late summer (Barnes *et al.* 1972). However, we will consider variations in surface winds and wind-driven currents as the primary cause of variability of the Columbia River plume.

Variability on seasonal and shorter time scales can be monitored effectively with satellite sensors covering large areas synoptically, with a resolution of $\sim 1$ km. Under good viewing conditions, the plume is clearly defined by its visible and infrared signature. The apparent phytoplankton pigment concentration of plume water, measured by the Coastal Zone Colour Scanner (CZCS), is very high. Its surface temperature, measured by the Advanced Very High Resolution Radiometer (AVHRR), is colder than surrounding coastal ocean water in winter and warmer in summer.

We examined the variability of the Columbia River plume as part of a study of survival of juvenile salmon released from Columbia River hatcheries. The goal of the larger study is to use satellite imagery and other real-time environmental data to optimize the timing of hatchery releases for maximum survival. We describe the plume variability results here as an illustration of the use of satellite imagery in studying and monitoring an important aspect of the coastal ocean in the northeast Pacific.

## 2. Methods

Satellite data were processed at the Scripps Satellite Oceanography Facility of the Scripps Institute of Oceanography in La Jolla, California. Image data were examined primarily from April–July for 1979–1985, because of the scope of the juvenile salmon survival study. For 1982, we processed a monthly time series of imagery to cover the entire annual cycle.

Daytime thermal infrared data, from channel 4 ($11\,\mu$m) of the AVHRR (on NOAA-6 and NOAA-7 satellites), were corrected for the effect of thin low clouds using channel 2 ($0{\cdot}7\,\mu$m–$1{\cdot}1\,\mu$m) near-infrared data (Gower 1985). Infrared radiance was then converted to brightness temperature following Lauritson *et al.* (1979).

Visible radiances from the CZCS (operational on the Nimbus-7 satellite from August 1978 to June 1986), were processed with an algorithm based on Gordon *et al.* (1983) to remove effects of Rayleigh and aerosol scattering and to compute pigment concentrations from corrected blue:green radiance ratios. AVHRR and CZCS images were co-registered to a Mercator grid covering the coast of Washington and Oregon.

CZCS pigment algorithms are appropriate for estimating phytoplankton pigment concentration only in Case 1 waters, where photoplankton cells and associated products are the only important determinants of optical properties (Gordon and Morel 1983). River plumes are Case 2 waters, containing terrigenous sediments and dissolved organic matter, as well as anthropogenic material. The 'apparent' pigment concentration derived by the CZCS algorithm is used here as a qualitative index of the green:blue colour signature of plume water, rather than as an estimate of phytoplankton pigment concentration. Any additional error in this estimate caused by using a single-scattering approximation to compute the Rayleigh scattering radiance (Gordon *et al.* 1988) does not affect its use as a colour-signature index.

The 1979–1985 coastal wind velocity and surface wind stress, in a three-degree square centred at 46° N 124·5° W (55 km SW of the river mouth), were computed at 6 h intervals from U.S. Navy Fleet Numerical Oceanography Center surface pressure analyses by the NMFS/Pacific Fisheries Environmental Group in Monterey, California (see Bakun (1975) for methodology). A smoothed time series of 12 h mean wind vectors (five-point running mean, weighted 1:2:3:2:1) is presented here.

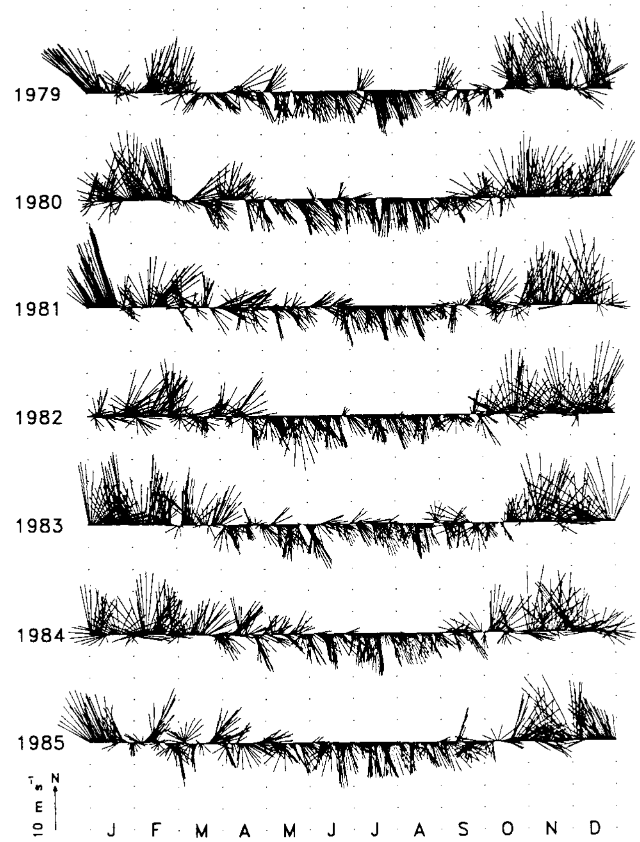


Figure 2. Time series of calculated wind vectors (smoothed 12 h means) at 46° N 124·5° W.

## 3. Results and discussion

### 3.1. *Winds*

The wind velocity time series (figure 2) shows strong seasonality, with northerly winds prevailing from May through September and strong southerly winds from October through April. The spring transition is marked by a change from prevailing southerly to northerly winds. The timing of the spring transition varies from year to year, with nominal dates as follows: 8 May 1979, 20 April 1980, 23 June 1981, 22 April 1982, 4 April 1983, 26 May 1984 and 5 May 1985.

Higher-frequency fluctuations in wind velocity, at the scale of about a week, appear as occasional relaxations or reversals of the seasonal prevailing winds. These fluctuations are caused by the passage of storm systems through the area.

### 3.2. *Plume*

Satellite images found to provide adequate coverage of the Columbia River plume and processed to yield sea surface temperature (AVHRR) or colour (CZCS) fields are listed in the table. Orientation, shape, size, intensity and relative temperature of the

Satellite imagery of the Columbia River plume region. Image data types: T = sea surface temperature from AVHRR, P = phytoplankton pigments from CZCS. Description includes: (1) orientations of major axis and secondary flows (for N or S major axis, onshore = adjacent to coast, offshore = separated from coast by coastal water); (2) shape, when well defined: round = relatively circular, short = elongated and less than twice as long as wide, long = elongated and more than twice as long as wide; (3) Front = intense temperature and/or colour front near the mouth at edges of the plume off the major axis, and (4) Temperature relative to surrounding coastal water (warm or cold).

| Date | Type | Plume description |
|---|---|---|
| 1979, 19 May | P | SSW, long, front |
| 21 May | P | SSW then WSW, long |
| 30 May | P | SW, short, front |
| 14 July | P | W then N, short, front |
| 1980, 10, 11 April | P,T, | N onshore, short, cold |
| 21 April | P | N onshore, some S |
| 26 April | P | W, some N, round, front |
| 17 May | P | SSW, short, front |
| 30 June | P | SSW, short, front |
| 6 July | T,P | SW then N onshore, short, cold |
| 1981, 28 May | P | W, some N, round |
| 10, 13 June | T,P | W, some S, round, front, warm |
| 2 July | T,P | W then SSW, long, warm |
| 1982, 5 February | T,P | N, round, front, cold |
| 21 March | T,P | W then N, long, cold |
| 21 April | P | W, short |
| 24, 25 April | T,P | WSW, short, front, warm |
| 24 May | T,P | SSW, long, front, warm |
| 28 May | T,P | S onshore, long, front, warm |
| 12 July | T,P | WSW, round, warm |
| 17, 18 August | T,P | SW, long, warm |
| 23 September | T,P | W, short, warm |
| 30 September | T,P | W then N, warm |
| 12, 13 October | P,T | W then N, not well defined |
| 9, 10 November | P,T | N onshore, front, cold |
| 1983, 13 April | P | W, some S, round, front |
| 15 April | T,P | W then S, short, front, cold |
| 16 April | P | SW, short, front |
| 12 May | T,P | W then N and W, some S, short, cold |
| 22 May | T,P | S offshore then W, long, warm |
| 20 June | T, | S onshore, short, front, warm |
| 15 September | T,P | SW, short, warm |
| 1984, 14 July | T | SW, long, warm |
| 16 July | T | W then SSW, long, front, warm |
| 20, 21 August | T,P | W then S, short, front, warm |
| 1985, 7 May | T,P | N, round, some S, front, warm |
| 15 May | T,P | SSW then W, long, warm |
| 9 June | T | W, round, front, warm |
| 17, 18 June | T,P | S offshore when W, long, front, warm |

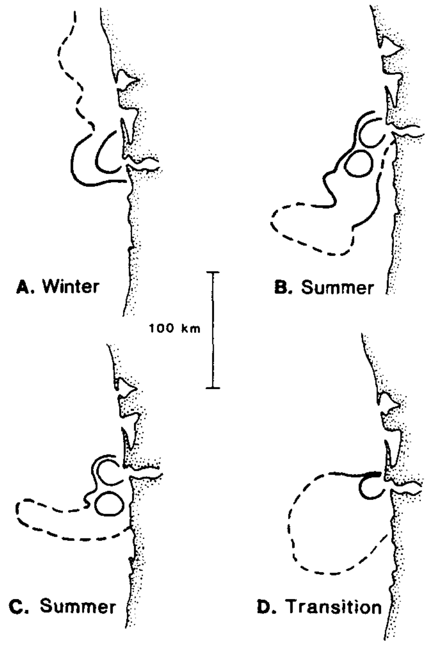


Figure 3. Schematic drawings of basic forms of the Columbia River plume. Solid lines represent strong colour and/or temperature boundaries, dashed lines represent weaker boundaries.

plume vary in these images. A seasonal pattern of two basic forms is illustrated schematically in figure 3.

During winter, plume water is advected northward along the coast (figure 3 (*a*)). The most obvious plume water is a semi-circular mass of green water, colder than the surrounding coastal water, just north of the mouth. Water along the coast north of this mass is still relatively cold and green, but is probably a mixture of Columbia River water, run-off from coastal rivers and oceanic surface water driven onshore.

During summer, the plume is advected southward, usually separated from the coast (figure 3 (*b*)) due to offshore Ekman transport, but sometimes adjacent to it (figure 3 (*c*)). Plume water is warmer than surrounding coastal water, which is cooled by upwelling. During transition between the basic winter and summer forms, the plume is roughly circular at the mouth of the river (figure 3 (*d*)).

Details of the plume's variable characteristics are briefly described in the table. These details will be discussed in the following descriptions of the plume's responses to winds and other forcing.

### 3.3. *Spring transition*

A sequence of CZCS images from 1982 (figure 4) illustrates a typical spring transition. On 2 February, the plume is in the typical winter form, advected to the north along the coast. Intermittent northerly winds during 4–24 March forced the plume offshore by 21 March. Northerly wind events also occurred on 6–10 April and

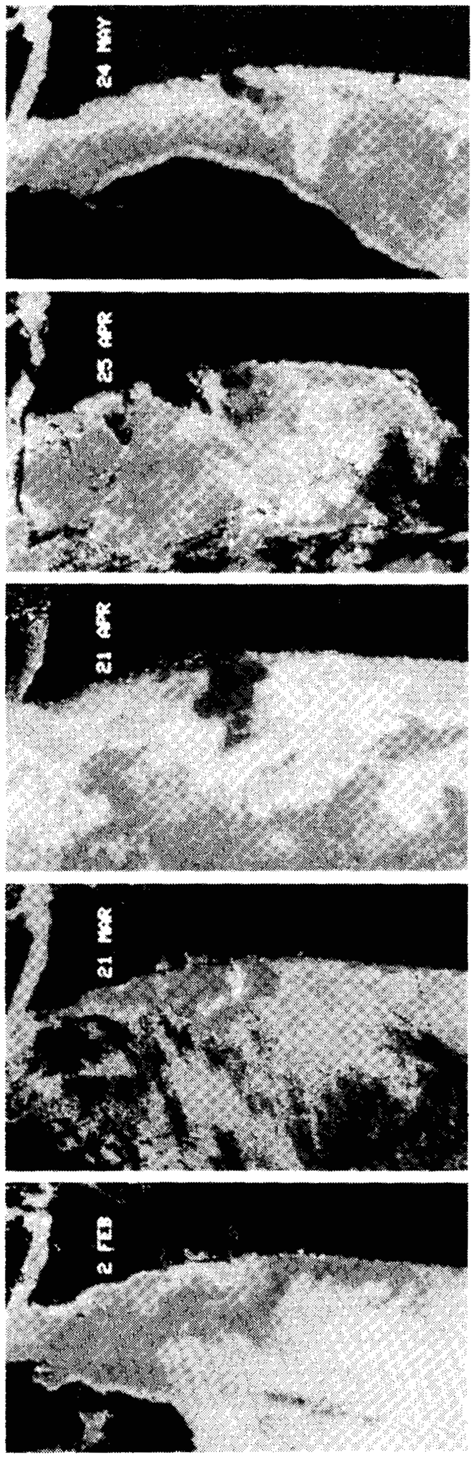


Figure 4. CZCS images illustrating changes in the Columbia River plume during spring transition in 1982. Colours indicate increasing phytoplankton pigment concentrations: purples ($<0{\cdot}1\,mg\,m^{-3}$), blues ($0{\cdot}1$–$0{\cdot}4\,mg\,m^{-3}$), greens ($0{\cdot}4$–$1{\cdot}5\,mg\,m^{-3}$), yellow and oranges ($1{\cdot}5$–$4{\cdot}0\,mg\,m^{-3}$), reds ($>4{\cdot}0\,mg\,m^{-3}$).

17–20 April, although prevailing northerly winds did not begin until 23 April, the nominal date of the spring transition. Thus, on 21 April, the plume is in transition, roughly circular and oriented W of the river mouth. On 25 April, the plume is still in transition, but now oriented WSW. On 24 May, after a month of prevailing summer northerlies, the plume is in the typical summer form, elongated and oriented SWS.

A rapid spring transition is seen in two images from 1985 (not shown here). The nominal date of spring transition was 14 May, although intermittent northerly winds occurred during 4–12 May. A CZCS image on 7 May shows the plume in a winter form, but beginning transition: most of the green plume water is along the coast to the north of the river mouth, but there appears to be some flow to the south. The next available image on 15 May shows the plume in a well developed summer form, elongated and oriented WSW.

These observations show that the spring transition of the plume may be initiated by intermittent northerly winds prior to the nominal spring transition of prevailing winds. Transition to the southward summer form is usually not complete until the prevailing summer northerlies are well-established, although the 1985 images show that this transition can be completed in a matter of days.

### 3.4. *Summer reversal*

A response of the plume to high-frequency wind variability is illustrated by two CZCS images from 1979 (figure 5). On May 19, the plume is in a well developed summer form, long and oriented SWS, following spring transition on 8 May. Prevailing summer northerlies were interrupted by a southerly wind event on 7–11 July. On 14 July, the plume is short and oriented W of the river mouth, with some plume water flowing north. Other imagery (e.g. 9 and 18 June 1985, see the table) shows that the plume returns to the summer form when winds return to normal after such a summer reversal.

Three other summer plume reversals were seen in the satellite imagery (6 July 1980, 12 May 1983 and 9 June 1985), shortly after very weak and brief southerly wind events. These observations suggest that the plume moves to the north, with the Coriolis deflection, much more readily than to the south.

### 3.5. *Coastal upwelling*

The pair of images in figure 6 illustrate that upwelled water replaces Columbia River plume water as the most important component of Washington–Oregon coastal waters in late summer. In 1983, summer northerly winds prevailed from 4 April to 14 October, although southerly winds occurred during 9–11 and 20–23 September.

In an AVHRR image from 21 September, coastal upwelling is indicated by cold water along the coast. Note the long streamers of very cold water extending offshore from the Oregon coast south of the Columbia River mouth. Coastal upwelling increases to the south of the river mouth, reaching a regional maximum at 40°N (Bakun 1975). Plume water can be discerned at the river mouth as a very small patch of warm water that seems to be turning north in response to the anomalous southerly winds. The structure of the green water in the CZCS image from 20 September is dominated by phytoplankton produced in the cold, nutrient-rich upwelled water.

From July until September, as upwelling strengthens and river flow declines, the

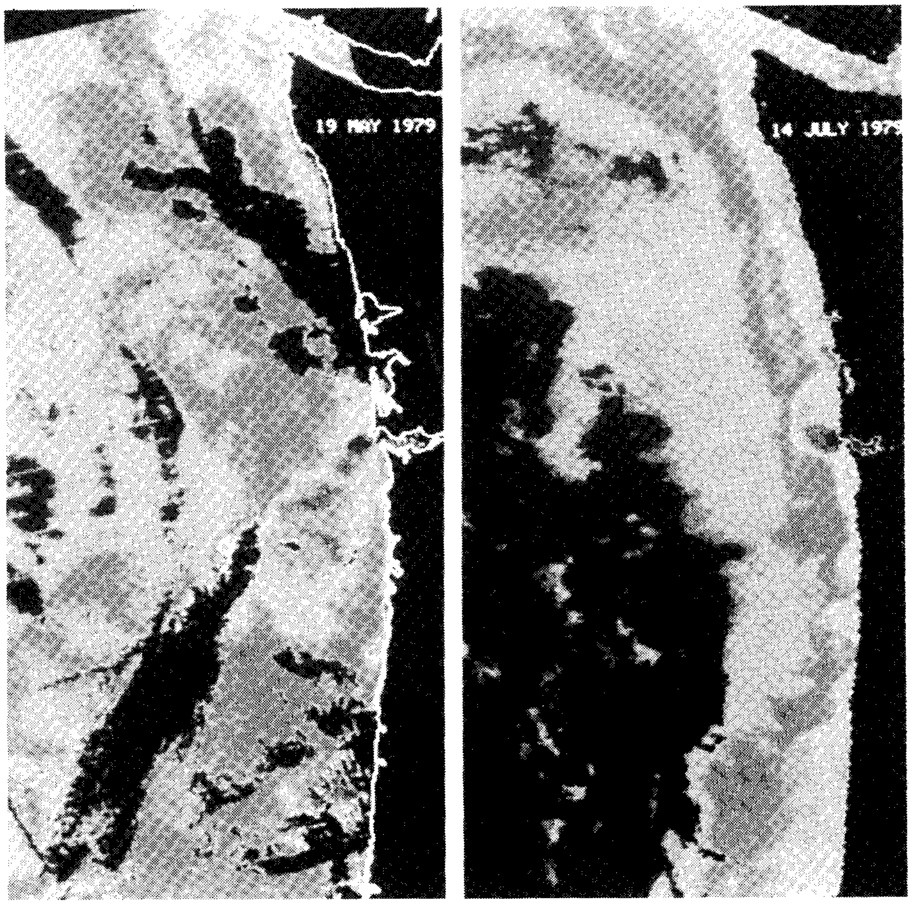


Figure 5. CZCS images illustrating the response of the Columbia River plume to a reversal of the summer prevailing winds during 7–11 July 1979.

plume can only barely be discerned in temperature images and cannot be differentiated from upwelled water in colour images. In our experience, this is the only time of year when the plume is more readily discernible in temperature imagery than in colour imagery.

### 3.6. *Tidal pulsing*

A CZCS image from 24 May 1982 (figure 7) shows the segmental structure of the plume, which is often evident in early summer when river flow is at its maximum. This pattern may be attributed to tidal pulsing of the river flow. Tidal currents reverse the flow at the mouth, causing two pulses of up to $10^9\,m^3$ of river water to enter the ocean daily. Each pulse is equivalent to a patch 2 m deep and up to 20 km in diameter, consistent with measured salinity distributions in the plume (Barnes *et al.* 1972) and with the pattern seen in this image. Identification and tracking of individual pulses could aid studies of mixing and productivity in these waters.

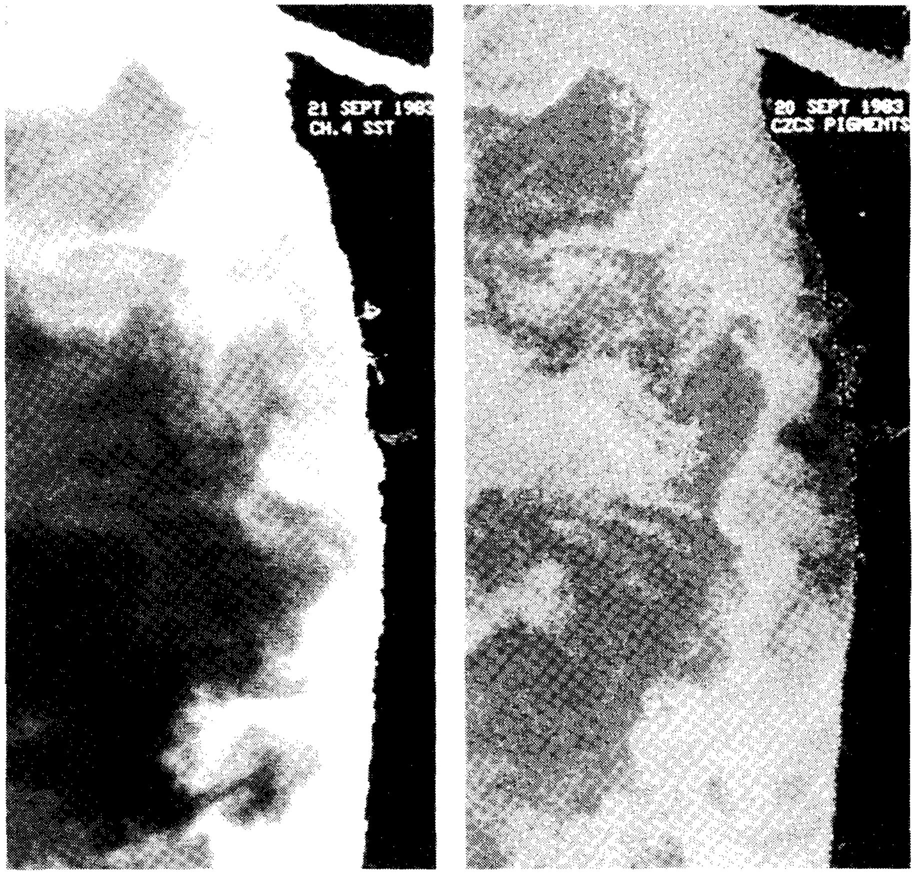


Figure 6. A pair of AVHRR and CZCS images, from 21 September 1983, illustrating the Columbia River plume region during strong summer upwelling. In the AVHRR image, cold sea surface temperatures are light grey and warm temperatures are dark grey.

## 4. Conclusions

The Columbia River plume has long been recognized as an important component of the coastal Pacific Ocean between Vancouver and northern California. However, it has been difficult to study and monitor its variability by shipboard sampling alone. Visible and infrared sensors on satellites offer the frequent and synoptic coverage of this region needed to follow the plume's rapid responses to seasonal and higher frequency forcing. We found that the plume was almost always more clearly defined in CZCS colour imagery than in AVHRR sea surface temperature imagery, because the magnitude and sign of the temperature difference between plume water and coastal ocean water varied seasonally. Remote sensing studies of such river plumes could be enhanced in the future by quantifying the visible–infrared signature of the plume. For example, the colour of plume water is determined by sediments and other substances, as well as by phytoplankton pigments, so a more appropriate pigment algorithm could perhaps differentiate plume and upwelled waters in CZCS imagery.


Figure 7. CZCS image, from 24 May 1982, illustrating the Columbia River plume during peak river flow in early summer.

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